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Fluvial geomorphological analysis of the recruitment of large woody debris in the Yalobusha River network, Central Mississippi, USA

Peter W. Downs [a,*,1], Andrew Simon [b,2]

[a] School of Geography, University of Nottingham, Nottingham, NG7 2RD, UK
[b] USDA-ARS National Sedimentation Laboratory, 598 McElroy Drive, Oxford, MS 38655, USA

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Abstract

The management of large woody debris (LWD) should be based on a rational assessment of its recruitment rate relative to its natural decay and removal. LWD recruitment may be controlled by 'natural' episodic terrestrial factors or by in-channel geomorphological controls related to the rate of bank erosion. The geomorphological controls are hard to quantify in laterally migrating channels, but in incising channels, a conceptual model may be developed based on the density of riparian trees relative to the knickpoint migration rate and bank stability analyses that predict the post-knickpoint width of the channel. The Yalobusha river network in Central Mississippi, USA, has twice been destabilised by channel straightening for flood defence and land drainage, most recently in 1967. System-wide rejuvenation has followed through a series of upstream migrating knickpoints several metres high that have caused mass failure of streambanks and the recruitment of large volumes of trees to the channel. LWD recruitment is maximised at the transition between stage III and stage IV channels, focusing attention on 11 sites in the network. The sites are upstream of knickzones ranging between 2.2 and 5.4 m high and migrating at rates of 0–13.8 m year^{-1}, based on 23–30 months of monitoring. Riparian conditions in 500 m^2 plots on each bank upstream of the knickpoints range from treeless to forested, containing 0–98 trees with an average diameter at breast height of 0.18 m and average maximum height of 14.0 m. The average volume of wood on each bank is 0.02 m^3 m^{-2}. Under rapid drawdown conditions, bank stability analyses suggest that the channels will widen in amounts ranging from 1.8 to 31.5 m. Combined with the knickpoint migration rates, riparian land losses are estimated to range from 8.0 to 433.8 m year^{-1}, resulting in the recruitment of almost 28 m^3 of wood (or 100 trees) annually from the 11 sites. Assuming this LWD recruitment rate, a model is developed for the in situ potential for debris dam initiation and growth, based on the ratio of tree height to channel width under current and post-knickpoint conditions, the annual delivery of 'large' trees and the annual total of LWD recruitment by volume. A longer-term model is also developed, based on 'knickpoint severity' and

* Corresponding author. Philip Williams and Associates, Ltd., Consultants in Hydrology, 770 Tamalpais Drive, Suite 401, Corte Madera, CA 94925, USA.

E-mail addresses: downs@pwa-ltd.com (P.W. Downs), simon@sedlab.olemiss.edu (A. Simon).

[1] Fax: +1-415-945-0606.

[2] Fax: +1-662-232-2915.

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vegetation density in upstream and headwater riparian zones of each tributary. The 11 study sites are classified into groups with similar LWD management concerns based on these analyses. The models developed in this research provide the first precise quantification of LWD recruitment according to geomorphological controls and standing vegetation, and a rational assessment of its meaning, but further research is required to improve the accuracy of such estimates.

Keywords: large woody debris; fluvial geomorphology; bank stability; knickpoints; recruitment; river channel management

1. Introduction

Large woody debris (LWD) resulting from tree-fall into rivers is a natural occurrence in wooded river systems. LWD can impact the hydrology and hydraulics of flows, the transport and storage of sediments, solutes and other organic matter, and the spacing and variance of fluvial geomorphology features (Gurnell and Sweet, 1998). This normally leads to far greater physical habitat diversity in river reaches with LWD rather than without. Conversely, river managers concerned with flood defence often view accumulated LWD as an obstruction to the passage of flood flows. These obstructions form generally at channel constrictions, such as under bridges, or in shallow channel sections where flow is divergent (Diehl, 1997) and may cause localised flooding and erosion where flow is deflected towards channel banks. LWD may even contribute to bridge failures by causing deflection of flows towards piers and abutments. Striking a balance between the environmental benefit of LWD and its possible economic consequences is a testing objective for contemporary river management. An analytical assessment of this issue is critically dependent on the rate of LWD recruitment into the river system relative to the rate of tree removal. Ideally, this understanding would result in a LWD 'budget' (Keller and Tally, 1979) that has parallels in geomorphology with a sediment budget.

Unless trees are removed by management action to de-snag channels, the removal rate of in-channel LWD will be some function of the combined rate of wood decay and the occurrence of large floods sufficient to float the trunks. Assuming climatic stationarity, the rate of removal may be imagined as a constant over the long-term, leaving the LWD 'budget' dependent primarily on the rate of tree input, or recruitment, into the river system. Therefore, for channels with a wooded riparian zone but not subject to commercial forestry operations, the recruitment rate is related to the geomorphological processes in the river channel, to mass slope-failure delivering trees directly to headwater channels and to other factors. Developing this theme, three typical recruitment scenarios can be envisaged.

(1) Rivers where the channel morphology is essentially static and LWD enters the channel as a function of dead trees toppling into the channel, of wind-thrown trees downed in storm events and trees contributed by fires, floods, landslides, ice storms and beaver activity, depending on the environment.

(2) Dynamically-stable or unstable meandering or braided rivers shifting across their floodplain in which recruitment is a function of the rate of outer bank migration (meandering rivers) or the more general rate of lateral erosion (braided rivers) in addition to the functions named in (1).

(3) Dynamically-unstable rivers where the channel width is increasing either according to progressive alterations in the hydrological regime or due to rapid base-level change that destabilises the banks, in addition to the functions named in (1).

The first scenario is largely a stochastic process of recruitment in natural or semi-natural rivers. The second scenario may also occur in response to natural channel mobility but could relate to cases where the rate of channel adjustment has been accelerated by upstream flow alterations caused by urban development or channelisation (Brookes, 1987a). The third scenario, of channel widening or cross-sectional enlargement, may occur in response to natural climatic variations or may be due to intrinsic material properties of a complex floodplain stratigraphy that provides the context for channel change (Brown, 1995, 1996). Alternatively, it may result from changes in hydrology or sediment transport downstream of human activity such as urbanisation (e.g. Neller, 1989; Roberts, 1989; Gregory et al., 1992) or channelisation (Brookes, 1987b). However, the most dramatic example of the third scenario is likely upstream of straightened channels. Here, the increased channel gradient in the straightened reach creates upstream-migrating knickpoints (a 'knickzone') that cause rapid base-level lowering and consequent channel widening (Parker and Andres, 1976; Simon, 1994; Simon and Hupp, 1986). Rapid base-level lowering may also occur downstream of river impoundments (Petts, 1984; Williams and Wolman, 1984). In straightened channels, the degree of channel incision varies according to the magnitude and distance from the imposed disturbance (Simon, 1994) and the character of the bed material, leading to models of straightened channel evolution that predict a sequence of accelerated bed and bank erosion rates (Schumm et al., 1984; Simon, 1989). Accelerated channel erosion leads to accelerated LWD recruitment rates, thus shifting the balance between LWD recruitment and removal in the river system. Potentially, this LWD build-up may be unacceptable from a flood management standpoint even though morphologically, LWD-associated sediment storage may be critical in stabilising the channel (Keller and MacDonald, 1995; Wallerstein, 1999).

Where rapid base level lowering exists, LWD management should be based on a quantitative assessment of the severity of the problem. This requires an understanding of the degree to which recruitment rates have been accelerated and knowledge of locations that are critical from a management perspective. There are however, few quantitative assessments of LWD recruitment (Lassettre, 1999) because of the complexity involved in combining the inter-related dynamics of fluvial geomorphology (particularly bank instability) and riparian vegetation. The assessments that do exist are based on the character of riparian vegetation and morphology and a probabilistic function of tree fall (e.g. Robison and Beschta, 1990a; Van Sickle and Gregory, 1990; Hairston-Strang and Adams, 1998). Fluvial geomorphological processes are not considered. This can be a serious omission, especially for incising rivers in which recruitment rate is primarily a function of the channel width increase caused by mass wasting of the banks. In this regard, we advance a method for predicting accelerated LWD input deterministically as the basis for judging the severity of the LWD management 'problem', at critical locations. The method requires data about channel morphology, the rate of knickpoint migration and characteristics of the riparian vegetation in conjunction with recent advances in bank instability modelling (e.g. Simon et al., 1999) to allow channel width increases to be predicted. The current study is applied to the Yalobusha River catchment, Central Mississippi, USA, and focuses on reaches that are the most critical from a LWD management perspective. An example management application is provided whereby the calculated LWD recruitment for each reach is used to predict the potential significance of the LWD recruitment in terms of debris dam formation. From this basis, rational management decisions may be taken. The overall accuracy of the model is largely dependent on three factors, namely: bank-stability analysis, knickpoint dimensions and migration rate, and characterisation of the riparian tree stand.

2. Channel evolution in the study area

A large number of rivers in the midwestern United States are subject to substantial changes in morphology following the migration of knickpoints promoted by channel straightening for flood defence and land drainage during the early 1900s, and again in the 1950s and 1960s (Speer et al., 1965; Simon, 1994; Simon and Rinaldi, 2000). In certain areas, such as those typified by highly erodible loess silts of the 'bluffline streams' of Mississippi, adjustment processes have been intense, with knickzones several metres high resulting in channels more than doubling their width. The trunk streams and tributaries of the Yalobusha catchment in Central Mississippi are no exception. Straightening of the trunk streams (Yalobusha River and Topashaw Creek; Fig. 1), most recently in 1967, has effectively altered the base level of these rivers and promoted system-wide rejuvenation through a series of knickpoints that are now eroding into cohesive upstream streambeds along many of the tributary streams (Simon, 1998).

The knickpoints have caused sufficient deepening to prompt significant channel widening by mass failure of streambanks. Large volumes of sediment and woody vegetation growing on these channel banks were delivered to the flow when the banks failed and have been transported through the

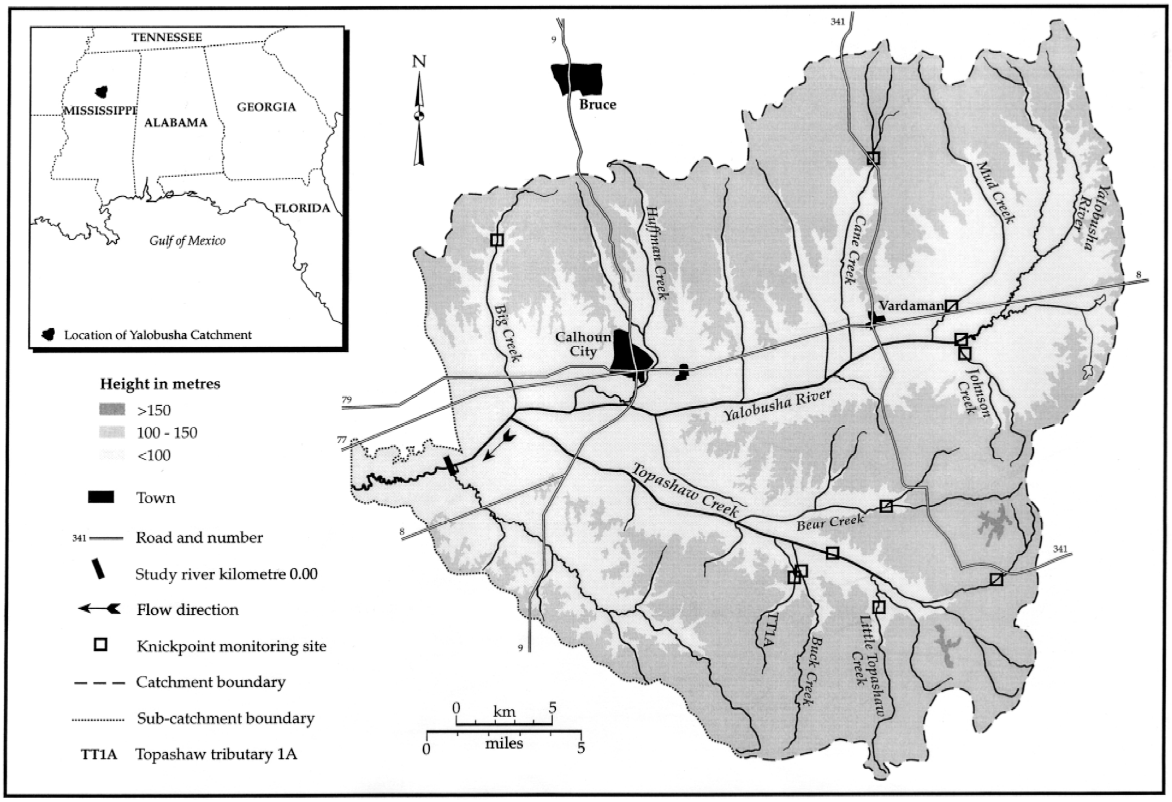

Fig. 1. The upper Yalobusha catchment, illustrating the study reaches and the location of the monitored knickpoints.

