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**Natural
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Conservation
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Part 654 Stream Restoration Design National Engineering Handbook

Chapter 11 Rosgen Geomorphic Channel Design

Issued August 2007

Cover photo: Stream restoration project, South Fork of the Mitchell River, NC, three months after project completion. The Rosgen natural stream design process uses a detailed 40-step approach.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

Chapter 11 Rosgen Geomorphic Channel Design

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654.1100 Purpose

This chapter outlines a channel design technique based on the morphological and morphometric qualities of the Rosgen classification system. While this approach is written in a series of steps, it is not a cookbook. This approach is often referred to as the Rosgen design approach. The essence for this design approach is based on measured morphological relations associated with bankfull flow, geomorphic valley type, and geomorphic stream type. This channel design technique involves a combination of hydraulic geometry, analytical calculation, regionalized validated relationships, and analogy in a precise series of steps. While this technique may appear to be straightforward in its application, it actually requires a series of precise measurements and assessments. It is important for the reader to recognize that the successful application of this design approach requires extensive training and experience.

The contents of this chapter were submitted to the technical editors of this handbook as a manuscript titled Natural Channel Design Using a Geomorphic Approach, by Dave Rosgen, Wildland Hydrology, Fort Collins, Colorado. This material was edited to fit the style and format of this handbook. The approaches and techniques presented herein are not universally applicable, just as other approaches and techniques presented in this handbook are not necessarily appropriate in all circumstances. However, the Rosgen Geomorphic Approach for Natural Channel Design has been implemented in many locations and is cited as the methodology of choice for stream restoration by several state and local governments.

654.1101 Introduction

River restoration based on the principles of the Rosgen geomorphic channel design approach is most commonly accomplished by restoring the dimension, pattern, and profile of a disturbed river system by emulating the natural, stable river. Restoring rivers involves securing their physical stability and biological function, rather than the unlikely ability to return the river to a pristine state. Restoration, as used in this chapter, will be used synonymously with the term rehabilitation. Any river restoration design must first identify the multiple specific objectives, desires, and benefits of the proposed restoration. The causes and consequences of stream channel problems must then be assessed.

Natural channel design using the Rosgen geomorphic channel design approach incorporates a combination of analog, empirical, and analytical methods for assessment and design. Because all rivers within a wide range of valley types do not exhibit similar morphological, sedimentological, hydraulic, or biological characteristics, it is necessary to group rivers of similar characteristics into discreet stream types. Such characteristics are obtained from stable reference reach locations by discreet valley types, and then are converted to dimensionless ratios for extrapolation to disturbed stream reaches of various sizes.

The proper utilization of this approach requires fundamental training and experience using this geomorphic method. Not only is a strong background in geomorphology, hydrology, and engineering required, but the restoration specialist also must have the ability to implement the design in the field. The methodology is divided into eight major sequential phases:

I Define specific restoration objectives associated with physical, biological, and/or chemical process.

II Develop regional and localized specific information on geomorphologic characterization, hydrology, and hydraulics.

III Conduct a watershed/river assessment to determine river potential; current state; and the nature, magnitude, direction, duration, and consequences of change. Review land use history and time trends of river change. Isolate the primary causes of instability and/or loss of physical and biological function. Collect and analyze field data including reference reach data to define sedimentological, hydraulic, and morphological parameters. Obtain concurrent biological data (limiting factor analysis) on a parallel track with the physical data.

IV Initially consider passive restoration recommendations based on land use change in lieu of mechanical restoration. If passive methods are reasonable to meet objectives, skip to the monitoring phase (VIII). If passive efforts and/or recovery potential do not meet stated multiple objectives, proceed with the following phases.

V Initiate natural channel design with subsequent analytical testing of hydraulic and sediment transport relations (competence and capacity).

VI Select and design stabilization/enhancement/vegetative establishment measures and materials to maintain dimension, pattern, and profile to meet stated objectives.

VII Implement the proposed design and stabilization measures involving layout, water quality control, and construction staging.

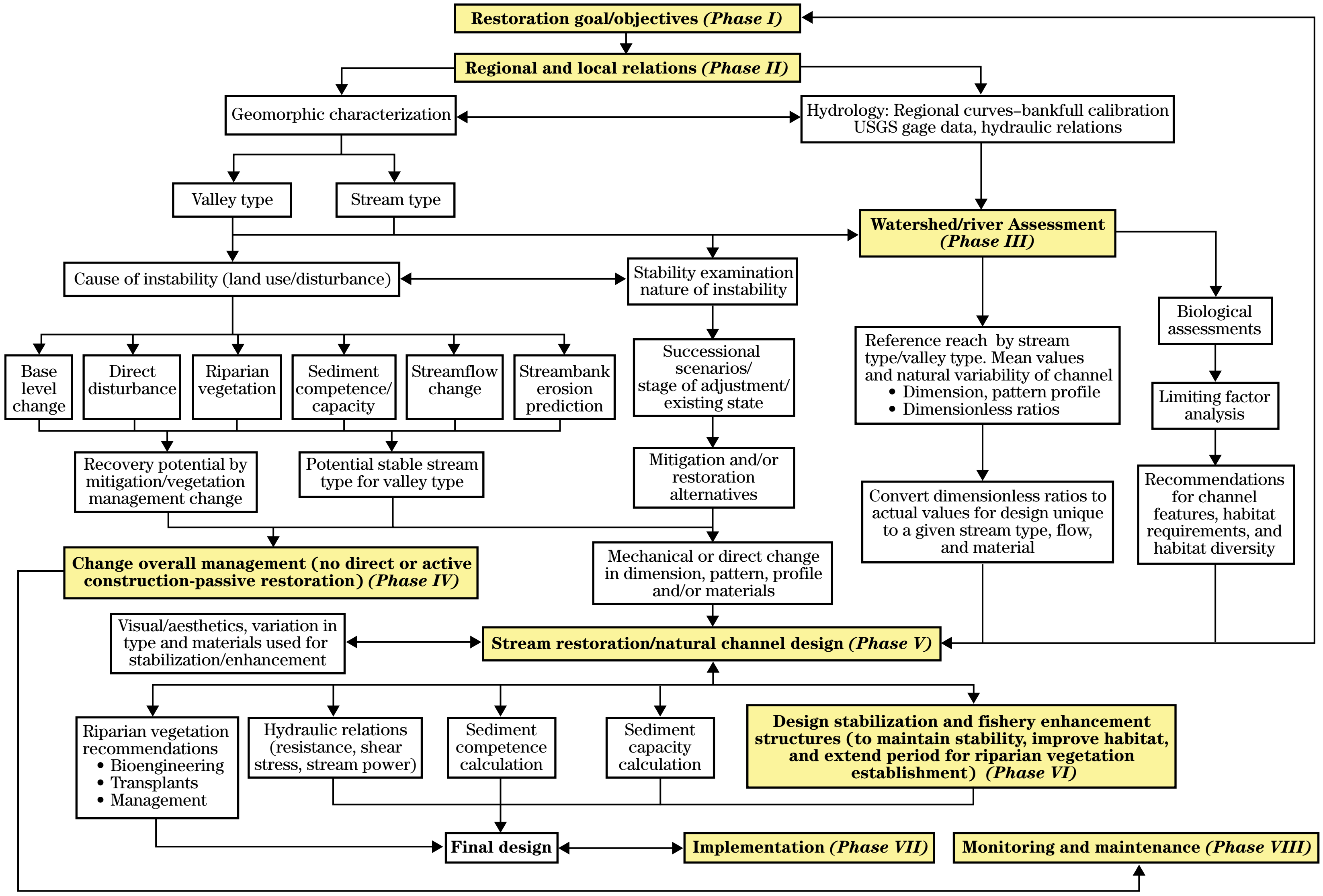
VIII Design a plan for effectiveness, validation, and implementation monitoring to ensure stated objectives are met, prediction methods are appropriate, and the construction is implemented as designed. Design and implement a maintenance plan.

