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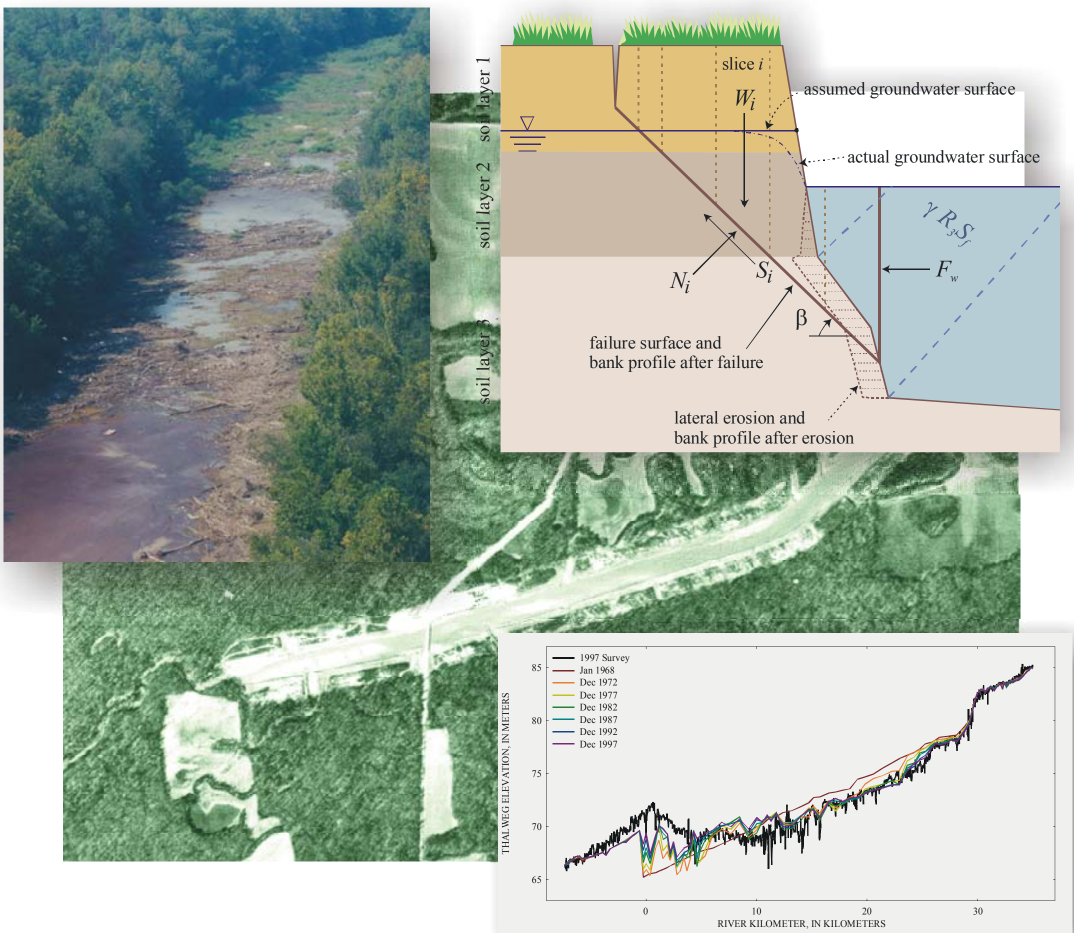
Numerical simulation of post-disturbance stream channel evolution: the Yalobusha River, Mississippi, USA.



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EXECUTIVE SUMMARY

The Yalobusha River system, North-Central Mississippi, USA, 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 283,000 tonnes yr^{-1} (Simon, 1998), while the input of vegetation due to bank failure in the vicinity of major knickpoints has been estimated to be 28 m^3 yr^{-1} or around 100 trees yr^{-1} (Downs and Simon, 2001). This has promoted the development of a large sediment/debris 'plug' at the downstream terminus of channelization works. This plug has caused increased stages and flood frequencies in the vicinity of Calhoun City, 5 km upstream.

The US Army Corps of Engineers (CoE), Vicksburg District have identified a number of remediation strategies to alleviate the downstream flooding problems while protecting the middle and upper reaches from further streambed and streambank erosion. These include total or partial plug removal, numerous grade-control structures to arrest headward migration of knickpoints following plug removal, and flood-retarding structures. Current plans (2002) are that 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.

The general objective of this study was to investigate potential responses of the Yalobusha River system to the two-phase removal of the plug and the effectiveness of potential mitigation measures, such as bed and bank stabilization works. Specifically, the US Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory was charged with:

1. calibrating the CONCEPTS computer model against existing data detailing channel changes over a 42.4 kilometer-long reach since the extensive channelization of the Yalobusha River system in 1967;
2. simulating the first phase of plug removal for a thirty year flow period over the same reach; and
3. simulating the second phase of plug removal for the same flow period over the same reach.

This report describes comparisons of predicted and observed channel hydraulics and morphology in fulfillment of the first objective. The preliminary date of completion for the second and third objectives is the closure of fiscal year 2002.

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. Simulated long-term statistics agree well with those measured, suggesting that for the study of channel evolution, runoff events are adequately simulated by CONCEPTS. Figures are presented that show that results of the CONCEPTS morphological simulations agree well with the observed thalweg profile and channel top widths, with respective r^2 values of 0.976 and 0.838. There is a slight over prediction of the amount of deposition between rkms 5 and 11 and an under prediction of the rate of deposition between rkms -0.5 and 4. The largest discrepancies occur within the areas under the influence of the plug, where flow patterns are more complex than it is currently possible to adequately simulate and where the effects of woody vegetation, likely to be responsible for the additional accumulated debris, cannot be accounted for. Narrowing, caused by berm development upstream of the plug associated with the later stages of

channel evolution, is another aspect that cannot presently be simulated. Overall, the general rates and trends of morphological changes are correctly simulated, as shown by the accuracy of the predictions of stage of channel evolution.

The largest discrepancies between observed and predicted values occur with the characteristics of deposited sediment. Of the total sediment mass downstream of Topashaw Creek, the model estimates that silt accounts for 63.2%, sand 36.6% and gravel 0.2%. Tables are included that show that in contrast, an average of 88.5% of the samples extruded in April 2002 were sand. This discrepancy is probably caused by an under representation of the sand size classes in tributary inflows. This may also be a reason for the difference between the sediment mass estimate of the model and that estimated by Simon (1998). Downstream of the confluence of the Yalobusha River and Topashaw Creek, the model predicts a total sediment mass over the 30-year simulation period of 4,520,000 tonnes, far less than the earlier estimate.

ACKNOWLEDGMENTS

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INTRODUCTION AND BACKGROUND

Human-induced disturbances imposed near the turn of the 20th century have caused thousands of kilometers of cohesive-bedded stream channels in the Midwestern United States to incise and erode at accelerated rates (Simon and Rinaldi, 2000). One example of such a channel network is the Yalobusha River system, North-Central Mississippi (Figure 1), which was extensively channelized near the turn of the 20^{th} 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. When these streambanks failed, woody riparian vegetation was delivered to the flow and 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 283,000 tonnes yr^{-1} (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 100 trees yr^{-1} (Downs and Simon, 2001).

Sediment and vegetation derived from the boundaries of the Yalobusha River, its tributaries and from upland areas have been deposited in downstream reaches of the Yalobusha River, instigating the development of a large sediment/debris plug at the downstream terminus of channelization works. This has caused higher stages and slower flow velocities than previously, promoting even greater rates of deposition, further reductions in channel capacity, and an increase in flood magnitude and frequency.

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 US Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory (NSL) has been assisting the US Army Corps of Engineers Vicksburg District (CoE) in developing a technical work plan for the purpose of mitigating drainage and flooding problems.

For its part, NSL has been investigating potential responses of the stream system to the planned two-phase plug removal and the effectiveness of potential mitigation measures, such as bed and bank stabilization works. In order to complete this task, NSL has implemented 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 42.4 kilometer-long reach extending from downstream of the plug upstream to the Highway 8 bridge over the 30-year period since the 1967 channelization works.

OBJECTIVES AND SCOPE

The general objective of this study was to provide the US Army Corps of Engineers, Vicksburg District with a working model to investigate potential responses of the Yalobusha River system to the two-phase removal of the plug and the effectiveness of potential mitigation measures, such as bed and bank stabilization works. Specifically, the US Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory was charged with:

1. calibrating this model against existing data detailing channel changes over a 42.4 kilometer-long reach since the extensive channelization of the Yalobusha River system in 1967;
2. simulating the first phase of plug removal for a thirty year flow period over the same reach; and
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This report describes comparisons of predicted and observed channel hydraulics and morphology in fulfillment of the first objective. The preliminary date of completion for the second and third objectives is the closure of fiscal year 2002.

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 US Department of Agriculture, Natural Resources Conservation Service (NRCS) SOILS5 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% water or urban areas. Analysis of the records of gauging stations at the Highway 9 bridge crossings of the Yalobusha River and Topashaw Creek (reported by the US Geological Survey (USGS) as station 07282000 Yalobusha River and Topashaw Creek at Calhoun City, MS) suggest that discharges of the 1.01-, 2-, 5-, and 10-year recurrence intervals are 155.7, 719.2, 1,161, and 1,472 $m^3 s^{-1}$, respectively. The combined contributing drainage area to these stations is 765 km^2.

Historical channel conditions

Prior to the rapid agricultural development of the region in the middle 1800s, the channel width of the Yalobusha River at its confluence with Topashaw Creek was about 6 m. A lack of proper soil conservation practices led severe sheet and gully erosion in upland areas to result in the filling and consequent reduction in channel capacity of stream channels, and frequent and prolonged flooding in downstream reaches (Simon, 1998). Cropland in valley bottoms was commonly buried with sediment and debris eroded from upstream.

Initial Channelization Projects (1910-1920s)

Both the Yalobusha River and Topashaw Creek were historically highly sinuous and avulsed several times across their floodplains in the past two centuries (Simon, 1998). However, with the exception of the downstream-most reach of Topashaw Creek, the present-day alignments of the Yalobusha River, the remainder of Topashaw Creek, and other tributaries were determined by 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 (Mississippi Board of Development, 1940a). In 1912, a 17.7 km-long ditch was excavated through the valley of Topashaw Creek from the Calhoun-Chickasaw County line to the Yalobusha River (Mississippi Board of Development, 1940b) and, in 1913, 7.64 km of Topashaw Creek and 2.82 km of Little Topashaw Creek were channelized to the Webster County line. This latter work was further extended into the upper watershed (Mississippi Board of Development, 1940c).

In response to channelization, incision oversteepened banks and helped promote failure, adding trees, sediment and other debris to the channels which were transported downstream to form a debris plug that closed the downstream end of Topashaw Creek and a reach of the Yalobusha River in the years prior to 1940 (Mississippi Board of Development, 1940b). In the late 1930s another outlet was provided for Topashaw Creek, but by 1940 this outlet was again obstructed in some places with sediment and debris, and the capacity of the Yalobusha River in the vicinity of Calhoun City had also been greatly reduced (Simon, 1998). It was therefore recommended that the downstream ends of both streams be deepened and widened to improve drainage in the area around Calhoun City.