straightened channel network to the transition with the 'unmaintained' sinuous reaches downstream (Simon, 1998). At this transition, the sediment transport capacity drops significantly and LWD is far more likely to snag on the channel banks. The result has been a rapid accumulation of combined LWD and sediment deposition on the lower Yalobusha River downstream of Calhoun City (Fig. 1). This debris and sediment jam, the third major jam in the system in the last 60 years, is now of critical importance to channel adjustment processes. Also, hydrologically, the blockage functions as a dam causing almost lake-like conditions in the lower Yalobusha River in combination with elevated water levels that compromise flood defence in Calhoun City. The present jam of wood and sediment is shown in Fig. 2a as a large hump in the 1997 thalweg profile of the lower Yalobusha River (Simon, 1998). The 1969 and 1970 profiles and cross-sections obtained from the National Resources Conservation Service (NRCS) indicate that the jam was already beginning to form, just 2 years after the completion of the channel work. It has grown steadily since this time (Fig. 2b) with eroded sediment from upstream reaches and tributaries, and woody vegetation from destabilised streambanks. Aerial reconnaissance of the wetland area surrounding the jam suggests that the river no longer flows in its original channel, having diverted to one of its former courses to the south, and that the downstream part of the jam is now an emergent land surface complete with secondary forest (see Fig. 3). Existence of the jam promotes further deposition, further reductions in channel capacity and an increase in the magnitude and frequency of floods to Calhoun City.

To alleviate the flooding problems caused by the 'debris dam', and localised flooding upstream caused by temporary accumulations of LWD in transit through the system, the US Army Corps of Engineers (CoE) is considering various management

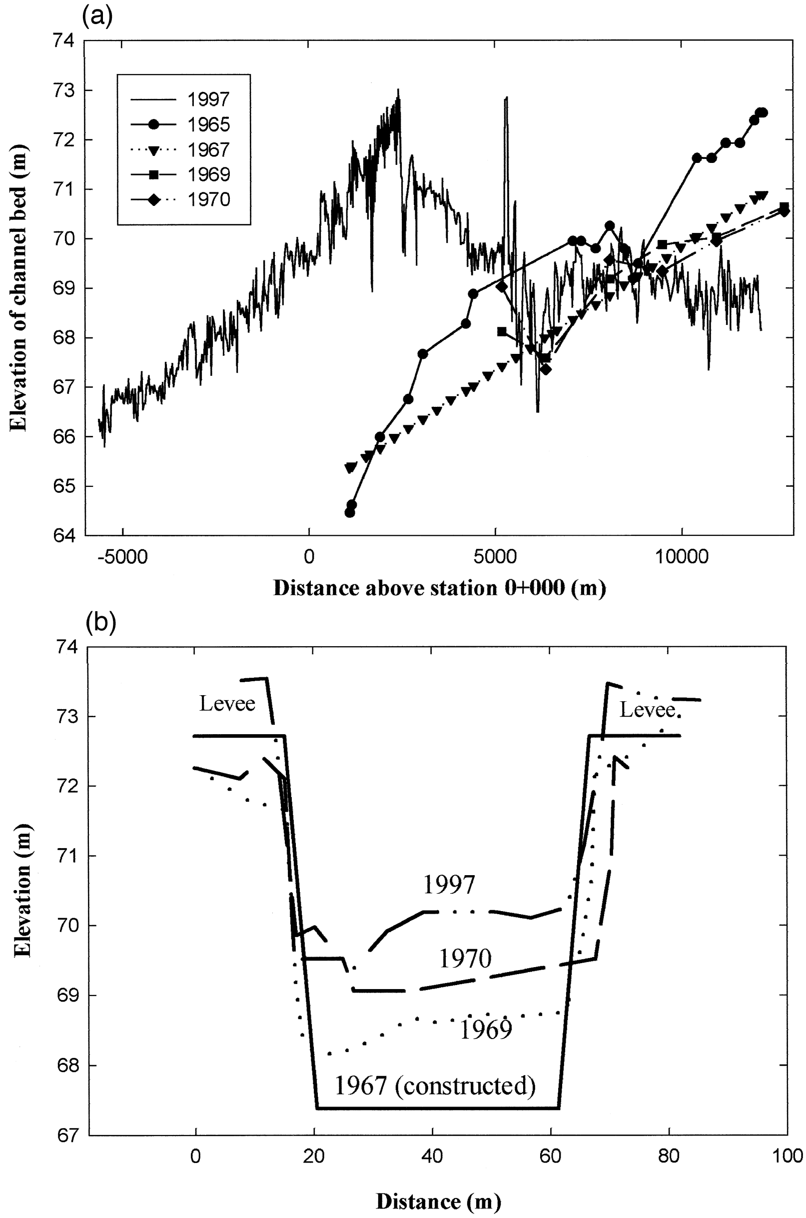

Fig. 2. (a) Yalobusha River lower reaches to showing the development of the debris-based 'dam' (maximum at approximately 2000 m above station 0 + 000) following the 1967 channelisation works (1997 survey is more detailed); (b) repeat cross-section survey at river kilometre 3.55 showing rapid deposition (modified from Simon, 1998).

strategies. While thought is given to the potential for removing the jam, it is clear that its growth rate can be slowed by reducing rates of upstream erosion caused by the still-migrating knickpoints. In fact, knickpoint erosion and migration may have recently accelerated in reaches near the upstream terminus of the 1967 channel work on the Yalobusha River because of the exposure of a more erodible substrate (Simon, 1998). The CoE is, therefore, planning a series of upstream grade-control structures on the

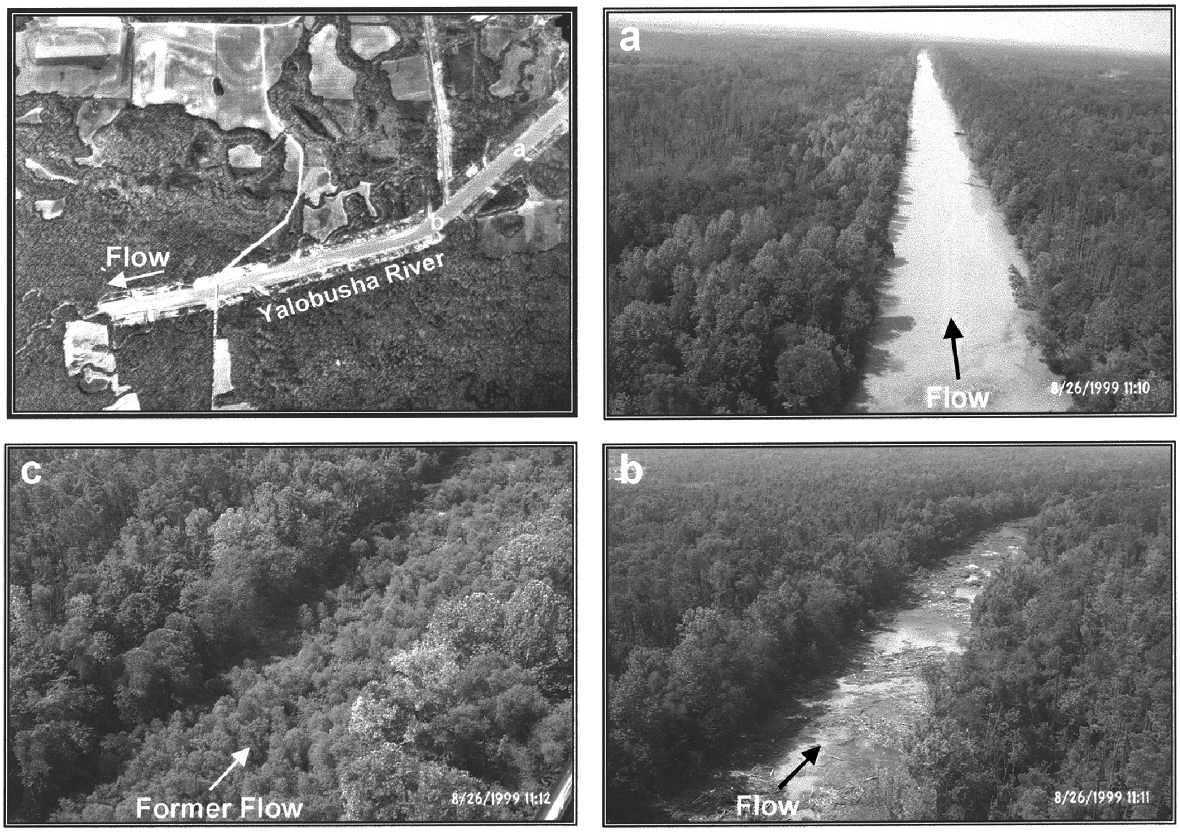

Fig. 3. Aerial photograph of the Yalobusha River taken in 1969 showing clearly the transition from the 1967 channelised reach (straight, broad channel with partially vegetated banks) to the sinuous section downstream (far left of the image). Oblique aerial photographs (a–c) plot the downstream onset of the debris dam (1999). Photograph (c) illustrates forest colonisation (the shorter trees) of the former course of the river. (Aerial photograph NRCS; oblique photographs: PWD).

main stem and tributary channels. The rational targeting of this or other management measures requires an estimate of the accelerated LWD recruitment rates at critical locations and an assessment of their likely local significance.

3. Method and data

A comprehensive geomorphological evaluation (Simon, 1998) has demonstrated that the processes of erosion in the Yalobusha River System conform well to a model of post-straightening channel-evolutionary adjustment noted previously by several authors (e.g. Schumm et al., 1984; Simon, 1989). The Simon model is illustrated in Fig. 4.

