Cyclical fluvial response caused by rechannelization

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Abstract

The Yalobusha River system in northwestern Mississippi was channelized ca. 1967 to enhance channel capacity and alleviate flooding. Design of the channelization project allowed the enlarged, straightened channel to discharge into an unmodified sinuous reach, and the junction between these two geometries featured a sudden reduction (~200x) in sediment transport capacity. A plug of sediment and large wood formed in the channelized reach immediately upstream of the point where the channelized reach terminated, filling the channel, forcing all flows over the banks, flooding low areas upstream and accelerating further deposition. In 2003, following strategic installation of erosion controls throughout the upstream watershed, the action agency decided to rechannelize 4 km of the blocked channel at a cost of $1.13 million. However, the sharp transition between the two geometries was retained. Fluvial response consisted of blockage and avulsion of the new channel less than one year later. This example highlights the importance of maintaining sediment transport continuity in river channel management.

Introduction

Ideally, watershed management should allow sustainable use of watershed lands for agriculture or urban purposes with minimal risk due to flooding, erosion, deposition or pollution. Prior to about 1970, hydraulic engineering for watershed management tended to focus on flood control, with channels designed to provide maximal conveyance or navigable widths and depths without much consideration to channel stability (e.g., Chow 1959). Erosion issues were often dealt with on a local rather than systemic basis (e.g., Petersen 1986). Channel straightening and enlargement (channelization) were widespread (Bulkley 1975; Brookes 1988, pp. 8-11; Rhoads and Herricks 1996), and public and professional reaction was severe (Anonymous 1972). Since then the state of the art in sedimentation engineering has advanced, and tools are available to analyze channel sediment transport

capacity and even bank erosion (e.g., Langendoen et al. 2009), although precision is dependent on the amount and quality of input data. Concurrent with advances in channel stability analysis, greater understanding of stream and river ecology has allowed better quantification of the consequences of stream channelization and channel instability (Shields et al. 1994). Despite these advances, "channel improvement," or simple channelization via large wood removal and excavation of straight, trapezoidal channels continues in many areas (Shields et al. 2008). In other cases, stream restoration projects feature creation of "natural" meandering channels without adequate analysis of the ability of the restored channel to transport sediment loads arriving from tributaries or upstream reaches (Shields 1997, Shields and Copeland 2006).

Sustainable river engineering requires maintaining continuity of sediment transport capacity in the streamwise direction. If continuity (at the scale of reaches several channel widths long) cannot be ensured, excessive transport capacity must be addressed with erosion controls and excessive sediment supply must be addressed by providing storage or removal (dredging). The literature provides a wealth of examples of destruction of habitats, bridges and culverts by channel incision caused by a shortage of sediment supply relative to transport capacity (Galay 1983). Equally impressive are problems associated with an oversupply of sediment relative to transport capacity: perched streams confined between levees that cause damage when floodways are breached or channels avulse (e.g., Shu and Finlayson 1993), valley sedimentation of many meters in a few decades (Happ et al. 1940), and detrimental effects on floodplain and channel ecosystems due to passage of watershed-scale sediment "waves" (Nicholas et al. 1995, James 2006). The Yalobusha River system in north central Mississippi is an instructive example regarding the consequences of not maintaining sediment transport continuity. Below we present a brief history and assessment of the channelization (1967) and rechannelization (2003) projects and describe available data documenting channel response.

Yalobusha River

The Yalobusha River is a fourth-order stream system with a watershed of about 880 km^2 that is 59% forest, 30% pasture, 7% cropland and 4% water or urban areas (Langendoen et al. 2009). Average annual rainfall is about 1400 mm, and soils tend to be highly erodible. Initial European settlement of the region (ca. 1830-1850) triggered massive soil erosion and valley sedimentation. Local (ca. 1913) and federal (1967) channelization projects were implemented to relieve flooding and drainage issues associated with this sedimentation (Watson et al. 2000). The 1967 project was devised to address conveyance issues associated with the earlier work, and included clearing and dredging the Yalobusha River and Topashaw Creek from a point 4.5 km downstream from their confluence to the Calhoun-Chickasaw County line (**Figure 1**). Tributaries were also channelized. The top width of the constructed channel of the Yalobusha River ranged from 58 m at the downstream end of the project to 22 m at the upstream end (Simon 1998). The constructed channel abruptly terminated in a narrow, sinuous, unmodified reach that ultimately emptied into Grenada Lake, a flood control reservoir (**Figure 2 a and b**). The conveyance of the constructed channel was about an order of magnitude greater than that of the meandering reach downstream, and its sediment transport capacity was about two orders of magnitude greater. A discharge of 570 $m^3 s^{-1}$ could be passed through the channelized reach, but as

flow entered the meandering reach, only about 70 $m^3 s^{-1}$ would remain in the channel, and the rest would spread across the floodplain.

