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PROCESSES AND FORMS OF AN UNSTABLE ALLUVIAL SYSTEM WITH RESISTANT, COHESIVE STREAMBEDS

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ABSTRACT

As a response to channelization projects undertaken near the turn of the 20th century and in the late 1960s, upstream reaches and tributaries of the Yalobusha River, Mississippi, USA, have been rejuvenated by upstream-migrating knickpoints. Sediment and woody vegetation delivered to the channels by mass failure of streambanks has been transported downstream to form a large sediment/debris plug where the downstream end of the channelized reach joins an unmodified sinuous reach. Classification within a model of channel evolution and analysis of thalweg elevations and channel slopes indicates that downstream reaches have equilibrated but that upstream reaches are actively degrading.

The beds of degrading reaches are characterized by firm, cohesive clays of two formations of Palaeocene age. The erodibility of these clay beds was determined with a jet-test device and related to critical shear stresses and erosion rates. Repeated surveys indicated that knickpoint migration rates in these clays varied from 0·7 to 12 m a^{-1}, and that these rates and migration processes are highly dependent upon the bed substrate. Resistant clay beds of the Porters Creek Clay formation have restricted advancement of knickpoints in certain reaches and have caused a shift in channel adjustment processes towards bank failures and channel widening. Channel bank material accounts for at least 85 per cent of the material derived from the channel boundaries of the Yalobusha River system.

Strategies to reduce downstream flooding problems while preventing upstream erosion and land loss are being contemplated by action agencies. One such proposal involves removal of the sediment/debris plug. Bank stability analyses that account for pore-water and confining pressures have been conducted for a range of hydrologic conditions to aid in predicting future channel response. If the sediment/debris plug is removed to improve downstream drainage, care should be taken to provide sufficient time for drainage of groundwater from the channel banks so as not to induce accelerated bank failures. Published in 2002 by John Wiley & Sons, Ltd.

KEY WORDS: channel evolution; cohesive sediments; erodibility; knickpoint; unstable channels

INTRODUCTION AND PURPOSE

The Yalobusha River system, north-central Mississippi, USA (Figure 1), was extensively channelized near the turn of the 20th century, and again in the late 1960s. As a consequence of channel adjustment processes, upstream-propagating knickpoints caused deepening of upstream reaches and tributary channels. This pulse of degradation rejuvenated tributaries and increased bank heights above stable conditions, causing significant channel widening by mass failure of channel banks. Woody vegetation growing on these channel banks was delivered to the flow when the banks failed and were transported downstream.

The Yalobusha River system exhibits the range of conditions identified in models of channel evolution derived elsewhere for other channelized streams (Schumm *et al.*, 1984; Simon and Hupp, 1986; Simon, 1989). Downstream reaches experience recovered, quasi-equilibrium conditions with sand beds and stable banks. Moving upstream, however, banks are increasingly unstable. This is typical of channelized streams of the mid-continent region of the United States (Schumm *et al.*, 1984; Simon, 1989, 1994; Simon and Rinaldi, 2000). However, in upstream reaches, the channel beds of the Yalobusha River system are characterized

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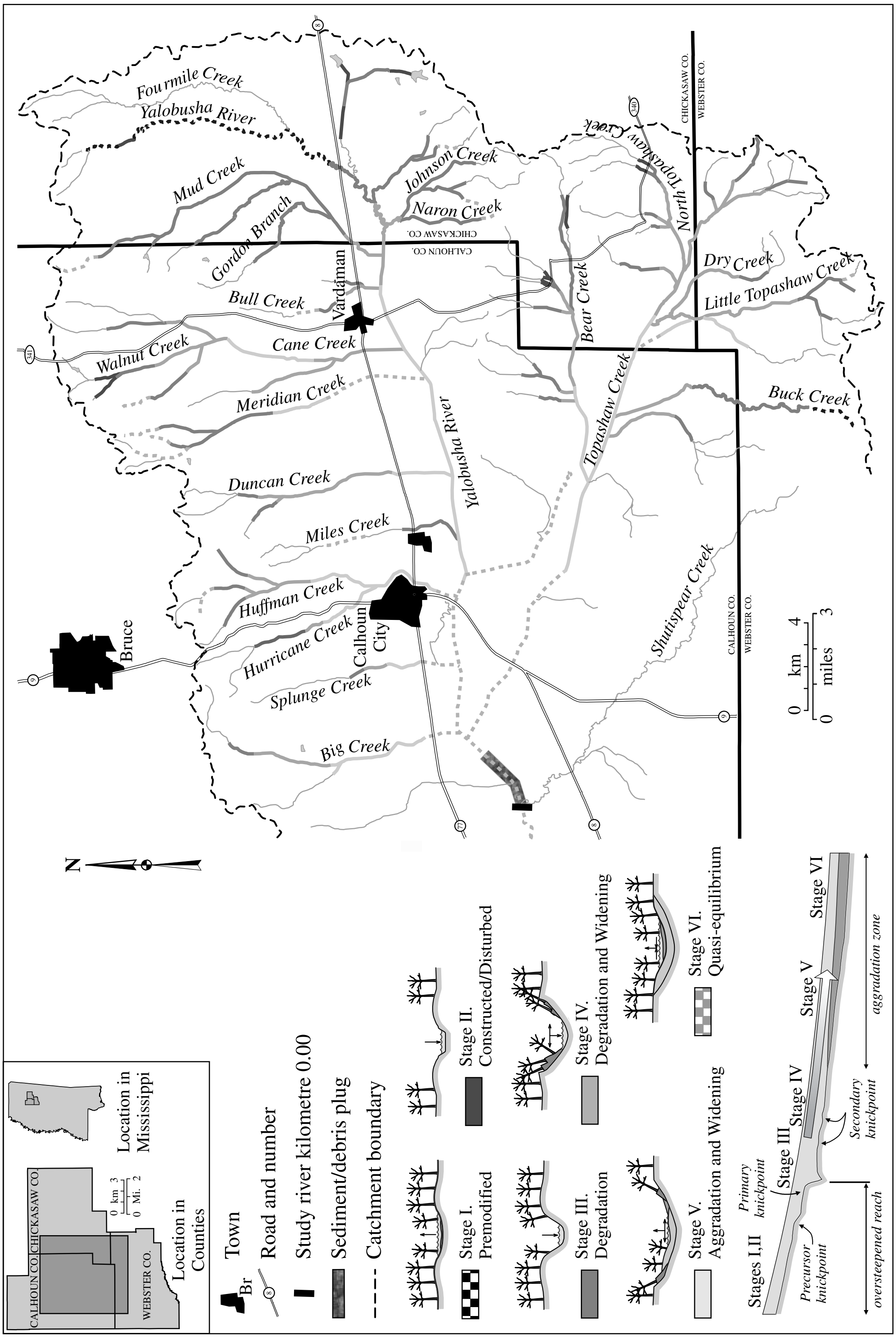

Figure 1. Map of the Yalobusha River basin showing location of study kilometre 0·00, location of the sediment/debris plug, major tributaries and stage of channel evolution (modified from Simon and Hupp, 1986)

by firm, cohesive clays that tend to resist hydraulic erosion. This characteristic makes the Yalobusha River system unique in this region.

The erosion of channel materials from the bed and banks of tributary channels and upstream reaches of the Yalobusha River and Topashaw Creek continues. The amount of sediment added to the river basin due to bank failures and bed degradation alone has been estimated to be 833 000 tonnes a^{-1} or a yield of 939 tonnes km^{-2} a^{-1} (Simon, 1998). Of this, channel banks have been estimated to contribute at least 85 per cent and as much as 92 per cent of the sediment eroded from the channel boundaries of the Yalobusha River system (Simon, 1998). In addition, the input of vegetation due to bank failure in the vicinity of major knickpoints has been estimated to be around 28 m^3 a^{-1} (Downs and Simon, 2001).

Sediment and vegetation derived from the boundaries of the Yalobusha River, its tributaries and from upland areas has been deposited in downstream reaches of the Yalobusha River and Topashaw Creek, thereby reducing flow capacity. This has promoted the development of a large sandbar and sediment/debris plug at the downstream terminus of channelization works. The debris cause higher water levels and slower flow velocities than previously. This in turn causes even greater rates of deposition, further reductions in channel capacity, and an increase in the magnitude and frequency of floods.

