RIVER RESEARCH AND APPLICATIONS

River Res. Applic. (2011)

Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/rra.1596

SPATIAL AND TEMPORAL WATER QUALITY VARIABILITY IN AQUATIC HABITATS OF A CULTIVATED FLOODPLAIN†

F. DOUGLAS SHIELDS, JR.*, RICHARD E. LIZOTTE, JR. and SCOTT S. KNIGHT

Agricultural Research Service, US Department of Agriculture, PO Box 1157, Oxford, Mississippi 38655, USA

ABSTRACT

The floodplains of lowland rivers contain diverse aquatic habitats that provide valuable ecosystem services but are perturbed when intensively cultivated. Hydrologic, water chemistry and biological (fish) conditions in five aquatic habitats along the Coldwater River, Mississippi, were measured for more than 4 years: the river, two severed meanders that functioned as backwaters, a managed wetland and an ephemeral channel draining cultivated fields. Off-channel habitats were connected to downstream regions 0.10% to 32% of the dry season and 24% to 67% of the wet season. The median temperatures for the five monitored sites ranged from 18°C to 23°C, the median total solids concentration for all sites was 135 mg L^{-1}, the median total phosphorus was 0.29 mg L^{-1} and the median total nitrogen was 1.56 mg L^{-1}. Chemical and physical water quality displayed strong seasonal differences between the wet winter/spring and the dry summer/fall periods so that temporal variation consisted of gradual seasonal trends superimposed on strong diurnal variations. All off-channel habitats exhibited periods of hypoxia and temperatures >30°C during the dry season. Between-site gradients of water and habitat quality were strongly coupled to water depth and runoff loading. The rehabilitation of one backwater by increasing water depth and diverting agricultural runoff was associated with improved water quality and fish species richness relative to an adjacent untreated backwater. The diversion of polluted runoff and the use of water control structures to maintain greater water depth were observed to be effective management tools, but the former reduces the water supply to habitats that tend to dry up and the latter reduces connectivity. Published in 2011 by John Wiley & Sons, Ltd.

KEY WORDS: water quality; floodplains; agriculture; fish; nitrogen; phosphorus; sediment; hypoxia; restoration; rivers; connectivity; backwaters; wetlands

Received 2 May 2011; Revised 12 August 2011; Accepted 18 August 2011

INTRODUCTION

The floodplains of lowland rivers provide valuable services in support of riverine ecosystems (Ward *et al*., 2001; Buijse *et al*., 2002; Wiens, 2002; Bondar-Kunze *et al*., 2009) but are often disturbed by agricultural development. Unmodified lowland floodplains are characterised by low relief and gentle undulating topography such as ridge and swale patterns that produce high levels of spatial heterogeneity and associated biological diversity. Vegetative cover is composed of bottomland forests, canebrakes and other wetland plants, and hydrology is characterised by periodic floods of long duration and low amplitude. Channels have high sinuosity and multiple, stage-dependent connections to lakes, sloughs, wetlands and depressions. Such systems tend to alternate between lentic conditions and sluggish flow (Pennington, 2004; Killgore *et al*., 2008a), with temporal variations dominated by high-amplitude, low-frequency flood pulses produced by main channel events (Junk *et al*., 1989; Ward and Stanford, 1995; Tockner *et al*., 2000) that produce rapid changes in the floodplain water chemistry and biology of varying duration (Roozen *et al*., 2008). Floodplain habitat resources, hydrology and water quality conditions are transformed by development. Agricultural development includes tile drainage, precision land levelling, stream channelization, filling of wetlands, excavation of ditches, flood control and water table manipulation.

Nutrient enrichment has been widely reported for water bodies in cultivated floodplains in the USA (Heatherly *et al*., 2007; Dubrovsky *et al*., 2010), and declining water tables (Clark and Hart, 2009) and weather extremes associated with climate change further threaten these resources. Higher sediment yields associated with cultivation lead to shoaling, and shallower lakes tend to experience lower dissolved oxygen (DO) concentrations than deeper ones because of respiration occurring throughout the water column (Miranda *et al*., 2001; Miranda, 2005). These shoaled lakes also tend to have lower water transparency because of phytoplankton and resuspension of bed sediments by benthivorous fish (Roozen *et al*., 2003; Miranda and Lucas, 2004; Lin and Caramaschi, 2005) and wind (Chao *et al*. 2008). Fish communities in such systems exhibit strong linkages to abiotic factors and are dominated by tolerant omnivores with few predators (Miranda and Lucas, 2004). Deeper lakes provide more stable water chemistry and a wider range of microhabitats, which are reflected in fish assemblages

*Correspondence to: F. D. Shields, Agricultural Research Service, US Department of Agriculture, PO Box 1157, Oxford, Mississippi 38655, USA.
E-mail: doug.shields@ars.usda.gov

†This article is a US Government work and is in the public domain in the USA.

that include more predators, more large-body species and less tolerant species (Miranda, 2010). Linkages between biotic characteristics and abiotic factors in streams, ditches and bayous in cultivated floodplain watersheds are not as clear as those for lakes (Maul *et al*., 2004; Rebich *et al*., 2004; Stephens *et al*., 2008).

Additional information is needed regarding water chemistry in aquatic systems of intensively cultivated floodplains to develop management and regulatory strategy, to conserve remaining ecosystem resources and to guide future monitoring and research. Spatially extensive but temporally intensive surveys of floodplain water chemistry have been provided by others (Table I). The objectives of this study were to assess water chemistry variations and associated fish community characteristics within a relatively small spatial domain over several years and to relate these variations to environmental factors. A further objective was to assess the efficacy of selected environmental manipulations as ecosystem restoration measures.

STUDY SITES

Study sites were located within the Yazoo River Basin of Northwestern Mississippi, USA. The Yazoo River Basin encompasses 34 600 km^2 and is separated into two distinct topographic regions of roughly equal size, the Bluff Hills (Hills) and the Mississippi Alluvial Plain (Delta). The Delta is a prime example of a floodplain modified for large-scale agricultural cultivation. Before European settlement, most of the Delta was covered with bottomland hardwoods and canebrakes, and annual floods from the Mississippi River inundated almost the entire landscape. In 1821, naturalist John James Audubon described the Yazoo River as 'a beautiful stream of transparent water' (Smith, 1954 in Kleiss *et al*., 2000). Now, approximately two thirds of the Delta is cultivated for row crops, and approximately two thirds of row cropland is irrigated. Soils in this region consist of clay and fine sand from alluvial deposition of the ancestral Mississippi and Ohio Rivers (Guedon and Thomas, 2004). Bottomland soils are often heavy clay but may be sandy silts, whereas occasionally low sandy ridges occur in ridge and swale topography. However, much of the productive land has been laser-levelled and is drained by a network of ditches. Streams in the Delta are typically sluggish because of the limited slope and are periodically turbid from sediment runoff. Stream bottom material varies from clay to fine sand. Most river and stream channels have been straightened more or less to facilitate drainage.

Clearing the Delta for agriculture ca. 1900 exposed the fine, alluvial soils to erosion, increasing turbidity levels, suspended sediment, nutrient and pesticide concentrations and otherwise degrading water chemistry (Cooper *et al*., 1982; Dendy *et al*., 1984; Cooper, 1987; Kleiss *et al*., 2000; Coupe *et al*., 2005; Killgore *et al*., 2008a; Stephens *et al*., 2008). Lake sedimentation rates increased as much as 50-fold (Wren *et al*., 2008). Twentieth-century deposition rates reported for Delta lakes range from 1 to 6 cm year^{-1} (Ritchie *et al*., 1979; McHenry *et al*., 1982; Cooper and McHenry, 1989; Wren *et al*., 2008; Shields *et al*., 2009a). Despite these changes and effects, lakes, wetlands, streams and remnants of such systems remain prominent features of the Delta landscape. Most of these systems exhibit degraded water chemistry (Table I). For example, depth reductions due to sedimentation are associated with decreasing DO minima. Both chronic and acute hypoxia are common in the Delta, and warmer weather often produces extreme diurnal variations in temperature, pH, DO concentration and other constituents, presumably because of algal blooms (Hicks and Stocks, 2010). Despite extreme anthropogenic effects on the morphology, hydrology and water chemistry of Delta aquatic systems, 102 species of fish have been reported for the Delta (Ross, 2001), and few extinctions have been recorded (Bryant, 2010). Most fish species found in pre-European archeological sites are still abundant (Bryant, 2010).

Five adjacent Delta water bodies were studied over a period of 4 years (water years 2007–2010, inclusive). These included (i) a 2-km reach of the Coldwater River approximately 20 km downstream from a flood control reservoir, (ii) an adjacent backwater (severed meander bend) affected by sedimentation, (iii) another adjacent severed meander bend rehabilitated by emplacement of a weir, (iv) a wetland and (v) an ephemeral slough (Figure 1). This stretch of the Coldwater River has been cited for water chemistry and habitat degradation associated with sediment and other agripollutants (Mississippi Department of Environmental Quality, 2003; US Corps of Engineers, undated), but reports from 1990 to 1994 indicated 13 to 22 species of fishes captured each year using hoop nets with higher catches per unit of effort than four other rivers in the Yazoo basin sampled during the same period (Jackson *et al*., 1995). The severed meander bends were created by man-made cutoffs constructed in 1941 to 1942 (Whitten and Patrick, 1981). Both meanders were 1.5 to 2 km long and 40 m wide and were inside the main stem flood control levee. Local watershed soils were primarily poorly drained Alligator (40%) or Sharkey clays (47%), with the remainder being Tensas silty clay loam. Lands outside the old bends were in row-crop cultivation (primarily soybeans, *Glycine max*, grown using no-till or minimum tillage), whereas lands inside the bends were in forest or fallow. Buffers of natural vegetation 5 to 100 m wide were on both banks of the old channels. Both backwaters received runoff from cultivated fields. Backwater levels were tightly coupled with Coldwater River stage when the river stage exceeded the controlling

DOI: 10.1002/rra

Table I. A review of the characteristics and key findings of previous studies of floodplain water quality within the Mississippi River embayment, USA

