CONCEPTS – A Process-Based Modeling Tool to Evaluate Stream-Corridor Restoration Designs

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Abstract

The success of proposed stream-corridor restoration measures to effectively restore stream structure and function is greatly aided by a thorough analysis of the potential geomorphic responses of the stream to the measures. Complex hydrologic and geomorphic processes determine channel form. Simple analysis tools are available for restoration practitioners, however few are process-based and dynamic. As a response to this, scientists at the US Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory (NSL) have developed the CONCEPTS model. CONCEPTS (Conservational Channel Evolution and Pollutant Transport System) is a process-based, dynamic computer model that simulates open-channel hydraulics, sediment transport, and channel morphology. CONCEPTS includes research conducted during the past five years by NSL scientists to improve our understanding of the processes controlling channel width adjustment and streambank mechanics. The streambank erosion component of CONCEPTS has been enhanced to include bank-material stratigraphy. Tests of the new component are underway with data obtained over a five-year period from a reach (a bendway) of Goodwin Creek, Mississippi. Initial results show that the enhanced component is able to predict undercutting of streambanks. It underpredicts the retreat of the top of the outside bank at the apex of the bendway by approximately 2 meters because critical shear stresses to initiate lateral erosion at the toe of the bank were too small.

Introduction

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. Sometimes channel disturbance is so severe that reconstruction of a new channel is required.

The Federal Interagency Stream Restoration Working Group (FISRWG 1998) suggest a five-step procedure to initial channel design:

1. Describe physical aspects of the watershed and characterize its hydrologic response.
2. Considering reach and associated constraints, select a preliminary right-of-way for the restored stream channel corridor and compute the valley length and valley slope.
3. Determine the approximate bed-material size distribution for the new channel.
4. Conduct a hydrologic and hydraulic analysis to select a design discharge or range of discharges.
5. Predict stable planform type (straight, meandering, or braided).

After these steps channel dimensions must be finalized and the channel stability must be checked.

Various tools or approaches are available to assist in natural channel design. Skidmore et al. (2001) categorize these approaches as: (1) analog approach (e.g., reference-reach method of Rosgen 1998), (2) empirical approach (e.g., hydraulic geometry relations, Leopold and Maddock 1953), and (3) analytical approach (e.g., computational models based on conservation laws). The analog approach adopts templates from historic or adjacent channel characteristics and assumes equilibrium sediment and hydrologic conditions. The empirical approach uses equations that relate various channel characteristics derived from regionalized or universal data sets, and also assumes equilibrium channel and watershed conditions. The analytical approach makes use of hydraulic models and sediment transport functions to derive equilibrium channel conditions, and thus is applicable to situations where historic or current channel conditions are not in equilibrium with existing or predicted sediment and hydrologic inputs.

Channel dimensions are dependent on complex physical processes such as discharge, sediment inflow, geology, roughness, bed slope, bank vegetation, and bed and bank materials. There is a large body of literature on the above methods to provide much of the information used for stream channel designs. Although these methods can be useful for estimating average stable channel dimensions and alignment, detailed predictions of the evolution (e.g., time-based erosion and deposition) of a channel following land use change or stream corridor management activity cannot be obtained. In addition, most of these methods lack capabilities for simulating bank erosion and the influence of bank vegetation on channel stability. A particular challenge we face today is the lack of integrated, comprehensive modeling tools to evaluate the long-term response of restored stream-riparian corridors. Any restoration design needs careful scrutiny because its long-term impact on corridor response is not easy to predict, and the cost of computer modeling is small compared to the cost of prototype failure. Research in recent years has been directed at incorporating our knowledge on channel processes into fully dynamic, physically-based stream models capable of tracking geomorphic changes over time [e.g., p. 8-42 of FISRWG (1998)]. None of the models simulates headcut formation and advancement, but all of them simulate bed degradation. Few, if any, simulate mass wasting of cohesive banks following bed incision. These are common and very destructive modes of channel erosion that have been widely observed in the highly erodible loess area of the United States (Simon et al. 1996). The long-term impact of channel incision on ecological integrity can be far greater than point and non-point source pollution (Karr 1991).

