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Channel Responses and Management Strategies in Disturbed Channels: a Numerical Simulation Approach

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Abstract

The Yalobusha River watershed underwent extensive channelization and channel repositioning during the 1960s. The newly channelized system experienced channel degradation, rejuvenating tributaries and increasing bank heights above stable conditions, causing bank failures and the addition of vegetation and sediment to the channels. 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/yr, while the input of vegetation due to bank failure in the vicinity of major knickpoints has been estimated to be around 100 trees/yr. This has promoted the development of a large logjam at the downstream terminus of channelization works. This debris ‘plug’ has caused increased stages and flood frequencies in the vicinity of Calhoun City, 5 km upstream. The U.S. Army Corps of Engineers have identified a number of remediation strategies including plug removal, numerous grade-control structures to arrest headward migration of knickpoints following plug removal, and flood-retarding structures. The one-dimensional, unsteady, gradually varying open channel flow model, CONCEPTS (CONservational Channel Evolution and Pollutant Transport System) is being used to model channel responses to channelization, including bed degradation, bank failures and hence sediment inputs and loads from 1968 to 1997. CONCEPTS has been shown to accurately depict in-channel and bank processes and hence can correctly predict the effects of channelization together with future rehabilitation measures.

Introduction

The Yalobusha River system, North-Central Mississippi (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 reaches and tributary channels were rejuvenated, increasing bank heights above stable conditions and 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 was transported downstream. Erosion of channel materials from the bed and banks of tributary channels and upstream reaches of the Yalobusha River continues to the present day. 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/yr or a yield of 939 tonnes/km^2/yr (Simon 1998). In addition, the input of vegetation due to bank failure in the vicinity of 11 major knickpoints has been estimated to be around 28 m^3/yr or 100 trees/yr (Downs and Simon 2001).

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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, promoting 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 apparent dichotomous problems of reduced downstream channel capacity and flooding problems with upstream erosion and land loss, restorative strategies have been contemplated by action agencies. The U.S. Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory (NSL) has been assisting the U.S. Army Corps of Engineers (CoE) in developing a technical work plan for the purpose of mitigating drainage and flooding problems. The CoE have identified a number of remediation strategies including plug removal and numerous grade-control structures to arrest headward migration of knickpoints. During the next few years, the plug will be removed in two phases. Initially, a channel will be formed through the plug, followed later by its complete removal.

