

A STREAM CHANNEL STABILITY ASSESSMENT METHODOLOGY

BY

David L. Rosgen, P.H.
Wildland Hydrology
Pagosa Springs, CO 81147

ABSTRACT: Various definitions of stream channel stability are presented including "the natural stable channel", the graded river, dynamic equilibrium, and regime channels, and a quantitative assessment methodology is presented that distinguishes between stability states. The assessment procedure involves a stream channel stability prediction and validation methodology on a hierarchical framework. The stream channel stability method develops field-measured variables to assess: 1) Stream state or channel condition variables, 2) Vertical stability (degradation/aggradation), 3) Lateral stability, 4) Channel patterns, 5) Stream profile and bed features, 6) Channel dimension factor, 7) Channel scour/deposition (with competence calculations of field verified critical dimensionless shear stress and change in bed and bar material size distribution), 8) Stability ratings (modified Pfankuch method) adjusted by stream type, 9) Dimensionless ratio sediment rating curves by stream type and stability ratings, and 10) Selection of position in stream type evolutionary scenario as quantified by morphological variables by stream type to determine state and potential of stream reach.

The stability assessment is conducted on reference reach (stable) reaches and a departure analysis is performed when compared to an unstable reach of the same stream type. The assessment procedure utilizes various hierarchical levels for prediction and subsequent validation. Changes in the variables controlling river channel form, primarily streamflow, sediment regime, riparian vegetation, and direct physical modifications can cause stream channel instability. Separating the difference between anthropogenic versus geologic processes in channel adjustment is a key to prevention/mitigation/restoration of disturbed systems

The adverse consequence of stream channel instability (dis-equilibrium) is associated with increased sediment supply, land productivity change, land loss, fish habitat deterioration, changes in both short and long-term channel evolution and loss of physical and biological function.

INTRODUCTION

Definitions: Within the scientific community, the terms "channel stability", "equilibrium", quasi-equilibrium and "regime channels" evoke a deluge of various interpretations. Imagine the quantitative inconsistency of the field observer in trying to implement a stream channel stability assessment procedure with which there is not common agreement on what is meant by the term? Thus, it is not uncommon for journey-level professionals working with rivers to disagree on a consistent working definition of what constitutes a stable river, even though they often use the term "channel stability". A review of the literature provides insight into previous interpretation of terms, that all appear to be synonymous, or at the least, have a common thread of similarity. Davis (1902), defined a "graded" stream as the condition of "balance between erosion and deposition attained by mature rivers". Mackin (1948), as reported by Leopold et al (1964), defined a graded stream as "one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for the transport of the load supplied from the drainage basin. The graded stream is a system in equilibrium; its diagnostic characteristic is that any change in any of the controlling factors will cause a displacement of the equilibrium in a direction that will tend to absorb the effect of the change." The controlling factors described by Leopold et al (1964) were width, depth, velocity, slope discharge, size of sediment, concentration of sediment and roughness of the channel. If any one of these variables were changed it sets up a series of concurrent adjustments of the other variables to seek a new equilibrium. The central tendency of rivers to seek a probable state was described by Leopold (1994). Strahler (1957) and Hack (1960), used the term "dynamic equilibrium" referring to an open system in a steady state in which there is a continuous inflow of materials, the form or character of the system remains unchanged. Equations showing river variables as a function of discharge were derived by Leopold and Maddock, (1953), and by Langbein, (1963). These hydraulic geometry relations described adjustable characteristics of open channel systems in terms of independent and dependent variables in quasi-equilibrium (not aggrading nor degrading). Streams described to be "in regime" are synonymous with "stable channels" and equations describing three dimensional geometry of stable, mobile gravel-bed rivers were presented by Hey and Thorne (1986).

Additional equations and discussion on stable river morphology were presented in Hey (1997). Regime channels, as discussed by Hey (1997) allows for some erosion and deposition but no net change in dimension, pattern and profile for a period of years. The following definition of stream channel stability was presented by Rosgen (1996): "is the ability of a stream, over time, in the present climate, to transport the sediment and flows produced by its watershed in such a manner that the stream maintains its dimension, pattern and profile without either aggrading nor degrading". Processes of stream channel scour and or deposition have to occur in a natural stable channel, but over time, if this leads to degradation or aggradation, respectively, then the stream would not be stable. This definition summarizes many of the key points previously presented in the literature. This definition is predictable and verifiable, and as such, was used in the development of the stream channel stability assessment methodology.