Location	Temporal domain	No. sites	Key findings	Source
Northwestern Mississippi	1977–1979	17	Widely variable water quality, but chronic Secchi disk depths $<$ 10 cm and DO levels $<$ 3.0 mg L^{-1} were common in this stream/lake/bayou system.	Price and Cooper (1981), Cooper *et al.* (1982)
Mississippi River alluvial plain in Mississippi	1993–1997	22	Mean nutrient concentrations highly correlated to mean turbidity and suspended sediment ($r^2 \geq 0.8$), which vary seasonally in response to runoff and agricultural practices (highest levels in winter and spring).	Pennington (1999)
Mississippi embayment of Mississippi, Louisiana, Arkansas, Missouri, Tennessee and Kentucky	1995–1998	38	Chronic low DO in streams due to low rates of re-aeration, abundant natural organic matter inputs and seasonally high water temperatures. In-stream algal growth was often light limited due to high turbidity. N concentrations were moderate, whereas TP concentrations were generally $>$0.1 mg L^{-1}.	Kleiss *et al.* (2000)
Mississippi River alluvial plain in Mississippi and Arkansas	2002	50	Strong seasonal differences in stream/bayou water quality (winter to summer). Turbidity and habitat assessment scores were most effective in indicating overall stream conditions. Mississippi sites were not categorised by water quality or habitat assessment.	Rebich *et al.* (2004)
Northwestern Mississippi	1996–2000	9	Runoff sampled from small ephemeral channels draining cultivated fields. Nutrient, sediment and pesticide loads were reduced by management practices. TP levels linked to suspended sediment concentrations.	Rebich (2004)
North Central Mississippi	1995–1999	3	Oxbow lakes responded to management measures within their watersheds. Chlorophyll concentrations inversely related to suspended sediment.	Knight and Welch (2004)
Northwestern Mississippi	May-June 2006	52	Streams were categorised trophically. Trophic levels were differentiated by TKN, turbidity and DO. Eutrophic streams had higher levels of TKN and turbidity and lower DO.	Bryson *et al.* (2007)
Eastern Arkansas and Northwestern Mississippi	Summer 2001	17	Water quality in wadeable ditches varied widely and was reflective of physical differences between sites. Ranges of measured variables similar to those reported by other studies in the region.	Stephens *et al.* (2008)
Northwestern Mississippi	Continuous 48-h collections during September or October 2007	28	Strong diurnal fluctuations in stream water quality common; most sites in violation of state standards for DO, turbidity, chlorophyll *a* and nutrients	Hicks and Stocks (2010)

DOI: 10.1002/rra

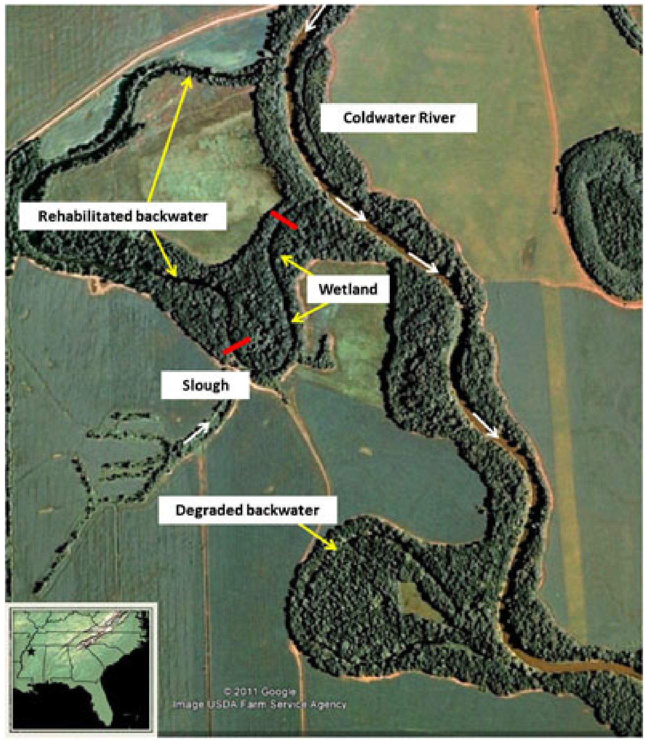

Figure 1. Location of the five floodplain water bodies sampled for this study. Red bars in rehabilitated backwater bend represent water control structures emplaced just before the study. Grey arrows indicate directions of flow in the river and the ephemeral slough. Imagery from the USDA Farm Service Agency. This figure is available in colour online at wileyonlinelibrary.com/journal/rra.

elevation in the downstream connecting channel, but during the warmer months, the river was 1 to 3 m lower than the backwaters, and the backwaters became quite shallow. Probing bed sediments at both sites with metal rods and sampling one of the sites with a Vibracore apparatus revealed 2 to 2.5 m of fine sediment deposition, with mean annual rates of approximately 3.1 cm year^{-1} on the basis of vertical profiles of sediment density and Cs-137 activity (Shields *et al*., 2010). Chemical analyses of the sediment samples and invertebrate bioassays suggested that metal concentrations in the sediments were unlikely to cause toxic effects, but several insecticides detected within the sediments had the potential to do so (Knight *et al*., 2009a, 2009b).

Before this study (in summer 2006), one of the two backwater sites was modified for habitat rehabilitation by constructing two weirs in its lower limb (Shields *et al*., 2010), whereas the other backwater was left in its degraded state. Weirs consisted of low earthen embankments placed at right angles to the old river channel and covered with stone riprap (Figure 2). Each weir included a water control structure that consisted of a 0.3-m-diameter pipe that penetrated the embankment bisected by a flashboard riser ‘manhole’. Flash boards could be added or removed through the manhole to adjust the controlling elevation of the water control structure (Figure 2). Weir water control structures were operated to retain water during March to November and were opened to allow more frequent connection to the Coldwater River during December, January and February. The weirs divided the old bend into two parts: a lake cell, with water levels managed to increase dry season depths, and a wetland cell, with water levels managed to produce conditions suitable for wetland plants and associated processes. Thus, the wetland cell was actually a 500-m-long segment of the restored backwater. One of the weirs was strategically located to divert runoff from cultivated fields into the wetland cell and away from the lake cell (Figure 1). The lake cell continued to receive runoff from approximately 100 ha of fields located on its northern and western sides and periodic overflow from the river. The ephemeral slough (‘slough’) received field runoff from a network of ditches draining approximately 350 ha of cultivated fields. The slough discharged into the wetland through a 0.6-m circular culvert.

METHODS

Hydrology

Climatic data were obtained from the National Weather Service (www.ncdc.noaa.gov, station 723340). Water levels were logged at all five sites at 30-min intervals, and flow

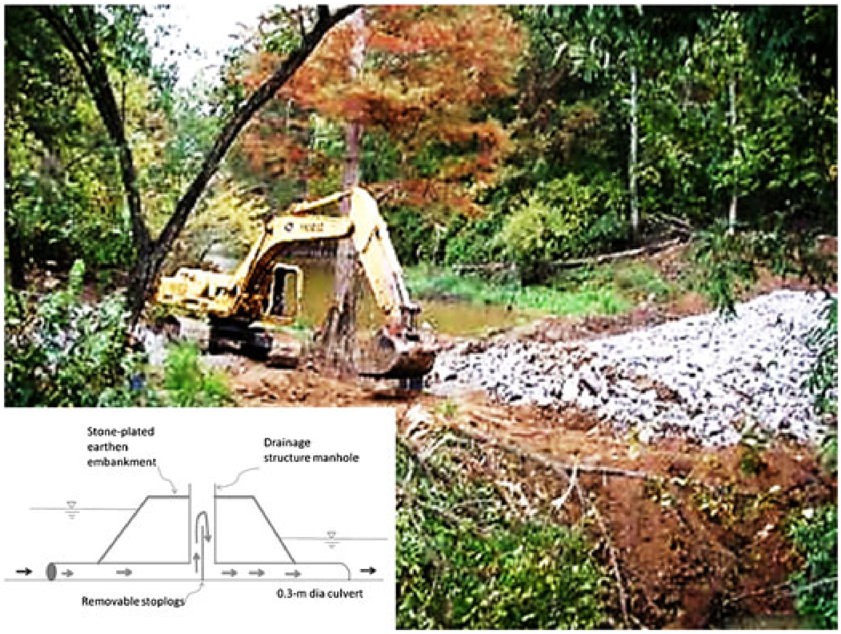

Figure 2. Construction of one of the water control structures in the rehabilitated backwater, October 2006. Inset schematic depicts drainage structure that allowed flow through stone embankment. This figure is available in colour online at wileyonlinelibrary.com/journal/rra.

rates were determined for the slough (acoustic Doppler device in culvert) and river (upstream reservoir releases measured by the US Corps of Engineers, Vicksburg District). Backwater, wetland and river stages were used to compute mean depth at each measurement interval using digital elevation models on the basis of the LiDAR coverage of terrestrial zones and bathymetric data collected using boat-mounted echosounders coupled with differentially corrected GPS. Maximum depth was computed at each measurement interval for the slough by subtracting minimum bed elevation from the measured water surface elevation.

Physical and chemical water quality

Weekly grab samples for water chemistry measurements were collected from October 2006 to September 2010 (Table II). Water temperature, conductivity, pH, DO and turbidity were measured *in situ* weekly using handheld meters, and grab samples were collected simultaneously and preserved via chilling while transported to the laboratory for analysis. Physical and chemical water parameters including turbidity, total solids (TS), dissolved solids (DS), ammonium (NH_4-N), nitrate (NO_3-N), nitrite (NO_2-N), total Kjeldahl nitrogen (TKN), soluble (filterable) phosphorus (P), total P (TP) and chlorophyll *a* were analysed using standard methods. Organic nitrogen (N) was computed as the difference between Kjeldahl N and NH_4-N, and suspended solids (SS) was computed as TS-DS. Water quality sondes in the backwaters, wetland and slough logged temperature, pH, DO, turbidity and specific conductivity at 4-h intervals. Sondes were deployed so sensors were 0.2 to 0.6 m below the water surface. Our measurements were unlikely to have been influenced by warm season vertical stratification because vertical stratification within our study sites was weak because of the shallow water depths. At the degraded backwater, the sonde was sometimes more deeply submerged during floods, but these occurred only during colder periods when there was no vertical stratification.

Fish

Fish assemblages offer much information regarding floodplain hydrology and water chemistry (Aycock, 2008; Rosso and Quiros, 2008; Miranda, 2010). For this study, fish were collected using a boat-mounted electroshocker at least semi-annually from the rehabilitated backwater and river sites during two to four 20-min sampling periods using pulsed direct current. In addition, three similar collections were made from the degraded backwater during high water (wet seasons) just before and during the study. Because conductivities varied at the collection sites both temporally and spatially, voltages were adjusted to provide the maximum catch possible for the given conditions. All major habitats were sampled including shore lines, large wood formations and open water. Fish were identified to species, enumerated and measured for total length, which was used to calculate weight using regression formulas on the basis of regional fish collections. Weights and numbers of fish were used to calculate catch by numbers, catch by weight, catch per unit of effort and numbers per unit of effort for each sample.