As a response to this, scientists at the US Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory (NSL) have developed the CONCEPTS model (Langendoen 2000). CONCEPTS (Conservational Channel Evolution and Pollutant Transport System) is a process-based, dynamic computer model that simulates open-channel hydraulics, sediment transport, and channel morphology. It can predict the dynamic response of flow and sediment transport to instream hydraulic structures. CONCEPTS also includes research conducted during the past five years by NSL scientists to improve our understanding of the processes controlling channel width adjustment and streambank mechanics.

Channel Processes, Dimensions, and Modeling

Successful implementation of stream corridor restoration depends on understanding how water and sediment are related to channel form and function, and on what processes are involved with channel evolution (FISRWG 1998). How fast, how much, how often, and when water flows are important questions that must be answered. Channel shape (cross section, planform, and profile)

affects the hydrology of a stream, conversely the hydrology of a stream affects channel shape. A stream corridor is stable if channel shape and hydrology are in a dynamic equilibrium.

The shape of a cross section of any river channel is a function of the flow, and the quantity and character or composition of the materials (including vegetation) that make up the bed and bank of the channel. Further, a natural channel commonly migrates laterally by erosion of one bank and by deposition on the opposite bank. A stream-corridor restoration design must consider these processes to assess the stability of the corridor. Computer models can be used to test the stability of a restoration design for a range of hydrologic and geomorphic conditions, or for a variety of alternative channel configurations.

The Conservational Channel Evolution and Pollutant Transport System (CONCEPTS) computer model simulates the processes that shape channels (Langendoen 2000). The present version (version 1.0) of CONCEPTS simulates unsteady, one-dimensional flow, graded-sediment transport, and bank-erosion processes in stream corridors. It can predict the dynamic response of flow and sediment transport to instream hydraulic structures. It computes channel evolution by tracking bed 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 includes channel boundary roughness varying along a cross section, for example due to varying vegetation patterns.

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).

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.

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 flow and the surface layer. Sediment particles exchange between surface layer and substrate when the bed scour and fills. The volumetric fraction

content by size class in the surface layer is determined by a mass conservation equation (Langendoen 2000).

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 hypothesis, or tractive force methods can accurately predict width adjustment over time. 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 the flow, and (2) mass bank failure due to gravity (Langendoen 2000).

Input Data Requirements. CONCEPTS requires similar input data as such models as HEC-6 (USACE 1993), HEC-RAS (USACE 1995), or GSTARS2.1 (Yang and Simões 2000). Typical input data are: (1) inflow of water and sediments at the upstream boundary of the model channel; (2) the geometry (cross sections) of the channel; (3) roughness coefficients; and (4) composition of bed and bank material. In addition the user needs to supply bank-material properties for the streambank erosion component of CONCEPTS: (1) shear stress required to entrain bank-material particles, and (2) the shear-strength parameters cohesion and friction angle. All input data can be obtained from federal agencies such as the US Geological Survey or can be measured *in situ*.

Application of Streambank Erosion Component

Bank stability analysis should be a major component of the stability assessment of a channel restoration design. In disturbed channel systems bank material may contribute as much as 80 percent of the total sediment eroded from the channel (Simon et al. 1996). Bank instability is commonly triggered by fluvial erosion at the bank toe. Natural streambanks frequently are composed of distinct layers reflecting the depositional history of the bank materials. Each layer can have physical properties quite different from those of other layers. The bank profile therefore will respond according to the physical properties of each layer.

Figure 1 shows how lateral erosion and mass wasting affect the geometry of a streambank in the next version of CONCEPTS under development. In the figure the erodibility of soil layer 3 is larger than that of soil layer 2. Lateral erosion will therefore lead to undercutting of the streambank. The next version of CONCEPTS accounts for the stratigraphy of the streambank. CONCEPTS is therefore able to more realistically simulate streambank erosion caused by undercutting and cantilever failures.

CONCEPTS calculates lateral erosion following the excess shear stress approach set forth by Ariathurai and Arulanandan (1978) with erosion parameters determined by the method of Hanson and Simon (2001). The user has to assign a critical shear stress to initiate erosion for each soil layer. The erodibility of the layer is then a function of the critical shear stress.