In an effort to alleviate the apparently dichotomous problems of reduced downstream channel capacity and flooding problems, with upstream erosion and land loss, restorative strategies have been contemplated by action agencies. One of the proposals involves removal or bypassing of the main sediment/debris plug on the lower Yalobusha River. However, because of concerns that this could rejuvenate the system, a study was conducted to evaluate and quantify the factors and processes controlling channel adjustment in the Yalobusha River basin. This paper describes the results of that study.

HISTORICAL CHANNEL CONDITIONS

Rapid agricultural development of the region occurred in the middle 1800s. Because of a lack of proper soil conservation practices, severe sheet and gully erosion in upland areas (Mississippi State Planning Commission, 1936) resulted in the filling of stream channels, consequent loss of channel capacity, and frequent and prolonged flooding. Cropland in valley bottoms was commonly buried with sand and debris eroded from upstream. Sediment deposited in channels contributed to increased incidence of flooding in downstream reaches.

Initial channelization projects (1910–1920s)

Both the Yalobusha River and Topashaw Creek were historically highly sinuous and avulsed several times across their floodplains in the past two centuries (Simon, 1998). However, with the exception of the downstream-most reach of Topashaw Creek, the present-day alignments of the Yalobusha River, the remainder of Topashaw Creek, and other tributaries were determined by the channelization projects undertaken by the newly formed Drainage Districts in the 1910s and 1920s. In about 1910, a 19·3 km-long straight ditch was excavated through the Yalobusha River valley from the Calhoun–Chickasaw County line, downvalley to an outlet into the sinuous channel of the river about 1·8 km downstream of State Highway 8, south of Calhoun City (Mississippi Board of Development, 1940a). In 1912, a 17·7 km ditch was excavated through the valley of Topashaw Creek from the Calhoun–Chickasaw County line to the Yalobusha River (Mississippi Board of Development, 1940b) and, in 1913, 7·64 km of Topashaw Creek and 2·82 km of Little Topashaw Creek were channelized to the Webster County line. This latter work was further extended into the upper watershed (Mississippi Board of Development, 1940c).

Channelization oversteepened the banks and helped to initiate upstream bank collapse and retreat which, combined with excess sediment transport capacity, meant that a debris plug (formed from trees, other debris and sediment transported from upstream reaches) closed the downstream end of Topashaw Creek and a reach of the Yalobusha River in the years prior to 1940 (Mississippi Board of Development, 1940b). In the late 1930s another outlet was provided for Topashaw Creek, but by 1940 this outlet was again obstructed in some places with sediment and debris, and the capacity of the Yalobusha River in the vicinity of Calhoun City had also been greatly reduced (Mississippi Board of Development, 1940c). Hence, it was recommended that the downstream ends of both streams be deepened and widened to improve drainage in the area around Calhoun City.

Channel work in 1960s

A comprehensive river basin work plan was devised and implemented by the US Soil Conservation Service in the late 1960s. This plan provided for the clearing, dredging, straightening, and widening of the Yalobusha River and many of its tributaries. It also provided for the construction of various types of erosion-control structures. We have been able to account for a total of 460 structures in the Yalobusha River Basin. The most common of these structures were overfall pipes (58 per cent of the total), constructed to prevent the formation and advancement of gullies into fields adjacent to the stream channels. Of the remainder, 11 per cent were box inlets, 9 per cent were hooded inlets, 9 per cent were drop inlets combined with a grade control dam, 6 per cent were drop inlets, 4 per cent were grade control dams, and the remaining 3 per cent were various types of dams and hooded pipes.

During 1967, the Yalobusha River and Topashaw Creek were cleared and dredged from a point 850 m downstream of Shutispear Creek, upstream to the Calhoun–Chickasaw County line. The Yalobusha River was dredged to a gradient of 0·0005, with top widths ranging from 58 m at the downstream end of the channel work to 22 m at the upstream end. Topashaw Creek was constructed at a gradient of 0·00075 with top widths ranging from 27 to 38 m. In addition, the following tributaries were cleared and/or dredged throughout most of their length: Bear, Big, Cane (Cook), Huffman, and Hurricane Creeks. Other tributaries were cleared, dredged and realigned only in their downstream ends. These were Duncan, Meridian, Miles, and Splunge Creeks, as well as numerous other laterals and ditches.

PRESENT CHANNEL CONDITIONS

The sediment/debris plug on the lower Yalobusha River downstream of Calhoun City is of critical importance to channel adjustment processes and conditions in the river system, because it functions as a blockage to the downstream transport of sediment. Sediment/debris plugs have been a relatively common phenomenon over the past 60 years in this river basin. This is related to the conditions imposed at the transition between the dredged and straightened channels upstream, and the unmaintained sinuous reaches downstream. For example, the conveyance of the 1967 modified channel was about an order of magnitude greater than the meandering reach downstream, and assuming $d_{50} = 0{\cdot}35$ mm, 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.

The present plug is shown in Figure 2 as a large hump in the 1997 thalweg profile of the lower Yalobusha River. A comparison of the 1967 and 1997 channel profiles shows that as much as 5 m of sediment and debris has accumulated on the channel bed of the Yalobusha River. Very flat (0·0001) or even negative channel gradients extend to about river kilometre (rkm) 10 (Figure 2), producing lake-like conditions downstream from Calhoun City. The sediment/debris plug also directly effects the downstream-most 2 km of Topashaw Creek where up to 2 m of deposition has occurred since 1967. The 1969 and 1970 profiles obtained from the National Resources Conservation Service (NRCS) indicate that the plug was already beginning to form, just two years after the completion of the channel work (Figure 2). It has grown steadily since that time with eroded sediment from upstream reaches and tributaries, and woody vegetation from destabilized streambanks (see Downs and Simon, 2001).

An analysis of gauging station data was conducted for the Yalobusha River at the Highway 8 bridge to better illustrate the period of plug development. Although there was a large initial reduction in the elevation of flows post-1967, in the past 30 years the elevation of the annual minimum stage has increased by about 1·5 m, with most of the increase occurring since 1980 (Figure 3). For Topashaw Creek, the elevation of the minimum stage increased by about 1 m since 1967, with most of the increase occurring since 1989.

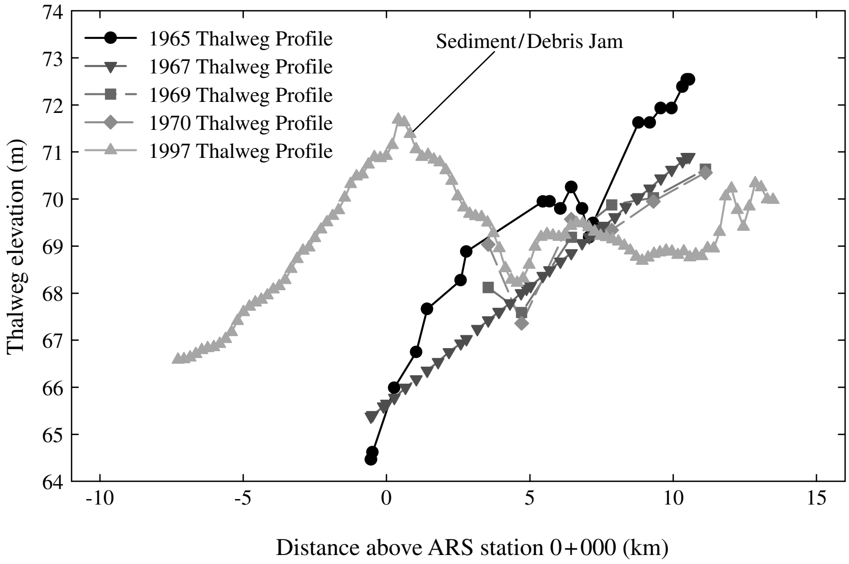

Figure 2. Thalweg profiles of the lower Yalobusha River in the vicinity of the sediment/debris plug showing extremely flat and even negative local channel gradients and initial plug development in 1969, just two years after the completion of the most recent channel work