Within the channel evolution sequence, accelerated LWD recruitment is achieved during the period of greatest bank erosion as riparian areas succumb to channel widening. For 21 unstable Mississippi streams, Wallerstein (1999) attributed about 73% of the LWD recruitment to mass-failure processes on the channel banks. These processes begin on the transition of the channel from Stage III to Stage IV (see Fig. 4) as the knickpoint passes through the reach increasing bank heights and destabilising them. Some bank widening also occurs during Stage V, along with channel aggradation (Fig. 4). Therefore, in evaluating the potential for accelerated LWD production, the focal nodes in the channel network are at the downstream end of Stage III channels where bed lowering has not yet been sufficient to desta-

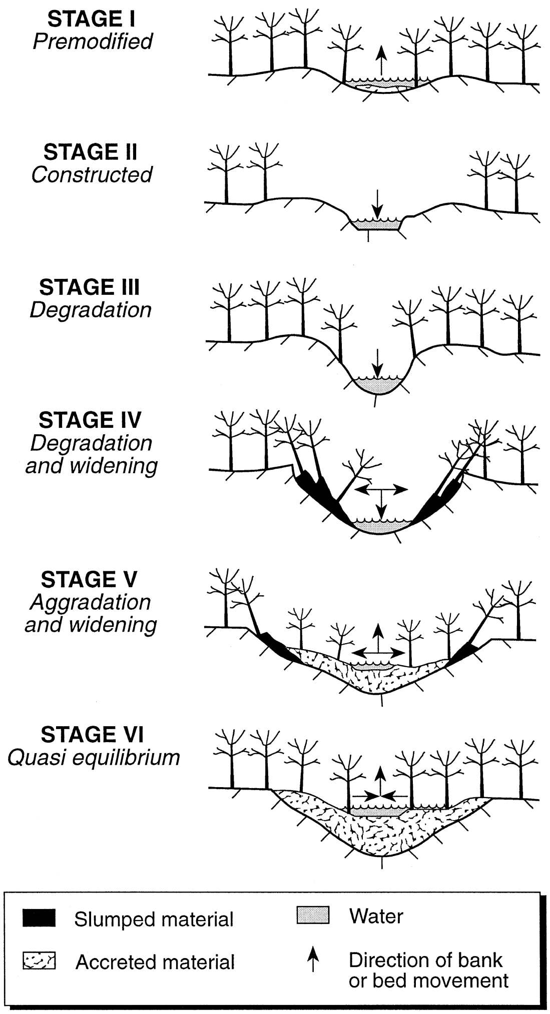

Fig. 4. Simon (1989) channel evolution model (modified from Hupp and Simon, 1991).

bilise the banks. The rate of destabilisation is determined by the rate of upstream migration of the knickpoint or knickzone. The extent of widening is determined by the height of the knickpoint and the stable angle obtained by the newly heightened bank under a 'worst-case' geotechnical condition according to its materials. This condition is defined by high pore-water pressures in the streambank relative to low flow levels (low confining pressure) in the channel. The importance of bank failures for LWD recruitment then depends on the nature of the bank top vegetation growing within the area of the failing banks. Therefore, the method requires three sets of input data: channel morphology surveys from existing channels, monitored rates of knickpoint migration and the quantitative characteristics of the riparian vegetation. Data collected from the Yalobusha catchment are outlined below.

3.1. Channel morphology in critical locations

Network-wide thalweg profiles surveyed by the CoE in 1997 combined with extensive field and aerial reconnaissance identified a total of 11 major knickpoints throughout the Yalobusha catchment (Simon, 1998; see Fig. 1). Characteristically, the knickpoints are in fact knickzones consisting of a closely-spaced sequence of near-vertical steps in the channel thalweg. The majority of the knickzones are located at stage III/IV reach transitions and are, therefore, critical to LWD recruitment. The knickzone locations generally represent the upstream terminus of channel adjustment processes and many of the largest ones seem to be almost equi-distant from the lower end of the river system, in the vicinity of river kilometre 28–30 (Simon, 1998). Knickzone heights range from 2.2 m on Johnson Creek to 5.4 m on the Yalobusha River main stem. Passage of these steps into previously non-incised reaches will increase the bank height by an amount equal to the height of the knickpoint.

Surveys of representative cross-sections were taken both upstream (stage III channels) and downstream (stage IV) of the knickpoints both by CoE in 1997 and are reported in Simon (1998). The stage III channels are already incised but will be subject to further deepening that will cause the bank to become unstable and retreat. Dimensions in the stage IV channels just downstream give a ready estimate of the likely deepening caused by the knickpoint or knickzone progressing past the cross-section. The bank height and top width of each of the stage III sections are given in Table 1. Bank heights are taken from the channel thalweg. With the exception of the Topashaw Creek main stem reach (bank height, 5.1 m), stage III bank heights vary from 3.2 to 4.0 m in drainage areas ranging from 6.2 to 103 km^2 indicating that, in these incising channels, there is no clear relationship between bank height and drainage area

Table 1
Current channel characteristics of 11 stage III Yalobusha river network sites used in this study (from Simon, 1998)

River/ creek name	Drainage area (km^2)	Top width (m)	Bank height (m)
Bear	14.9	9.5	3.7
Big	6.2	11.2	4.0
Buck	20.1	13.0	3.3
Cane	20.7	6.9	3.6
Johnson	21.9	6.2	3.2
Little Topashaw	21.5	16.7	3.5
Mud	26.0	9.1	3.3
North Topashaw	13.7	7.1	3.3
Topashaw	15.1	19.5	5.1
Topashaw Tributary 1A	8.8	13.1	4.0
Yalobusha	103.0	7.3	3.2
Mean	24.7	10.9	3.7
Std. Dev.	26.63	4.33	0.56

because of the varying amounts of time that the reaches have been actively incising.

3.2. Knickpoint migration rates

Knickpoint migration in cohesive-bedded streams is a complex issue and, currently, cannot be modelled. Knickpoint migration rates were obtained from analysis of repeat surveys. General rates of migration can be interpreted (with caution) from the early post-channelisation surveys (1969, 1970) in the lower part of the channel but may not be applicable to the upstream locations critical for this research. However, since the CoE 1997 survey and identification of the critical locations by Simon (1998), on-going research by the USDA Agricultural Research Service (ARS) has included repeat surveying of individual knickpoints after significant flow events (Fig. 5: Simon et al., 2000). From these data, estimates of the rate of knickpoint migration have been possible (Simon et al., 2000; Thomas, 2000). The rates, illustrated in Table 2, vary from 0.5 m $year^{-1}$ to as much as 13.8 m $year^{-1}$ averaged over periods of 23–30 months (except Bear Creek = 6 months). The large knickzone on the Yalobusha River has migrated about 30 m between April 1997 and June 1999.

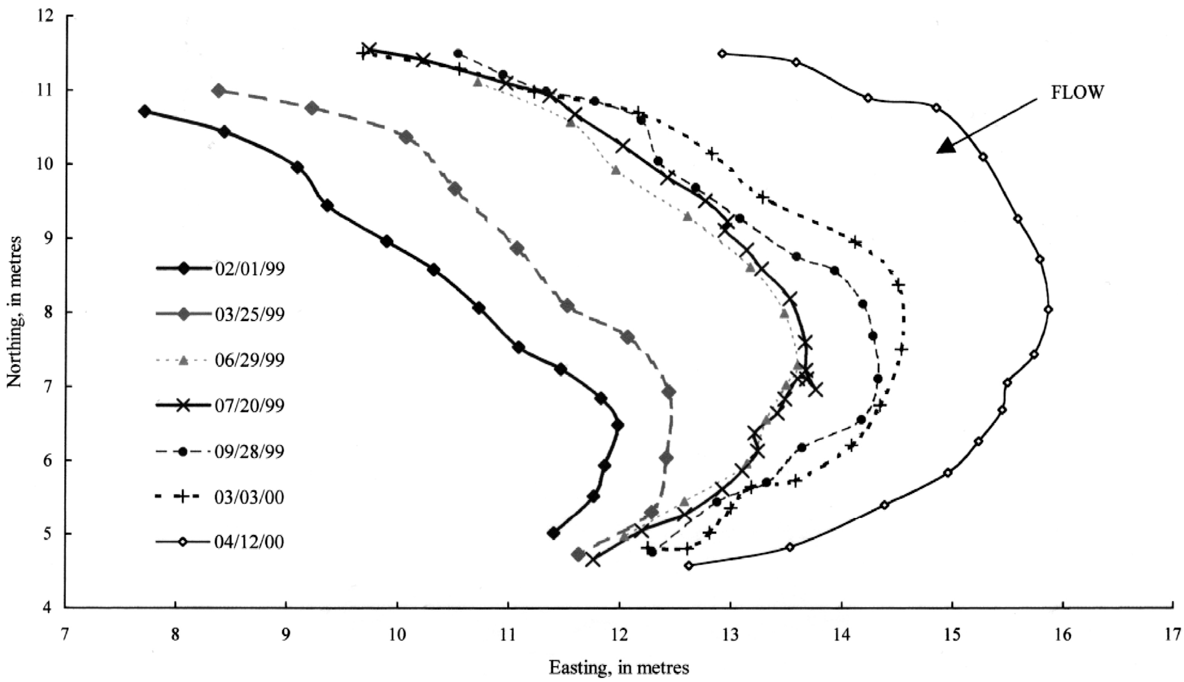

Fig. 5. Example plan view of knickpoint migration: Big Creek (modified from Simon et al., 2000). The uppermost point attaches to the right bank, the lowermost point to the left bank.

Table 2
Knickpoint migration rates for the 11 study sites (from Thomas, 2000)

River/creek name	Date of earliest survey	Date of most recent survey	Initial location	Current location	Migration distance (m)	Migration rate (m year^{-1})
Bear	5-Mar-99	1-Sep-99	8215.472	8223.142	7.67	15.55
Big	25-Feb-97	12-Jul-99	9669.48	9701.616	32.136	13.53
Buck	14-Apr-97	18-Aug-99	1374	1375.266	1.266	0.54
Cane	13-Mar-97	8-Oct-99	11620.5	11627.351	6.851	2.66
Johnson	16-Apr-97	30-Aug-99	217	244.808	27.808	11.72
Little Topashaw						
Mud	14-Mar-97	23-Feb-99	2164.08	2173.896	9.816	5.04
North Topashaw	20-Feb-97	20-Aug-99	5214	5215.471	1.471	0.59
Topashaw	24-Apr-97	31-Aug-99	14324	14327.632	3.632	1.54
Topashaw	16-Apr-97	19-Aug-99	2320	2332.904	12.904	5.51
Tributary 1A						
Yalobusha	16-Apr-97	22-Jun-99	18707	18737.069	30.069	13.77
Mean						7.05

3.3. Characteristics of riparian vegetation

Quantitative characteristics of riparian trees in the Yalobusha River catchment were obtained during summer 1999 using a sample of sites on both banks immediately upstream of the 11 monitored knickpoint locations. Supporting evidence in the form of ground, aerial and oblique aerial photographs obtained during helicopter reconnaissance were used to extend the representativeness of these sites.

Data were collected from 500 m^2 plots on each bank, extending 10 m inland from each bank toe and 50 m upstream. The plot size was based on a hypothesised worst-case scenario for bank failure in the tributaries under current knickpoint conditions (i.e. no single bank is expected to recede more than 10 m) and an early indication of knickpoint migration rates (R. Thomas, personal communication, 1999). The sample site is measured inland from the bank toe because of the potential for the bank itself to contribute trees in addition to the riparian floodplain/terrace. In all, 22 banks were surveyed from the eleven sites, encompassing a range of land management conditions.

