Geomorphic adjustment to hydrologic modifications along a meandering river: implications for surface flooding on a floodplain

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Abstract

Responses of large regulated rivers to contemporary changes in base level are not well understood. We used field measurements and historical analysis of air photos and topographic maps to identify geomorphic trends of the lower White River, Arkansas, USA, in the 70 years following base-level lowering at its confluence with the Mississippi River and concurrent with flood control by dams. Incision was identified below a knickpoint area upstream of St. Charles, AR, and increases over the lowermost ~90 km of the study site to ~2 m near the confluence with the Mississippi River. Mean bankfull width increased by 30 m (21%) from 1930 to 2010. Bank widening appears to be the result of flow regulation above the incision knickpoint and concomitant with incision below the knickpoint. Hydraulic modeling indicated that geomorphic adjustments likely reduced flooding by 58% during frequent floods in the incised, lowermost floodplain affected by backwater flooding from the Mississippi River and by 22% above the knickpoint area. Dominance of backwater flooding in the incised reach indicates that incision is more important than flood control on the lower White River in altering flooding and also suggests that the Mississippi River may be the dominant control in shaping the lower floodplain. Overall, results highlight the complex geomorphic adjustment in large river-floodplain systems in response to anthropogenic modifications and their implications, including reduced river-floodplain connectivity.

Keywords: floodplain geomorphology; channel incision; flood modeling; anthropogenic modification

1. Introduction

Rivers and their floodplains are process-response systems whose geomorphic state is the sum result of geologic setting and hydrologic drivers (Nanson and Croke, 1992; Phillips, 2010). Significant changes to hydraulic gradient, discharge, or sediment load result in adjustment toward a new geomorphic condition (e.g., Knox, 2006; Hupp et al., 2009a, 2015). The impacts of localized geomorphic change are often insignificant to the function of entire large river systems (Phillips, 2010), but geomorphic adjustment at the reach and regional scale can trigger substantial change to river-floodplain interactions and feedback mechanisms between geomorphic, hydrologic, and ecological processes (e.g., Hupp, 1992; Ligon et al., 1995; Knox, 2006; Hupp et al., 2009b; Osterkamp and Hupp, 2010).

The majority of rivers have been impacted to some degree by anthropogenic activity, and most of the world's large river systems have been extensively modified to harness resources, improve navigation, and control flooding (e.g., Surian and Rinaldi, 2003; Hudson et al., 2008). Cause-effect relationships between modifications and geomorphic response are well documented in the literature, but the spatial and temporal extent and implications of geomorphic change are still not well understood (Gregory, 2006). We can reasonably predict what type of change will occur in response to a specific modification and what physical processes drive change; but predicting, e.g., relaxation time, the degree of geomorphic change, or how geomorphic response affects other components of the riparian landscape is much more difficult. This is especially true in cases when multiple geomorphic response mechanisms are operating simultaneously in a single system.

22 The purpose of this study is to describe and interpret geomorphic response to upstream
23 flow regulation and lowered base level in the lower White River, USA, a tributary of the
24 Mississippi River, and to investigate consequences of geomorphic adjustment for overbank
25 flood extent, a critical linkage between hydrologic, geomorphic, and ecological processes. Flow
26 regulation often results in reduced peak stages, flood frequency, duration of overbank flooding,
27 and sediment load (Williams and Wolman, 1984) and commonly causes subsequent channel
28 degradation downstream of dams (e.g., Phillips et al., 2005; Hupp et al., 2009a). Lowered base
29 level increases hydraulic gradient, resulting in consequent increases in sinuosity via
30 meandering, channel incision, or bank widening (Nanson and Huang, 2008) depending on
31 geomorphic constraints, e.g., substrate or bank stability (Simon and Rinaldi, 2006). Both can
32 reduce flooding.

33 The lower White River provides a valuable opportunity to investigate the combined
34 effects and relative contributions of these two perturbations to overall geomorphic adjustment.
35 While the effects of each have been studied independently, few cases (e.g., Harvey and
36 Schumm, 1987) highlight the effects of both on channel adjustment or changes to flood regime.
37 Further, much of the literature on channel response to base-level change focuses on main stem
38 response to sea level change and tectonic activity, which operate over relatively large time
39 scales (e.g., Schumm, 1993; Merritts et al., 1994; Zaitlin et al., 1994). Few cases investigate base-
40 level response over short time scales (e.g., Hassan and Klein, 2002) and many of these focus on
41 small streams (e.g., Germanoski and Ritter, 1988; Florsheim et al., 2001; Musselman, 2011).
42 Thus, understanding how contemporary base-level adjustments will affect large rivers and their
43 floodplains has been identified as a key need (Blum and Tornqvist, 2000).