1960s Channel Work

A comprehensive work plan detailing the clearing, dredging, straightening, and widening of the Yalobusha River system was devised and implemented by the US Soil Conservation Service in the late 1960s. 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. It 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.

This channelization prompted a new wave of incision to travel through the channel network, rejuvenating upstream reaches, increasing bank heights above stable conditions and causing numerous bank failures. When the banks failed, woody vegetation was delivered to the flow and transported downstream. Since channelization, the sediment yield due to bank failures and bed degradation alone has been estimated to be 320 tonnes km^{-2} yr^{-1} (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^{-1} or 100 trees yr^{-1} (Downs and Simon, 2001). Sediment, debris and vegetation has been deposited in downstream reaches of the Yalobusha River, promoting the development of a large sandbar and latterly a sediment/debris plug at the downstream terminus of channelization works.

Figure 2 shows pictorially the development of the sediment/debris plug. Figure 2a looks upstream from the downstream terminus of channelization after completion in November 1966. By 1968 (Figure 2b), bars were already beginning to develop and the channel was developing a meandering thalweg. By 1973, these bars had developed into berms, forming a new floodplain level within the original channel (Figure 2c). Finally, by 2002 (Figure 2d), the plug was so well developed that the channel was barely evident, and the channel and its margins had been afforested with a dense stand of secondary forest. Figure 3 shows graphically that the sediment/debris plug has grown steadily since 1967, represented as a large hump in the 1997 thalweg profile of the lower Yalobusha River. Profiles taken in 1969 and 1970 confirm photographic evidence that the plug was beginning to form only two years after completion (Figure 3). A comparison of the 1967 and 1997 channel profiles shows that as much as 6 m of sediment and debris has accumulated on the channel bed of the Yalobusha River. Very flat (0.0001) or even negative channel gradients extend to about river kilometer (rkm) 10, producing lake-like conditions downstream of Calhoun City.

Channel evolution and present channel conditions

Alluvial channels, destabilized by a variety of natural and human-induced disturbances, pass through a temporal sequence of channel forms and active processes (Schumm *et al.*, 1984; Simon and Hupp, 1986; Simon, 1989). A six-stage model of these forms and adjustment processes (channel evolution) has been developed by the USGS based on data collected from a 27,500 km^2 area of West Tennessee (Simon and Hupp, 1986; Simon, 1989; 1994).

Disruption of the dynamic equilibrium of alluvial channels often results in some amount of upstream degradation and downstream aggradation. Simon and Hupp (1986) consider the equilibrium channel as the initial, predisturbed stage (I) of channel evolution and the disrupted channel as an instantaneous condition (stage II). As the channel begins to adjust, rapid degradation of the channel bed ensues due to an imbalance between sediment supply and available stream power (stage III). Concurrently, bank heights are increased and bank angles are steepened by fluvial undercutting. Once bank heights and angles exceed the critical conditions of the bank material, channel banks are destabilized and exhibit mass failures, even though bed degradation continues (stage IV). Channel widening combined with aggradation (stage V) becomes the dominant trend in previously degraded downstream sites because degradation flattens channel gradients, preventing them from transporting the increased sediment loads emanating from degrading reaches upstream. This secondary aggradation occurs at rates roughly 60% less than the associated degradation rate (Simon, 1992), causing bed-level recovery to be incomplete. The new dynamic equilibrium (stage VI) will hence be reached after bank stability has been regained and the channel gradient reduced by meander extension and elongation. Concurrently, riparian vegetation will begin to establish and proliferate, adding roughness elements, enhancing bank accretion, and reducing the stream power for given discharges.

Simon and Thomas (2002) detail channel conditions of the Yalobusha River Basin within the framework of the six-stage channel evolution model (Simon and Hupp, 1986; Simon, 1989; 1994). Their findings suggest that:

- Downstream of rkm 9.2, main stem channels are characterized by stage VI recovered conditions, with accretion on bed and banks, the proliferation of “pioneer” woody riparian species, and the regaining of bank stability.
- Upstream of rkm 9.2, main stem channels shift to stage V conditions, as evidence of mass failures can be observed even though deposition of sand-sized materials is still evident. However, it should also be noted that Simon (1998; Table 21) noted oscillations between stage V and stage VI conditions upstream as far as rkm 17. Aggradation in these depositional areas was found by Simon (1998) to be episodic; dendrochronologic data point to 1979, 1983, and 1991 as periods of intensified deposition (and, it is surmised, channel widening (Simon, 1998)).
- Channel conditions deteriorate to stage IV at around rkm 28.6, indicated by channel bed degradation and more rapid channel widening by mass failures. Tributaries entering in this reach are also characterized by stage IV conditions and are highly unstable. Examples are Johnson, Cane, and Mud Creeks which all exhibit large, recent bank failures.

- At around rkm 30, conditions shift to stage III, where the bed is degrading but the banks remain stable and vegetated. These reaches contain knickpoints and knickzones, with steep bank surfaces smoothed by fluvial erosion and with exposed root systems. These conditions persist to the upstream boundary of our model reach.
- At rkm 44, these stage III conditions merge into undisturbed (stage I) conditions, free of exposed roots and excessive fluvial erosion.

MODELING CONTEXT

The CoE is charged with alleviating the downstream flooding problems while protecting the middle and upstream reaches from further streambed and streambank erosion. The CoE have identified a number of remediation strategies including total or partial plug removal or bypass, numerous grade-control structures to arrest headward migration of knickpoints following plug removal, and flood-retarding structures. Current plans (2002) are that 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. The CoE is also protecting upstream reaches by constructing grade-control and other structures at critical knickzones in the basin.

The CoE has charged NSL 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. To fulfill its role, NSL has utilized the computer model CONCEPTS (CONservational Channel Evolution and Pollutant Transport System) (Langendoen, 2000). The present study requires the simulation of the evolution of the Yalobusha River for a reach extending from downstream of the plug (rkm -7.4) upstream to the Highway 8 bridge near Pyland (rkm 35.0) over the 30-year period between channelization in 1967 and the basin-wide surveys conducted in 1997.

MODEL DESCRIPTION

CONCEPTS simulates unsteady 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 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 (e.g. Anderson *et al.*, 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). 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, based on the method of Ariathurai and Arulanandan (1978):

$$\varepsilon = k\left(\frac{\tau_0}{\tau_c} - 1\right) \tag{1}$$

where ε = erosion rate (m s^{-1}), k = erodibility coefficient (= $0.1 \times 10^{-6}\ \tau_c^{0.5}$ m s^{-1} (Hanson and Simon, 2001)), τ_0 = applied boundary shear stress (N m^{-2}), and τ_c = critical shear stress for entrainment (N m^{-2}). The deposition rate is calculated following the method of Krone (1962):

$$D = B\omega c\left(1 - \frac{\tau_0}{\tau_d}\right) \tag{2}$$

where D = deposition rate (m s^{-1}), B = wetted width of streambed (m), ω = particle fall velocity (m s^{-1}), c = point sediment concentration (ppmw), and τ_d = threshold shear stress below which deposition of cohesive sediments occurs (N m^{-2}). Meanwhile, for cohesionless materials, CONCEPTS assumes that the erosion or deposition rate is proportional to the difference between the sediment transport rate and sediment transport capacity (Bennett, 1974). Sediment transport is calculated by a modified version of the sediment transport capacity predictor SEDTRA developed by Garbrecht *et al.* (1996). Total sediment transport is calculated by size fraction for thirteen predefined size classes, with a suitable transport equation for each class: as wash load without deposition for sizes smaller than 10 μm; Laursen (1958) for silts; Yang (1973) for sands; and Meyer-Peter and Müller (1948) for gravels.

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 applied average boundary shear stress on each soil layer is computed by initially dividing the flow area at a cross section into segments that are affected only by the roughness of the bank or the bed (Figure 4). After the initial flow division, the bank-affected segment is further subdivided to determine the flow area affected by the roughness of each soil layer (Figure 4). The average shear stress exerted by the flow on each soil layer i, τ_i, reads:

$$\tau_i = \gamma R_i S_f \tag{3}$$

where γ is unit weight of water, $R_i = A_i / P_i$ is hydraulic radius of the flow-area segment affected by soil layer i, A_i is area and P_i is wetted perimeter of the segment, and S_f is friction slope. The resulting shear stress distribution enables CONCEPTS 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 bank's geometry, soil properties (e.g. effective cohesion, c', and effective angle of internal friction, ϕ'), pore-water pressure, confining pressure, and riparian vegetation determine the stability of the bank. CONCEPTS performs stability analyses of planar slip failures and cantilever (shear type) failures of overhanging banks by dividing the bank into slices and evaluating the balance of forces on each slice in vertical and horizontal directions (Figure 4). For planar failure, the factor of safety (FOS), defined as the ratio of resisting to driving forces or moments, is:

$$\mathrm{FOS} = \frac{\cos\beta \sum_{j=1}^{J} \left(L_j c'_j + N_j \tan\phi'_j - U_j \tan\phi_j^b \right)}{\sin\beta \sum_{j=1}^{J} N_j - F_w} \tag{4}$$

where β = angle of the failure plane (°), J = number of slices in the failure block, L_j = length of the base of slice j (m), c'_j = effective cohesion of slice j (N m^{-2}), N_j = normal force per unit channel length on the base of slice j (N m^{-1}), ϕ'_j = effective angle of internal friction of slice j (°), U_j = pore-water force per unit channel length on the base of slice j (N m^{-1}), ϕ_j^b = angle indicating the increase in shear strength for an increase in matric suction on the base of slice j ($-U_j$) (ϕ^b varies between ϕ' for saturated soils and a value commonly ranging from 15 to 20° for unsaturated soils (e.g. Fredlund and Rahardjo, 1993)), and F_w = hydrostatic force per unit channel length exerted by the surface water on the vertical part of the slip surface (N m^{-1}). The slope of the failure surface is defined as that slope for which the factor of safety is a minimum. For further information on the bank stability and erosion component of CONCEPTS, see Langendoen *et al.* (in prep.).

MODEL SETUP

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 (rkm 35.0) and at the mouths of major tributaries (Fair, Johnson, Mud, Naron, Cane, Meridian, Duncan, Miles, Hurricane, Splunge, Big, Topashaw, Unnamed and Shutispear Creeks (Figure 3)). 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 Section 4 of the National Engineering Handbook (Natural Resources Conservation Service, 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. The storm event duration can be empirically estimated as:

$$D = 2V / Q_p \qquad (5)$$

where V is runoff volume (m^3) and Q_p is peak discharge ($m^3\ s^{-1}$) (F.D. Theurer, personal communication, 2001). In the present simulation, where time-to-peak was greater than 0.375 D, time-to-peak was set to 0.375 D. Triangular hydrographs can be constructed at the downstream end of each stream segment using base flow, peak discharge, time-to-peak and storm event duration. Example input data required 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 "07282000 Yalobusha River and Topashaw Creek at Calhoun City". Mean-daily discharge and peak flow data are available since 1950 and 15-minute records are available since 1987. Figure 5 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 $m^3\ s^{-1}$ are underpredicted but flows above this, those which transport the most sediment, are well simulated. The differences for peak discharges smaller than 80 $m^3\ s^{-1}$ may possibly be caused by backwater effects at the gauging stations due to the plug, producing erroneously large measured discharges. Differences can be further attributed to:

- the use of a single rain gauge in an area where rainfall events tend to be convective and so 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;
- rainfall events that cross midnight are seen by AnnAGNPS as two different rainfall events; and
- 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 (Figure 5). The relationship of predicted to observed discharges has an r^2 of 0.722, while there is a Spearman Rank correlation coefficient of 0.784.