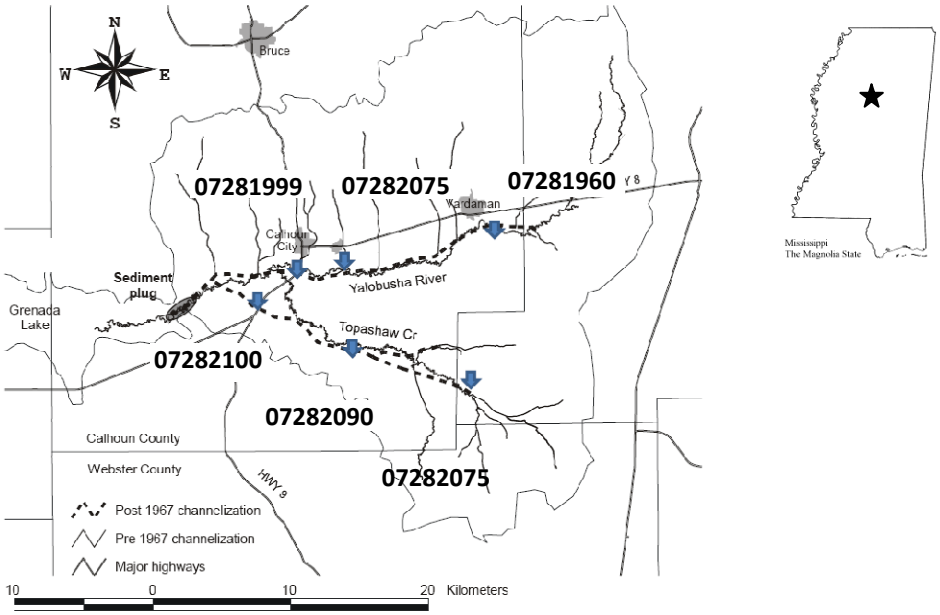

Figure 1. Yalobusha River watershed, northern Mississippi. Vertical arrows indicate locations of stream gages, and 8-digit codes beside arrows are U.S. Geological Survey gage numbers. Note that flows for gages 07281999 and 07282100 are summed and published as a single discharge for site 07282000 due to merging of the two streams during overbank stages.

Channelization triggered classical headward-advancing incised channel evolution, which was slowed but not stopped by cohesive bed strata exposed by the erosion (Simon and Thomas 2002, Langendoen et al. 2002). Attendant bed and bank erosion produced an estimated annual average sediment yield of 939 t km^{-2}, which is about twice the national average for watersheds of this size (Simon 1998, Simon and Thomas 2002). Knickpoint advancement and channel widening also recruited large volumes of wood as riparian buffers were undercut (Downs and Simon 2001). Sediment and large wood derived from these processes were transported downstream and formed a ~10-km-long plug near the downstream terminus of the channelization project (**Figure 1**), forcing all flow to exit the channel through more than 28 distributary gaps along the embankments of excavated materials that ran parallel to the channel (**Figure 2 c and d**). Flow was conveyed to downstream reaches through numerous, complex channels traversing the heavily forested floodplain. Analysis of core samples of sediments in the downstream reservoir suggest that 76% of sediment exiting the Yalobusha watershed has been trapped in the plug or on the floodplain (Bennett et al. 2005).

