Numerical simulation of the morphology of the Upper Yalobusha River, Mississippi between 1968 and 1997.

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ABSTRACT: The 1960s channelization of the Upper Yalobusha River, North-Central Mississippi, caused a wave of upstream-migrating incision which deepened upstream reaches and tributaries. Ensuing widening of the channels delivered woody vegetation to the flow, forming a large debris jam at the downstream terminus of channelization. Plans are being developed to remove the debris jam, which may prompt a new cycle of channel adjustment processes. A numerical modeling study is presently being carried out to investigate the response of the Upper Yalobusha River to debris jam removal. This paper reports on the testing of the computer model CONCEPTS against the observed morphological changes between 1968 and 1997. Comparison of observed and simulated peak discharges at the downstream end of the modeling reach (R^2=0.71) shows that CONCEPTS adequately describes the observed hydraulics. Despite a lack of calibration, preliminary results of the morphological simulations show that CONCEPTS correctly illustrates the erosional and depositional patterns within the study reach.

1 INTRODUCTION

The potential for catastrophic flooding along reaches of the Yalobusha River upstream of Grenada Lake in North-Central Mississippi has dramatically increased since the late 1960s. Between the 1910s and the 1940s, the Yalobusha River and Topashaw Creek were channelized and the downstream end of Topashaw Creek was relocated to improve drainage and reduce the frequency of flooding (e.g. Mississippi Board of Development 1940a, b, Fig. 1). However, by 1940, the new outlet was obstructed in some places with sediment and debris, and the capacity of the Yalobusha River in the vicinity of Calhoun City, Mississippi had been greatly reduced (Mississippi Board of Development 1940c). As a response to this, a comprehensive river basin work plan was devised and implemented in the late 1960s to deepen and widen the downstream ends of both streams. As a consequence of channel adjustment processes related to channelization, upstream-migrating knickpoints caused deepening of upstream reaches and tributary channels. Sufficient deepening occurred to cause 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. A large debris jam formed at the downstream terminus of the channelization works, where channelized reaches terminate into an unmodified, sinuous reach with much smaller cross-sections and conveyances (Fig. 2). Sediment eroded from the boundary of the Yalobusha River, its tributaries, and from upland areas has been deposited at the debris jam, further reducing sediment-transport capacity. The debris jam has caused increased stages and flood frequencies in the vicinity of Calhoun City, 10 km upstream.

After a geomorphic evaluation of the Yalobusha River system, Simon (1998) reported that the channel banks contribute at least 85% and as much as 92% of the sediment eroded from the channels of the stream system. Sediment yields range from about 320 tonnes/km^2/yr for the Yalobusha River to almost 1,800 tonnes/km^2/yr for Cane Creek.

The US Army Corps of Engineers (USACE) have identified a number of remediation strategies including debris jam removal, numerous grade-control structures to arrest headward migration of knickpoints, and flood-retarding structures. The US Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory (NSL) has been assisting USACE in developing a technical work plan for the purpose of mitigating drainage and flooding problems.

Simon et al. (2002) carried out an extensive study of the resistance of the cohesive bed and bank materials to erosion. Results of this study are being used to determine locations of future grade-control structures and possible responses of the stream system to debris jam removal. During the next few years, the