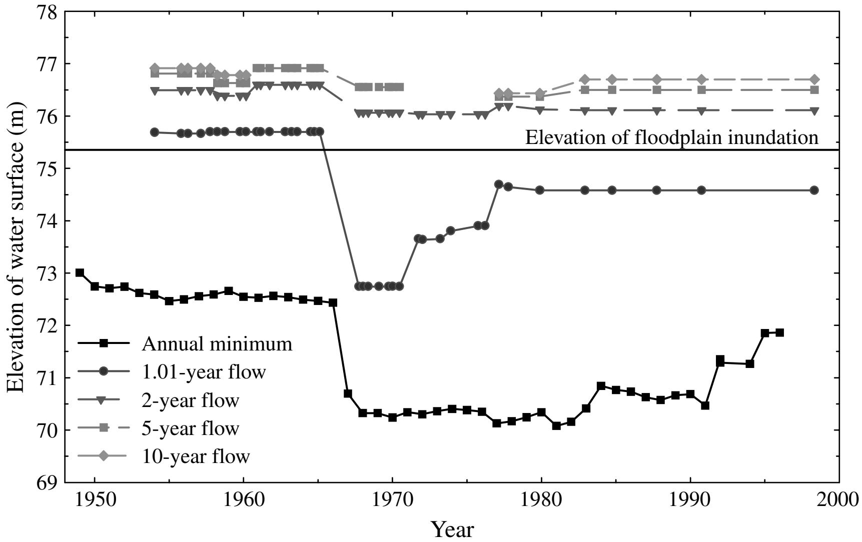

Figure 3. Change in annual minimum stage and specific-gauge elevations for recurrence interval flows of 1·01, 2, 5, and 10 years for the Yalobusha River at Calhoun City

Channel evolution

The remainder of the discussion on channel conditions is centred around channel forms and processes typical of channelized streams. To accomplish this in an organized way, a six-stage model of channel evolution (Simon and Hupp, 1986; Simon, 1989; Figure 1) is used to differentiate changing conditions along streams of the Yalobusha River system.

Researchers in fluvial geomorphology have noted that alluvial channels in different environments, destabilized by different natural and human-induced disturbances, pass through a sequence of channel forms through time (Schumm *et al.*, 1984; Simon and Hupp, 1986; Simon, 1989). These systematic temporal adjustments are collectively termed 'channel evolution' and permit interpretation of past and present channel processes, and prediction of future channel processes. A six-stage model of channel evolution was developed by the US Geological Survey from data collected from a 27 500 km^2 area of West Tennessee, based on shifts in dominant adjustment processes (Simon and Hupp, 1986; Simon, 1989, 1994; Figure 1).

Stage VI – restabilized. In downstream reaches, main stem channels are characterized by aggradation, sediment accretion on channel banks, the proliferation of 'pioneer' woody riparian species such as willow, river birch, sycamore and sweetgum, and the regaining of bank stability. Channel beds are characterized by fine to medium sand. These reaches extend from rkm −7·4 to 9·2 on the Yalobusha River, and 8·0 km up Topashaw Creek.

Stage V – aggrading and widening. With increasing distance upstream, evidence of mass failures can be observed as bank heights increase to more than 10 m even though deposition of sand-sized materials is still evident. These stage V conditions begin at about rkm 9·2 and 8·0 on the Yalobusha River and Topashaw Creek respectively. Aggradation in both of these areas, and along the other aggrading downstream reaches, has been episodic. These episodes are associated with periods of accelerated bank erosion during years when the banks have remained saturated for long periods. Dendrochronologic data from streambanks throughout the Yalobusha River system point to 1979, 1983, and 1991 as periods of accelerated channel widening (Simon, 1998).

Stage IV – degrading and widening. Channel conditions deteriorate to stage IV with increasing distance upstream, indicating a shift to degradation on the channel bed and more rapid channel widening by mass failures. This occurs just upstream of the confluence of Bull Creek on the Yalobusha River (about rkm 28·6) and about 1 km upstream of the confluence of Little Topashaw Creek on Topashaw Creek (about rkm 22·1). Tributary streams entering in these reaches are also characterized by stage IV conditions and are highly unstable. In the Yalobusha River basin, the downstream ends of Johnson, Cane, and Mud Creeks are particularly unstable with large, recent bank failures. In the Topashaw Creek basin, the downstream parts of Buck, Dry, Little Topashaw, and North Topashaw Creeks are particularly unstable.

Stage III – degrading knickpoints and knickzones. Upstream of the failing stage IV reaches are locations where the bed is degrading but bank heights and angles have not exceeded the critical conditions of the material and the banks remain stable and vegetated. These reaches may be characterized by steep bank surfaces smoothed by fluvial erosion and by trees with exposed root systems. On both the Yalobusha River and Topashaw Creek, the transition to stage III conditions occurs at about rkm 30 and is indicated by knickpoints and knickzones. Knickpoints and knickzones are cut into resistant materials (in the Yalobusha basin, these are clays and ironstone outcrops). Although there are individual knickpoints of the order of 1·5 m high, Big Creek has a major knickzone between rkm 6·5 and 6·8 that is about 3 m high. Other particularly unstable tributary reaches are the downstream ends of Dry, Johnson and Mud Creeks, and the middle reaches of Bear, Little Topashaw and North Topashaw Creeks.

Processes in degrading reaches

Bed material characteristics. In the transitional areas between downstream aggrading and upstream degrading reaches, the dominant type of bed material changes gradually from fine or medium sand, to stiff silty clay that is often manifest as knickpoints or knickzones up to 3·5 m high (Simon, 1998). The sand is relatively uniform, with an average d_{50} of about 0·35 mm (0·27 to 0·39 mm on the lower Yalobusha; 0·24 to 0·48 mm on the lower Topashaw).

The presence of the resistant clay material makes the Yalobusha River system unique in comparison to other adjusting stream systems in this region. A geologic section taken longitudinally along the Yalobusha River shows the Midway Group of Palaeocene age as the dominant formation in the valley (Newcome and Bettandorff, 1973). Bed material in degrading reaches is characterized by two formations of the Midway Group: Porters Creek Clay, and Naheola (Parks, 1961). Porters Creek Clay is a hard, dark grey to black silty clay with undrained cohesive strengths as great as 287 kPa (Mississippi Department of Transportation, personal communication, 1998). These clays are found on the channel beds as:

1. relatively smooth and solid ledges (much like bedrock);
2. rounded sand-, to gravel-, to cobble-sized clasts; or
3. desiccated flakes in the clay size range.

Notwithstanding the strength of this clay formation, the Yalobusha River, Topashaw Creek, and other degrading tributary streams in the basin have been able to incise as much as 1·5 m into this resistant material. In contrast, the Naheola formation is a composite of orange and grey clays, and is generally much softer and more pliable than Porters Creek Clay.

Incipient motion of bed material. To address the problem of estimating erosion resistance and hence likely knickpoint migration and bed degradation amounts and rates, tests on representative clay beds in the Yalobusha River system were conducted between 1998 and 2001 with a submersible jet-test device (Hanson, 1990). This device has been developed based on knowledge of the hydraulic characteristics of a submerged jet and the characteristics of soil material erodibility. A number of studies have used a submerged jet for testing materials in the laboratory (Dunn, 1959; Moore and Masch, 1962; Hollick, 1976; Hanson and Robinson, 1993). Hanson (1991) developed a soil-dependent jet index, which is based on the change in maximum scour depth caused by an impinging jet. Jet-test results have been used to develop a relation between critical shear stress (τ_c) and the erodibility coefficient (k) for cohesive streambeds in the midwestern United States (Hanson and Simon, 2001).

