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ANALYSIS OF CHANNEL INSTABILITY DUE TO CATCHMENT LAND-USE CHANGE

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ABSTRACT Many of the streams draining the Bluff-line hills of north-central Mississippi have experienced serious instability as a result of catchment land-use changes and adverse impacts of river management for drainage and flood control. The primary response in the fluvial system is through degradation, leading to damage to in-stream and riparian ecosystems, damage to infra-structure and the generation of heavy sediment loads which cause problems of aggradation further downstream. Bed lowering also reduces bank stability with respect to mass failure under gravity. The critical bank height for mass failure and the characteristic mechanism of failure depend on the bank stratigraphy and the geotechnical properties of the bank materials. When the banks attain the critical height for mass instability an important geomorphic threshold is crossed and the thrust of channel instability switches from degradation to rapid widening. Widening involves destruction of valuable valley bottom land, damage to infra-structure and the prolongation of heavy sediment supply to the system downstream. Accurate prediction of the critical bank height is possible on the basis of a bank stability model. The bank stability model is shown to have useful applications both in developing conceptual models of channel evolution following catchment changes and in designing engineering solutions to problems of channel instability.

INTRODUCTION

Central Mississippi lies in the Gulf Coast Plain Physiographic Province of North America (Thorne, 1990). It comprises three sub-divisions. These are, from East to West: the North-central Plateau, a heavily dissected plain underlain by Eocene clays and Wilcox and Claiborne sands; the Loess Hills of calcareous loess with about 30 m of relief; and the Yazoo Basin, a low lying segment of the Mississippi Valley drained by the Yazoo River and separated from the Loess Hills by the Bluff-line. This study is concerned with streams draining westwards from the Loess Hills into the Yazoo Basin. These streams have beds formed in sands and gravels with occasional outcrops of more resistant lithologic units and banks formed from alluvially re-deposited loess.

Many of these streams have experienced severe instability in recent years leading to disruption of the fluvial system and severe impacts on local infrastructure and flood plain dwellers and farmers.

In the late 1970s the US Department of Agriculture, Agricultural Research Service, Sedimentation Laboratory at Oxford, Mississippi was commissioned to investigate the Bluff-line streams and make recommendations for engineering intervention and improved catchment management to ameliorate the problems associated with their instability. This work was jointly funded by the USDA and the Vicksburg District, US Army Corps of Engineers. Over the next decade a series of studies was undertaken involving the staff at the Sedimentation Laboratory, engineers from Vicksburg and scientists and engineers on funded research contracts, including the author. More recently the Corps of Engineers at Vicksburg have taken the lead in the Demonstration Erosion Control Program, an initiative designed to perfect a basin-wide approach to stream restoration and stabilization.

Through these studies a fairly complete understanding has been built up of the causes, mechanisms and impacts of channel instability. This paper presents an overview of that understanding, stressing the relatively under researched role of bank stability and demonstrating how quantification of bank stability criteria can be useful in modelling and managing stream response. These are generalities that may be of use in other disturbed systems.

CHANGES OF LAND-USE AND STREAM MANAGEMENT

While the precise causes of stream instability vary between basins, there are three underlying factors which are common to all the unstable systems. These concern changes of land-use and erosion management in the catchments, land drainage operations involving channelization of reaches of river and the regulation of flows in trunk streams by flood control reservoirs.

Land-use and erosion management

Historically, the basins drained by the Bluff-line streams have been subject to over-extensive and intensive agriculture and forestry. When the area was first settled by Europeans in the 1830s large stands of hardwood forest were cleared to allow arable farming. For a period of about 100 years intensive row-cropping of cotton on relatively steep, marginal land led to serious soil loss by sheet, rill and gully erosion. At this time the abundant output of sediment from the uplands to the valleys resulted in heavy deposition, with as much as 5 m of vertical sedimentation in the valley floors. The deposit produced by this accretionary phase of valley sedimentation is called the post-settlement alluvium (PSA) (Happ *et al.*, 1940).

