

Kondolf diagram for river backwater restoration

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Abstract

Rehabilitation, protection, and management of riverine backwaters (floodplain aquatic habitats that are seasonally or periodically connected to the main channel) are becoming increasingly common. General criteria for selecting restoration goals and evaluating alternative designs are lacking. An approach for assessing aquatic system status before and after restoration proposed by Kondolf and others (<http://www.ecologyandsociety.org/vol11/iss2/art5/>) is based on assigning a position to the system in a four-dimensional space that represents temporal variability on one axis and connectivity in the three spatial dimensions on the remaining three axes. Use of the Kondolf approach for evaluating restoration design for an example site is described. A plan featuring two small water control weirs was proposed, and a simple numerical water budget model was constructed to allow simulation of temporal variability and connectivity with the main river channel for any imposed annual hydrograph. The impacts of varying the backwater control structure (weir) design and its operation on Kondolf position were assessed using the model.

Introduction

Current thinking in river ecology emphasizes the dependence of lowland riverine ecosystems on the materials and habitats provided by floodplain backwaters (Ward et al. 2001). Conversely, studies of floodplain lakes indicate that connectivity with the adjacent river is a key determinant of fish species assemblages (Miranda 2005). Lowland floodplains typically have low relief and gentle undulating topography such as ridge and swale patterns that, when coupled with unregulated hydrographs, produce high levels of physical and biological diversity in complexes that include side channels, lakes, wetlands, sloughs, and forests. Along lightly-impacted larger rivers, flooding tends to be periodic with long-duration, low-amplitude hydrographs. Such river systems tend to have multiple stage-dependent connections to floodplain backwaters: lakes, sloughs, wetlands, and depressions. Since about 1800, these types of off-channel habitats have declined in quality and quantity due to modification and development of most of the world's major rivers and their floodplains (Gore and Shields 1995, Aarts et al. 2004). Attendant reductions in freshwater ecological resources, particularly in the southeastern U.S. have been reported (Warren et al. 2000). Zalewski (2006) pointed out that functional

floodplains hold great potential for trapping and processing nutrients and other pollutants. This paper seeks to provide information supporting planning and design of a riverine backwater rehabilitation demonstration project.

The Lower Mississippi River alluvial plain (“the Delta”) contains numerous floodplain lakes that experience varying levels of hydrologic connectivity during periods of high stage in adjacent streams and rivers. Many of these water bodies receive significant inflows of water and associated pollutants from cultivated lands, and have experienced precipitous declines in water quality and fisheries in recent decades. Recent studies of Delta lake fisheries indicate that lake area, lake elongation and lake water clarity are key abiotic variables that control fish community structure, with small, shallow elongated lakes most seriously impacted (Miranda and Lucas 2004). Backwater ecosystems often suffer from problems associated with hydrologic perturbation due to levees, dams, main channel incision, and backwater sedimentation. Additional issues include water quality degradation, aquatic plant infestation, and extreme variation in water temperature and habitat volume. One of the most pernicious problems may be described as vertical disruption of lateral connectivity. Hydrologic connections between the river and backwaters become shorter and less frequent when river stages are lowered by incision or controlling elevations for floodplain water bodies are raised by sediment deposition (Light et al. 2006).

Restoration

Ecological restoration may be thought of as an attempt to return an ecosystem to its historic (pre-degradation) trajectory (Society 2002). 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 2002). 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 manifested in many ways: principally in the rise and fall (advance and retreat) of water, but also in complex patterns of velocity, water temperature, turbidity, and movements of organisms. Variation is particularly intense in backwaters, which experience long periods with static or slowly-changing conditions followed by rapid shifts during periods of river connection. Backwater movements and quality may be quite dynamic during river flow events. Because of the inherent variability and unpredictability of river corridors, Hughes et al. (2005) urged definition of restoration trajectories using a range of ecological outcomes that are more representative of real system attributes.

Proposals for rehabilitation and management of backwaters typically include restoring connection with the main channel by re-opening channels closed by sedimentation, adding water control structures to manipulate water levels, increasing inflow from groundwater, or diverting polluted runoff away from backwater inflow. Although large sums are spent annually on backwater rehabilitation (Anonymous

2007), general design criteria for such projects are lacking. Such criteria are needed to address basic questions, such as:

- How high should the weir be?
- How much water should be pumped, and when?
- When should culverts be opened and closed?