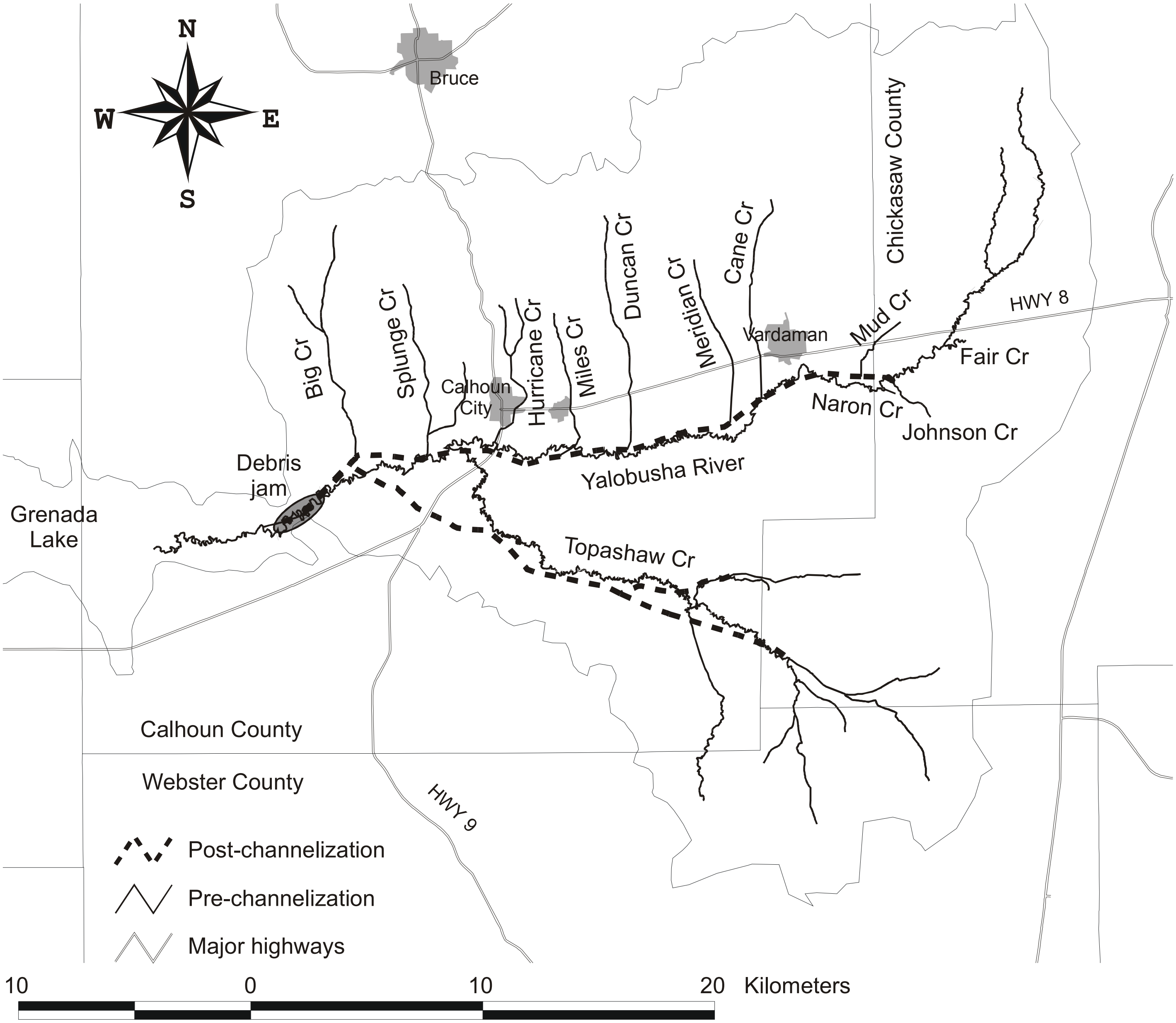

Figure 1. Map of the Yalobusha River Watershed upstream of Grenada Lake, MS showing the pre- and post-channelization course of the Upper Yalobusha River and the Topashaw Creek, and the location of the debris jam. The modeled reach extends from the Highway 8 bridge crossing upstream of Fair Creek to the debris jam.

debris jam will be removed in two phases: first, a channel will be dredged through the debris jam, followed by its complete removal. In the future, a numerical study with the CONCEPTS computer model will be performed to determine channel response to the two-phase removal of the debris jam. At present, CONCEPTS is being tested to simulate the changes in channel geometry of the Yalobusha River upstream of the debris jam between 1968 and 1997. This paper reports preliminary comparisons of predicted and observed channel hydraulics and morphology.

2 GOVERNING PHYSICAL PROCESSES AND THEIR NUMERICAL APPROXIMATION

Incision of alluvial, channelized streams is widespread in the Mid-south and Midwestern United States, with the concomitant loss of land and stream habitat. The highly erodible loess soils are unable to halt the incision and widening of many of these stream systems, leading to increased sediment production and yields as material is eroded from beds and banks. Post-disturbance, incised channels follow an evolutionary sequence of degradation, continuing degradation with channel widening, followed by aggradation and widening, and final attainment of quasi-equilibrium (e.g. Schumm et al. 1984, Simon & Hupp 1986). The aggradational phase can also be accompanied by incipient channel meandering. This sequence can last well over 100 years. To evaluate remediation strategies, it is very important to obtain a proper understanding and description of these processes. Further, there is a need for comprehensive computer models that simulate the long-term morphology of incised channels.

Figure 2. Photograph of debris jam.