Bank stability is analyzed using a limit equilibrium method. Limit equilibrium methods are based upon static equilibrium of forces and/or moments. Bank stability is expressed by a factor of safety. Factor of safety is defined as that factor by which the shear strength of the soil must be reduced in order to bring the mass of soil into a state of limiting equilibrium along a
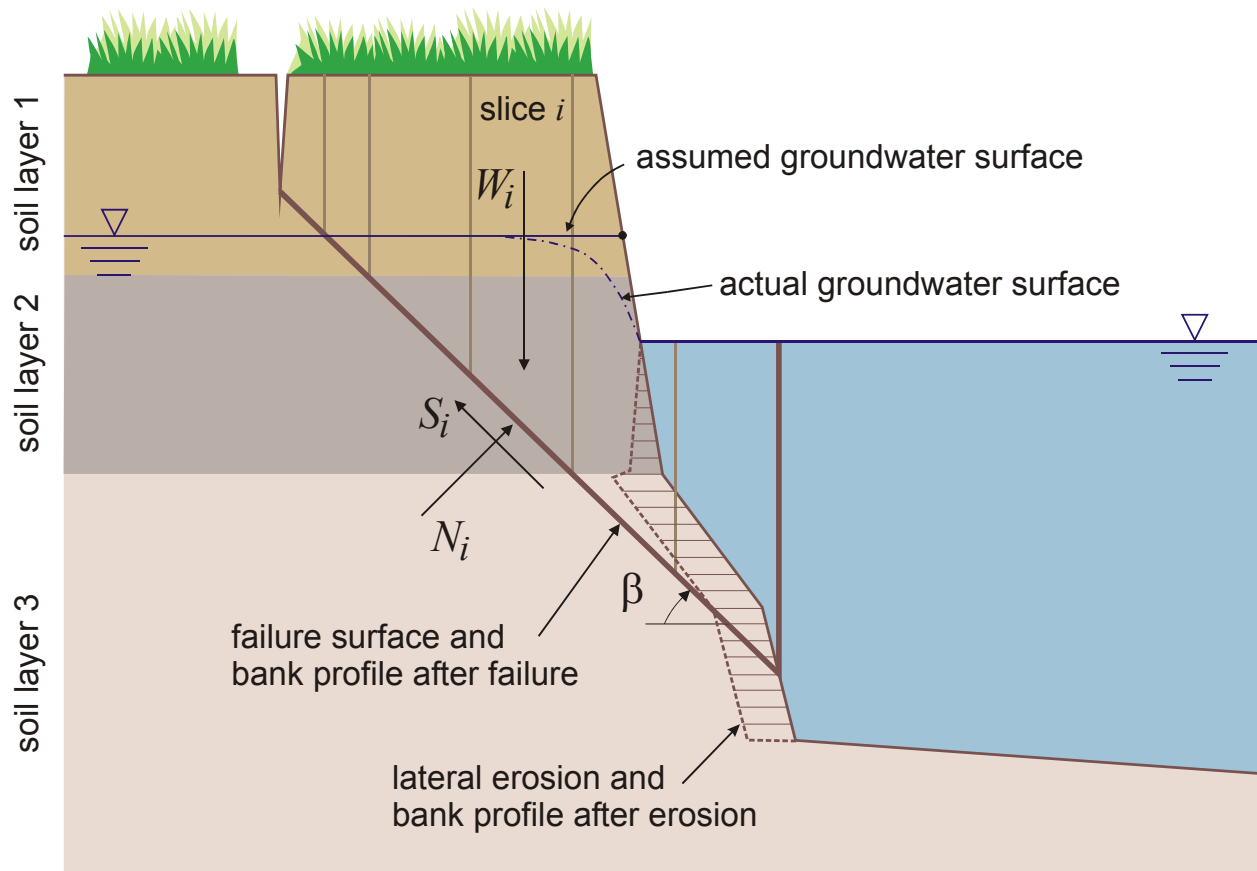
Figure 1. Representation of lateral erosion and mass wasting of a stratified streambank. The erodibility of soil layer 3 is larger than that of soil layer 2.

selected slip surface. If factor of safety is larger than one the bank is assumed stable. Because cohesion and friction angle may be different for each soil layer, one cannot evaluate the stability of a streambank assuming the failure block is a single unit as is currently done by CONCEPTS version 1 (Langendoen 2000). The new bank stability algorithm divides the bank into slices, and evaluates the balance of forces on each slice in vertical and horizontal directions. Figure 1 shows some of the forces acting on slice i: weight of the slice (W), the normal force (N) on the base of the slice, and the shear force (S) mobilized on the base of the slice. Other forces possibly acting on a slice (not shown in Figure 1) are interslice forces and the hydrostatic force exerted by the surface water on the vertical part of the slip surface. The shear force (S) is expressed by the shear-strength equation of Fredlund and Rahardjo (1993) for either unsaturated or saturated soils. The slope of the failure surface (β) is defined as that slope for which the factor of safety is a minimum.