PRINCIPLES

River instability needs to be evaluated on spatial and temporal scales. It is also critical to recognize natural geologic erosion and transport mechanics versus anthropogenic influences. Following major floods, due to requirements to provide flood damage restoration plans, the author studied alluvial gravel-bed streams on slopes less than 0.02 where the pre and post-flood morphological variables were similar. Other reaches, however, that were in poorer stability condition prior to the flood, received major damage by the same flow. The stable rivers became reference reaches where data were collected on dimension, pattern, profile and channel materials. The 1984 Lawn Lake flood in Colorado inundated Fall River, a C4 stream type (for stream type descriptions see Rosgen, 1994, 1996) that was in a stable meandering pattern. The extensive sediment load and corresponding "flood of record" did not create instability. The stream maintained its dimension, pattern and profile and did not aggrade nor degrade. Accumulations of sand occurred in the channel and within a few years the sand was routed through without the net effect of aggradation. This stream is but one of many examples where the author has field evidence where post-flood instability did not occur, even though these streams had potentially erodible material in their bed and banks. Reference reaches such as this become a blueprint of the variables associated with stable natural channels. Field and photographic evidence of channel change over time is an excellent reference procedure. Selection of the reference reach involves collection of such evidence. Descriptions and applications of the reference reach methodology are described in Rosgen (1998).

Stream channels that have been improperly managed and have poor riparian vegetation are subjected to accelerated streambank erosion and corresponding channel adjustments leading to instability. An example of instability that occurred due to willow removal on a C4 stream type on the Weminuche River in Southwestern Colorado is dramatic not only for the magnitude of change, but the consequence of change, as well. The details of the combined effects of willow spraying on stream channel instability and changes in dimension, pattern and profile for this reach are summarized in Rosgen (1996). The consequence of a wide range of stream channel instability can be described and quantified through an evolution of stream types (Figure 1). The evolution sequence that ensued on the Weminuche River due to channel adjustment following disturbance, created a change in morphological stream types that is associated with sequence category #3 in Figure 1. The conversion changed the pre-disturbance C4 stream type (gravel-bed, meandering channel with a floodplain), to D4 (braided), to G4 (incised gully due to avulsion), to an F4 (entrenched, meandering channel) and was widening to eventually re-establish a C4 stream

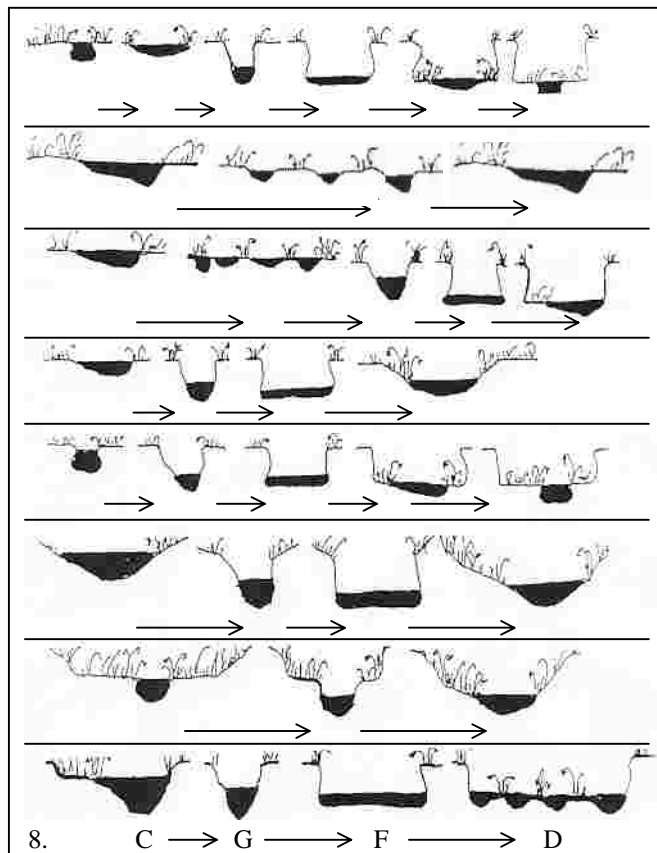


Figure 1. Various Stream Type Evolution Scenarios

type, but at a lower elevation. Every tributary was rejuvenated due to the change in local base level, which created a tremendous increase in sediment supply and transport and caused the water table to drop in the meadow, decreasing productivity. Thus, the consequence of spraying the willows and induced stream channel instability was associated with major loss of: land, vegetation productivity, fish habitat, visual values and loss of ability to handle future floods. Increased sedimentation, both on-site and downstream occurred. Many other evolutionary scenarios induced by channel instability and associated channel adjustment can occur. The author has observed at least eight separate evolutionary scenarios as shown in Figure 1. One challenge in stability assessment is to determine the evolutionary state and sequence of the stream. The *cause* of the instability is as important to understand as well as the *consequence*.

OBJECTIVES

To prevent and or to correct stream channel instability, it is imperative to understand the mechanisms causing the shift in morphological variables and stability indices. The diversity of opinion has made it difficult to conduct consistent quantitative river stability assessments. It is not uncommon to have five individuals all "trained in these matters", simultaneously standing on the same bank of a river, having five divergent and conflicting opinions. Unless there are documented measurements, coupled with consistent, quantitative indices of stability, these subjective opinions will persist. Understanding of these complex processes can only come with a program of detailed measurements so that observations, stability indices and field assessment techniques can become effective. To meet this objective, the author set up a river inventory hierarchy (Rosgen, 1996), (Figure 2). This would allow