The highest points of the plug of sediment were ~7 m above the thalweg of the constructed channel and about 5 m above the adjacent floodplain (**Figure 3**). Comparison of 1967 and 1997 channel profiles showed ~5 m of deposition in channel, and earlier measurements (1969 and 1970) showed deposition started soon after construction was completed (Simon and Thomas 2002). Ten sediment cores collected from the plug in Mar-

Apr 2002 indicated that the plug was comprised of sand covered with a 0.5 to 1-m-thick veneer of silt and clay enriched in trace metals and pesticides (Bennett and Rhoton 2009). Prolonged flooding was noted on the floodplain to the north of the constructed channel in 1998-1999, and chronic backwater flooding of sewers in the adjacent town were reported (personal communication, Mr. Chodie Myers, Mayor, Calhoun City, MS). While the channel plug caused nuisance flooding, it also produced much greater water depths in the channelized reach at baseflow, effectively transforming the channel into a floodplain lake (Shields et al. 2000). Channelized and incised streams in this region frequently exhibit severely degraded ecosystems due to shallow water depths and flashy hydrology (Shields et al. 1994, 1998, 2010). Thus the blockage in the Yalobusha River produced some ecological recovery relative to its status when freshly channelized, providing 17 times as much aquatic habitat per unit valley length than an adjacent channelized stream and damping stage fluctuations (Shields et al. 2000). Fish species richness and ecological indices based on fish samples were greater in the blocked reach than for the adjacent channelized stream (Shields et al. 2000).

Some evidence suggests that watersheds in northwestern Mississippi experienced prehistoric cycles of such valley plugging (occlusion by sediment and debris) (Grissinger and Murphey 1982 and 1983). More clearly, since 1940 at least seven channels in western Mississippi have exhibited cycles of anthropogenically driven channel plugging, relief by channelization, and reformation of the plug (Shields et al. 2000). Approaches for addressing this situation include channel excavation, large wood removal from existing distributary channels, forced deposition of sediment in selected areas, upstream erosion controls, and adaptation to the blocked condition by changing land use patterns and objectives in low lying areas impacted by flooding or poor drainage (Diehl 1994). The decision was made to remove the channel plug from the Yalobusha River by conventional excavation (rechannelization) following construction of grade control structures and drop-pipe structures at strategic locations within the network of channelized streams upstream from the plug. Two phases of excavation were planned: the first would consist of excavating a channel up to 2 m deep and 4 km long through the “crown” of the sediment plug, while the second would lower the first channel about 1.7 m and extend it to a total length of 10 km (US Army Corps of Engineers, Vicksburg District 2010). A contract for the first phase was awarded on 24 Sept 2002, and excavation proceeded in 2003. Before the excavation was complete, a remnant of the plug was breached during one or more high flow events between November 2003 and January 2004. The proposed second phase of channelization has not been undertaken to date.

Data and analysis

Thalweg profiles were obtained from the mainstem of the Yalobusha River immediately following the breach event in January and February 2004 and six years later in May 2010 for comparison with previously published thalweg profiles. In both 2004 and 2010, echosounders were used to measure water depth, and bed elevation was determined by subtracting the depth from the water surface elevation measured by survey-quality differentially corrected global positioning system (DGPS) supplemented by water surface elevations measured at USGS gages 07281999, 07281977, and 07282100. Water surface slopes were ~0 in 2010 and 0.00004 in 2004. Horizontal position for the 2010 thalweg survey was obtained by DGPS.