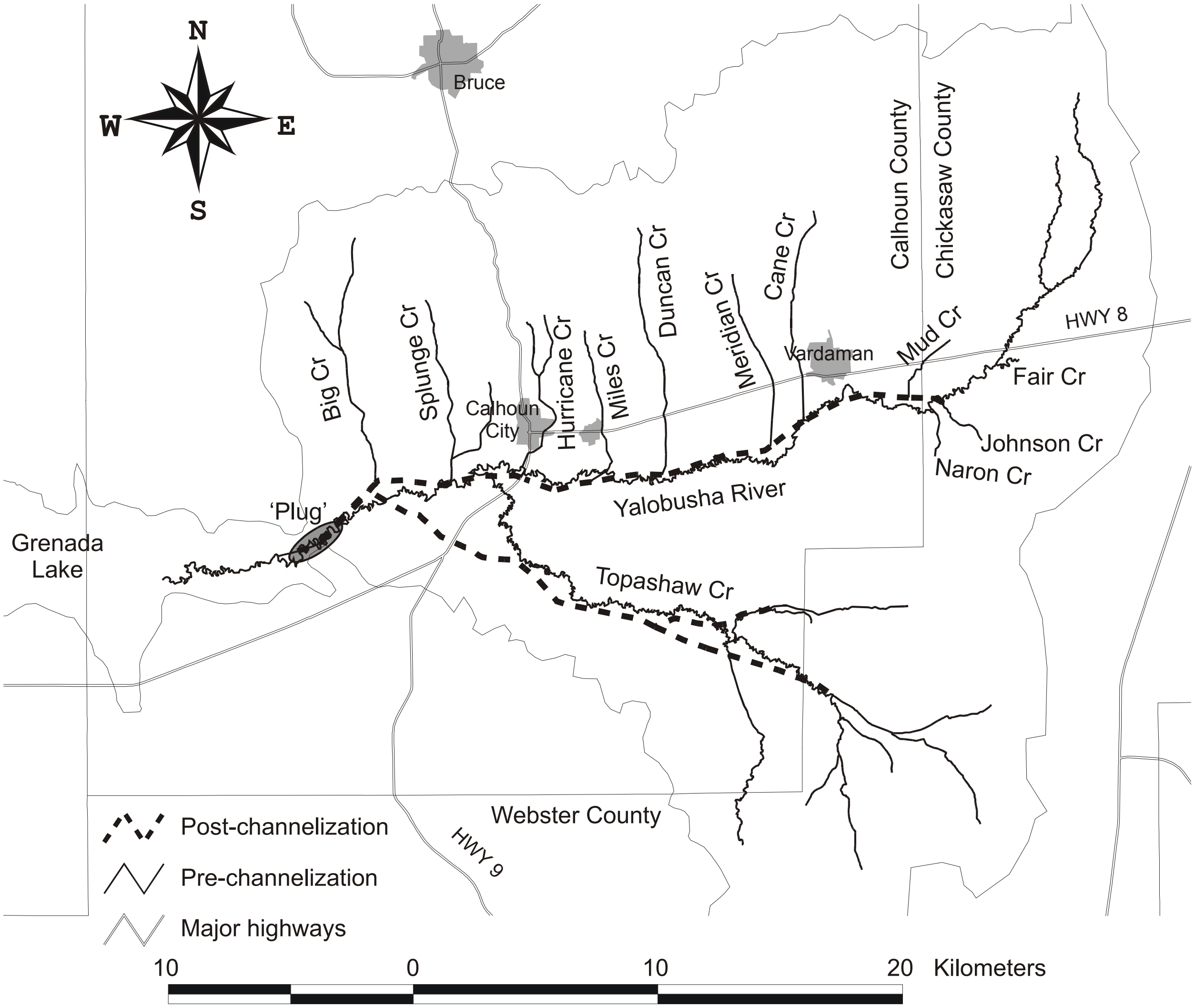


Figure 1. Map showing pre- and post-channelization stream courses, and the plug location. The modeled reach extends from the Highway 8 bridge crossing upstream of Fair Creek to the plug.

NSL has been charged with investigating potential responses of the stream system to plug removal and the effectiveness of potential mitigation measures, such as bed and bank stabilization works. In order to complete this task, NSL has developed the computer model CONCEPTS (CONservational Channel Evolution and Pollutant Transport System) (Langendoen 2000). CONCEPTS can be used to simulate the evolution of incised streams and to evaluate the long-term impact of rehabilitation measures to stabilize stream systems and reduce sediment yield. In the future, CONCEPTS will be utilized to perform a study to determine channel response to the two-phase removal of the plug. At present, for calibration purposes, it is being tested to simulate channel evolution of the Yalobusha River for a reach extending from the plug (model kilometer (Mkm) 35) upstream to the Highway 8 bridge (Mkm 0) over a 30-year period. This paper reports preliminary comparisons of predicted and observed channel hydraulics and morphology.

Model Description

CONCEPTS simulates unsteady, one-dimensional flow, transport of cohesive and cohesionless sediments in suspension and on the bed selectively by size class, and bank erosion processes in stream corridors (Langendoen 2000). Hence, it can predict the dynamic response of flow, sediment transport and channel form ('channel evolution') to disturbances including channelization, altered hydrologic regime (e.g. by dam construction or urbanization), or instream hydraulic structures.

Hydraulics. CONCEPTS assumes stream flow to be one-dimensional along the centerline of the channel. It computes the flow as a function of time simultaneously at a series of cross sections along the stream using the Saint Venant equations [e.g. Cunge et al. 1980]. The governing equations are discretized using the generalized Preissmann scheme, and the resulting set of algebraic equations are solved using Gaussian elimination with partial pivoting for banded matrices (*LAPACK* 1999). Four types of hydraulic structures are included in CONCEPTS: box and pipe culverts, bridge crossings, grade control (drop) structures, and any structure for which a rating curve is available.

Sediment transport and bed adjustment. CONCEPTS calculates total-load sediment transport rates by size fraction from a mass conservation law, and taking into account the differing processes governing entrainment and deposition of cohesive and cohesionless bed material (Langendoen 2000). For graded bed material, the sediment transport rates depend on the bed material composition, which itself depends on historical erosion and deposition rates. Following Hirano (1971), CONCEPTS divides the bed into a surface or active layer and a subsurface layer. These layers constitute the so-called 'mixing layer'. Sediment particles are continuously exchanged between the flow and surficial layer, whereas particles are only exchanged between the surface layer and substrate when the bed scours and fills. For cohesive materials, the erosion rate is calculated by an excess shear-stress approach while the deposition rate is calculated following the method of Krone (1962).