NSL has developed the CONservational Channel Evolution and Pollutant Transport System (CONCEPTS) computer model 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. CONCEPTS simulates unsteady, one-dimensional flow, graded sediment transport, and bank-erosion processes in stream corridors (Langendoen 2000). It can predict the dynamic response of flow and sediment transport to instream hydraulic structures. It computes channel evolution by tracking bed elevation changes and channel widening. The bank erosion module accounts for basal scour and mass wasting of unstable cohesive banks. CONCEPTS simulates transport of cohesive and cohesionless sediments, both in suspension and on the bed, and selectively by size classes. CONCEPTS also includes channel boundary roughness varying along a cross section, for example due to varying vegetation patterns.

2.1 *Hydraulics*

CONCEPTS assumes the flow in stream systems 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 by a double sweep algorithm (Langendoen 2000). CONCEPTS switches to a modified formulation of the governing equations to handle flashy runoff events, common to the size and locale of disturbed streams in the Mid-south and Midwestern US.

There are four types of hydraulic structures included in CONCEPTS: (1) box and pipe culverts, (2) bridge crossings, (3) grade control (drop) structures, and (4) any structure for which a rating curve is available. The mathematical representation of the flow at hydraulic structures is equivalent to that of open-channel flow, resulting in an efficient implementation of hydraulic structures into the solution method.

2.2 *Sediment transport and bed adjustment*

Sediment-transport rates are a function of flow hydraulics, bed composition, and upstream sediment supply. The composition of the channel bed may change as particles are eroded from or deposited on the bed, thereby changing flow hydraulics and fractional transport rates. 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 substrate or subsurface layer. These layers constitute the so-called ‘mixing layer’. The subsurface layer may be composed of several layers reflecting historical deposition patterns. Sediment particles are continuously exchanged between the flow and the surface layer, whereas particles are only exchanged between the surface layer and substrate when the bed scours and fills. The volumetric fraction content by size class in the surface layer is determined by a mass conservation equation (Langendoen 2000). CONCEPTS uses 13 predefined size classes to represent graded sediment: < 0.01, 0.01-0.025, 0.025-0.065, 0.065-0.250, 0.25-0.841, 0.841-2.0, 2.0-3.36, 3.36-5.66, 5.66-9.57, 9.57-16.0, 16.0-26.9, 26.9-38.1, and 38.1-50.0 mm.

For cohesive bed material, erosion rate is calculated following an excess shear-stress approach (e.g. Ariathurai & Arulanandan 1978):

$$E = K\left(\tau/\tau_c - 1\right) \tag{1}$$

where K is erosion-rate coefficient, τ is average bed shear-stress, and τ_c is critical shear-stress to initiate erosion. The deposition rate is calculated following the method of Krone (1962).

2.3 *Streambank erosion*

Channel-width adjustment occurs in a wide variety of geomorphic contexts and is usually accompanied by changes in other morphological parameters such as channel depth, roughness, bed material composition, riparian vegetation, energy slope, and channel planform. The processes responsible for width adjustment are diverse, and the adjustment process itself displays a wide variety of spatial and temporal patterns (ASCE 1998).

It is unlikely that equilibrium approaches such as regime theory, extremal hypotheses, or tractive force methods can accurately predict width adjustment over time (ASCE 1998). CONCEPTS simulates channel width adjustment by incorporating the fundamental physical processes responsible for bank retreat: (1) fluvial erosion or entrainment of bank-material particles by flow, and (2) bank mass failure due to gravity (Langendoen 2000, Langendoen et al., in prep.). Bank material may be cohesive or non-cohesive and may comprise numerous soil layers.

The detachment of cohesive soils is calculated following an excess shear-stress approach (Eq. 1). An average shear-stress on each soil layer is computed, which increases with distance below the water surface (Langendoen et al., in prep.). If the critical shear stress of the material is exceeded, entrainment occurs. CONCEPTS is therefore able to simulate the generation of overhanging banks.

Streambank failure occurs when gravitational forces that tend to move soil downslope exceed the forces of friction and cohesion 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 (Langendoen et al., in prep.). The bank's geometry, soil shear-strength (cohesion and angle of internal friction), pore-water pressure, confining pressure exerted by the water in the stream, and riparian vegetation determine the stability of the bank.

3 MODEL SETUP AND RESULTS

3.1 *Upper Yalobusha River Watershed description*

The drainage area of the Yalobusha River Watershed at the downstream terminus of channelization works is approximately 880 km^2. Terrain elevations range from 63 to 186 m above mean sea level. From Landsat satellite imagery taken July 31, 1991, the landuse of the watershed comprises 7% cultivated, 30% pasture or grassed areas, 59% forested areas, and 4% containing water or urban areas. The soils range from a silty clay to loamy sand. Based on mean-daily rainfall data from 1968 to 1997, the local National Weather Service climate station (Calhoun City, Mississippi) receives a mean annual rainfall of 1362 mm. Precipitation occurs mainly in winter and early spring.