DOI: 10.1002/rra

Table II. Date ranges for data collections (month/year)

Site	Water level	Grab samples	Temperature	*In situ* measurements other than temperature	Fish
Slough	March 2008–September 2010, discharge monitoring November 2006–September 2010	October 2007–August 2010	November 2006–June 2010	March 2007–June 2010	Only visual observations
Wetland	November 2006–September 2010	June 2007–August 2010	October 2006–July 2010	January 2007–July 2010	Only visual observations
Degraded backwater	December 2006–November 2010	June 2009–August 2010	October 2006–July 2010	May 2009–July 2010	March 2005–January 2010
Rehabilitated backwater	October 2006–November 2010	October 2006–November 2010	October 2006–November 2010	October 2006–November 2010	May 2007–December 2010
River	October 2006–November 2010	October 2006–November 2010	October 2006–November 2010	None	October 2007–July 2009

Some data series terminate prior to November 2010 because water depths became to shallow to obtain data.

Data analysis

Exploratory analyses indicated strong hydrologic and chemical variation between wet and dry seasons, consistent with earlier work on cultivated floodplains (Schlosser and Karr, 1980; Pennington, 1999, 2004; Rebich *et al*., 2004; Shields *et al*., 2009b). On the basis of these exploratory analyses, seasons were defined as June to November (dry) and December to May (wet). As noted earlier, we sampled five floodplain water bodies in one locale over a 4-year period, producing a 'mensurative' rather than 'manipulative' experiment *sensu* Hurlbert (1984). Ecological field studies often suffer from pseudoreplication because of the difficulty of replicating study sites. Herein, inferential statistics (ANOVA) are used to compare grab-sampled physical and chemical water quality data using site and season (wet or dry) as treatments although sites were not replicated—each site is sampled at one point in space multiple times during each season. However, exploratory analysis of physical and chemical water data from collected at three distinct locations within the rehabilitated backwater indicated no significant differences among these locations thus; the results herein are from one location deemed representative of the entire water body. We assumed similar situations obtained for the other four water bodies. When sites were sampled for fish, multiple electrofishing collections were made from the site (water body) on a given date. These collections were treated as replicates for purposes of one-way ANOVA using site as the treatment. Although our study design is not entirely free from pseudoreplication, we feel that our data do depict spatial and temporal variations across this floodplain. Readers must decide if our results apply to their areas of interest.

Grab-sampled water chemistry data were analysed using a two-way ANOVA with season (wet or dry) and site as factors and the critical level of significance set at $\alpha = 0.001$ (Glantz, 1992; Systat Software, Inc., 2009). Data were fourth-root transformed before ANOVA because of nonnormal distributions and unequal variances, and the Holm–Sidak method with $\alpha = 0.05$ was used for pairwise comparisons. Spearman rank-order correlation analyses were run to examine associations among variables and between measures of water chemistry and water quantity. Continuous (sonde) water quality data were analysed by preparing time series plots, by computing summary statistics and by plotting daily extrema against water depth due to its influence on processes controlling DO and related variables (Miranda, 2005). For spatial comparison, dry season and wet season box plots were prepared using the *in situ* measurements of temperature, pH, conductivity and turbidity collected manually from the river and sonde data from other sites. Sonde data used for these box plots were limited to measurements made during morning hours when the manual measurements were made in the river.

DOI: 10.1002/rra

The number of fish species per sample and the numerical and biomass catch per unit effort were subjected to a one-way ANOVA using the three sampled habitat types (degraded backwater, rehabilitated backwater and river) as treatments (Systat Software, Inc., 2009). When data were nonnormally distributed (Shapiro–Wilk test) or when variances were unequal, ANOVA on ranks was run. The Holm–Sidak method was used for pairwise comparisons for ANOVA, and the Dunn method was used for ANOVA on ranks, both with $\alpha = 0.05$.

For purposes of ordination analysis, a matrix containing fish species abundances for each collection was created. Nonmetric multidimensional scaling (NMS) and ancillary graphical and correlation analyses (McCune and Grace, 2002) were run using PC-ORD 4.41 software (McCune and Mefford, 1999) to assess distributional patterns. NMS analysis was limited to collections containing more than six individuals (40 collections of the 41 total) and to the 27 most common species (species found in five or more collections). Collections used for NMS contained 4 to 15 species each. Because of extreme variation in the abundances of some species between collections, all entries in the 40 collections $\times$ 27 species matrix were $\log 10(x+1)$ transformed before ordination. Sorenson distances were constructed with NMS from the 40×27 data matrix with a random starting configuration and 50 runs with actual data using the autopilot 'slow and thorough' mode in PC-ORD. The significance of patterns revealed by NMS ordination was assessed with Monte Carlo tests of the probability that a similar final stress could be obtained by chance. The Monte Carlo test randomised the data by randomly reallocating elements within columns of the 40×27 data matrix and repeatedly running the NMS. Then the stress obtained from NMS of actual (unshuffled) data was compared with the Monte Carlo outputs (McCune and Grace, 2002). To pass the Monte Carlo test, the final stress had to be lower than that found for 95% of the randomised runs.

RESULTS

Water quality during warm, base flow seasons was often dominated by water column photosynthesis, whereas water quality during spring and winter was governed by hydrologic processes such as runoff and erosion. Clear signatures for river flooding events were noted in the records from lentic water bodies because river flooding normally occurred within rainy periods when local runoff affected these sites before river overflow. However, there were strong differences in driving processes between the drier months of June to November and the wetter winter–spring period (December–May) (Table III). The mean air temperature during the dry season portion of our study was 23.1°C, which compares with

Table III. Hydrologic relationships among sampled sites

Site	Mean water depth (m)[1]		Average discharge ($m^3 s^{-1}$)		Primary inflows from	Discharge into	% Time connected to downstream water body	
	Dry season	Wet season	Dry season	Wet season			Dry season	Wet season
Slough	0.59 ± 0.33	0.94 ± 0.25	0.009	0.022	Fields	Wetland	32	58
Wetland	0.11 ± 0.20	0.41 ± 0.63	Unknown	Unknown	Slough, river, rehabilitated backwater	River	15	67
Degraded backwater	0.50 ± 0.12	0.72 ± 0.32	Unknown	Unknown	Fields, river	River	10	39
Rehabilitated backwater	0.69 ± 0.12	0.79 ± 0.19	Unknown	Unknown	Fields, river	Wetland	0.1	24
River	2.22 ± 0.68	2.67 ± 1.24	31.3 ± 25.2	38.7 ± 38.8	Upstream reservoir	Downstream reaches	100	100

Dry season defined as June to November, wet season as December to May.
[1]For backwaters and wetland, the mean water depth is the average of water body volume divided by water surface area at each 30-min time step. For the slough and the river, the mean water depth is the average of the difference between the minimum bed elevation and the measured water surface elevation at each 30-min time step.

DOI: 10.1002/rra

11.9°C for the wet season. Precipitation means were 86 mm month^{-1} during the dry season and 134 mm month^{-1} during the wet seasons. Hydrologic connections among sites were highly cyclical, with limited connections during the drier months, which coincided with most of the growing season. Much more frequent but sporadic connections occurred during the wet season, which also coincided with higher sediment loadings because fields were frequently left without winter cover.

The waters of our study site were generally warm, turbid and enriched with nutrients, particularly P. The median temperatures for the five sites ranged from 18°C to 23°C, and turbidities reached as high as 2600 NTU in the slough and as high as 1300 NTU elsewhere. The median TS concentration for all sites was 135 mg L^{-1}, the median TP was 0.29 mg L^{-1} and the median total N was 1.56 mg L^{-1}. An average of 89% of total N was composed of organic N, whereas an average of 84% of the TP was particulate P. Eight of the 12 grab-sampled water chemistry variables that were subjected to a two-way ANOVA displayed significant interaction effect between the factors site and season (Table IV). Secchi disk readings and chlorophyll *a* levels varied widely and were not significantly different across wet and dry seasons.

Dry season physical and chemical water quality

Except for the river, dry seasons were periods of scant inflow, hydrologic isolation and extremely low water levels. The slough, wetland and degraded backwater dried up during droughts every year except for 2009. Organic N and DS were generally greater during the dry season at the lentic sites, and at all sites, the concentrations of DS, NH_4+ and organic N were inversely proportional to mean water depth, perhaps because of evaporation (Table IVB). Turbidity was highly correlated with TS and SS ($r > 0.98$, $p < 10^{-74}$), but not with chlorophyll *a* ($r = 0.07$, $p = 0.48$) when all sites were considered, but chlorophyll *a* was positively correlated with turbidity in the rehabilitated backwater ($r = 0.76$, $p < 10^{-16}$) and in the slough ($r = 0.34$, $p = 0.01$). Secchi depth was inversely related to turbidity ($r = -0.51$, $p < 0.001$) and positively related to water depth ($r = 0.43$, $p = 0.004$). Turbidity levels in the slough and wetland were about twice as great as those in other sites, reflecting their shallow depths and their hydraulic linkage to fields and to each other. Turbidity increased as water depths declined in the slough and rehabilitated backwater ($r \leq -0.22$, $p < 0.05$). The backwaters were clearer and had smaller concentrations of SS and NO_2+NO_3 than the river or the shallower floodplain sites but differed strongly from one another in chlorophyll *a* levels (Table IVB). Water column photosynthesis degraded backwater was limited by a mat of floating duckweed (*Lemna minor*) that covered the surface, producing hypoxic or anoxic conditions. A similar mat of *L. minor* occurred in the wetland,