Streambank Erosion. CONCEPTS simulates channel width adjustment by incorporating the fundamental physical processes responsible for bank retreat: (1) fluvial erosion or entrainment of bank toe material by flow, and (2) bank mass failure due to gravity (Langendoen 2000). Natural streambank material may be cohesive or noncohesive and may comprise numerous soil layers reflecting the depositional history of the bank materials; each layer can have physical properties quite different from those of other layers. CONCEPTS accounts for streambank stratigraphy by allowing variable critical shear-stresses to be assigned to the bank materials. An average shear-stress on each soil layer is computed, which increases with depth. Because of the resulting shear stress distribution, CONCEPTS is able to more realistically simulate streambank erosion caused by undercutting and cantilever failures.

Bank stability is analyzed via the limit equilibrium method based on static equilibrium of forces and/or moments. Streambank failure occurs when gravitational forces that tend to move soil downslope exceed the forces that resist movement. The risk of failure is usually expressed by a factor of safety, defined as the ratio of resisting to driving forces or moments. CONCEPTS performs stability analyses of planar slip failures and cantilever failures of overhanging banks by dividing the bank into slices, and evaluating the balance of forces on each slice in vertical and horizontal directions. The slope of the failure surface is defined as that slope for which the factor of safety is a minimum. The bank's geometry, soil shear-strength (effective cohesion, c', and angle of internal friction, ϕ'), pore-water pressure, confining pressure, and riparian vegetation determine the stability of the bank.

Input Data Requirements. CONCEPTS requires similar input data to other such models [e.g. HEC-RAS (*HEC-RAS* 1995), or GSTARS2.1 (*GSTARS2.1* 2000)]. Typical input data are: water and sediment inflow at the upstream boundary of the model channel and any tributaries; the geometry (cross sections) of the channel; Manning's n roughness coefficients; and composition of bed and bank material. In addition, the user needs to supply bank material properties for the streambank erosion component of CONCEPTS, such as the critical shear stress required to entrain bank material particles, and the shear-strength parameters effective cohesion, c', and angle of internal friction, ϕ'. All input data can be obtained from Federal agencies such as the United States Geological Survey or can be measured *in situ*.

Yalobusha River watershed description

At the downstream terminus of channelization works, the drainage area of the Yalobusha River is approximately 880 km^2. Within the watershed, terrain elevations range from 63 to 186 m above mean sea level. Based on mean-daily precipitation data from 1968 to 1997, the local National Weather Service climate station (Calhoun City, MS) receives a mean annual rainfall of 1362 mm, with precipitation occurring mainly in winter and early spring. The soil type, as derived from the U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS) Soils 5 database, ranges from silty clay to loamy sand. From Landsat satellite imagery taken on July 31, 1991, the land use of the watershed comprises 7% cultivated, 30% pasture, 59% forest, and 4% containing water or urban areas.

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 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, down valley to an outlet into the sinuous channel of the river about 1.8 km downstream of State Highway 9, south of Calhoun City (MSBD 1940a). This work was followed two years later by the excavation of a 17.7 km ditch through the valley of Topashaw Creek, work further extended into the upper watershed (MSBD 1940b). After a debris jam closed the downstream end of Topashaw Creek and a reach of the Yalobusha River 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 had also been greatly reduced (MSBD 1940b). Hence, it was recommended that the downstream ends of both streams be deepened and widened to improve drainage in the area around Calhoun City.

A comprehensive river basin work plan was devised and implemented by the U.S. Soil Conservation Service (SCS) in the late 1960s. This plan provided for the clearing, dredging, straightening, and widening of the Yalobusha River and many of its tributaries. During 1967, the Yalobusha River was cleared and dredged from a point 4.5 km downstream of its confluence with Topashaw Creek upstream to the Calhoun-Chickasaw County line (Fig. 1). 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. In addition, most tributaries were cleared, dredged or realigned for some of their length.