In addition, understanding how major tributaries respond geomorphically to main stem modifications within large river systems is critical to predicting the trajectory of ecologically high-value riparian ecosystems. Human development has long been concentrated on large rivers, and consequently, much of the remaining undeveloped riparian landscape is concentrated along tributary corridors (Tockner and Stanford, 2002; King et al., 2012). The Lower Mississippi Alluvial Valley (LMAV) supports ecologically important floodplain forests, many of which have already become degraded owing in part to river modifications (King et al., 2012). Understanding possible implications of geomorphic adjustment in the LMAV is paramount to managing the region's valuable resources toward a sustainable future and can provide insight to management of other large river systems.

2. Study site and methods

2.1. Study site

The White River is an ~1160-km-long tributary of the Mississippi River. The river heads in the Boston Mountains of northwest Arkansas, USA, and flows in a generally eastward direction through the Ozark Highlands before entering the Mississippi Alluvial Valley and turning southward toward its confluence with the Mississippi River (Fig. 1). Headwater flow is regulated by a series of high dams and reservoirs that were constructed between 1913 and 1966 primarily to control flooding and to a lesser degree provide hydroelectric power. Dams on the main stem of the White River include Power Site Dam, Bull Shoals Dam, Table Rock Dam, and Beaver Dam, completed in 1913, 1951, 1956, and 1966, respectively. In addition, dams on the North Fork (Norfork Dam), Black, and Little Red rivers, completed in 1943, 1948, and 1962,

respectively, were built to control flow from tributaries into the lower White River. Bull Shoals dam is the farthest downstream and final main stem control structure before the White River flows to its confluence with the Mississippi River (Fig. 1). Releases from upstream structures are contingent on lake levels behind Bull Shoals Dam, and releases from Bull Shoals Dam and Norfork Dam are determined by downstream stage. The study area for this work is the portion of the White River between DeValls Bluff, AR, and the Norrell lock, which controls water level in the Arkansas Post Canal. Between the canal entrance and the confluence with the Mississippi River, the White River is part of the McClellan-Kerr navigation system, which is frequently maintained to support shipping and thus was excluded from the present study.

Mean and median discharge for publicly available records (1928-1981) at Clarendon, AR, is 834 and 524 m³/s, respectively (USGS gage 07077800). However, dam implementation significantly affected flow in the lower White River (Fig. 2). Prior to completion of the Bull Shoals Dam in 1951, mean discharge was 891 m³/s in contrast to 790 m³/s following construction, while median discharge increased from 501 pre-dam to 538 m³/s post-dam. Daily mean discharges range from 101 to 5380 m³/s over the post-dam period of record (30 years). Dam construction also moderated flow variability: high flow events became smaller, low flows are higher, and local upstream flow events are more frequent (Fig. 2, Craig et al., 2001).

Channel training and meander cutoffs on the Mississippi River from 1933 to 1942 designed to shorten navigation routes and control flooding have reduced stream length by ~30%, causing channel incision (Beidenharn and Watson, 1997; Hudson et al., 2008) and leading to a lower effective base level for tributaries (Beidenharn et al., 2000; Jemberie et al., 2008; Shaffner, 2012). Researchers have estimated between ~2 and 3 m of incision occurred in the

vicinity of the confluence of the White and Mississippi rivers, most of which was complete by 1950 (Beidenharn and Watson, 1997; Shaffner, 2012). However, the depth and upstream extent of channel incision on the lower White River has not been documented.

The White River and its floodplain support the second largest floodplain forest in North America, and alterations to the frequency and duration of flooding or groundwater processes have implications for floodplain ecology. For example, tree species composition and productivity of these floodplain forests are a function of surface and subsurface hydrologic regime (Klimas et al., 2009; Gee et al., 2015; Allen et al., 2016). River connections to the numerous waterbodies on the floodplain also control structure of aquatic ecosystems (Amoros and Bornette, 2002).

2.2. Methods

2.2.1. Channel planform measurements

Topographic maps and aerial photographs were used to conduct a historical analysis of channel planform on the lower White River from DeValls Bluff to Norrell lock (Fig. 1; Table 1). The dates analyzed span ca. 1930-2010. The exact starting year of the study period is indeterminate; survey data used to produce topographic maps published in 1939-1941 are listed as collected from 1929-1941, collectively. We chose 1930 as the estimated start date because the majority of data collection dates listed for each map began in 1930. Airphoto index mosaics were used for 1950 data, National High Altitude Photography (NHAP) images were used for 1984 data, digital orthophoto quadrangles (DOQ) were used for 1994 and 2001 data,

and National Agriculture Imagery Program (NAIP) images were used for 2010 data. Topographic maps and the 1950 and 1984 photos were georeferenced to 1994 DOQs prior to analysis.

