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USE OF INCISED CHANNEL EVOLUTION MODELS IN UNDERSTANDING REHABILITATION ALTERNATIVES[1]

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ABSTRACT: Incised channels are caused by an imbalance between sediment transport capacity and sediment supply to the stream. The resulting bed and bank erosion alter channel morphology and stability. Geomorphological models of incised channel evolution can provide guidance in the selection of engineering design alternatives for incised channel rehabilitation. This paper describes how incised channel evolution models may be coupled with a dimensionless stability diagram to facilitate evaluation of rehabilitation alternatives. In combination, the models provide complementary views of channel processes from geomorphic and engineering perspectives.

(KEY TERMS: channel evolution; channel rehabilitation; erosion; sedimentation; stream incision.)

DEFINITION OF AN INCISED CHANNEL

Channel incision, or bed lowering by erosion, results from an imbalance in the power available to move a sediment load and the power needed to move a sediment load (Bull, 1979; Galay, 1983). When the sediment transport capacity of a sand bed channel exceeds the sediment supply delivered to the channel, erosion will occur. Erosion of either the bed or banks or both may occur, depending on the relative erosion resistance of the two (Simon and Darby, 1997; Bledsoe, 1999). Where banks are cohesive and resistant to hydraulic forces, bed erosion is initially dominant over channel widening. As bank heights on an incising channel increase by degradation, flow events of increasingly greater magnitudes are contained within the channel banks. This deepening may create a positive feedback process wherein shear stress on the bed and toe of the banks is increased as larger flow events are contained within the banks. Consequently, the frequency of inundation of the floodplain decreases, effectively reducing the hydrologic interaction between the channel and the former floodplain. If bed degradation continues until banks reach a critical height for mass failure, rapid channel widening may be initiated. Widening can proceed at a rapid rate with tenfold increases in cross-sectional area within a few years (Harvey and Watson, 1986).

There is no clear consensus on the definition of an incised channel. Pickup and Warner (1976) state that a channel is incised when the floodplain becomes a terrace. A floodplain may be defined as the active depositional surface adjoining a river channel that is constructed by the river in the present climate and overflowed at times of high discharge (Dunne and Leopold, 1978). A terrace is defined as an abandoned floodplain that was formed when the river flowed at a higher elevation than at present (Ritter, 1978). Pickup and Warner (1976) refer to Wolman and Leopold (1957) who define a terrace as a former floodplain surface that is not overtopped by a flood of less than a two-year recurrence interval. Williams (1978) provides a thorough review of methods to determine the bankfull discharge and stage in rivers. Bankfull elevation, generally a field determined parameter, is associated with indicators such as: the height of a depositional feature, topographic breaks along the bank, lower limit of woody vegetation, a change in the particle size along the bank, stain lines, or other similar features (Harrelson *et al.,* 1994). In general, the bankfull discharge of non-incised stable streams is generally accepted to be in the range of one- to two-year recurrence interval flow (Simon and Darby,

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1999). Field studies generally support the notion that bankfull discharge commonly approximates a flow event with a 1.4- to 1.6-year recurrence interval in the annual maximum series (Rosgen, 1994; Annable, 1996a, 1996b) although the recurrence interval may vary widely (1.01 to 32 years; Williams, 1978). The modal value reported by Williams (1978) was 1.5 years. Therefore because most authors agree that bankful discharge is, on average, equal to or less than the two-year flood, the working definition in the present research is that an incised channel will contain the two-year recurrence interval flood (50 percent chance of occurrence in any one year) and is vertically separated from the adjacent former floodplain due to bed degradation, which requires it to be bounded by terraces.

A word of caution is appropriate in determining the return period of flows. It is unlikely that a gauging station will be located in an unstable, incising channel, which, of course, is the type of location that is frequently investigated. Regionalized regression methods generally yield a standard error of estimate in the range of 30 to 60 percent (Jennings *et al.,* 1994).

CAUSES OF CHANNEL INCISION

Schumm (1999) lists six general causes of incision: geologic, geomorphologic, climatic, hydrologic, animals, and humans. In each category, he lists several more specific causes. Fundamentally, each cause is the same (i.e., imbalance between the sediment transport capacity and the sediment supply). For example, urbanization of the watershed increases runoff and increases sediment transport capacity. Stream sediment transport capacity can be abruptly increased through channelization, an increase in flow velocity or duration as a result of land use change, or lowering base level. Sediment supplies may be abruptly reduced by sediment trapping in reservoirs, erosion control practices on uplands, and imperviousness. Natural causes such as uplift or subsidence, climate change, and lateral shifting of the channel can also cause the balance between sediment supply and sediment transport capacity to be disrupted.

