Towards a basis for designing backwater and side channel restorations

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Introduction

Lowland riverine ecosystems depend on the materials and habitats provided by floodplain backwaters, and studies of floodplain lakes indicate that connectivity with the adjacent river is a key determinant of lake fish species assemblages. Since about 1800, 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. 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. Proposals for rehabilitation and management of backwaters typically include restoring connection with the main channel by re-opening channels closed by sedimentation, 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, general design criteria for such projects are lacking.

Kondolf diagram

Approaches for setting backwater rehabilitation objectives include meeting habitat requirements for selected species, increasing the quantity of floodplain aquatic habitat, or a multidimensional assessment of hydrologic connectivity and variability suggested by Kondolf et al. (2006). The Kondolf approach is based on assigning a position to the system in a four-dimensional space that represents temporal variability on one axis and hydrologic connectivity in the three spatial dimensions on the remaining three axes. Connectivity is 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 is primarily defined as temporal variation in discharge, but also encompasses parameters such as temperature, sediment and trophic levels.

The status of a given riverine ecosystem may be mapped by plotting a point representing the system within a Cartesian plane where the horizontal axis represents variability and the vertical axis represents connectivity of a selected dimension ("Kondolf diagram"). 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 (Kondolf et al. 2006). In general, river ecosystems have tended to experience reduced connectivity and variability as they degrade, but some river reaches (e.g., base flow diversions, channelization) have become more variable as they were degraded. 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 follow the reverse path of the degradation vector, returning the system to its pre-degradation connectivity and flow variability. In practice, rehabilitation or restoration has often increased connectivity but rarely increased variability. If pre-degradation data are not available, reference conditions may be inferred from lightly degraded sites.

Herein we adopt the Kondolf approach not for river reaches as originally proposed but for individual floodplain backwaters. Retrospective use of the Kondolf diagram is illustrated using three case studies. All three sites experienced perturbed hydrology, as two were downstream of reservoirs and one was within a reservoir impoundment (Figure 1).

Case study 1--American River side channel

Site

Construction of dams on the American River upstream from Sacramento, California has reduced the frequency and duration of high flows and trapped coarse sediments. Spawning habitats for migratory salmonids have been lost upstream from the dams, increasing the importance and value of such habitats in the reaches downstream from dams. The Sunrise Side Channel is an existing, natural, moderate-flow, seasonal side channel that bifurcates a point bar on the south bank of the lower American River about 5.6 km downstream of Nimbus Dam (38^{o} 37' 45.72"N, 121^{o} 16' 30.09"W). Prior to rehabilitation project construction in late 2008, the side channel was inundated only during flows above approximately 110 m^3/s and was used by spawning steelhead when flows sufficiently inundated the side channel during the December through March timeframe. However, flows exceeding 110 m^3/s were often of such short duration that dewatering of redds and subsequent desiccation of eggs and stranding of larval fish occurred. This condition was documented in 2002 through 2004.