Both channel bank lines were digitized for each data year and centerlines were created in a GIS environment using midpoint distance between bank lines. Resulting centerlines were then filtered to successive points 100 m distance along the digitized centerline to provide a common resolution for each data year.

Channel migration over the study period was estimated by superimposing the 1930 and 2010 channel centerlines and creating a series of polygons between successive points of intersection (Fig. 3). Channel migration rate (M) was estimated for each polygon as $M = A/(0.5 * P)/y$, where A is the area of the polygon, P is the perimeter of the polygon, and y is the number of years (80) between channel centerlines (method similar to, e.g., Shields et al., 2000; Micheli et al., 2004). Polygons with $M < 10$ m for the entire study period were removed from subsequent analysis because that distance is smaller than spatial registration error between data sets.

Bankfull width was estimated by measuring the distance between digitized bank lines approximately every 500 m along the river for each data year. The along-stream position of width measurements were normalized to 2010 stream distance for comparison among years. Sinuosity was estimated as the ratio of stream length to valley length (total valley distance = 98.49 km).

2.2.2. Bank height and bed elevation surveys

A bank height survey was conducted 21-23 August 2014 to assess the degree and upstream limit of channel incision on the lower White River. We used a laser rangefinder to measure the vertical distance from the water line to the top of cutbanks from Norrell lock to DeValls Bluff, AR (Fig. 1). There was negligible (<6 cm) variability in stage at Clarendon during the survey period. Measurements were conducted by boat ~ 20 m from the bank. We conducted 30 trial measurements to estimate measurement error and found ~ 20 -cm mean error for bank height measurements. Bed elevation data was taken from 1971 and 2013 hydrographic surveys conducted for the U.S. Army Engineers Memphis District. Data from 1971 was digitized from U.S. Army Engineers, Memphis District, Maps of the White River, 1999.

2.2.3. Hydraulic modeling

We used a HEC-RAS model parameterized for the White River by L. Yu Lin (undated, unpublished report to the U.S. Army Corps of Engineers Memphis District) to model surface flooding on the floodplain of the lower White River. Model cross sections were constructed from a 2009 hydrographic survey merged with contemporary digital elevation data. The model domain is slightly different than the study area for air photo and geomorphic analyses; there are 61 unevenly spaced (downstream direction) cross sections that span the White River floodplain between Clarendon, AR, and the confluence with the Mississippi River. The model uses calculated flooding across the cross sections to interpolate flooding for the entire domain.

Two geomorphic scenarios were modeled to estimate the effects of geomorphic adjustment on floodplain inundation: current channel geomorphology and an idealized historic condition prior to 1930 (before adjustment documented in this study). We simulated separate

steady-state regional headwater and backwater floods, defined as White River source water flooding and backwater flood effects from the Mississippi/Arkansas rivers, respectively, for pre- and post-adjustment channel configurations. These two event types are not exclusive, but the goal of the simulations was to estimate effects separately. We used flood return intervals of 1, 1.5, 5, 10, and 32 years calculated using Weibull plotting position and annual peak data from 1983 to 2013 (Table 2). For headwater flooding, we used HEC-GeoRAS to simulate flow using an upstream boundary condition of discharge at Clarendon and downstream boundary condition of normal depth (water surface parallel to the channel bed) to eliminate backwater effects from the Mississippi River. For backwater flooding, we used an upstream boundary condition of zero flow on the White River and downstream boundary condition of stage of the Mississippi River at the White River confluence. There is no long-term gage data at the confluence, thus data were interpolated from stage at Helena, AR (gage MS133, USACE) and Arkansas City, AR (gage ARSA4, USACE). We corrected for nonlinearity in river slope between Helena and Arkansas City using the relation between interpolated stage at the confluence and observed stage at the Arkansas Post Canal at lock 1 (Norrell) for 2005-2013.

We used the same HEC-GeoRAS model with the channel in its current location but with channel cross sections modified from current dimensions using estimates of channel incision and bank widening to mimic idealized pre-1930 conditions. Thalweg elevations were increased from current elevations (de-incised to 1930 condition) proportional to distance upstream from Norrell lock to the incision knickpoint, and channel widths were decreased (narrowed to 1930 condition) by an amount obtained by a LOWESS-smoothed ($\alpha = 0.5$) relationship between observed channel width changes and distance from Clarendon to Norrell lock (Fig. 4). We

modified channel cross sections by maintaining the current shape, but stretching proportionally to estimated changes in depth and width.