Table IVA. Grab-sampled water quality means ± SDs for sampled sites

	TS (mg L^{-1})*		SS (mg L^{-1})		Turbidity (NTU)*		Secchi disk (cm)	TP (mg L^{-1})*		Total N (mg L^{-1})*	
Site	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season	Both seasons	Dry season	Wet season	Dry season	Wet season
Slough	228 ± 252^{a}	226 ± 107^{a}	**143 ± 252^{a}**	**158 ± 110^{a}**	**140 ± 258^{a}**	**151 ± 127^{a}**	N/A	0.50 ± 0.18^{a}	0.52 ± 0.19^{a}	**3.34 ± 3.55^{a}**	**2.12 ± 0.93^{a}**
Wetland	222 ± 418^{a,b}	183 ± 81^{b}	**132 ± 419^{a}**	**114 ± 85^{b}**	**143 ± 479^{a}**	**118 ± 120^{b}**	17 ± 7^{a}	**0.47 ± 0.22^{a}**	**0.38 ± 0.17^{b}**	**3.05 ± 1.82^{a}**	**1.81 ± 1.00^{a,b}**
Degraded backwater	165 ± 200^{b,c}	145 ± 70^{c}	84 ± 198^{b}	77 ± 73^{c}	**76 ± 209^{b}**	**77 ± 86^{c}**	24 ± 8^{b}	0.32 ± 0.20^{b}	0.35 ± 0.16^{b}	**2.31 ± 4.34^{b}**	**1.20 ± 0.52^{c}**
Rehabilitated backwater	126 ± 68^{c}	108 ± 37^{d}	39 ± 52^{b}	42 ± 38^{d}	35 ± 44^{b}	39 ± 34^{d}	35 ± 14^{c}	0.16 ± 0.13^{c}	0.16 ± 0.09^{c}	**3.26 ± 3.78^{a}**	**1.28 ± 0.39^{c}**
River	**177 ± 79^{a,b}**	**253 ± 131^{a}**	**108 ± 76^{a}**	**189 ± 126^{e}**	**65 ± 49^{a}**	**185 ± 142^{a}**	N/A	**0.21 ± 0.12^{d}**	**0.31 ± 0.12^{b}**	1.34 ± 0.63^{c}	1.59 ± 1.19^{b,c}

Data were fourth-root transformed before ANOVA. Values in boldface imply significant difference between dry and wet seasons, and means in the same column with different superscript letters are significantly different.
*Significant interactions ($p < 0.001$) between site and season.

Table IVB. Grab-sampled water quality means ± SDs for sampled sites

Site	DS (mg L^{-1})*		Filterable P (mg L^{-1})*		NO_2+NO_3 (mg L^{-1})*		NH_4^+ (mg L^{-1})		Dissolved organic C (mg L^{-1})*		Chlorophyll *a* (µg L^{-1})
	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season	Both seasons
Slough	**84 ± 18^a**	**68 ± 18**	0.103 ± 0.089^a	0.083 ± 0.057^a	**0.24 ± 0.58^a**	**0.25 ± 0.55^a**	**0.025 ± 0.035**	**0.027 ± 0.021^a**	**12.2 ± 6.4^a**	**9.7 ± 18^a**	$51 \pm 80^{a,b}$
Wetland	**90 ± 27^a**	**69 ± 16**	0.067 ± 0.058^a	0.052 ± 0.032^b	0.31 ± 0.70^a	0.20 ± 0.48^a	0.026 ± 0.051	$0.020 \pm 0.019^{a,b}$	**9.7 ± 5.7^b**	**7.3 ± 16^b**	65 ± 81^a
Degraded backwater	**51 ± 17^a**	**68 ± 10**	0.037 ± 0.030^b	0.045 ± 0.026^b	**0.05 ± 0.04^b**	**0.13 ± 0.10^a**	0.012 ± 0.020	$0.012 \pm 0.015^{b,c}$	**7.5 ± 3.7^b**	**7.3 ± 2.7^b**	29 ± 22^b
Rehabilitated backwater	**87 ± 23^a**	**67 ± 11**	**0.012 ± 0.022^c**	**0.023 ± 0.022^c**	**0.04 ± 0.04^b**	**0.08 ± 0.06^b**	0.013 ± 0.022	0.010 ± 0.012^c	**8.1 ± 4.9^b**	**6.4 ± 4.0^b**	70 ± 120^a
River	70 ± 28^b	64 ± 16	0.046 ± 0.080^b	0.043 ± 0.023^b	**0.16 ± 0.11^a**	**0.31 ± 0.11^c**	0.012 ± 0.012	$0.015 \pm 0.016^{b,c}$	5.6 ± 2.7^c	6.0 ± 3.0^b	25 ± 18^b

Data fourth-root transformed before ANOVA. Values in boldface indicate significant difference between dry and wet seasons, and means in the same column with different superscript letters are significantly different.
*Significant interactions ($p < 0.001$) between site and season.

whereas the rehabilitated backwater supported rooted macrophytes (*Ludwigia peploides*) along its margins and in other shallow areas during the dry season. In the rehabilitated backwater, turbidity, TS and DS, hardness and N in the form of NH_4+ and organic N all increased as water levels fell.

Dry season diurnal variations in temperature, DO and pH were extreme and accentuated by diminishing water depth. Scatter plots of the daily range (max–min) of continuously measured constituents for nonriver sites displayed two populations: one for water depths less than approximately 1 m and one for greater depths (e.g. Figure 3). Depth-driven variability occurred in both wet and dry seasons but was more pronounced in dry seasons, as shown in Table V. In most cases, dry season ranges became extreme as depths declined, but in the degraded backwater, DO ranges moderated as depths declined because maximum values were so low (mean of shallow dry season daily max = 1.6 mg L^{-1}). Continuous data for the river site were limited to temperature. Depth dependency of the daily temperature range was observed in the river, but it was muted relative to the sites without flow.

To allow spatial comparison, morning values of continuously monitored constituents were compared with manually measured values from the river. In general, dry season river physical and chemical water quality was superior to the other sites in terms of criteria for aquatic life (e.g. higher DO and lower turbidity; Figure 4). All sites exhibited elevated temperatures, with shallower sites becoming much warmer during the afternoon (see wider ranges for slough and degraded wetland; Table V). Morning temperatures varied little from site to site, except the range of river temperatures was wider and included much cooler values. DO values were more variable, with lowest values in the shallow degraded backwater (median = 0.14 mg L^{-1}) that was covered with a floating mat of duckweed (*Lemna* sp.) and highest values in the river (median = 7.3 mg L^{-1}). All floodplain sites experienced hypoxic episodes. Dry season morning pH values varied little in the wetland or rehabilitated backwater but were highly variable elsewhere, with differences between the 75th and the 25th percentiles (interquartile range) of approximately 1.2 pH units. Dry season turbidities scattered across four log cycles, with greatest variation in the shallower sites (slough, wetland, degraded backwater). All sites generally had conductivity values between 100 and 200 µS cm^{-1}. With the exception of a few high outliers, river specific conductivities were lower than for the floodplain sites.

Wet season physical and chemical water quality

Wet season conditions were characterised by lower temperatures and specific conductivities and higher levels of DO and turbidity (Table V and Figure 4). Wet season morning temperatures were approximately 10°C cooler at each site than for the dry season. Hypoxia was observed even during the

DOI: 10.1002/rra

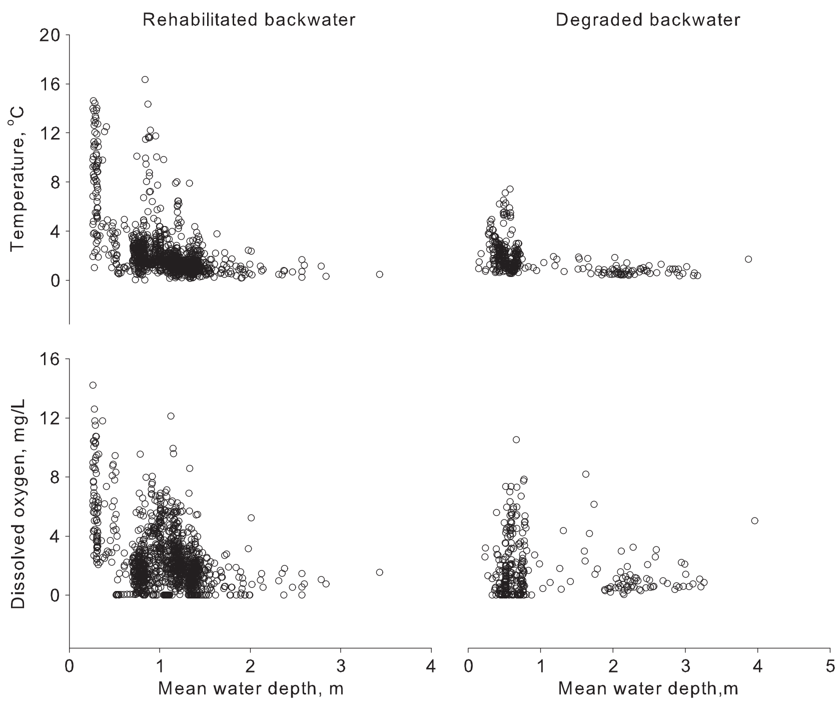

Figure 3. Typical scatter plots of the daily range (daily max–daily min) for continuously monitored water quality constituents versus mean daily water depth.

wet season at all sites except for the river and the rehabilitated backwater. The pH values were similar to dry season levels but were less variable. Median grab-sampled turbidity across all sites was about twice as high in the wet season as in the dry season (Table IVA). TS were composed of approximately 60% SS (median across all sites) in the wet season but only approximately 41% during the dry season. Wet season water quality was dominated by inflow concentrations, with inflows from local runoff or river flooding influencing all sites to some degree. In the river, concentrations of P, SS and DOC were directly proportional to stage ($r > 0.28$, $p < 0.01$), whereas DS, hardness and alkalinity declined with increasing stage ($r \leq -0.32$, $p < 0.01$). Furthermore, river total and suspended solids, TP and NO_2+NO_3-N were higher in the wet season than in the dry season. Backwater depth reflected antecedent precipitation, and concentrations of NO_2+NO_3 were proportional to water depth ($r > 0.59$, $p < 10^{-8}$), for both the degraded and the rehabilitated backwaters. In opposite fashion to the dry season behaviour, turbidity, total and suspended solids, total and filterable P, NH_4+, total N and DOC were all positively correlated ($r > 0.23$, $p < 0.05$) with water depth in the rehabilitated backwater. The slough exhibited opposite behaviour to the backwater, with DS, P, NO_2+NO_3 and DOC all inversely related to water depth. Chlorophyll *a* was positively correlated with turbidity, TS and SS in the slough and rehabilitated backwater ($r > 0.24$, $p < 0.04$) and with total N in the wetland, slough and rehabilitated backwater ($r > 0.26$, $p < 0.04$).