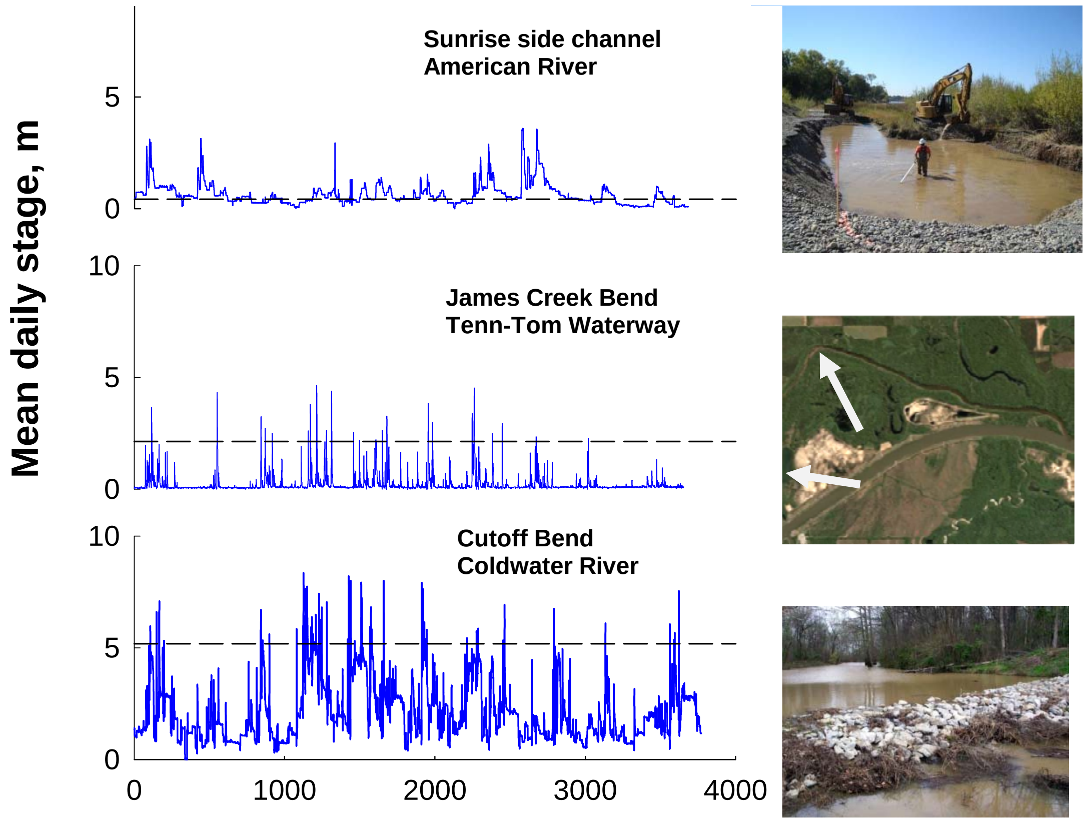

Figure 1. Mean daily stage hydrographs in meters for rivers adjacent to the three case study backwaters, water years 1998- 2008. For purposes of comparison, mean daily stages were referenced to the minimum recorded stage during the 10-yr study period. Sunrise side channel and Coldwater cutoff are downstream from large reservoirs; James Creek Bendway is within a navigation impoundment. Horizontal dashed lines indicate stage needed for upstream connection to main channel following rehabilitation.

Rehabilitation

A coalition of stakeholders developed a project to modify the side channel so that flow variability posed less of a risk to spawning and rearing steelhead. By lowering the side channel invert elevation, spawning habitat (flowing water with depth > 0.10 m) has been made available for all flows > ~ 25 m3/s—a flow consistently exceeded during the December through March spawning/rearing time period for 2000 - 2007. Incipient motion analyses indicated that redds would not be swept away during the normal range of flows, and that the side channel itself had a design life of about 20 years. Comparison of the existing bed material gradation with published criteria based on fish size (Kondolf and Wolman 1993), and two-dimensional numerical modeling of flow depths and velocities indicated the side channel would provide appropriate physical habitat conditions.

Outcome

Side channel construction occurred in late summer and early fall, 2008. Initial monitoring detected 20 to 25 fall run Chinook redds within 1 m of the water's edge.

Case study 2--Cutoff bends, Tennessee-Tombigbee Waterway

Site

Construction of the river section of the Tennessee-Tombigbee Waterway (TTW) in Mississippi and Alabama involved constructing a series of locks and dams and cutting off 39 meander bends with a total length of 120 km and a total water surface area of 17 km2. The bends, which were cutoff during 1976-1984 were located within the navigation impoundments (36) and their tailwaters (3). The affected reach of river was a major ecological resource, with 123 species of fish reported for the entire watershed. As part of the long-running litigation which was associated with construction of the TTW (McClure 1985), concerns were expressed by opponents that loss of backwater connectivity as bend entrances filled with sediments would "create thousands of acres of stagnate and eutrophic water" (U.S. Army Corps of Engineers 1984). In response, the constructing agency promised to, "seek measures to maintain flow through cutoff bendways of the river to preserve riverine conditions," (U. S. Fish and Wildlife Service 1981) and to conduct additional studies "to determine the most appropriate management options," (U.S. Army Corps of Engineers 1984).

Rehabilitation

Perhaps due to the pressure of this litigation, initial efforts to manage the backwater habitats provided by the cutoff bends consisted of dredging to maintain hydraulic connection to the main channel despite the knowledge that sediments would continue to deposit in upstream bend entrances. Deposition rates were a function of bend entrance geometry, sediment concentration and river discharge (Shields and Abt 1989), and the feasibility of maintaining hydrologic connections with the main stream by modifying bend entrance geometries was considered. About 11.5 million m^3 of sediment deposited in the severed meanders by 1987, not including about 187,000 m^3 dredged from three bends (Shields and Gibson 1989, Shields 1990). The rapidity of sediment deposition and the cost of dredging quickly led to a transition in management strategy away from dredging and toward construction of embankments to exclude all but the highest flows and associated sediment loads from the bends. Under the new strategy, flow maintenance was secondary to habitat preservation. Accordingly, blockage structures were placed in the upstream entrances of four bendways in 1985, and an additional eight upstream entrances were blocked in 1987.