Goodwin Creek Bendway. Since February 1996, NSL has been conducting extensive research on streambank failure mechanics along a bendway of Goodwin Creek, northern Mississippi (Simon and Darby 1997; Simon et al. 2000; Simon and Collison, 2001). The following data are being collected: cross section geometry, water surface elevations, bank material properties, bank material shear strength parameters, pore-water pressures in the bank, root mapping and tensile strength, and plant stem flow. Two flow measuring flumes (flumes #3 and #4, Alonso 1997) in upstream tributaries provide continuous discharge and fine sediment data. Figure 2 shows a plan
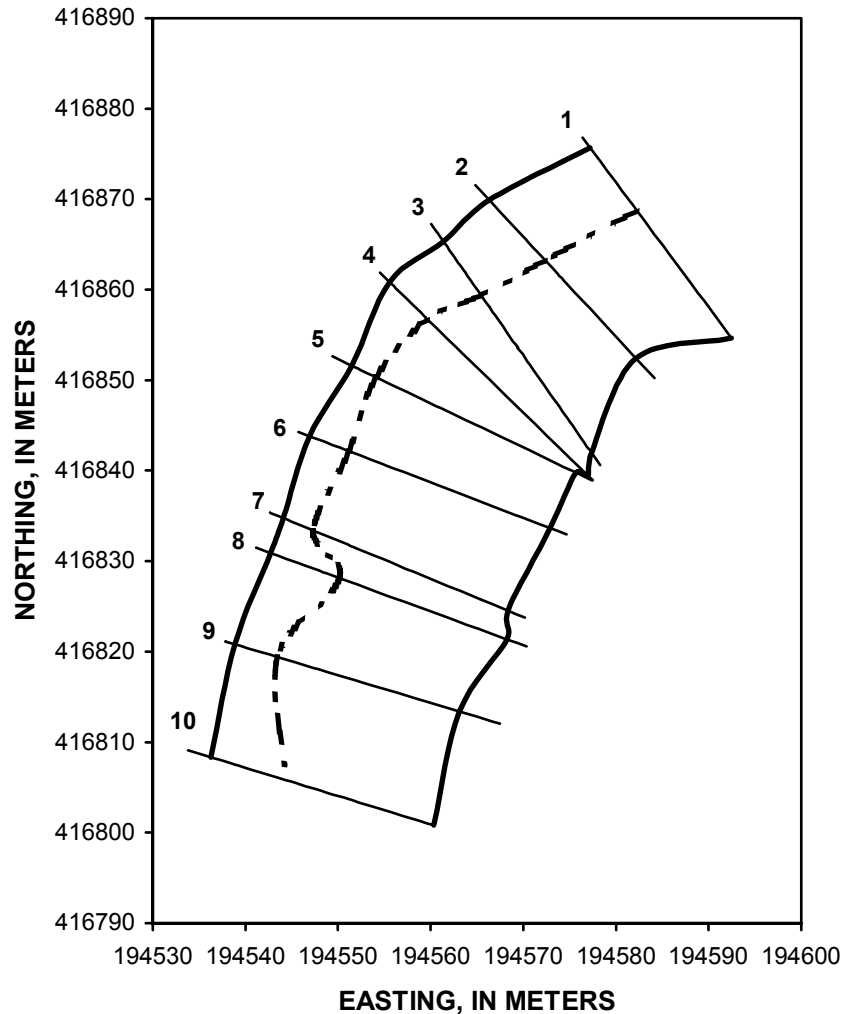
Figure 2. Plan view of the Goodwin Creek Bendway site showing the locations of the ten cross sections. Flow is from top to bottom. The dashed line is the channel thalweg.

view of the bendway with the locations of ten surveyed cross sections. The flow is from top to bottom.

Bank material consists of about 2 m of brown, clayey-silt of late Holocene age (LH unit) overlying 1.5 m of early Holocene gray, blocky silt of lower permeability (EH unit). Both these units have been separated into two further delineations by Simon and Collison (2001). The EH and LH units are separated by a thin (0.1 to 0.2 m) layer containing manganese nodules and characterized by very low permeability, which perches water. These materials overlie 1 m of sand and 1.5 m of packed sandy gravel.