By the early 1940s the upland areas had lost practically all of their fertile top soil and had been heavily dissected by gullies. The resulting decrease in productivity was sufficient to render the uplands uneconomic for row-cropping. Since the 1940s much of this land has been returned to pasture and woodland with a continuous cover of vegetation year round. Also, the Mississippi Soil Conservation Service (SCS) has enacted wide programs of gully stabilization by tree planting and sediment retention by pond construction in the uplands. As a consequence of these land-use and erosion management changes there were marked reductions in run-off and sediment yield from the uplands during the 1950s and 1960s.

It is difficult to be precise about the hydrologic and sedimentary impacts of these changes, but data collected by the US Department of Agriculture Agricultural Research Service can give some insights into their orders of magnitude. Studies by McGregor *et al.* (1969) and Dendy *et al.* (1979) show that the annual water and sediment yields from forested basins are in the range 125-250 mm and 0.1-0.2 t ha^{-1}, respectively. These figures may be taken as indicative of conditions prior to settlement by Europeans. Estimates for annual water and sediment yields during the period of intense arable farming are given by Schumm *et al.* (1984) as 380-635 mm and 100 t ha^{-1}. Present run-off is still about 380-635 mm, but sediment yield has been reduced to 10-20 t ha^{-1}.

Land drainage operations involving channelization

In the 1950s and 1960s many streams were channelized. Channelization consisted of straightening, enlarging and clearing of vegetation in order to increase channel capacity and improve drainage of the valley bottom lands. Straightening involved reductions in channel sinuosity from the characteristic values for natural single-thread streams, in the range of 1.5 to 2, to that for a straight channel which is unity. Consideration of the appropriate sediment transport formulae for sands and fine gravels suggests that the capacity of Bluff-line streams to transport sediment would increase by a factor of between 2 and 5 in response to the increase in bed slope resulting from straightening. However, this does not account for further increases in sediment transport capacity due to reduced flow resistance and increased channel capacity which also result from channelization. When these factors are taken into account, the sediment transport capacity following channelization is estimated to be of the order of fifty times that of the previous natural channel (Schumm *et al.*, 1984).

Regulation of flows in trunk streams by flood control reservoirs

Since the clearance of the virgin forests and settlement of Mississippi by Europeans, the major valleys have been prone to catastrophic flooding. Even before settlement, the existence of dwellings and villages on Indian mounds in flood plains attests to flooding problems. Chronic inundation of low lying areas in the first part of this century led to the construction of four large flood control reservoirs along the base of the bluff-line in the 1930s and 1940s. These dams (Enid, Grenada, Sardis and Arkabutla) regulate flows in the trunk streams draining North-central Mississippi (the Yalobusha, Yocona, Little Tallahatchie and Coldwater Rivers) and prevent flooding by retaining high flows and releasing the water after the flood has receded. However, in doing so they have the effect of lowering the base-level for unregulated tributaries which confluence with the trunk streams downstream of the dam. This occurs because in an unregulated system tributary and trunk streams are in flood together and there is little difference between their flow levels. But in a system where the trunk stream is regulated and the tributary is not, during floods the tributary may have much higher flow lines than the trunk stream. As a result, the water surface slope in the tributary is steepened, velocity and sediment transport capacity are increased and the bed tends to scour.

STREAM RESPONSE

Stream response to land-use and management impacts can initially be considered in two categories: depth response and width response.

Depth response

The primary fluvial response of the streams draining the Loess Hills has been one of bed degradation. The combination of decreasing sediment supply from catchment erosion due to changes in land-use since the 1940s, with massively increased sediment transport capacity due to base level lowering due to trunk stream regulation in the 1940s and channelization in the 1950s and 1960s, led to a gross imbalance between sediment supply and transport capacity. Severe degradation resulted, as the bed was scoured to make up the difference between the sediment load which the stream was competent to transport and the supply of sediment from upstream. Over-steepened reaches developed either associated with straightening or base level lowering, or both. Due to the lack of bed rock or other erosion resistant materials in the stream bed in this region, degradation was not limited by geology as it is in many other areas. As a result bed scour was able to migrate upstream through the tributary systems during the 1960s and 1970s. Over-steepened reaches eventually worked their way right through the fluvial system and into the headwaters, leading to renewed gullying and extension of the drainage network into the uplands. In some places somewhat resistant outcrops of cemented ironstone and massive clay do occur in the bed. In such places scour became concentrated as a head-cut or knick-point with an overfall height of 1 to 2 m. The bed control provided by these materials proved to be temporary, however, as the streams were able to destroy the controls quite quickly. Destruction occurred either because the scour hole developed on the downstream side of the resistant materials led to their removal by under-mining, or because the limited horizontal extent of resistant layers allowed the stream to flank the bed control by eroding around it. Usually, degradation was halted for some weeks or months at an over-fall associated with a resistant layer, only to breach it and progress rapidly upstream during a storm run-off event.