CHANNEL EVOLUTION MODEL (CEM) FOR SAND BED CHANNELS

Numerous geomorphologic studies have used a variety of data from different locations to infer landform development through time. One technique used is location-for-time substitution. This technique assumes that by observing channel form as one moves downstream along a channel, the effect of physical processes at one location through time can be observed, that is, location-for-time substitution. Chorley *et al.* (1984) explain that space-time transformations are permissible as a working tool. The classic landform study by Glock (1931) is a cited example.

Chorley *et al.* (1984) also caution that space-time transformations are dangerous in that a series of landform may be assembled into an assumed time sequence to fit a preconceived theory. The researcher can then fashion a rather circular argument to support the hypothetical sequence. In the assumed location-for-time transform used in developing the CEM sequence, time is the primary variable and changes in materials, sediment supply, valley slope, and other factors were ignored. However, even with the obvious weaknesses in the approach and inherent danger of circularity, the first author has observed the CEM through time for approximately 20 years at some locations to verify the general application of the CEM.

This technique was used to develop a CEM for Oaklimeter Creek, an incised stream in northern Mississippi (Schumm *et al.,* 1984). Simon and Hupp (1986) developed a similar model of channel evolution based on their observations of incised streams in western Tennessee.

The CEM (Figure 1) consists of five channel-reach types, which describe the evolutionary phases typically encountered in an incised channel. These evolutionary phases range from total disequilibrium to a new state of quasi-equilibrium. Quasi-equilibrium implies that the system is not static, changes through time, but over a period of years the average condition is one of stability. The model is based on the assumption that distance downstream is equivalent to the passage of time. The response at any given location in the channel can then be predicted from the morphology of downstream channel locations.

The channel reach types in the CEM are labeled I through V, and are assumed to occur consecutively in a downstream direction. The CEM assumes each channel type will occur at a given location as the channel evolves. The CEM channel types are shown in Figure 1. Type I reaches are generally characterized by a U-shaped cross section with little or no recently deposited sediment stored in the channel bed. Type I reaches are located upstream of the actively degrading reach and have not yet experienced significant bed or bank instabilities.

Immediately downstream of Type I reaches, Type II reaches are encountered. Bed degradation is the dominant process in the Type II reach. Type II channels are oversteepened reaches where the sediment transport capacity exceeds the sediment supply. Although