Simulated channel dimensions and properties

The model reach was subdivided into 107 inter-cross sectional subreaches. Cross sections for the upstream-most 34 km were provided by Colorado State University, Colorado (C.C. Watson, personal communication, 2001), 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 geometry of the remaining 8.4 km downstream of the terminus of the channelized reach was obtained by simplifying the 1997 CoE surveys. In sinuous upstream and plugged downstream reaches, Manning's *n* values for the channel bed and banks were 0.033 and 0.035, respectively, while in middle reaches (between rkms 4.5 and 30.4), Manning's *n* for the channel bed was set to 0.022.

The particle size distribution of the bed and bank materials used in the computer simulations are listed in Table 2. The bed material in depositional reaches in and upstream of the plug (rkms -0.4 to 4.5) is sand; D_{50} varies from 0.06 to 0.26 mm. Different compositions were used for the slack water reaches downstream of the plug (rkms -7.4 to -0.4) and for depositional middle reaches (rkms 4.5 to 25.5), representing deposited silty-sands from upstream reaches, and also for degrading reaches (upstream of rkm 25.5), representing a shift in the bed material to silt-clay composed of two geologic formations: Naheola and Porters Creek Clay. Porters Creek Clay, located between rkms 25.5 and 30.5, is very firm and highly resistant to erosion, requiring shear stresses in the hundreds of Pascals to cause erosion. Utilizing a submerged jet-test device (Hanson, 1990) to measure critical shear stress and erodibility at sites across the entire basin, Simon *et al.* (2002) found critical shear stress to be fairly constant for Porters Creek Clay, the mean value of 67 tests was 185 Pa; the mean erosion-rate coefficient was 2.0×10^{-6} m s^{-1}. Upstream of this reach, the bed is composed of the relatively soft and erodible Naheola formation. The critical shear stress was quite variable for the Naheola formation, 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^{-1} (Simon *et al.*, 2002).

Bank material shear-strength properties were obtained from *in situ* testing and sampling and are listed in Table 3. A Borehole Shear Tester (BST) was utilized to rapidly determine drained, effective strength values (Lutenegger and Hallberg, 1981). Seven tests were undertaken at three sites throughout the Yalobusha River system to depths of about 5.2 m as dictated by bank stratigraphy. Samples of streambank material were then removed from these boreholes to determine particle-size distributions, moisture contents and bulk unit weights. To substitute for the lack of deeper BST testing, triaxial-test data were obtained for several sites in the river basin from the Mississippi Department of Transportation (MDOT).

CONCEPTS MORPHOLOGICAL SIMULATION RESULTS

Surveys of the Yalobusha River system were conducted in 1997. These surveys, of the thalweg profile and selected cross sections throughout the watershed, have been used for comparison with the predicted model results.

Thalweg elevation adjustment

Figure 6 shows the temporal evolution of the thalweg profile between 1968 and 1997. Overall, comparison between the modeled and observed thalweg profile 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 is a slight over prediction of the amount of deposition between rkms 5 and 11, a discrepancy likely to be caused by two things. Firstly, the developing plug creates backwater conditions, which causes sand- to silt-sized material to be deposited, perhaps at rates not adequately predicted by a one-dimensional model. Secondly, because of berm development (this will be expanded upon shortly), flow is concentrated in a narrower channel than simulated within CONCEPTS, which has promoted deepening of the thalweg. In contrast, the rate of deposition in areas between rkms -0.5 and 4 of the model reach is under predicted. This may be due to three things. Firstly, because of the premature deposition noted above, the model channel carries less sediment into this reach than the Yalobusha River does in reality. Secondly, the discharge-stage relationship at the downstream boundary may not adequately represent the effects of the plug. And thirdly, and most importantly, the model cannot simulate the transport and deposition of woody vegetation, which is likely to be responsible for the additional accumulated debris. This deposition would be most pronounced where the channel gradient is most negative- for example, immediately upstream of the downstream terminus of channelization.

Active channel top width

The 1997 survey cross sections have been analyzed and active channel top widths noted. Figure 7 compares the adjustment of the channel top width and how the model predicts top width changes to occur temporally. Generally, there is good agreement; discrepancies in upstream reaches are due to uncertainties in assigning bank top locations, while those in middle reaches are due to narrowing caused by berm development upstream of the plug associated with the later stages of channel evolution, an aspect that cannot presently be simulated. Utilizing dendrochronologic methods, Simon (1998) found that 1979, 1983 and 1991 were periods of accelerated widening. CONCEPTS predicts 1978 and 1991 as periods of particularly rapid widening, which compares favorably with Simon's (1998) findings.

Numerical comparison

In addition to the visual comparisons made, a numerical analysis of the differences between observed and predicted thalweg elevations and channel top widths has also been conducted. Figures 8 and 9 illustrate these differences. The r^2 for the thalweg elevation and top width comparisons are 0.976 and 0.838, respectively. The points furthest off the line of perfect agreement lie in the middle to lower reaches, where the effects of the plug are most pronounced. To confirm this point, Figures 10 and 11 plot the streamwise difference (Observed-Predicted) for both thalweg elevation and channel top width. The maximum over prediction of the thalweg elevation in the middle reaches is 2.12 m, while there is a maximum under prediction of 4.30 m in the plug (Figure 10). In terms of channel top width, there is a maximum over prediction of 21.89 m, which is due to an error in the supplied cross sections. As stated earlier, the maximum constructed channel width at the downstream terminus of channelization was 58 m; in the supplied cross sections, maximum width is 66.52 m. In middle reaches, there is a maximum over prediction of 14.7 m, which is due to the effects of the plug in promoting berm development on a relatively large scale (Figure 11).

Stage of channel evolution

Combining the results for both the channel top width and thalweg evolution, a picture of the predicted stage of channel evolution (Simon and Hupp, 1986) can be developed. Figure 12 compares the predicted and observed (Simon and Thomas, 2002) stage of channel evolution. Model results compare favorably to the observed results. The model predicts that stage VI conditions occur from rkms -7.4 to 15.7, stage V conditions between rkms 15.7 and 28.8, stage IV conditions between rkms 28.8 and 30.5, and stage III conditions from rkms 30.5 to 35. The only significant difference between the model results and the observed conditions occurs at the downstream onset of stage V conditions (Figure 12), although the model result (rkm 15.7) does lie within the oscillatory/ transitional reach (rkm 9.2 to 17) noted by Simon (1998; Table 21).

Deposited sediment amounts and characteristics

CONCEPTS estimates the maximum total sediment mass (defined as the sediment concentration passing through a cross-section integrated with respect to time) along the Yalobusha River to be nearly 16,000,000 tonnes between 1968 and 1997 (Figure 13). At the USGS gauging station at Calhoun City, which is where the reach experiencing the most rapid deposition begins, the amount is estimated to be 8,020,000 tonnes, while immediately downstream of the confluence with Topashaw Creek, the amount is estimated to be 4,520,000 tonnes (Figure 13). Note that the amount reduces in a downstream direction as deposition reduces the amount of sediment in the water column. Theoretically, these amounts include the effects of all inputs, not just those due to channel margins.

The estimated amount is substantially lower than that predicted by Simon (1998), who estimated that the amount of sediment sourced from bank failures and bed degradation ranged from 7,159,000 to 11,628,000 tonnes (sediment density 1,631 to 2,650 kg m^{-3}). It is difficult to account for this difference. Perhaps the methods employed by Simon (1998), whereby estimated differences in cross sectional area were multiplied by stream length, overestimated sediment inputs. For example, top bank station assignments may not be accurate; Figure 14 compares channel top widths taken from Simon (1998) and those after reanalysis. Differences are due to assigning levée extremes as bank top locations. Potentially of greater importance is the fact that the amount of sand inputted into the Yalobusha system may have been under represented during the CONCEPTS simulations. Of the total sediment mass downstream of Topashaw Creek, the model estimates that silt accounts for 63.2%, sand 36.6% and gravel 0.2%. Sediment cores have been extruded from a variety of locations within the plug (S. J. Bennett and F. E. Rhoton, personal communication, 2002) to compare the predicted caliber of deposited material against that observed. Details of the results of these coring experiments can be found in Table 4. The sand fractions account for, on average, 88.5% of the cored samples, far in excess of that predicted by CONCEPTS. Figure 15 plots the streamwise variation in predicted D_{16}, D_{50}, D_{84} and D_{90} with the observed values. It can clearly be seen that for the majority of the plug, the D_{xx} of the sediment is underestimated, reinforcing the suspicion that the sand-size fraction may be under represented.

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, has been used to simulate the channel morphology of a 42.4 kilometer-long reach of the Yalobusha River upstream of Grenada Lake, North-Central Mississippi between 1967 and 1997. Major features of the Yalobusha 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.

Comparisons between results of the CONCEPTS morphological simulations and the observed thalweg profile and channel top widths show good agreement, with respective r^2 values of 0.976 and 0.838. The largest discrepancies in thalweg elevations occur within the areas under the influence of the plug, where flow patterns are more complex than it is currently possible to adequately simulate. There is a slight over prediction of the amount of deposition between rkms 5 and 11 and an under prediction of the rate of deposition between rkms -0.5 and 4. Further reasons for these discrepancies include berm development promoting flow concentration and degradation, and an inadequate stage-discharge relationship. Most importantly the effects of woody vegetation, likely to be responsible for the additional accumulated debris, cannot be accounted for. Equally, comparison of 1997 observed and predicted channel top widths suggests good agreement; errors in middle reaches are due to narrowing caused by berm development upstream of the plug associated with the later stages of channel evolution, an aspect that cannot presently be simulated. Overall, the general rates and trends of morphological changes are correctly simulated, as shown by the accuracy of the predictions of stage of channel evolution.

The largest discrepancy between observed and predicted values occurs with deposited sediment characteristics. Of the total sediment mass downstream of Topashaw Creek, the model estimates that silt accounts for 63.2%, sand 36.6% and gravel 0.2%. In contrast, an average of 88.5% of the samples extruded in April 2002 were sand. This discrepancy is probably caused by an under representation of the sand size classes in tributary inflows. This may also be a reason for the difference between the sediment mass estimate of the model and the yield estimated by Simon (1998). However, the morphological accuracy of the simulations suggests that the estimates of the model may be reasonably accurate for planning purposes. Downstream of the confluence of the Yalobusha River and Topashaw Creek, the model predicts a total sediment mass over the 30-year simulation period of 4,520,000 tonnes.

