FLOODPLAIN RIVER BACKWATER RESTORATION: A CASE STUDY

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Abstract: Current thinking in stream ecology emphasizes the importance of floodplain backwaters within lowland riverine ecosystems. However, these types of habitat are becoming increasingly rare as development is transforming floodplain landscapes in fundamental ways. Two floodplain backwaters (severed meander bends) along the Coldwater River in northern Mississippi, USA were studied for four years. The study sites contained up to 2.5 m of sediments deposited since cutoff, and connections to the river were brief and sporadic. During drier months, water quality reflected combined effects of nonpoint source pollution and very shallow water depths. One backwater was used as an untreated reference, and the other was modified by adding a weir that included an operable culvert that was opened during winter to maintain river connectivity but closed during drier months to increase water depth. Furthermore, placement of the weir diverted agricultural runoff away from the modified backwater. Responses to treatment included reduced river connectivity, increased summer water depth, moderation of severe diurnal water quality fluctuations, and reductions in concentrations of solids (~70%), nutrients (~30%-60%), and chlorophyll *a* (~50%). Similar changes were not observed in the untreated backwater. Fish species richness, numbers and biomass were unchanged following rehabilitation, but trophic structure shifted away from omnivorous species and toward predators, making the treated site less similar to the degraded reference. Ecological services provided by floodplain riverine backwaters may be enhanced by modest management measures, but regaining and maintaining connectivity with adjacent ecological functional patches is difficult.

INTRODUCTION

Freshwater ecosystems in the U.S. are exceptionally diverse, even compared with the tropics (Master et al. 1998). In particular, streams in the southeastern United States ("Southeast") are important ecological resources, but resident fauna are experiencing accelerated extinction rates (Ricciardi and Rasmussen 1999, Warren et al. 2000, Karr et al. 2000). Apparently, faunal declines reflect disruption of important connections between main channel and slackwater habitats such as wetlands, abandoned channels, sloughs, severed meander bendways and borrow pits (Buijse et al. 2002, Ward et al. 2001, Wiens 2002, Jackson 2003, Kondolf et al. 2006), or in more current terminology, disruptions of connections between hydrogeomorphic patches (Thorp et al. 2006). Prior to European settlement, much of the area presently under cultivation in the Southeast was characterized by low relief and gentle undulating topography such as ridge and swale patterns that produced high levels of physical and biological diversity. Vegetation cover was comprised of virgin bottomland hardwoods, cane breaks, and other wetland plants. Most importantly, hydrology of these regions was dominated by periodic flooding. Flood hydrographs tended to be of long duration and low amplitude. Stream channels were complex, with high sinuosity and multiple stage-dependent connections to floodplain backwaters such as lakes, sloughs, wetlands, and depressions. Following European settlement, floodplains were developed using practices including tile drainage, precision land leveling, filling of wetlands, excavation of ditches, flood control, and water table manipulation. Larger rivers were dammed, channelized, stabilized, and leveed, reducing aquatic area and the numbers of islands and back channels as well as the area of other high-quality habitats (Gore and Shields 1995, Hohensinner et al. 2004). Despite the large sums of money spent on control and management of water pollution, the quality of floodplain ecosystems continues to decline (Aarts et al. 2004).

Ecological restoration may be thought of as an attempt to return an ecosystem to its historic (pre-degradation) trajectory (Society 2004). Restoration workers attempt to establish this “trajectory” through a combination of information about the system’s previous state, studies on comparable intact ecosystems, information about regional environmental conditions, and analysis of other ecological, cultural and historical reference information (Society 2004). Ward et al. (2001) argue that large river restoration has been hampered by mistaken assumptions about the simplicity and stability of river corridors in their natural state. Natural rivers exhibit high levels of spatio-temporal heterogeneity due to the interplay of hydrologic, geologic, and topographic factors, particularly in the lateral dimension. These patterns are manifest in many ways: principally in the rise and fall (advance and retreat) of water, but also in complex patterns of velocity, water temperature (Uehlinger et al. 2003), turbidity, and movements of organisms. River corridors may be thought of as complex mosaics of various types of habitat patches, with permanent or temporary linkages through surface waters, subsurface waters, or the atmosphere (Wiens 2002). These patches are arranged within “functional process zones” along river corridors in hierarchies controlled by landscape scale variables (Thorp et al. 2006). Backwaters are especially valuable if they are permanently or periodically connected to the river (Penczak et al. 2004).