Apparent cohesion and effective friction angle were measured *in situ* using an Iowa Borehole Shear Tester (BST, Luttenegger and Hallberg 1981). For the LH unit, BST results revealed an apparent cohesion of 1.41 kPa with an effective friction angle of 33.1° for layer 1 with an apparent cohesion of 2.7 kPa and an average effective friction angle of 28.1° for layer 2. The underlying two-layered EH unit has apparent cohesion values of 6.3 kPa with an estimated average friction angle of 27° for the period between June 1996 and July 1998 (Simon et al.
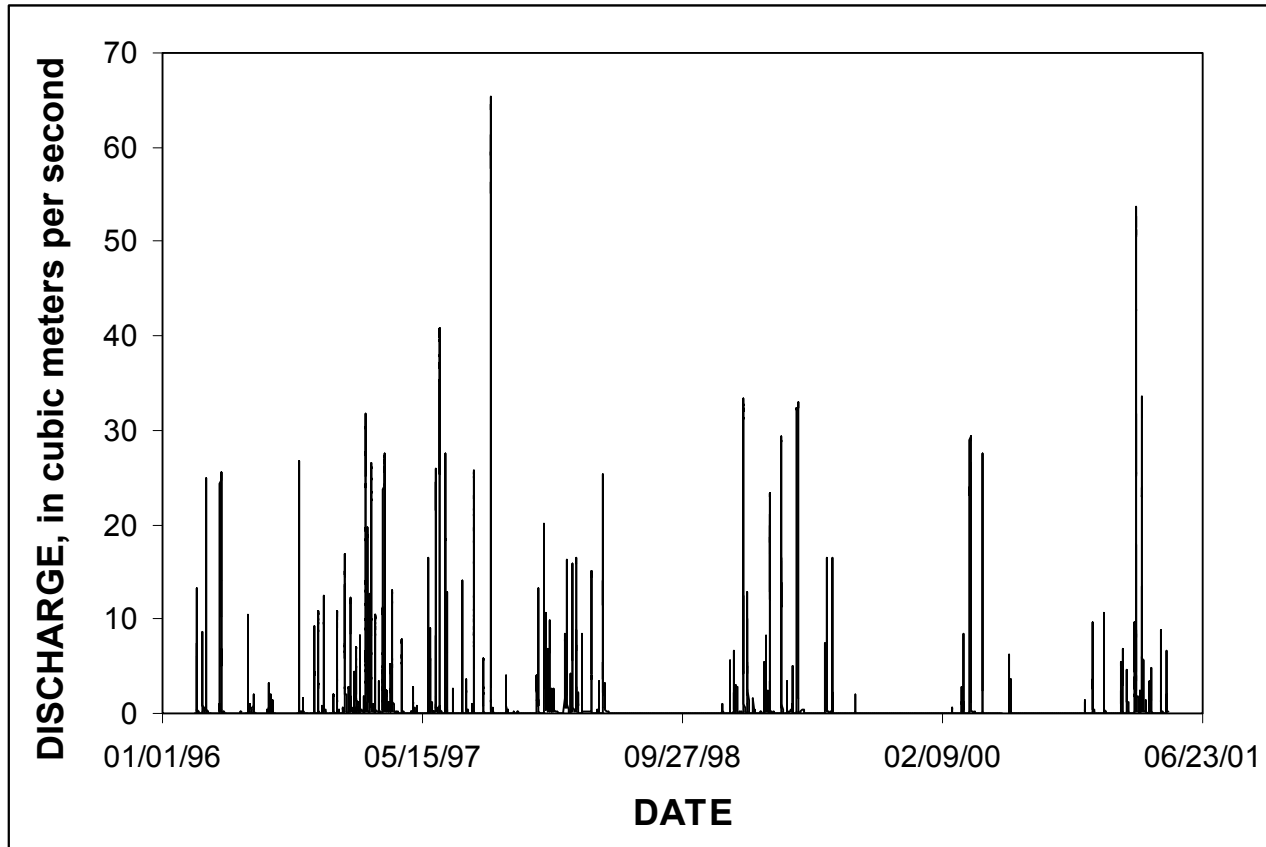
Figure 3. Discharge hydrograph at the upstream boundary of the bendway.