3. Results

3.1. Channel migration and sinuosity

Channel migration rates ranged from 0.13 to 5.4 m/y over the entire study reach (Fig. 5). The greatest migration rates (mean 1.4, range 0.59-5.4 m/y) were between DeValls Bluff and Clarendon. In comparison, channel position remained relatively stable between Clarendon and St. Charles (Fig. 5), where migration rates were mean 0.56, ranging from 0.15 to 1.3 m/y. Below St. Charles, migration rates were slightly higher (mean 0.70 m/y) but were more variable, ranging from 0.13 to 2.9 m/y (Fig. 5).

Overall, channel sinuosity remained relatively stable over the entire study reach, increasing slightly from 1.81 to 1.85 between 1930 and 2010 (Fig. 5). Channel sinuosity is highest above Clarendon and has decreased from 2.47 to 2.29 as stream length has decreased, although some variability throughout the study period exists. Punctuated decreases are the result of avulsions. Sinuosity between Clarendon and St. Charles has gradually increased from 1.73 to 1.80. Sinuosity below St. Charles is slightly lower and has increased from 1.65 to 1.74.

3.2. Channel incision

Bank-height survey data and bed-elevation data show incision over the lower half of the study reach (Fig. 6). The knickpoint area is upstream of St. Charles, between approximately 90 and 110 km upstream of the lower boundary of the study reach. Comparison of the 1971 and

2013 thalweg data indicates incision of ~ 1.73 m in the lowest portion of the study area, at a maximum rate of between ~ 0.04 and 0.05 m/y (Fig. 7) and up to approximately river kilometer 70. Bank heights above and below about river kilometer 90 exhibit significantly different trends (Fig. 6B). There is a slight negative trend in bank height above the knickpoint area. Below St. Charles the trend in bank height with downstream distance is positive and increases to a slope of ~ 0.026 m/km. Data indicate the positive trend of bank height increase may cease near the end of the study reach, which is a similar pattern to the amount of incision between thalweg surveys (Figs. 6 and 7). However, data are insufficient to conclude whether this is because of scatter, a local trend, or if the trend continues past the end of the study reach.

Bank height data suggest incision in the study reach of between ~ 1.67 and ~ 2.07 m, depending on the interpretation of bank heights near the end of the study reach. Above the knickpoint area, the mean bank height above water surface was ~ 4.08 m (Fig. 6B). The linear fit of bank height below the knickpoint area suggests an expected bank height of 6.15 m at Norrell lock. A moving average fit of bank height suggests an expected bank height of 5.75 m at Norrell lock. Both estimates approximately agree with the mean amount of incision, 1.73 m, between 1971 and 2013 in the lowest portion of the study reach (Fig. 7).

If the linear trend in bank height data with downstream distance is extrapolated to the confluence of the White and Mississippi Rivers, 16 km from the lower boundary of the study reach, an additional 0.42 m of incision could be expected, resulting in 2.53 and 2.13 m of incision at the confluence. However, the White River below the Arkansas Post Canal is part of the McClellan-Kerr navigation system and is maintained at greater depth through dredging.

Thus, predicting how trends extend downstream of the lower study area boundary toward the confluence is difficult.

3.3. Bankfull width

Channel width persistently increased over much of the study reach throughout the study period (Fig. 8A). The average bankfull width increased from 138 to 170 m from 1930 to 2010 (0.40 m/y; Fig. 8B). The most rapid period of bank width increase was between 1930 and 1950, with the majority of change taking place over the upper 70 km of the study reach. Since 1950, the majority of channel width increase occurred over the lower portion of the study area. The highest rates of change between about 70 and 160 km occurred between 1984 and 1994 and between 1965 and 1984 over approximately the last 24 km of the study reach (Fig. 8A). Contemporary (1994-2010) rates of width increase were the lowest of the study period.

3.4. Simulated flood extent

3.4.1. Headwater flood extent

Geomorphic adjustment has had the greatest effect on floodplain inundation during frequent, 1 and 1.5-year headwater flood events (Fig. 8A), with a proportional decrease of ~20 and 15% in flooded area, respectively, for the entire study area (Fig. 10). The incised reach was more affected by geomorphic adjustment than was the reach above St. Charles, with ~35 and 17% less flooded area, respectively, for the 1 and 1.5-year flood simulations. Frequent floods inundate much of the floodplain above St. Charles; but even the largest, 32-year, modeled flow did not completely flood the lowermost floodplain (Fig. 9A).