The conceptual layout for the phases of the Rosgen geomorphic channel design approach is shown in figure 11–1. The various phases listed above are indicated on this generalized layout. The flowchart is indicative of the full extent and complexity associated with this method.

Because of the complexity and uncertainty of natural systems, it becomes imperative to monitor each restoration project. The following are three objectives of such monitoring:

- Ensure correct implementation of the design variables and construction details.
- Validate the analog, empirical, and analytical methods used for the assessment and design.
- Determine effectiveness of the restoration methods to the stated physical and biological restoration objectives.

Figure 11–1 River restoration using Rosgen geomorphic channel design approach



654.1102 Restoration phases

(a) Phase I—Restoration objectives

It is very important to obtain clear and concise statements of restoration objectives to appropriately design the solution(s). The potential of a certain stream to meet specific objectives must be assessed early on in the planning phases so that the initial restoration direction is appropriate. The common objectives are:

- flood level reduction
- streambank stability
- reduce sediment supply, land loss, and attached nutrients
- improve visual values
- improve fish habitat and biological diversity
- create a natural stable river
- withstand floods
- be self-maintaining
- be cost-effective
- improve water quality
- improve wetlands

It is essential to fully describe and understand the restoration objectives. The importance of formulating clear, achievable, and measurable objectives is described in detail in NEH654.02. Often the objectives can be competing or be in conflict with one another. Conflict resolution must be initiated and can often be offset by varying the design and/or the nature of stabilization methods or materials planned.

The assessment required must also reflect the restoration objectives to ensure various related processes are thoroughly evaluated. For example, if improved fishery abundance, size, and species are desired, a limiting factor analysis of habitat and fish populations must be linked with the morphological and sedimentological characteristics.

(b) Phase II—Developing local and regional relations in geomorphic characterization, hydrology, and hydraulics

Geomorphic characterization

The relations mapped at this phase are the geomorphic characterization and description levels for stream classification (Rosgen 1994, 1996). Valley types (table 11–1) are mapped prior to stream classification to ensure reference reach data are appropriately applied for the respective valley types being studied. Morphological relations associated with stream types are presented in figures 11–2 (Rosgen 1994) and 11–3 (Rosgen 1996) and summarized in table 11–2. In natural channel design using the Rosgen geomorphic channel design approach, it is often advantageous to have an undisturbed and/or stable river reach immediately upstream of the restoration reach. Reference reach data are obtained and converted to dimensionless ratio relations to extrapolate channel dimension, pattern, profile, and channel material data to rivers and valleys of the same type, but of different size. If an undisturbed/stable river reach is not upstream of the restoration reach, extrapolation of morphological and dimensionless ratio relations by valley and stream type is required for both assessment and design.

An example of the form used to organize reference reach data, including dimensionless ratios for a given stream type, is presented in table 11–3. Specific design variables use reference reach data for extrapolation purposes, assuming the same valley and stream type as represented. These relations are only representative of a similar stable stream type within a valley type of the disturbed stream.

Hydrology

The hydrology of the basin is often determined from regional curves constructed from long-term stream gage records. Relationships of flow-duration curves and flood-frequency data are used for computations in both the assessment and design phases. Stream Hydrology is also addressed in NEH654.05. Relations are converted to dimensionless formats using bankfull discharge as the normalization parameter. Bankfull discharge and dimensions associated with stream gages are plotted as a function of drainage area for extrapolation to ungaged sites in similar hydro-physiographic provinces. A key requirement in the development of

Table 11–1 Valley types used in geomorphic characterization

Valley types	Summary description of valley types
I	Steep, confined, V-notched canyons, rejuvenated side slopes
II	Moderately steep, gentle-sloping side slopes often in colluvial valleys
III	Alluvial fans and debris cones
IV	Gentle gradient canyons, gorges, and confined alluvial and bedrock-controlled valleys
V	Moderately steep, U-shaped glacial-trough valleys
VI	Moderately steep, fault, joint, or bedrock (structural) controlled valleys
VII	Steep, fluvial dissected, high-drainage density alluvial slopes
VIII	Wide, gentle valley slope with well-developed flood plain adjacent to river and/or glacial terraces
IX	Broad, moderate to gentle slopes, associated with glacial outwash and/or eolian sand dunes
X	Very broad and gentle valley slope, associated with glacio- and nonglacio-lacustrine deposits
XI	Deltas

Figure 11–2 Broad-level stream classification delineation showing longitudinal, cross-sectional, and plan views of major stream types