In lightly altered natural systems, backwaters tend to follow a trajectory similar to classical lake eutrophication: due to sedimentation and perhaps migration of the river mainstem, these areas become shallower, and connections to the river become briefer and less frequent. However, the formation of new backwaters due to main channel avulsion and more gradual processes continues as old backwaters become wetlands and, eventually, terrestrial systems. In altered floodplains, however, backwater formation processes are hindered or absent. Backwaters gradually disappear from the landscape as sedimentation accelerates due to floodplain cultivation or as main channel incision causes water levels to drop (Light et al. 2006). Flood control and channel stabilization prevent formation of new backwaters as existing backwaters age, becoming shallower, more turbid and often experiencing lower dissolved oxygen (DO) concentrations (Miranda 2005). Extremely shallow backwaters tend to experience lower DO than deeper ones due to respiration occurring throughout the water column (Miranda et al. 2001) and lower water transparency due to benthivorous fish and phytoplankton (Roozen et al. 2003, Miranda and Lucas 2004). Fish communities in such systems exhibit strong linkages to abiotic factors and are dominated by tolerant omnivores with few predators (Miranda and Lucas 2004).

Many river restoration projects have focused on managing floodplain water bodies and their connectivity with the main channel. Functional values associated with backwaters have been reclaimed by pumping in water, breaching levees, re-opening relatively small connecting channels and by constructing water control structures to increase water depth during dry periods (Shields and Abt 1989, Galat et al. 1998, Buijse et al. 2002, Valdez and Wick 1981, Grift et al. 2001, Shields et al. 2005, Schultz et al. 2007). Substantial sums have been spent in these efforts, but little information is available regarding the performance of existing projects to guide future design efforts (O’Donnell and Galat 2007, Palmer et al. 2007). The purpose of this paper is to document preliminary findings of an experimental backwater rehabilitation project.

STUDY SITES

A reach of the Coldwater River about 20 km downstream from Arkabutla Dam in northwestern Mississippi was selected for study due to the presence of more than 20 severed meander bends and other floodplain water bodies along the river. Elevated suspended sediment concentrations, habitat reduction associated with sedimentation, and water pollution associated with agriculture are primary resource problems in this locale (Mississippi Department of Environmental Quality 2003). Despite these problems, reports indicate viable fish populations within the Coldwater River. Jackson et al. (1995) reported capture of 22 species of fish from this reach during 1990-1994, and catch per unit effort for the Coldwater River (all species and seasons) exceeded the four other Yazoo basin rivers sampled during the same time period.

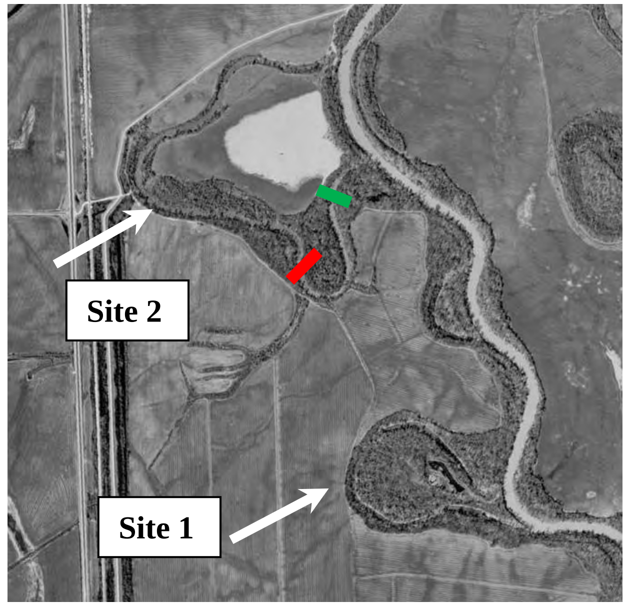

Figure 1. Study sites in 1957. Bends (arrows) were cut off from Coldwater River in 1941-42. Northern bend was treated by addition of weir (red bar) in 2006. A second weir (green bar) allowed management of an existing wetland in the downstream limb of the bendway.