3.4.2. Backwater flood extent

Backwater flooding simulations indicated that the impact of geomorphic adjustment is also greatest in frequent floods (Fig. 9B). The largest proportional decrease in total flooded area between the two modeled scenarios occurred in the 1-year flood (Fig. 10) where ~60% less area was flooded in simulations using current channel morphology as opposed to idealized pre-adjustment conditions. In contrast to headwater floods, backwater floods did inundate most of the lower floodplain in less frequent floods (Fig. 9B). The largest backwater floods inundated the entire floodplain to the upstream limit of the study area.

4. Discussion

Overall, results indicate three distinct reaches based on channel-bed slope and trends in channel adjustment (Figs. 4-6). Reach 1 is characterized by relatively high sinuosity and low bed slope and extends from the upper bounds of the study area at DeValls Bluff to Clarendon (Figs. 4, 5). Between 1930 and 2010, reach 1 experienced high channel-migration rates and decreasing sinuosity. Reach 2 is characterized by a high bed slope and a relatively stable channel with low channel migration rates and sinuosity and extends from Clarendon to St. Charles. Reach 3 is incised and extends from St. Charles to the downstream extent of the study area. Reach 3 has higher migration rates and sinuosity than reach 2 and a higher bed slope. Sinuosity in reaches 2 and 3 increased slightly over the study period.

Interpreting some variations in reach morphology requires considering local forcings. The break in slope of bed elevation and difference in sinuosity above Clarendon suggest a local

base level (Leopold and Bull, 1979) for the river above that point. Above Clarendon, the river bed slope is near zero (Fig. 6A) and there have been punctuated decreases in sinuosity via avulsions (Fig. 5), which suggest historical aggradational conditions. There are several possible explanations for this, including an inerodible bed at Clarendon, effects of faulting (Schumm and Spitz, 1996; Holbrook and Schumm, 1999), and the influence of the White-Cache river confluence just above Clarendon. It is also possible that increased sediment load from bank widening following dam closure exacerbated preexisting aggradational conditions. Indeed, in a specific gage analysis, Shaffner (2012) observed significant degradation at DeValls Bluff compared to Clarendon following dam closure, suggesting that little to no substantive change occurred to the channel at Clarendon.

4.1. Geomorphic adjustment to anthropogenic modifications

Rapid channel width increase between 1930 and 1950 in the upper portion of the study area followed by a much more gradual, consistent increase in bankfull width indicates a relatively rapid response to dam construction, similar to that found in other studies (e.g., Grams et al., 2007; Skalak et al., 2013; Hupp et al., 2015). Bull Shoals Dam was not completed until 1951, but dams on major tributaries (the North Fork and Black rivers) were completed in 1943 and 1948, respectively. Reduction in sediment load coupled with flow regulation, specifically an increase in low-flow discharge starting during the early to mid-1940s (Fig. 2), is likely responsible for bank widening during this period. Bankfull width changed relatively little from 1930 to 1950 over the lower half of the study reach, suggesting that the effects of the dam closure diminished downstream.

The dominant channel adjustment in the lower portion of the study area has been channel incision with coupled bank widening. Incision and bank widening processes are vehicles for dissipating excess energy following perturbation to existing slope-sediment transport regimes (Simon, 1992; Nanson and Huang, 2008; Phillips, 2010). Geomorphic adjustment of river channels can be framed as a consequence of slope (S) surplus or deficit relative to the critical slope (S_{cr}), where for a given discharge, stream power is just enough to transport sediment load (Phillips, 2010). Disturbances that lead to $S > S_{cr}$ create an energy surplus that must be expended. Excess energy can be expended through a variety of processes but will selectively opt for the most efficient route (Simon and Rinaldi, 2006; Nanson and Huang, 2008).

Lack of more historical bathymetric data makes it difficult to precisely estimate sequencing between incision and bank widening on the lower White River, but some general inferences can be made regarding the response of the system to lowered base level. First, results indicate that incision and lateral erosion occurred near concurrently. Significant bank widening occurred between 1965 and 1984 (Fig. 8) over the lowest portion of the study area where incision between 1971 and 2013 was greatest (Fig. 7). Possibly, incision led to oversteepening of the banks, increases in bank height, and bank toe removal (e.g., Simon and Hupp, 1992). These effects of incision either singly or in combination generally increase bank erosion rates through heightened fluvial entrainment and, often, mass wasting of banks (Schumm et al., 1984; Simon and Hupp, 1992; Hupp et al., 2009b). Field observations suggest that the majority of bank retreat on the lower White River occurs as the result of punctuated mass wasting events.