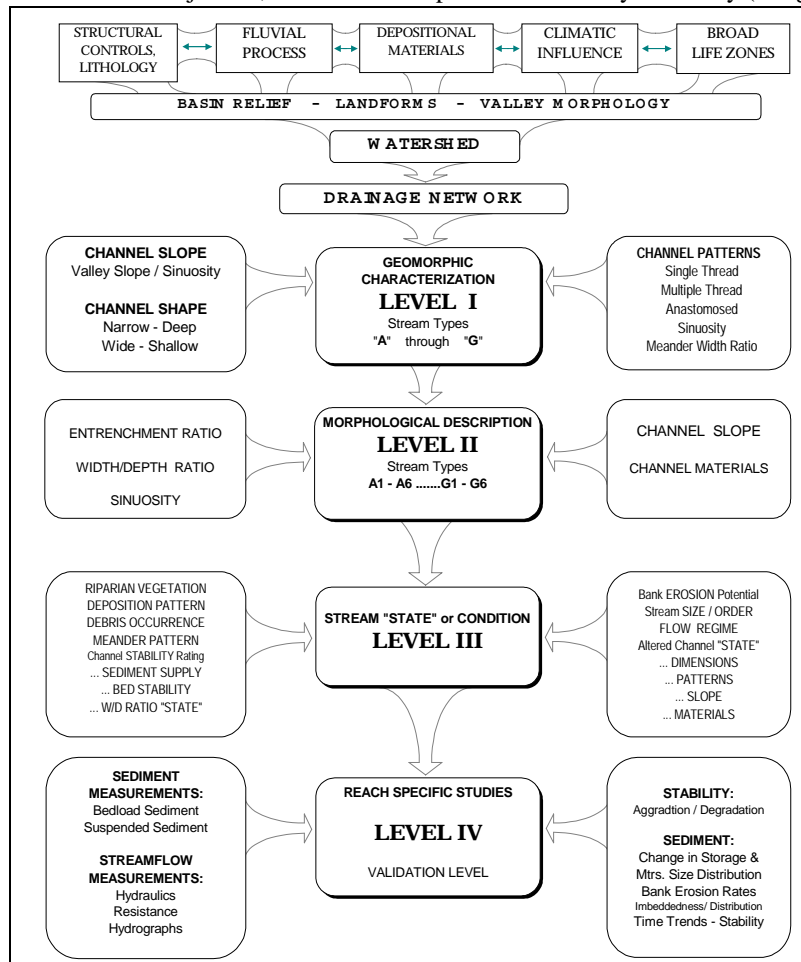


Figure 2. The Hierarchical River Inventory stratifying stability prediction and detailed river measurements by valley types and stream types for various levels of inquiry

an assessment at various levels appropriate to the level of inquiry. All 4 levels are used initially, until quantitative relations are established with the prediction methods. Initial stratification is accomplished at both levels I and II. This is not done to determine stability, but to stratify the reach by valley and stream type. Reference reach data is also obtained from adjacent stable reaches of the same valley and stream type. Reference reaches do not have to be pristine or relic sites, but meet the criteria of a stable river. Prediction of stability is made at level III, the "state" or condition level. Level IV is the validation inventory that requires the greatest level of measurement detail over a longer time period. For example, one may estimate vertical stability or bank erosion rate at level III, however permanent cross-sections are re-measured following runoff to verify bed elevation shifts, and erosion pins/toe pins are established at level IV to verify the actual erosion that occurred. This design allows prediction model validation at level III, thus, the prediction model can be extrapolated without the need to always accomplish level IV. Since these assessments involve large areas and many miles of river, this approach was designed to provide a prediction methodology with some credible validation.

METHODOLOGY

This section of methodology is meant to be a sequence of suggested steps for the field practitioner to use in reaching final conclusions and making recommendations for management and/or restoration. The stream channel stability assessment methodology is broken into the following ten major categories. Based on field inspection and measurements the categories of assessment are applied to the reference reach, as well as for impacted reaches. This provides a consistent comparative analysis of departure and assists in selecting evolutionary shifts in stream type and associated dimensionless sediment rating curves. A general summary of stability ratings and interpretations are included at the end of these categories of assessment.

1) Stream Channel Condition or "State" Categories: Determine condition categories from field inspection and measurement of stream channel condition characteristics. Specific categories are evaluated and documented based on the criteria for each variable. Detailed descriptions and examples for each category are presented in Chapter 6 (Rosgen, 1996) which will help completing these assessments. The seven categories and associated variables evaluated are: a) Riparian vegetation, (composition, density, and potential, climax riparian communities); b) Sediment deposition patterns (8 patterns); c) Debris occurrence (includes large woody debris); d) Meander patterns (8 patterns); e) Stream size/Stream order; f) Flow regime (perennial, ephemeral, intermittent, subterranean, snowmelt, stormflow, rain-on-snow, spring-fed, glacial-fed, tidal, diversions, and reservoir regulated, and; g) Altered states due to direct disturbance (dimension, pattern, profile and materials such as, channelization, straightening, levees, concrete, rip-rap, etc.). These seven major condition states provide insight into specific characteristics of the reference reach, as well as the stream type being assessed.