During the channel works completed in 1967, the Yalobusha River and Topashaw Creek were cleared and dredged from a point 4.5 km downstream of their confluence up 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 tributary streams were cleared, dredged, and realigned.

The US Geological Survey (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.

CONCEPTS will be utilized to simulate the morphology of the Yalobusha River for a reach extending from the Highway 8 bridge to the downstream terminus of the channelization works. The streamwise distance in kilometers from the Highway 8 bridge crossing is hereafter referred to as model kilometer. Figure 3 compares the 1968 (from US Soil Conservation Service channelization plans) and 1997 thalweg profiles of the modeled reach of the Yalobusha River. Figure 3 clearly shows the accumulation of sediment and debris along the downstream 8 km of the river, with a maximum deposition amount of approximately 7 m. The middle section has incised by approximately 2 m. The dominant type of bed material changes gradually from fine or medium sand at the downstream end to clay, a change accompanied by knickpoints or knickzones. The sand D_{50} varies from 0.27 to 0.39 mm. The clay formations are Naheola and Porters Creek Clay. Porters Creek Clay, located between model kilometers 5 and 10, is very firm and highly resistant to erosion. Upstream and downstream of this reach, the bed is composed of the Naheola formation. Critical shear-stresses needed to erode these formations were measured by Simon et al. (2002). The critical shear-stress for the Naheola formation is quite variable, the mean and median values of 105 tests are 23.1 and 1.5 Pa, respectively; the mean erosion-rate coefficient is 4.4×10^{-6} m/s. The critical shear-stress for the Porters Creek Clay formation is fairly constant, the mean value of 67 tests is 185 Pa; the mean erosion-rate coefficient is 2.0×10^{-6} m/s.

The banks are composed of two principle units. The upper unit comprises about 90% of the bank