At least three approaches (or combinations of these) for generating criteria are possible. First, backwater treatments may be designed, maintained and operated to meet habitat requirements for a selected species or group of species. Secondly, criteria may be set to reproduce selected characteristics of a reference site. Thirdly, using an approach described by Kondolf et al. (2006), backwater physical conditions may be assessed in terms of hydrologic variation and main channel connectivity. Herein we demonstrate the third approach.

Kondolf diagram

Kondolf et al. (2006) proposed the use of hydrologic connectivity and variability (also referred to as flow dynamics) as key descriptors of riverine ecosystem status. Hydrologic connectivity was defined as water-mediated fluxes of material, energy, and organisms among the major ecosystem components: main channel, floodplain, aquifer, etc. Connectivity occurs in all three spatial dimensions: longitudinal (upstream and downstream), lateral (main channel and floodplain), and vertical (surface water and the hyporheic or deeper subsurface regions). Variability was primarily defined as temporal variation in discharge, but also encompasses parameters such as temperature, sediment and trophic levels. Connectivity and variability tend to be related. For example, construction of a dam to regulate flow often reduces the frequency and duration of floods downstream, reducing lateral connectivity and flow variation. Furthermore, the dam may reduce longitudinal connectivity by presenting a barrier to movements of sediment and organisms. The status of a given riverine ecosystem may be mapped by plotting a point representing the system within a Cartesian plane with the horizontal axis representing variability and the vertical axis representing connectivity in a selected dimension (Figure 1). Multi-dimensional plots may be used if connectivity is mapped in more than one dimension. If information is available, points may be plotted representing pre-degradation and current conditions, giving a degradation trajectory. Ideally, restoration would simply follow the reverse path of the degradation vector, returning the system to its pre-degradation connectivity and flow variability. If pre-degradation data are not available, reference conditions may be inferred from lightly degraded sites.

To illustrate this concept, Kondolf et al. (2006) plotted degradation trajectories for 23 rivers using at least one dimension to measure connectivity. Month-to-month flow variation, with special emphasis on the probability of intermittent flow, was used to indicate streamflow variability. Restoration trajectories were plotted for systems that were sites for restoration projects. In general, the bivariate plots showed that systems tended to follow paths that resulted in reduced connectivity and variability as they degraded. Some sites (e.g., those subjected to base flow diversions or channelization) became more variable as they were degraded.

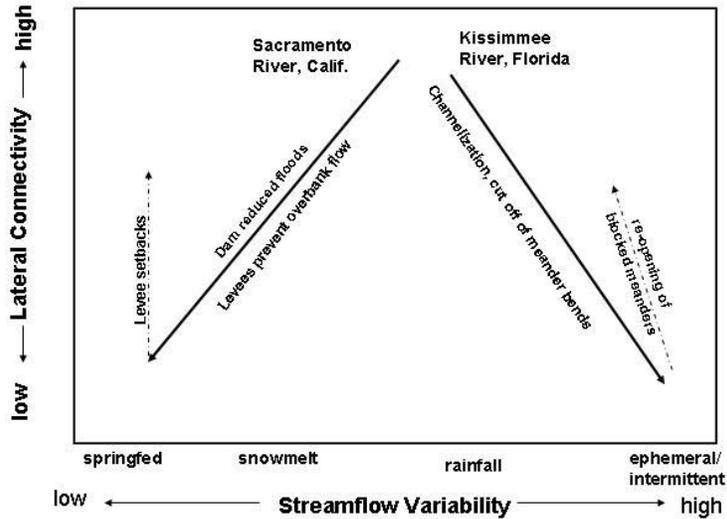


Figure 1. Kondolf diagram for assessment of aquatic ecosystem status. Solid arrows represent ecological degradation and dashed arrows represent restoration trajectories plotted on axes of lateral connectivity and flow dynamics. After Kondolf et al. (2006).

Rehabilitation or restoration often increased connectivity but rarely increased variability. Preparing a “Kondolf diagram” for a system selected for restoration requires completion of four key tasks: assessment of historical conditions, definition of degradation in process-based terms, identification of factors triggering degradation, and setting goal trajectories for selected processes. Herein we adopt this approach not for river reaches as originally proposed but for individual floodplain water bodies, or backwaters. Clearly, the overarching goal of backwater rehabilitation is to contribute positively to the entire river ecosystem, but the open nature of the river system and the mobility of its fauna make measurement of the effects of restoring one or a few backwaters impossible.