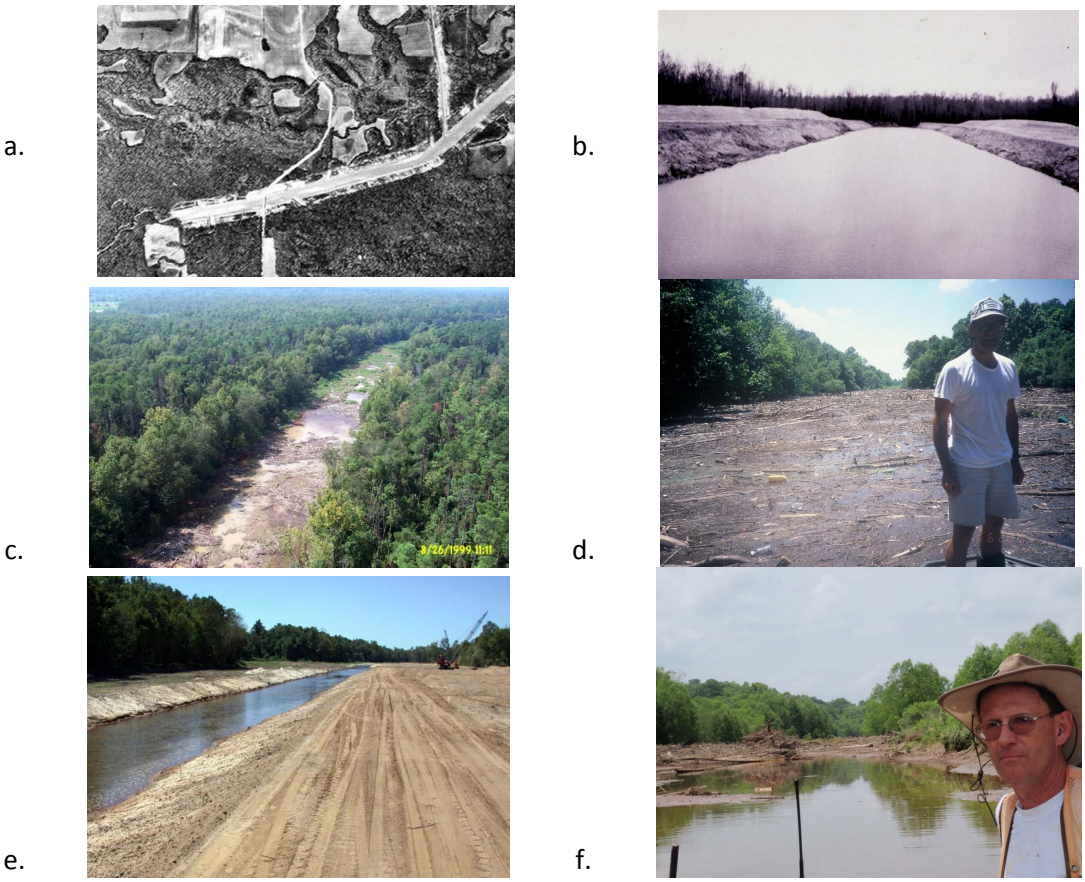

Figure 2. Yalobusha River downstream from Calhoun City, MS. a) Aerial view of downstream terminus of channelization works ca. 1967 showing constructed trapezoidal canal discharging to unmodified sinuous channel. b) View of recently completed channel shown in (a). c) Aerial view of sediment and large wood plug facing downstream in lower end of constructed channel August 26, 1999. d) Ground level view of plug facing downstream taken from boat June 20, 1997. e) Rechannelization of plugged reach September 16, 2003. f) Ground level view from boat facing downstream at approximately the same point as for (d) on May 13, 2010. Boat is aground in less than 0.3 m of water. Note large wood and sediment deposits in background.

Mean daily stage records were either downloaded from the http://waterdata.usgs.gov or obtained from the Mississippi district office of the US Geological Survey for gages along the main stem of the Yalobusha River and its primary tributary, Topashaw Creek Canal (**Figure 1**). Time series of monthly and annual minima were plotted and examined for patterns. In addition, measured instantaneous discharges and stages for 07281977 and 07282000 were obtained from the same website and used to plot stage-discharge relations for seven-year periods before and after the sediment plug breach in late 2003. Furthermore, these measurements were used to develop specific gage plots for increments equal to 10% of the range of measured discharges.