2) Vertical Stability/Degradation/Aggradation: From field measurements of bank height and entrenchment ratios and documented observations of excessive erosion and/or deposition, determine vertical stability of the stream reach. The degree of incision involves a measurement of bank height ratio (Table 1). It is measured as the ratio of the *lowest* bank height of the cross-section divided by maximum bankfull depth. For example a stream could be incising and not yet abandoned its floodplain or flood-prone areas. Bank height ratios of 1.2 and 1.3 are characterized by both streambanks eroding as the bank height is often below the rooting depth of the riparian vegetation. To determine if the stream has incised to the extent that the stream has abandoned its floodplain is determined by the entrenchment ratio, which indicates vertically containment. The entrenchment ratio is calculated by first determining the elevation of the flood-prone area as measured at twice the maximum bankfull depth. The flood-prone area width at this elevation is then divided by the bankfull width. If the Entrenchment ratio is less than 1.4 (+ or- 0.2), the stream is entrenched (Rosgen, 1994,1996). Additional indicators of incision/degradation are: both left and right stream banks actively eroding, depositional features are being scoured, decrease in width/depth ratio corresponding with increase in bank height ratio, and mobilization of largest size D-100 of bed material (see category 8). The aggradation category is determined from a summary of the depositional patterns, coarse deposition on floodplains and very high to extreme width/depth ratios. Longitudinal profiles of the reach showing elevations of the bed, water surface, bankfull and *lowest* bank height indicate if the incision is advancing downstream or if a head-cut is advancing from the downstream direction. Profiles and cross-sections should be permanently monumented and read annually to verify the prediction of vertical stability.

Table 1. Conversion of bank height ratio (degree of incision) to adjective ratings of stability

| Stability Rating | Bank Height Ratio |
|-------------------------------------|-------------------|
| Stable (low risk of degradation) | 1.0 - 1.05 |
| Moderately unstable | 1.06 - 1.3 |
| Unstable (high risk of degradation) | 1.3 - 1.5 |
| Highly unstable | > 1.5 |

3) Lateral Stability: Determine the degree of lateral containment (confinement) and potential lateral accretion. The categories used for lateral stability are: a) Meander width ratio (degree of confinement) and b) Streambank Erosion Hazard Index (BEHI) and Near-Bank Stress (NBS) (see Rosgen, 1996 and 2001, In Press). Meander width ratio is the meander belt width (lateral containment of the channel within its valley) divided by bankfull channel width. Values of meander width ratio by stream type are shown in Rosgen (1996, p.4 -9). Some streams can be confined, but not entrenched. This provides insight into channel adjustment processes by stream type and degree of confinement. Annual, lateral streambank erosion rates are multiplied times the bank height and stream length of specific BEHI and NBS ratings along the reach. These values are converted to tons/year in order to apportion

sediment supply sources. Many miles of stream can be evaluated using this method of prediction.. Level IV data involves installing toe pins and cross-sections to accurately measure streambank erosion rates/lateral accretion. This helps validate the model or revise estimates and better reflect actual rates. The validation work can also be used for effectiveness monitoring prior to and following restoration and/or streambank stabilization.

4) Channel Pattern: Measure meander width ratios (meander length/bankfull width), ratio of radius of curvature/bankfull width, sinuosity, meander width ratio (belt width/bankfull width), arc length and arc angle. Convert all values to dimensionless ratios for comparative purposes. Additional assistance can be provided in assessing channel pattern categories as shown in Chapter 6, Rosgen, (1996). Changes in pattern are compared using dimensionless ratios when the reference reach data for the same valley and stream type may be of a different size. Channel adjustment due to instability can often be interpreted from these variables such as accelerated down-valley meander migration and excessive near-bank stress due to ratios of radius of curvature/width less than 2.0. Level IV data utilizes aerial photo time/trends and cross-sections showing down-valley meander migration.

5) River Profile and Bed Features: A longitudinal profile is measured to determine changes in river slope compared to valley slope which is very sensitive to sediment transport, competence and the balance of energy. Pool to pool spacing, ratios of maximum depth of pools/mean depth of channel, and maximum depth of riffles/mean bankfull depth are also obtained from longitudinal profile data. When pools start to fill (decrease in max depth/mean depth ratio), and the stream is widening with a corresponding decrease in sinuosity and increase in slope, the stream is becoming unstable. The reference condition for the same stream type will have dimensionless ratios that are used for comparison of the magnitude of departure. Spacing of step/pools in steeper stream types are inversely proportional to slope and directly proportional to width, and as such, are shown as a ratio of bankfull width by slope categories. The total removal of large woody debris often increases the step/pool spacing and as a result the excess energy increases the potential for channel degradation. Level IV validation of prediction estimates are accomplished by installing permanent longitudinal profiles with bench marks tied into permanent cross-sections or stationing pins. Measurements taken on a thalweg survey provides data on maximum bankfull depths, the various bed features, including riffles and pools, and documents any change in slope. Elevation measurements of the bed, water surface, bankfull, and low bank height also identifies changes in degree of incision along the profile as presented above in assessment item 2). Data summaries including dimensionless ratios for bed features and river profile can be recorded and analyzed in the "Reference Reach Field Book", (Silvey and Rosgen, 1998).