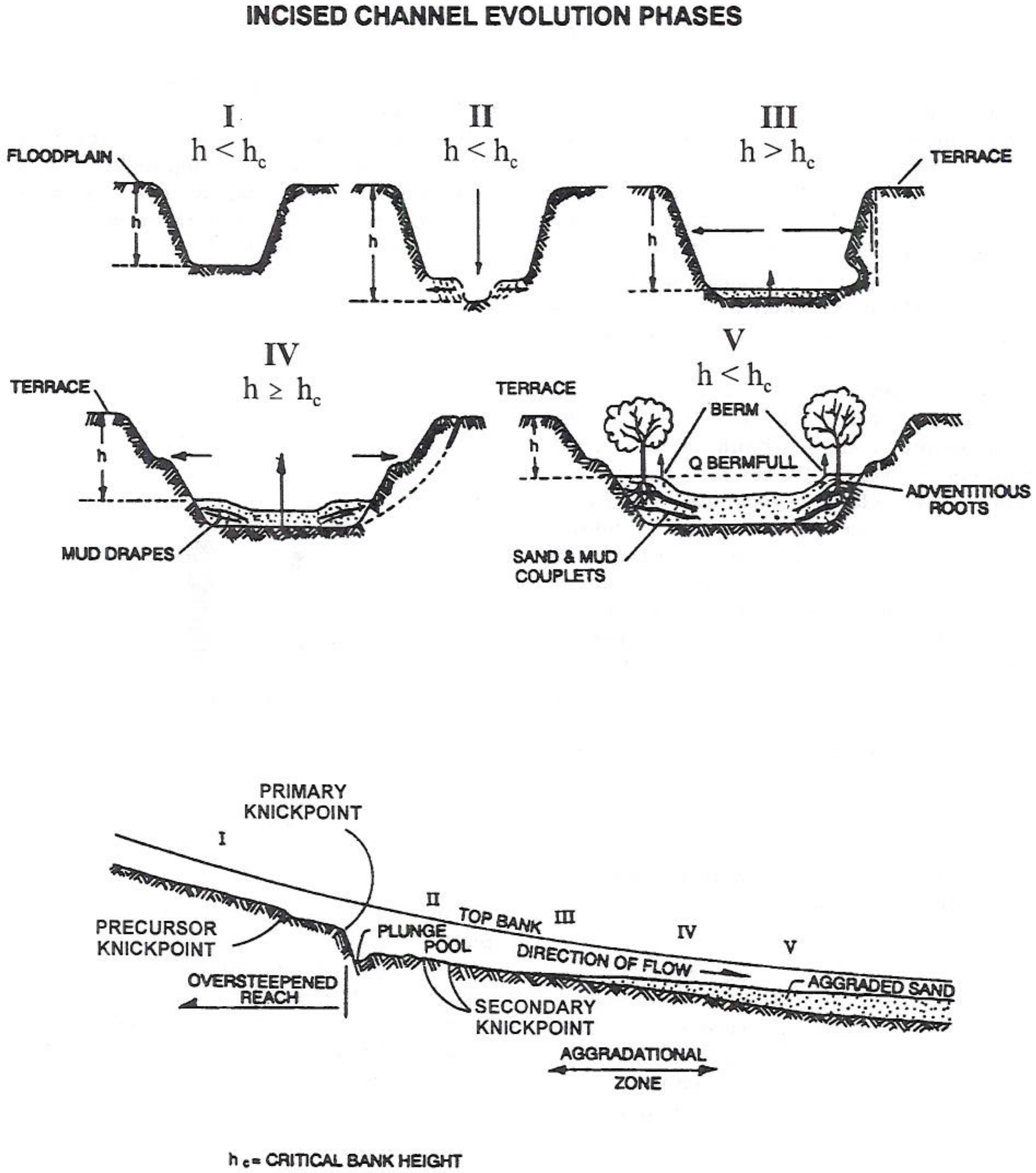

Figure 1. Incised Channel Evolution Sequence (after Schumm *et al.*, 1984).

the channel is actively degrading in a Type II reach, the bank heights (h) have not exceeded the critical bank height (h_c), and, therefore, geotechnical bank instability is not encountered.

As bed degradation continues, the bank heights and angles will continue to increase. When the bank heights have exceeded the critical bank height for stability, mass failures (geotechnical instability) begin to occur in the Type III reaches. The dominant process in the Type III reach is channel widening. In places, the Type III reach may continue to be slightly degradational. However, the reduced sediment transport capacity resulting from the longitudinal channel slope decreasing combined with increased sediment supply from upstream due to instability and from bank failures within the reach often results in the initiation of sediment deposition on the channel bed.

The Type IV reaches are downstream of the Type III reaches and represent the first manifestation of the incised channel returning to a new state of dynamic equilibrium. In the Type IV reach, geotechnical bank instabilities and channel widening may continue, but at a much reduced rate. The sediment supply from upstream (Type III) exceeds the sediment transport capacity resulting in aggradation of the channel bed (Type IV). The Type IV reach is also characterized by the development of depositional features along margins of the over-widened channel. These depositional features, berms, represent the beginning of a new inner channel.

Type V reaches represent a state of dynamic equilibrium with a balance between sediment transport capacity and sediment supply. Bank heights in the Type V channel are generally less than the critical bank height, and therefore, geotechnical bank instabilities do not exist. However, local bank instabilities can still exist as part of the meander process, or as the results of constrictions, obstructions, or other local factors. The berms which were initiated in the Type IV reach have now become colonized by riparian vegetation forming a compound channel within the old channel boundaries. The equilibrium channel of Type V is of a compound shape, with a smaller inner channel bounded by narrow floodplain. The original floodplain of the Type I channel is now a terrace.

DIMENSIONLESS STABILITY DIAGRAM FOR INCISED CHANNELS

The CEM can be considered using two parameters that address sediment continuity and the geotechnical stability of stream banks. The parameters are two dimensionless stability numbers: N_g is a measure of bank stability and N_h is a measure of sediment continuity, which is equality between sediment supply and sediment transport capacity. For a channel to be in quasi-equilibrium, sediment continuity and bank stability are essential.

N_g is defined as the ratio between the existing bank height and angle (h) and the critical bank height at the same bank angle (h_c). Bank stability is attained when Ng is less than unity ($N_g < 1$). Therefore, N_g provides a rational basis for evaluating the geotechnical stability of the banks and for evaluating the consequences of mass wasting in the event of additional bed degradation.

The hydraulic stability number, N_h, is defined as the ratio of the sediment transport capacity to the target sediment supply. Target sediment supply should be quantified in the project planning process. Sediment continuity is attained at $N_h = 1$. If N_h is < 1 the channel will aggrade, and if N_h is > 1 it will degrade.

Combining N_g and N_h on the dimensionless stability diagram (DSD) provides design criteria that define both bank and hydraulic stability in the channel (Figure 2). N_h and N_g can be computed with a number of hydraulic and geotechnical methods. An inherent value of the DSD is that the approach is free of location-for-time transforms.