The present sediment/debris plug is shown in Figure 2 as a large hump in the 1997 thalweg profile of the lower Yalobusha River. A comparison of the 1968 and 1997 channel profiles shows that as much as 7 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 Mkm 25.7, producing lake-like conditions downstream of Calhoun City. The plug has grown steadily since 1968 with eroded sediment from upstream reaches and tributaries, and woody vegetation from destabilized streambanks (see Downs and Simon 2001). The bed material in

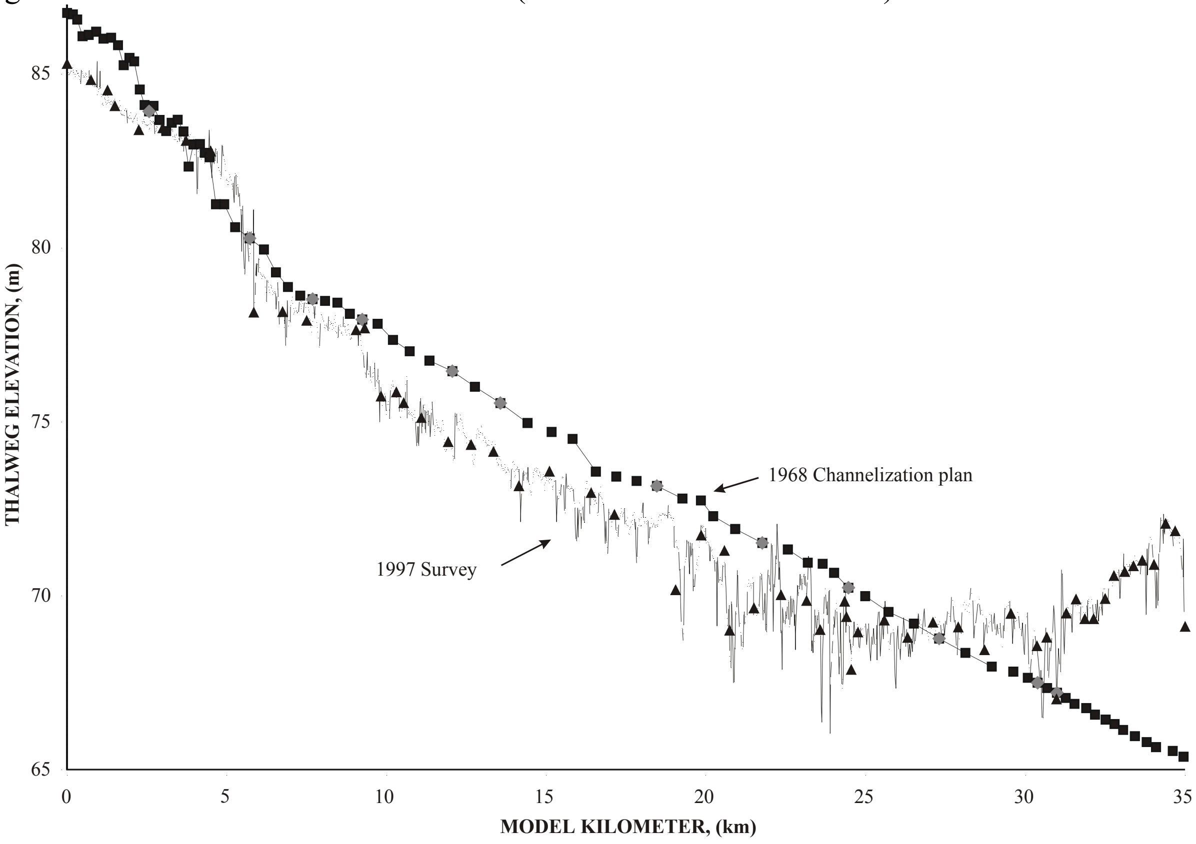


Figure 2. Comparison of 1968 and 1997 thalweg profiles. Squares and triangles depict cross-section locations in 1968 and 1997 respectively. Gray diamonds indicate tributary locations.

depositional downstream reaches (below Mkm 12) is sand; D_{50} varies from 0.27 to 0.39 mm. In degrading reaches (upstream of Mkm 7.1), the bed material is stiff silt-clay composed of two geologic formations: Naheola and Porters Creek Clay. Porters Creek Clay, located between Mkms 5 and 10, is very firm and highly resistant to erosion, requiring shear stresses in the hundreds of Pascals to initiate downcutting. Utilizing a submerged jet-test device, Simon et al. (2002) found critical shear-stress for the Porters Creek Clay formation to be fairly constant, the mean value of 67 tests was 185 Pa; the mean erosion-rate coefficient was 2.0×10^{-6} m/s (Simon et al. 2002). Upstream and downstream of this reach, the bed is composed of the relatively erodible Naheola formation. The critical shear-stress for the Naheola formation was quite variable, the mean and median values of 105 tests were 23.1 and 1.5 Pa, respectively; the mean erosion-rate coefficient was 4.4×10^{-6} m/s (Simon et al. 2002).