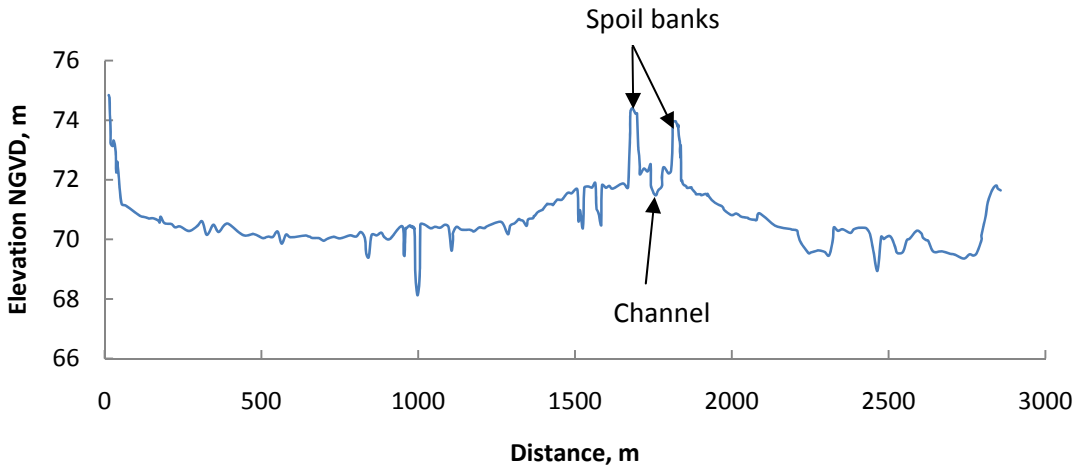

Figure 3. Yalobusha River cross-valley elevation profile survey prior to rechannelization. Data from file YYA-8-18, Silt range Y23, U.S. Army Corps of Engineers, Vicksburg District. No date given.

Results

Plans for the 1967 channelization called for abrupt termination of the constructed channel such that a negative slope (~0.015) occurred at the junction between the constructed and unmodified channel. Thalweg profiles show that by 1997, sediments derived from upstream headcutting and attendant bank failure had formed a wedge up to 6.7 m thick in the lower end of the constructed channel (**Figure 4**). The 1997 thalweg has a negative slope downstream from the mouth of Topashaw Canal and very low slope upstream from that point. However, the 1997 thalweg lies below the 1967 channelization thalweg upstream from RKM 8, indicating up to 2 m of bed degradation. The 2004 thalweg was limited to the reach upstream from the confluence with Topashaw and shows about 1 m of deposition since 1997 over the first few km upstream from Topashaw and negligible change upstream from that point. The 2010 thalweg indicates about 1 m of deposition over the 2003 excavated channel thalweg for the most downstream 1 km, and then follows the planned 2003 excavated thalweg for about 1.7 km to about RKM 2.8 (**Figure 4**). Upstream from that point (from RKM 2.8 to 10.8), 0.5 to 1.0 m of deposition has occurred between 1997 and 2010. Heaviest deposition occurred in a delta at the mouth of Topashaw Creek Canal.

Time series of the annual and monthly minimum stage showed that backwater effects from the plug induced sedimentation as far as 14.3 km upstream (**Figure 5c**, Yalobusha River at Derma), but minimum stages further upstream were more or less stable. Response over this 14 km reach was characterized by increasing stages prior to the 2003 channel work, a sudden drop of about 1m in late 2003, and gradual increasing stages since then, confirming indications from thalweg profiles described above. However, plots of minimum stage show that 2010 minimum stages have not reached levels that existed in late 2003 just prior to rechannelization. Perhaps the channel work increased overall baseflow conveyance through the blocked reach, even though thalweg elevations are higher now (see RKM 0-2 elevations in **Figure 4**). Fluvial systems often display nonlinear responses to disturbance (Shields and

Abt 1989, Simon 1989) described by power functions of time. Rates of aggradation and degradation before and after rechannelization and plug breaching were characterized by fitting the contemporaneous records of minimum monthly stage for the three gages that displayed responses to plug formation and removal. Rates of change were similar at all three gages with exponents for the plug formation phase varying over a narrow range (0.190-0.201). Exponents for the period since plug removal indicate that it is reforming at a somewhat slower rate than previously, varying between 0.081 and 0.173.