Fish

A total of 3023 fishes were captured in 41 separate collections. Five collections were made in the degraded backwater, 11 in the river and 25 in the rehabilitated backwater. A total of 40 species were found, with 7 found at all sites, 7 found only in the river and 15 found in both backwaters. Three tolerant species (*Lepomis macrochirus*, *Dorosoma cepedianum* and *Pomoxis annularis*) comprised 70% of the numerical total catch, whereas the tolerants *Ictiobus bubalus*, *Lepisosteus oculatus* and *D. cepedianum* comprised 62% of the total catch biomass. Four of these five species have temperature tolerances between 31.3°C and 32.1°C (Eaton *et al.*, 1995), whereas the fifth, *L. oculatus*, can breathe air at the surface when anoxic conditions occur. Three species, all small-bodied insectivores (*Cyprinella lutrensis*, *Fundulus chrysotus* and *Noturus gyrinus*), were represented by only one individual. Ictalurids (catfishes), which are common throughout the region, comprised only 0.05% of the catch. Eight of the 40 species were classified as intolerant, and these comprised less than 5% of the numerical catch. Three of these were found only in the river and two were found only in the rehabilitated backwater.

DOI: 10.1002/rra

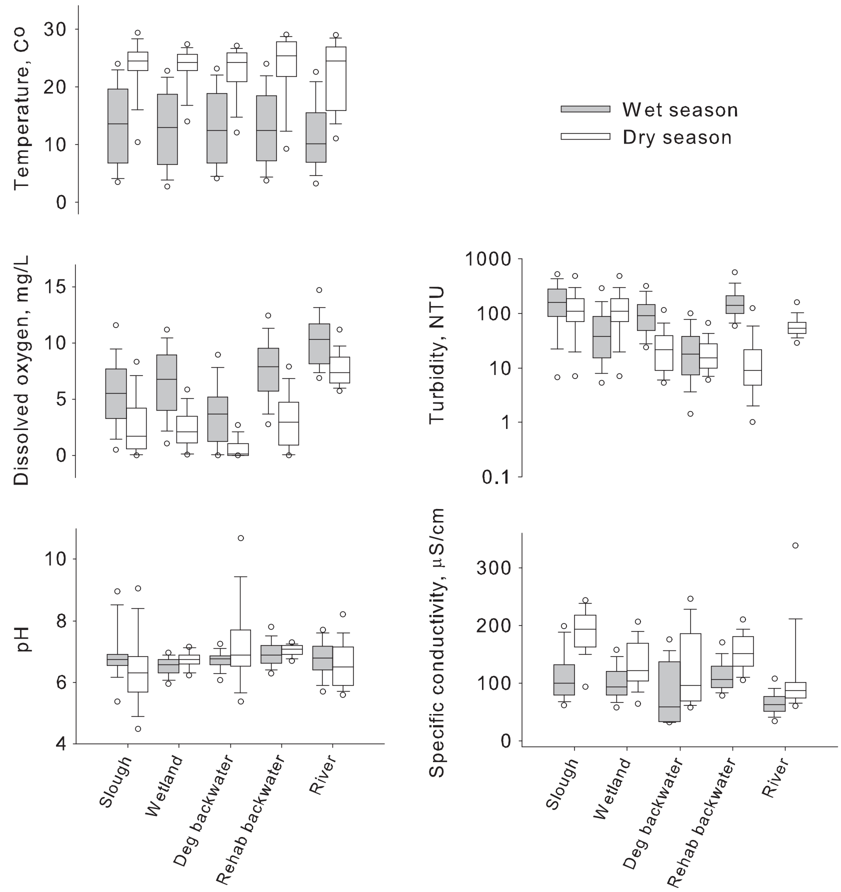

Figure 4. Box plots of distributions of continuously monitored water quality constituents in five floodplain water bodies. Whiskers represent the 90th and 10th percentiles, upper and lower sides of rectangles represent 75th and 25th percentiles, and the central line represents median. Symbols represent 95th and 5th percentiles.

No fish were collected from the slough or the wetland, but visual observations of numerous small-bodied fishes were noted, although these habitats dried up during late summer and early fall every year except one. Species observed included *Gambusia affinis*, an assortment of *Fundulus* spp. and compact schools of newly hatched *Ameiurus* spp. (Figure 5). Although adult catfish were not observed, the parents typically stay near such broods guarding the young until they leave the group on their own accord. Fish collections from the river were composed of much larger but fewer individuals than the backwaters (Table VI). Collections from the degraded backwater produced fewer fish and fewer species, with smaller individuals. Degraded backwater collections were highly variable and reflected stresses because of water chemistry and hydrologic factors. A wet season sample preceded by a 90-day period that included 31 days of connection to the river yielded 215 individuals representing 16 species. Similar levels of effort during each of two subsequent wet seasons that were preceded by prolonged periods of shallow water and hypoxia and less than 1.2 days of connection in the prior 6 months yielded averages of 49 individuals representing only seven species. The latter collections were dominated (80% of numbers) by the ubiquitous tolerant planktivore, *D. cepedianum*. Conversely, fish collections from the deeper rehabilitated bend exhibited less temporal variation.

Biological gradients among the sample units were detected by the NMS ordinations. NMS ordination using the 27 most common species produced three axes that together explained 93% of the variation in the sample space with a final stress of 10.43 with a final instability of 10^{-7} at 110 iterations. A plot of fish collections in the NMS space shows definite separation of the river and rehabilitated backwater with collections from the degraded backwater in an intermediate position (Figure 6). NMS axes 1 and 3 were positively associated, and axis 2 was negatively associated, with mean water depth. Abundances of many fishes were related to the NMS axes (Table VII). The small, intolerant insectivores, *Cyprinella venusta* and *Notropis atherinoides*, and the tolerant planktivore, *D. cepedianum*, were positively correlated with axis 1. Lentic species such as *L. macrochirus* and *P. annularis* were positively correlated with axis 1

DOI: 10.1002/rra

Table V. Mean daily range (daily max–daily min) of continuously measured water quality constituents

Site	Temperature, C°	DO, mg L^{-1}	pH	Specific conductivity, µS cm^{-1}	Turbidity, NTU
Dry season					
Slough	2.0/3.5	3.7/5.5	0.72/1.3	0/4	66/236
Wetland	0.8/3.4	2.4/4.7	0.25/0.38	11/14	133/66
Degraded backwater	0.8/1.6	3.4/1.4	0.34/0.60	6/7	54/28
Rehabilitated backwater	1.4/3.8	2.7/3.4	0.23/0.41	6/10	8/111
River	1.3/1.7	N/A	N/A	N/A	N/A
Wet season					
Slough	1.8/4.4	2.5/3.7	0.10/0.78	1/18	155/115
Wetland	1.5/2.9	2.4/3.1	0.23/0.24	12/9	41/52
Degraded backwater	0.5/2.0	1.1/2.7	0.12/0.19	2/7	63/103
Rehabilitated backwater	1.4/2.7	1.6/1.8	0.17/0.26	6/6	20/42
River	1.2/1.8	N/A	N/A	N/A	N/A

In each cell, the mean before the slash (/) is for data collected when water depths were deep (>1 m), whereas the mean after the slash is for data collected when water depths were shallow (<1 m). Continuously measured data for river were limited to temperature.

($r > 0.58$) and negatively correlated with axis 3 ($r \leq 0.60$). Rheophilic species such as *Ictalurus furcatus*, freshwater drum *Aplodinotus grunniens* and *I. bubalus* were positively correlated with axis 3 ($r > 0.53$).

DISCUSSION

Water quality conditions reported here were typical of this region (Kleiss *et al*., 2000). The mean concentrations of SS and nutrients (TP, filterable P, TKN, NO_3- and NH_4+) were near the lower end of the range of means for nine similar channels conveying agricultural runoff into three oxbow lakes located approximately 125 km south of our study area (Rebich, 2004). Chlorophyll and P levels in the degraded and rehabilitated backwaters were similar to those reported for these three lakes, whereas SS, NO_3- and NH_4+ were lower in our backwaters (Knight and Welch, 2004). Our river site exhibited mean values for TS, SS,

Figure 5. Spherical (~50 cm diameter) school of newly hatched Ameiurus sp observed in slough, 4 June 2010. This figure is available in colour online at wileyonlinelibrary.com/journal/rra.

Table VI. Mean or median characteristics of fish communities from backwaters and river

	Mean no. species	Median catch per unit effort (fish/min)	Median catch per unit effort (g/min)	Median fish size (g)
Degraded backwater	6.6^{a}	$3.4^{a,b}$	89^{a}	46^{a}
Rehabilitated backwater	10.6^{b}	3.9^{a}	$267^{a,b}$	76^{a}
River	$9.2^{a,b}$	1.6^{b}	299^{b}	275^{b}

Means or medians in the same column with different superscript letters are significantly different ($p < 0.05$) based on single-factor ANOVA (means) or Kruskal–Wallis ANOVA on ranks (medians), which was applied in cases where data were nonnormal or variances were unequal.

DOI: 10.1002/rra

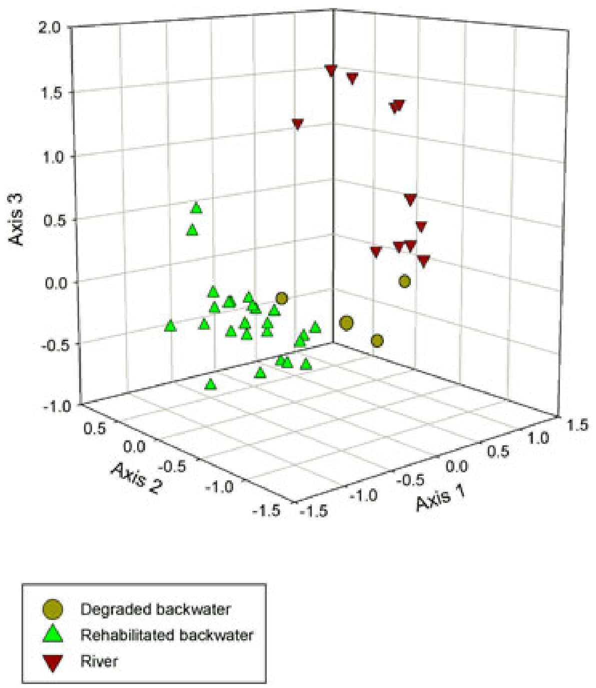

Figure 6. Nonmetric multidimensional ordination of fish collections from degraded backwater, rehabilitated backwater and adjacent river. This figure is available in colour online at wileyonlinelibrary.com/journal/rra.