Two floodplain backwaters that were severed meander bends created by manmade cutoffs constructed in 1941-42 (Whitten and Patrick 1981) were selected for study (Figure 1). Both backwaters were 1.5 to 2 km long and 40 m wide and were inside the mainstem flood control levee. Lands outside the old bends were in row-crop cultivation, while lands inside the bends were in forest (Site 1) or fallow (Site 2). Buffers of natural vegetation 5-100 m wide were on both banks of the old channels. Both backwaters received runoff from cultivated fields. River stages were controlled by the operation of Arkabutla Dam, located about 20 km upstream on the Coldwater River. Backwater levels were tightly coupled with Coldwater River stage when the river stage exceeded the controlling elevation in the downstream connecting channel, but during the warmer months the river was 1 to 3 m lower than the backwaters, and they became quite shallow due to evaporative losses. Site 1 was almost completely choked with aquatic plants during warmer months. Probing bed sediments at both sites with metal rods and sampling Site 2 with a Vibracore apparatus revealed 2-2.5 m of fine sediment deposition, with mean annual rates of about 3.1 cm yr^{-1} based on vertical profiles of sediment density (Figure 2) and Cs-137 activity. Previously reported sediment sample chemical analyses and invertebrate bioassays indicated sediment metal concentrations were likely not high enough to create toxic impacts, but several pesticides were detected and impacted bioassay results (Knight et al. 2009a and 2009b).

REHABILITATION

Rehabilitation strategy focused on increasing water depth and reducing pollutant inputs while maintaining connectivity with the river. For rehabilitation, Site 2 was modified by constructing two low weirs across the old channel. Weirs consisted of low (< 2 m high) earthen embankments placed at right angles to the old river channel and covered with stone riprap. 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." Weir water control structures were operated to retain water during March – November, and were opened to allow more frequent connection to the Coldwater River during December, January and February. Weirs divided the backwater into two compartments: a lake cell and a wetland cell. The southern (upstream) weir was located so as to divert runoff from agricultural fields away from the lake cell and into the wetland cell, thus reducing loadings of sediment, nutrients and pesticides to the lake (Shields and Wilson, accepted; Lizotte et al. 2009).

METHODS

The two backwaters were monitored for a range of characteristics for about 18 months before and 36 months after rehabilitation. Site 1 (degraded reference) was sampled during the first and final years of this period; Site 2 (rehabilitated) was sampled throughout the study period. For the duration of the study, water surface elevations and temperatures in both backwaters and in the adjacent river were logged at 30-min intervals; and pH, DO, turbidity and specific conductance in the backwaters were logged at 4-h intervals and were measured using handheld meters weekly. Water quality sensors were placed at middepth (0.2 to 0.6 m below the surface), but thermal stratification was transient and < 4 ^{o}C m^{-1} throughout the study. Grab samples were collected weekly and analyzed for solids and nutrients. Since water quality data were not normally distributed, nonparametric ANOVA (Kruskal-Wallis one-way ANOVA on ranks with Dunn's method for multiple comparisons) were used to compare distributions, with a variable defined as "status" (degraded reference, rehabilitated backwater before treatment and rehabilitated backwater after treatment) as the factor. Fish samples were collected using pulsed DC boat-mounted electroshockers with two dippers. Maximum effective voltage (which varied with water conductivity and depth) was determined for each sample collected. Fish were identified to species and measured to length. Weights were determined by measurement or using regional length- weight relationships developed for each species. Pearson product-moment correlation coefficients were computed between key descriptors of fish collections and physical (hydrologic) variables. For example, we computed r-values between the number of species captured on a given date from a given backwater and the mean water depth recorded for that date and backwater.

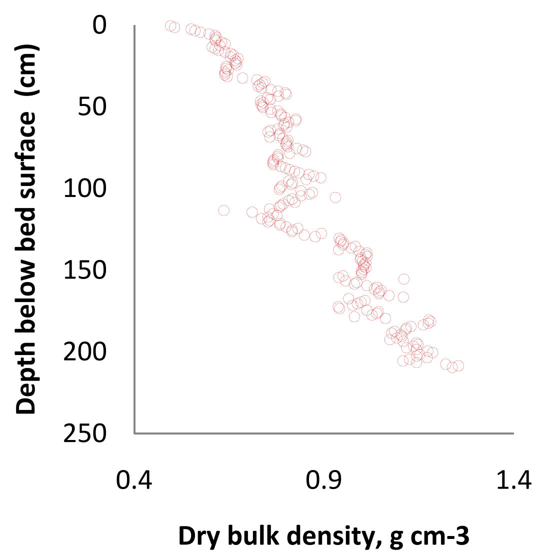

Figure 2. Bulk density profile of Site 2 backwater sediment core collected in 2008. Density increases down to about 210 cm below the surface. Particle size gradation shifts from 55% clay and 26% silt near bed surface to 29% clay and 45% coarse silt at 236 cm below surface.