The success of proposed stream-corridor restoration measures to effectively restore stream structure and function is greatly aided by a thorough analysis of existing stream-corridor conditions and the potential geomorphic responses of the stream to the measures. Various tools or approaches are available to assist in natural channel design. Of the available approaches, the only approach applicable to situations where historical or current channel conditions are not in equilibrium with existing or predicted sedimentological and hydrological inputs is the analytical approach (e.g. computational models based on conservation laws) (Langendoen *et al*., 2001). The Yalobusha River is an example of a system presently and historically (at least, over the past century) in a state of disequilibrium. The CONCEPTS model (CONservational Channel Evolution and Pollutant Transport System) simulates unsteady flow, transport of cohesive and cohesionless sediments in suspension and on the bed selectively by size class, and bank erosion processes in stream corridors, enabling it to predict the dynamic response of flow, sediment transport and channel form to disturbances. This report summarizes efforts to calibrate the CONCEPTS model for a 42.4 kilometer-long reach of the Yalobusha River over a 30-year post-channelization period, in order that it may be used to simulate future channel responses to identified management strategies. Future reports will describe model simulations with the purpose of predicting such responses.

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FIGURES

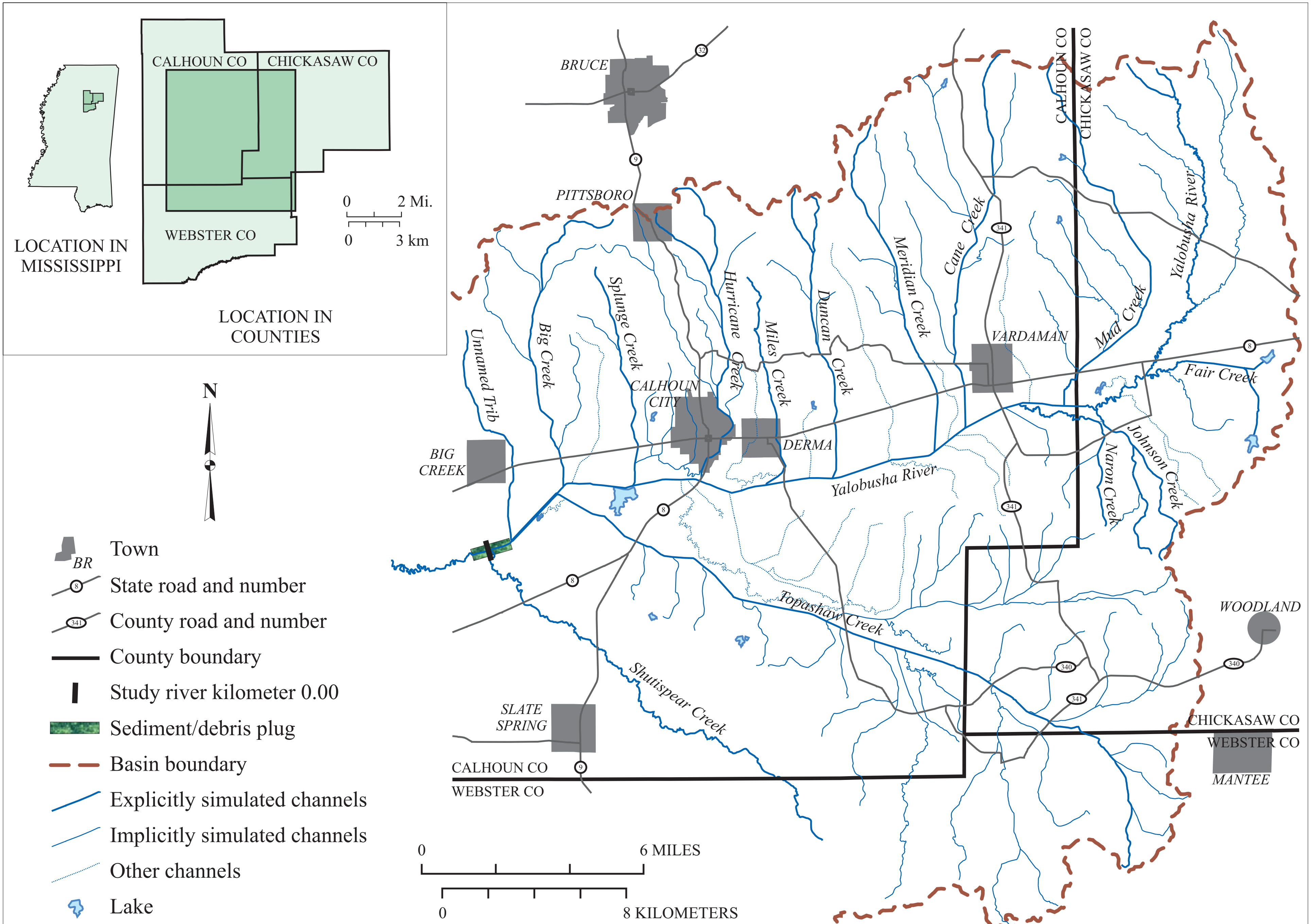

Figure 1 - Map showing the location of the study area, towns, roads, watercourses, and the location of the plug. The modeled reach extends from the Highway 8 bridge crossing upstream of Fair Creek to the sinuous reach downstream of the plug.

Figure 2 - Looking upstream from rkm 0 (the abandoned bridge just upstream of the downstream terminus of channelization works) in a.) November 1966; b.) May 1968; c.) September 1973; and d.) April 2002

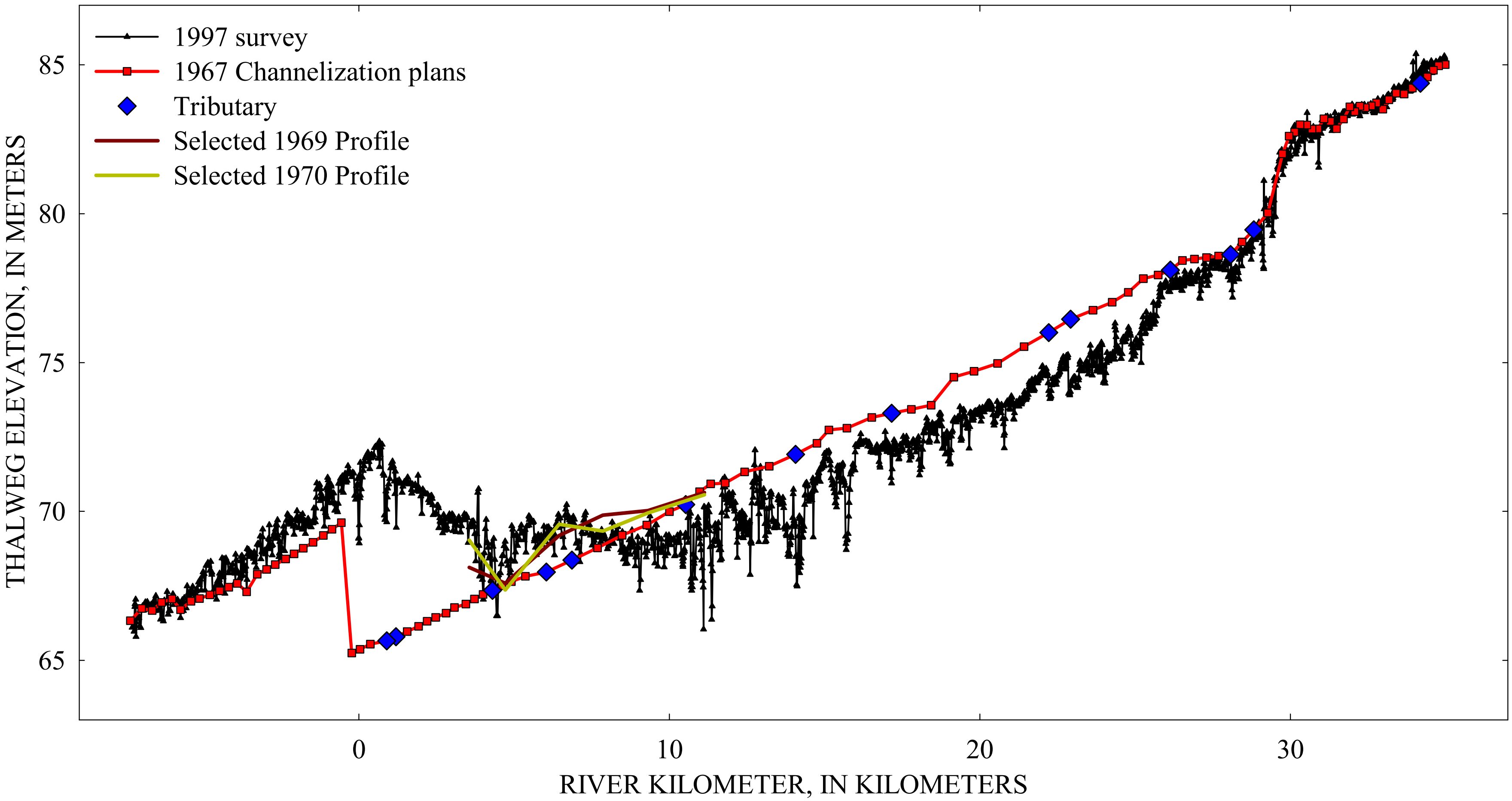

Figure 3 - Comparison of 1967, 1969, 1970 and 1997 thalweg profiles. Red squares and black triangles depict cross-section locations in 1967 and 1997 respectively. Blue diamonds indicate tributary locations