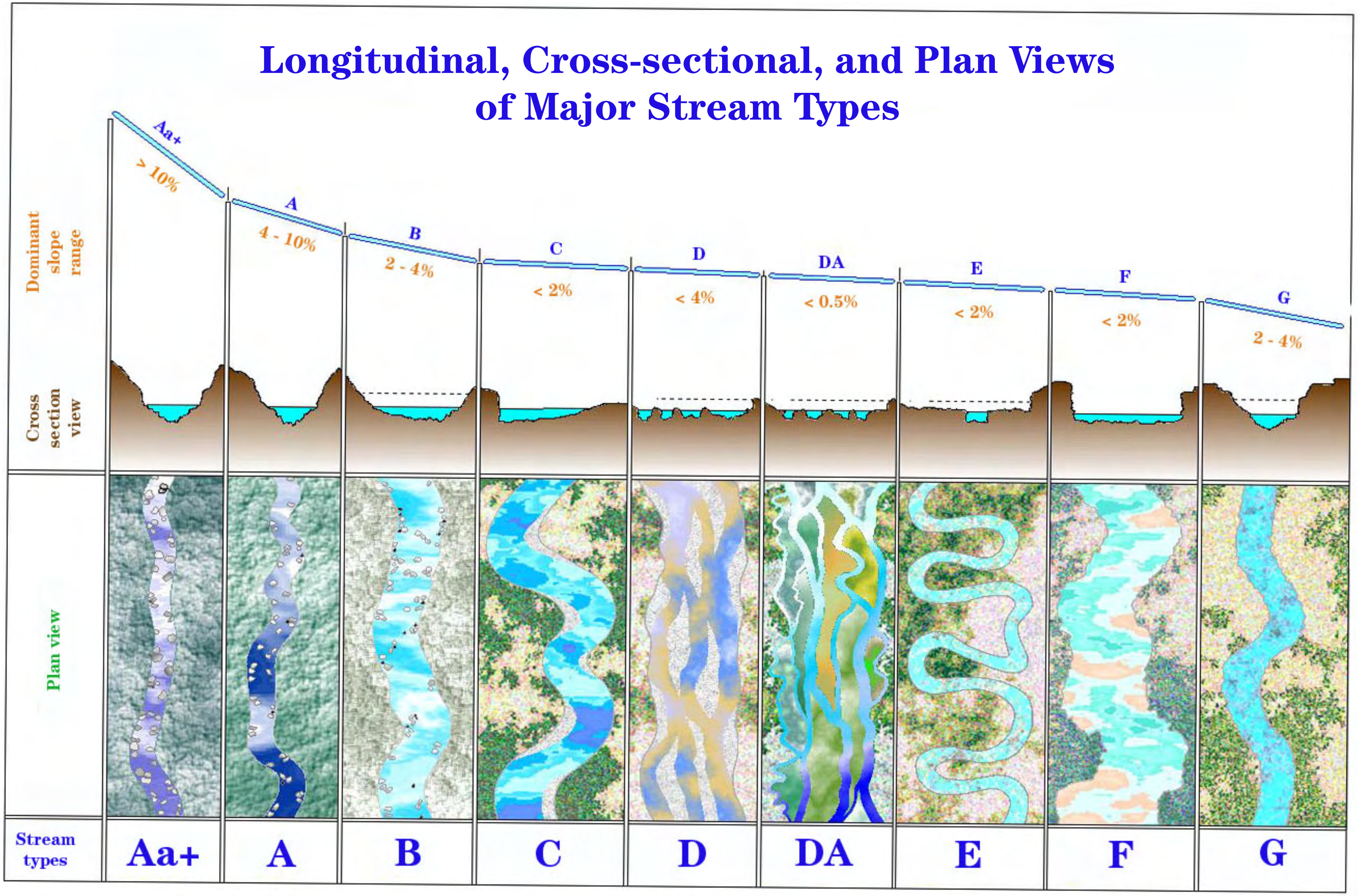
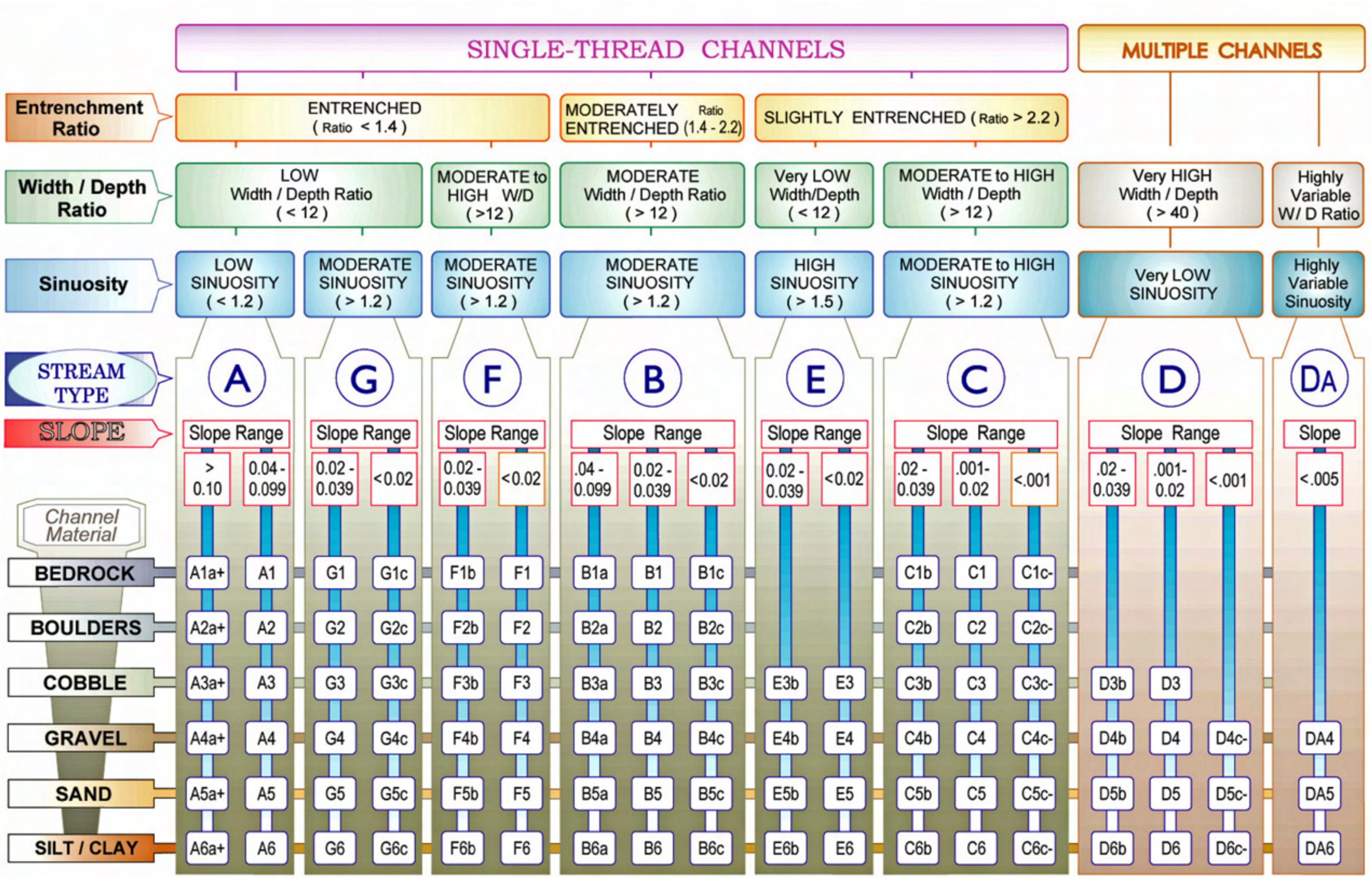


Figure 11–3 Classification key for natural rivers



KEY to the *ROSGEN* CLASSIFICATION of NATURAL RIVERS. As a function of the *"continuum of physical variables"* within stream reaches, values of ***Entrenchment*** and ***Sinuosity*** ratios can vary by +/- 0.2 units; while values for ***Width / Depth*** ratios can vary by +/- 2.0 units.