Within each 500 m^2 plot, all trees with diameters greater than 0.05 m were measured at breast height (DBH). The 0.05 m threshold was used (rather than the 'standard' LWD threshold of 0.10 m) because of the interest in estimating the total volume of woody recruitment into the river network, and not just the 'key debris' (Nakamura and Swanson, 1993) provided by the larger trees. Estimates of tree heights from bankside trees were taken using an angular reading from a known horizontal distance. Species included American Elm (*Ulmus americana* L.), Southern Red Cedar (*J. virginiana* L. var. *silicicola*), Sweetgum (*Liquidamber styraciflua* L.), Willow Oak (*Quercus phellos* L.), Red Maple (*Acer rubrum*) and Loblolly Pine (*Pinus taeda* L.). Table 3 shows summary characteristics of the riparian trees by site. The riparian character of each bank varied between sites and the number of trees present varied from 0 to 98. Trees are, on average, about 0.18 m DBH (range 0.11–0.27 m) with an average of the maximum diameters obtained from each the 22 plots of 0.51 m (range, 0.18–1.15 m). The DBH wooded area of >0.05 m diameter trees covers about 1.6 m^2 of the 500 m^2 plots, giving a density of 0.0032 m^2 m^{-2} or one tree for every 12.5 m^2. Established trees are, therefore, about 3.5 m apart. The average tree height at each site was estimated using either all the trees in the plot (where the total number was low) or, in forested areas, a sample from the canopy of bankside trees. From the 22 plots, the average tree height was approximately 14 m so the average volume of riparian wood on the banks is about 0.02 m^3 m^{-2} of ground, assuming a conical tree shape.

With specific reference to the potential of recruited LWD to form debris dams, it is the number of larger trees that may be of particular interest (see

Table 3
Summary riparian tree characteristics for the 11 study sites. Surveys covered 500 m^2 (10 m inland from the channel toe $\times$ 50 m upstream) on each bank of each site. Riparian vegetation classification is: ‘Forest’, riparian trees extend more than 10 m inland from the channel bank toe consistently throughout the 50 m reach, likely to indicate a forest riparian zone; ‘Patch’, riparian trees are sporadic in nature, with gaps in cover, some areas are only one tree deep whereas others extend more than 10 m inland; ‘Bank’, reserved for larger streams with significant but possibly patchy tree cover on their banks, the banks themselves extend more than 10 m in horizontal distance; ‘One-line’, riparian zone characterised by a single line of trees, often representing a narrow buffer at the edge of cultivated fields; ‘0’, no riparian trees present

Measure	Both banks	Bank	Mean average	Bear	Big	Buck	Cane	Johnson	Little Topashaw	Mud	North Topashaw	Topashaw	Topashaw Tributary 1A	Yalobusha
Classification		LB		Forest	One-line	Forest	One-line	One-line	0	Forest	One-line	Bank	Forest	Forest
		RB		Forest	One-line	Patch	Patch	Forest	0	0	Patch	Bank	Forest	Forest
Number of trees	40	LB	38	55	4	98	20	7	0	63	20	77	35	37
		RB	42	69	7	58	75	83	0	0	19	31	73	50
Number of trees > 0.25 m	14		14	25	3	16	13	19	0	11	4	20	18	28
Average diameter (DBH, m)	0.18	LB	0.175	0.170	0.165	0.137	0.153	0.107	NO	0.187	0.190	0.192	0.182	0.272
		RB	0.186	0.211	0.244	0.181	0.160	0.193	NO	NO	0.146	0.183	0.169	0.185
Maximum diameter (DBH, m)	0.51	LB	0.52	0.60	0.20	0.45	0.40	0.18	0.00	0.90	0.80	0.52	0.70	1.00
		RB	0.49	0.76	0.40	0.55	0.45	0.80	0.00	0.00	0.35	0.30	1.15	0.66
Sum of tree area (DBH, m^2)	1.58	LB	1.47	1.90	0.09	2.01	0.44	0.07	0.00	2.77	1.17	2.83	1.68	3.17
		RB	1.69	4.07	0.39	1.80	1.94	3.76	0.00	0.00	0.41	0.90	3.14	2.14
Average area per tree (DBH, m^2)	0.039	LB	0.038	0.034	0.023	0.021	0.022	0.011	NO	0.044	0.059	0.037	0.048	0.086
		RB	0.039	0.059	0.056	0.031	0.026	0.045	NO	NO	0.022	0.029	0.043	0.043
Density of trees 1 (number per m^2)	0.080	LB	0.076	0.110	0.008	0.196	0.040	0.014	0.000	0.126	0.040	0.154	0.070	0.074
		RB	0.085	0.138	0.014	0.116	0.150	0.166	0.000	0.000	0.038	0.062	0.146	0.100
Density of trees 2 (m^2 m^{-2})	0.0032	LB	0.0029	0.0038	0.0002	0.0040	0.0009	0.0001	0.0000	0.0055	0.0023	0.0057	0.0034	0.0063
		RB	0.0034	0.0081	0.0008	0.0036	0.0039	0.0075	0.0000	0.0000	0.0008	0.0018	0.0063	0.0043
Average maximum tree height (m)	14.0	LB	13.2	14.7	7.9	14.5	9.2	4.5	no	16.4	7.7	16.1	24.3	16.8
		RB	14.7	20.1	13.4	13.2	14.1	18.0	no	no	8.7	12.4	18.3	14.0
Estimated volume (m^3 m^{-2})	0.0202	LB	0.0171	0.0185	0.0005	0.0194	0.0027	0.0002	no	0.0304	0.0060	0.0304	0.0273	0.0354
		RB	0.0228	0.0546	0.0035	0.0159	0.0183	0.0452	no	no	0.0024	0.0074	0.0384	0.0199

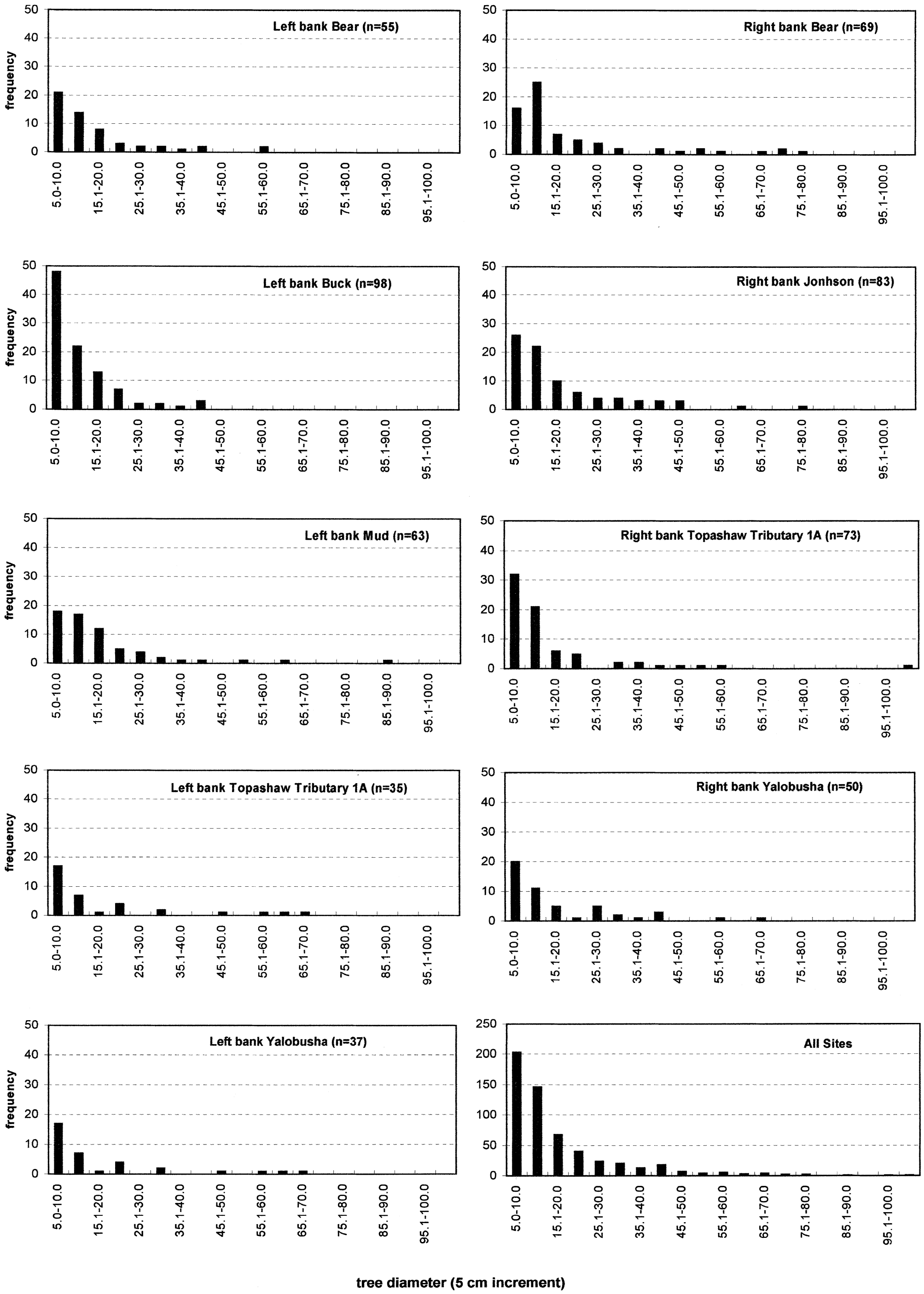

Fig. 6. Tree distribution characteristics by 0.05 m increment for the nine ‘forested’ banks from the 11 Yalobusha river network sites by site and by total.

Table 3), as they form the 'key debris' (Nakamura and Swanson, 1993). Fig. 6 illustrates the diameter mix of the nine banks characterised by fully-developed 'forested' riparian areas. The charts show that the forested stands are dominated by a large number of young trees with diameters less than 0.15 m. With the exception of the right bank of Bear Creek ($n = 7$), no individual bank possesses in total more than three trees with a diameter greater than 0.5 m.

4. Analysis—shear strength and channel-bank stability

Accurately estimating LWD recruitment in incising channels is determined largely by the accuracy in estimating the extent of channel widening that occurs after the banks are destabilised by the retreating knickpoint. Widening occurs until the bank reaches a stable angle and is a function of the shear strength of the bank material relative to the height of the knickpoint. Therefore, there is no simple empirical relation of channel widening to discharge or drainage area, and the river length involved between destabilising stage III reaches and stabilised stage VI reaches prohibits any safety in space-for-time substitutions as a basis for predicting the final bank width. Therefore, the extent of channel widening must be based on a physically-based assessment of the bank's geotechnical properties.

Shear strength comprises two components—cohesive strength and frictional strength. For the simple case of a planar failure of unit length, the Coulomb equation is applicable

$$S_r = c' + (\sigma - \mu)\tan\phi' \quad (1)$$

where S_r = shear stress at failure, in kPa; c' = effective cohesion, in kPa; σ = normal stress on the failure plane, in kPa; μ = pore-water pressure, in kPa; and ϕ' = effective friction angle, in degrees.

Also

$$\sigma = W(\cos\beta) \quad (2)$$

where W = weight of the failure block, in kN; and β = angle of the failure plane, in degrees.

The gravitational force acting on the bank is $W\sin\beta$. Factors that decrease the erosional resistance (S_r), such as excess pore-water pressure from saturation and the development of vertical tension cracks, favour bank instabilities. Similarly, increases in bank height by bed degradation and bank angle by undercutting favour bank failure by causing the gravitational component to increase.

4.1. Shear strength testing

Data on cohesion and friction angle were obtained from in situ shear strength testing with a borehole shear tester (BST). The instrument provides drained strength parameter values for use in stability analyses. Testing was undertaken at 21 sites throughout the Yalobusha River network (38 tests) to depths of about 6.8 m as part of a previous study (Simon, 1998). To substitute for the lack of deeper BST testing, triaxial-test data were obtained for several sites in the watershed from the Mississippi Department of Transportation. The weighted-mean values of c_a and ϕ' used to represent all of the stream banks investigated in this paper were 11.5 kPa and 22.3°, respectively. Data on soil unit weight (γ) were obtained from undisturbed core samples. The mean value obtained and used in this study was 16.9 kN m^{-3}.