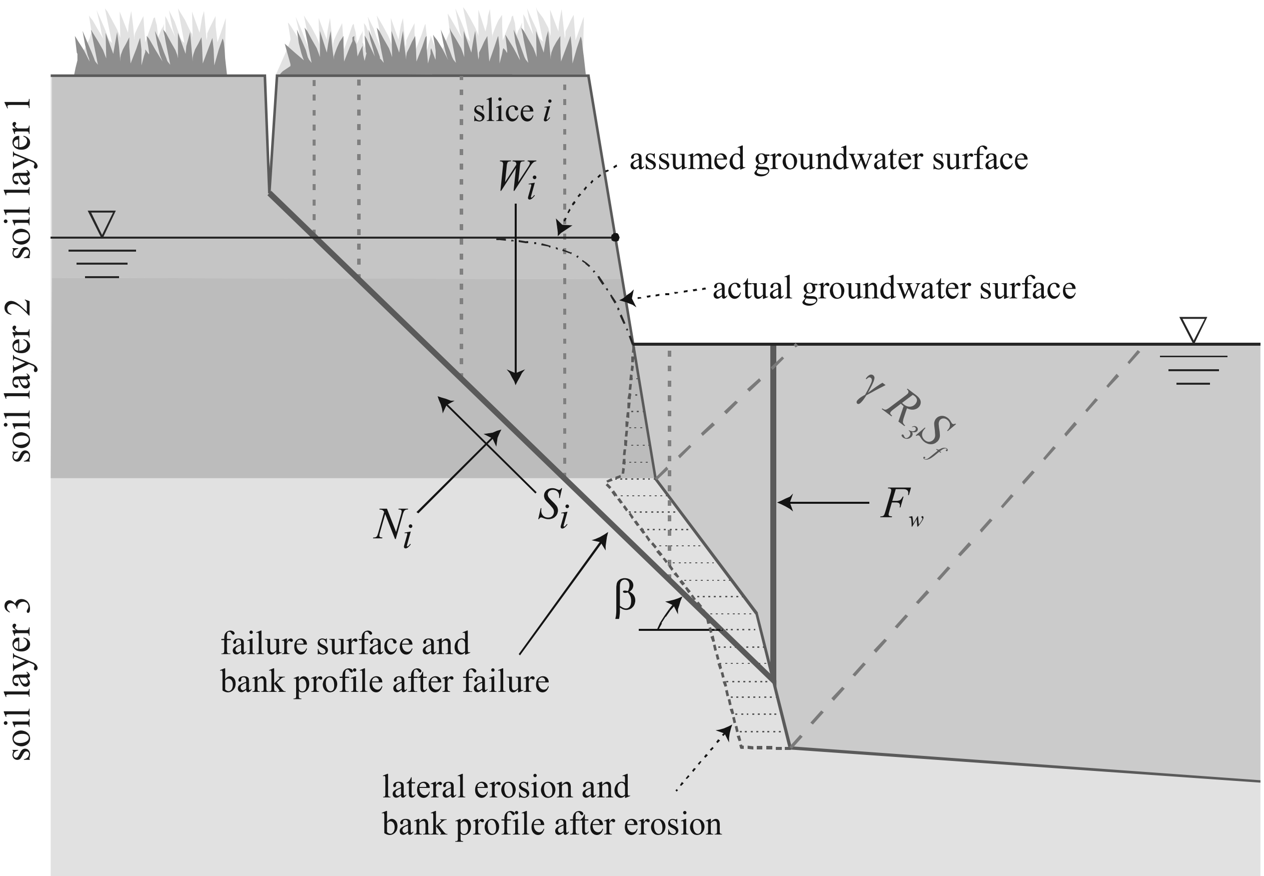

Figure 4 - Bank geometry as applied within CONCEPTS

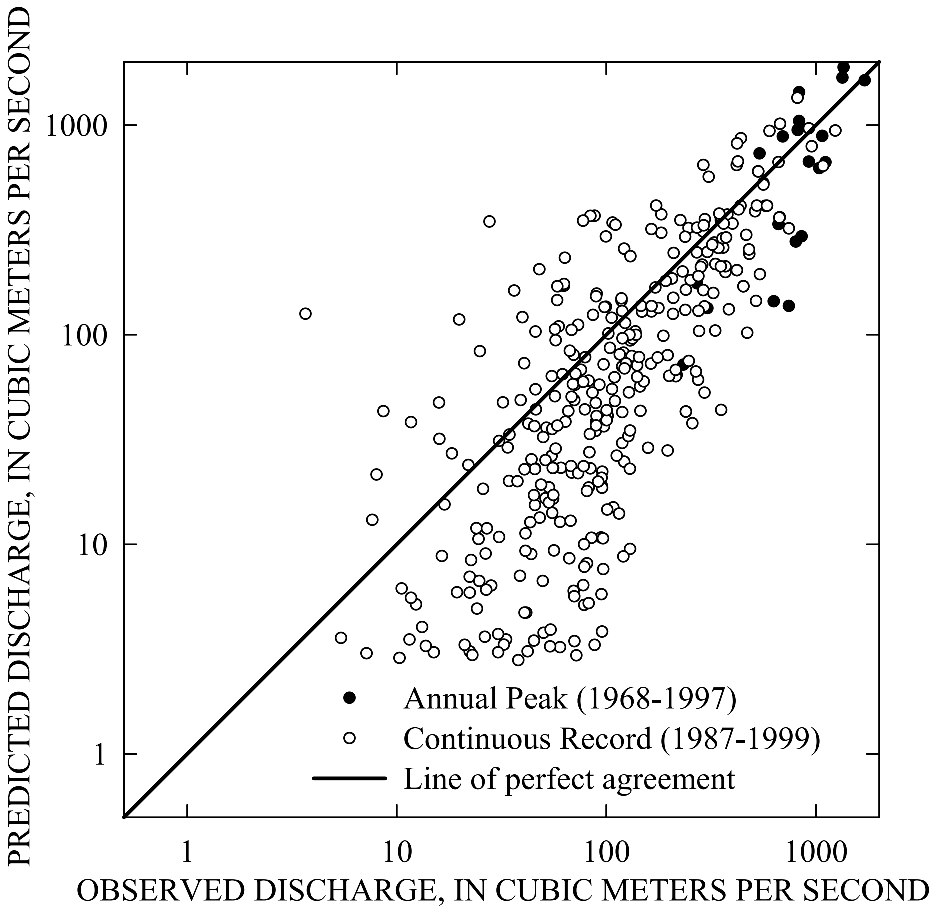

Figure 5 - Comparison of observed and simulated annual peak and storm event peak discharges

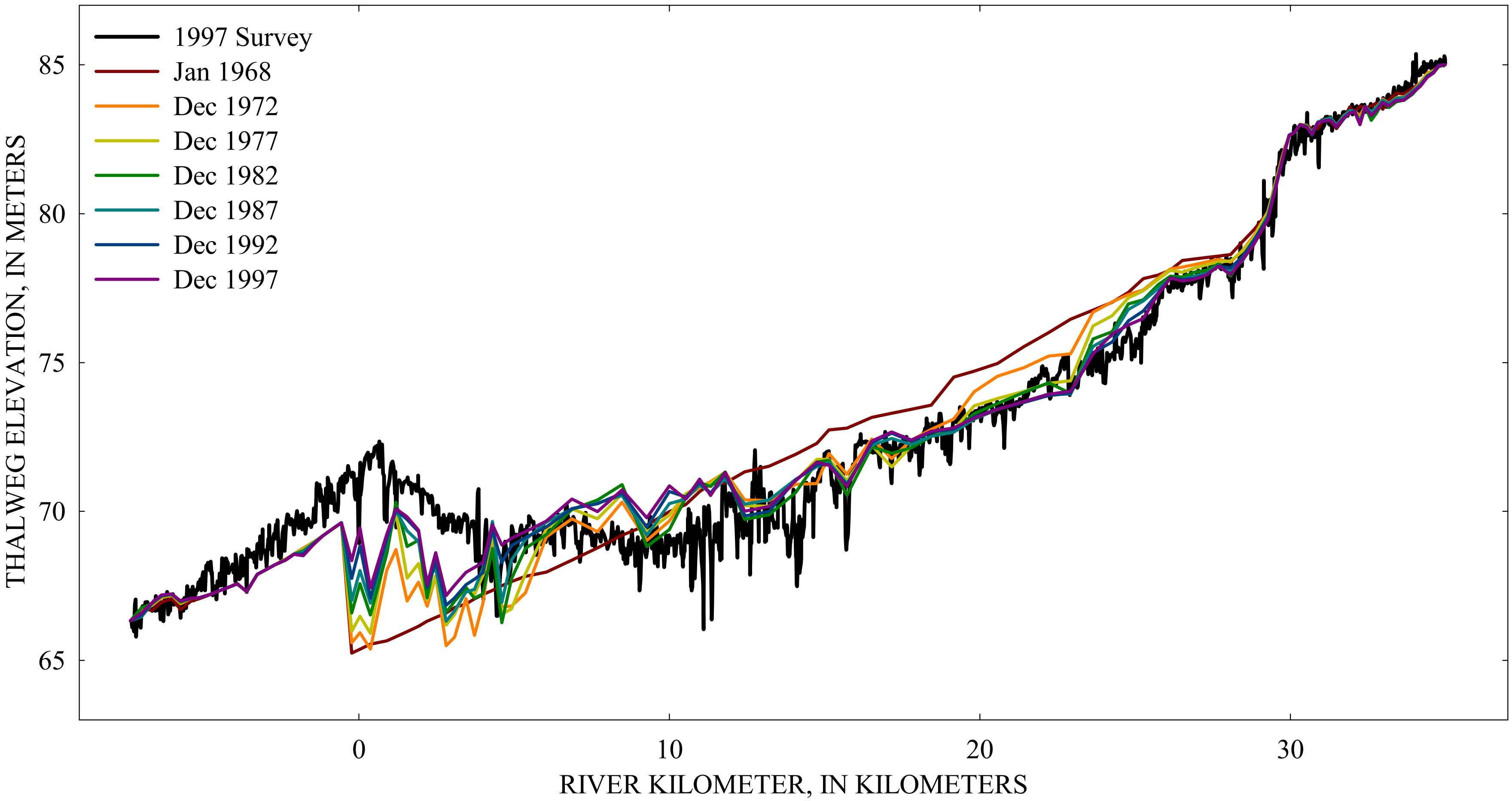

Figure 6 - Temporal evolution of the channel thalweg elevation and comparison to 1997 channel survey

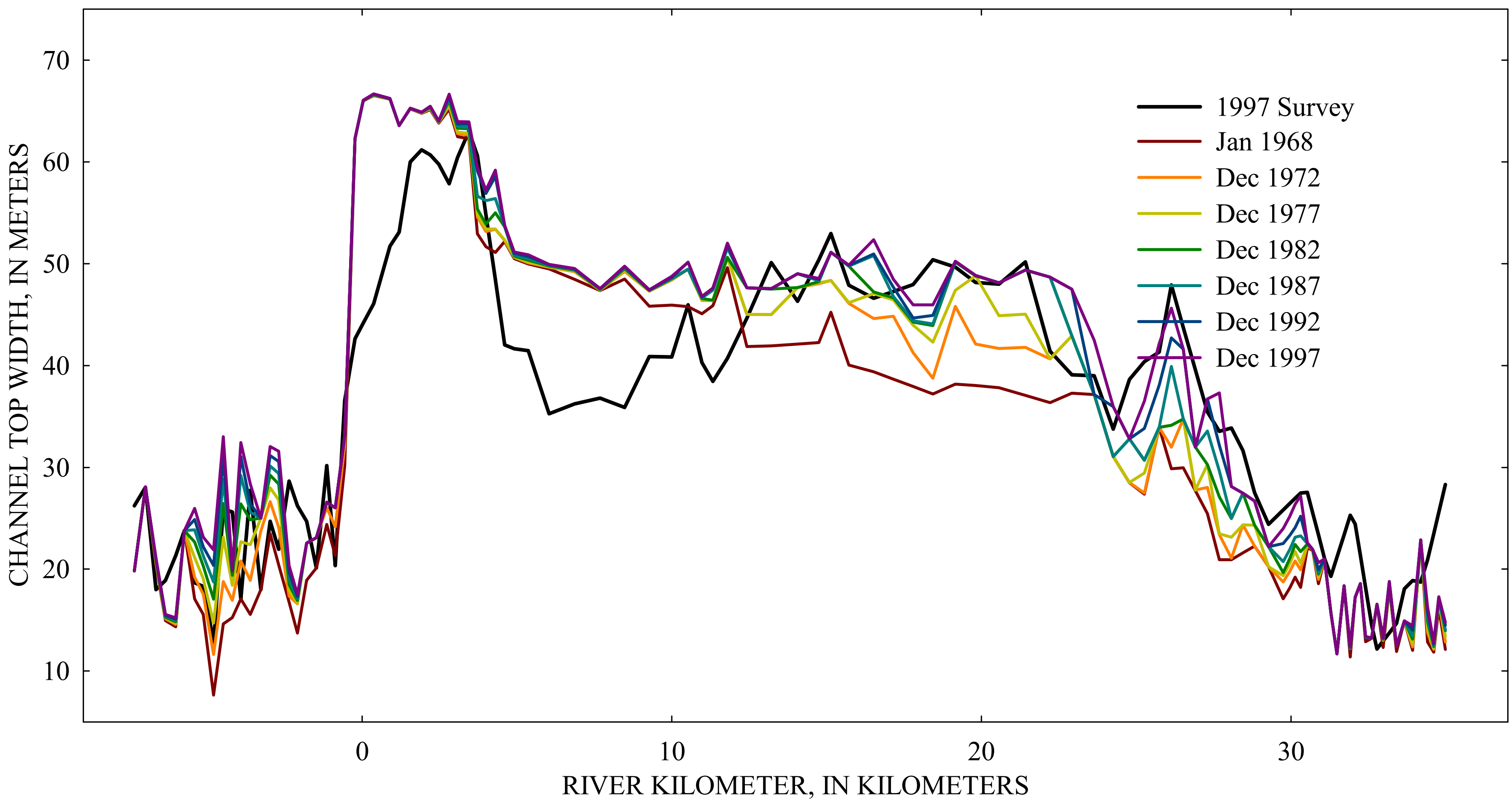

Figure 7 - Temporal evolution of the channel top width and comparison to 1997 channel survey