Water surface elevation time series were used to compute time series of water volume, surface area, and mean depth using digital elevation models based on LiDAR coverage of terrestrial zones and bathymetric data collected using a boat-mounted echosounder coupled with differentially-corrected GPS during high stages. Mean daily values of backwater stage and mean depth were further examined using the suite of indices of hydrologic alteration proposed by Richter et al. (1998).

RESULTS

Placement of the weir in Site 2 moderated stage fluctuations (Figure 3). During the three water years following weir placement, the median duration of high stage events in the degraded reference site was 2 days, but 32 days in the rehabilitated site. Median rise rates for high stages were 0.19 m/day and 0.01 m/day, for the degraded and rehabilitated backwaters, respectively. Fall rates were -0.09 m/day and -0.01 m/day, respectively. The more gradual post-rehabilitation rise and fall rates were typical of a less-impacted backwater site located further upstream on the same river, as described by Shields and Knight (2008). Thus backwater rehabilitation tended to reduce hydrologic variability. At the same time, connectivity between the backwater and river channel were considerably lower following rehabilitation (Table 1).

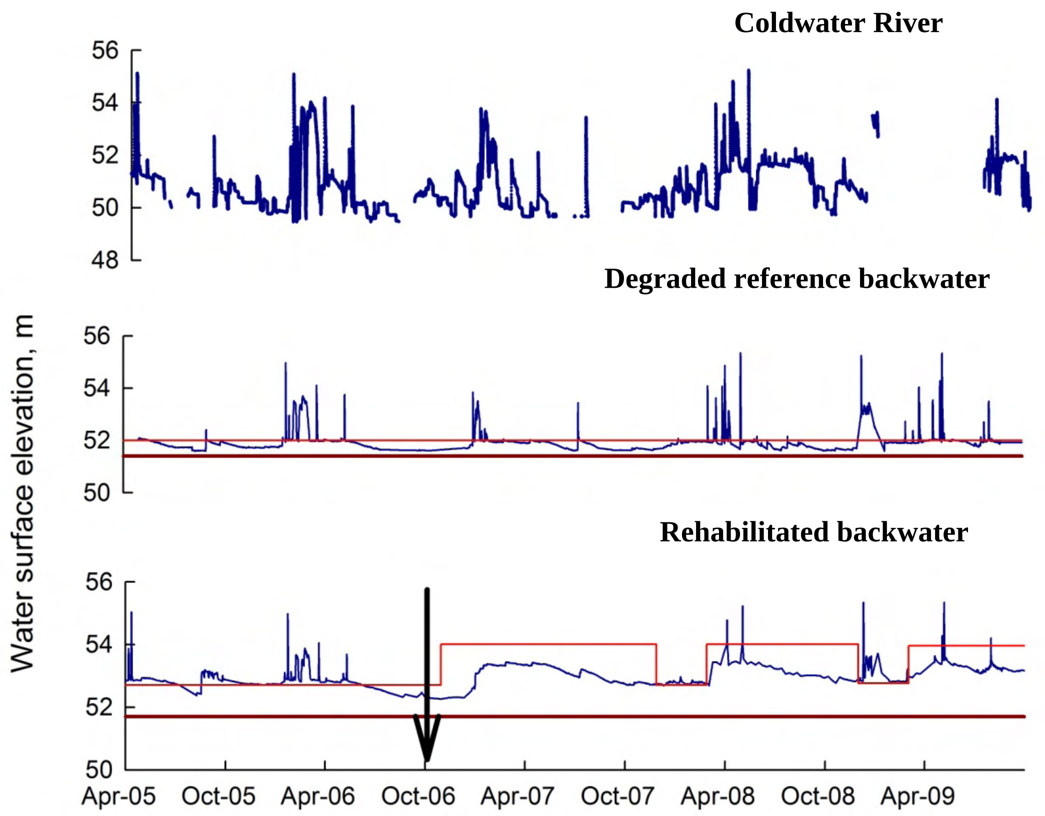

Figure 3. Stage hydrographs for river adjacent to backwaters, degraded reference backwater, and rehabilitated backwater. Red lines on backwater hydrographs indicate controlling elevations for connection between river and backwater. Brown lines indicate approximate thalweg elevations. Vertical black arrow indicates date for completion of weir construction.