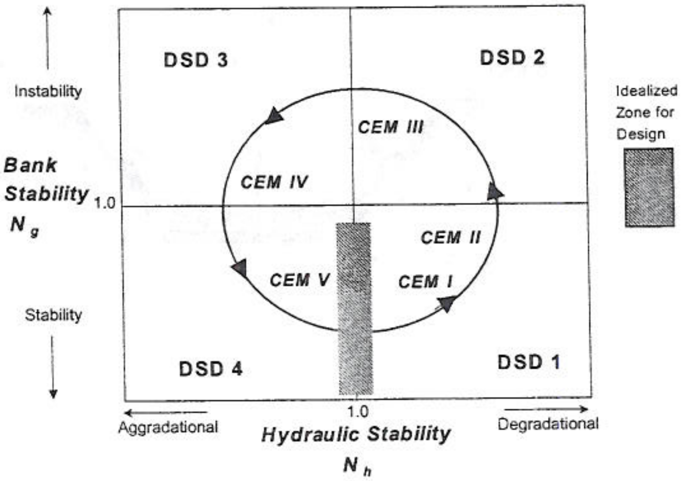

Figure 2. Comparison of the Channel Evolution Sequence and the Channel Stability Diagram.

The selection of the appropriate method for computing N_g and N_h is a function of factors such as the level of study (reconnaissance, feasibility, and detailed design), funding and time constraints, complexity of project and stream characteristics, consequences of failure of the design, and available data. During early reconnaissance studies, it may be appropriate to utilize some of the less computationally intense empirical methods. However, as the level of study increases, more rigorous analyses using numerical models are necessary.

The dimensionless bank stability number (N_g) for preliminary studies could be based on field-determined stable bank heights. For example, banks less than 3 meters in height may be observed to be relatively stable (no recent failure block, vegetation is present, or other field determined factors) ($N_g = h/h_c = h/3$). As funds become available and geotechnical data are acquired at selected sites, limiting stability curves can be developed similar to Figure 3 (Thorne, 1988). Computational techniques for developing these curves have appeared in Thorne (1988), Zellars and Hotchkiss (1997), and Lawler *et al.* (1997).

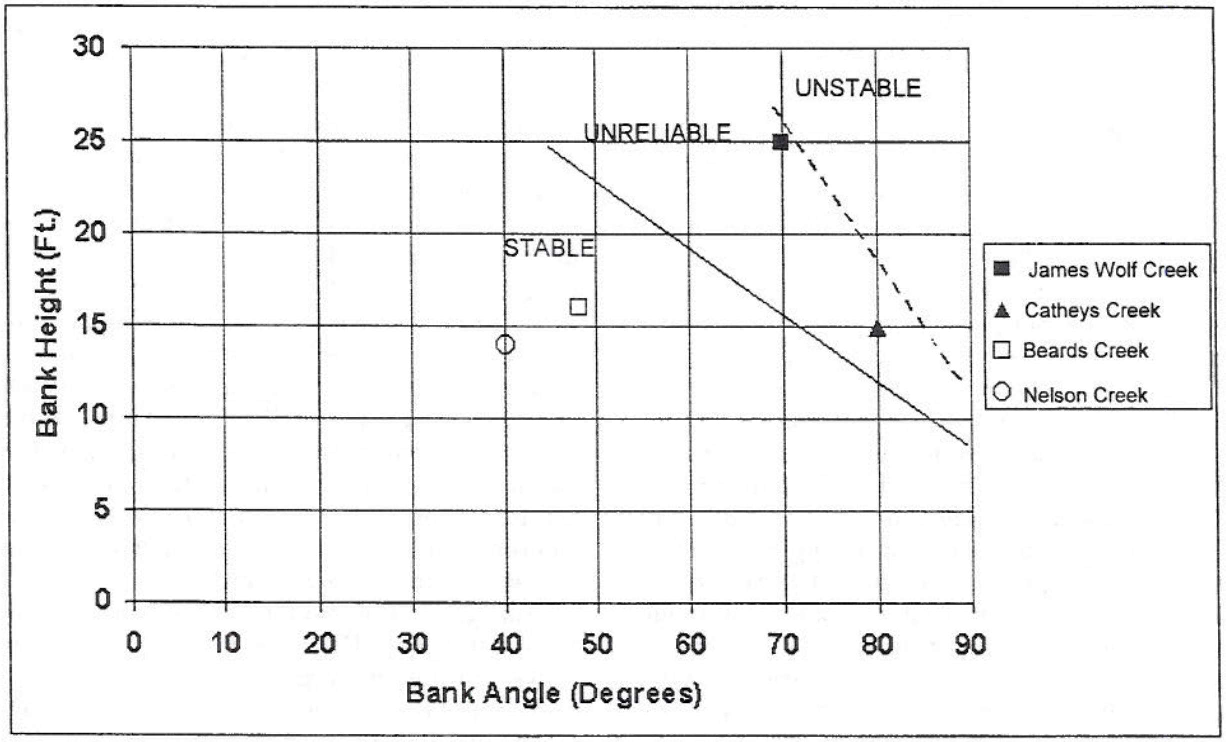

Figure 3. Limiting Stability Relationships (after Thorne, 1988).