Characteristically, between 2 and 5 m of bed lowering occurred in the Bluff-line streams during the 1960s and 1970s, as documented in studies of typical streams such as Goodwin, Johnson and Long Creeks (Decoursey, 1981), Tillatoba Creek (Patrick & Smith, 1982), Oaklimiter Creek, Pigeon Roost Creek and the Tippah River (Schumm *et al.*, 1984), Hotopha Creek (Watson *et al.*, 1988a) and Batupan Bogue (Watson *et al.*, 1988b).

Degradation has caused serious damage to the streams. Upstream of head-cuts and oversteepened reaches the channels have an attractive appearance with reasonable but not excessive accumulations of sediment usually arranged in an orderly fashion as alternate bars, point bars and gravel riffles. But downstream of head-cuts the channels have a ragged appearance, show no coherent hydraulic geometry and are bereft of bed sediment. During degradation the benthic layer is destroyed with negative environmental impacts, pool-riffle variability is reduced which degrades in-stream habitat, and the riparian zone is de-watered due to bed incision, with adverse effects on riparian vegetation and habitat. Bridges and other structures suffer scour around their footings and pilings, causing costly repair work and risk of failure.

Also, the massive output of sediment from the bluff-line streams associated with this degradation has led to severe aggradation in the trunk streams. The loss of channel capacity has resulted in the need for extensive and expensive dredging to maintain flood capacity on rivers such as the Little Tallahatchie.

Width response

Although the initial and primary response of the fluvial system to land-use and stream management changes is bed degradation, the channel banks have also been seriously affected. This is the case because scouring of the bed and bank toe increases both the bank height and bank angle, which in turn reduce the stability of the bank with respect to mass failure under gravity.

In a degrading channel over-heightening and over-steepening of the banks continues until a state of limiting stability is reached and mass failure is imminent. The mechanism by which the bank then fails depends on the size and geometry of the bank and the stratigraphy and geomorphic properties of the bank materials. In a study of bank erosion in the Bluff-line streams, Thorne *et al.* (1981) observed that the banks close to head-cuts and oversteepened reaches are relatively low, but are very steep and usually fail by a slab-type mechanism, where a slab of soil, partly detached from the bank by a tension crack, topples forward into the channel. Further downstream bank heights are greater and angles are flatter and as a result rotational slip failures are more common than slab-type failures.

Failure is often triggered by "worst case" conditions when the strength of the bank materials is minimized and their weight is maximized. Such conditions are associated with saturation of the bank due to prolonged rainfall and/or snowmelt. Stability with respect to mass failure can be even further reduced when there is rapid drawdown in the channel adjacent to the bank. This promotes strong seepage as water drains out of the bank and into the channel. Seepage can lubricate potential failure surfaces, especially if there is an aquitard low in the bank which causes seepage lines to be horizontally rather than vertically orientated. In extreme cases where water flow is concentrated in thin horizontal sand layers in an otherwise cohesive bank, seepage can lead to failure by piping. In poorly drained banks drawdown can generate positive pore water pressures in the soil. Positive pore pressures reduce the effective friction angle of the soil leading to loss of strength. Hence, for a number of reasons, failure often occurs after, rather than during, high flow events.

After failure the bank is stable in its new configuration and it remains so until the basal accumulation of failed material is removed by the flow and the bank is again eroded to a limiting condition. It then fails again, the type of failure depending on the new bank geometry. Hence the frequency of failures and the time-averaged rate of bank retreat over a prolonged period are determined by the capacity of the near bank flow to entrain and remove failed and intact bank material from the toe, even though the mechanism and timing of failure are not directly fluvially controlled.