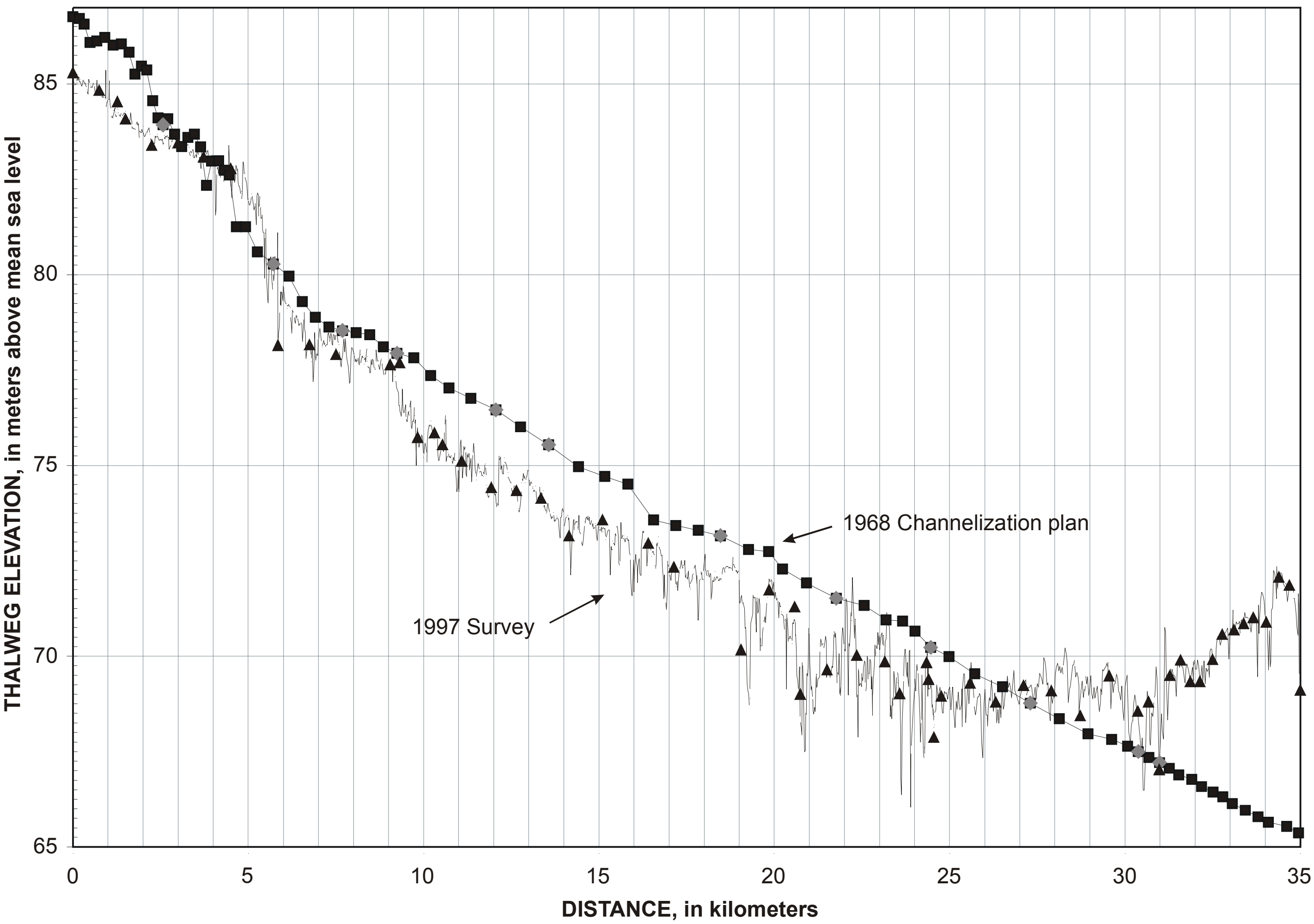

Figure 3. Comparison of 1968 and 1997 thalweg profiles of the Upper Yalobusha River. The triangles on the 1997 profile depict the location of surveyed cross sections. The squares on the 1968 profile depict cross sections obtained from the 1968 channelization plan and were used in the computer simulation. The gray diamonds indicate the location of the tributaries.

height and is composed of sandy clays. The lower unit is composed of low-plasticity clays.

3.2 *Simulated hydrology and hydraulics*

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 (model kilometer 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, pollutant loading model (Cronshey & Theurer 1998). Daily climate information is needed to account for temporal variations in the weather. The spatial variability of soils, landuse, and topography is accounted for by dividing a watershed into many homogeneous drainage areas. These simulated drainage areas are then integrated together by simulated rivers and streams, which route the runoff and pollutants from each individual homogeneous area downstream. Hydrographs can be constructed at the downstream end of each stream segment using empirical relations for peak discharge and time-to-peak. AnnAGNPS uses an extended version of US Soil Conservation Service Technical Release 55 (TR-55) to compute peak discharge (Bingner & Theurer 2001). The derivation of time-to-peak is based on the topography and roughness of the landscape.

The watershed was delineated into cells using a standard 30 × 30 m digital elevation model obtained from the USGS. The soil and landuse assigned to each cell were based on the predominant soil type and landuse within each area. The soil type was derived from the US Department of Agriculture, Natural Resources Conservation Service (NRCS) Soils 5 database. The landuse was derived from Landsat satellite imagery captured on July 31, 1991. AnnAGNPS uses NRCS curve number technology to calculate runoff. Curve numbers were selected based on the National Engineering Handbook, Section 4 (NRCS 1985). The curve number for all cultivated fields was selected assuming that a crop of cotton was growing. The measured precipitation at the Calhoun City, Mississippi climate station was applied uniformly over the entire watershed.