Relatively little bank widening after 1984 in the lowest portion of the study reach suggests that incision reached near-current levels over this reach during the same time frame, and an optimum width-depth ratio (Huang and Chang, 2006) may have been reached. Bank widening after 1984 was substantial over the middle portion of the study area, suggesting upstream migration of incision and bank widening during this period. This is consistent with field observations during the 1990s of headcutting on small tributaries in the area above Jacks Bay (Dennis Sharp, retired USFWS, personal communication, 2011). Bank widening during this period and for the study period overall decreased upstream, which implies upstream distance decay of response to lowered base level similar to that noted by other researchers (e.g., Musselman, 2011). Further, contemporary (1994-2010) rates of bank widening were the lowest of the study period, suggesting that the lower White River may be completing its relaxation or adjustment to anthropogenic modifications of the early twentieth century.

Based on this sequencing and results from previous work, a very coarse estimate of the rate of adjustment can be made beginning from 1971, the date of the first thalweg survey. The data suggest that incision and bank widening over approximately the lowest 40 km of the study area occurred by 1984, over a period of 13 years. Schumm and Spitz (1996) showed an inflection point in projected bank heights (p. 255, Fig. 11, adapted from an unpublished 1994 report) at the Big Creek and White River confluence. The slope of increase in that projected bank height and the measured bank height in this study is nearly identical, suggesting that significant incision had not occurred above that point prior to 1994, for a rate of about 25 km degradation over the 10 years between 1984 and 1994. The remaining channel adjustments

have occurred since that time, for a rate of about 27 km (from bank height survey) to 47 km (from thalweg comparison) of degradation over the last 20 years.

The above analysis should be caveated by the fact that the date when significant channel adjustment began on the lower White is unknown. Channel training of the Mississippi River, ultimately responsible for lowered base level of the White, was completed during the 1930s and 1940s. However, the close correspondence of the increase in bank height and incision between 1971 and 2013 presented herein suggests that the bulk of adjustment may have occurred since ca. 1971. The confluence zone of the White and Mississippi Rivers (roughly below the Arkansas Post Canal) is complex and has been managed as part of the McClellan-Kerr navigation system for decades. Further, it also includes the confluence of the Arkansas and Mississippi rivers. It is possible that flood timing between the systems was such that flows on the White with potential to do the most work corresponded to high-water events on the main stem, thus preventing adjustment of the White River until some other trigger occurred.

Geomorphic response of the lower White River to flow regulation and lowered base level suggests that the dominant geomorphic agent transitions from headwater-downstream influence to backwater effects from the Mississippi between Clarendon and St. Charles. Bankfull width changed little between 1930 and 1950 over the lower half of the study reach, suggesting that either the effects of dam closure diminished downstream or were overwhelmed by backwater effects, or both. Conversely, since 1950, bank width in the uppermost portion of the study area has been relatively stable compared to downstream, suggesting little upstream effects of lowered base level. Finally, the downstream reaches exhibit fundamentally different geomorphology than that above Clarendon. It is thus likely that backwater effects from the

Mississippi were more dominant in shaping the lower floodplain than upstream influences (e.g., Phillips et al., 2005).

4.2. Role of headwater versus backwater flood events

We chose the more conservative estimate of incision (2.1 m) at the Mississippi and White river confluence to model effects of geomorphic channel adjustment on surface flooding in the lower White River floodplain. While channel incision could be of greater magnitude, using the lower estimate still allows interpretation of effects of incision on river-floodplain connectivity. With a larger estimate of incision, we would expect further reduction in flooded area from pre-1930 to modern channel simulations.

Flood modeling results also indicate a transition between White River dominance and backwater influence from the Mississippi River. In simulations, the regions inundated by high frequency headwater and backwater floods overlapped near the middle of the study area. Based on results of modeling flows in idealized, pre-adjustment geomorphic conditions, headwater floods likely did not generate frequent flooding in much of the lower reach even before geomorphic adjustment. Even so, it is remarkable that the largest flood of the 1983 to 2013 period (32-year event) was apparently insufficient to generate headwater flooding at the confluence.

Extensive backwater flooding means that backwater floods likely have had more influence on floodplain evolution in the lower half of the study reach than have headwater floods. It is also likely that backwater flow has always influenced the lowermost floodplain because the Mississippi River can easily overwhelm a smaller river such as the White. Thus, the

lower White River floodplain potentially formed as a response to sediment transport in the presence of Mississippi River flow and sediments. The lowermost portion of the modeling domain includes a former channel and natural levee of the Mississippi River as mapped by Fisk (1944), so it is probable that section has always been largely unaffected by flooding on the White River.