4.2. Factor of safety analysis for current and future conditions

To evaluate the potential for recruitment of large woody debris from presently stable channel banks (stage III channels), an analysis was performed that compared current conditions with future bank-stability conditions assuming passage of a knickpoint. The most common type of bank failures along streams of the Yalobusha River System are wedge-shaped, planar failures. These failures occur on steep slopes that have often been undercut by flow. To conceptualise threshold conditions, a given bank angle will fail at a certain critical height when the ratio of the resisting forces to the driving, gravitational forces (factor of safety) equals unity. Consideration of both the pore-water and confining pressures were included in the analysis of bank stability because of their important roles in determining critical conditions (Simon and

Curini, 1998; Simon et al., 1999; Rinaldi and Casagli, 1999; Casagli et al., 1997). Analyses of current and future bank-stability conditions were conducted using an equation for the factor of safety (F_s) which includes the effects of bank hydrology (Simon, 1998)

$$F_s = \frac{c_a L + [(W\cos\beta) - U + P\cos(\alpha-\beta)]\tan\phi'}{W\sin\beta - [P\sin(\alpha-\beta)]} \tag{3}$$

where c_a = apparent cohesion, in kPa; L = length of the failure surface, in m; U = hydrostatic uplift force acting on the failure surface, in kN m^{-1}; P = hydrostatic confining force due to external water level, in kN m^{-1}; and α = bank angle, in degrees.

Assuming wedge-shaped, planar bank failures, the failure geometries shown in Fig. 7 are appropriate for estimating the length of the failure surface (L) and the weight of the failure block (W) as

$$L = H/\sin\beta \tag{4}$$

$$W = 0.5\gamma[H^2/\tan\beta - H^2/\tan\alpha] \tag{5}$$

where γ = soil unit weight and is assumed constant and independent from the degree of saturation, in kN m^{-3}; and H = bank height as measured from the flood-plain surface or levee top to the proximal channel bed, in m.

The uplift (U) and confining (P) forces are calculated from the area of the pressure distribution of pore-water $(\gamma_w h_u)$ and confining $(\gamma_w h_{cp})$ pressures (μ_w) as shown in Fig. 7.

$$U = 0.5\gamma_w h_u^2/\sin\beta \tag{6}$$

$$P = 0.5\gamma_w h_{cp}^2/\sin\alpha \tag{7}$$

where $\gamma_w = 9.81$ kN m^{-3}; h_u = pore-water head, in m; and h_{cp} = confining-water head, in m.

The failure plane angle is represented by (Carson, 1971)

$$\beta = 0.5(\alpha + \phi'). \tag{8}$$

The bank-stability algorithm (Eq. (3)) and its supporting calculations (Eqs. (4)–(8)) were solved initially for present (1999) bank heights just upstream of the 11 study knickpoints (see Table 4). Two conditions are simulated, differentiated on the basis of the height of the (1) phreatic surface (below which experiences positive pore-water pressure; H_u) and (2) river stage (below which experiences confining pressure; H_{cp}), relative to the total bank height. These are expressed as percentages of the total bank height. A rapid drawdown condition is described as $H_u = 75\%$ and $H_{cp} = 5\%$, that is, three quarters of the bank is saturated while only a low-flow condition

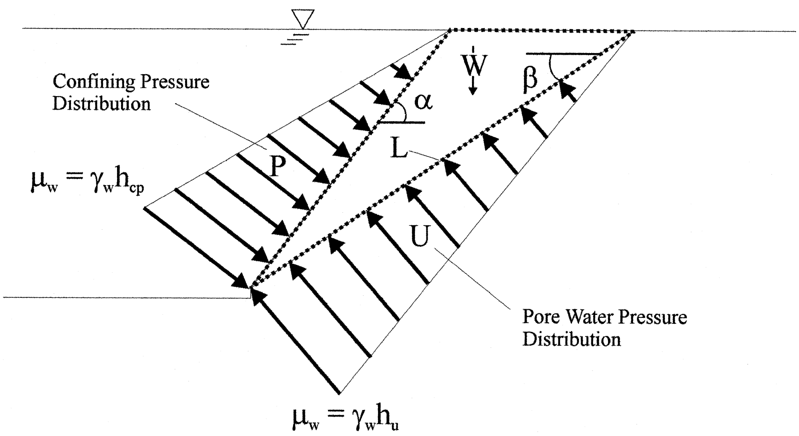

Fig. 7. Bank failure geometry for factor-of-safety analysis of wedge-shaped, planar failures characteristic of the Yalobusha river network (from Simon, 1998). Note: L = length of failure surface, in m; U = hydrostatic uplift force acting on the failure surface, in kN m^{-1}; P = hydrostatic confining force due to external water levels, in kN m^{-1}; W = weight of the failure block, in kN m^{-1}; α = bank angle, in degrees; β = failure plane angle, in degrees; μ_w = water pressure at a point, in kN m^{-2}; $\gamma_w = 9.81$ kN m^{-3}; h_u = pore-water head, in m; h_{cp} = confining-water head, in m.

Table 4
Factor-of-safety bank stability analysis for the 11 study sites for current and post-knickpoint conditions (see also Figs. 7 and 8)

Tributary	Current conditions				Post-knickpoint conditions			
	Bank height (m)	Bank angle (degrees)	Hydrological condition		Bank height (m)	Bank angle (degrees)	Hydrological condition	
			$H_u = 75$; $H_{cp} = 5$, F_s	$H_u = 25$; $H_{cp} = 5$, F_s			$H_u = 75$; $H_{cp} = 5$, F_s	$H_u = 25$; $H_{cp} = 5$, F_s
Bear Creek	3.7	40	2.353	3.342	6.8	40	0.959	1.948
	3.7	50	1.686	2.351	6.8	50	0.749	1.414
	3.7	60	1.314	1.813	6.8	60	0.611	1.109
	3.7	70	1.062	1.457	6.8	70	0.506	0.900
	3.7	80	0.874	1.195	6.8	80	0.421	0.742
	3.7	90	0.723	0.988	6.8	90	0.350	0.615
Big Creek	4	40	2.124	3.113	6.6	40	1.013	2.014
	4	50	1.532	2.196	6.6	50	0.786	1.459
	4	60	1.198	1.697	6.6	60	0.638	1.143
	4	70	0.971	1.365	6.6	70	0.527	0.927
	4	80	0.799	1.120	6.6	80	0.439	0.764
	4	90	0.662	0.927	6.6	90	0.365	0.633
Buck Creek	3.3	40	2.724	3.713	7.7	40	0.764	1.753
	3.3	50	1.935	2.600	7.7	50	0.619	1.283
	3.3	60	1.501	2.000	7.7	60	0.512	1.011
	3.3	70	1.210	1.605	7.7	70	0.428	0.823
	3.3	80	0.994	1.315	7.7	80	0.358	0.679
	3.3	90	0.823	1.087	7.7	90	0.298	0.563
Cane Creek	3.6	40	2.460	3.461	6.5	40	1.040	2.041
	3.6	50	1.758	2.430	6.5	50	0.804	1.477
	3.6	60	1.368	1.873	6.5	60	0.651	1.156
	3.6	70	1.105	1.504	6.5	70	0.538	0.938
	3.6	80	0.908	1.233	6.5	80	0.448	0.772
	3.6	90	0.752	1.020	6.5	90	0.372	0.640
Johnson Creek	3.2	40	2.858	3.859	5.4	40	1.399	2.400
	3.2	50	2.025	2.698	5.4	50	1.045	1.718
	3.2	60	1.568	2.073	5.4	60	0.833	1.338
	3.2	70	1.264	1.663	5.4	70	0.681	1.081
	3.2	80	1.037	1.362	5.4	80	0.564	0.889
	3.2	90	0.858	1.126	5.4	90	0.468	0.736
Little Topashaw	3.5	40	2.528	3.517	6.3	40	1.091	2.080
	3.5	50	1.804	2.468	6.3	50	0.838	1.503
	3.5	60	1.402	1.901	6.3	60	0.677	1.176
	3.5	70	1.132	1.527	6.3	70	0.558	0.953
	3.5	80	0.930	1.251	6.3	80	0.464	0.785
	3.5	90	0.770	1.035	6.3	90	0.385	0.650
Mud Creek	3.3	40	2.724	3.713	6	40	1.187	2.188
	3.3	50	1.935	2.600	6	50	0.903	1.575
	3.3	60	1.501	2.000	6	60	0.726	1.231
	3.3	70	1.210	1.605	6	70	0.597	0.996
	3.3	80	0.994	1.315	6	80	0.495	0.820
	3.3	90	0.823	1.087	6	90	0.411	0.679
North Topashaw	3.3	40	2.724	3.713	6.7	40	0.983	1.973
	3.3	50	1.935	2.600	6.7	50	0.766	1.430
	3.3	60	1.501	2.000	6.7	60	0.623	1.122
	3.3	70	1.210	1.605	6.7	70	0.516	0.910
	3.3	80	0.994	1.315	6.7	80	0.429	0.750
	3.3	90	0.823	1.087	6.7	90	0.357	0.621

Table 4 (*continued*)

Tributary	Current conditions				Post-knickpoint conditions			
	Bank height (m)	Bank angle (degrees)	Hydrological condition		Bank height (m)	Bank angle (degrees)	Hydrological condition	
			$H_u = 75$; $H_{cp} = 5$, F_s	$H_u = 25$; $H_{cp} = 5$, F_s			$H_u = 75$; $H_{cp} = 5$, F_s	$H_u = 25$; $H_{cp} = 5$, F_s
Topashaw Creek	5.1	40	1.524	2.525	7.8	40	0.746	1.747
	5.1	50	1.129	1.802	7.8	50	0.607	1.279
	5.1	60	0.896	1.401	7.8	60	0.503	1.008
	5.1	70	0.731	1.131	7.8	70	0.421	0.820
	5.1	80	0.605	0.929	7.8	80	0.352	0.677
	5.1	90	0.501	0.769	7.8	90	0.293	0.561
Topashaw Tributary 1A	4	40	2.142	3.143	7.6	40	0.783	1.772
	4	50	1.544	2.217	7.6	50	0.632	1.296
	4	60	1.207	1.712	7.6	60	0.522	1.021
	4	70	0.978	1.377	7.6	70	0.436	0.830
	4	80	0.805	1.130	7.6	80	0.364	0.685
	4	90	0.667	0.935	7.6	90	0.303	0.568
Yalobusha River	3.2	40	2.858	3.859	8.6	40	0.610	1.599
	3.2	50	2.025	2.698	8.6	50	0.515	1.180
	3.2	60	1.568	2.073	8.6	60	0.435	0.934
	3.2	70	1.264	1.663	8.6	70	0.367	0.761
	3.2	80	1.037	1.362	8.6	80	0.308	0.629
	3.2	90	0.858	1.126	8.6	90	0.257	0.521

exists in the channel. While this condition may not occur often, the resulting bank geometry from individual knickpoints will reflect these critical conditions when mass failure occurs. As a comparison, a less critical but more frequent scenario is also evaluated ($H_u = 25\%$ and $H_{cp} = 5\%$).