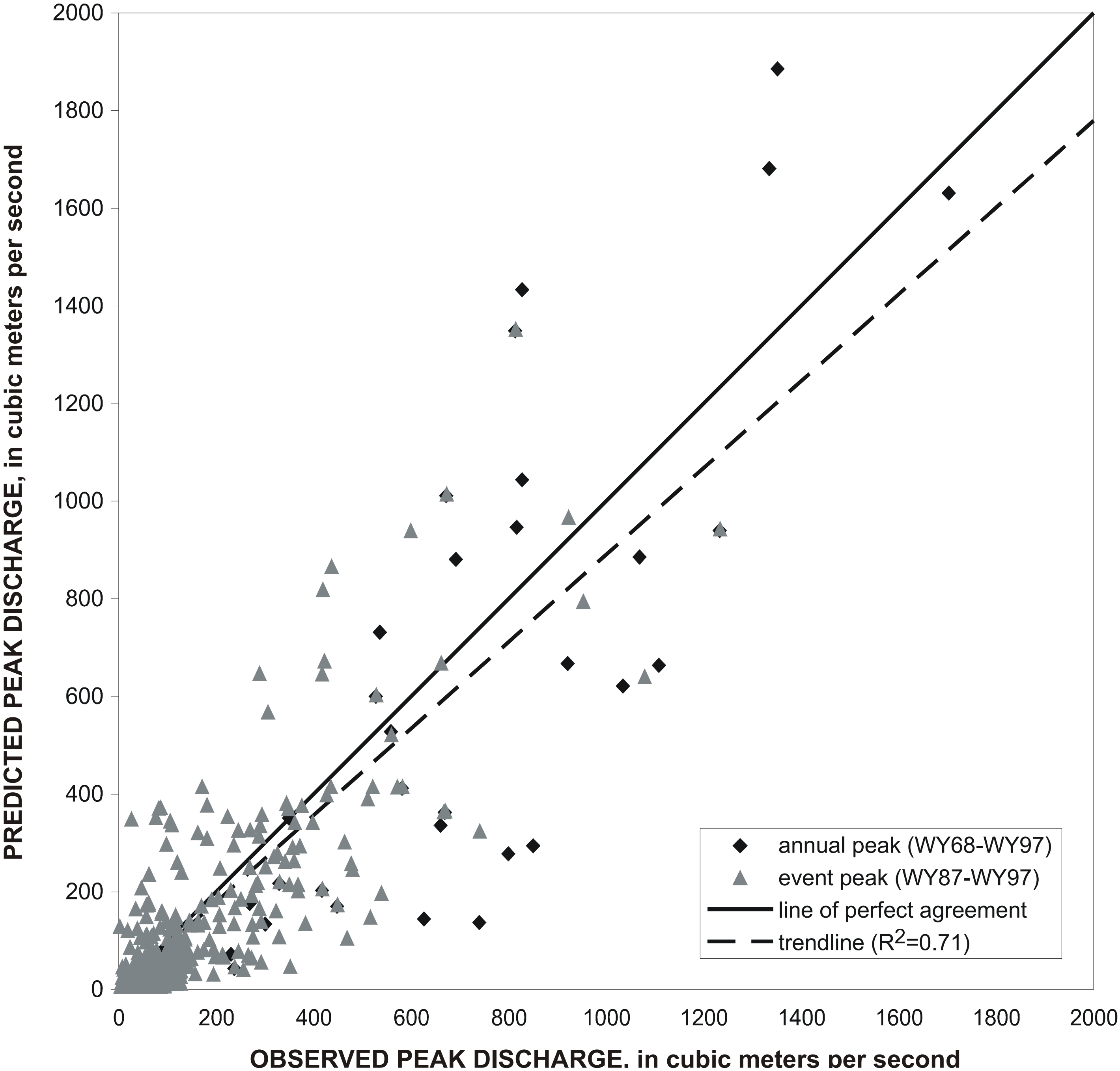

Figure 4. Comparison of the observed and simulated annual peak discharges (water years 1968-1997) and storm event peak discharges (water years 1987-1997). The R^2 value of the trendline is 0.71.

The hydrologic simulation yielded the peak discharge, time-to-peak, and runoff volume for each rainfall event and cell. From this, triangular hydrographs were constructed for the mouths of the major tributaries and the upstream end of the model reach. Runoff is assumed to begin at midnight. CONCEPTS was then used to simulate the hydraulics of the modeling reach. The model reach was subdivided into 85 inter-cross sectional subreaches (Fig. 3). Cross sections were provided by Colorado State University, Colorado (C.C. Watson, pers. comm.). Manning's *n* values for the channel bed and banks were 0.033 and 0.035, respectively.

Figure 4 compares the observed and simulated annual peak discharges for water years (WYs) 1968 to 1997 and the observed and simulated storm event peak discharges for WYs 1987 to 1997. The R^2 value of the trendline is 0.71. Figure 5 compares event peak runoff discharge exceedance probabilities for WYs 1987 to 1997. Both figures show that peak discharges up to 500 m^3/s are underpredicted. 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 debris jam, producing erroneously large discharges.

Differences can be further attributed to: the use of a single raingauge, coarse watershed delineation, inaccurate curve numbers, rainfall events crossing midnight, or rainfall events with large temporal variations in rainfall intensity. Rainfall events can be