2000). Simon and Collison (2001) provide the following values for the angle ϕ^b and the unit weight γ_s (from top bank to toe): LH unit layer 1, $\phi^b = 17°$, $\gamma_s = 16.9$ kNm^{-3}; LH unit layer 2, $\phi^b = 10.2°$, $\gamma_s = 19.3$ kNm^{-3}; EH unit layer 1, $\phi^b = 17°$, $\gamma_s = 20.0$ kNm^{-3}; and EH unit layer 2, $\phi^b = 17°$, $\gamma_s = 19.7$ kNm^{-3}.

Eleven major failure episodes occurred at the research site between February 1996 and April 2001, resulting in up to 4.7 m of top-bank retreat. This rate is greater than the 30-year average of about 0.5 m/yr, and is attributed to three winters with periods of persistent precipitation, each manifest with a number of discharge peaks with a 1-year recurrence interval or greater. Planar and cantilever failures were relatively common along the steepest section of the 4.7 m high banks. Cantilevers were formed by (1) preferential erosion of sands and silts by fluvial undercutting about 3.0 to 3.5 m below the top bank, and (2) by sapping and small pop-out failures in the region of contrasting permeabilities in the Holocene units about 1.6 to 2 m below the top bank. Both processes resulted in oversteepening at the base of the EH unit and subsequent collapse during wet periods.

Modeling Results. We employed the new version of CONCEPTS under development to simulate the above failure processes between March 1, 1996 and April 17, 2001. Figure 3 shows the flow discharge at the upstream end of the bendway (cross section 1). A rating curve was imposed at the downstream end of the bendway (cross section 11). Manning's *n* was calibrated
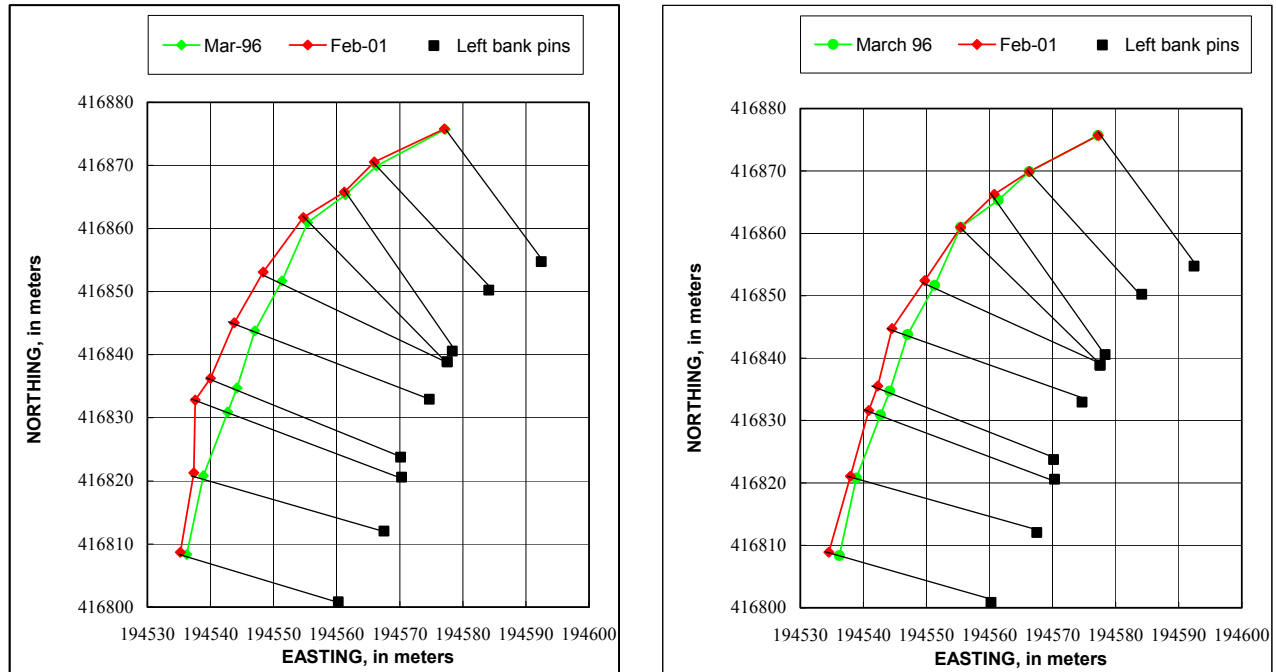
Figure 4. Comparison of observed (left) and simulated (right) retreat of the top of the right bank.

to 0.032. The phreatic surface was located at 82 m above Mean Sea Level. Critical shear stresses varied from 10 Pa at cross section 1 to 0.2 Pa at the apex of the bend (cross sections 6 through 8) to 5 Pa at cross section 11.