The hydraulic stability number can be estimated from field identification of a series of quasi-equilibrium reaches, plotting bed slope as a function of drainage area, and comparing the bed slope and drainage area of a reach under investigation to the quasi-equilibrium slope-area relationship (Figure 4). With the proper survey, discharge, and sediment data,

$$N_h = \frac{\tau_o}{\tau}, \frac{Q_{s\,existing}}{Q_{s\,desired}}$$

(annual sediment yield$_{existing}$/annual sediment yield$_{desired}$) or other similar parameters.

The dimensionless stability numbers, N_g and N_h, can be related to the channel evolution model, as shown in Figure 2. However, the use and determination of N_g and N_h can be developed independent of CEM, which allows DSD to be independent of location-for-time substitution assumptions. As the channel evolves from a state of disequilibrium to a state of dynamic equilibrium through the five reach types of the CEM, the channel condition will progress through the DSD quadrants as depicted (Figure 2) in a counter-clockwise direction. It is unlikely that the response trajectory from instability to stability will be a smooth curve as generalized in Figure 2. By the very definition of N_g and N_h, a series of morphologic

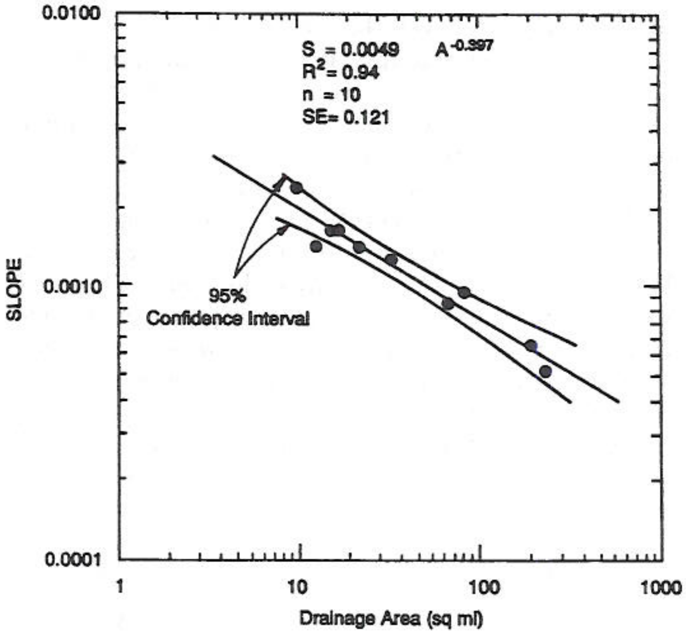

Figure 4. Equilibrium Channels of Hickahala Creek Watershed Plotted on a Slope Area Diagram (after USACE, 1990).

thresholds (Schumm, 1977) must be crossed. Rehabilitation of the channel should attempt to provide the most direct trajectory to DSD 4 to avoid channel widening and deepening. This will reduce the habitat loss and sediment introduced into the stream system.

DSD 1 ($N_g < 1$, $N_h > 1$, CEM Types I and II) streams are degradational (Type II) or may be incipiently degradational (Type I), but the channel banks have not yet become geotechnically unstable. Although banks are not geotechnically unstable, local bank erosion may occur. As shown in Figure 2, the Type I reach streambeds are vertically stable, and may be beginning to exhibit slight degradational tendencies by removal of recently deposited sediment. Local bank stabilization measures (riprap, armor, dikes, bio-engineering) (Biedenharn *et al.,* 1997) and habitat enhancement features can be applied successfully in the Type I reach, provided that the grade remains stable. Should the bed continue to degrade and the channel transitions from Type I to Type II, then local stabilization features alone are generally no longer feasible and some form of grade control is necessary. Before local stabilization features are attempted, the system instability (bed degradation) must be corrected. If the anticipated bed degradation is not too severe, it may be possible to apply local stabilization features that are designed to accommodate the bed lowering; however, the added cost to these features often reduces the cost effectiveness of these alternatives. For example, if stone riprap is placed to provide basal end point control (Lawler *et al.,* 1997), the volume of riprap may be increased to accommodate bed degradation (Biedenharn *et al.,* 1997).