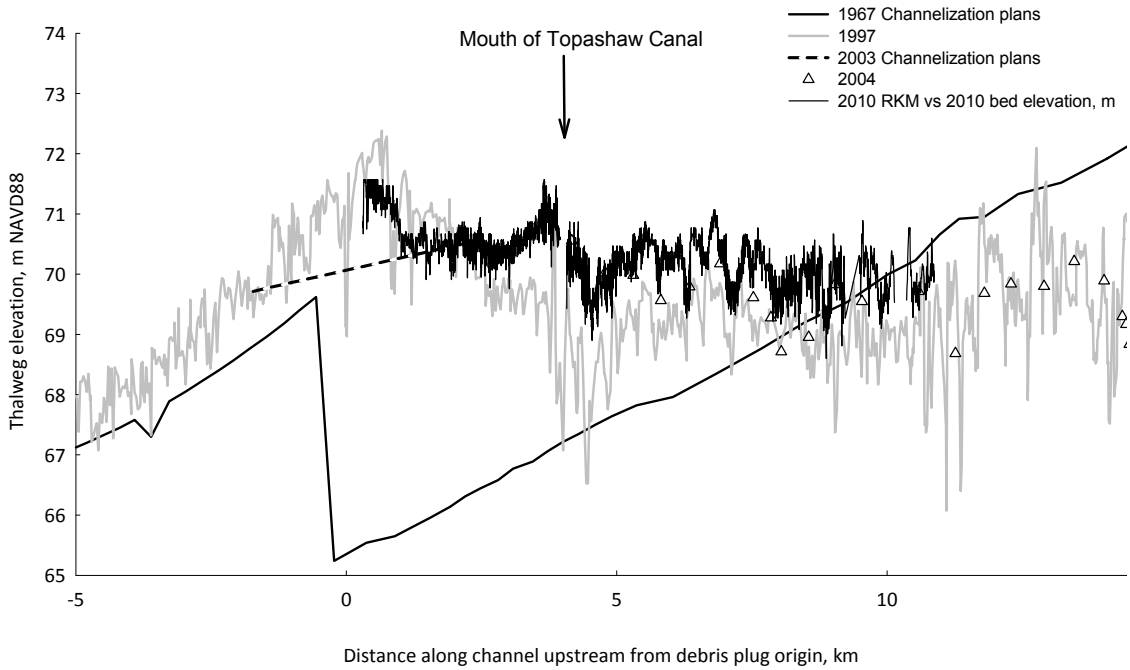

Figure 4. Thalweg profiles for Yalobusha River, 1967 plans, 1997, 2004 and 2010. Note that direction of flow is from right to left.

Stage-discharge relations based on measured discharges for the seven-year-long periods immediately before and after rechannelization and plug breaching displayed a clear pattern (**Figure 6**). Data from gages within 15 km of the plug indicated that stages for low to moderate discharges dropped about 1 m after the plug was dredged. The discharge ratings showed no effects of plug removal for discharges higher than ~30 $m^3 s^{-1}$ at Calhoun City or for discharges higher than ~16 $m^3 s^{-1}$ upstream at Derma. Stages were slightly higher during the most recent three years (2008-2010) than for the four years immediately after channelization (2004-2007) (**Figure 6**). Specific gage plots based on directly measured discharges were populated with too few points to be conclusive, but they produced similar indications.

Discussion

Rechannelization of the plugged 4 km of the Yalobusha was intended to be a short term expedient to alleviate flooding in the nearby town of Calhoun City (personal communication,

John Smith, US Army Corps of Engineers, Vicksburg District). The project goal was that extensive grade controls and other measures placed in the contributing watershed during 1996-2003 would reduce watershed sediment yield and allow the rechannelized reach to be stable at least for several years. The longer term plan, similar to a more successful effort in Hickahala Creek watershed about 100 km to the north (U.S. Army Corps of Engineers 1990, Runner and Rebich 1997, Biedenharn et al. 2004), was for even more extensive downstream channelization following construction of intensive erosion control treatments of channels and gullies throughout the contributing watershed. It should be noted that the Hickahala channel extends all the way to a downstream flood control reservoir while the Yalobusha channel terminates in a naturally narrow, meandering channel, and project plans made no provision for the huge change in sediment transport capacity at the junction between the channelization project and the unmodified channel. Since stage-discharge relations (Figure 6) were not affected for higher flows, the rechannelization project provided limited flood control benefits. Furthermore, rechannelization may have temporarily triggered higher sediment yield if the rapid drawdown of impounded waters following the plug breach resulted in failure of streambanks (Simon and Thomas 2002). Plans by the Corps of Engineers to further address issues associated with this reach of the Yalobusha River are unknown to us.