Table 1. Hydrologic conditions in study backwaters before and after rehabilitation

Period	Degraded reference backwater (Site 1)		Rehabilitated backwater (Site 2)	
	Mean (std) water depth, m	River connection, % of time	Mean (std) water depth, m	River connection, % of time
Before rehabilitation (Apr 2005 – Sept 2006)	0.53 (0.22)	6.3	0.59 (0.15)	10.5
After rehabilitation (Oct 2006 – Sept 2009)	0.54 (0.20)	6.5	0.69 (0.16)	3.2

Table 2. Medians of annual extreme mean depths, m. Values computed using software package, Indices of Hydrologic Alteration (Richter et al. 1998).

	30 day minimum	90 day minimum
Degraded reference backwater (Site 1)	0.37	0.39
Site 2 before rehabilitation	0.39	0.45
Site 2 after rehabilitation	0.54	0.55

Prior to rehabilitation, water depths in both backwaters were extremely shallow, with monthly mean water depths generally < 0.65 m. Periods with deeper water, which were driven by high river stages, were brief and limited to Winter and Spring (Figure 3). The rehabilitation weir increased dry season (Summer-Fall) water depths there by 0.15 to 0.30 m, while conditions in Site 1 remained unchanged (Table 1). Dry season extreme lows were greatly moderated by the presence of the weirs in Site 2 (Table 2). Prior to weir placement, water quality conditions in the two backwaters were similar except that temperature, DO and chlorophyll *a* were lower, and total N was greater in the degraded reference backwater, Site 1 (Figure 4 and Table 3). These differences were likely due to the heavy mat of floating duckweed (*Lemna sp.)* that covered the water surface in the degraded reference site during all but the coldest months. Weir placement transformed Site 2 water quality, making it less similar to the degraded Site 1. Diversion of agricultural runoff away from the lake cell in Site 2 (Figure 1) resulted in reductions in turbidity and suspended solids of about 70%, while nutrient levels were 30% to 60% lower. Accordingly, chlorophyll *a* values were about half as great after weir placement. Summer maximum temperatures and diurnal fluctuations in temperature and DO were moderated by greater depths produced by the weir, but minimum DO levels were not (Figures 4 and 5).

The rehabilitated backwater was sampled for fish on 11 occasions over the course of the study, with a total effort of 818 minutes of electrofishing, producing 2,523 fish representing 32 species with a total mass of 259 kg. The degraded reference site yielded 402 fish representing 19 species with a total mass of 20 kg when sampled on two dates with a total effort of 65 minutes. Two species, *Ictiobus bubalus* and *Lepisosteus oculatus*, comprised 53% of the biomass from the rehabilitated site and 66% of the biomass from the degraded site.

Rehabilitation caused the reference and rehabilitated backwater fish populations to be less similar. Simple correlation coefficients between numerical abundances of species collected from the two sites declined from r = 0.94 prior to rehabilitation to r = 0.40 after rehabilitation. Collections from the degraded reference and the rehabilitation site held 16 species in common prior to rehabilitation; after rehabilitation the treated site gained six new species and lost three, and there were only 15 species found in both backwaters.