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. A severed compound meander bend about 2.5 km long and 40 m wide was selected for rehabilitation. The bend is inside the mainstem flood control levee, and is the result of a 0.4 km cutoff constructed in 1941-42. Lands both inside and outside the bend are in row-crop cultivation, but there was a buffer of natural vegetation 5-100 m wide on both banks. The backwater receives runoff from about 100 ha of cultivated lands, principally through an intermittent slough.

Initial monitoring showed that the backwater channel contained 2-3 m of soft sediment, and average water depths ranged from about 1 m during spring and winter to only about 0.4 m in late summer and fall. Water quality conditions were extremely poor during these hot, dry periods, with extreme diurnal variations. Lateral connection between the backwater and the river occurred at the downstream end of

the old bend as water moved through a narrow connecting channel and over elevated sediment deposits, at the upstream end through a 0.6-m-diameter culvert, and, when river stages were high enough, at the upstream end over a low roadway embankment. Examination of LiDAR topographic data verified that additional connecting channels do not exist except at extremely high (and thus very rare) river stages. River stages adjacent to the backwater reflected regulation by the flood-control reservoir just upstream and main channel incision; analysis of 40 years of once-daily stage records indicated that the mean annual duration of backwater – river connection was 66 days. There was an average of 11 connection events per year with a maximum duration of 94 days. Connections most often occurred in December – April, less so in May – August and were rare in September – November. Physical conditions in the backwater changed rapidly during the initial phase of a river connection event, with rapid quality changes occurring as water depth doubled during the first few minutes. Even during connection events, only negligible velocities (< 0.1 m/s) were observed in the backwater.

A second severed bendway located on the same river, but upstream from Arkabutla Lake and outside of the zone of reservoir influence, was used as a reference. There were no significant local inflows, and runoff from adjacent fields was diverted away from the bend by a low levee. The backwater channel was about 0.35 km long and 20 m wide and was subjected to more frequent connection with the river, with fully developed lotic conditions (velocities ~ 0.3 m/s) occurring during high river stage. Analysis of 40 years of once-daily stage records indicated that the mean annual duration of backwater – river connection was 248 days. There was an average of 8 connection events per year with a maximum duration of 68 days. This type of long-duration, pulsed connectivity is typical of the regime that persisted at the degraded site downstream of the reservoir prior to reservoir and levee construction, and fish species in this system are adapted to such conditions.

Methods

After consideration of a range of alternative approaches for backwater rehabilitation (Shields et al. 2005), it was decided to treat this backwater by constructing two low weirs in the downstream meander limb (Figure 2), effectively dividing the backwater into two “cells”—a larger, deeper one to be managed as aquatic habitat and a smaller, shallower one currently supporting wetland and terrestrial plants to be managed as a wetland. Weir construction was selected over alternate approaches based on total cost, maintenance requirements and operational flexibility. The weir controlling the aquatic cell was located so that most of the runoff from adjacent fields was diverted away and into the wetland cell. Both weirs were designed with adjustable crest drainage structures protected by “Clemson” beaver exclusion screens at their upstream intakes. Weirs were protected with riprap to allow for overflow in either direction.

A simple numerical model was constructed to allow simulation of the aquatic cell water budget. For purposes of this study, the wetland cell was ignored. The model was used to compute water surface elevation, mean water depth and surface area and the volumes of water exchanged with the main channel with a time step of 10^{-4} day to prevent numerical instabilities. Regression relationships among backwater surface elevation, surface area, and volume were derived from topographic

data (a combination of LiDAR, total station, and echosounder surveys). Precipitation data were obtained from the nearest weather station, and rainfall-runoff and evaporation were computed using seasonally-adjusted regional averages. Flow through drainage structures, culverts and over weirs and in connecting channels was computed using depth-dependent Manning coefficients or weir coefficients. After calibration and verification using data representing pre-rehabilitation conditions, the model was used to assess backwater connectivity and variability for the reference site, the rehabilitation site before weir construction, and the rehabilitation site under a range of weir crest elevations and operational scenarios. Conditions at all three sites (reference, pre-rehabilitated, and rehabilitated) were assessed using river stage records representing the wettest, driest, and median water years on record. The total duration of connection events during a simulated water year was selected as an indicator of connectivity. Total volume of water exchanged with the river was also examined as an indicator of connectivity, but it was redundant with the total duration of connection events. The standard deviation of mean water depth was used as an indicator of variability. Annual mean water depth was also computed due to its importance in regulating water quality and fish community structure in backwaters in this region (Miranda 2005).