In the case of the Bluff-line streams the bank materials are fluvially re-worked loess. These structured silts and clays in their intact state are not easily eroded by the flow and banks below the critical height for mass failure are not subject to rapid retreat. However, much of the cohesion of these soils depends on their fabric, which is destroyed during mass failure. Disturbed materials are easily eroded and disintegrate to very fine grained wash load upon entrainment. As the relatively steep Bluff-line streams have an almost unlimited capacity for wash load, bank sediments are flushed rapidly through the streams and make a large contribution to problems of aggradation and sedimentation in the trunk streams. Consequently, the rate of bank retreat is high once the critical bank height for mass failure is reached and this stage in the response of the streams to land-use and management changes involves rapid widening. Analysis of historical aerial photographs indicates that width increases of 200 to 300% occur commonly within a few months of the passage of a head-cut which triggers mass bank instability in a formerly stable reach (Decoursey, 1981; Patrick & Smith, 1982; Schumm *et al.*, 1984).

The limit to width increase is eventually reached when the channel becomes so wide that the flow adjacent to the banks is unable to continue eroding the bank and removing the failed bank material. Unremoved slump material then accumulates at the toe, buttressing the bank against mass failure, allowing vegetation to grow there, inducing deposition of suspended sediment and encouraging the establishment of a basal wedge or berm at the foot of the bank. The development of the berm allows the bank behind it to lie back at a flatter angle, stabilizing it with respect to mass failure. Often berms form on alternate sides of the channel to produce a sinuous thalweg which in time leads to a recovery of sinuosity to pre-channelization levels in the whole channel.

CHANNEL EVOLUTION MODEL

Identification of the tendency of disturbed channels first to degrade and then to widen has led to the development by geomorphologists and engineers of a general models for channel evolution following de-stabilization (Watson *et al.*, 1986; Simon & Hupp, 1986). As early as 1981 the central role played by the critical bank height for mass instability had been recognized (Thorne *et al.*, 1981; Little *et al.*, 1982) and the concept of the critical bank height as an important intrinsic geomorphic threshold is implicit in the proposed models for channel evolution.

Watson *et al.* (1986) put forward a five stage model based on field observations along unstable streams and a location-for time substitution which allows changes along the channel at a given time to suggest how changes at a given point would take place through time. The stages are associated with conditions ranging from total dis-equilibrium to a new state of quasi-equilibrium. The evolutionary stages are as follows:

Stage	Location	Condition
Stage I	Upstream of head-cut	Channel stable
Stage II	Downstream of head-cut	Bed degrading, banks stable (H<HC)
Stage III	Downstream of Stage II	Bed degrading, banks unstable (H=HC)
Stage IV	Downstream of Stage III	Bed aggrading, banks unstable (H>HC)
Stage V	Downstream of Stage IV	Slow aggradation, banks stable (H<HC)

Note: H = Actual bank height, HC = Critical bank height for mass failure.

Simon and Hupp's six stage model (1986) was developed for channelized streams draining loess hills in west Tennessee. It differs from Watson *et al.*'s only in that a construction stage exists between stages I and II of the Watson *et al.* model, reflecting the emphasis placed by them on the impacts of channelization and dredging in de-stabilizing channels there.

Application of the five stage model for channel evolution in the late 1980s highlighted the importance of accurately predicting the critical bank height for mass instability in order to account for the switch in dynamic response from degradation to widening (Watson *et al.*, 1988a and b). In model terms, that is the changes from stage II to stage III of channel evolution. This requires application of a model for bank stability with respect to the slab-type and rotational failures observed in degrading streams.

BANK STABILITY MODEL: BACKGROUND

In a one year study in 1979/80 a simple set of dimensionless stability charts for slab-type failures was developed for use in the prediction of critical bank height for the banks of Bluff-line streams (Thorne *et al.*, 1981; Little *et al.*, 1982). However, these charts were developed quickly, as a first approximation and they involved several simplifying assumptions that were unsatisfactory. Subsequently, in doctoral studies at Colorado State

University, Osman (Osman, 1985; Osman & Thorne, 1988) re-designed the charts to better account for the combination of near-bank bed scour and lateral toe erosion responsible for bringing a bank to an unstable state. The analysis developed was tested theoretically in his thesis (subsequently reported in Thorne & Osman, 1988), but no real world application was attempted until 1987. The Osman-Thorne analysis marked a significant improvement over the earlier analysis in that both slab-type and rotational failures were dealt with. From the theory underlying the analysis it was apparent that slab failures should be the most likely on banks steeper than about 60° and rotational slips most likely on banks flatter than 60°. The calculations involved in applying the Osman-Thorne bank stability model are quite long and involved and so calculator programs and computer spread-sheets have been developed in parallel to the applied studies (Thorne, 1988; Thorne & Abt, 1989).