Table 11–2 General stream type descriptions and delineative criteria for broad-level classification (level 1)

Stream type	General description	Entrenchment ratio	W/d ratio	Sinuosity	Slope	Landform/ soils/features
Aa+	Very steep, deeply entrenched, debris transport, torrent streams	<1.4	<12	1.0 to 1.1	>.10	Very high relief. Erosional, bedrock, or depositional features; debris flow potential. Deeply entrenched streams. Vertical steps with deep scour pools; waterfalls
A	Steep, entrenched, cascading, step-pool streams. High energy/ debris transport associated with depositional soils. Very stable if bedrock or boulder-dominated channel	<1.4	<12	1.0 to 1.2	.04 to .10	High relief. Erosional or depositional and bedrock forms. Entrenched and confined streams with cascading reaches. Frequently spaced, deep pools in associated step-pool bed morphology
B	Moderately entrenched, moderate gradient, riffle dominated channel with infrequently spaced pools. Very stable plan and profile. Stable banks	1.4 to 2.2	>12	>1.2	.02 to .039	Moderate relief, colluvial deposition and/or structural. Moderate entrenchment and width-to-depth ratio. Narrow, gently sloping valleys. Rapids predominate with scour pools
C	Low gradient, meandering, point bar, riffle/pool, alluvial channels with broad, well-defined flood plains	>2.2	>12	>1.2	<.02	Broad valleys with terraces, in association with flood plains, alluvial soils. Slightly entrenched with well-defined meandering channels. Riffle/ pool bed morphology
D	Braided channel with longitudinal and transverse bars. Very wide channel with eroding banks	n/a	>40	n/a	<.04	Broad valleys with alluvium, steeper fans. Glacial debris and depositional features. Active lateral adjustment with abundance of sediment supply. Convergence/divergence bed features, aggradational processes, high bed load and bank erosion
DA	Anastomizing (multiple channels) narrow and deep with extensive, well-vegetated flood plains and associated wetlands. Very gentle relief with highly variable sinuosities and width-to-depth ratios. Very stable streambanks	>2.2	Highly variable	Highly variable	<.005	Broad, low-gradient valleys with fine alluvium and/or lacustrine soils. Anastomized (multiple channel) geologic control creating fine deposition with well-vegetated bars that are laterally stable with broad wetland flood plains. Very low bed-load, high wash load sediment
E	Low gradient, meandering riffle/pool stream with low width-to-depth ratio and little deposition. Very efficient and stable. High meander width ratio	>2.2	<12	>1.5	<.02	Broad valley/meadows. Alluvial materials with flood plains. Highly sinuous with stable, well-vegetated banks. Riffle/pool morphology with very low width-to-depth ratios
F	Entrenched meandering riffle/pool channel on low gradients with high width-to-depth ratio	<1.4	>12	>1.2	<.02	Entrenched in highly weathered material. Gentle gradients with a high width-to-depth ratio. Meandering, laterally unstable with high bank erosion rates. Riffle/pool morphology
G	Entrenched gully step-pool and low width-to-depth ratio on moderate gradients	<1.4	<12	>1.2	.02 to .039	Gullies, step-pool morphology with moderate slopes and low width-to-depth ratio. Narrow valleys, or deeply incised in alluvial or colluvial materials (fans or deltas). Unstable, with grade control problems and high bank erosion rates

Table 11–3 Reference reach summary data form

River Reach Summary Data

Channel dimension

Mean riffle depth (d_{bkf})		ft	Riffle width (W_{bkf})		ft	Riffle area (A_{bkf})		ft²
Mean pool depth (d_{bkfp})		ft	Pool width (W_{bkfp})		ft	Pool area (A_{bkfp})		ft²
Mean pool depth/mean riffle depth		$d_{bkfp}/(d_{bkf})$	Pool width/riffle width		W_{bkfp}/W_{bkf}	Pool area/riffle area		A_{bkfp}/A_{bkf}
Max riffle depth (d_{mbkf})		ft	Max pool depth (d_{mbkfp})		ft	Max riffle depth/mean riffle depth		
Max pool depth/mean riffle depth						Point bar slope		
Streamflow: estimated mean velocity at bankfull stage (u_{bkf})					ft/s	Estimation method		
Streamflow: estimated discharge at bankfull stage (Q_{bkf})					ft³/s	Drainage area		mi²

Channel pattern

Geometry	Mean	Min.	Max.		Dimensionless geometry ratios	Mean	Min.	Max.
Meander length (Lm)				ft	Meander length ratio (Lm/W_{bkf})			
Radius of curvature (Rc)				ft	Radius of curvature/riffle width (Rc/W_{bkf})			
Belt width (W_{blt})				ft	Meander width ratio (W_{blt}/W_{bkf})			
Individual pool length				ft	Pool length/riffle width			
Pool to pool spacing				ft	Pool to pool spacing/riffle width			

Channel profile

Valley slope (VS)		ft/ft	Average water surface slope (S)		ft/ft	Sinuosity (VS/S)	
Stream length (SL)		ft	Valley length (VL)		ft	Sinuosity (SL/VL)	

Low bank height (LBH)	start		ft	Max riffle depth	start		ft	Bank height ratio (LBH/max riffle depth)	start	
	end		ft		end		ft		end	

Facet slopes	Mean	Min.	Max.		Dimensionless geometry ratios	Mean	Min.	Max.
Riffle slope (S_{rif})				ft/ft	Riffle slope/average water surface slope (S_{rif}/S)			
Run slope (S_{run})				ft/ft	Run slope/average water surface slope (S_{run}/S)			
Pool slope (S_p)				ft/ft	Pool slope/average water surface slope (S_p/S)			
Glide slope (S_g)				ft/ft	Glide slope/average water surface slope (S_g/S)			

Feature midpoint[a]	Mean	Min.	Max.		Dimensionless geometry ratios	Mean	Min.	Max.
Riffle depth (d_{rif})				ft	Riffle depth/mean riffle depth (d_{rif}/d_{bkf})			
Run depth (d_{run})				ft	Run depth/mean riffle depth (d_{run}/d_{bkf})			
Pool depth (d_p)				ft	Pool depth/mean riffle depth (d_p/d_{bkf})			
Glide depth (d_g)				ft	Glide depth/mean riffle depth (d_g/d_{bkf})			

Channel materials

Geometry		Reach[b]	Riffle[c]	Bar		Reach[b]	Riffle[c]	Bar	
% Silt/clay					D_{16}				mm
% Sand					D_{35}				mm
% Gravel					D_{50}				mm
% Cobble					D_{84}				mm
% Boulder					D_{95}				mm
% Bedrock					D_{100}				mm

a/ Minimum, maximum, mean depths are the average midpoint values except pools which are taken at deepest part of pool
b/ Composite sample of riffles and pools within the designated reach
c/ Active bed of a riffle

such relations is the necessity to field-calibrate the bankfull stage at each gage within a hydro-physiographic province (a drainage basin similar in precipitation/runoff relations due to precipitation/elevation, lithology and land uses).