Table 4 illustrates the solution of Eqs. (4)–(8) using bank angles ranging from 40° to 90° to calculate the maximum stable angle (α_s) under the two pore-water and confining pressure scenarios (H_u75, H_{cp}5 and H_u25, H_{cp}5) for both current and 'post-knickpoint' conditions. The maximum stable angle occurs where the $F_s = 1.0$ and can be derived either numerically or graphically, shown by the example in Fig. 8. The increase in bank heights resulting from passage of a knickpoint is accommodated by adding the knickpoint height in a given reach by the present bank height upstream of the knickpoint. Estimating directly the effective deepening caused to a channel cross-section by the passage of a knickpoint is difficult because the incision may actually result from numerous knickpoints as part of a migrating knickzone. Therefore, in this study, the effective knickzone height is summarised as the difference in bank height between the current stage III channels and representative stage IV channels downstream.

5. Results

Having collected the necessary input data and performed the bank stability analysis, the estimation of LWD recruitment at each site is performed through a sequence of calculations as to

1. identify channel dimensions at critical locations upstream of major knickpoints and add knickpoint/knickzone height to existing bank heights;
2. apply bank-stability analysis to determine the stable angle under future conditions;
3. estimate future top width of the channel at the critical locations;
4. calculate remaining channel widening required to provide a stable bank angle under these conditions;
5. use the knickpoint migration rate to obtain an estimate of annual land lost through channel

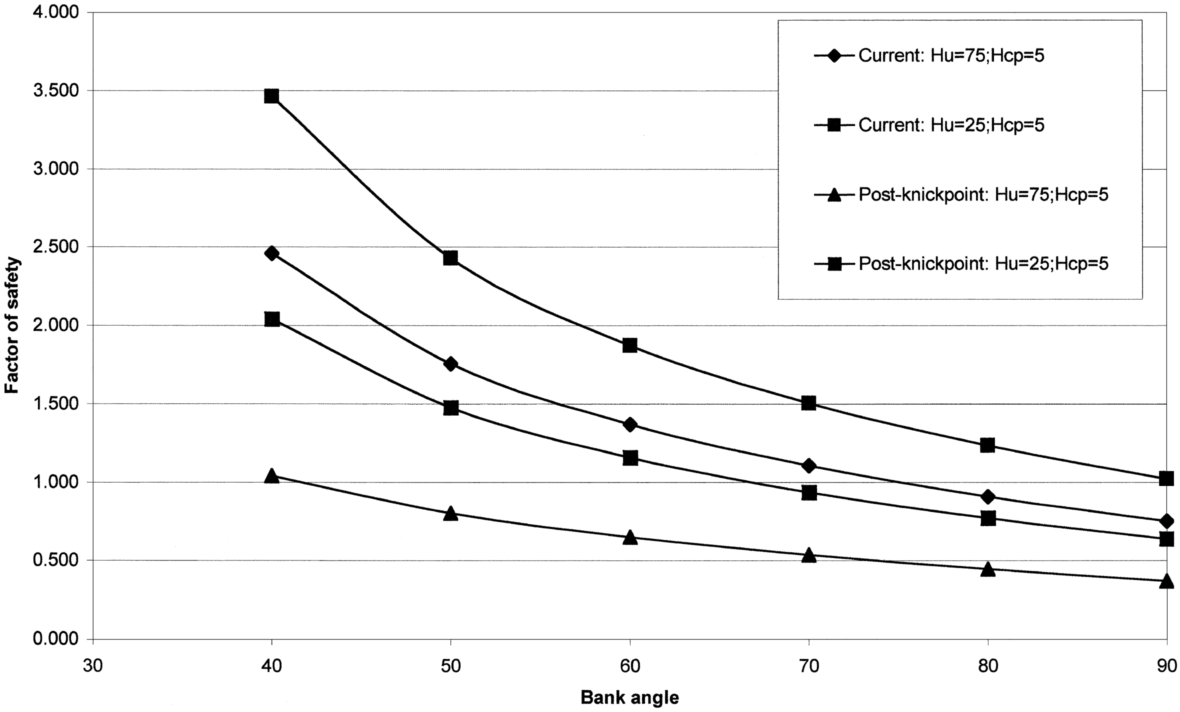

Fig. 8. Graphical illustration of factor-of-safety (F_s) analysis for Cane Creek site. Current bank heights and post-knickpoint bank heights are modelled under rapid drawdown (H_u75; H_{cp}5) and average (H_u25; H_{cp}5) conditions of pore-water and confining pressure. The maximum stable bank angle is achieved at $F_s = 1.0$. The rapid drawdown conditions are more realistic (see text). Under current conditions, the maximum stable angle is estimated at 75° (or 90° at H_u25; H_{cp}5) and, after the passage of the 2.9 m knickpoint, at 42° (67° at H_u25; H_{cp}5). See also Table 4.

widening as the banks fail back to their stable angle;

6. calculate the number of trees and volume of LWD recruited per metre length of bank from knowledge of the vegetation characteristics as they fail to stable dimensions.

These points are followed below.

No information is available on the progressive decay in knickpoint heights as they migrate upstream but it appears by observation and previous surveys that, in these cohesive-bedded channels, knickpoint height is a reasonably conservative property. Certainly, its does not decay appreciably over the short distances migrated by knickpoints on a yearly basis. Applying this logic indicates that knickzones in the Yalobusha catchment vary from 2.2 to 5.4 m resulting in post-knickpoint bank heights of between 5.4 and 8.6 m (Table 5).

The stable bank height under this condition will be determined by a worst-case saturation condition (H_u75; H_{cp}5) rather than an average one (given by H_u25; H_{cp}5). Applying this more critical condition suggests the post-knickpoint banks will stabilise at angles ranging from 30° to 52° in comparison with their current 'near-vertical' stable angles calculated at 70–82° (except the larger Topashaw Creek = 56°). Measuring bank angle in the field is difficult because of the indistinct nature of the bank toe in these cohesive channels. However, by observation, the calculated angles appear to relate well to field angles observed in quasi-equilibrium reaches downstream (i.e. stage V and VI channels of the Simon (1989) channel evolution model). Certainly, the post-knickpoint stable angles calculated under the 'average' H_u25; H_{cp}5 conditions (57–74°) seem too steep.

Table 5
Impact of knickpoint migration on channel dimensions through each of the study sites. H_u25; $H_{cp}5$ factor-of-safety conditions are for illustration only. Area land loss is calculated from the rapid drawdown conditions given by H_u75; $H_{cp}5$

	Current conditions				Post-knickpoint conditions											
	Top width (m)	Bank height (m)	Maximum stable angle H_u75; $H_{cp}5$	Maximum stable angle H_u25; $H_{cp}5$	Knickzone height (m)	Bank height (m)	Maximum stable angle H_u75; $H_{cp}5$	Maximum stable angle H_u25; $H_{cp}5$	Drainage area (km^2)	Projected quasi-equilibrium bottom width (m)	Projected top width H_u75; $H_{cp}5$ (m)	Projected unit land loss H_u75; $H_{cp}5$ (m^2 m^{-1})	Projected top width H_u25; $H_{cp}5$	Projected unit land loss H_u25; $H_{cp}5$ (m^2 m^{-1})	Knickpoint migration rate (m $year^{-1}$)	Area land loss H_u75; $H_{cp}5$ (m^2 $year^{-1}$)
Bear	9.5	3.7	73	89	3.1	6.8	39	65	14.9	4.9	21.7	12.2	11.2	1.7	15.6	189.7
Big	11.2	4.0	70	86	2.6	6.6	41	67	6.2	3.7	18.9	7.7	9.3	−1.9	13.5	104.0
Buck	13.0	3.3	80	90	4.4	7.7	34	61	20.1	5.3	28.1	15.1	13.8	0.8	0.5	8.2
Cane	6.9	3.6	75	90	2.9	6.5	42	67	20.7	5.4	19.8	12.9	10.9	4.0	2.7	34.5
Johnson	6.2	3.2	82	90	2.2	5.4	52	74	21.9	5.5	13.9	7.7	8.6	2.4	11.7	90.7
Little Topashaw	16.7	3.5	76	90	2.8	6.3	44	68	21.5	5.5	18.5	1.8	10.6	−6.1	0.0	0.0
Mud	9.1	3.3	80	90	2.7	6	47	70	26.0	5.8	17.0	7.9	10.2	1.1	5.0	39.8
North Topashaw	7.1	3.3	80	90	3.4	6.7	40	66	13.7	4.7	20.7	13.6	10.7	3.6	0.6	8.0
Topashaw	19.5	5.1	56	77	2.7	7.8	34	61	125.0	9.5	32.6	13.1	18.1	−1.4	1.5	20.3
Topashaw Tributary 1A	13.1	4.0	70	86	3.6	7.6	35	61	8.8	4.1	25.8	12.7	12.5	−0.6	5.5	70.0
Yalobusha	7.3	3.2	82	90	5.4	8.6	30	57	103.0	9.0	38.8	31.5	20.2	12.9	13.8	433.8
Mean	10.9	3.7	74.9	88.0	3.3	6.9	39.8	65.2	34.7	5.8	23.3	12.4	12.4	1.5	6.4	90.8
Std. Dev.	4.33	0.56	7.67	3.97	0.93	0.92	6.42	4.85	39.95	1.84	7.40	7.42	3.67	4.72	6.05	126.77

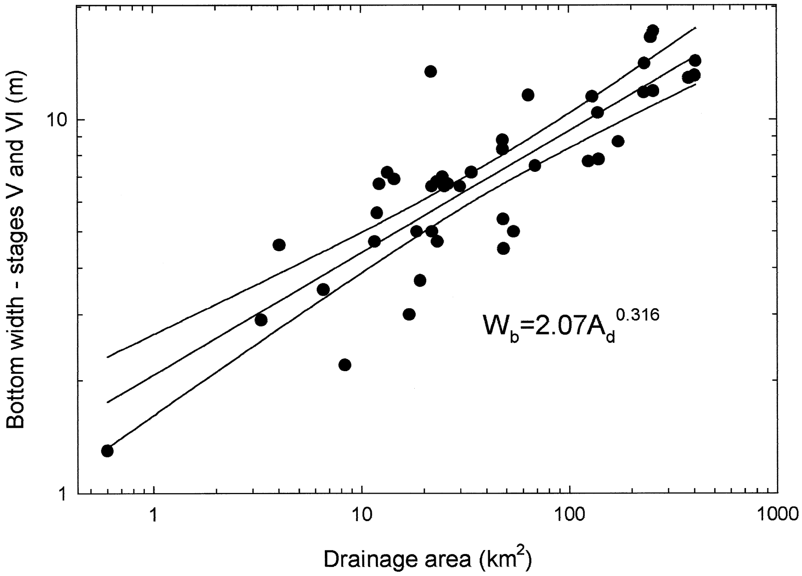

Fig. 9. Regional regression relationship between drainage area and bottom widths for 'quasi-equilibrium' channel stages (V and VI) in the Yalobusha river network ($n = 43$; $r^2 = 0.72$).

Future channel top-widths (W_t) are then calculated from

$$W_t = 2(\tan\alpha_s) + W_b \qquad (9)$$

where W_b = future bottom width, in m; α_s = future stable angle, in degrees.

The use of present bottom widths to estimate future top widths is unrealistic in that the passage of

Fig. 10. Oblique aerial photograph of widening caused by channel incision in the neighbouring Johnson Creek, Panola County, MS, USA. Flow is towards the camera. Channel incision is not obscured by riparian vegetation but has been arrested by bridge crossings (middle photograph). Comparison with the channel above the bridge shows the incised cross-sections to be considerably wider and deeper (Photographer: unknown).