Table VII. Pearson product–moment correlation between the 27 most common fish species abundances and NMS axes

Species	Axis 1	Axis 2	Axis 3
Carpiodes carpio	0.411	−0.092	0.457
Dorosoma petenense	0.165	−0.009	0.104
Cyprinella venusta	**0.635**	−0.189	**0.586**
Cyprinella camura	0.409	−0.313	**0.701**
Opsopoeodus emiliae	−0.461	0.240	−0.142
Ictalurus furcatus	0.235	−0.328	**0.751**
Ictiobus cyprinellus	−0.061	0.147	0.157
Lepisosteus platostomus	**0.513**	−0.155	0.445
Aplodinotus grunniens	0.188	−0.289	**0.667**
Notropis atherinoides	**0.755**	−0.165	0.428
Labidesthes sicculus	−0.108	0.131	−0.298
Lepomis miniatus	0.156	−0.218	**0.525**
Lepomis megalotis	−0.183	0.335	−0.327
Carpiodes carpio	−0.265	0.111	−0.309
Amia calva	−0.249	0.449	−0.081
Lepomis cyanellus	−0.129	0.140	−0.344
Notemigonus crysoleucas	−0.232	**0.512**	−0.227
Fundulus olivaceus	**−0.593**	0.356	−0.269
Pomoxis nigromaculatus	−0.08	0.495	−0.274
Lepomis humilis	−0.148	**0.604**	−0.485
Micropterus salmoides	**−0.543**	**0.617**	−0.433
Lepomis gulosus	−0.309	**0.562**	**−0.595**
Lepisosteus oculatus	0.068	0.444	0.200
Ictiobus bubalus	0.213	−0.252	**0.719**
Lepomis macrochirus	**−0.509**	**0.609**	**−0.791**
Pomoxis annularis	0.013	**0.577**	**−0.589**
Dorosoma cepedianum	**0.535**	−0.101	−0.406

Coefficients ≥0.5 or ≤−0.5 are in boldface.

turbidity, TP and TKN that were lower than means reported by Pennington (2004) for 22 sites along unregulated streams in the Delta because most of the contributing watershed for our site lay in the hills outside the Delta, where nutrient levels, turbidities, water temperatures and conductivities are lower (Killgore *et al*., 2008b; Shields *et al*., 2009b). Considering all of our sites, N levels were generally lower and P levels higher than those reported for the Mobile River Basin, approximately 350 km to the east (Harned *et al*., 2004), likely reflecting relatively high landscape N processing and soil P concentrations in our region (Shields *et al*., 2009b).

Floodplains tend to be highly dynamic environments with rich spatial heterogeneity that features extended interfaces between terrestrial, wetland and deeper aquatic habitats. However, the area we studied featured fields that were cleared, levelled and planted to crop monoculture, and aquatic habitats were degraded by sedimentation. Water quality conditions partitioned the five water bodies we studied into three rather distinct groups: the river, which was relatively turbid, cool and well oxygenated; the rehabilitated backwater, which was relatively clear, moderately well oxygenated and highly productive; and the shallower lentic sites (slough, wetland and degraded backwater), which were turbid, hypoxic and subject to highly variable but generally warmer temperatures. In contrast to spatial homogenisation, anthropogenic influences accentuate the amplitude and frequency of temporal water chemistry and temperature variations, particularly during dry seasons as noted by Miranda (2010). Extreme dry season diurnal variation in DO (from near 0 to ~20 mg L^{-1}) has been reported for floodplain lakes in Arkansas, with even lightly affected ‘reference’ lakes displaying diurnal swings between ~4 and 9 mg L^{-1} (Justus, 2010). Although rivers are physically more dynamic than adjacent lentic habitats, diurnal water temperature variation in the river was less extreme than for shallow floodplain sites (Table VI).

The addition of water control structures slightly increased dry season water depth and reduced diurnal physical and chemical water quality variation in the rehabilitated backwater. However, the placement of the weir that defined the lake cell reduced the frequency and duration of hydrologic connections to the main channel and the volume of local runoff supplied to the lake cell (Shields *et al*., 2011). Although some workers have found floodplain lakes resistant to rehabilitation actions (e.g., Moss *et al*., 2005), the greater depth in the rehabilitated backwater and the diversion of agricultural runoff from approximately 75% of its watershed produced less turbid conditions that were associated with the elevated levels of chlorophyll *a* relative to the other four sites. Cooper (1993) reported that the diversion of agricultural runoff away from a large oxbow lake within the same region reduced suspended sediment

DOI: 10.1002/rra

concentrations by an order of magnitude and allowed strong increases in primary production. The deeper rehabilitated backwater also had higher levels of organic N and lower levels of TP, NH_4+ and NO_3−. These findings are similar to those from a study of 42 Mississippi Delta lakes by Miranda (2010), who found strong inverse relationships between maximum water depth and surface DO, turbidity and chlorophyll *a*. Further, Roozen *et al.* (2003) reported that turbidity and nutrient concentrations varied inversely with water depth in 93 floodplain lakes along the lower Rhine. In-lake processes (the resuspension of bed sediments by benthivorous fish) rather than flooding from the river dominated lake water quality and explained why chlorophyll *a* showed a strong positive correlation to suspended sediment concentration (Roozen *et al*., 2007). Coveney *et al.* (2005) studied a shallow, eutrophic Florida lake subject to agricultural runoff and found that reduction in external P loading produced attendant reductions in in-lake TP and chlorophyll *a* concentrations and increased Secchi depths. Variations in lake quality about these trends were strongly influenced by water depth.

The improvements in the rehabilitated backwater conditions after weir placement were not adequate to avert hypoxia during late summer: there were 10 to 29 consecutive days in which minimum DO was less than 1 mg L^{-1} each summer of our study except for 2009, which experienced the greatest total summer precipitation (411 mm compared with 209–322 mm for other years). Periods of hypoxia are endemic in floodplain streams and bayous in this region (Justus, 2009; Hicks and Stocks, 2010; Shields and Knight, In press). Kleiss *et al*. (2000) attribute chronic low DO to a combination of natural and anthropogenic factors, including low stream reaeration rates due to low channel gradients, abundant riparian vegetation and swamps that contribute organic material, and high temperatures. The question of how these conditions compare to those that prevailed before the agricultural development of the floodplains in the 19th century remains open. Some workers argue that hypoxic conditions may have prevailed in the predevelopment floodplains (Ice and Sugden, 2003; Kaller and Kelso, 2007; Mason *et al*., 2007; Justus and Wallace, 2009; Todd *et al*., 2009). No data exist to describe the fish populations of the Delta before European settlement, but a review of reports of archaeological remains (middens of food refuse left by aboriginal peoples) suggests that many of the larger taxa suitable for food that were present then remain (Bryant, 2010). Some species (e.g., sauger, *Sander canadense*, and walleye, *Sander vitreus*) found in the middens are relatively intolerant of high temperatures and hypoxia, whereas others are very tolerant (e.g., bowfin, *Amia calva*; and gar, Lepisosteidae). Many fish species native to undeveloped lowland floodplains exhibit moderate tolerance to degraded physical and chemical water quality, and several of these native species have physiological adaptations for surviving extremely low DO levels (Hoover and Killgore, 1998).

All fish species captured in this study were previously reported by other workers who sampled streams (Killgore *et al*., 2008a) or lakes (Aycock, 2008) in the same region. Evidently, chronic hypoxia produced backwater fish assemblages dominated by tolerants, quite distinct from the river assemblage (Figure 6). The position of the degraded backwater in the three-dimensional NMS ordination intermediate to the rehabilitated backwater and the river may reflect the effect of the rehabilitation weirs on connectivity because fish movements between river and floodplain may be sensitive to water level fluctuations and connectivity (Lyon *et al*., 2010). After weir emplacement, the degraded backwater was connected to the river 24% of the time, but the rehabilitated backwater only 12% of the time (water years 2007–2010 inclusive). Fish community structure in floodplain backwaters is tightly linked to water depth, with clear shifts in species relative abundance along an environmental gradient of maximum water depth (Miranda, 2010). Depth interacts with other environmental influences to control temperature, DO, transparency, trophic state and habitat structure. In addition to the linkage between depth and water quality, pooling water for rehabilitation using weirs also provides benefits in terms of fish habitat quality and quantity, especially for fishes with 'equilibrium' life history strategies such as the centrarchids *L. macrochirus* and *P. annularis* (Zeug and Winemiller, 2008). Equilibrium strategists are characterised by nest guarding and relatively low interannual variation in recruitment. Backwaters along the Lower Mississippi River are heavily used by fishes that continue to spawn and rear throughout summer into early autumn: Centrarchidae (sunfishes), Catostomidae (suckers) and Atherinidae (silversides) (Hoover *et al*., 2000). All three groups were common in our backwaters, comprising more than half of the catch biomass. These groups together comprised 75% of the total numerical catch from the rehabilitated backwater, but only 32% from the degraded backwater. Lightly modified floodplains feature high levels of connectivity with the main channel, which floods the adjacent backwaters in long duration pulses (Junk *et al*., 1989; Ward and Stanford, 1995). Like many disturbed ecosystems, shallow lakes and backwaters are dominated by opportunists that have small adult size, extended breeding seasons and early sexual maturity that allow populations to survive periods of drying and extreme water quality degradation. Adding weirs to increase water depth and stability in floodplain backwaters can reduce connectivity (Shields *et al*., 2010, 2011) yet produce definite benefits in terms of shifting fish community structure toward the increased representation of desirable forage and game species and away from tolerant omnivores (Pegg *et al*., 2006). Thus, the stewardship of ecosystem services may be better served by focussing on outcomes rather than natural references (Dufour and Piégay, 2009; Jackson and Pringle,

DOI: 10.1002/rra

2010). We recognise, however, that strong arguments may be made against this position and that such a focus forces managers to choose target states ('outcomes') on the basis of criteria other than the emulation of a preexisting state or reference.

CONCLUSIONS

The study reach of the Coldwater River and associated floodplain habitats exhibits long-term degradation due to upstream impoundment, channelization and floodplain cultivation. Floodplain aquatic habitats exhibited strong seasonal cycles between relatively cool, wet winter/spring and hot, dry summer/fall. Superimposed on these cycles were diurnal variations in temperature, DO and related constituents that were amplified by diminishing water depths. Dry season physical and chemical water quality was dominated by these diurnal variations and internal processes such as algal blooms, whereas wet season conditions reflected primarily local inflows and only weak coupling to the river. The river represented one end point of a continuum defined by flow and water depth (current, deep, cool, well oxygenated and relatively temporally stable physical and chemical water quality), with the ephemeral floodplain sites clustered near the other end (no current, shallow, warm, hypoxic and high-frequency temporal variations in quality). Fish community structure reflected water depth and connectivity. The rehabilitation and protection of floodplain aquatic habitats in agricultural landscapes is possible through measures such as flow augmentation (Lizotte *et al*., In press), constructing water control structures and diversion of polluted runoff away from protected areas. However, such measures may be too costly and require trade-offs such as reduced water supply or reduced main channel connectivity. In this case, rehabilitation was not adequate to prevent chronic dry season hypoxia in the treated backwater.