Regional curves—The field-calibrated bankfull stage is used to obtain the return period associated with the bankfull discharge. Regional curves of bankfull discharge versus drainage area are developed (fig. 11–4) (adapted from Dunne and Leopold 1978)). To plot bankfull dimensions by drainage area, the U.S. Geological Survey (USGS) 9–207 data (summary of stream discharge measurements at the gage) are obtained to plot the at-a-station hydraulic geometry relations (fig. 11–5 (adapted from Rosgen 1996; Rosgen and Silvey 2005)). These data are then converted to dimensionless hydraulic geometry data by dividing each value by their respective bankfull value. These relations are used during assessment and design to indicate the shape of the various cross sections from low flow to high flow. In the development of the dimensionless hydraulic geometry data, current meter measurements must be stratified by stream type (Rosgen 1994, 1996) and for specific bed features such as riffles, glides, runs, or pools.

Figure 11–4 Regional curves from stream gaging stations showing bankfull discharge (ft^3/s) vs. drainage area (mi^2)

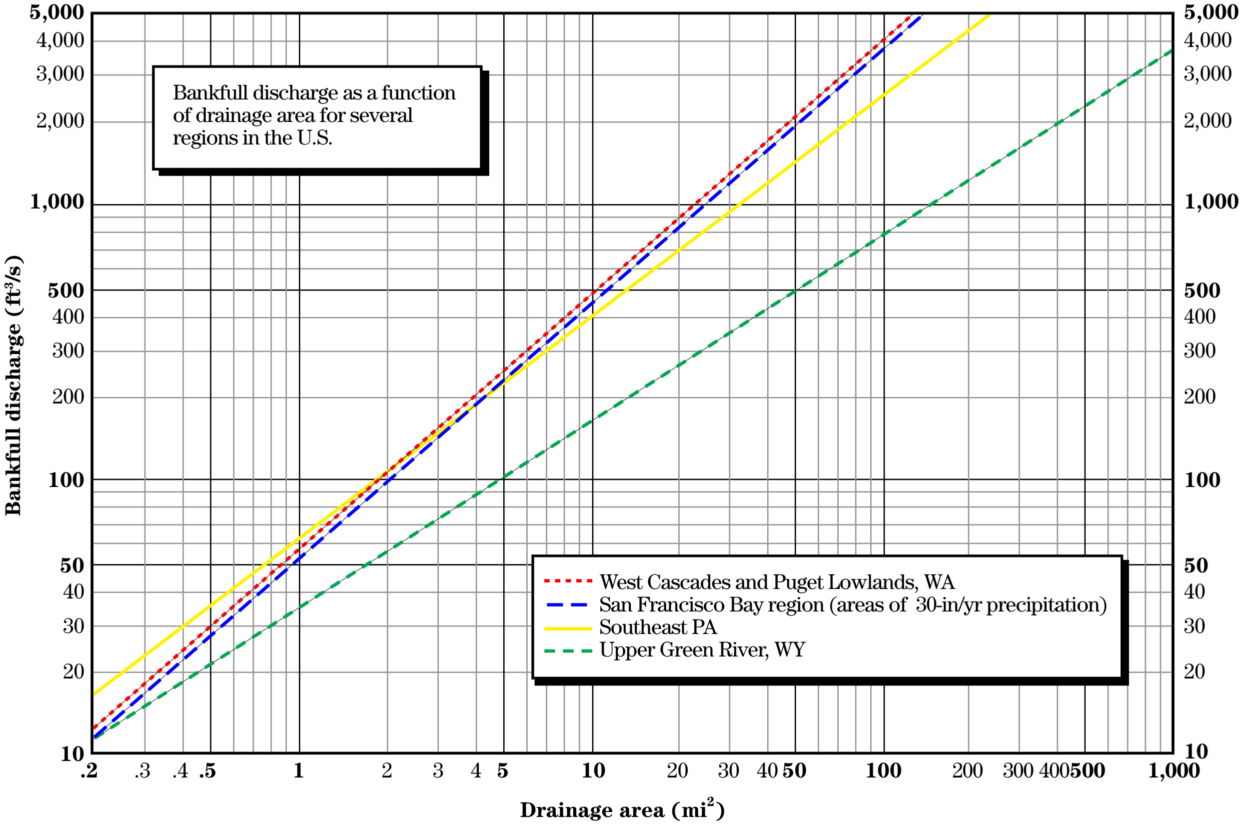
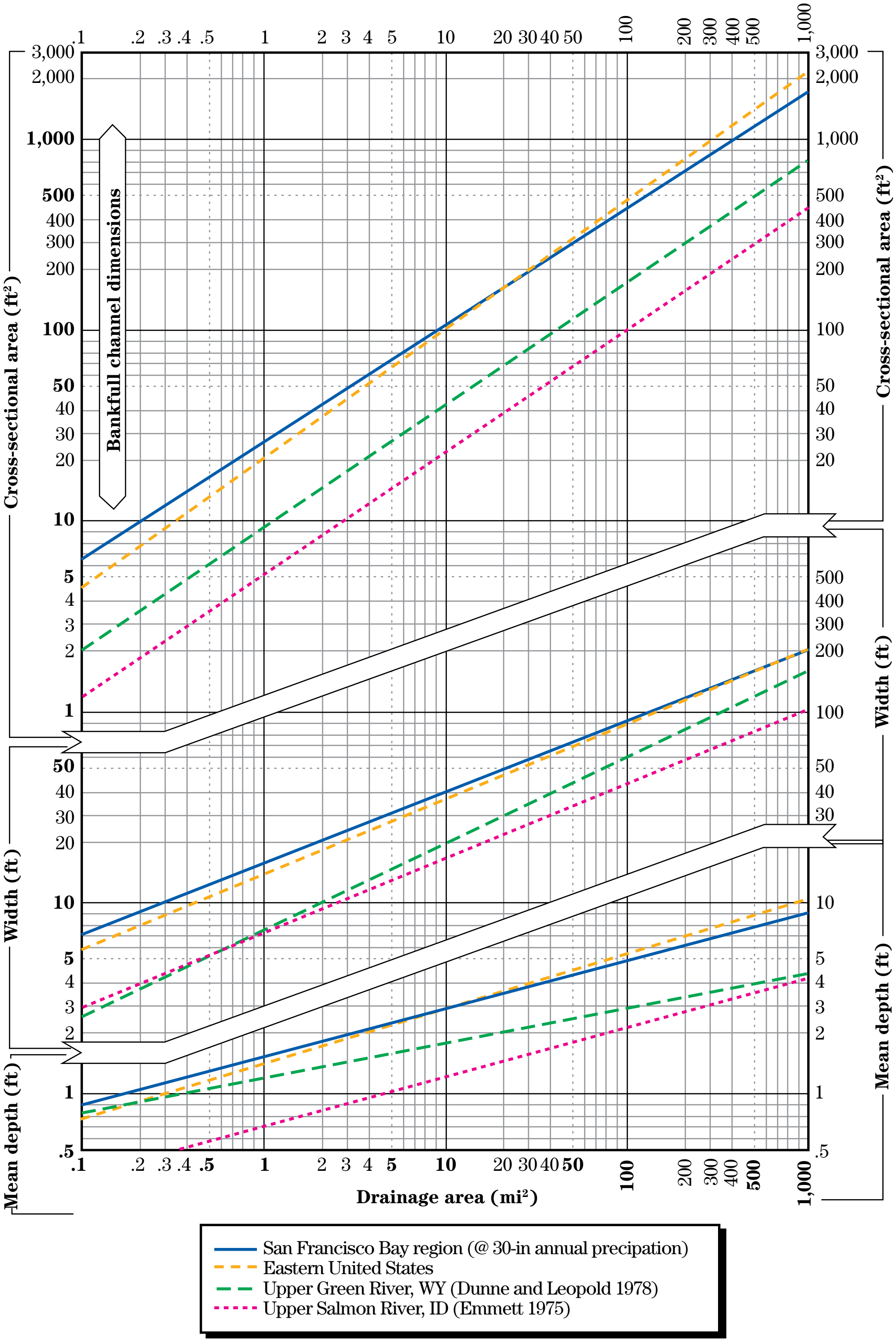