The Yalobusha River watershed upstream from the rechannelized reach was part of an ambitious federally-funded erosion control, research and demonstration project (Shields et al. 1995, Watson et al. 2000). Many of the papers cited herein were products of that project. The availability of federal funds to address issues caused by the sediment plug in the Yalobusha River channel provided a unique opportunity to employ innovative channel management concepts such as development of a wide, forested floodway bounded by setback levees as was done at the smaller Abiaca Creek watershed ~100 km to the southwest of the Yalobusha (U.S. Army Corps of Engineers 1993). There long-term sediment storage is provided within the leveed, forested floodway, and water side borrow pits complement the restored floodplain ecosystem. The floodway is designed to trap sediments to prevent deposition in national wildlife refuge downstream. Workers in other regions have also proposed alternatives to rechannelization for flood management (Bechtol and Laurian 2005). Other options proposed for the region containing the Yalobusha include large wood removal from existing distributary channels and forced deposition of sediment in sediment basins or traps (Diehl 1994 in Shields 2000). Although channelization projects often degrade riverine habitats, the resulting sediment deposition in the rechannelized reach has reproduced ecologically favorable conditions which prevailed prior to plug dredging (Shields et al. 2000). The large, quiescent backwater in the blocked, constructed channel functions as a relatively deep floodplain lake while the numerous complex overflow channels, heavily loaded with wood, provide a diverse range of physical conditions. It remains to be seen how long the current condition will persist before the cycle of channelization, instability and blockage is renewed.