ACKNOWLEDGEMENTS

Support for construction of weirs for backwater habitat rehabilitation was provided by the Tunica County Soil and Water Conservation District. The collaboration of landowners Dennis Paulk, the Norfleet Family Trust and Steve Walters is gratefully acknowledged. Cooperation and advice were provided by Ken Oatis, Dean Pennington and David Melton. Assistance with data acquisition was provided by Charles Bryant, Terry Wade, John Massey, Calvin Vick, Terry Welch, Duane Shaw, John Stofleth, Michael Ursic, Casey Pearce, Alexandra McCaskill and Lisa Brookes. Justin Murdock, Steve Miranda and J. R. Rigby read an earlier version of this manuscript and made many helpful comments.

REFERENCES

Aycock N. 2008. Development of a fish-based index of biotic integrity for oxbow lakes of the Yazoo River Basin, Mississippi. Thesis, Mississippi State, Mississippi.

Bondar-Kunze E, Preiner S, Schiemer F, Weigelhofer G, Hein T. 2009. Effect of enhanced water exchange on ecosystem functions in backwater of an urban floodplain. *Aquatic Sciences* **71**: 437–447. DOI: 10.1007/s00027-009-0101-7

Bryant MD. 2010. Past and Present Aquatic Habitats and Fish Populations of Yazoo-Mississippi Delta. United States Department of Agriculture Forest Service, Southern Research Station. General Technical Report SRS-130.

Bryson JR, Coupe RH, Manning MA. 2007. Characterization of Water Quality in Unmonitored Streams in the Mississippi Alluvial Plain, Northwestern Mississippi, May–June 2006. U.S. Geological Survey Scientific Investigations Report 2007–5116.

Buijse AD, Coops H, Startas M, Jans LH, Van Geest GJ, Grifts RE, Ibelings BW, Oosterberg W, Roozen FCJM. 2002. Restoration Strategies for River Floodplain Along Large Lowland Rivers in Europe. *Freshwater Biology* **47**: 889–907.

Chao X, Jia Y, Shields FD Jr., Wang SSY, Cooper CM. 2008. Three Dimensional Numerical Modeling of Cohesive Sediment Transport and Wind-Wave Impact in a Shallow Oxbow Lake. *Advances in Water Resources* **31**: 1004–1014.

Clark BR, Hart RM. 2009. The Mississippi Embayment Regional Aquifer Study (MERAS): Documentation of a groundwater-flow model constructed to assess water availability in the Mississippi Embayment. U.S. Geological Survey Scientific Investigations Report 2009–5172, 61 p.

Cooper CM. 1987. Benthos in Bear Creek, Mississippi: Effects of Habitat Variation and Agricultural Sediments. *Journal of Freshwater Ecology* **4**(1): 101–113.

Cooper CM. 1993. Effects of Suspended Sediment Reduction on Chlorophyll and Water Quality in a Large Natural Lake. In *Proceedings of the International Association for Theoretical and Applied Limnology*, Kausch H, Lampert W (eds). E. Schweizerbart'sche Verlagsbuchhandlung: Stuttgart, Germany; 392–395.

Cooper CM, Knight LA, Herring J. 1982. Fish Composition in a Sediment-Laden Mississippi Delta Stream System. *Journal of the Mississippi Academy of Sciences* **27**: 163–175.

Cooper CM, McHenry JR. 1989. Sediment accumulation and its effects on a Mississippi River Oxbow Lake. *Environmental Geological and Water Science* **13**(1): 33–37.

Coupe RH, Welch HL, Pell AB, Thurman EM. 2005. Herbicide and degradate flux in the Yazoo River Basin. *International Journal of Environmental Analytical Chemistry* **85**(15): 1127–1140.

Coveney MF, Lowe EF, Battoe LE, Marzolf ER, Conrow R. 2005. Response of a eutrophic, shallow subtropical lake to reduced nutrient loading. *Freshwater Biology* **50**: 1718–1730. DOI: 10.1111/j.1365-2427.2005.01435.x

Dendy FE, Cooper CM, Schiebe FR, Ritchie JC. 1984. Sediment in a Delta Stream. *Southeastern Geology* **24**(4): 179–187.

Dubrovsky NM, Burow KR, Clark GM, Gronberg JM, Hamilton PA, Hitt KJ, Mueller DK, Munn MD, Nolan BT, Puckett LJ, Rupert MG, Short TM, Spahr NE, Sprague LA, Wilber WG. 2010. The quality of our Nation's waters—Nutrients in the Nation's streams and groundwater, 1992–2004. U.S. Geological Survey Circular 1350, 174 p.

Dufour S, Piégay H. 2009. From the myth of the lost paradise to targeted river restoration: forget natural reference and focus on human benefits. *River Research and Applications* **25**: 568–581.

Eaton JG, McCormick JH, Stefan H, Hondzo M. 1995. Extreme value analysis of a fish /temperature field database. *Ecological Engineering* **4**: 289–305.

Glantz SA. 1992. *Primer of Biostatistics*, 3rd edn. McGraw-Hill, Incorporated, Health Professions Division: New York, New York.

Guedon NB, Thomas JV. 2004. *State of Mississippi water quality assessment 2004 section 305(b) report appendum*. Mississippi Department of Environmental Quality: Jackson, Mississippi; 62 pp.

Harned DA, Atkins JB, Harvill JS. 2004. Nutrient mass balance and trends. Mobile River Basin, Alabama, Georgia, and Mississippi. *Journal of the American Water Resources Association* **40**(3): 765–793.

Heatherly T, Whiles MR, Royer TV, David MB. 2007. Relationships between habitat quality, water quality, and macroinvertebrate assemblages in Illinois streams. *Journal of Environmental Quality* **36**: 1653–1660.

Hicks MB, Stocks SJ. 2010. Water-Quality Data for Selected Streams in the Mississippi Alluvial Plain Ecoregion, Northwestern Mississippi, September-October 2007. U.S. Geological Survey Data Series Report 493, 118 p.

Hoover JJ, Killgore KJ. 1998. Fish Communities. In *Southern Forested Wetlands Ecology and Management*, Messina MG, Conner WH (eds). Lewis Publishers: New York.

Hoover JJ, Killgore KJ, Young GL. 2000. Quantifying Habitat Benefits of Restored Backwaters, ERDC TN-EMRRP-EI-01. U. S. Army Engineer Research and Development Center, Vicksburg, MS.

Hurlbert SH. 1984. Pseudoreplication and the design of ecological field experiments. *Ecological Monographs* **54**(2): 187–211.

Ice G, Sugden B. 2003. Summer Dissolved Oxygen Concentrations in Forested Streams of Northern Louisiana. *Southern Journal of Applied Forestry* **27**(2): 92–99.

Jackson CR, Pringle CM. 2010. Ecological Benefits of Reduced Hydrologic Connectivity in Intensively Developed Landscapes. *BioScience* **60**(1): 37–46.

Jackson DC, Ye Q, Stopha ME, Rhine TD, Brown-Peterson NJ. 1995. Riverine fisheries resources assessments in the upper Yazoo River basin. Department of Wildlife and Fisheries. Federal Aid Project F-94. Mississippi Department of Wildlife, Fisheries and Parks, Jackson.

Junk WJ, Bayley PB, Richard ES. 1989. The Flood Pulse Concept in River-Floodplain Systems (Canadian Special Publication of Fisheries and Aquatic Sciences 106). In *Proceedings of the International Large River Symposium (LARS)*, Dodge DP (ed). Department of Fisheries and Oceans: Ottawa, Canada; 110–127.

Justus BG. 2009. Characterization of Macroinvertebrate and Fish Assemblages at 35 Streams in Southwestern Louisiana and an Assessment of Their Relations to Water-Quality and Physical Habitat. http://ar.water.usgs.gov/PROJECTS/REMAP.html.

Justus BG, Wallace JE. 2009. Fish and Invertebrate Assemblage Relations to Dissolved Oxygen at 35 Sites in Southern Louisiana. Abstract. In *39th Annual Mississippi Water Resources Conference*, Mississippi Water Resources Research Institute, Starkville, Mississippi. http://www.wrri.msstate.edu/results.asp?Author=justus&submitbutton=Search.

Justus BG. 2010. Water quality of least-impaired lakes in eastern and southern Arkansas. *Environmental Monitoring and Assessment* **168**: 363–383.

Kaller MD, Kelso WE. 2007. Association of Macroinvertebrate Assemblages with Dissolved Oxygen Concentration and Wood Surface Area in Selected Subtropical Streams of the Southeastern USA. *Aquatic Ecology* **41**(1): 95–110.

Killgore KJ, Hoover JJ, Murphy CE, Parrish KD, Johnson DR, Myers KF. 2008a. Restoration of Delta Streams: A Case History and Conceptual Model, EMRRP-ER-08. U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Killgore KJ, Hoover JJ, Murphy C, George S, Johnson D. 2008b. Index of biotic integrity for the fishes of the Yazoo River Delta, Mississippi. Draft report, US Army Engineer Research and Development Center, Vicksburg, MS.

Kleiss BA, Coupe RH, Gonthier GJ, Justus BG. 2000. Water Quality in the Mississippi Embayment, Mississippi, Louisiana, Arkansas, Missouri, Tennessee, and Kentucky, 1995–98. U.S. Geological Survey Circular 1208, 36 p.