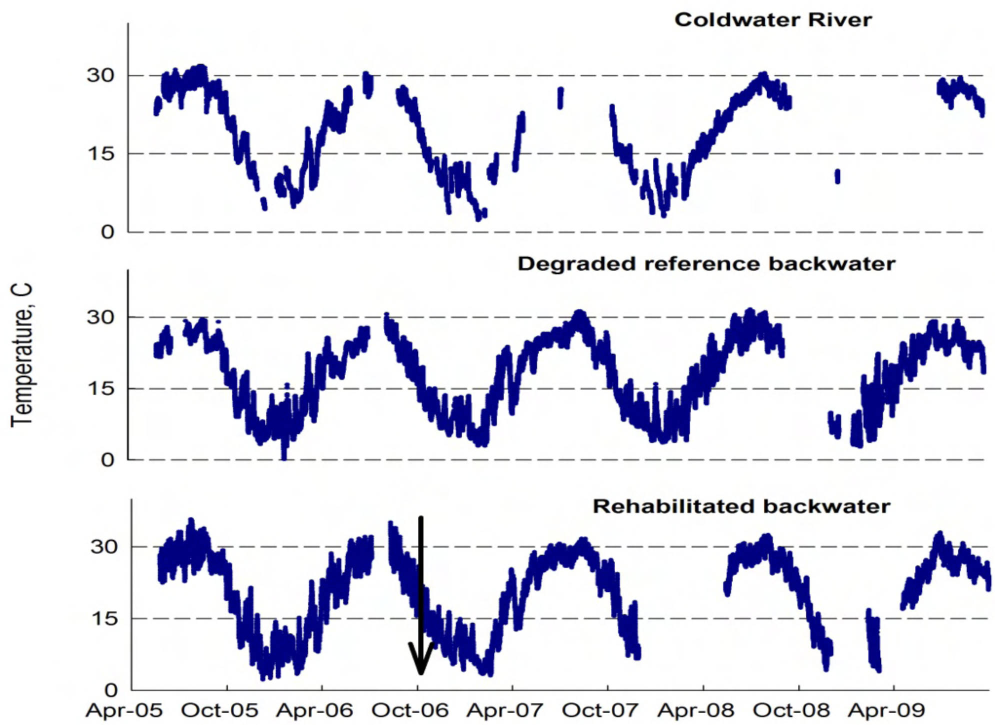

Figure 4. Water temperature time series for Coldwater River downstream from Arkabutla dam, degraded reference backwater, and rehabilitated backwater. Vertical black arrow indicates date for completion of weir construction.

Fish populations in both backwaters appeared relatively insensitive to antecedent connection to the river, but were varied with mean water depth (Table 4). Greater depths in the treated backwater were associated with larger fish, more fish species and a shift in species composition from planktivores to piscivores. Dominance (as % of sample biomass) of the top predator, *Micropterus salmoides*, was positively correlated with mean water depth, while the tolerant insectivore, *Lepomis humilis*, and the planktivore, *Dorosoma cepedianum*, were negatively correlated with mean water depth (Table 4).

Table 3. Medians for mean water depth and selected water quality variables from degraded reference backwater and rehabilitated backwater before and after addition of weirs. Medians with different superscripts are significantly different ($p < 0.05$, Dunn's Method for multiple comparisons, Kruskal-Wallis ANOVA on ranks).

	Degraded reference backwater	Rehabilitated backwater	
		Before weir	After weir
Mean depth on days when samples were collected, m	0.56[a]	0.60[a]	0.71[b]
pH	6.8[a]	6.7[a]	6.0[b]
Dissolved oxygen, mg/L	4.2[a]	5.4[b]	6.2[b]
Turbidity, NTU	38[a]	51[a]	16[b]
Suspended solids, mg/L	40[a]	60[a]	17[b]
Secchi Disk depth, cm			
Total P, mg/L	1.18[a]	0.77[a]	0.33[b]
Filterable P, mg/L	0.061[a]	0.052[a]	0.041[b]
NH_3-, mg/L	0.001[a]	0.012[a]	0.009[a]
Total N, mg/L	1.056[a]	0.132[b]	0.092[c]
Chlorophyll *a*, µg/L	23[a]	78[b]	39[c]

Table 4. Pearson correlation coefficients, r, between descriptors of electrofishing samples from the rehabilitated backwater and key physical variables. Numbers in parentheses are p-values. Figures in bold font show $p \leq 0.10$.

	Days with hydraulic connection to river		Mean water depth
	during previous 6 months	during previous 3 months	
No. of fish species	0.139 (0.684)	0.329 (0.323)	**0.579 (0.062)**
Mean fish size, g	-0.287 (0.391)	-0.209 (0.537)	0.501 (0.116)
% of catch biomass as piscivores	-0.132 (0.698)	0.117 (0.733)	0.512 (0.107)
% of catch biomass as planktivores	-0.161 (0.599)	-0.170 (0.616)	**-0.589 (0.057)**
% of catch biomass as *M. salmoides*	0.233 (0.491)	0.417 (0.202)	0.515 (0.105)
% of catch biomass as *L. humilis*	0.311 (0.351)	0.156 (0.647)	**-0.817 (0.002)**
% of catch biomass as *D. cepadium*	-0.081 (0.813)	-0.170 (0.618)	**-0.592 (0.055)**