6) Channel Dimension Relations: Determine changes in the bankfull width and mean bankfull depth (width/depth ratio). This ratio indicates departure from the reference reach and is very sensitive and diagnostic of instability. Increases in width/depth ratio are often associated with accelerated streambank erosion, excessive sediment deposition, streamflow changes, channel widening due to evolutionary shifts from one stream type to another (i.e., G4 to F4 to C4), and direct alteration of channel shape from channelization, etc. The degree of width/depth ratio increases are shown as a departure from the reference condition of the stable stream type to establish stability ratings (Table 2). A decrease in width/depth ratio departure analysis will have a proportionate reduction in width/depth ratio values. This reduction from the reference condition is only applied when the bank height ratio is greater than 1.0. For example a "moderately unstable" rating for a stream channel with a bank height ratio greater than 1.0 would have a width/depth ratio decrease of 0.8 to 0.6 This is associated with a width/depth ratio that is decreasing as the stream is incising (i.e., C4 stream type conversion to a type G4). The corresponding reduced width/depth ratio creates excess shear stress in an incising stream type, which is adjusting toward an unstable condition. The level IV analysis establishes permanent, monumented cross-sections to determine the rate and extent of change in both the width/depth and bank height ratios.

Table 2. Conversion of width/depth ratios to adjective ratings of stability from reference conditions

| Stability Rating | Ratio of W/D Increase |
|---------------------|-----------------------|
| Very stable | 1.0 |
| Stable | 1.0 - 1.2 |
| Moderately unstable | 1.21 - 1.4 |
| Unstable | > 1.4 |

7) Stream Channel Scour/Deposition Potential (Sediment Competence): Compute critical dimensionless shear stress to determine the size of sediment particle that can be moved. Relations modified from Andrews (1984) and Andrews and Nankervis (1995) are used for this computation. Subsequent calculations using a Shields relation compares the existing slope and depth of a stream to be able to transport the largest size made available annually (during bankfull stage) to the channel. The procedure involves sampling the bed material on the riffle to obtain d_{50} ,

excavate a core sample of bar material (located on the lower 1/3 of meander on the point bar midway between the thalweg and the bankfull stage). The bar sample is used to obtain d_{s50} of the relation as a surrogate of the sub-pavement size distribution. Locations of this specific depositional feature and subsequent are shown in Chapter 7, (Rosgen, 1996). The bar also provides an interpretation of the size distribution of bedload at the bankfull stage and the largest size on the bar is used to obtain data representing the largest size of sediment frequently made available to the channel. The following calculations are used to make the competence prediction:

$$\tau_{ci} = .0834 (d_{50}/ds_{50})^{.872}$$

Where: τ_{ci} = critical dimensionless shear stress

d_{50} = median diameter of pavement or bed material on riffle

ds_{50} = median diameter of bar sample (sub-pavement)

The following equation is used to predict the depth and slope to move the largest size of sediment made available to the channel on a frequent basis:

$$\tau_{ci} = \frac{dS}{(\gamma_s)(D_i)}$$

$$\text{transformed to: } d = \frac{(\tau_{ci})(\gamma_s)(D_i)}{S}$$

Where: γ_s = submerged specific weight of sediment

D_i = Largest diameter of particle on bar (use mm if depth is in meters)

d = mean bankfull depth of the channel

S = water surface slope at the bankfull stage

If the combination of depth and/or slope does not move the largest size, then potential aggradation or excessive deposition and corresponding high width/depth ratio is anticipated. If the depth and or slope exceeds that required to move the largest size, then potential degradation, or excess scour leading to incision has potential for instability. This procedure is verified by three methods at level IV: 1) Measured bedload size distribution of bedload at the bankfull stage, and corresponding slope and bankfull depth measurements at the bankfull stage, 2) Monumented cross-sections and vertical scour chains are installed before and after runoff. The scour chains give the depth of scour and subsequent change of particle size over chain. The largest particle over the scour chain exhibits the largest size of particle moved for the corresponding shear stress of the flows responsible. The cross-section shows net change of bed elevation, and specific changes over the scour chain, and 3) Annual replicate core samples at the same location on the bar shows sizes moved for a back-calculated shear stress as well as shifts in size distribution of bedload at the bankfull stage. It is the coarse fragment that determines channel morphology of gravel-bed streams (Leopold, 1992), thus it is important to be able to move the largest sediment clasts frequently made available to the river at the bankfull stage. These data can also be compared to measured bedload size distribution with the USGS, Helley-Smith bedload sampler. This field method has been tested on many rivers by the author with excellent success when compared to both scour chain and measured bedload data.