BANK STABILITY MODEL: APPLICATIONS

Field study of bank stability

In a two year study of Long Creek, Panola County, Mississippi, data were collected on bank geometries, bank material properties and bank failures in response to the passage of a headcut through an over-steepened reach and the subsequent stabilization of the reach by installation of a grade-control structure (Thorne, 1988; Thorne *et al.*, 1988; Biedenharn *et al.*, 1990). Long Creek was at that time one of six catchments being investigated under the Demonstration Erosion Control (DEC) programme of the US Army Corps of Engineers. Long Creek is a tributary of the Yocona River and enters that river just downstream of Enid Reservoir. It has a drainage area of 27,000 hectares split about equally between pasture and row crops. Like most Bluff-line streams, Long Creek has experienced severe instability for the last twenty years.

The site selected for the bank study was in a reach known to be over-steepened, degrading and suffering serious bank retreat. The engineering properties of the bank materials were previously established in a USDA study (Thorne *et al.*, 1981) from field and laboratory measurements. The characteristic properties for "worst case" conditions are: cohesion = 13 kPa, friction angle = 16°, saturated unit weight = 2100 kg m^{-3}. Seventeen sections along a 1 km reach were surveyed by levelling on 2 December 1987 and were re-surveyed on 21 January 1988, 21 April 1988 and 10 October 1989. The results illustrate graphically the response of bank stability to changing bed levels due to degradation and aggradation.

Failure of banks due to degradation

During the first period of observation the basin experienced prolonged and heavy precipitation (both rain and snow), melting of the snow which had accumulated on the flood plain and high stages in the channel. It is certain that "worst case" conditions occurred during this period and also likely that rapid drawdown conditions led to positive pore water pressures during the falling stage at the end of the high flow event. Of the 17 surveyed sections, 16 failed during this period. Based on the shape of the failure surface and orientation of failed block remnants observed in January 1988, 11 had suffered slab-type failures and 5 rotational slips. When the type of failure was related to the bank geometry prior to failure these field observations confirmed that, as predicted from theory, slab-type failures predominate on banks steeper than about 60°. It appeared that banks with angles ranging from 50 to 60°