The modeled scenario of incision and assumptions about floodplain development do not account for all downstream conditions that may have had significant influence on the lower boundary conditions for the White River. First, the White-Mississippi confluence zone also includes the confluence of the Arkansas River with the Mississippi River; the point of confluences among these three rivers has varied through time (Fisk, 1944). In addition, the Arkansas River carried a sediment load around 81 million metric tons until the construction of locks and dams from 1963 to 1970 decreased the average load to 10 million metric tons (Keown et al., 1986). The Arkansas River undoubtedly affected the geomorphic development of the confluence zone and likely even the slope of the Mississippi River itself (Schumm and Spitz 1996), but we modeled the hydraulic effects of the Mississippi River because we assumed the large changes there likely overwhelmed effects of the Arkansas River.

Secondly, previous work has given some insight on hydrologic changes at the confluence, but there is conflicting evidence about the nature and magnitudes of changes. Heine and Pinter (2012) found an increase in flood stage following levee construction, but channel incision resulting from confined flow and channel cutoffs may have offset some of the increase (Remo et al., 2009). Finally, the Mississippi River has had reduced sediment load from river modifications (Keown et al., 1986), which suggests that backwater effects on current

geomorphic development have diminished. Uncertainties in the configuration of the Mississippi River prior to extensive modifications prevent detailed interpretation pending more precise work on, for example, stratigraphy of the lowermost floodplain of the White River.

4.3. Implications of geomorphic adjustment for river-floodplain interaction

Incision of the lower White River in response to base-level lowering has consequences for floodplain ecological processes by altering flood frequency and depth. High frequency (1-2 year) flood events often drive channel morphology and exert strong control on long-term river-floodplain connectivity (Wolman and Miller, 1960; Tockner et al., 1999). Flood tolerance is a key ecological parameter controlling floodplain forest composition, and flood frequency is one of the most important variables (Wharton et al., 1982; Sharitz and Mitsch, 1993). Geomorphic adjustment of the lower White River channel has significantly reduced flooding extent during frequent floods, with the majority of the reduction occurring in the incised reach. Surface flooding has significant effects on tree regeneration processes (Streng et al., 1989) and alterations in flood frequency and other hydrologic parameters can cause gradual (Smith et al., 2013) or rapid changes in tree species composition (Gee et al., 2014) to favor less flood tolerant species.

Geomorphic adjustment also impacts river-floodplain connectivity through groundwater processes during low flow periods. Channel incision lowers the water table in adjacent floodplains (e.g., Hupp, 1992; Tucci and Hileman, 1992), which can alter tree growth and increase mortality (Cunningham et al., 2011). Reduced connectivity of the river to the floodplain because of incision can also limit access to floodplain habitat resources for aquatic

and wetland-dependent organisms, such as fish and waterfowl (e.g., Heitmeyer, 2006; Beesley et al., 2012). Late summer and early fall flow is significantly higher following dam closure on the lower White River (Fig. 2; Craig et al., 2001), and the impacts of incision on water availability to floodplain forests may be mitigated to some degree by higher than historical base flow. However, Allen et al. (2016) found that the water table in at least one location in the incised reach was less reactive to flow pulses and trees were limited in water availability compared to upstream.

Reduced flooding in the incised reach also has potential ramifications for sediment storage and transport. Sediment storage is an important function of coastal plain floodplains (Hupp, 2000; Hupp et al., 2009b). If overbank flooding is reduced in the incised reach then much of the sediment load may bypass the lower floodplain and exit to the Mississippi River. Further, deposition could be limited to localized zones with relatively low banks or near isolated river-floodplain conduits, which would likely significantly increase deposition rates in those areas while reducing deposition elsewhere.

5. Conclusions

Results highlight the complexities of geomorphic response to anthropogenic modifications to fluvial systems; upstream dam closure and base-level change have been significant drivers of geomorphic adjustment of the White River. Significant bank widening occurred upstream. In the lower floodplain, response to lowered base level has resulted in an incision and bank widening. Only a slight increase in sinuosity has occurred, possibly because of relative stability in terms of channel migration provided by forested banks. Results also indicate

a transition within the study area from watershed to backwater control, with backwater effects from the Mississippi River being more dominant in shaping the lower floodplain.

Model flood simulations suggest incision and bank widening in response to anthropogenic modifications have had a significant impact on surface flooding regime, a key linkage between hydrological, geomorphic, and ecological processes. Impacts of geomorphic adjustment on flood extent are greatest for high frequency floods in the incised reach, and have been greatest for backwater events. Reduction of flood extent during high frequency floods has significant ecological implications for floodplain forests.