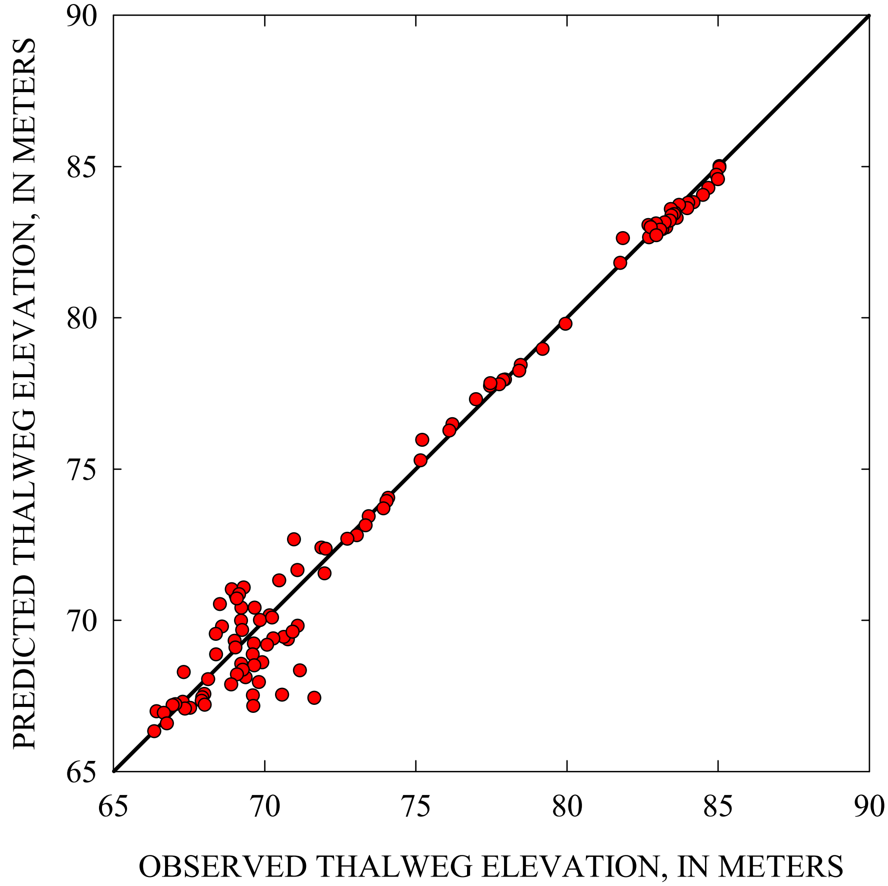

Figure 8 - Observed and Predicted Thalweg Elevation

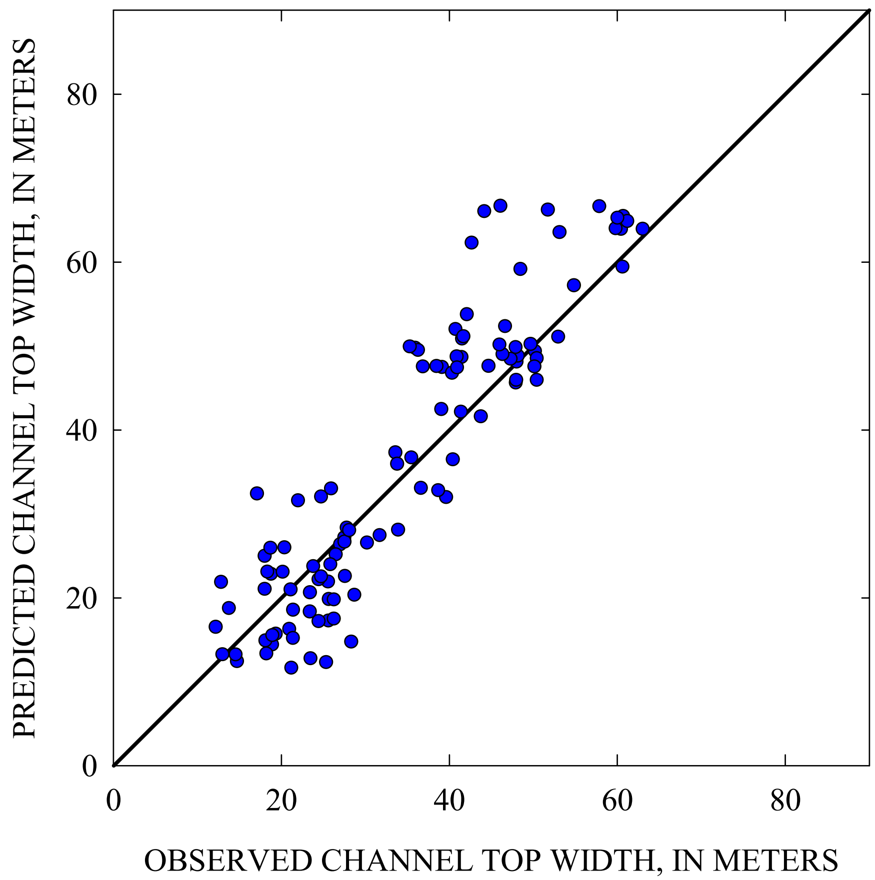

Figure 9 - Observed and Predicted Channel Top Width

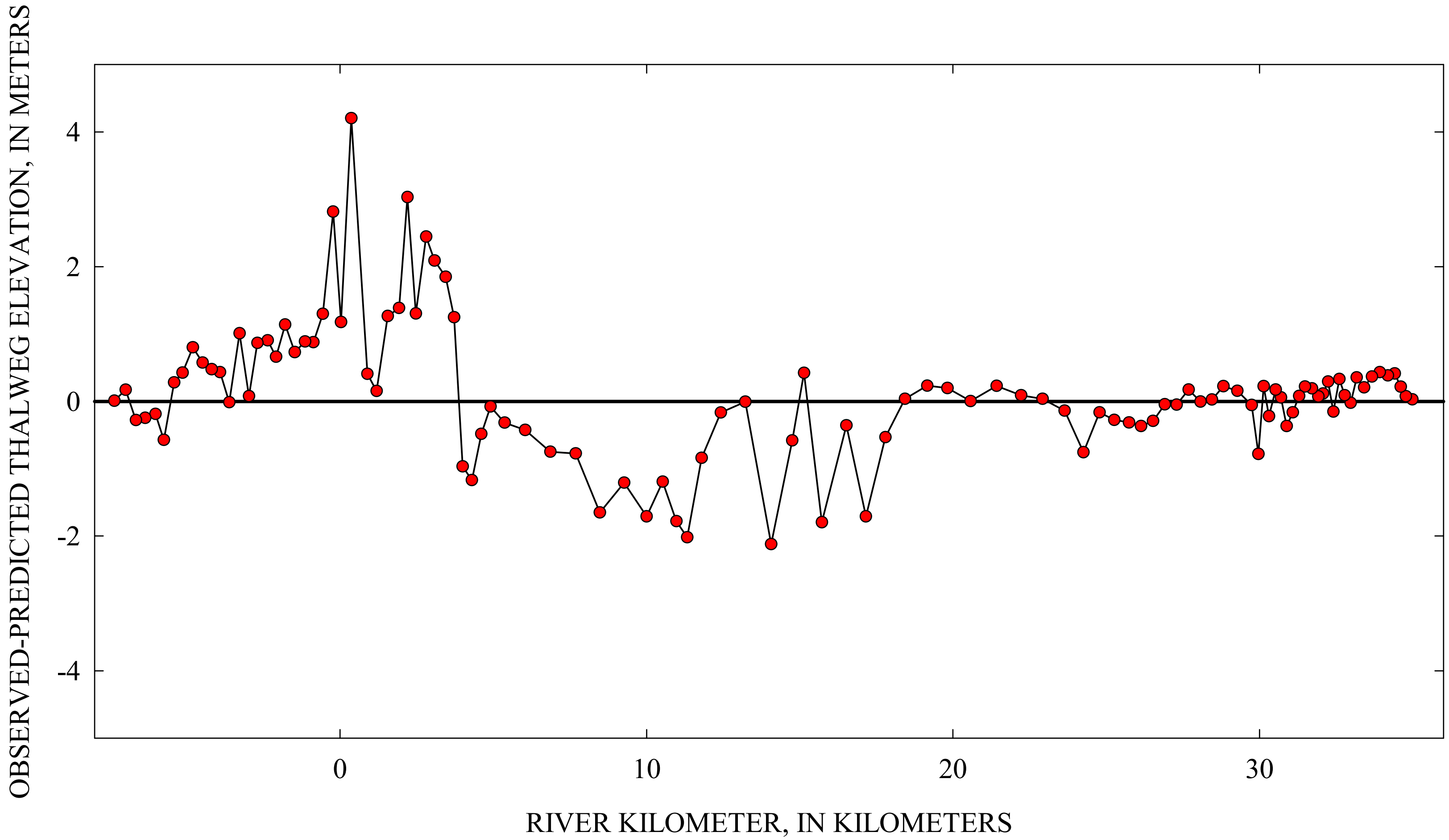

Figure 10 - Longitudinal variation in the difference between observed and predicted thalweg elevation