Results of 153 jet-tests (83 in the Naheola formation, 66 in the Porters Creek Clay formation, and four in other materials) indicate that there is a wide variation in the erosion resistance of the streambeds, with τ_c-values spanning almost four orders of magnitude from near 0·0 to greater than 400 Pa (mean = 105 Pa; standard error = 10·6 Pa). An inverse relationship between τ_c and k was observed, where soils exhibiting a low τ_c have a high k, and soils having a high τ_c tend to have a low k. Because those sites with the greatest values of τ_c maintain the lowest erodibility coefficients, they can be expected to erode by hydraulic stresses at the lowest rates. Based on these observations, k can be estimated as a function of $\tau_c (r^2 = 0{\cdot}60$; Figure 4):

$$k \approx 0{\cdot}1\tau_c^{-0{\cdot}5} \tag{1}$$

The relatively low r^2 value is probably due to differences in antecedent temperature and moisture, clay mineralogy and proportion, density, soil structure, organic content, as well as pore- and surface-water chemistry (Kelly and Gularte, 1981; Grissinger, 1982). The relation is very similar to the one developed by Hanson and Simon (2001) (some sites from the Yalobusha River system were included) and to observed trends reported

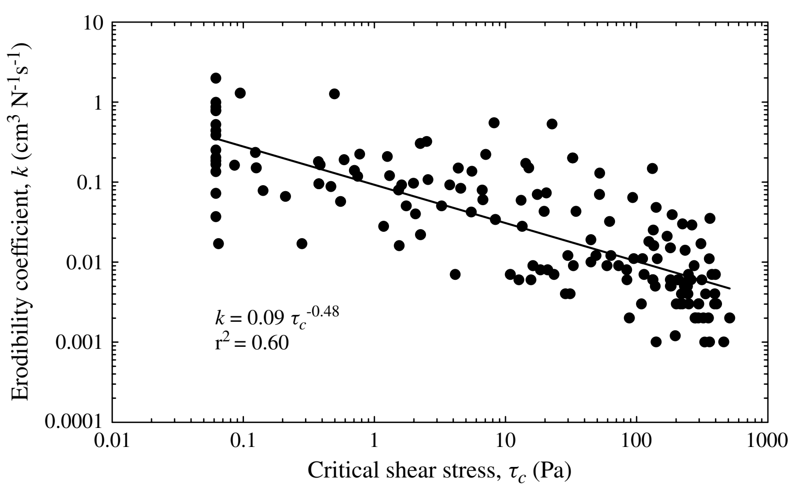

Figure 4. Relation between critical shear stress (τ_c) and erodibility coefficient (k) for tested streambeds in the Yalobusha River system

by Arulanandan *et al.* (1980) in laboratory flume testing of soil samples from streambeds across the United States. To relate these values to the relative potential for flows to erode cohesive beds, an excess shear stress approach is utilized (Partheniades, 1965):

$$\begin{aligned} \varepsilon &= k(\tau_o - \tau_c)^a \quad (\text{for } \tau_o > \tau_c) \\ \varepsilon &= 0 \quad\quad\quad\quad\;\; (\text{for } \tau_o \le \tau_c) \end{aligned} \tag{2}$$

where ε = erosion flux (m s^{-1}); k = erodibility coefficient (cm^3 N^{-1} s^{-1}); $(\tau_o - \tau_c)$ = excess shear stress (Pa); τ_o = average boundary shear stress (Pa); τ_c = critical shear stress (Pa); and a = an exponent (often assumed = 1·0). In the absence of local shear stress data, an average boundary shear stress is calculated:

$$\tau_o = \gamma_{\mathrm{w}} RS \tag{3}$$

where γ_{w} = unit weight of water (9·81 kN m^{-3}); R = hydraulic radius (which is, for a wide open channel, equal to the flow depth) (m); and S = channel gradient.

Table I shows minimum, mean, median and maximum values for τ_c and k sorted by formation. Distinct differences in susceptibility to erosion by hydraulic stresses exist for the two dominant formations, with the Porters Creek Clay formation clearly much more resistant to erosion by hydraulic forces than the Naheola formation.

To provide a concise picture of the distribution of τ_c values throughout the Yalobusha River system, τ_c data were assigned an erodibility class based on the five classes developed by Hanson and Simon (2001). The five classes for τ_c are:

- <0·374 Pa = very erodible
- 0·375 to 1·99 Pa = erodible
- 2·00 to 9·99 Pa = moderately resistant
- 10·0 to 99·9 Pa = resistant
- >99·9 Pa = very resistant

Streambed erodibility characteristics in the Yalobusha River system are highly skewed, representing the two dominant material types (Figure 5A). Median values hence provide a better estimate of the central tendency of the data, given that they are not normally distributed. The upper class of Figure 5A represents the Porters Creek Clay formation while the lowest classes represent the overlying Naheola formation. Order of magnitude variation of τ_c within each material type is a function of varying degrees of subaerial exposure, weathering, and the amount of cracking along bedding planes and other planes of weakness. Under most conditions the Porters Creek Clay is extremely resistant, as evidenced by the great majority of test results falling in the highest τ_c class (Figure 5B). In contrast, τ_c data from streambeds composed of the Naheola formation are quite variable, bridging all data classes (Figure 5C). Most flows are competent to erode streambeds composed of the Naheola formation (τ_c = 4·30 Pa), but only the deepest flows and steepest profiles generate average boundary shear stresses great enough to erode streambeds composed of the Porters Creek Clay formation (τ_c = 206 Pa).

Possible rates of erosion (in mm s^{-1}) were calculated by Equation 2 for all study sites in the Yalobusha River system using τ_c and k values obtained from jet-testing and by assuming a range of steady-flow conditions with boundary shear stresses of 50, 100, 150, 200, 250 and 300 Pa (Table I). Values in this table provide an estimate of the rates of downwearing that would occur at a given site under the given range of shear stress conditions. Median values are again used as a measure to differentiate between sites with streambeds composed of the two different formations. As indicated previously, streambeds composed of the Porters Creek Clay formation are non-erodible until flows of about 200 Pa are encountered. At this shear stress, these beds can erode via particle-by-particle detachment at a rate of about $7{\cdot}5 \times 10^{-6}$ mm s^{-1}. Streambeds composed of the Naheola formation are readily eroded over the entire range of shear stresses at rates of 0·005 to 0·03 mm s^{-1} (Table I). In contrast, invoking the Shields criterion, only 0·25 Pa is required to entrain

Table I. Minimum, mean, median, and maximum values of τ_c, k, and erosion rates for Naheola formation, Porters Creek Clay formation and all tests, assuming $\tau_o = 50$, 100, 150, 200, 250 and 300 Pa

Formation	Statistic	Critical shear stress, τ_c (Pa)	Erodibility coefficient, k ($cm^3 N^{-1} s^{-1}$)	ε_{50} ($mm s^{-1}$)	ε_{100} ($mm s^{-1}$)	ε_{150} ($mm s^{-1}$)	ε_{200} ($mm s^{-1}$)	ε_{250} ($mm s^{-1}$)	ε_{300} ($mm s^{-1}$)
Naheola	Minimum	0·062	0·002	0·000	0·000	0·000	0·000	0·000	0·000
	Mean	32·0	0·202	0·009	0·019	0·029	0·039	0·049	0·059
	Median	4·30	0·116	0·005	0·010	0·015	0·021	0·026	0·032
	Maximum	296	1·98	0·064	0·129	0·194	0·259	0·324	0·389
Porters Creek Clay	Minimum	0·065	0·001	0·000	0·000	0·000	0·000	0·000	0·000
	Mean	190	0·012	0·000	0·000	0·000	0·001	0·001	0·002
	Median	206	0·009	0·000	0·000	0·000	0·000	0·000	0·001
	Maximum	512	0·129	0·001	0·002	0·003	0·003	0·004	0·007
All	Mean	105	0·118	0·005	0·011	0·016	0·022	0·028	0·034
	Median	29·3	0·022	0·000	0·001	0·002	0·002	0·004	0·005
	σ^2	114	0·216	0·011	0·022	0·032	0·043	0·054	0·065

ε_{50} = erosion rate for an applied shear stress of 50 Pa.

the 0·35 mm sand, characteristic of the downstream ends of the Yalobusha River and Topashaw Creek. The ease with which channel degradation has proceeded through the sand-bedded portions of the river basin is indicated by the low shear stress required to erode the sand beds. By Equation 3, it is shown that entrainment of the 0·35 mm sand from reaches just upstream of the sediment/debris plug would require a flow depth of only 64 mm assuming the current, average channel gradient of 0·0004.