Owing to complex controls on river evolution and site-specific factors, each river-floodplain system is unique. However, advances in understanding the relationship among present and future (predicted) geomorphic processes, surface and subsurface hydrologic processes, and ecosystem services is critical for evaluating the effects of future development and management within large watersheds.

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Figure Captions

Fig. 1. *Location of White River in the Mississippi valley. Field data collection and historical analyses were conducted for the portion of the White River between DeValls Bluff, AR, and Norrell lock, which controls water level in the Arkansas Post Canal.*

Fig. 2. *Discharge and flow-duration curves (inset) at Clarendon, AR (1928-1981), before and after completion of Bull Shoals Dam in 1951.*

Fig. 3. *Example of polygons used to calculate channel migration rates.*

Fig. 4. *Example of adjustment of hydraulic model cross section from modern channel to idealized pre-adjustment channel.*

Fig. 5. *Channel migration rate (1930-2010) and changes in channel sinuosity by reach for the lower White River. Total valley length is ~98.49 km. Valley length for reaches 1, 2, and 3 is ~15.60, 38.36, and 44.54 km, respectively.*

Fig. 6. (A) *Bed elevation and 10-km moving average trend from 1971 and 2013 thalwegs, and*
(B) *bank height 21-23 August 2014 above and below estimated break in slope based on moving*
average fit (approximate river kilometer 90). Dashed line is linear fit of slope below break. Solid
line is 10-km moving average of bank height. Mean bank height above the knickpoint was 4.08
m. DeValls Bluff, AR, is 0 km river distance.

Fig. 7. *Amount and rate of incision between 1971 and 2013 thalweg surveys. Solid line is 10-km*
moving average of incision.

Fig. 8.(A) *Mean channel width on the lower White River from 1930-2010, (B) mean rate of*
bankfull width increase between data years and over the entire study period. DeValls Bluff, AR,
is 0 km river distance.

Fig. 9. (A) *Modeled flood extent for headwater flood scenarios for 1-, 1.5-, 5-, 10-, and 32-year*
return intervals, and (B) modeled backwater flood scenarios for 1-, 1.5-, 5-, 10-, and 32-year
flood scenarios. The discontinuity in flooding extent (distinct lines) in the 1-year and 1.5-year
flood extent is an artifact of modeling because of shallow depths on the floodplain between
cross sections. The model scale is not fine enough to represent the localized floodplain
connections. The model may not be precise in the low magnitude floods, but general flood
trends still are relevant.

Fig. 10. *Percent decrease in simulated flood extent area from idealized conditions prior to geomorphic adjustment of the lower White River to current channel morphology. Geomorphic adjustment has had the greatest effect during frequent, e.g., 1-year and 1-5 year flood events. The incised reach was more affected by adjustment for simulated headwater floods. The reach above the incision knickpoint area was more greatly affected by adjustment for simulated backwater floods for all but the most frequent events.*

Table 1

Map and aerial photograph data used in historical analysis of channel planform

Data type	Acquisition date	Publication date	Scale/ resolution	Source
Topographic map: Mississippi River Commission	1929-1939	1939 & 1940	1:62,500	USGS
Airphoto index mosaic	1950		6 meters	Dale Bumpers White River NWR
Topographic map: Geological Survey	1964 & 1965	1967 & 1968	1:24,000	USGS
NHAP	1984		5 meters	USGS
DOQ	1994		1 meter	USGS
DOQ	2001		1 meter	USGS
NAIP	2010		1 meters	USDA

Table 2

726 *Return interval and associated discharge and stage used to simulate headwater and backwater*
727 *events, respectively*

Return interval (y)	Headwater simulation: discharge at Clarendon (cms)	Backwater simulation: stage at confluence, modern channel (m)	Backwater simulation: stage at confluence, idealized channel (m)
1	1634	42.7	44.8
1.5	1943	46.0	48.1
5	3194	48.2	50.3
10	3882	48.8	50.9
32	7552	51.8	53.9

728

729

Figure 1 (Color) 1.5 Column

Figure 2 (Color) 1 column

Figure 5 (Color), 1.5 column

Figure 6 (Color) 1 Column

Figure 7 (Color) 1 counn

Figure 8 (Color) 1 Column

Figure 9 (Color) 1.5 Column

Figure 10 (Color) 1 Column

Figure 1 (Greyscale) 1.5 column

Figure 2 (Greyscale) 1 column

Figure 3 (Greyscale) 1 column

Figure 4 (Greyscale) 1 column

Figure 5 (Greyscale) 1.5 column

Figure 6 (Greyscale) 1 column

Figure 7 (Greyscale) 1 column

Figure 8 (Greyscale) 1 column

Figure 10 (Greyscale) 1 column