8) Stream Channel Stability rating (modified Pfankuch procedure): Determine channel stability ratings to predict potential state from the stable reference reach of the same stream or potential evolutionary type. The stability rating procedure evaluates the upper and lower banks and streambed for evidence of excessive erosion/deposition. The procedure has been used for 25 years by the USDA Forest Service and other Federal Agencies, (Pfankuch, 1975). The system evaluates mass wasting potential adjacent to the channel, detachability of bank and bed materials, channel capacity and evidence of excessive erosion and/or deposition. The larger the number, the greater the risk for instability. The risk rating of the classification was later converted to ratings by stream type. This modification was made to reduce the likelihood of applying the same numerical rating of "good" to C4 versus B4 stream types. Naturally, C4 stream types by their meandering nature, flatter slopes and point bars will obtain higher channel stability numbers than the steeper B4 stream types, even though both streams are very stable. In contrast, the channel stability ratings for a very stable B4, will be much lower than the C4 stream type, when both are stable. To remedy this dilemma, relations were developed to place numerical categories in adjective ratings by stream type (Table 3). For example a rating of "Good" for a B4 has a range of 40-64, whereas, the "good" rating for C4 stream types is 60-95. Applications for stability and sediment supply have been related to measured sediment rating curves. For example, the higher the stability rating number, the higher the intercept and steeper the slope of the suspended sediment rating curve as shown in Figure 3 for Redwood Creek, California (Leven, 1977). A similar analysis was performed on measured stream data in North Carolina (Coweeta Experimental Forest), Northern California, Idaho, Montana and Colorado (Rosgen, 1980). This is used in conjunction with dimensionless ratio sediment rating curves in the next category of assessment. Level IV verification involves the combination of

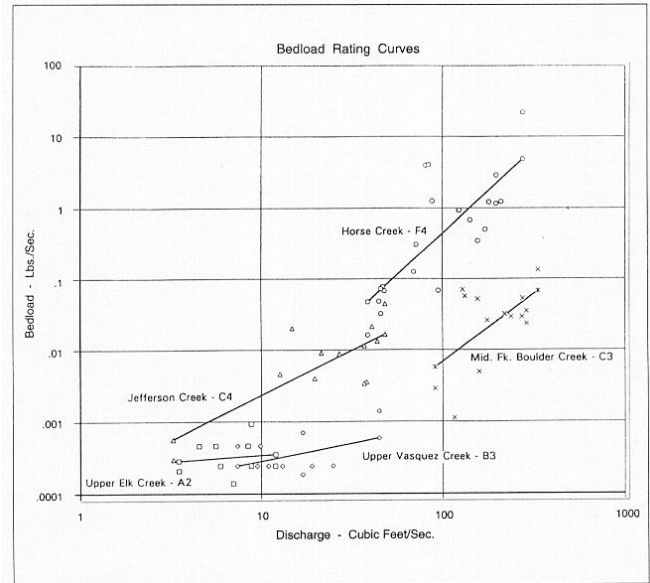
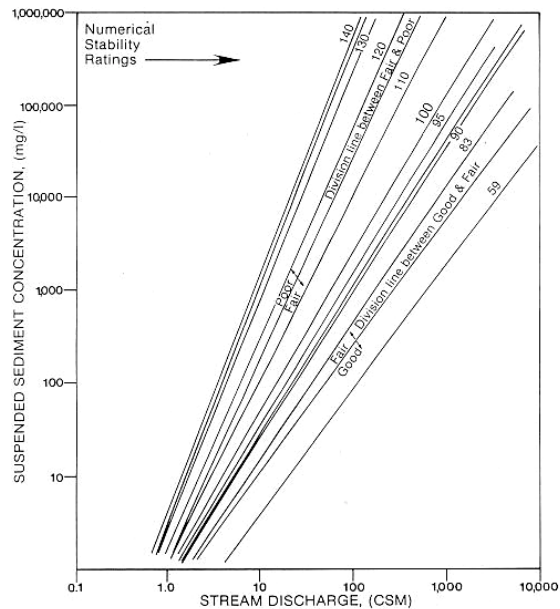
measured sediment rating curves, cross-sections, longitudinal profiles and channel material size distributions. This level of assessment compares predicted to observed values of sediment and stability.