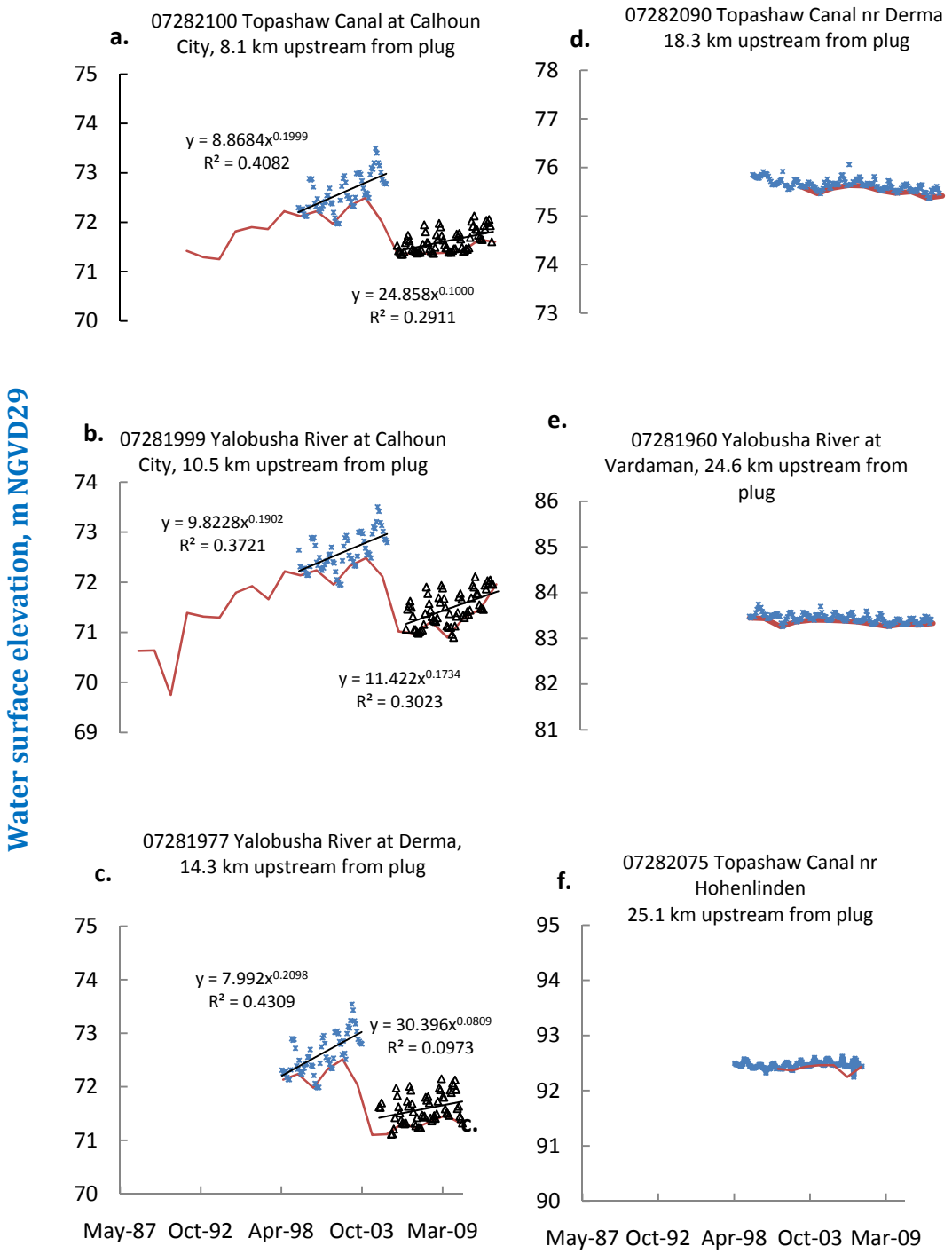

Figure 5. Annual (solid lines) and monthly minimum (symbols) water surface elevations for stream gages upstream from plug. Gage locations are shown in Figure 1. In figures a, b and c the blue symbols are for months prior to rechannelization; black symbols are for points following rechannelization.

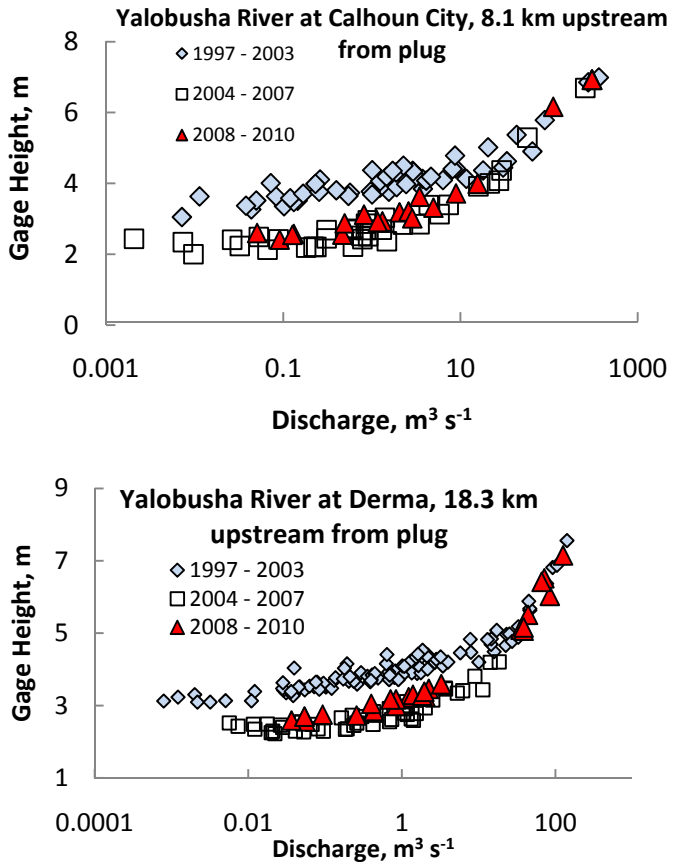

Figure 6. Stage-discharge relations based on current meter measurements, Yalobusha River at Calhoun City and Yalobusha River at Derma. Discharge values for Yalobusha River at Calhoun City represent the sum of values measured for the gages on the Yalobusha and Topashaw Creek Canal immediately south of Calhoun City, while the gage heights are for Yalobusha River at Calhoun City. The overbank areas of these two channels merge at high flows. Flood stage at Calhoun City = 7 m.

Conclusions

A ~10-km-long plug of sediment and large wood formed in the lower end of the channelized Yalobusha River, Mississippi between 1967 and 2003. The upstream flooding associated with the plug was addressed in 2003 by dredging a channel through the top of the plug. Before construction was completed, the plug was breached during a high flow event, and the channel avulsed. Channel management efforts for systems such as this one should incorporate features that allow for development of floodplain aquatic habitats and sediment storage while allowing for future conditions under which watershed sediment yield may be drastically reduced due to upstream stabilization works.

Acknowledgments

Mark Griffith, Lauren Klimetz, Laura Shields and Casey Pearce provided assistance with field operations, and Alexandra McCaskill assisted with manuscript preparation. Data were provided by the Mississippi District of the U. S. Geological Survey. Andrew Peck, Sue Niezgoda, John Smith and James MacBroom read an earlier version of this paper and made many helpful comments.

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