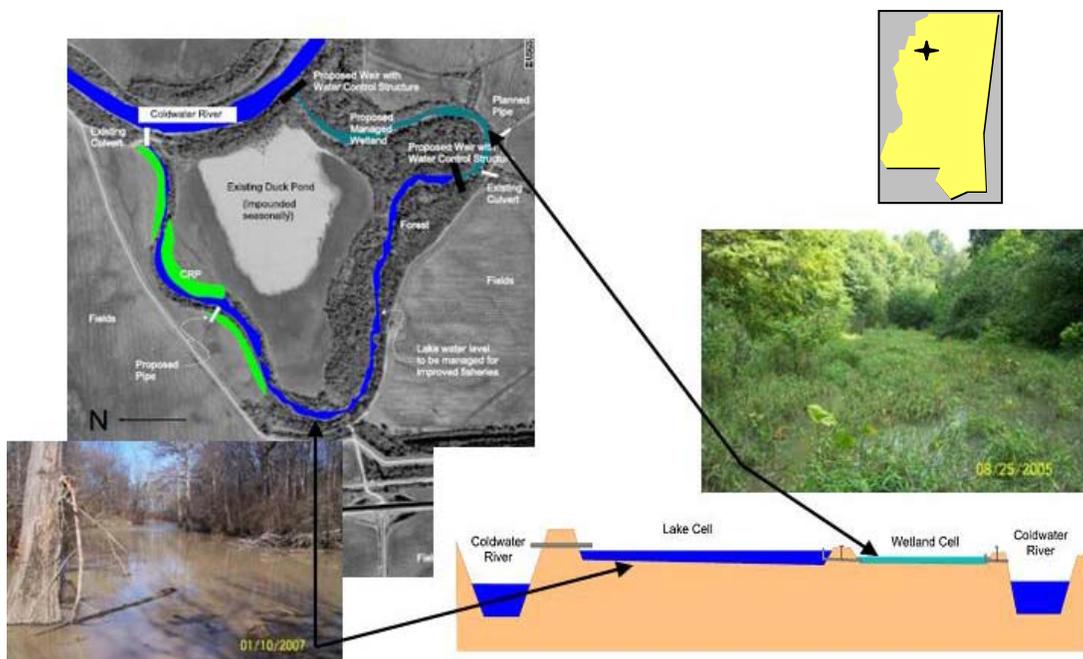


Figure 2. Plan for backwater rehabilitation, Coldwater River, Tunica County, MS.

For simulation of water exchange with the main channel, the topography of the reference backwater was assumed to resemble the river channel at the time of cutoff, prior to deposition of sediment deposits, except for a major blockage in the upstream entrance, which is typical of recently cutoff bends (Shields and Abt 1989). The pre-cutoff topography was estimated by probing the bed with a 1-cm diameter metal rod along several surveyed cross sections.

Backwater temperature, conductivity, dissolved oxygen, pH and turbidity were monitored in-situ using YSI 6000 or 6600 instruments every four hours, and water levels were recorded every half hour using Onset water level recorders (trade names for information purposes only). Water samples and Secchi disk readings were collected biweekly, and samples were analyzed for nutrients and solids. Fish were sampled from the backwater five times (four times in the spring and summer and once in early winter) over two years prior to rehabilitation and twice following rehabilitation (spring and fall). Sampling was accomplished using a boat-mounted Coffelt Model VVP-2C (name provided for information purposes only and should not be taken as an endorsement of any particular brand or product) electroshocker operating at 250-350 volts. Effort per sample ranged from 18 to 72 min of electrofishing time to provide adequate survey coverage given varying water levels while minimizing damage to recovering populations. Captured fish were placed in holding tanks until they could be measured for length, and released. Weight was estimated from length based on length weight relationships for each species. Catch per effort was calculated as the total weight in kg divided by the sampling time in hours. Fish too small or difficult to identify in the field were preserved in 10% formalin, labeled and bottled for transport and identification at the USDA National Sedimentation Laboratory. Capture mortality was generally limited to smaller individuals.