Table 3. Conversion of Stability Rating to Reach Condition by Stream Type

| Stream Type | A1 | A2 | A3 | A4 | A5 | A6 | B1 | B2 | B3 | B4 | B5 | B6 |
|----------------------|--------|--------|---------|---------|---------|--------|---------|---------|---------|---------|---------|---------|
| Good (Stable) | 38-43 | 38-43 | 54-90 | 60-95 | 60-95 | 50-80 | 38-45 | 38-45 | 40-60 | 40-64 | 48-68 | 40-60 |
| Fair (Mod. Unstable) | 44-47 | 44-47 | 91-129 | 96-132 | 96-142 | 81-110 | 46-58 | 46-58 | 61-78 | 65-84 | 69-88 | 61-78 |
| Poor (Unstable) | 48+ | 48+ | 130+ | 133+ | 143+ | 111+ | 59+ | 59+ | 79+ | 85+ | 89+ | 79+ |
| Stream Type | C1 | C2 | C3 | C4 | C5 | C6 | D3 | D4 | D5 | D6 | | |
| Good (Stable) | 38-50 | 38-50 | 60-85 | 70-90 | 70-90 | 60-85 | 85-107 | 85-107 | 85-107 | 67-98 | | |
| Fair (Mod. Unstable) | 51-61 | 51-61 | 86-105 | 91-110 | 91-110 | 86-105 | 108-132 | 108-132 | 108-132 | 99-125 | | |
| Poor (Unstable) | 62+ | 62+ | 106+ | 111+ | 111+ | 106+ | 133+ | 133+ | 133+ | 126+ | | |
| Stream Type | DA3 | DA4 | DA5 | DA6 | E3 | E4 | E5 | E6 | | | | |
| Good (Stable) | 40-63 | 40-63 | 40-63 | 40-63 | 40-63 | 50-75 | 50-75 | 40-63 | | | | |
| Fair (Mod. Unstable) | 64-86 | 64-86 | 64-86 | 64-86 | 64-86 | 76-96 | 76-96 | 64-86 | | | | |
| Poor (Unstable) | 87+ | 87+ | 87+ | 87+ | 87+ | 97+ | 97+ | 87+ | | | | |
| Stream Type | F1 | F2 | F3 | F4 | F5 | F6 | G1 | G2 | G3 | G4 | G5 | G6 |
| Good (Stable) | 60-85 | 60-85 | 85-110 | 85-110 | 90-115 | 80-95 | 40-60 | 40-60 | 85-107 | 85-107 | 90-112 | 85-107 |
| Fair (Mod. Unstable) | 86-105 | 86-105 | 111-125 | 111-125 | 116-130 | 96-110 | 61-78 | 61-78 | 108-120 | 108-120 | 113-125 | 108-120 |
| Poor (Unstable) | 106+ | 106+ | 126+ | 126+ | 131+ | 111+ | 79+ | 79+ | 121+ | 121+ | 126+ | 121+ |

9) Dimensionless Ratio Sediment Rating Curves: Instability and the corresponding increase in sediment supply is often reflected in measured sediment rating curves. The source of this increase in sediment supply often is associated with channel adjustment, including degradation and lateral accretion (bank erosion). The variation in sediment rating curves is shown in Figure 4, reflecting differences in sediment supply for various Colorado streams (Williams and Rosgen, 1989, and Rosgen, 1996). Additional sediment rating curves by channel stability ratings indicating changes in stability and associated sediment supply are shown in Rosgen, (1980). On the Hatchie River in West Tennessee, Simon (1989) summarized the effects of channelization and corresponding stream stability change comparing evolution stages of channels to measured upward shifts in the slope of the measured suspended sediment rating curves. The sediment yields, from the Hatchie River, a stable, meandering, low width/depth channel with a well developed floodplain (E6 stream type) was 62.9 tons/km² (163 tons/year/mi²). The South Fork Forked Deer River which, following channelization, became incised (F6 stream types) with resultant sediment yields of 961.4 tons/km² (2,490 tons/yr/mi²). Simon (1989) was showing these changes in sediment yield associated with channel instability and adjustments using the channel evolution model (Shumm, et al 1984 and Simon and Hupp, 1986). The channel evolution model and stages of adjustment are related to quantitative morphological values corresponding to stream types (Rosgen, 1999). Both of these approaches are compatible at describing the consequence of channel adjustment. As the E6 stream type incises and changes to a G6 and eventually F6, the channel goes through an evolutionary adjustment of instability and associated stream type change. The evolutionary sequence of the Hatchie and South Fork Forked Deer Rivers matches scenario #5 (Figure 1). When instability due to change in energy, sediment supply or direct disturbance occurs, the severity is such that stream types can change. This change reflects increases in sediment supply due to channel adjustment (streambed and streambank erosion) and eventual increased sediment yield as shown by Simon (1989). This does not infer, however, that all F stream types are unstable, such as the Colorado River in the Grand Canyon. The best assessment approach is a combination of stability analysis with stream morphology necessary to establish potential departure from the reference condition.

Reference reach sites representing stable stream reaches are used to establish dimensionless sediment rating curves by stream type and stream stability and as such, can be used to ascertain departure (Troendle, et al, In Press). Significant departure from the reference dimensionless sediment rating curves when comparing good and fair with poor stability ratings. Stream types that become unstable to the extent that they change morphological type are generally associated with poor stability and an increase in sediment supply. Sediment delivery ratios provide a means of extrapolation of sediment rating curves for rivers of different geology, size, stability, and associated



morphology. These ratios are developed by taking the bedload and suspended sediment values and dividing them by the same units of sediment values at the bankfull discharge. Their corresponding discharges are also divided by the bankfull discharge to establish dimensionless ratio sediment rating curves. To convert these curves to actual numbers following extrapolation, sediment and discharge measurements at bankfull are obtained at the most detailed level of river stability assessment, then multiplied by the dimensionless ratios established for that stream type and stream condition. Sediment and flow data should also be collected at a lower flow to insure the slope and intercept of the dimensionless ratio sediment rating curve matches observed values. Confidence bands above the reference reach for the same, but stable stream type using the dimensionless ratios give a preliminary range of departure. In other words, the natural variability in sediment supply as shown in the sediment rating curves for the reference reach is documented to avoid the unwise tendency of trying to establish sediment TMDL's as a fixed value for a given stream. Also, natural geologic sediment rates can be established as reflected in the various stream types such as the A3a+ (steep, debris torrent channel incised in heterogeneous, unconsolidated landslide debris and or glacial till). These stream types have periodic and catastrophic, naturally high to extreme erosion rates due to their unlimited sediment supply and high energy. Sediment yields from these systems cannot and should not be altered, as the entire fluvial system has adjusted over time to accommodate such sediment loads. Efforts to restore "stability" in these channel types are fighting natural processes and face a high risk of failure.