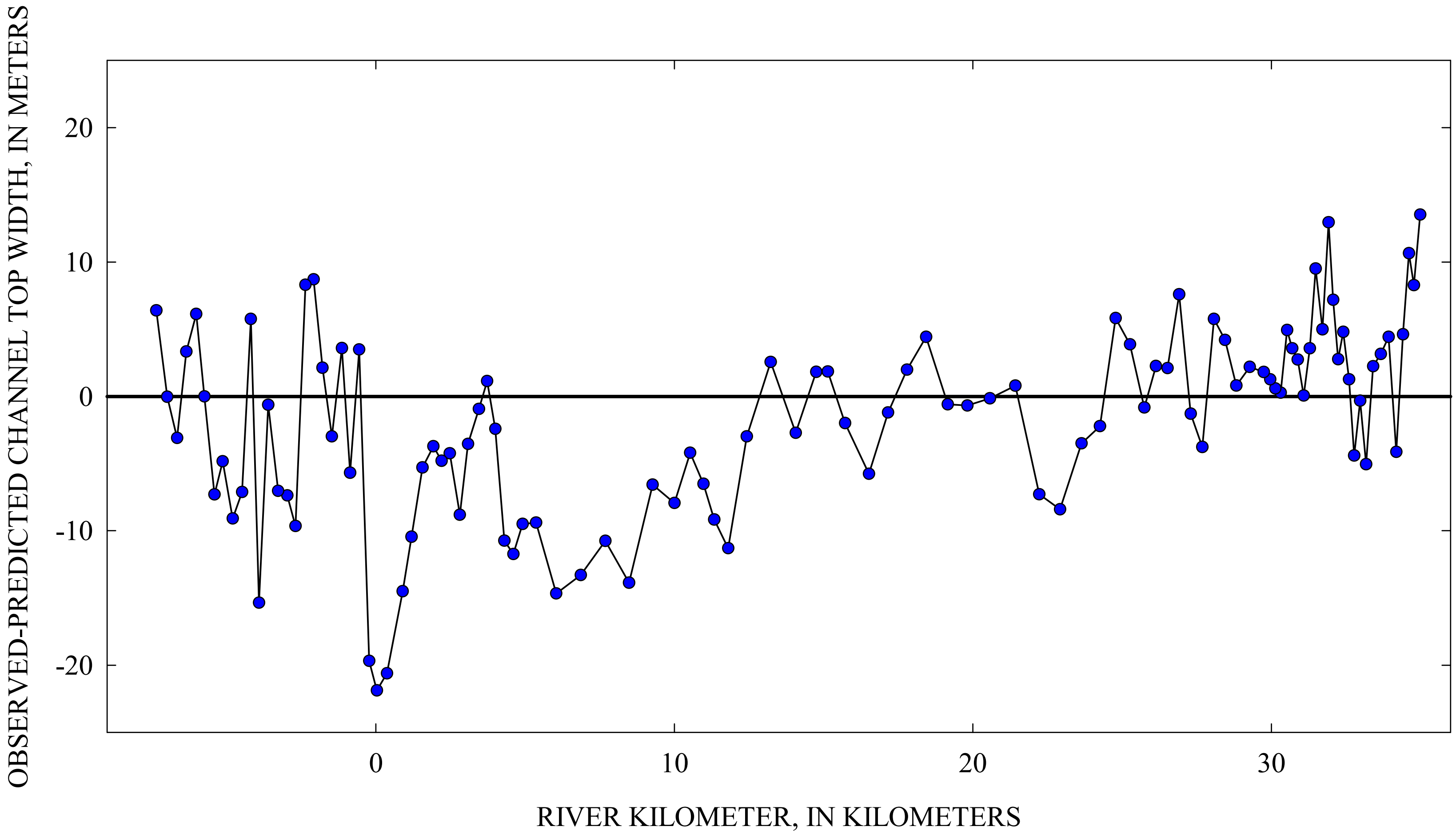

Figure 11 - Longitudinal variation in the difference between observed and predicted channel top width

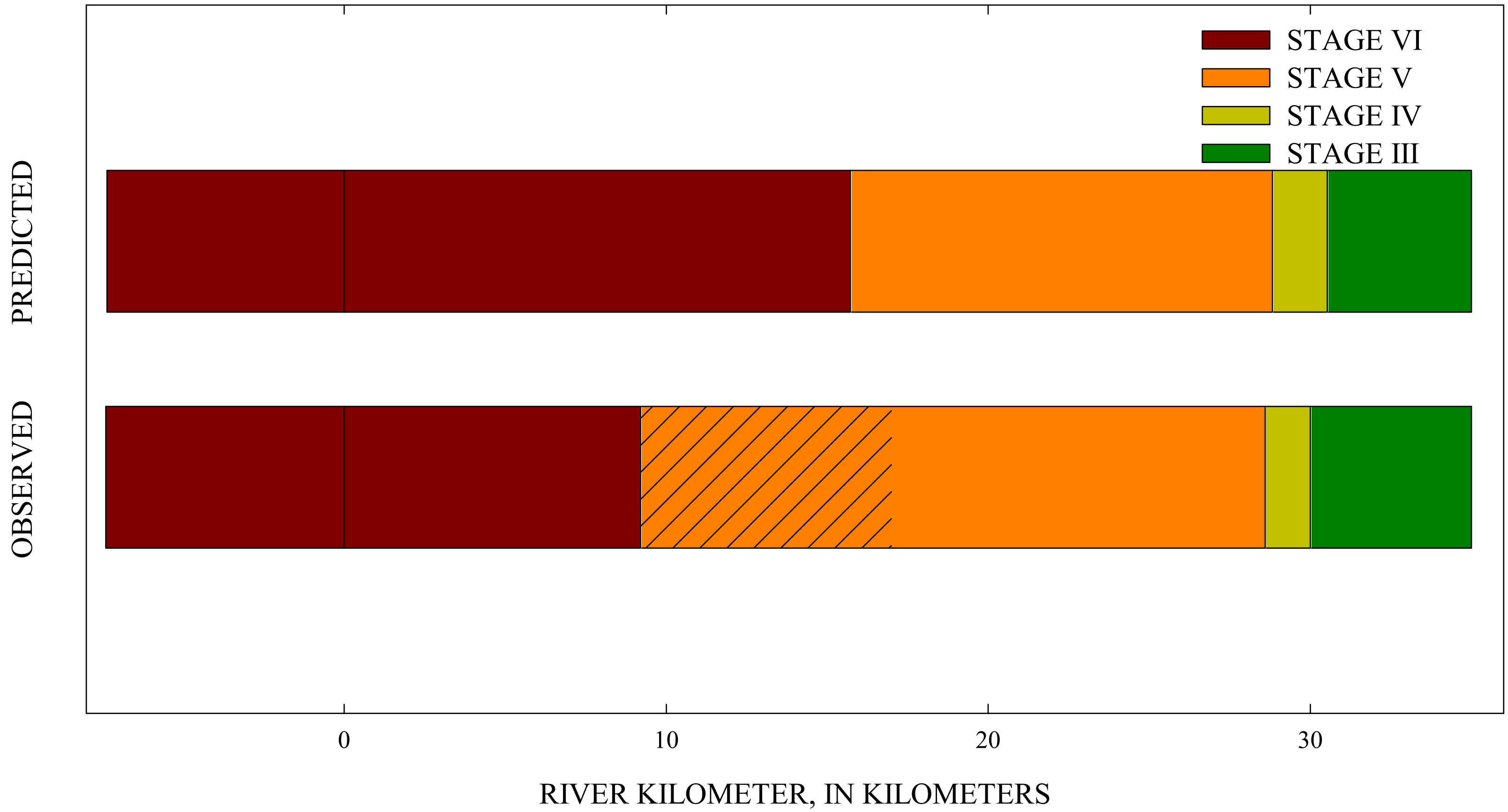

Figure 12 - Observed and predicted longitudinal variation in stage of channel evolution. Hashing represents transitional reach

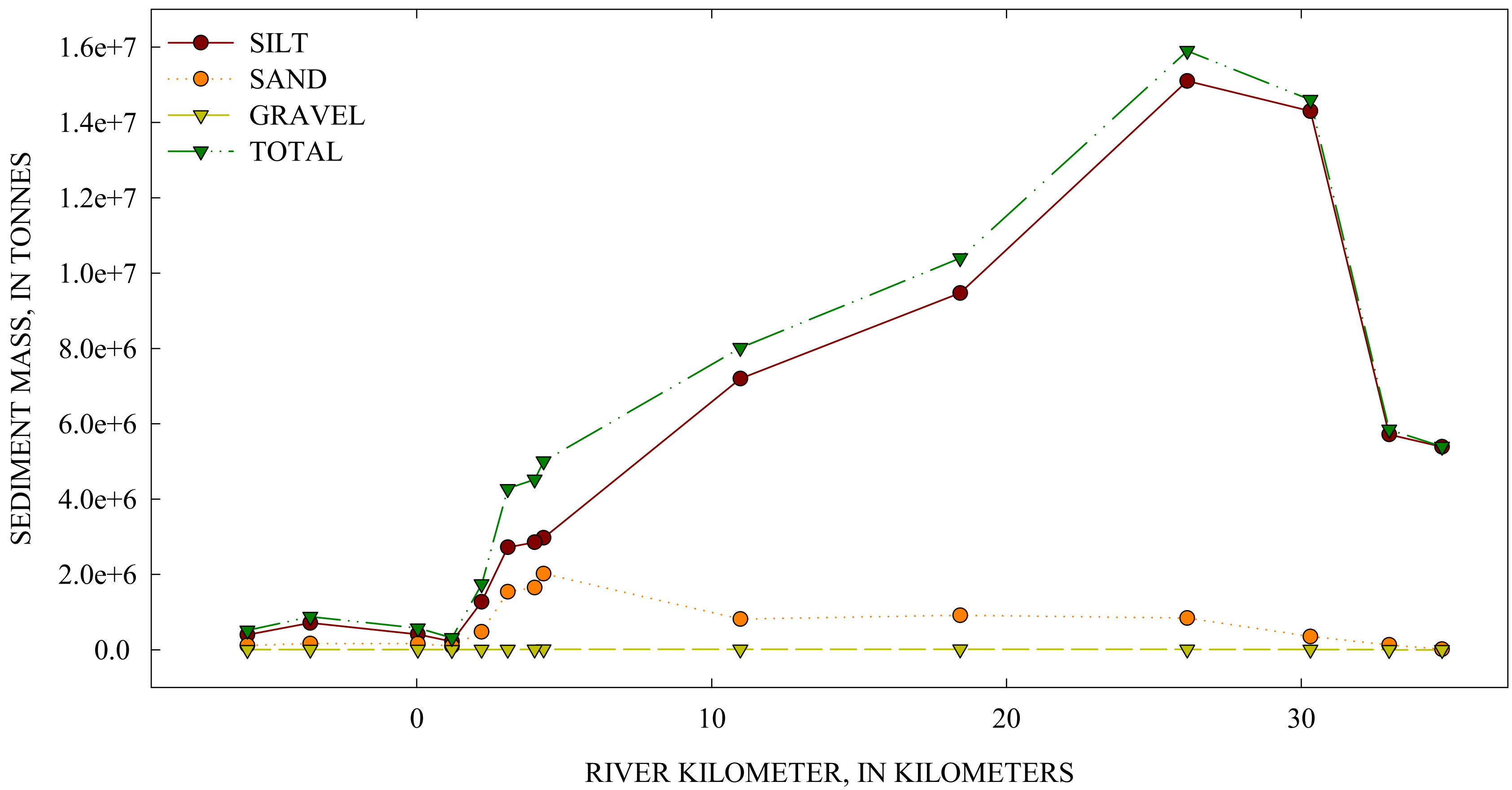

Figure 13 - Longitudinal variation in predicted silt, sand, gravel and total sediment mass