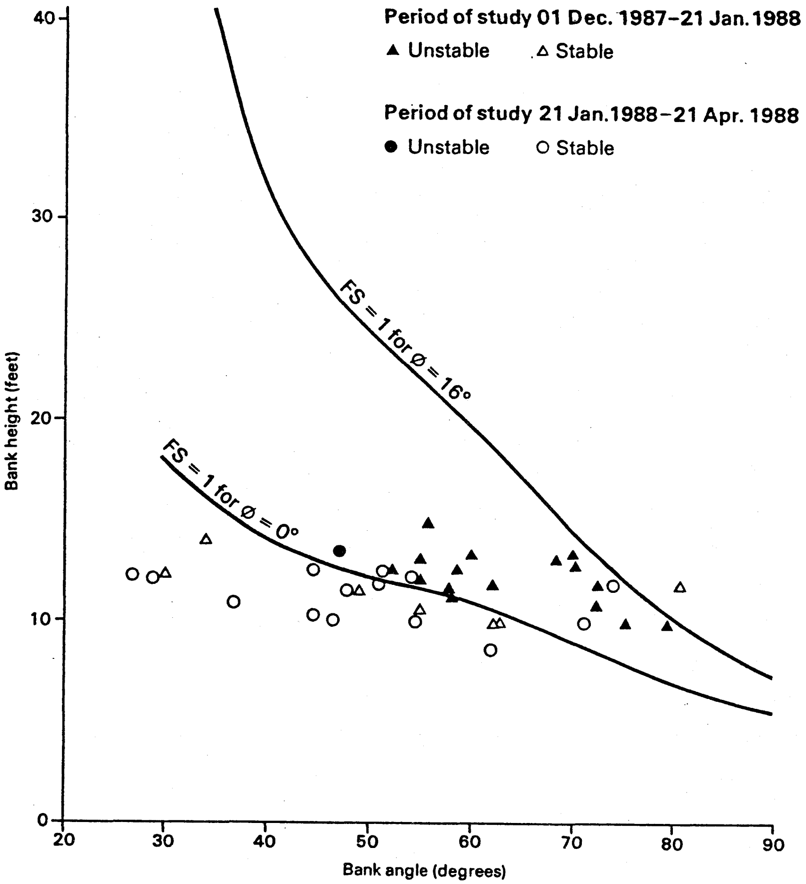

FIG. 1 Bank stability for the study reach at Long Creek.

were equally likely to collapse by either slab or rotational slip failure. No banks with angles less than 50° were observed on this reach of Long Creek at that time.

The results are plotted on a graph of bank height versus bank angle (Fig. 1). Also shown are the lines of limiting stability for "worst case" (phi = 16 degrees) and "worst case plus rapid drawdown" (phi = 0) conditions. Examination of Fig. 1 shows that the line of limiting stability for the combination of worst case plus rapid drawdown conditions is a good discriminator between banks which were stable and those which failed in the period December 1987 to January 1988. In the first period of observation the combination of high levels of soil saturation, toe scour by high flow in the channel and seepage due to rapid drawdown at the end of the flow event was sufficient to trigger failures all along the 1 km reach.

During the second period of observation (January - April 1988) there were periods of precipitation, but no major flow events. In the second period only one bank failed. On Fig. 1, the stable sections mostly plot below the "worst case" plus drawdown line. Field observation of these banks showed that they were buttressed by blocks of failed material yet to be removed following the Dec-Jan failures. These banks should be expected to remain stable so long as the slump debris remains in place. Four points, corresponding to the outside of a meander where basal clean-out of slump debris had been completed, do lie in the zone between that line and the limiting line for "worst case" conditions alone. These banks were stable during the second period of observation but only because although they were at times saturated, they were not also subject to rapid drawdown and lubrication of potential failure surfaces. In this regard their stability cannot be relied upon, as a combination of saturation and rapid drawdown could occur at any time. They could be described as "at risk" of failure, since failure could be triggered at any time by a combination of "worst case" and rapid drawdown conditions without further degradation of the bed or lateral erosion of the bank at the toe.

Stabilization of banks due to aggradation

In the summer of 1987 a grade control structure was constructed on Long Creek about 500 m downstream of the study reach. Its primary purpose was to stop any head-cuts in the system downstream from migrating through the over-steepened reach. A second aim was to induce deposition in the over-steepened reach and to this end the invert on the structure was set approximately 1 m above bed level. The effect of the grade control structure on the bed is shown in Fig. 2. By April 1988 a sediment wave had formed in the backwater zone behind the structure, with the front of the wave at about station 312+00. Sediment accumulation continued throughout 1988 and into 1989. By May 1989 the sediment wave had reached 309+00 and by October 1989 it had reached the structure itself. But not only did the structure protect the bed from degradation, by inducing aggradation it had the effect of stabilizing the banks as well. This can be illustrated by plotting reach averaged values of bank height and angle on the Osman-Thorne bank stability chart. Figure 3 shows that average bank geometry moved from the unreliable zone in December 1987 and January 1988 (before the aggradation wave had reached the study reach) to the "stable" zone in April 1989 and October 1989. The building of berms of unremoved failure blocks with accreted sediment from the depositionary wave was able to reduce bank heights and angles suffi-