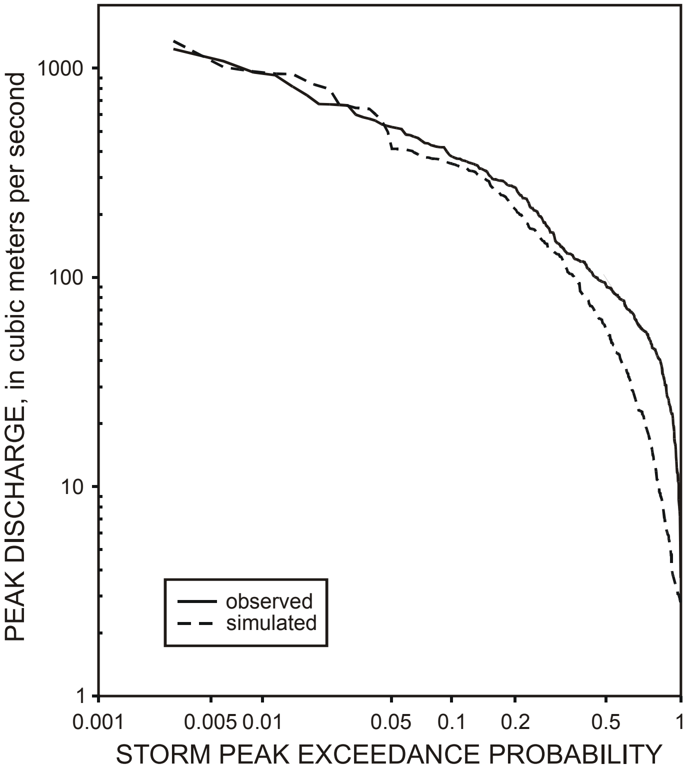

Figure 5. Comparison of observed and simulated storm peak discharge exceedance probabilities.

highly localized in North-Central Mississippi. For a watershed of this size, the spatial variation of rainfall is therefore important. The size of the cells may be too large because many contain varying landuses. Curve numbers and hence runoff prediction is very sensitive to watershed characteristics. Hence, an improved delineation of the watershed may improve the accuracy of the predicted runoff. Finally, rainfall events that cross midnight are seen by AnnAGNPS as two different rainfall events. Further, because AnnAGNPS uses a daily time step, it cannot model 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 Upper Yalobusha River is generally agreeable with that observed. The hydrological input to CONCEPTS therefore adequately represents the record required to perform the morphological simulation.

3.3 *Simulated channel morphology*

The compositions of the bed and bank materials used in the computer simulations are listed in Table 1. Two different compositions were used for the bed material; one for the Naheola and Porters Creek Clay formations (model kilometers 0-10), and another for the more sandy bed material along the downstream end of the model reach (model kilometers 10-35). Table 1 also lists the composition of the bank material, which was used along the entire model reach.

Table 1 Fractional composition of bed and bank materials.

Size class	Clay bed*	Sandy bed	Bank
1	0.22	0.31	0.42
2	0.20	0.16	0.17
3	0.51	0.16	0.14
4	0.06	0.24	0.25
5	0.01	0.10	0.02
6	0.0	0.02	0.0
7	0.0	0.01	0.0
8	0.0	0.0	0.0
9	0.0	0.0	0.0
10	0.0	0.0	0.0
11	0.0	0.0	0.0
12	0.0	0.0	0.0
13	0.0	0.0	0.0

* Naheola and Porters Creek Clay formations.

Table 2 Shear-strength properties of the bank material.

Model kilometer	Cohesion kPa	Friction angle °	Unit weight kN/m^3
0-23	3.5	25	16.9
23-35	1.1	32	15.6

Table 2 lists the shear-strength (geotechnical) properties of the bank material.

Colorado State University, Colorado (C.C. Watson, pers. comm.) 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 sediment discharge by size class at the upstream boundary of the model reach was assumed to equal the local sediment transport capacity of the flow.

Figure 6 shows the initial results on the temporal adjustment of the thalweg profile between 1968 and 1977. The rate of incision between model kilometers 10 and 27 is overpredicted. The rate of deposition along the lower 8 km of the model reach is underpredicted. For both cases there are two possible causes.

The bed downstream of model kilometer 10 comprises the Naheola formation. The critical shear stress used in the simulation, 2.25 Pa, is close to the median value of the measurements. However, τ_c for the Naheola formation is quite variable. It is therefore possible that the value used is too small. Further, the simulated sediment inflows from the local tributaries (Naron, Cane, Meridian, Duncan, and Miles) may be too small. Simon's (1998) geomorphic evaluation of the Yalobusha River channel network will be used for verification.

There are also two possible reasons for the underpredicted deposition rate at the downstream end of the model reach. Firstly, as stated above, the simulated sediment load may be too small, because the tributaries are not contributing sufficient sediment. Secondly, the discharge-stage relation at the downstream boundary may not adequately represent the effects of the debris jam.