Figure 11–5 Regional curves from stream gage stations showing bankfull dimensions (width, depth, and cross-sectional area) vs. drainage area (mi²)



Hydraulic relations

Hydraulic relations are validated using resistance equations for velocity prediction at ungaged sites. (Stream Hydraulics is addressed in more detail in NEH654.06) Validation is accomplished by back calculating relative roughness (R/D_{84}) and a friction factor (u/u^*) from actual measured velocity for a range of streamflows including bankfull:

$$u = \left[2.83 + 5.66\log\left(\frac{R}{D_{84}}\right)\right]u* \qquad \text{(eq. 11–1)}$$

where:
u = mean velocity (ft/s)
R = hydraulic radius
D_{84} = diameter of bed material of the 84th percentile of riffles
u^* = shear velocity $(gRS)^{1/2}$
g = gravitational acceleration
S = slope

Measured velocity, slope, channel material, and hydraulic radius data from various Colorado rivers using this friction factor (u/u^*) and relative roughness (R/D_{84}) relation are shown in figure 11–6 (Rosgen, Leopold, and Silvey 1998; Rosgen and Silvey 2005).

Manning's *n* (roughness coefficient) can also be back-calculated from measured velocity, slope, and hydraulic radius. Another approach to predict velocity at ungaged sites is to predict Manning's *n* from a friction factor back-calculated from relative roughness shown in figure 11–7 (Rosgen, Leopold, and Silvey 1998; Rosgen and Silvey 2005). Manning's *n* can also be estimated at the bankfull stage by stream type as shown in the relationship from gaged, large streams in figure 11–8. Vegetative influence is also depicted in these data (Rosgen 1994).

Dimensionless flow-duration curves—Flow-duration curves (based on mean daily discharge) are also obtained from gage stations then converted to dimensionless form using bankfull discharge as the normalization parameter (fig. 11–9 (Emmett 1975)). The purpose of this form is to allow the user to extrapolate flow-duration curves to ungaged basins. This relationship is needed for the annual suspended and bed-load sediment yield calculation along with channel hydraulic variables.

(c) Phase III—Watershed and river assessment

Land use history is a critical part of watershed assessment to understand the nature and extent of potential impacts to the water resources. Past erosional/depositional processes related to changes in vegetative cover, direct disturbance, and flow and sediment regime changes provide insight into the direction and detail for assessment procedures required for restoration. Time series of aerial photos are of particular value to understand the nature, direction, magnitude, and rate of change. This is very helpful, as it assists in assessing both short-term, as well as long-term river problems.

Assessment of river stability and sediment supply

River stability (equilibrium or quasi-equilibrium) is defined as the ability of a river, over time, in the present climate to transport the flows and sediment produced by its watershed in such a manner that the stream maintains its dimension, pattern, and profile without either aggrading or degrading (Rosgen 1994, 1996, 2001d). A stream channel stability analysis is conducted along with riparian vegetation inventory, flow and sediment regime changes, limiting factor analysis compared to biological potential, sources/causes of instability, and adverse consequences to physical and biological function. Procedures for this assessment are described in detail by Rosgen (1996, 2001d) and in Watershed Assessment and River Stability for Sediment Supply (WARSSS) (Rosgen 1999, 2005).

It is important to realize the difference between the dynamic nature of streams and natural adjustment processes compared to an acceleration of such adjustments. For example, bank erosion is a natural channel process; however, accelerated streambank erosion must be understood when the rate increases and creates a disequilibrium condition. Many stable rivers naturally adjust laterally, such as the "wandering" river. While it may meet certain local objectives to stabilize high risk banks, it would be inadvisable to try to "control" or "fix in place" such a river.