Table 6

Estimated recruitment of large woody debris by site according knickpoint impacts. Recruitment is given by volume of wood, by number of trees and by number of large trees

	Area land loss H_u75; $H_{cp}5$ (m^2 $year^{-1}$)	Woody volume by area (m^3 m^{-2})	Wood recruitment per year (m^3 $year^{-1}$)	Tree density by number (no. m^{-2})	No. trees recruited per year (no. $year^{-1}$)	Large tree density by number (no. m^{-2})	Number large trees recruited per year (no. $year^{-1}$)
Bear	189.7	0.0386	7.32	0.126	23.8	0.025	4.7
Big	104.0	0.0024	0.25	0.012	1.2	0.003	0.3
Buck	8.2	0.0181	0.15	0.166	1.4	0.016	0.1
Cane	34.5	0.0150	0.52	0.127	4.4	0.013	0.4
Johnson	90.7	0.0417	3.78	0.154	14.0	0.019	1.7
Little Topashaw	0.0	0.0000	0.00	n/a	n/a	n/a	n/a
Mud	39.8	0.0304	1.21	0.126	5.0	0.011	0.4
North Topashaw	8.0	0.0042	0.03	0.039	0.3	0.004	0.0
Topashaw	20.3	0.0238	0.48	0.128	2.6	0.020	0.4
Topashaw Tributary 1A	70.0	0.0348	2.44	0.121	8.5	0.018	1.3
Yalobusha	433.8	0.0265	11.50	0.089	38.6	0.028	12.1
Mean			2.52		9.97		2.16
Total			27.7		99.7		21.6

the knickpoint is likely also to erode failed cohesive materials at the bank toe and result in greater bottom widths than present. To overcome this problem, W_b for the study reaches were obtained empirically by establishing a regression relation between bottom width and drainage area for reaches in the Yalobusha River network that have already undergone degradation and widening, and are now approaching a new quasi-equilibrium condition (stages V and VI channels). Using data from 43 sites reported in Simon (1998), the following regression equation was developed (explained variance, $r^2 = 0.72$; Fig. 9)

$$W_b = 2.07 A_d^{0.316} \quad (10)$$

where A_d = drainage area in km^2.

By then, comparing the channel top width before and after passage of the knickpoint, the average horizontal component of total land loss can be calculated (Table 5). The channels are all expected to widen in amounts ranging from 1.8 (i.e. 0.9 m on each bank, Little Topashaw Creek) to 15.1 m (7.05 m per bank, Buck Creek) and, for the larger knickpoint on the Yalobusha River main stem, 31.5 m (16.25 m each bank). Again, application of the $H_u 25$; $H_{cp} 5$ condition is suggested to be unrealistic as four sites were predicted to be narrower than present and overall amounts of channel widening were much reduced. These amounts conflict plainly with field evidence, as shown clearly in Fig. 10 for a neighbouring stream not obscured by riparian cover.

Land lost per year is obtained by multiplying the estimate of bank retreat by the monitored knickpoint migration rate (Table 5). One assumption is, therefore, that the banks can retreat to their new stable angle during 1 year and, as migration rates have been monitored in detail for only 2 years, caution should be exercised is extrapolating the results beyond the short-term. The results range from an estimated land loss of 0.0 m^2 year^{-1} for the currently (1997–1999) stationary knickzone on Little Topashaw Creek to a value of 434 m^2 year^{-1} for the large and very mobile knickzone in the Yalobusha River main stem. On average, about 90 m^2 of land will be lost per year from the 10 sites with active knickpoints as the channel widens following the passage of the knickzone.

LWD recruitment to the system is calculated by combining the estimate of yearly land lost at each site with its surveyed riparian tree density of > 0.05 m DBH trees. Table 6 illustrates this calculation both for volumetric LWD input per year and for the number of trees recruited. An average of over 2.5 m^3 of LWD are added per site per year ranging from 0 where there is no riparian cover (Little Topashaw Creek) to nearly 11.5 m^3 year^{-1} for the wooded riparian fringe of the Yalobusha River. Likewise, it is apparent from the estimated number of trees recruited (> 0.05 m DBH) that particular sites are more critical than others for LWD recruitment. Foremost in this list is the Yalobusha River, providing nearly 40 trees year^{-1}, followed by Bear and Johnson Creeks, and Topashaw tributary 1A. In terms of key debris, these tributaries also provide more than one ‘large’ tree (> 0.25 m DBH) per year, ranging up to 12 for the Yalobusha River site.

6. Application—LWD recruitment and significance for debris dam formation

In the Yalobusha River catchment, the obvious final resting place for LWD that does not decay during its passage along the river network is the major debris dam at the transition from the channelised to non-channelised section downstream of the Topashaw Creek confluence (see Figs. 1 and 3). According to our analyses, the ‘accelerated’ rate of LWD recruitment is approximately 28 m^3 of wood per year, comprising about 100 trees (22 ‘large’ trees) from the eleven major knickpoints. Assuming this accelerated rate as a constant, along with a constant throughput and decay rate, then this amount of wood should equate approximately to the total yearly addition of LWD to the debris dam. In time, if the rate of upstream knickpoint migration remains unaltered, the LWD recruitment rate will vary according to the balance between the increasing numbers of rejuvenated tributaries, their riparian land uses and the progressive reduction in riparian land lost per channel, assuming that the knickpoints decay towards the catchment headwaters.

A second prospect concerns the potential for debris dam accumulation wherever engineering structures such as bridge piers act to constrict the cross-sectional area of channel available to pass flow.

These sites are largely self-evident and the potential is greatest at bridges with in-stream piers as this effectively reduces the size of the maximum tree length passable at any approaching angle of flow. The overall 'tree trapping' potential is a function of the tree height, trunk diameter, canopy or root bole diameter (whichever is greater) and pier span distance (Simons and Li, 1979 in Wallerstein, 1999). Wallerstein (1999) has modelled debris accumulation in northern Mississippi streams using these factors along with a probability function to account for the progressive reduction in free space once debris has begun to accumulate.

A third prospect is the natural formation of debris dams at certain locations within the channel where particular vegetation and geomorphological conditions coincide. Clearly, two precursors are that trees are growing on the banks and that the banks are subject to failure. Therefore, at present, Little Topashaw Creek in the vicinity of its knickpoint cannot deliver LWD because its has no riparian trees in the 500 m^2 upstream plots, a stationary knickpoint and minimal projected widening. Conversely, on the forested Yalobusha River main stem, the knickpoint threatens to more than quadruple the channel width and is moving upstream at a rate estimated at 13.8 m $year^{-1}$. In the latter example, the prospect for LWD generation is very high, as Table 6 shows. However, for debris jams to accumulate, a third pre-cursor is that the recruited vegetation has the potential to initiate a blockage. In this regard, Nakamura and Swanson (1993) highlight the role of 'key debris' (i.e. 'large' trees) in becoming jammed on the channel perimeter and initiating a jam. Subsequently, other LWD is required to maximise the jam potential of the key debris and eventually for leaves and sediment to fill the interstices in the amassed LWD. Debris jam residence times have been estimated to range from 1 to 200 years (Keller and Tally, 1979; Gregory et al., 1985, respectively) according the size and decay rate of the tree species. The jam is either an obstruction to flood flows or vital component of ecosystem structure, depending on the river manager's objectives.

The 'jam potential' of LWD can be classified according to the ratio of the tree length to the channel width, but the geomorphology of the recruitment process should also be considered. Modifying Robison and Beschta's (1990b) classification of pool formation mechanisms for rivers in the Pacific Northwest of the USA, Wallerstein (1999; following Wallerstein and Thorne, 1994) proposes a fourfold classification of debris dam types based on field observations of the alpha (angle relative to flow) and beta (incline) angles of key debris at 99 jams found in 17 rivers in Mississippi, USA (Fig. 11). The significance of the debris jam varies with the jam type: 'dam' jams have a high significance because they effectively impede flows whereas 'underflow' jams are usually considered of limited importance as

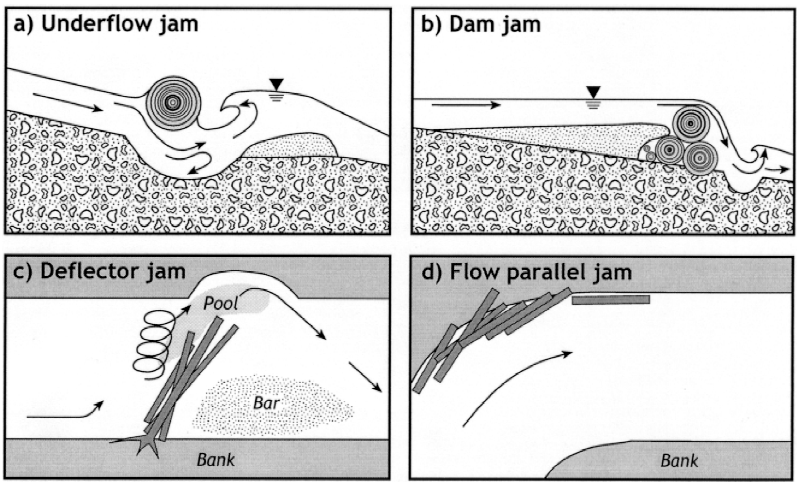

Fig. 11. Wallerstein classification of debris jams in incised Mississippi rivers (modified from Wallerstein, 1999).

they straddle the channel allowing flow to pass relatively unimpeded underneath the tree (Fig. 12a). ‘Deflector jams’ are usually partial jams (Gregory et al., 1993) but, in incised channels, they may still represent an efficient damming mechanism (especially if a tree on the opposite bank has a similar failure) because the tree slides down the bank during mass failure, resting with its root bole at the channel toe and the canopy jammed at an inclined angle against the opposite bank (Fig. 12b). Conversely, ‘flow parallel’ jams are of low significance because the relative lack of protrusion minimises the chance of the LWD becoming a piece of ‘key debris’ around which a debris dam forms (Fig. 12c). Overall, incised channels, especially straightened ones, are effective at transporting LWD as their low width-depth ratio and flashy-flood flows are effective creating the draught necessary to turn fallen trees (and their roots and canopy) towards the flow direction and transport them. Therefore, debris dam initiation is critically dependent on the ‘in situ’ jamming of a fallen tree, reinforcing the notion that LWD significance is greatest where trees are growing immediately adjacent to a migrating knickpoint (Wallerstein, 1999).

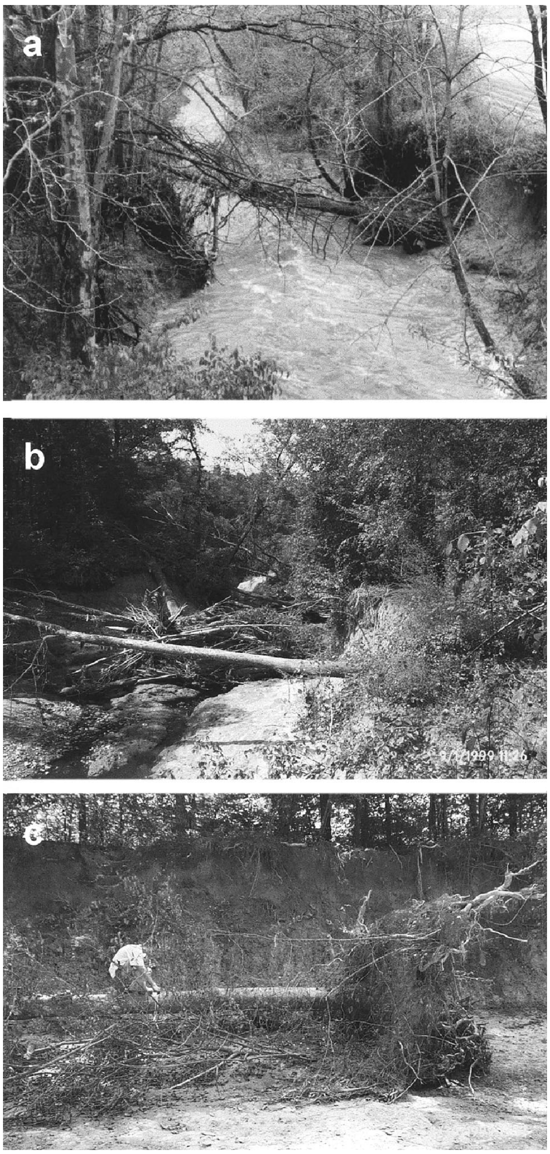

Fig. 12. Example debris jams in the Yalobusha river network: (a) underflow jam, Cane Creek; (b) deflector jam, Bear Creek; (c) flow parallel debris, Yalobusha River (Photographs: PWD).