Outcome

In accordance with studies conducted on cutoff bends on the adjacent Alabama River (Shipp and Hemphill 1974) and during and immediately following construction on the Tombigbee (Pennington et al. 1981, Shields et al. 1990), the severed bends provide extremely valuable sport fish habitats and recreational resources (Schramm and Spencer 2006). However, sandy point bars and other shallow, coarse-bed, flowing water habitats were lost. Sedimentation reduced the overall amount of habitat provided by the bends (Schramm and Spencer 2006). The area of connected bendways decreased 44% and disconnected bendways increased 260% along the portion of the TTW in Mississippi between 1985 and 2003 due to natural and manmade blockages. Overall, backwater area declined 784 ha while main channel habitats increased 248 ha. All of the severed meanders located in navigation pools became lentic or wetland habitats. Three years of fish collections within 12 of the severed bends between 1985 and 1987 yielded 25 to 47 species per bend, although at least seven rheophilic fish species disappeared from the bends. Although summer bottom dissolved oxygen concentrations were lower and Secchi disk readings were higher in the more deeply inundated bendways located in the downstream portions of the navigation impoundments, fish communities of 12 monitored bends were similar, with popular sport fish species well represented relative to the navigation channel (Shields et al. 1990).

Case study 3--Cutoff bend, Coldwater River

Site

The Lower Mississippi River alluvial plain has been developed for agriculture. Most of the area formerly flooded for long periods on an annual basis, is now isolated by earthen levees along the Mississippi River and many of the smaller streams and rivers that traverse the area. A severed compound meander bend inside flood control levees along the Coldwater River in northwestern Mississippi was selected for rehabilitation (34^{o} 40' 22.73"N, 90^{o} 13' 38.34"W). The bend is located about 20 km downstream from a flood-control reservoir and is the result of a 0.4 km cutoff constructed in 1941-42. The 2.5-km-long by 40-m-wide backwater receives runoff from about 100 ha of cultivated lands, principally through an intermittent slough. The bend channel contains about 2.4 m of soft sediment, and core samples analyzed for Cs-137 activity indicated an average deposition rate of about 2.8 cm/yr since 1964. Average water depths ranged from about 1 m during spring and winter to only about 0.4 m in late summer and fall in 2004-2006. Water quality conditions were extremely poor during these hot, dry periods, with extreme diurnal variations. During high stages, connection between the backwater and the river occurred at the downstream end of the old bend by way of a narrow connecting channel and less frequently at the upstream end. Analysis of 40 years of once-daily stage records indicated that with the current channel geometry, the backwater would be connected to the river an average of 66 days per year. There was an average of 11 connection events per year with a maximum duration of 94 days. By way of comparison, similar data for a cutoff bend on the same river upstream from the Corps reservoir indicated that backwater was connected to the river an average of 248 days per year during an average of 8 connection events per year with a maximum duration of 68 days.

Rehabilitation

For rehabilitation, a weir was constructed of earthen fill capped with riprap within the old bend to maintain higher water levels during prolonged low river stage in the summer and fall. An adjustable drainage structure integrated within the weir allowed seasonal raising and lowering of the controlling elevation to create a simulated long-amplitude flood pulse and to allow more frequent connection with the river during the wetter months. The weir was strategically located to divert most of the agricultural runoff from the contributing watershed away from the impoundment.

Outcome

Two years of monitoring indicated that the weir significantly increased water depths during summer and fall, thus damping extreme diurnal variations in water quality. However, the backwater was still subject to periods of excessively high temperature and low dissolved oxygen during summer. Fish sampling before and after rehabilitation yielded similar fish catches with regard to species richness, fish numbers and biomass. However, fish population trophic structure shifted dramatically. Prior to rehabilitation, each fish sample was comprised of about 29% + 29% piscivores by weight (mean + std dev), but this increased to 54% + 30% following rehabilitation. Differences were most pronounced in Spring samples: two omnivores, *Ictiobus bubalus* and *Cyprinus carpio*, comprised 50% of the fish biomass prior to rehabilitation, but only 15% afterward. Five piscivores; *Lepisosteus oculatus, Pomoxis annularis, Micropterus salmoides, Amia calva, and Pomoxis nigromaculatus*; comprised 32% of fish biomass in Spring samples prior to rehabilitation but 68% afterward.