Results

After calibration, the simulation model reproduced an observed annual backwater stage hydrograph with an RMS error of 0.24 m. The first eight months of the hydrograph were used for calibration, while the last four months, which included a month-long period with intermittent experimental pumping of up to 0.35 m³/s into the bend (Cooper et al. 2006), was used for verification. The simulation model reproduced lake stage variations in response to river inflows and evaporative losses during long dry spells rather well but did a poorer job of reproducing lake fluctuations in response to local inflows (Figure 3). This is not surprising given the lack of on-site precipitation data and the crude algorithm for predicting runoff.

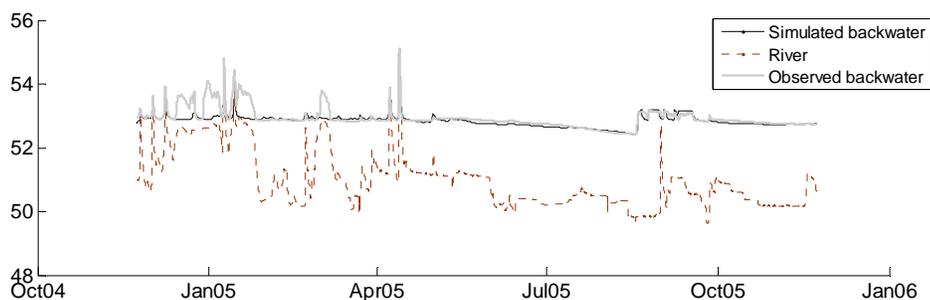


Figure 3. Simulated and observed stage hydrographs, November 2004-October 2005 for degraded backwater site, Coldwater River, Tunica County, MS. River hydrograph is shown also since peak river stages drive overflows into the backwater.

Simulations of backwater levels using river levels from the year of record with median annual mean stage indicated that the degraded site exhibited less variability

and connectivity than the reference site, as expected (Figure 4). Effects of rehabilitation were sensitive to weir crest elevation, but relatively insensitive to the schedule used to operate the weir. In general, the weir depressed connectivity but increased variability. For the wettest year on record, the degraded and reference sites exhibited similar levels of connectivity. Weir addition again increased variability while decreasing connectivity. Weir installation had little effect on simulation results for the driest year of record. Simulated and observed stage hydrographs for the reference, degraded and rehabilitated backwaters indicated that water levels fluctuated more gradually following weir placement, making the degraded site more like the reference (Figure 5).

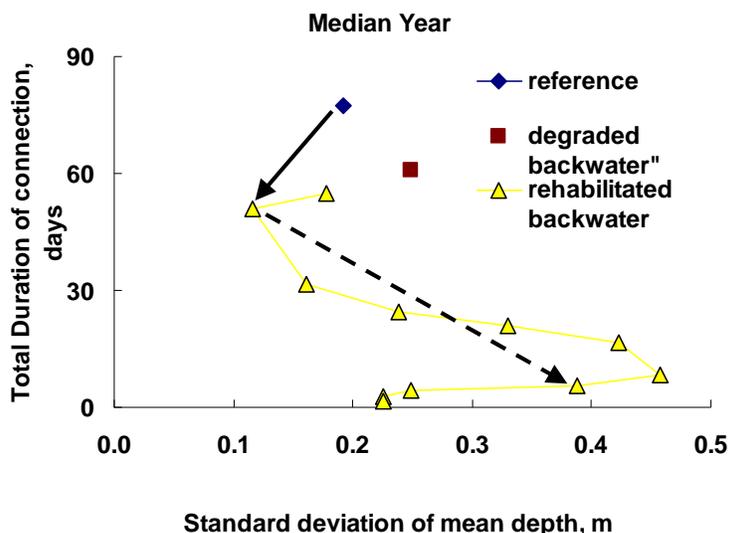


Figure 4. Kondolf diagram for backwater restoration, Coldwater River, Tunica County, MS. Plotted points are based on results of numerical simulations of backwater levels using river levels recorded during the year with the median mean annual stage of a 40-yr record. Standard deviation of mean depth was computed using the time series of the ratios of lake volume to lake surface area. Total duration of connection refers to the amount of time there was a hydrologic connection between the river and the backwater during the simulated year. Rehabilitation points show conditions for a range of weir crest elevations. Dashed arrow point toward the condition associated with the constructed project.