The channel stability in DSD 2 ($N_h > 1$, $N_g > 1$, CEM Type III) is severely unstable, with reaches characterized by bed degradation and geotechnical bank instabilities. Consequently, the DSD 2 (Type III) reach represents the most dynamic phase of the evolutionary process, and presents some of the biggest challenges in channel rehabilitation. Local stabilization and habitat enhancement features are generally not feasible in the DSD 2 (Type III) reach. As with rehabilitation in any of the DSD quadrants, both degradation and mass wasting must be addressed; however, in DSD 2 widening is extremely active. In most contexts where channel relocation is prohibitively expensive or infeasible, grade control is the most effective method of treating DSD 2 (Type III) reaches. Application of grade control features to reduce slope and sediment transport capacity can successfully halt the bed degradation (Watson and Biedenharn, 1999) (reducing N_h) in the DSD 2 (Type III) reach; however, the geotechnical bank instabilities and channel widening may continue since the bank heights will not have been reduced. One strategy is to stabilize the grade with bed stabilization features, apply local bank stabilization as required locally to protect valuable infrastructure and important riparian features, allowing the remaining geotechnical bank instabilities to continue until such time that stability occurs by channel evolution. Another strategy is to design grade control features that induce sediment deposition in the bed, thereby building the bed up and decreasing the bank height. While this methodology can be successful, there are potential drawbacks that must be considered such as loss of flood capacity in the upstream channel, environmental impacts such as impairment to fish passage, and increased cost.

In any planned rehabilitation strategy, the limits of the project reach must be carefully considered. For example, if a reach is manipulated to reduce sediment supply (grade control, riprap revetment, bioengineered stabilization), the downstream reach may become unstable due to degradation.

Another option that has potential for stabilizing the DSD 2 (Type III) reach is flow control using reservoirs or other management practices. Flow control can improve the overall stability of the reach if the new flow duration curve reduces cumulative bed material transport; however, changing the flow duration curve and reducing the available sediment supply in a stream are potentially destabilizing, and requires a rigorous hydraulic and sediment transport analysis.

DSD 3 ($N_g > 1$, $N_h < 1$, CEM Types III and IV) streams are characterized by geotechnically unstable banks, but without continued bed degradation. DSD 3 represents the transition zone from the Type III to IV reaches as the slope flattens, resulting in initiation of sediment accumulation in the bed. Bank stabilization with grade control emplacement should be considered. Local bank stabilization measures alone in either DSD 2 or DSD 3 are unlikely to be successful. Flow control in these two quadrants could be beneficial but must be considered in the context of extreme reach instability. Grade control is likely to be required.

Since sediment supply to a channel can change through time, it is prudent to design rehabilitation measures that will allow for the change in sediment supply. For example, if a series of grade control features are constructed in an actively degrading watershed, the stability resulting from the features will result in a lower channel slope. Therefore, the structure foundations must be designed to match the expected grade. Grade-control features constructed in the channel may induce upstream deposition of sediment in the bed of the stream as a result of slope reduction. This emulates the natural evolution of the channel. The aggradation upstream of the grade-control feature eventually will result in increasing bank stability.

DSD 4 ($N_g < 1$, $N_h < 1$, CEM Types IV and V) is characterized by general aggradation. Local bank stabilization and habitat enhancement features are likely to be effective. Since the streams have attained a new state of dynamic equilibrium, system solutions such as grade control features are generally not necessary.

The goal for long-term channel stability is for N_g to be less than one, and for N_h to be approximately one ($N_g < 1$, $N_h \approx 1$). If channel flood capacity is not sufficient as N_g increases toward 1.0, additional channel depth would not be appropriate because the bank would be geotechnically unstable. A compound channel or other flood mitigation strategy should be considered (Brookes, 1988).

As stated earlier, N_h may be defined as the sediment transport capacity divided by the target sediment transport supply. Emphasis must, in some situations, be placed on the desirability of the existing sediment transport capacity and sediment supply. For example, if the stream appears stable in accordance with CEM Type V, but is transporting too much sediment into a downstream wetland, the system could be altered to reduce sediment yield. This would best be accomplished through a simultaneous reduction in sediment supply and transport capacity. Sediment supply is decreased by reducing the availability of sediment sources by a combination of upland watershed practices, bank stabilization, flow control, and grade control. Transport capacity is reduced primarily by flow control and grade control. Bank stabilization is generally considered to cause local reduction in sediment supply from a single source; however, when considering the project reach in a system context, any measure can be considered to have positive and negative aspects, as shown in Table 1.

In general, the dimensionless stability diagram can be used to depict a shift from actual to a desired target sediment supply (Figure 5), whereas the CEM provides an understanding of only the existing natural sequence of channel evolution. The combined models provide complementary view of channel processes from engineering and geomorphic perspectives.