Knickpoint erosion and migration

Network-wide thalweg profiles surveyed by the US Army Corps of Engineers (CoE) in 1997, combined with extensive field and aerial reconnaissance, identified a total of nine major knickpoints in the Yalobusha River system (Simon, 1998). Some of these knickpoints are knickzones, steeper reaches of channel representing a headward migrating zone of incision (Schumm *et al*., 1984). Knickzone locations generally represent the upstream terminus of channel adjustment processes and many of the largest ones seem to be almost equidistant from the lower end of the river system, in the vicinity of rkm 28–30 (Figure 1; Simon, 1998). Since the 1997

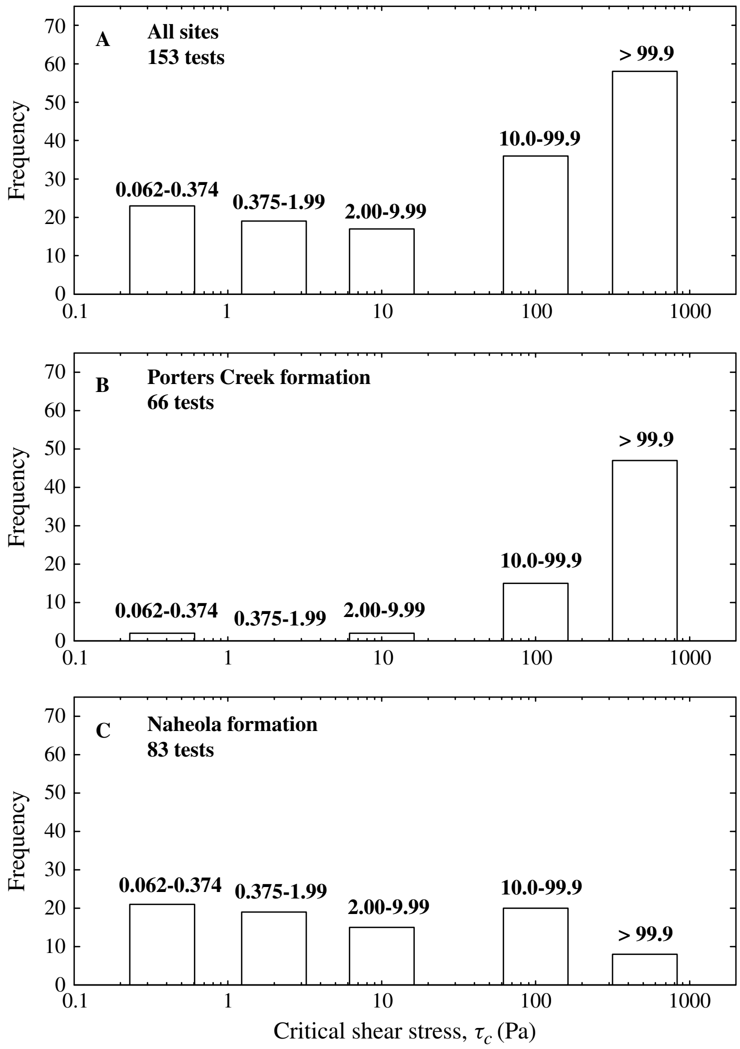

Figure 5. Frequency distributions of critical shear stress (τ_c) for (A) all jet-tests conducted in the Yalobusha River Basin, (B) the Porters Creek Clay formation, and (C) the Naheola formation

CoE survey, repeated surveys (starting in February 1999) of individual knickpoints were conducted after major flow events.

Knickpoint migration rates were obtained from analysis of the repeated surveys. Migration rates vary from about 0·7 m a^{-1} to about 12 m a^{-1} over periods ranging to 47 months. Several knickzones cut into the Naheola formation migrated about 30 m between early 1997 and July 2000. Their average rate of migration over the period was 7·5 m a^{-1}. Those cut into the Porters Creek Clay formation migrated at significantly slower rates, with an average rate of migration of 1·2 m a^{-1}. That the migration of some knickpoints or erosion zones, particularly those cut into the Porters Creek Clay formation, has been severely limited is directly related to its erosion resistance.

We have identified four main mechanisms for erosion and migration of cohesive knickpoints.

1. Where streambeds become partially exposed during low-flow periods, the result is weathering and the formation of cracks, enhanced by tension cracking of the headwall related to pressure release and stress-induced deformation. Field observations of Porters Creek Clay beds confirm that these streambeds erode in aggregates or chips where bedding planes, fractures and tension cracking are extensive. Generally, particle-by-particle erosion forms a 'slot' up to several metres wide along a plane of weakness during a high flow event in an area of the bed that was previously subaerially exposed. The slot expands longitudinally as well as laterally, concentrating low and moderate flows into the zone and leaving other areas of the bed to dry and desiccate. The main erosion pathway can then shift to this dried area of the bed during a subsequent flood event.
2. Detachment of aggregates of flocculated particles may be instigated by upward-directed seepage forces on the falling limb of hydrographs (Simon and Collison, 2001). Upward-directed seepage forces result from pressure imbalance at the bed surface, and are caused by the inability of a streambed to dissipate a build-up of excess pore-water pressure.
3. Where there is very little jointing, upward-directed seepage forces may cause static liquefaction in cohesive streambeds. Strong upward-directed seepage forces may increase the distance between cohesive particles resulting in reduced cohesion and a 'super-saturated' or almost fluidized state (Simon and Collison, 2001).
4. Observations of failed blocks at the toe of knickpoints indicate that more rapid erosion and migration occurs by mass failure of the knickpoint face. The cycle can be represented by the following stages:
   (1) hydraulic stresses linked to the development of a marked hydraulic jump and turbulence in the plunge-pool undercut and heighten the knickpoint face through a combination of vortex and splash erosion (Piest *et al*., 1975; De Ploey, 1989; Bennett *et al*., 2000);
   (2) the face fails via a mass-failure mechanism, such as cantilever or planar, with deposition of the failed material in the plunge pool; and
   (3) this debris is removed, and is followed by further scour in the plunge pool, thereby preparing the knickpoint for subsequent failure (Simon *et al*., 2000a).

A similar cycle was noted by Robinson and Hanson (1996). An example from a knickpoint cut into the Naheola formation on Big Creek is provided that aids in demonstrating the cycle of knickpoint erosion and migration. The survey of 1 February 1999 shows a scoured area at the base of the knickpoint face (Figure 6). Three flows between 15 February and 6 March resulted in failure of the knickpoint face and deposition of the failed material in the scoured area beneath the face (Figure 6). By Equation 3, maximum average boundary shear stresses during these flows were about 15 Pa (average $\tau_c = 7{\cdot}9$ Pa), resulting in little downwearing at the knickpoint threshold. The flow on 27 June 1999 of 20 Pa again resulted in little downwearing but did remove the failed debris, further scoured the toe and caused failure of the knickpoint face and deposition of debris (Figure 6). Flows during spring 2000 again removed debris and caused failure of the face. Thomas *et al*. (2001) successfully simulated this cycle with coupled finite element hydrologic and limit equilibrium slope-stability models.

The relative dominance of the four identified mechanisms is partly a function of the hydraulic and geotechnical resistance of the cohesive materials (Simon and Collison, 2001) as well as the form of the nappe and

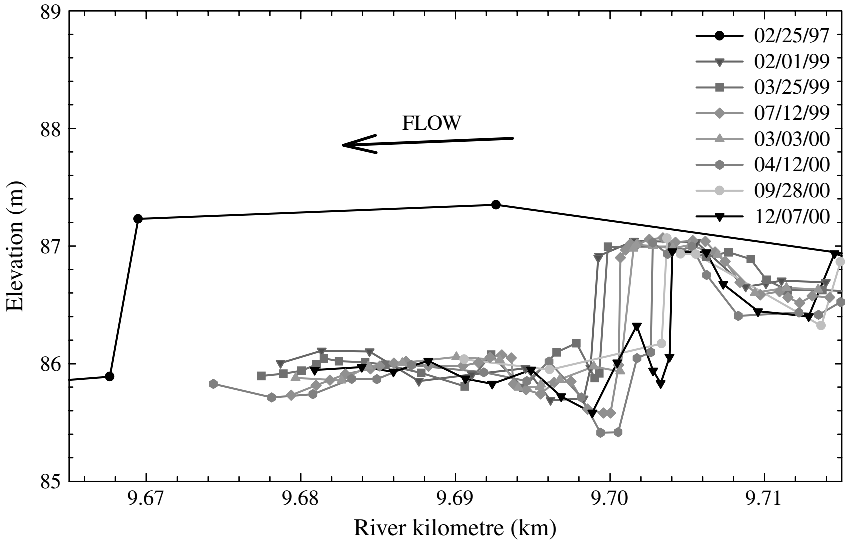

Figure 6. Example of cross-sectional view of knickpoint migration along Big Creek

the relative tailwater depth (Bennett *et al*., 2000). At a knickpoint with a deeply scoured toe, it is likely that during periods of low tailwater, relatively steep hydraulic gradients within the knickpoint aid in initiating undercutting and mass failure of the face. In cases where high tailwater elevations occur, knickpoint erosion by mass failure is probably less likely because of the confining pressure afforded to the knickpoint face. In this case, erosion is probably dominated by particle-by-particle erosion, while moderate tailwater heights are associated with a combination of both. Robinson and Hanson (1995) suggest that, with some exceptions, knickpoints in homogeneous materials have a sloping face, while two-layered bed materials with resistant caps have a more vertical face. In the present study, Naheola clay knickpoints with layering tend to form distinct headcuts, and migrate by a mass failure cycle described above. Non-layered Naheola clay knickpoints migrate by erosion of the downstream facing side, accompanied by shear stress-induced erosion on the upstream side. Conversely, the erosion-resistant Porters Creek Clay knickpoints tend to migrate via chipping from the knickpoint face or by the removal of blocks, dependent upon the extent of jointing and tension cracking.