Data from in-situ water quality monitors showed that midsummer was characterized by extreme diurnal variations driven by algal blooms, with dissolved oxygen concentrations reaching supersaturated levels up to 270% during daytime and approaching anoxia at night. During a similar period following implementation of the rehabilitation project, water quality variations were damped, with dissolved oxygen varying only about 3 mg/L between day and night. However, dissolved oxygen levels were definitely suboptimal, with minimum values near 1 mg/L.

The five fish samples collected prior to rehabilitation contained a total of 25 species; the two collected afterward contained 14. Total fish catch per unit of effort was reduced by 33% following weir construction. Catch per unit of effort decreased for suckers, drum, minnows and sunfish and increased for catfish, gar and bowfin. Construction of the weir resulted in an increase in the relative abundance of sunfishes,

rough fish and catfish and a decrease in gizzard shad and drum. These results reflect only the first year following weir placement; no overflow events occurred during this time that connected the backwater to the river.

Discussion and Conclusions

Application of the Kondolf et al. (2006) approach to backwater restoration projects appears to hold promise, but key issues must be resolved. Among these issues are selection of variables to serve as indicators of connectivity and variability, and determination of values for the existing, reference and rehabilitated conditions. Furthermore, the uncertainty in measuring connectivity and variability associated with hydrologic variation must be assessed. Here we addressed these issues by developing a crude hydrologic simulation model and applying it to the pre-rehabilitation site, a hypothetical reference based loosely on a real site not subject to flow regulation, and the rehabilitated site which was simulated by modifying values used in the algorithm to describe flow controls. The model suggested that the selected rehabilitation strategy (weir construction) would improve variability at the expense of connectivity when these variables were defined based on water levels. Alternatively, project assessment could have been based on water quality conditions, water depth and surface area, or seasonal water levels thought important to key biota.

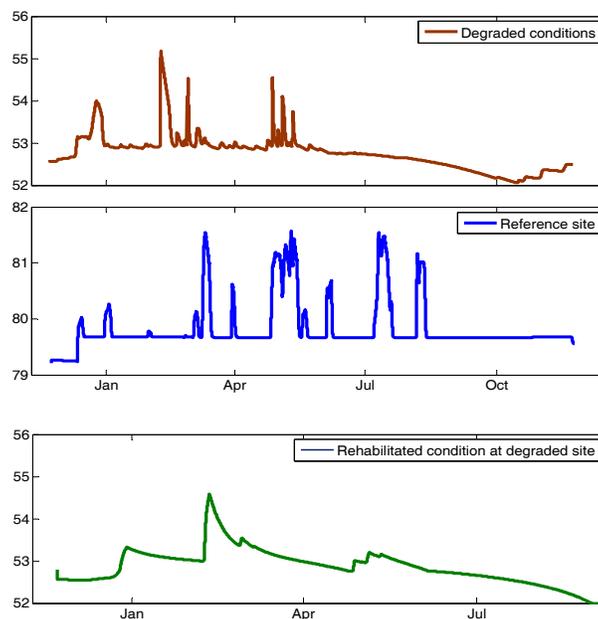


Figure 5. Simulated annual stage hydrographs for degraded backwater, reference backwater and rehabilitated backwater, using Coldwater River stages from median year in 40-yr record as input.

Implementation of a real project at the study site produced immediate water quality improvements and moderated water level fluctuations, but these changes were not effective over the very short term (one year) in backwater fish populations. The significant decrease in cyprinid catch following rehabilitation was due to the failure to capture carp after construction. Carp were seen though not boated during electrofishing trips in 2007. The observed declines in catostomids and centrarchids were more troubling but may be accounted for by the lower post-rehabilitation

sampling effort and low water due to drought. The mean river stage for the water year coinciding with the first year after weir construction was the second lowest on record, while the year immediately before construction was near the median of the record. Extremely low water levels likely have a detrimental effect on fish growth and reproduction and may effectively reset the existing communities in very dry years. Poor water quality may also limit the size or at least provide a survival advantage to smaller centrarchids and catostomids. Smaller individuals are less susceptible to low dissolved oxygen concentrations because they are able to exploit the higher dissolved oxygen concentrations typically found immediately below the water surface.

Acknowledgements

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