Figure 4 compares the observed and simulated retreat of the top of the right bank of the bendway between March 1996 and February 2001. It shows that CONCEPTS underpredicts the retreat of the bank top at the apex of the bendway (cross sections 5 through 8) by an average of approximately 2 meters.

Figure 5 compares the simulated and observed changes in geometry of cross section 8. Figure 5 shows that five major failures of the right bank occurred between March 1996 and January 1999. The observed retreat of the bank top is approximately six meters. CONCEPTS simulated three major failures of the bank in March 1996, March 1997, and September 2000. CONCEPTS accurately predicts the amount of lateral erosion at the toe of the bank. However, CONCEPTS underpredicts the amount of erosion one meter above the bank toe. Hence, the simulated retreat of the bank top is smaller than that observed. This is also the case for cross sections 5, 6, and 7, which explains the underprediction of the retreat of the top bank.

Concluding Remarks

Channel width adjustment is an important response of disturbed stream systems. Channel width adjustment is a combination of scour of bed and bank material near the bank toe by flow, and ensuing mass wasting of bank material because of steepening and increasing height of the streambank. Quantitative channel evolution models are needed to evaluate the success of stream stabilization and rehabilitation measures in protecting infrastructure and farmland adjacent to streams. The channel evolution model CONCEPTS simulates not only scour and fill of the

channel bed but also streambank-erosion processes. The bank stability algorithm is able to evaluate the effect of surface water (confining pressures) and pore-water pressures on the factor of safety, and automatically searches for the slip surface that produces the smallest factor of safety. Currently, the streambank erosion component is being enhanced to include the effects of the stratigraphy of the bank material on lateral erosion and mass failure. Initial tests of the enhanced component to a bendway in the Goodwin Creek, Mississippi shows that it more accurately simulates lateral erosion near the toe of the outside bank of the bendway. Differences in the retreat of the bank top are due to an underprediction of the lateral erosion one meter above the bank toe.