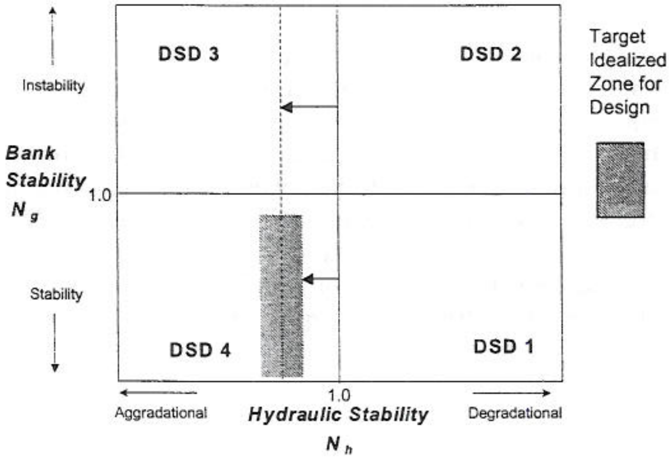

Figure 5. Dimensionless Stability Diagram for a Reduced Sediment Supply.

APPLICATION OF DSD AND CEM

As in any actual application of channel rehabilitation methods, limitation in resources requires making choices between techniques, and in the completeness of the design. Combination of the CEM with the dimensionless stability diagram provides some basis for these choices. Each quadrant of the stability diagram is characterized by geotechnical and hydraulic stability number pairs, and stream reaches that plot in each quadrant have common characteristics with respect to stability, flood mitigation, and measures that may be implemented to achieve a project goal.

The U.S. Army Corps of Engineers (USACE) used the DSD and CEM concepts for the selection of rehabilitation alternatives for the Hickahala Creek watershed in north Mississippi (USACE, 1991). The streams in the Hickahala Creek watershed have been extensively channelized over the past 50 to 80 years and were experiencing severe bed and bank instability. The application of the design approach is presented for four actual streams within the Hickahala Creek

TABLE 1. Positive and Negative Analysis of Rehabilitation Measures.

Rehabilitation Measure	Positive Effect	Negative Effect
Bank Stabilization	Reduces sediment supplied from a bank site	May induce local bed erosion
Grade Control	May induce upstream deposition and eventual stability upstream	May induce downstream incision and instability by reducing sediment supply
Flow Control	May reduce flood peaks and improve downstream stability	May decrease sediment supply locally downstream or system-wide; both cause incision

watershed. Following an intense geomorphic field analysis of the Hickahala Creek watershed, threshold values for the quasi-equilibrium condition based on channel slope were identified (Figure 4). For the sand bed channels (D_{50} = 0.28 mm) that predominate the watershed, a relationship between quasi-equilibrium channel slope and drainage area was developed (Figure 4). Hydraulic stability (N_h) for this application was defined by the ratio of existing channel slope to the corresponding quasi-equilibrium slopes for the various study reaches

$$N_h = \frac{S_{existing}}{S_{quasi-eq.}}.$$

The dominant mode of bank failure in the incised reaches of the Hickahala Creek watershed is mass failure. Geotechnical stability (N_g) was assessed on the basis of field observations and previously developed limiting stability relationships by Thorne (1988) as shown in Figure 3. The reach average values of bank height and angle of the four study reaches are also plotted in Figure 3. The DSD depicting the four study reaches is shown in Figure 6.

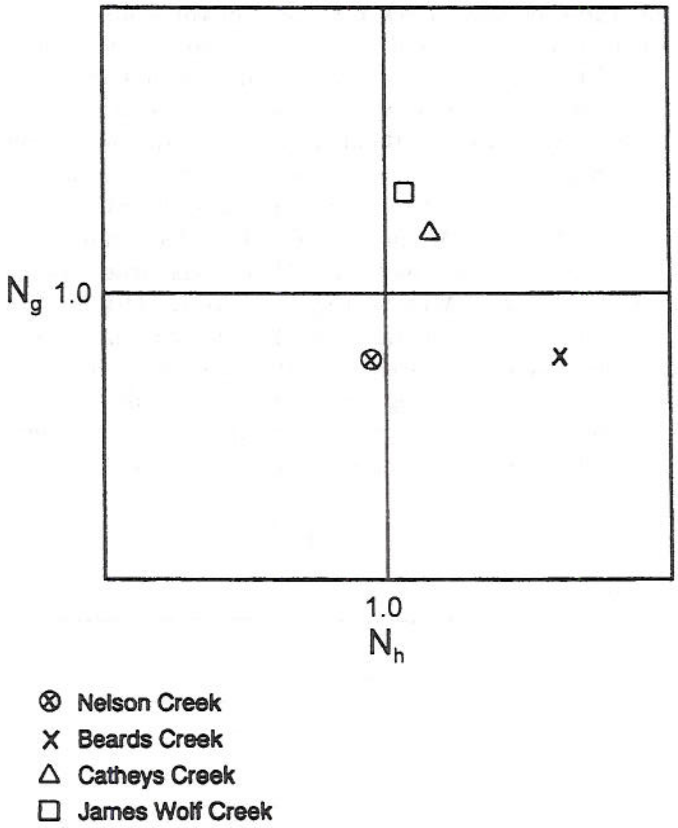

Figure 6. Dimensionless Stability Diagram With Four Sites (after USACE, 1990).