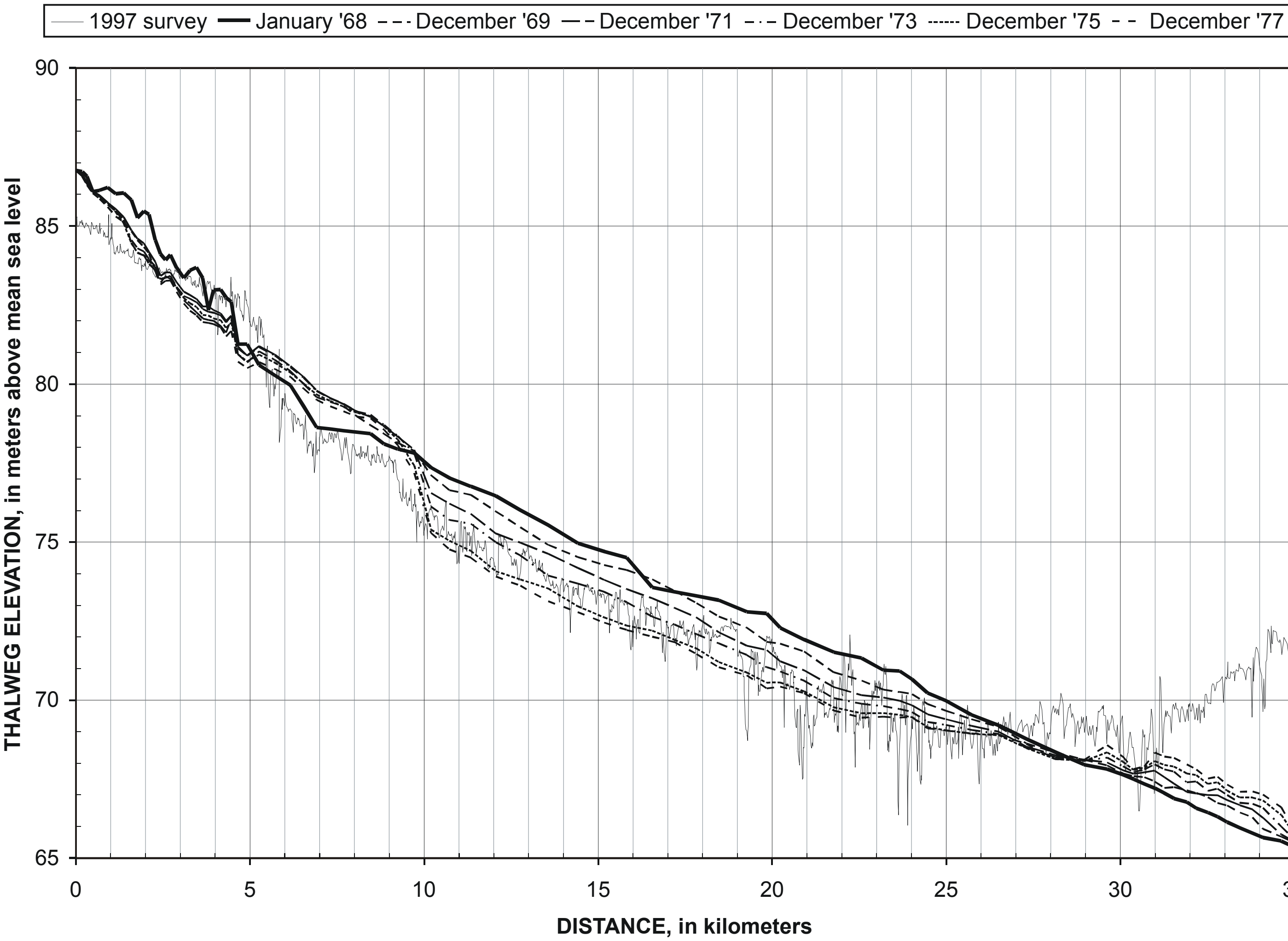

Figure 6. Predicted temporal evolution of the thalweg profile.

4 CONCLUSIONS

CONCEPTS, a complex computer model of channel evolution, has been 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. 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. Physical properties of the cohesive bed and bank materials were measured in situ.

Preliminary conclusions are:

- 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.
- For the study of channel morphological changes, runoff events are adequately simulated by CONCEPTS. Although the runoff of individual storm events may not be accurately predicted, simulated long-term statistics agree well with those measured.
- Initial results of the morphological simulations indicate that CONCEPTS overpredicts the rate of incision between river kilometers 10 and 27, and underpredicts the rate of deposition along the lower 8 km of the reach. However, the trend of the morphological changes is correctly simulated.
- Given the lack of calibration, initial results are promising. After further calibration, the model will be used to predict future channel responses to debris jam removal and potential mitigation strategies.

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