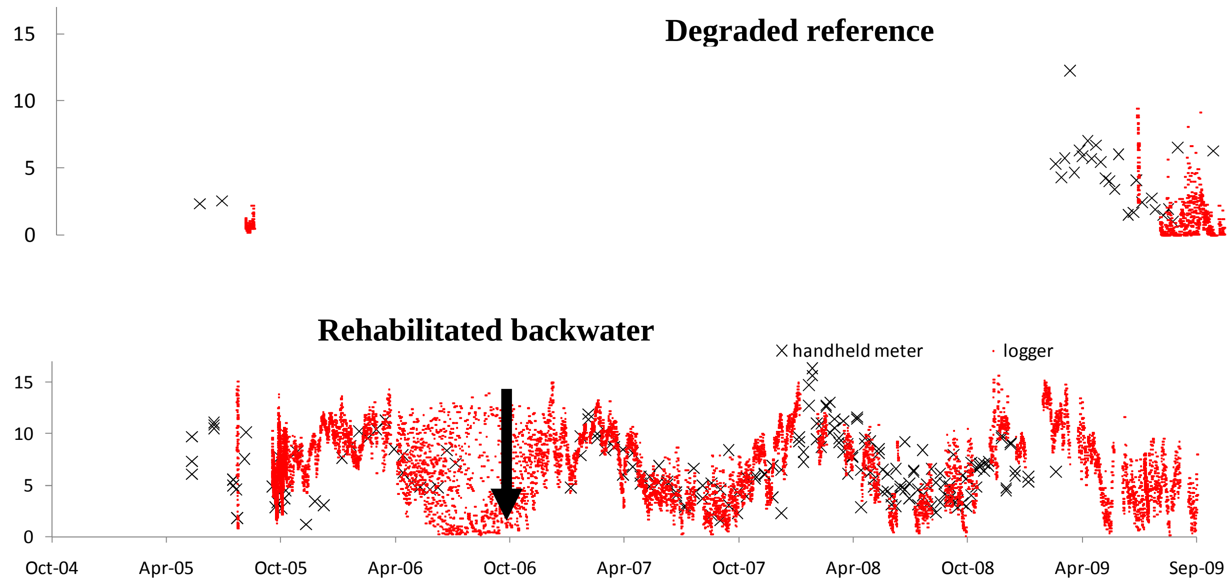

Figure 5. Dissolved oxygen concentrations, degraded reference backwater and rehabilitated backwater. Vertical black arrow indicates date for completion of weir structure.

DISCUSSION AND CONCLUSIONS

Future development of stream corridors should adopt an ecological engineering paradigm (Mitsch and Jørgensen 2004) that manages ecosystems for the totality of services they can provide. Since cutoff bends and other types of floodplain backwaters are common along large, lowland rivers, these areas merit special attention. Cutoff bends may be managed using a combination of water control/flow diversion techniques (Shields et al. 2005). Key questions regarding the design of these measures have to do with the timing and duration of flow connection with the main channel (Shields et al. 2009). Alternative designs may be evaluated by comparing the level of main channel connectivity and hydrologic variability they produce relative to degraded and least impacted sites (Kondolf et al. 2006). Installation and operation of a low weir in the degraded cutoff bend described here reduced main channel connectivity and stage variation relative to the preconstruction and degraded reference site conditions. Water quality generally improved, but periodic periods of depressed DO concentration continued. Fish population trophic structure shifted away from tolerant omnivores toward a more diverse community with more predators, consistent with reports by others linking water depth to fish population structure in natural lakes in this region (Miranda and Lucas 2004). Observed chemical and biological changes were evidently related to moderating temporal hydrologic variations, by increasing dry season water depths by about 0.15 m, and by diverting agricultural runoff from about 100 ha of cultivated fields. Others have reported lake quality improvements produced by diversion of polluted runoff (Cooper 1993, Cooper et al. 1995). The failure of our project to address the problem of hypoxia during warmer months reflects the high level of nutrient enrichment and attendant algal activity common to shallow backwater systems in cultivated floodplains in this region (Miranda et al. 2001, Justus 2006). An approach for increasing backwater depth while maintaining high levels of hydrologic connectivity in a landscape such as ours remains elusive.

ACKNOWLEDGMENTS

Assistance with field data collection was provided by Charles Bryant, Terry Welch, Duane Shaw, and John Massey. The cooperation of the Tunica County Soil and Water Conservation District and of landowners Dennis Paulk, Steve Walters and the Norfleet Family Trust are gratefully acknowledged. John Stofleth, Steve Miranda and Xiaobo Chao read an earlier version of this paper and made many helpful comments.

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