Model Setup and Results

Simulated hydrology. To simulate the hydraulics and morphology of the model reach, hydrographs of all runoff events between January 1, 1968 and December 31, 1997 had to be imposed at the upstream boundary (Mkm 0) and at the mouths of major tributaries (Fair, Johnson, Mud, Naron, Cane, Meridian, Duncan, Miles, Hurricane, Splunge, Big, and Topashaw Creeks). These hydrographs were not available. The hydrologic model AnnAGNPS (Annualized AGricultural Non-Point Source pollutant loading model) was therefore used to generate these hydrographs.

AnnAGNPS is a continuous simulation, daily time step, watershed scale, pollutant loading model (Bingner and Theurer 2001). AnnAGNPS analyzes a watershed subdivided into suitably small cells of homogeneous land use management, climate and soils, which can adequately approximate site conditions. Runoff, sediment, and other contaminants are routed from each cell through a channel network to the outlet of the watershed. AnnAGNPS uses NRCS curve number technology to calculate runoff. Curve numbers are selected based on the National Engineering Handbook, Section 4 (NRCS 1985). AnnAGNPS uses an extended version of SCS Technical Release 55 (TR-55) to compute peak discharge (Bingner and Theurer 2001). The derivation of time-to-peak is based on the topography and roughness of the landscape. Hydrologic simulation yields the peak discharge, time-to-peak, and runoff volume for each rainfall event and cell. Triangular hydrographs can be constructed at the downstream end of each

Table 1. Input data for AnnAGNPS simulation of the Yalobusha Watershed.

INPUT VARIABLE	DESCRIPTION
Base Digital Elevation Model (DEM)	Standard USGS 30 × 30 × 1m DEM
Land use	7% cultivated, 30% pasture, 59% forested, 4% water or urban (from Landsat satellite imagery dated July 31 1991)
Curve number	Curve number for cultivated fields assigned assuming a cotton crop
Soil type	Type for each cell derived from STATSGO GIS soil layer and NRCS Soils 5 database
Precipitation	Measured daily precipitation from National Weather Service Calhoun City, MS gauge applied uniformly over watershed
Channel slope in channelized reaches	Slope for each cell assigned from 1997 CoE channel network surveys

stream segment using empirical relations for peak discharge and time-to-peak. Example input data for the AnnAGNPS simulation of the Yalobusha Watershed can be seen in Table 1.

The USGS operates gauging stations at the Highway 9 bridge crossings of the Yalobusha River and Topashaw Creek. Flow data from these stations are combined and reported as "Yalobusha River and Topashaw Creek at Calhoun City". The contributing drainage area is 765 km^2. Mean-daily discharge and peak flow data are available since 1950 and 15-minute records are available since 1987. Discharges of 1.01-, 2-, 5-, and 10-year recurrence intervals are 155.7, 719.2, 1161, and 1472 m^3/s, respectively. Figure 3 compares the observed and simulated annual peak discharges from 1968 to 1997 and the observed and simulated storm event peak discharges from 1987 to 1997. Peak discharges up to 500 m^3/s are underpredicted but flows above this, those which transport the most sediment, are well simulated. The differences for peak discharges smaller than 80 m^3/s may possibly be caused by backwater effects at the gauging stations due to the plug, producing erroneously large discharges. Differences can be further attributed to:

- the use of a single rain gauge in an area where rainfall events can be highly localized;
- coarse watershed delineation with varying land uses within cells may cause inaccurate curve number selection. This may lead to poor runoff prediction;
- the use of a daily time-step model that cannot simulate rainfall events with large temporal variations in rainfall intensity.

In spite of the above deficiencies in the hydrologic model and the fact that no calibration has taken place, the predicted hydrology of the Yalobusha River is generally agreeable with that observed (Fig. 3).

Simulated channel hydraulics and morphology. CONCEPTS was used to simulate the hydraulics of the model reach. The reach was subdivided into 85 inter-cross sectional subreaches. Cross sections were provided by Colorado State University, Colorado (C. C. Watson, pers. comm.), who also provided sediment rating curves for sands and fine gravels for each tributary. Rating curves for silts were developed based on the fractional content of silt within the bed material. The compositions of the bed and bank materials used in the computer simulations are listed in Table 2. Two different compositions were used for the bed material; one

Table 2. Fractional composition of bed and bank materials.