10) Stream Type Evolutionary Scenarios: Determine the current state and evolutionary sequences as shown in Figure 1. The use of this relation requires the field observer to select not only the stream type, but the location in a particular sequence of evolution. This not only provides a current state evaluation, but provides an interpretation of the physical potential of this reach. A stability assessment can assist those doing restoration design. Often, unstable channels are "patched in place"...unfortunately it is often the "wrong place"...or perhaps, the wrong stream type. Another use of this specific assessment protocol is to be able to identify the potential stable stream type as opposed to the currently existing stream type. Restoration can speed up the adjustment or recovery period by obtaining the morphological data used from the reference reach of the appropriate stream type to match the stable form. Another application of stream type evolution is to specify a potential dimensionless sediment rating curve that would apply associated with the stability of a particular morphological evolutionary state as depicted in figures 5 and 6.

Summary of condition assessment and stability ratings: The summary of the ten major stability rating categories and condition variables of the level III prediction analysis are shown in Table 4. By completing each of the above assessments, the field practitioner can see the pattern of channel change and note a change in one variable is

accompanied by changes in several others. The interpretation of the stability categories allows the observer to conclude as to the overall stability and potential state of sediment supply.

| <i>Table 4. Summary of stability condition categories for the Level III inventory</i> | |
|---|---|
| Stream Name _____ | Observers _____ |
| Location _____ | Stream Type _____ Date _____ |
| Riparian Vegetation, comp/density _____ | Flow regime _____ |
| Stream size, Stream order _____ | Depositional pattern _____ |
| Meander pattern _____ | Debris/channel blockages _____ |
| Channel stability rating (Pfankuch) _____ | Describe altered channel state _____ |
| Stability category by stream type _____ | |
| Sediment supply (check appropriate category) | Dimension/shape: |
| Extreme _____ | Width _____ |
| Very high _____ | Depth _____ |
| High _____ | Width/depth ratio _____ |
| Moderate _____ | Patterns (*show as function of W_{bkf}) |
| Low _____ | Meander length* _____ |
| Streambed (vertical) stability | Radius of curve * _____ |
| Bank Height ratio _____ | Belt width* _____ |
| Aggrading _____ | Sinuosity _____ |
| Degrading _____ | Arc angle _____ |
| Stable _____ | Arc length* _____ |
| | Profile: |
| Width/depth ratio/condition: | Water surface slope _____ |
| Excellent (stable) _____ | Valley slope _____ |
| Good _____ | Bed features: (Type and/or ratio max. depth/bankfull depth) |
| Fair _____ | Riffle _____ |
| Poor _____ | Pool _____ |
| Streambank erosion hazard: | Step/pool (p/p spacing) _____ |
| Bank erodibility: Near-bank stress: | Convergence/divergence _____ |
| Extreme _____ Extreme _____ | Riffle/pool spacing * _____ |
| High _____ High _____ | Dunes/antidune/smooth bed _____ |
| Moderate _____ Moderate _____ | Describe channel evolution scenario: |
| Low _____ Low _____ | Evolution type number _____ |
| Very Low _____ Very Low _____ | Existing state (type) _____ |
| Annual streambank erosion rate _____ | Potential state (type) _____ |
| Length of banks studied _____ | Competence calculation: |
| Tons/year _____ | Critical dimensionless shear stress _____ |
| Curve used _____ | Largest particle on bar _____ |
| | Bankfull depth (existing) _____ |
| Dimensionless Sediment rating curve: | Bankfull depth required _____ |
| Normal _____ | Slope (existing) _____ |
| Above normal _____ | Slope required _____ |

CONCLUSION

Although this stability prediction method may seem onerous, it has been applied in watershed management and for geomorphological assessments for many years. The author has trained hundreds of individuals in this procedure that have collected both level III and IV data to help improve and validate the prediction relations. An additional application of this approach has been used for restoration proposals, where an understanding of the cause, consequence and correction of the problem involves an inventory that isolates the processes associated with stream

channel instability. The recent requirement to establish TMDL's for clean sediment involves an understanding of natural rates, natural variability and documenting departure conditions leading to adverse consequence of instability and corresponding disproportionate sediment yields. If we understand the various processes of change, prevention through good management and application of mitigation measures can be appropriately applied to the problem. Continued field measurements are the key to improving upon these procedures and add to the collective understanding of these complex and valuable river systems.

"A consistent chronicle of field observations and collected data is essential to the practice of hydrology. As with opportunities, good data are available only once.".... Luna B. Leopold.

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