Knight SS, Welch TD. 2004. Evalution of Watershed Management Practices on Oxbow Lake Ecology and Water Quality. *Water Quality Assessments in the Mississippi Delta*, Chapter 9. ACS Symposium Series, Vol. **877**: 119–133. DOI: 10.1021/bk-2004-0877.ch009

Knight SS, Lizotte RE Jr., Shields FD Jr. 2009a. *Hyalella azteca* (Saussure) Responses to Coldwater River Backwater Sediments in Mississippi, USA. *Bulletin of Environmental Contamination and Toxicology* **83**: 493–496. DOI: 10.1007/s00128-009-9804-7

Knight SS, Lizotte RE, Moore MT, Smith S, Shields FD. 2009b. Mississippi Oxbow Lake Sediment Quality During an Artificial Flood. *Bulletin of Environmental Contamination and Toxicology* **82**: 496–500. DOI: 10.1007/s001-28-009-9653-4

Lin DSC, Caramaschi ÉP. 2005. Responses of the fish community to the flood pulse and situation in a floodplain lake of the Trombetas River, Brazil. *Hydrobiologia* **545**: 75–91. DOI: 10.1007/s10750-005-2186-x

Lyon J, Stuart I, Ramsey D, O'Mahony J. 2010. The effect of water level on lateral movements of fish between river and off-channel habitats and implications for management. *Marine and Freshwater Research* **61**: 271–278.

Lizotte RE Jr., Shields FD Jr., Knight SS, Cooper CM, Testa S III, Bryant CT. In press. Effects of artificial flooding on water quality of a Coldwater River floodplain backwater. *River Research and Applications*.

Mason A, Xu YJ, Saksa P, Vioska A, Grace JM, Beebe J, Stich R. 2007. Streamflow and Nutrient Dependence of Temperature Effects on Dissolved Oxygen in Low-Order Forest Streams. In *Proceedings of the 10–14 March 2007 Fourth Conference Forest Service personnel*, McFarland A, Saleh A (eds). American Society of Agricultural and Biological Engineers: St. Joseph, Michigan; 374–380.

Maul JD, Farris JL, Milam CD, Cooper CM, Testa S III, Feldman DL. 2004. The Influences of Stream Habitat and Water Quality on Macroinvertebrate Communities in Degraded Streams of Northwest Mississippi. *Hydrobiologia* **518**: 79–94.

McCune B, Grace JB. 2002. *Analysis of Ecological Communities*. MjM Software Design: Gleneden Beach, Oregon. http://www.pcord.com

McCune B, Mefford MJ. 1999. PC-ORD. Multivariate Analysis of Ecological Data, version 4. MjM Software Design, Gleneden Beach, Oregon.

McHenry JR, Cooper CM, Ritchie JC. 1982. Sedimentation in Wolf Lake, Lower Yazoo River Basin, Mississippi. *Journal of Freshwater Ecology* **1**(5): 547–558.

Miranda LE. 2005. Fish Assemblages in Oxbow Lakes Relative to Connectivity With the Mississippi River. *Transactions of the American Fisheries Society* **134**: 1480–1489.

Miranda LE. 2010. Depth as an organizer of fish assemblages in floodplain lakes. *Aquatic Sciences*. DOI: 10.1007/s00027-010-0170-7

Miranda LE, Hargreaves JA, Raborn SW. 2001. Predicting and managing risk of unsuitable dissolved oxygen in a eutrophic lake. *Hydrobiologia* **457**: 177–185.

Miranda LE, Lucas GM. 2004. Determinism in Fish Assemblages of Floodplain Lakes of the Vastly Disturbed Mississippi Alluvial Valley. *Transactions of the American Fisheries Society* **133**: 358–370.

Mississippi Department of Environmental Quality. 2003. Sediment TMDL for the Coldwater River. Office of Pollution Control. Water Quality Assessment Branch, TMDL/WLA Section. Jackson, Mississississippi.

Moss B, Barker T, Stephen D, Williams AE, Balayla DJ, Beklioglu M, Carvalho L. 2005. Consequences of reduced nutrient loading on a lake system in a lowland catchment: deviations from the norm? *Freshwater Biology* **50**: 1687–1705. DOI: 10.1111/j.1365-2427.2005.01416.x

Pegg MA, Irons KS, O'Hara TM, McClelland MA. 2006. Initial response of a floodplain lake fish community to water-level stabilization. *Ecology of Freshwater Fish* **15**: 40–47. DOI: 10.1111/j.1600-0633.2005.00118.x

Pennington KL. 1999. Mississippi Delta surface water quality, a summary. In *29th Mississippi Water Resources conference Proceedings*, Mississippi Water Resources Research Institute, 78–86.

Pennington KL. 2004. Surface Water Quality in the Delta of Mississippi. *Water Quality Assessments in the Mississippi Delta*. Chapter 3. ACS Symposium Series **877**: 30–42. DOI: 10.1021/bk-2004-0877.ch003

Price RE, Cooper CM. 1981. A Survey of the Net plankton from Bear Creek, Mississippi. *Journal of Mississippi Academy of Sciences* **26**: 42–49.

Rebich RA. 2004. Suspended sediment and agrochemicals in runoff from agricultural systems in the Mississippi Delta: 1996–2000. *Water Quality Assessments in the Mississippi Delta*, Chapter 8. ACS Symposium Series, Vol. **877**: 104–118. DOI: 10.1021/bk-2004-0877.ch008.

Rebich RA, Welch HL, Coupe RH. 2004. Evaluation of water-quality and habitat assessment data to determine ranges in stream conditions in the Mississippi River Alluvial Plain of Northwestern Mississippi and Eastern Arkansas. U.S. Geological Survey Water-Resources Investigations Report 03–4251, 47 p.

Ritchie JC, Cooper CM, McHenry JR. 1979. Recent accumulation of sediment in lakes in the Bear Creek watershed in the Mississippi Delta. *Southeastern Geology* **20**(3): 173–180.

Roozen FCJM, Van Geest GJ, Ibelings BW, Roijackers R, Scheffer M, Buijse AD. 2003. Lake age and water level affect the turbidity of floodplain lakes along the lower Rhine. *Freshwater Biology* **48**: 519–531.

Roozen FCJM, Lürling M, Vlek H, Van Der Pouw Kraan EAJ, Ibelings BW, Scheffer M. 2007. Resuspension of algal cells by benthivorous fish boosts phytoplankton biomass and alters community structure in shallow lakes. *Freshwater Biology* **52**: 977–987. DOI: 10.1111/j.1365-2427.2007.01729.x

Roozen FCJM, Peeters ETHM, Roijackers R, Wyngaert IVD, Wolters H, De Coninck H, Ibelings BW, Buijse AD, Scheffer M. 2008. Fast Response of Lake Planton and Nutrients to River Inundations on Floodplain Lakes. *River Research and Applications* **24**: 388–406. DOI: 10.1002/rra.1071

Ross ST. 2001. *The Inland Fishes of Mississippi*. University Press of Mississippi: Jackson; 624 p.

Rosso JJ, Quiros R. 2008. Interactive effects of abiotic, hydrological and anthropogenic factors on fish abundance and distribution in natural run-of-the-river shallow lakes. *River Research and Applications* **25**: 713–733. DOI: 10.1002/rra.1185

Schlosser IJ, Karr JR. 1980. Determinants of Water Quality in Agricultural Watersheds. Report UILU-WRD-80-0147, University of Illinois Water Resources Center (1980).

Shields FD Jr., Knight SS, Stofleth JM, Wren DG. 2009a. Towards a basis for designing backwater and side channel restorations. Water Engineering for a Sustainable Environment. Proceedings, International Association for Hydraulic Research 33rd Congress, IAHR, Madrid, CD-ROM.

Shields FD Jr., Testa S III, Cooper CM. 2009b. Nitrogen and Phosphorus Levels in the Yazoo River Basin, Mississippi. *Ecohydrology* **2**(3): 270–278. DOI: 10.1002/eco.49

Shields FD Jr., Knight SS, Lizotte RE, Wren DG. 2010. Floodplain river backwater restoration: a case study. *Proceedings, 9th Federal Interagency Sedimentation Conference*, *Joint Federal Interagency Conference Organizing Committee*, Washington, D. C., CD-ROM.

Shields FD Jr., Knight SS, Lizotte RE, Wren DG. 2011. Connectivity and variability: Metrics for riverine floodplain backwater rehabilitation. In *The Scientific Basis for Stream Restoration in Dynamic Fluvial Systems: Deterministic Approaches, Analyses and Tools*, Simon A, Bennett S, Castro J, Thorne CR (eds). American Geophysical Union: Washington, D. C.

Shields FD Jr., Knight SS. In press. Significance of riverine hypoxia for fish. *Journal of American Water Resources Association*.

Stephens WW, Moore MT, Farris JL, Bouldin JL, Cooper CM. 2008. Considerations for Assessments of Wadable Drainage Systems in the Agriculturally Dominated Deltas of Arkansas and Mississippi. *Archives of Environmental Contamination and Toxicology* **55**(3): 432–441.

Systat Software, Inc. 2009. SigmaPlot 11.2 User's Guide. San Jose, California.

Tockner K, Malard F, Ward JV. 2000. An Extension of the Flood Pulse Concept. *Hydrological Processes* **14**(16–17): 2861–2883.

Todd MJ, Vellidis G, Lowrance RR, Pringle CM. 2009. High Sediment Oxygen Demand Within an Instream Swamp in Southern Georgia: Implications for Low Dissolved Oxygen Levels in Coastal Blackwater Streams. *Journal of the American Water Association (JAWRA)* **45**(6): 1493–1507. DOI: 10.1111/j.1752-1688.2009.00380.x

U.S. Corps of Engineers. Undated. Coldwater River Basin below Arkabutla Lake, Mississippi, Section 905(b) Reconnaissance Report. U.S. Army Corps of Engineers, Vicksburg, MS.

Ward JV, Stanford JA. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. *Regulated Rivers: Research and Management* **11**(1): 105–119.

Ward JV, Tockner K, Uehlinger U, Malard F. 2001. Understanding Natural Patterns and Process in River Corridors As the Basis for Effective River Restoration. *Regulated Rivers: Research & Management* **17**: 311–323.

Whitten CB, Patrick DM. 1981. Engineering Geology and Geomorphology of Streambank Erosion (Report 2: Yazoo River Basin Uplands, Mississippi). Technical Report GL-79-7, Report 2 of a Series, TR GL-79-7. U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Wiens JA. 2002. Riverine Landscapes: Taking Landscapes Ecology into the Water. *Freshwater Biology* **47**: 501–515.

Wren DG, Davidson GR, Walker WG, Galicki SJ. 2008. The evolution of an oxbow lake in the Mississippi alluvial floodplain. *Journal of Soil and Water Conservation* **63**(3): 129–135.

Zeug SC, Winemiller KO. 2008. Relationships between hydrology, spatial heterogeneity, and fish recruitment dynamics in a temperate floodplain river. *River Research and Applications* **24**: 90–102. DOI: 10.1002/rra.1061