MITIGATION OPTIONS

The US Army Corps of Engineers (CoE), Vicksburg District, is charged with alleviating the downstream flooding problems while protecting the middle and upstream reaches from further streambed and streambank erosion. The CoE have identified a number of remediation strategies including total or partial plug removal, numerous grade-control structures to arrest headward migration of knickpoints following plug removal, and flood-retarding structures. Currently (2001), the CoE are also protecting upstream reaches by constructing grade-control and other structures at critical knickzones in the basin.

FUTURE CHANNEL CHANGES AND RESPONSES

Thalweg elevations

Thalweg elevation data from 1965 to 1997 were used to identify temporal changes in bed elevation at various locations. A dimensionless exponential equation (Simon, 1992) was used to fit these data to represent bed level change at a site with time. Examples of fitting the historical data to the equation are shown for an aggradational setting (cross-section Y-1) (Figure 7A) and for a degradational setting (cross-section Y-13) (Figure 7B). The equation is of the form:

$$\frac{z}{z_o} = a + be^{-kt} \tag{4}$$

where z = elevation of the channel bed (at time t); z_o = elevation of the channel bed at time 0 (t_o); a = a dimensionless coefficient, determined by regression and equal to the dimensionless elevation (z/z_o) when Equation (4) becomes asymptotic; b = a dimensionless coefficient, determined by regression and equal to the total change in the dimensionless elevation (z/z_o) when Equation (4) becomes asymptotic; k = a coefficient determined by regression, indicative of the rate of change of the channel bed elevation per unit time; and t = time since the year prior to the onset of the adjustment process (in years).

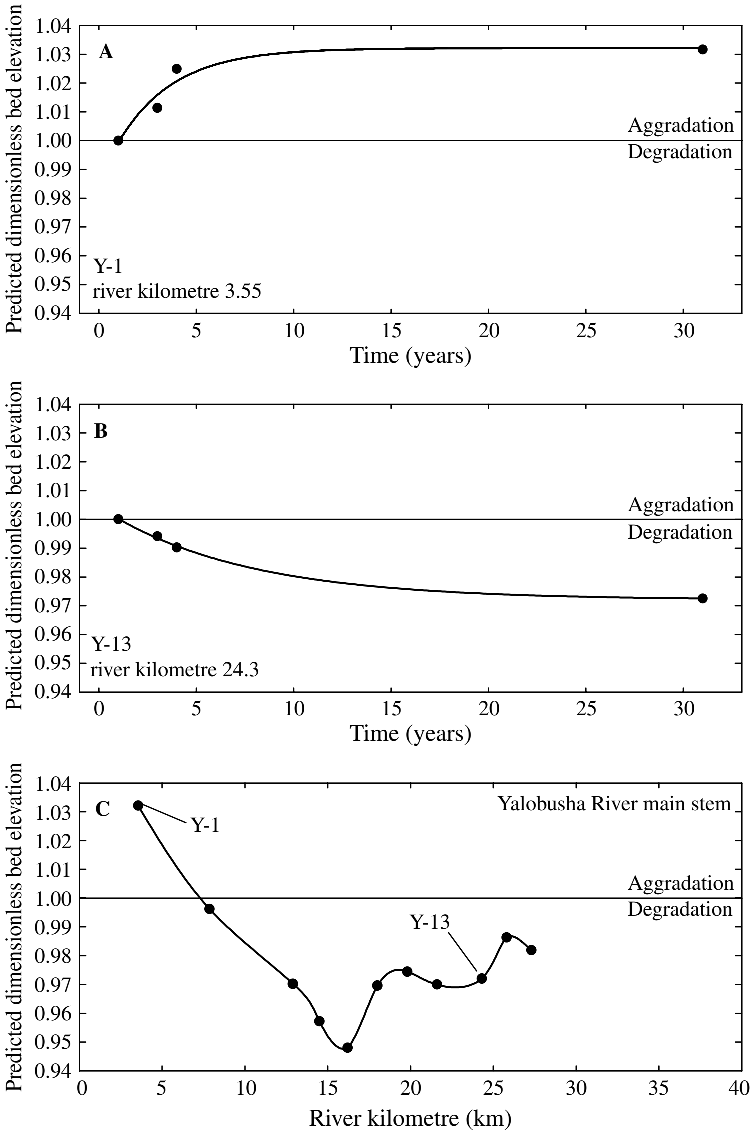

Figure 7. Examples of fitting historical bed elevation data to Equation (4) for (A) aggrading and (B) degrading conditions, and (C) empirical model of bed-level response for the Yalobusha River

The *a*-value is a convenient parameter to identify long-term changes in bed elevation representing the elevation (z/z_o) in the future. An *a*-value less than 1·0 signifies degradation, a value of 1·0 signifies no net change and a value greater than 1·0 signifies aggradation (Simon, 1992). Results (*a*-values) are plotted against distance upstream to develop an empirical model of bed-level response (Figure 7C). Minimum *a*-values for the Yalobusha River main stem occur in the vicinity of rkm 15, with a secondary minimum between rkm 22 and 25.

Table II shows initial (1967), predicted equilibrium, and 1997 thalweg elevations. Comparing predicted and 1997 elevations, it can clearly be seen that upstream reaches (upstream of rkm 16·5), and downstream reaches (downstream of rkm 10) have equilibrated. The reach between rkm 10 and 16·5 has experienced less incision than predicted by *a*-values. This is probably due to the lake-like effects of the sediment/debris plug, reducing erosion capacity of the flows. It should be noted that the upstream end of the reach is at rkm 27·3, downstream of current erosional reaches and knickpoint zones (which clearly have not equilibrated).

Stable channel slopes

To estimate future, stable (stage VI) slopes along presently unstable reaches, a relation between drainage area and slope for current stage VI conditions was established for the Yalobusha River system ($r^2 = 0{\cdot}63$):

$$S = 0{\cdot}0028\, A^{-0{\cdot}33} \tag{5}$$

where S = slope, and A = drainage area (in km^2). Because of the potential bias towards very flat slopes at large drainage areas, five sites on the Yalobusha River downstream of the Highway 8 bridge that are directly impacted by the sediment/debris plug have been removed to prevent the calculated 'stable' slope values from being overly conservative (flat) (Figure 8). The r^2 value for the relation indicates that about 37 per cent of the variance remains unexplained. This is probably due to exceptionally low slope values in the downstream reaches because of the sediment/debris plug, and the decreased availability of sand-sized bed sediment from upstream reaches because of the exposure of resistant clay beds.