Acknowledgments

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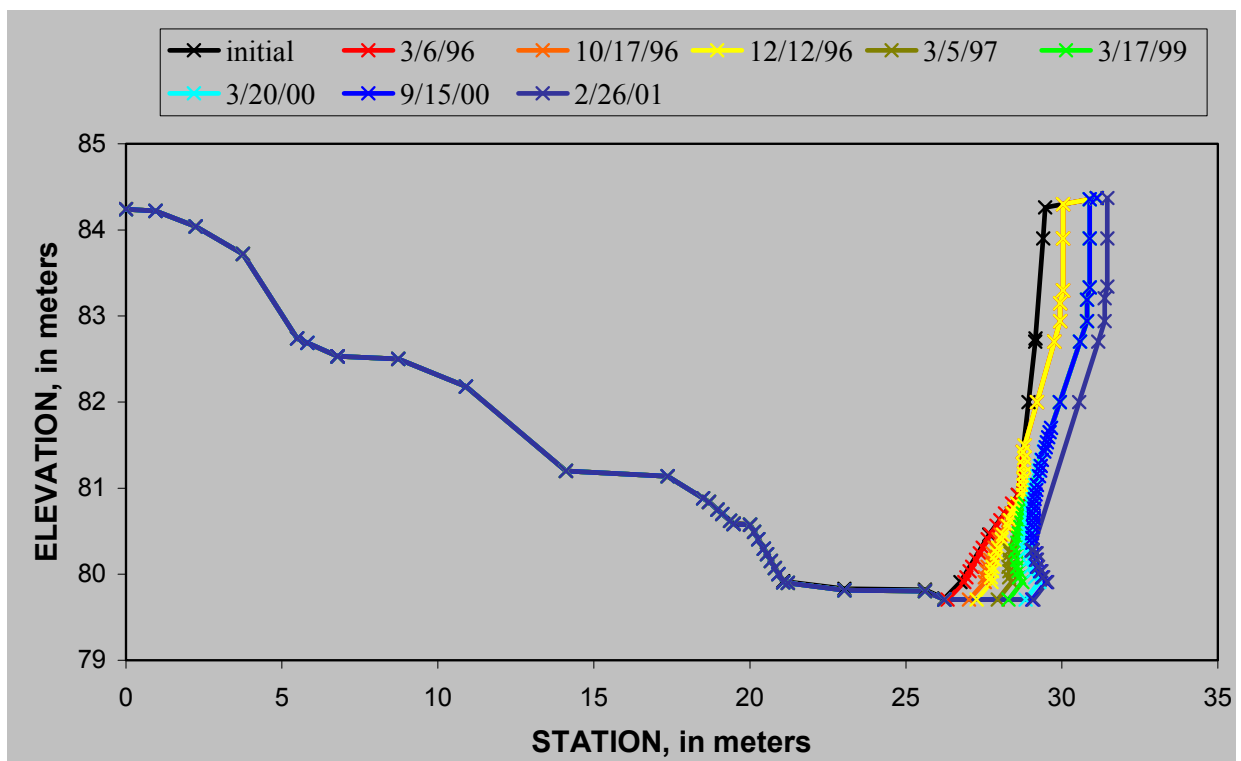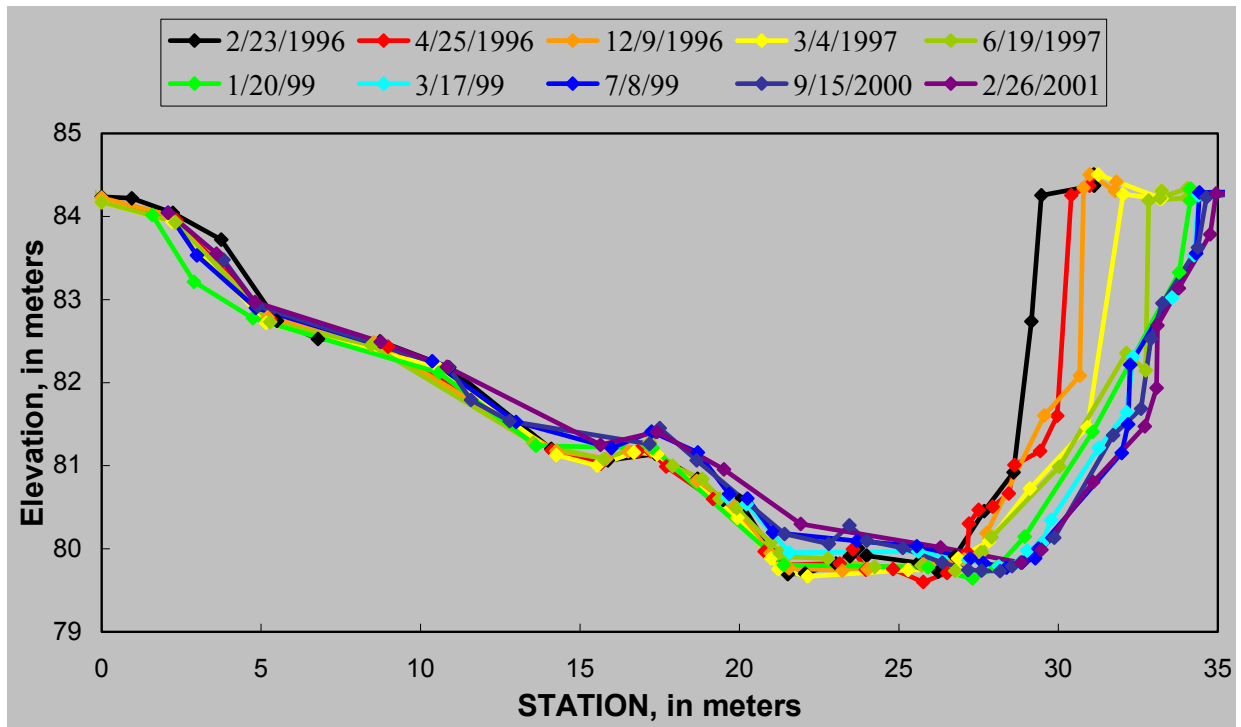
Figure 5. Comparison of observed (top) and simulated (bottom) changes in geometry of cross section 8 (see Figure 2).

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