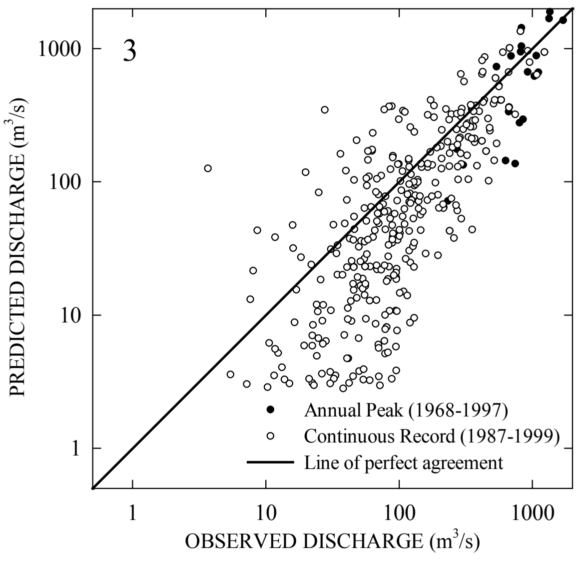
SIZE CLASS (mm)	CLAY BED	SANDY BED	BANK
< 0.01	0.22	0.31	0.42
0.01-0.03	0.20	0.16	0.17
0.03-0.07	0.51	0.16	0.14
0.07-0.25	0.06	0.24	0.25
0.25-0.84	0.01	0.10	0.02
0.84-2.00	0.00	0.02	0.00
2.00-3.36	0.00	0.01	0.00
3.36-5.66	0.00	0.00	0.00
5.66-9.57	0.00	0.00	0.00
9.57-16.0	0.00	0.00	0.00
16.0-26.9	0.00	0.00	0.00
26.9-38.1	0.00	0.00	0.00
38.1-50.0	0.00	0.00	0.00

for the Naheola and Porters Creek Clay formations (Mkms 0-10), and another for the more sandy bed material along the downstream end of the model reach (Mkms 10-35). Critical shear stresses were applied according to data from Simon et al. (2002). Table 3 lists the shear-strength (geotechnical) properties of the bank material. Manning's *n* values for the channel bed and banks were 0.033 and 0.035, respectively.

Figure 4 shows the temporal adjustment of the channel top width [1997 top widths taken from Simon (1998)]. Generally, there is good agreement; discrepancies in upstream reaches are due to uncertainties in assigning bank top locations, while those in downstream reaches are due to berm development upstream of the plug, an aspect that cannot presently be simulated. Timings of periods of accelerated widening agree with those found by Simon (1998). Figure 5 shows the temporal evolution of the thalweg profile between 1968 and 1997. Overall, comparison between the modeled and observed thalweg profiles shows good agreement; middle reaches were found by Simon (1998) to have incised by approximately 2 m, an amount closely comparable to that predicted by CONCEPTS. There are some discrepancies in the region of Mkms 4-5, apparently due to differences in survey stationing between 1968 and 1997. Additionally, there is a slight overprediction of the amount of deposition between Mkms 24-32, caused by the developing plug creating backwater conditions. In contrast, the rate of deposition along the lower 3 km of the model reach is underpredicted. It is likely that this is due to one of two things. Firstly, the discharge-stage relation at the downstream boundary may not adequately represent the effects of

Table 3. Shear-strength properties of the bank material.

MODEL KILOMETER (km)	LAYER NUMBER	COHESION (kPa)	FRICTION ANGLE (°)	UNIT WEIGHT (kN/m^3)
0-20	1	8.6	31.4	15.9
	2	8.6	18.3	16.6
	3	8.6	12.0	16.7
20-23	1	3.4	25.0	16.9
23-35	1	1.1	32.0	15.6