According to the argument above, the significance of LWD is a function of the ratio of the tree height to channel width both before (stage III) and after (stage IV) the passage of the knickpoint. Underflow and parallel jams are of low significance, and dam and deflector jams of high significance. The extent of channel widening will determine whether the LWD recruitment is of highest significance now, or in the future. In addition, LWD significance is a function also of the recruitment potential of ‘key debris’ (in this case, trees > 0.25 m DBH) and the estimated total load of LWD.

This conceptual model is developed in Table 7. The similar mix of tree sizes at the Yalobusha sites results in a similar ranking both for ‘key debris’ and ‘accumulation’ potential, but in other river networks this need not necessarily occur. For illustration, the final column in Table 7 sub-divides the sites into management groups according to the in situ debris jam potential. Group A (Big Creek) has a continually high jam potential as the knickpoint passes (i.e. always involves dam or deflector jam types) whereas the Group D sites (Little Topashaw Creek and Yalobusha River) pass directly from one low jam potential to another as the bank fails (i.e. underflow to parallel types). In Groups B and C, the jam potential increases or decreases in time (respectively) as the sites move towards or away from favouring the dam and deflector dam types. The suffix in each management group ranks the load of ‘key debris’ and the ‘accumulation’ potential from high (i) to low

Table 7
Contemporary potential for in situ debris jam formation for the 11 study sites ranked according to the ratio of tree height: channel width (Wallerstein, 1999) for current conditions and post-knickpoint conditions and according to quantitative estimates of key debris and total debris load. For explanation of management group classification, see text

	Weighted maximum representative tree height (m)	Projected top width H_u75; $H_{cp}5$	Current top width (m)	Stage III jam potential tree height: current top width	Jam type	Stage IV jam potential tree height proposed top width	Jam type	Channel suitability potential rank	Large trees recruited per year (no.year^{-1})	Key debris recruitment potential rank	Total LWD recruited per year (m^3 year^{-1})	Accumulation potential rank	Management group
Bear	17.7	21.7	9.5	1.863	Underflow	0.816	Deflector	L > M	4.7	H	7.32	H	Bi
Big	11.4	18.9	11.2	1.018	Dam	0.604	Deflector	H > M	0.3	M	0.25	L	Aii
Buck	14.0	28.1	13	1.077	Dam	0.498	Parallel	H > L	0.1	L	0.15	L	Ciii
Cane	13.1	19.8	6.9	1.899	Underflow	0.660	Deflector	L > M	0.4	M	0.52	M	Bii
Johnson	17.0	13.9	6.2	2.742	Underflow	1.220	Dam	L > H	1.7	H	3.78	H	Bi
Little Topashaw	0.0	18.5	16.7	0.000	n/a	0.000	n/a	L > L	n/a	L	0.00	L	Diii
Mud	16.4	17.0	9.1	1.802	Underflow	0.965	Dam	L > H	0.4	M	1.21	M	Bii
North Topashaw	8.2	20.7	7.1	1.155	Dam	0.397	Parallel	H > L	0.0	L	0.03	L	Ciii
Topashaw	15.1	32.6	19.5	0.774	Deflector	0.463	Parallel	M > L	0.4	M	0.48	M	Ciii
Topashaw Tributary 1A	20.3	25.8	13.1	1.550	Underflow	0.787	Deflector	L > M	1.3	H	2.44	H	Bi
Yalobusha	15.2	38.8	7.3	2.082	Underflow	0.392	Parallel	L > L	12.1	H	11.50	H	Di
					Underflow = > 1.3 Dam = 0.95–1.3 Deflector = 0.6–0.95 Parallel = < 0.6		Underflow = > 1.3 Dam = 0.95–1.3 Deflector = 0.6–0.95 Parallel = < 0.6	Underflow = Low Dam = High Deflector = Medium Parallel = Low		High = > 1.0; Low = < 0.2		High = > 2.0 Low = < 0.4	

(iii). It is evident that not only do the Group C sites (Buck, North Topashaw and Topashaw Creeks) become less prone to debris jams as the knickpoint passes, but their potential LWD load is low also. Therefore, these sites are unlikely to be management priorities. Group D sites are also likely to be low management priorities because, irrespective of their LWD loading, the ratio of channel width to tree height make them unlikely to be prone to in situ debris jam formation. Conversely, for B sites that become more prone to debris jams with the passage of the knickpoint, their riparian conditions are highly significant. Therefore, management priorities are likely to be higher at the Bear Creek, Johnson Creek and Topashaw Tributary 1A sites (high potential loading) than at the Mud and Cane Creek sites (medium potential loading). The Big Creek site is clearly of high management significance due to its in situ debris jam characteristics, but its riparian conditions (medium potential loading) prevent it from reaching the maximum attainable management priority that would be ranking *Ai*.

In Table 8, an attempt is made to extrapolate the longer-term prospects for debris dam initiation and growth according to the nature of the upstream riparian vegetation and the severity of impact of the contemporary knickpoint. Knickpoint severity is judged according to the annual land loss (i.e. product of migration rate and bank retreat in Table 5) and upstream riparian vegetation conditions ascertained by an examination of aerial photographs for each tributary. Clearly, the temporal component implicit in the ranked data means that the judgement may be highly prone to error. However, it is notable that the Yalobusha River ranks High on all counts just as Topashaw Creek ranks Low. This suggests alternative strategies should be considered for these two main stem channels in terms of LWD management. Four of the tributaries combine the High, Medium and Low ranks and, in this case, the order of the ranks becomes important. For instance, the LWD significance of the migrating knickpoint seems set to reduce over time in the case of Bear Creek from its current high significance (H–M–L ranks, see Table 8) to a lower impact in its largely de-forested headwaters. Conversely, should the knickpoint in Buck Creek survive to its headwaters, its overall impact seems set to increase (L–M–H ranks). In the medium-term, the need for appropriate management of LWD seems greatest in the Yalobusha River, Bear, Johnson and Mud Creeks (first two ranks H–H, H–M or M–H in all cases).

7. Conclusions

This paper examines LWD recruitment and significance from a fluvial geomorphology perspective. Unlike analysis of LWD in non-incising streams where recruitment is driven primarily by tree death, wind-throw and/or channel shifting and must be examined stochastically (or retrospectively, Piégay et al., 1999), short-term LWD recruitment in incising channels can be examined deterministically in terms of riparian vegetation characteristics and bank stability. The significance of the recruited LWD in terms of potential for in situ channel blockage involves relations between riparian vegetation, channel morphology and hydrogeomorphological processes that are not fully understood but, in Tables 7 and 8, one perspective is developed based on the research results. Management options are not the concern of this paper, but should clearly proceed from judgement of the 'value' of the LWD. LWD may be perceived as a nuisance to the passage of flood flows to be contained through riparian tree clearance or through engineering a series of grade-control structures to prevent knickpoint migration. Conversely, LWD may be viewed both as fundamental to ecosystem value in degraded streams and as 'nature's own' grade-control structures: Wallerstein's (1999) estimate of relative volumes of erosion and sediment accumulation around debris dams in 17 rivers in Mississippi, USA, provides evidence to support this assertion. He found that 13 reaches had net sediment accumulation (1.2–28.4 m^3 per 100 m reach), with only three showing net sediment erosion (0.5–1.9 m^3 per 100m reach) (one reach had a net zero balance), suggesting that the dams create, albeit temporarily, increased bed stability in these unstable sand-bed rivers.

Knowledge of knickpoint migration rates and riparian vegetation characteristics along with the application of bank-stability analysis has enabled a

Table 8
Medium-to-long term potential for in situ debris jam formation for the 11 study sites ranked according to ‘knickpoint severity’ (i.e. area land loss under contemporary conditions) and the riparian conditions upstream and in the catchment headwaters. Riparian terminology follows convention in Table 3

	Area land loss H_u75; H_{cp}5 (m^2 $year^{-1}$)	Rank	Upstream buffer description	Rank	Headwaters description	Rank
Bear	189.7	H	wide buffer grades to one-line	M	mostly one-line buffer	L
Big	104.0	H	less than one-line buffer	L	patchy forest	M
Buck	8.2	L	mostly one-line, some patchy forest	M	forest (secondary?)	H
Cane	34.5	M	one-line buffer or less	L	forest	H
Johnson	90.7	M	forest, at least one bank	H	varied, one-line and some forest	M
Little Topashaw	n/a	L	one-line to patchy	M	n/a	n/a
Mud	39.8	M	forest, at least one bank	H	patchy forest and one-line buffer	M
North Topashaw	8.0	L	one-line or less	L	regnerating forest and reservoir	M
Topashaw	20.3	L	one-line buffer	L	one-line buffer	L
Topashaw Tributary 1A	70.0	M	mostly one-line, some forest patches	M	patchy forest, narrow buffer	M
Yalobusha	433.8	H	forest, then one-line buffer	H	forest	H
		H = > 100; L = < 25		H includes forest; L = one-line buffer and less		H = forest; L = one-line buffer

more precise, quantitative approach to LWD recruitment than in previous cases. However, the combined data sources and stability analysis demand great care in error minimisation in order to avoid the prospect of a technique of great precision but little accuracy. In this regard, the analysis depends upon the accuracy in factors such as: interpreting channel conditions from reconnaissance surveys, obtaining channel morphology surveys in representative locations, providing robust knickpoint migration rates, consistent definitions of the knickpoint face, representative and accurate riparian vegetation surveys, and the applicability of the bank stability analysis. Clearly, each of these factors warrants and will undoubtedly receive further detailed examination. In this research, careful applications of 'best available data' and 'fitness-for-purpose' criteria are the basis for ensuring overall accuracy in the approach.

With respect to the recruitment and significance of LWD in river networks such as the Yalobusha River, further research is suggested. First, as the application section demonstrates, more analytical approaches to the long-term recruitment of LWD are required in addition to progressive improvements to bank stability models and continued knickpoint monitoring. Decay coefficients for the knickpoints would also be of great benefit. Secondly, understanding the significance of the recruited debris requires more detailed investigation into their jamming mechanisms (in situ and at obstructions, e.g. Wallerstein, 1999), the character of individual dams (Gregory et al., 1993), their decay characteristics (including buoyancy changes during decay, (Thévenet et al., 1998) and the routing dynamics of LWD via hydraulic models. Preliminary flume experiments into this latter topic have suggested that transport characteristics vary according to the overall density of LWD, the shape of individual pieces, the flow depth and drag (Braudrick et al., 1997). Thirdly, for the Yalobusha River network, the existence of the downstream debris dam provides the opportunity to combine the improvements noted in the previous points with survey of the debris dam to provide an LWD budget for the network. Together, these phases could benefit authorities concerned with management at the land-river interface and also continue the steady improvement in understanding vegetation-geomorphology interactions.

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