Nelson Creek

Nelson Creek has a drainage area of 14 square miles and a corresponding quasi-equilibrium slope of 0.0017 as indicated in Figure 4. The reach average slope for this reach was surveyed as 0.0017, which suggests that hydraulic stability exists. Field investigations verified quasi-equilibrium conditions (Type V). Figure 5 shows that the banks on Nelson Creek plot well within the stable zone indicating that system-wide bank instability should not be a problem. Therefore, Nelson Creek is a stable channel with respect to both hydraulic

$$\left(N_h = \frac{0.0017}{0.0017} = 1\right)$$

and geotechnical

$$\left(N_g = \frac{h_{existing@40^\circ}}{h_{c@40^\circ}} = \frac{14\text{ ft}}{27\text{ ft}} = 0.52\right)$$

stability criteria as indicated in Figure 6. Consequently rehabilitation measures were not required. Local bank stabilization and habitat enhancement features could be applied locally as required.

Beards Creek

Beards Creek has a drainage area of 8 square miles and the relationship in Figure 4 indicates an equilibrium slope of 0.0021. The surveyed reach average slope for this reach is 0.0028, which indicates that the channel may be degradational. Field investigations confirmed that the reach was degradational. However, system-wide bank instability does not exist as shown in Figure 5. The channel stability parameters plot in DSD 1 of Figure 6. Since the channel is hydraulically unstable (N_h = 1.33), but the critical bank height has not been exceeded

$$\left(N_g = \frac{16\text{ ft}}{24\text{ ft}} = 0.67\right),$$

a system of properly spaced grade control features designed to prevent further degradation will provide the needed stability to the reach. After the bed has been stabilized, local bank stabilization may be implemented as needed to protect bridges, culverts, or other threatened infrastructure and valuable riparian features.

Catheys Creek

The surveyed reach values of channel slope varied from 0.0025 to 0.0035 for Catheys Creek, fluctuating about the equilibrium slope value of 0.0032. Therefore, there is some uncertainty with respect to the hydraulic stability criteria. Part of this uncertainty exists because of the small drainage area (3 square miles) of the Catheys Creek reach; most of the data used to develop the equilibrium slope curve in Figure 4 were obtained from larger watersheds. However, field investigations revealed numerous indicators of vertical instability. Therefore, for a conservative design, the reach was classified as degradational. Geotechnical investigations indicate that the banks plot in the unreliable zone of Figure 5, and are at risk of mass failure

$$\left(N_g = \frac{15\,\text{ft}}{12\,\text{ft}} = 1.25\right).$$

The stability parameters for this reach plot in DSD 2 of Figure 6. Since the critical bank height had been exceeded, merely stabilizing the bed or reducing flows to promote hydraulic stability would not prevent the system-wide bank instabilities. Therefore, grade control features will need to raise the bed elevation and reduce the bank height below the critical value, or grade control to prevent increased bank heights could be combined with bank shaping to reduce bank angle.

James Wolf Creek

James Wolf Creek has a drainage area of 14 square miles and an equilibrium slope of 0.0017 (Figure 4). The reach average bed slope for James Wolf Creek is 0.002, which is slightly larger than the equilibrium slope and which suggests that the channel is unstable. Field investigations were conducted and did provide conclusive evidence as to the vertical stability of this reach. Therefore, the geotechnical consequences of future degradation in the reach were assessed carefully. If the banks could withstand additional bed lowering without affecting the bank stability then it might be acceptable to forego the use of grade control. However, Figure 5 reveals that the reach average bank height and angle data plot in the unreliable zone near the threshold of the unstable zone. Therefore, for James Wolf Creek, the risk of assuming that the channel bed is stable is too great since any amount of bed lowering would further destabilize the channel banks. Consequently, grade control was required in this reach and geotechnical stability could be achieved by decreasing bank height or bank angle.

CONCLUSIONS

The dimensionless stability diagram may be used to select appropriate rehabilitation methods for incised channel systems. Selection of a rehabilitation measure that is not compatible with the existing morphologic characteristics and response trajectory of the channel often leads to more costly and less effective features, and increased maintenance costs over the life of the project. Therefore, it is critical during the design process to identify the evolutionary trends in the channel system and to select rehabilitation measures that compliment the morphologic phases. The CEM and DSD presented here provide a rational basis for the selection of alternatives that are based on the physical processes functioning in the system.

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