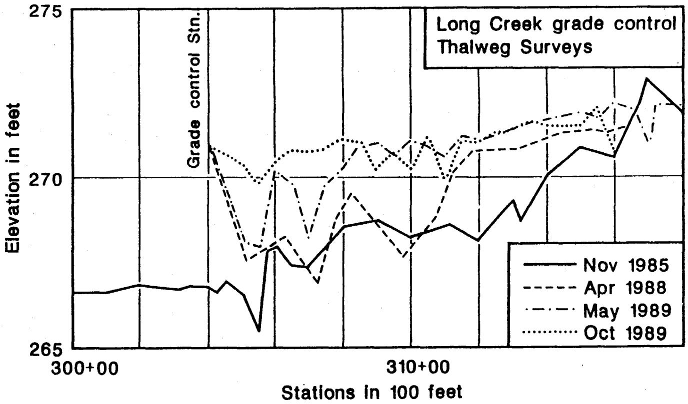

FIG. 2 Thalweg profiles in the Long Creeek study reach.

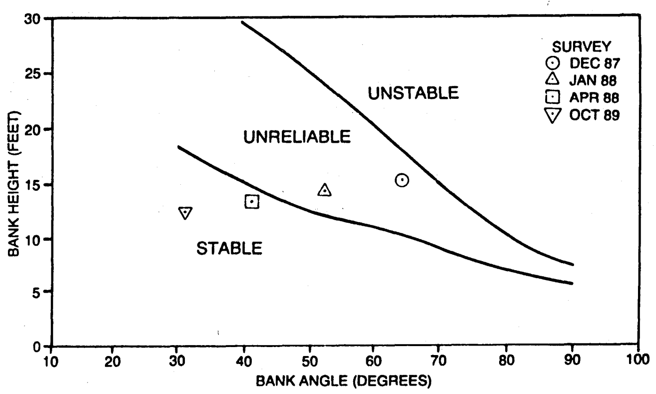

FIG. 3 Bank stability chart showing progressive stabilization of banks due to bed aggradation behind the grade control structure.

ciently that mass failures were no longer likely. While some shallow slides did occur on the upper portions of some banks, resulting in a little further retreat of the top bank, by the end of 1989 the banks were entirely stable in the study reach and bank retreat had ceased.

The success of the grade control structure on Long Creek in controlling bank retreat demonstrates the link between bed and bank stability, and shows how the condition of the banks is ultimately determined by the ability of the flow in the near bank zone to entrain and remove bank material even though the mechanics of failure and the conditions which trigger collapse are more intimately concerned with bank material stratigraphy, geomorphic properties and catchment hydrology.

CONCLUSIONS

Application of the Osman-Thorne bank stability model to the banks of a study reach on Long Creek illustrates the important link between processes operating on the bed and banks of an unstable stream which is responding to imposed changes in land-use and river management.

Application of the bank stability model verifies that rapid widening is associated with mass instability of the banks due to over-heightening and over-steepening caused by bed scour and lateral toe erosion in the degrading channel. This confirms an important component in conceptual models of channel evolution. Quantitative application of such conceptual models in the analysis and explanation of channel process-response rests on accurate determination of the critical height for mass instability of the banks to identify the important geomorphic threshold when instability switches from vertical to lateral activity.

The observations and analysis show that the precise timing of failure and the characteristic mode of collapse are controlled by bank geometry, bank stratigraphy, bank material properties and catchment hydrology rather than by stream hydraulics per se. However, that the ultimate control of bank retreat by channel hydraulics is clearly demonstrated by the response of the banks to the construction of the grade control structure in the channel downstream. By halting degradation and inducing aggradation the structure was able to use the linkage between bed and bank processes to produce width stabilization through control of the sediment balance at the toe of the bank. Between January 1988 and October 1989 this switched from a condition where bank failure debris was quickly removed and erosion continued, to one where a berm of material built up, reducing the bank height and slope angle, stabilizing it with respect to mass failure and protecting the bank from flow attack. As a result the banks were able to heal naturally through slope relaxation behind the stable toe. The top bank width of the channel did increase marginally as shallow slips occurred for a few months on the upper bank, but bottom width decreased through berm building on the lower bank.

In the context of the Long Creek flood plain, which is used for arable and pasture farming, the bank stabilization provided by the grade control structure over a 1500 m reach represents an adequate and cost-effective solution to chronic problems of bank retreat and channel widening in this area. These benefits are additional to those associated from the control of bed level, which was the primary purpose of the structure, and mean that the overall cost/benefit ratio for the structure is further improved.

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