Equation (5) may be a realistic predictor of 'stable' slopes for the Yalobusha River system, particularly for large drainage areas, since the exponent is similar to those derived for a nearby river system (Coldwater River; US Army Corps of Engineers, 1993). Predicted equilibrium slopes using the modified stage VI equation

Table II. Comparison of initial (1967), predicted equilibrium and 1997 thalweg elevations for cross-sections on the Yalobusha River

River kilometre (km)	Initial (1967) elevation, z_o (m)	Predicted equilibrium elevation ($z_o \cdot a$) (m)	1997 elevation (m)	Difference (Predicted−1997) (m)
3·55	67·36	69·52	69·47	0·05
4·72	67·82	–	68·95	–
6·45	68·88	–	69·77	–
7·86	69·49	69·23	69·30	−0·07
9·31	70·26	–	69·15	–
11·1	71·17	–	70·14	–
12·9	72·09	69·94	71·10	−1·16
14·5	72·85	69·73	70·45	−0·72
16·2	73·69	69·86	72·30	−2·44
18	74·60	72·33	72·35	−0·02
19·8	75·51	73·58	73·25	0·33
21·6	76·43	74·14	74·27	−0·14
24·3	77·72	75·54	75·26	0·29
25·8	78·71	77·63	77·46	0·17
27·3	79·25	77·82	77·89	−0·08

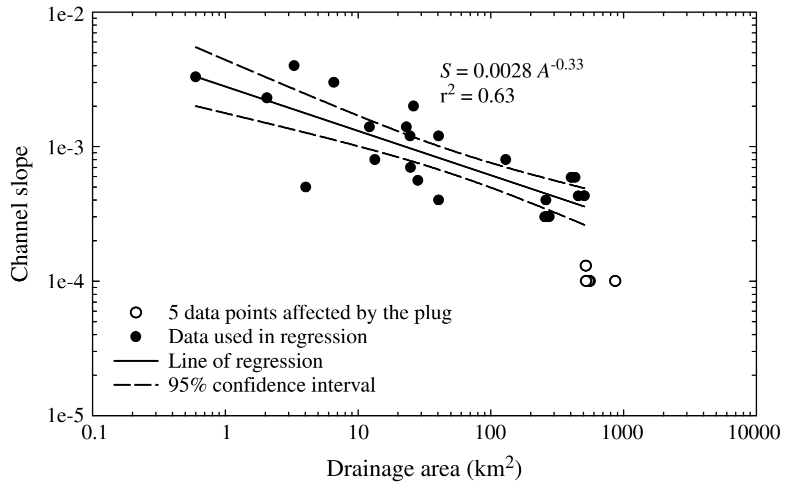

Figure 8. Slope–drainage area relation for stable (stage VI) sites. The empty circles are the five most downstream sites on the Yalobusha River that were discounted

(Equation (5)) are provided in Table III. Table III displays average observed and average predicted equilibrium slopes for the main stem channels and their tributaries. The range of river kilometres and drainage areas for which the predictions are valid is also shown. The table illustrates the fact that the slopes of all channels are still far greater than the equilibrium (stage VI slopes). Of all the channels, only the Yalobusha River and Big Creek have attained slopes within 20 per cent of their equilibrium values. Cane, Johnson and North Topashaw Creeks display the greatest discrepancies between observed and predicted equilibrium slopes. These tributary channels all experience stage IV conditions in their downstream reaches, and degradation has not yet progressed upstream. Only after considerable upstream degradation and downstream aggradation will these channels attain quasi-equilibrium.

Table III. Comparison of observed (1997) and predicted average slopes for the Yalobusha River, Topashaw Creeks and their tributaries

Stream	Range of modelled rkm (km)	Range of modelled drainage areas (km^2)	Average observed slope, O ($m\ m^{-1}$)	Average predicted equilibrium slope, P ($m\ m^{-1}$)	Difference (P − O) for stream (%)
Bear Creek	0·86–13·20	4·16–48·5	0·00257	0·00102	−54.41
Big Creek	1·92–8·38	16·1–34·9	0·00118	0·00097	−10.74
Buck Creek	1·31–13·10	4·10–20·2	0·00266	0·00120	−52.55
Cane (Cook) Creek	1·91–13·27	20·7–63·9	0·00241	0·00085	−63.24
Duncan Creek	2·37–8·94	7·80–18·5	0·00236	0·00123	−47.17
Huffman Creek	1·90–4·51	16·3–21·9	0·00197	0·00106	−45.48
Hurricane Creek	2·80–7·78	5·51–11·9	0·00223	0·00130	−38.76
Johnson Creek	0·15–4·18	7·91–22·0	0·00361	0·00111	−61.24
L Topashaw Creek	0·78–11·00	2·47–68·8	0·00259	0·00122	−54.76
Meridian Creek	5·88–10·11	5·47–22·0	0·00263	0·00125	−51.08
Mud Creek	1·95–14·60	8·28–35·7	0·00157	0·00102	−27.42
N. Topashaw Creek	0·25–4·41	13·7–25·2	0·00305	0·00107	−63.44
Topashaw Creek	9·97–29·80	2.48–248	0·00206	0·00092	−40.36
Yalobusha River	17·84–34·80	75.7–379	0·00077	0·00054	−19.36

Channel bank stability

Shear strength testing and geotechnical data. Data on cohesion and friction angle were obtained from *in situ* shear strength testing with an Iowa Borehole Shear Tester (BST). This instrument enables rapid determination of drained, effective strength values (Lutenegger and Hallberg, 1981). Thirty-eight tests were undertaken at 21 sites throughout the Yalobusha River system to depths of about 6·8 m as dictated by bank stratigraphy. Samples of streambank material were then removed from these boreholes to determine particle-size distributions, moisture contents and bulk unit weights. To substitute for the lack of deeper BST testing, triaxial-test data were obtained for several sites in the river basin from the Mississippi Department of Transportation (MDOT). Distributions of the shear-strength parameters c' and ϕ', as well as the soil unit weight (γ_s) are not normally distributed, justifying the use of median values as representative. Median values of geotechnical parameters used in bank stability analyses for the Lower Yalobusha River and Topashaw Creek are $c' = 11{\cdot}6$ kPa, $\phi' = 21{\cdot}8°$ and $\gamma_s = 17{\cdot}2$ kN m^{-3}.

Factor of safety analysis. Consideration of pore-water and confining pressures was included in an analysis of bank stability to evaluate present and long-term stability conditions. A bank stability algorithm that incorporates variations in bank material (layering) and additional forces acting on the failure plane has been developed by the US Department of Agriculture, Agricultural Research Service (Simon and Curini, 1998; Simon *et al.*, 2000b). The algorithm accounts explicitly for the force produced by matric suction on the unsaturated part of the failure plane (S) which increases the shearing resistance of the bank in the unsaturated zone (Fredlund *et al.*, 1978), the hydrostatic-uplift force due to positive pore-water pressures on the saturated part of the failure plane (U), and the hydrostatic-confining force provided by the water in the channel and acting on the bank surface (P) (Casagli *et al.*, 1997, 1999; Curini, 1998, Simon and Curini, 1998; Rinaldi and Casagli, 1999; Simon *et al.*, 2000b).

The hydrostatic-uplift (U) and confining (P) forces are calculated from the area of the pressure distribution of pore-water ($h_u \cdot \gamma_w$) and confining ($h_{cp} \cdot \gamma_w$) pressures by:

$$U = \frac{\gamma_w h_u^2}{2} \tag{6}$$

$$P = \frac{\gamma_w h_{cp}^2}{2} \tag{7}$$

where $\gamma_w = 9{\cdot}81$ kN m^{-3}; h_u = pore-water head (m); and h_{cp} = confining-water head (m). P and U both have units of kN m^{-1}. The loss of the hydrostatic-confining force (P) provided by the water in the channel is the primary reason why bank failures often occur after the peak flow and on the recession of stormflow hydrographs.

Multiple layers are incorporated through summation of forces in a specific (ith) layer acting on the failure plane. The factor of safety (F_s) is (Simon *et al.*, 2000b):

$$F_s = \frac{\sum \left(c_i' L_i + (S_i \tan\phi_i^b) + [W_i cos\beta - U_i + P_i \cos(\alpha - \beta)] \tan\phi_i'\right)}{\sum (W_i \sin\beta - P_i \sin(\alpha - \beta))} \tag{8}$$

where c_i' = effective cohesion for the ith layer (kPa); L_i = length of the failure plane incorporated within the ith layer (m); ϕ^b = rate of increase in shear strength due to increasing matric suction for the ith layer (°); W_i = weight of the failure block in the ith layer (kN m^{-1}); β = angle of the failure plane (°); α = bank angle (°); and ϕ_i' = effective friction angle for the ith layer (°).

In the section that follows, conditions along specific reaches are differentiated on the basis of the height of the phreatic surface (or pore-water pressure; h_u) and river stage (or confining pressure; h_{cp}) as a percentage of the total bank height.