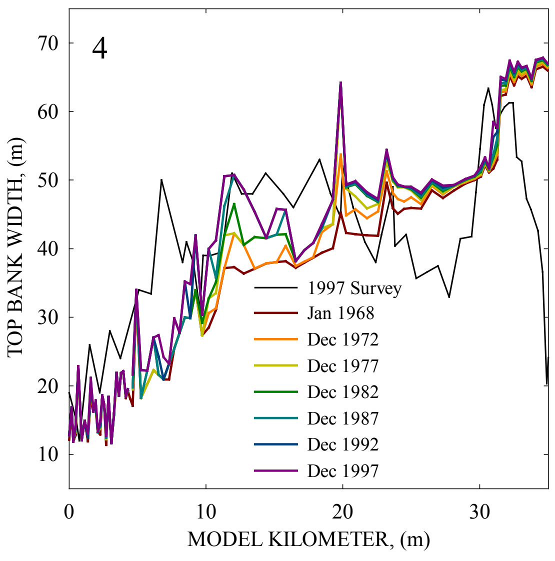


Figure 3. Comparison of observed and simulated annual peak and storm event peak discharges and **Figure 4.** Predicted and observed temporal variation of channel top width.

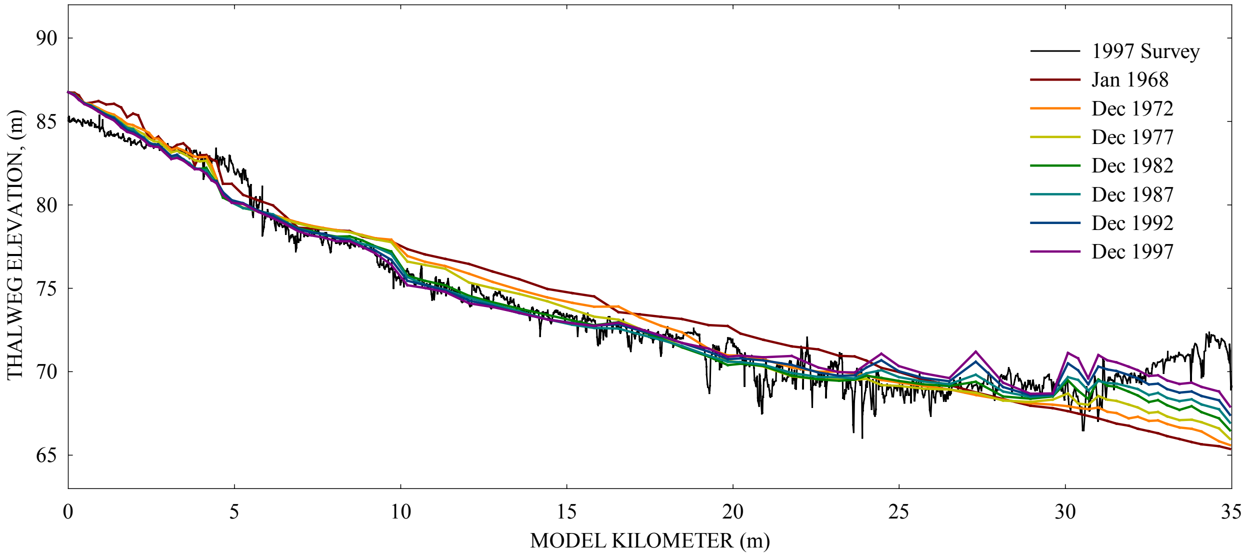


Figure 5. Predicted and observed temporal evolution of the thalweg profile.

the plug. And secondly, and most importantly, the model cannot simulate the transport and deposition of woody vegetation, which is likely to be responsible for the additional 3 m of accumulated debris.

Conclusions

Mitigation of downstream flooding and upstream erosion problems requires a full consideration of boundary conditions and dominant processes throughout the entire fluvial system. CONCEPTS, a complex computer model of channel evolution, is being used to simulate the channel morphology of a 35 kilometer-long reach of the Yalobusha River upstream of Grenada Lake, North-Central Mississippi between 1968 and 1997. 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.

The historical inflows of water at the upstream boundary of the model reach and from tributaries were produced by the watershed model AnnAGNPS based on mean-daily historical rainfall. Results suggest that AnnAGNPS can satisfactorily generate boundary conditions (tributary inflows) to open-channel flow models, although drainage areas of contributing tributaries should not exceed 1000 km^2. Simulated long-term statistics agree well with those measured, suggesting that for the study of channel evolution, runoff events are adequately simulated by CONCEPTS. Initial results of the morphological simulations indicate that CONCEPTS slightly overpredicts the amount of deposition between model kilometers 24-28 and model kilometers 30-32, and underpredicts the rate of deposition along the lower 3 km of the model reach. In both cases, the cause is likely to be the additional deposition caused by vegetative debris. However, the general rates and trends of morphological changes are correctly simulated.

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