Application of Kondolf diagram

Time series of mean daily river stage for the decade ending October 1, 2008 were obtained for all three sites by extrapolating or interpolating records from nearby gages. Only one of the TTW cutoff bends was selected for Kondolf analysis, James Creek bend (33^o 47' 44.31"N, 88^o 29' 46.31"W). Lateral connectivity was quantified as the average number of days per year that each of the backwaters experienced connection with the main channel, and both slackwater (downstream connection only) and flow-through (connection at both upstream and downstream ends) connectivity were explored. Connection was assumed to occur whenever river stage exceeded controlling elevations determined from cross-section surveys. Variability was quantified as the standard deviation of the time series of mean daily water depth in each backwater, in meters. Mean water depth was computed using simple geometric models of backwater bathymetry based on representative cross sections. Three conditions were examined for the two cutoff bends: a reference or pre-degradation condition, a degraded condition, and a post-rehabilitation condition. No reference condition was defined for the Sunrise side channel, but degraded and rehabilitated conditions were examined. Due to the difficulty of defining "without dam" conditions in the absence of pre-dam stage data for each site, no effort was made to remove effects of dams on hydrology when computing reference connectivity and variability. Therefore, computed shifts in connectivity and variability were due only to changes in the boundary geometry of the backwaters and adjacent channels that were caused by sedimentation, erosion, or management actions.

Degradation and rehabilitation trajectories were plotted on a Kondolf diagram (Figure 2). Decreasing invert elevation at the Sunrise side channel increased flow-through and slackwater connectivity by factors of 5 and 3, and increased the standard deviation of water depth in the side channel from 0.4 m to 0.5 m. Variability at James Creek Bendway was limited by the operation of navigation locks and dams up- and downstream; local river stages varied only through a very narrow range during the ten years of record used for computation. Sedimentation reduced estimated mean water depth in the bend from 2.2 to 1.4 m. Placing a blockage structure in the upstream bend entrance reduced flow-through connectivity to near zero and had no impact on downstream connectivity, but extended the life of the backwater by limiting sedimentation from the main channel. The Coldwater bend experienced major loss of connectivity and variability as the bend experienced sedimentation and incision of the adjacent main channel. However, installation of a weir in the main channel had little impact on variability and slightly decreased downstream connectivity even though mean water depth increased from 0.5 to 0.7 m.

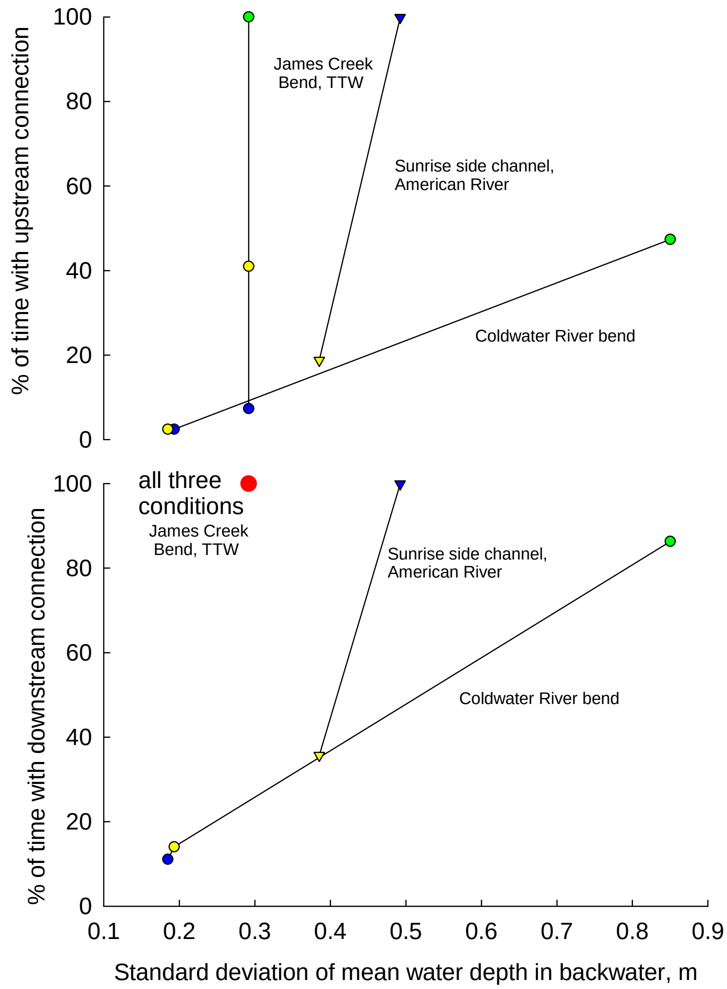

Figure 2. Kondolf diagrams based on flow-through (upper plots) and slackwater (lower plot) connectivity for the three case studies in this paper. Green symbols represent reference conditions, yellow represent degraded conditions, and blue represent rehabilitated conditions.

Summary and conclusion

Kondolf et al. (2006) reported that mainstem river habitat rehabilitation projects usually improve lateral connectivity, but have little impact on variability due to the lack of political will to modify reservoir operations. Examination of three cases of backwater rehabilitation confirmed this finding; only one of the three projects had significant positive effects on both connectivity and variability relative to the degraded (pre-rehabilitation) condition. The natural temporal instability of river backwaters complicates selection of a reference condition for application of the Kondolf approach.

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