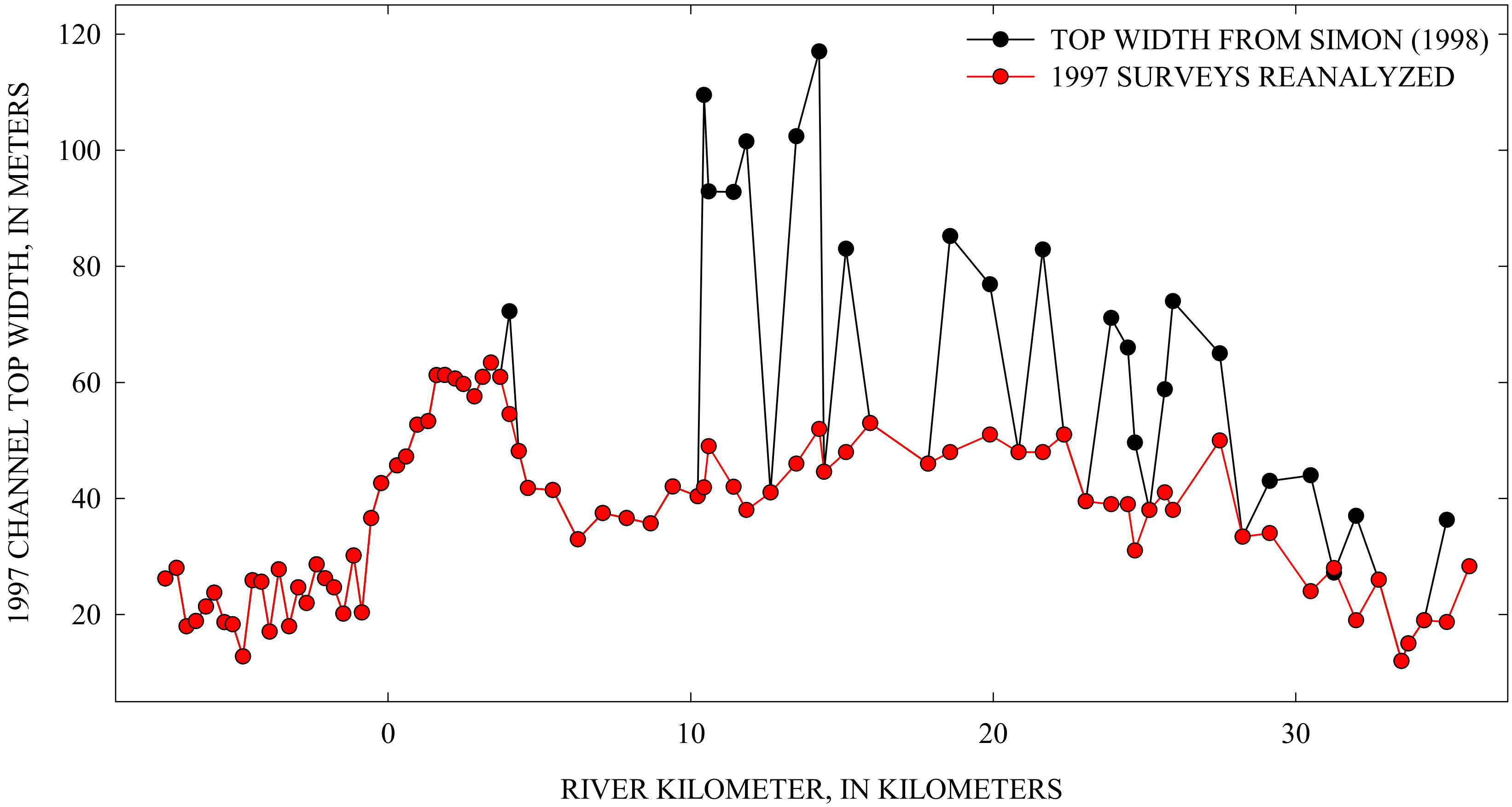

Figure 14 - Comparison of channel top widths from Simon (1998) and reanalyzed in this study from the 1997 channel surveys

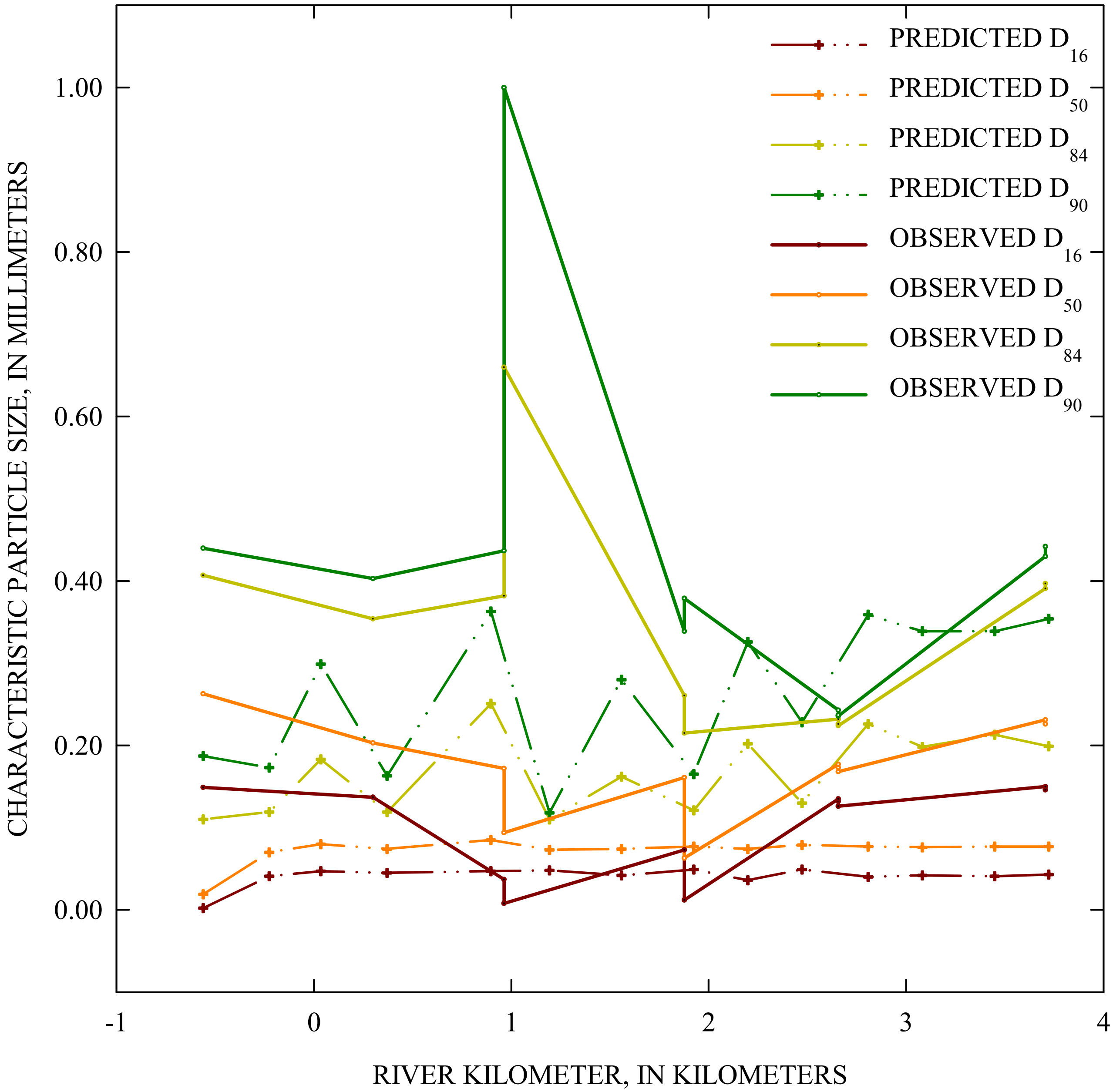

Figure 15 - Observed and predicted longitudinal variation in downstream D_{16}, D_{50}, D_{84}, and D_{90}

TABLES

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 SOILS5 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

Table 2 - Fractional composition of bed and bank materials

SIZE CLASS (mm)	CLAY BED (rkm 25.5 to 35.0)	SILTY BED (rkms -7.4 to -0.4 and 4.5 to 25.5)	SANDY BED (rkm -0.4 to 4.5)	BANK
< 0.01	0.22	0.31	0.14	0.42
0.01-0.03	0.20	0.16	0.07	0.17
0.03-0.07	0.51	0.16	0.07	0.14
0.07-0.25	0.06	0.24	0.46	0.25
0.25-0.84	0.01	0.10	0.19	0.02
0.84-2.00	0.00	0.02	0.04	0.00
2.00-3.36	0.00	0.01	0.01	0.00
3.36-5.66	0.00	0.00	0.01	0.00
5.66-9.57	0.00	0.00	0.00	0.00
9.57-16.0	0.00	0.00	0.00	0.00
16.0-26.9	0.00	0.00	0.00	0.00
26.9-38.1	0.00	0.00	0.00	0.00
38.1-50.0	0.00	0.00	0.00	0.00

Table 3 - Shear-strength properties of the bank material

MODEL KILOMETER (km)	LAYER NUMBER	COHESION (kPa)	FRICTION ANGLE (°)	UNIT WEIGHT (kN/m^3)
	1	8.6	31.4	15.9
0-15	2	8.6	18.3	16.6
	3	8.6	12.0	16.7
15-23	1	3.4	25.0	16.9
23-35	1	1.1	32.0	15.6

Table 4 - Summary statistics of bed material coring experiments

RKM	SAMPLE DEPTH (m)	SAMPLE TYPE	TEXTURAL GROUP	D_{10} (mm)	D_{16} (mm)	D_{25} (mm)	D_{50} (mm)	D_{75} (mm)	D_{84} (mm)	D_{90} (mm)
-0.561	1.22-1.52	Unimodal, Moderately Sorted	Sand	0.134	0.149	0.174	0.263	0.363	0.407	0.440
0.299	1.22-1.52	Unimodal, Moderately Sorted	Sand	0.128	0.137	0.152	0.203	0.291	0.354	0.403
0.963	0.91-1.22	Trimodal, Very Poorly Sorted		0.004	0.008	0.025	0.094	0.305	0.660	1.000
0.963	2.44-2.74	Unimodal, Poorly Sorted	Muddy Sand	0.017	0.037	0.077	0.172	0.313	0.382	0.437
1.877	0.61-0.91	Bimodal, Very Poorly Sorted	Muddy Sand	0.006	0.012	0.018	0.063	0.138	0.215	0.379
1.877	1.83-2.13	Unimodal, Poorly Sorted	Muddy Sand	0.037	0.073	0.101	0.161	0.225	0.261	0.339
2.657	0.1-0.2	Unimodal, Well Sorted	Sand	0.094	0.126	0.136	0.168	0.208	0.224	0.236
2.657	0.7-0.8	Unimodal, Well Sorted	Sand	0.125	0.132	0.141	0.173	0.211	0.226	0.237
2.657	1.2-1.3	Unimodal, Well Sorted	Sand	0.129	0.135	0.145	0.177	0.216	0.232	0.243
3.706	0.1-0.2	Unimodal, Moderately Well Sorted	Sand	0.135	0.146	0.164	0.226	0.338	0.397	0.442
3.706	0.5-0.6	Unimodal, Moderately Well Sorted	Sand	0.139	0.150	0.168	0.231	0.338	0.391	0.430