Current bank-stability conditions along the Lower Yalobusha River and Topashaw Creek. Results for current conditions along the downstream ends of the main stem channels ($h_{cp} = 50$ per cent) show that where bank heights are 8 m, all bank slopes are unstable at $h_u = 95$ per cent, as are those steeper than about 60°

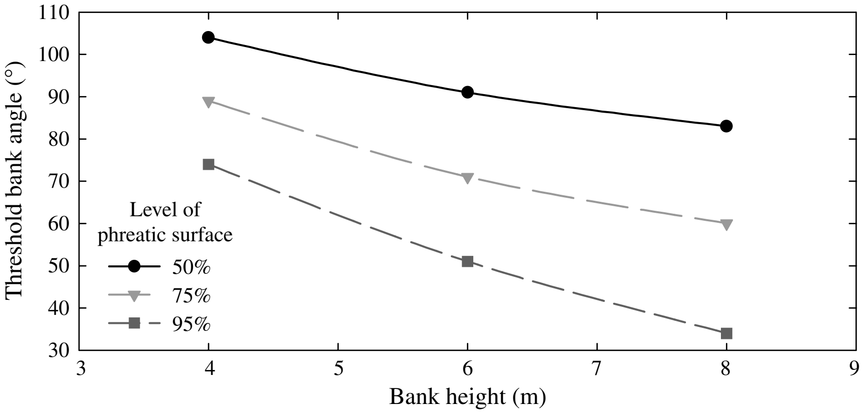

Figure 9. Threshold (critical) bank angles assuming current bank-stability conditions along the lower Yalobusha River and Topashaw Creek for 4, 6, and 8 m banks under three different hydrologic scenarios

at $h_u = 75$ per cent (Figure 9). Figure 9 indicates that the threshold bank angle (and F_s) decreases with increasing bank height (4, 6, and 8 m) for a given set of h_{cp} and h_u combinations. Similarly, as pore-water pressures increase, the threshold bank angle decreases (Figure 9). At a bank height of 4 m, banks are unstable only at angles steeper than 74° and when $h_u = 95$ per cent.

Effects of potential removal of sediment/debris plug on bank stability. Plug removal was analysed as a long-term case ($h_u = 10$ and $h_{cp} = 10$ per cent), where the phreatic surface has time to adjust to the lowering of water levels and as a short-term, rapid-drawdown (more critical) case where the phreatic surface cannot adjust fast enough because of rapid draining of channel water. The rapid-drawdown case was modelled assuming that flow levels in the channel would drop significantly, and thus $h_{cp} = 10$ per cent with a corresponding $h_u = 50$ or 75 per cent. For the long-term low-flow case, banks remain stable (threshold bank angles are greater than 90°), even at bank heights greater than 8 m. However, if plug removal involves the quick draining of water from the channel, the confining pressure afforded by the water in the channel will not sufficiently counteract pore-water pressures in the banks. Under these conditions, instability is induced at lower bank angles (representing a larger percentage of the banks in these reaches) for the $h_u = 50$ per cent and 75 per cent cases (Figure 10). For 6 m banks, all bank slopes in the reach are unstable if pore-water pressures are maintained at $h_u = 75$ per cent during rapid draining of the plug (Figure 10). Should sufficient degradation occur to cause bank heights to reach 10 m, and if pore-water pressures are maintained at $h_u = 50$ per cent, banks could fail at angles as shallow as 64°, causing a failure block weight of 506 kN per metre of channel. Clearly, rapid removal of the plug may therefore have major negative impacts on bank stability and considerable care should be exercised to ensure that drainage occurs slowly.

SUMMARY AND CONCLUSIONS

The Yalobusha River system experiences deposition and flooding problems in downstream reaches and erosion via headward-progressing knickpoints and bank failures in upper reaches. These general patterns are typical of unstable stream systems throughout this region of the United States (Schumm *et al.*, 1984; Simon, 1989, 1994; Simon and Rinaldi, 2000) and are associated with the consequences of accelerated erosion stemming from land mismanagement and channelization. Major features of the river system include: (1) an almost entirely channelized stream network; (2) at its downstream end, a straightened and enlarged main stem terminates into an unmodified, sinuous reach with much smaller cross-sections and conveyances; and (3) a plug of sediment and debris completely blocks the lower end of the channelized reach. This sediment/debris plug is of critical importance to channel adjustment processes and conditions in the river system.

Adjustment of the Yalobusha River system is somewhat different from other disturbed systems because of the resistant nature of its clay beds. In unstable channel systems that have excess stream power and energy

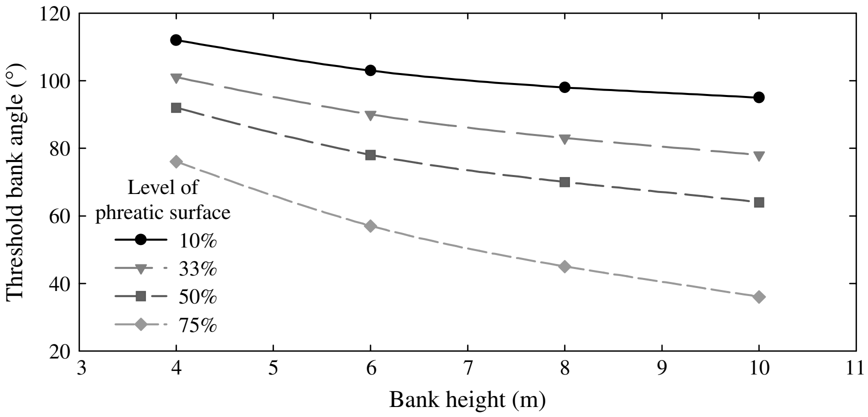

Figure 10. Threshold (critical) bank angles along the lower Yalobusha River and Topashaw Creek under future conditions assuming removal of the debris plug for 4, 6, 8, and 10 m banks and four different hydrologic scenarios

relative to bed material load, the system tends to reduce stream power and energy by adjusting aspects of its morphology, hydraulics, and sediment load. Generally, this takes place by increasing bed material loads through erosion of sand- or gravel-sized materials from the channel bed in upstream reaches, with consequent deposition in downstream reaches. However, if there is an insufficient supply of sediment from the channel beds, the channel system maintains excess stream power and a discrepancy between transporting capacity and sediment availability from the channel banks (Simon, 1992; Simon and Darby, 1997). This is the case for the Yalobusha River system. The resistant clay beds have restricted advancement of knickpoints and knickzones in certain reaches and have caused a shift in the focus of channel adjustment to bank failures and channel widening.

Presently, engineering solutions to these problems employ combinations of small reservoirs, grade-control structures, and bank protection. In some cases, rechannelization of aggraded downstream reaches has also been performed. Protection against upstream erosion and downstream flooding is often diametrically opposed because methods to increase downstream channel capacity can result in rejuvenation of already oversized reaches upstream. This rejuvenation occurs as a pulse of degradation through the network, its physical representation being the formation of a knickpoint. In the Yalobusha River basin, rates of migration of these loci of disturbance have varied between 0·7 and 12 m a^{-1} over the past four years, but these rates are by no means maxima. For example, for the more erodible streambeds of Tillatoba Creek, northern Mississippi, Winkley (1971) documented upstream migration rates that averaged 539 m a^{-1} between 1951 and 1971.

The amount of degradation and its rate of propagation may have major implications for bank stability. Faster migration rates imply that longer reaches of channel will concurrently experience bed degradation, and potentially bank failures. The sediment/debris plug has increased thalweg elevations by up to 5 m. If plug removal involves the quick draining of water from the channel and beds degrade by 2 m, bank-stability analyses of lower reaches indicate that banks could fail at angles as shallow as 64°, with a failure block weight of 506 kN per metre of channel. Hence, assuming a maximum rate of migration of 500 m a^{-1}, bank material from this reach may cause sediment inputs of up to 51 580 tonnes a^{-1}, representing 8 per cent of the basin-wide sediment yield from channel boundaries (Simon, 1998).

The enlargement of the lower Yalobusha River and Topashaw Creek to reduce flooding potential must therefore be accomplished without causing a drastic change in the flow energy–sediment supply balance at the transition zone. With bank material constituting between 85 and 92 per cent of the material eroded from channels in the river system, this becomes a serious consideration in terms of maintaining downstream channel capacity.

Mitigation of downstream flooding and upstream erosion problems requires a full consideration of boundary conditions and dominant processes throughout the entire fluvial system. Processes of erosion and sediment supply by mass-wasting and fluvial deposition must be balanced relative to the distribution of available stream power and flow energy. In the Yalobusha River system, because upstream channels cannot easily entrain material from the channel bed, sediment-transport rates are probably considerably less than capacity for most if not all flows. Hence, strategies for stable slopes and hydraulic conditions must account for this imbalance between available flow energy and the limited sediment availability from the channel bed. Such an approach may yield substantial benefits in terms of channel recovery.

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