In many instances, a braided river and/or anastomizing river type is the stable form. Designing all stream systems to be a single-thread meandering stream may not properly represent the natural stable form. Valley types are a key part of river assessment to understand

Figure 11–6 Relation of channel bed particle size to hydraulic resistance with river data from a variety of eastern and western streams

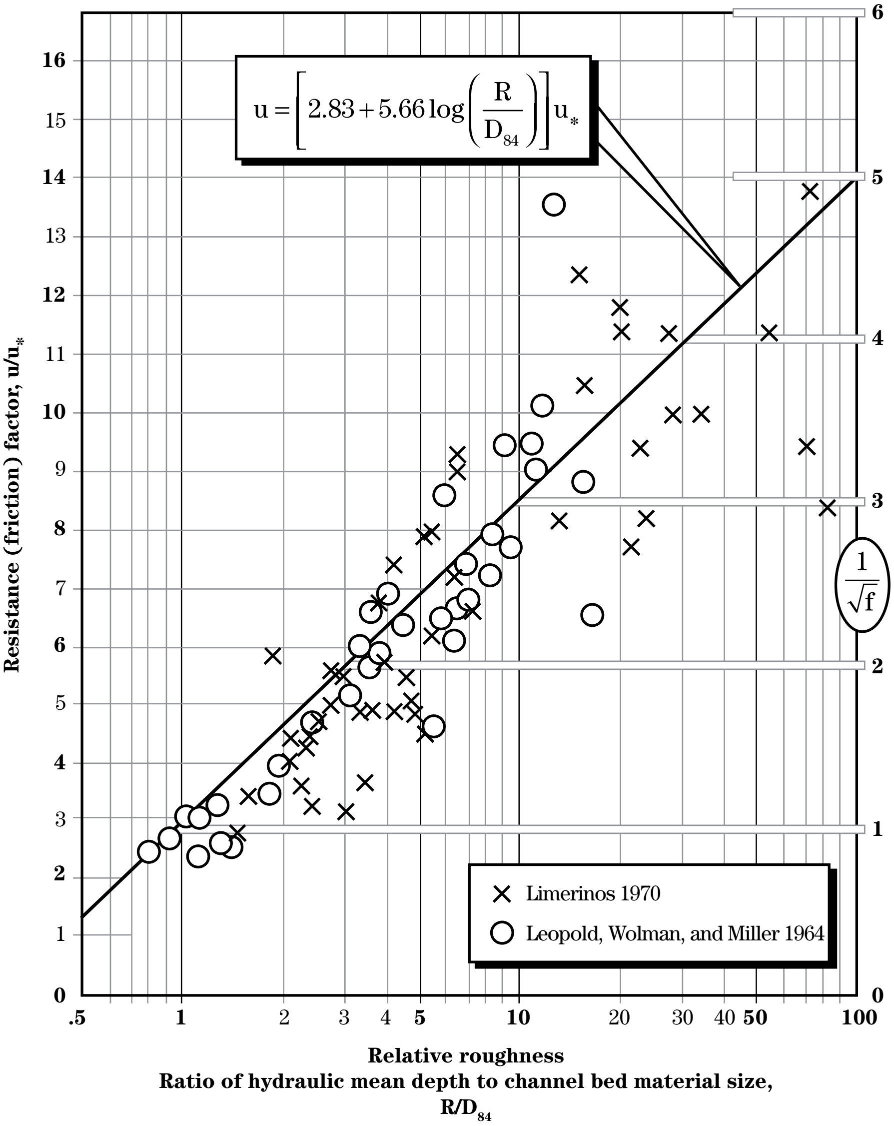


Figure 11–7 Prediction of Manning's *n* roughness coefficient

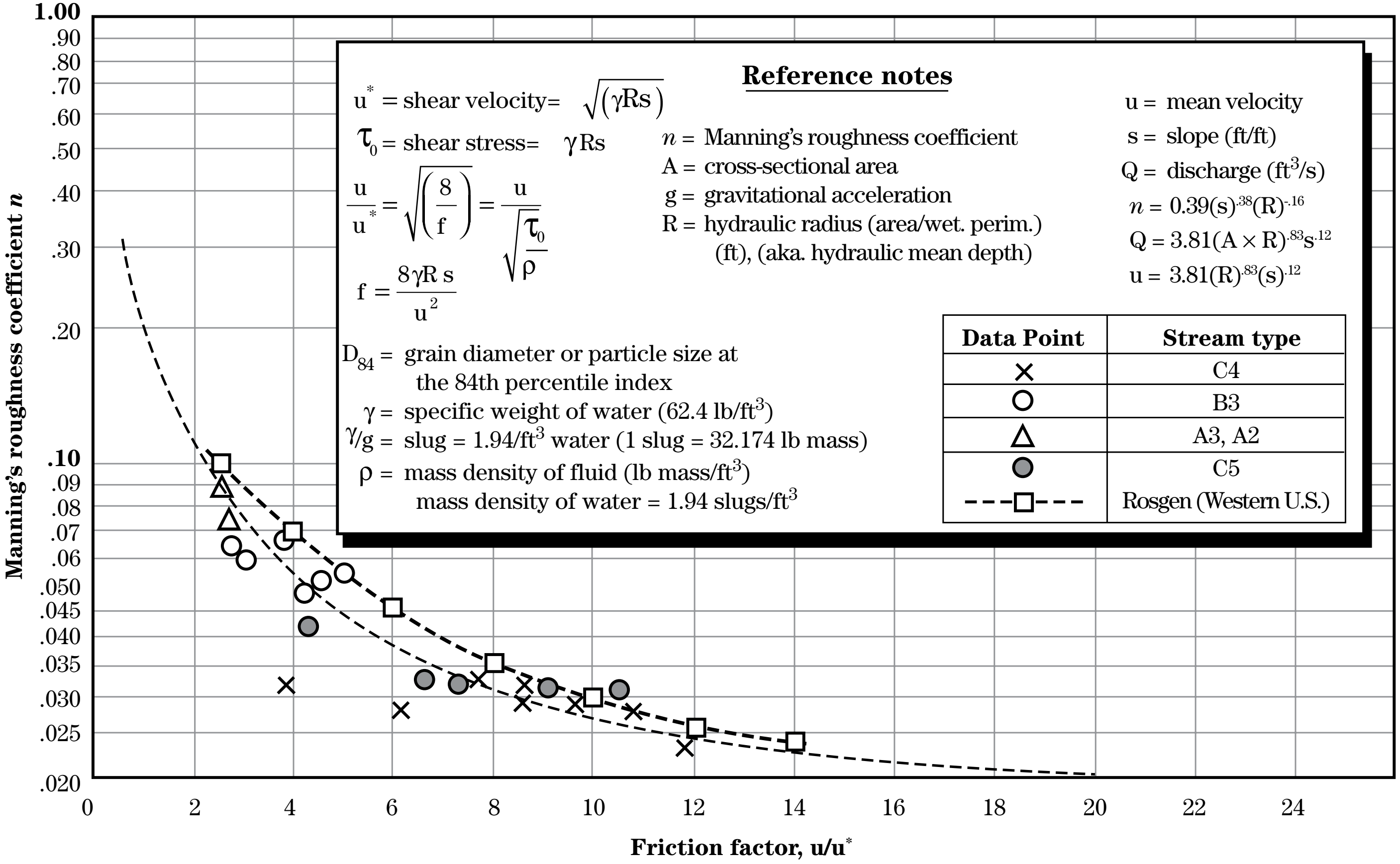
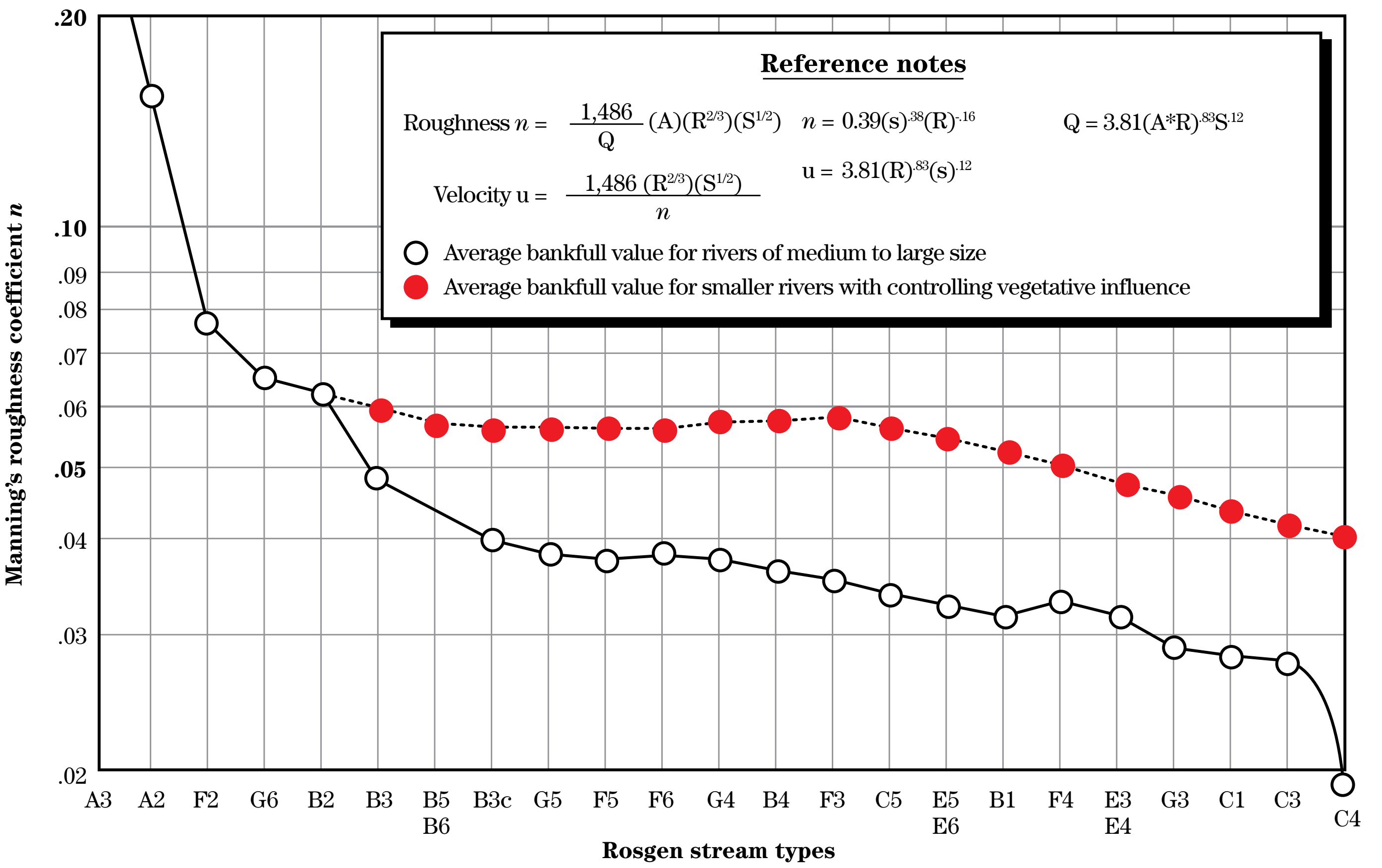


Figure 11–8 Bankfull stage roughness coefficients (*n* values) by stream type for 140 streams in the United States and New Zealand

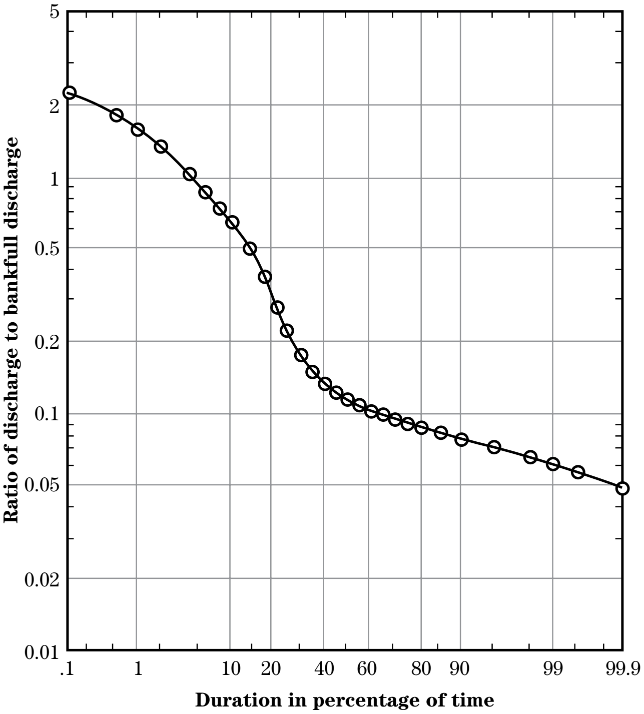


which stream types are stable within a variety of valley types in their geomorphic settings. Reference reaches that represent the stable form have to be measured and characterized only for use in similar valley types. This prevents applying good data to the *wrong* stream type.

Time-trend data using aerial photography is very valuable at documenting channel change. Field evidence using dendrochronology, stratigraphy, carbon dating, paleochannels, or evidence of avulsion and avulsion dates can help the field observer to understand rate, direction, and consequence of channel change.

The field inventory and the number of variables required to conduct a watershed and river stability assessment is substantial. The flowchart in figure 11–10 represents a general summary of the various elements used for assessing channel stability as used in this methodology. The assessment effort is one of the key procedural steps in a sound restoration plan, as it identifies the causes and consequences of the problems leading to loss of physical and biological river function. Some of the major variables are described to provide a *general* overview.

Figure 11–9 Dimensionless flow-duration curve for streamflow in the upper Salmon River area

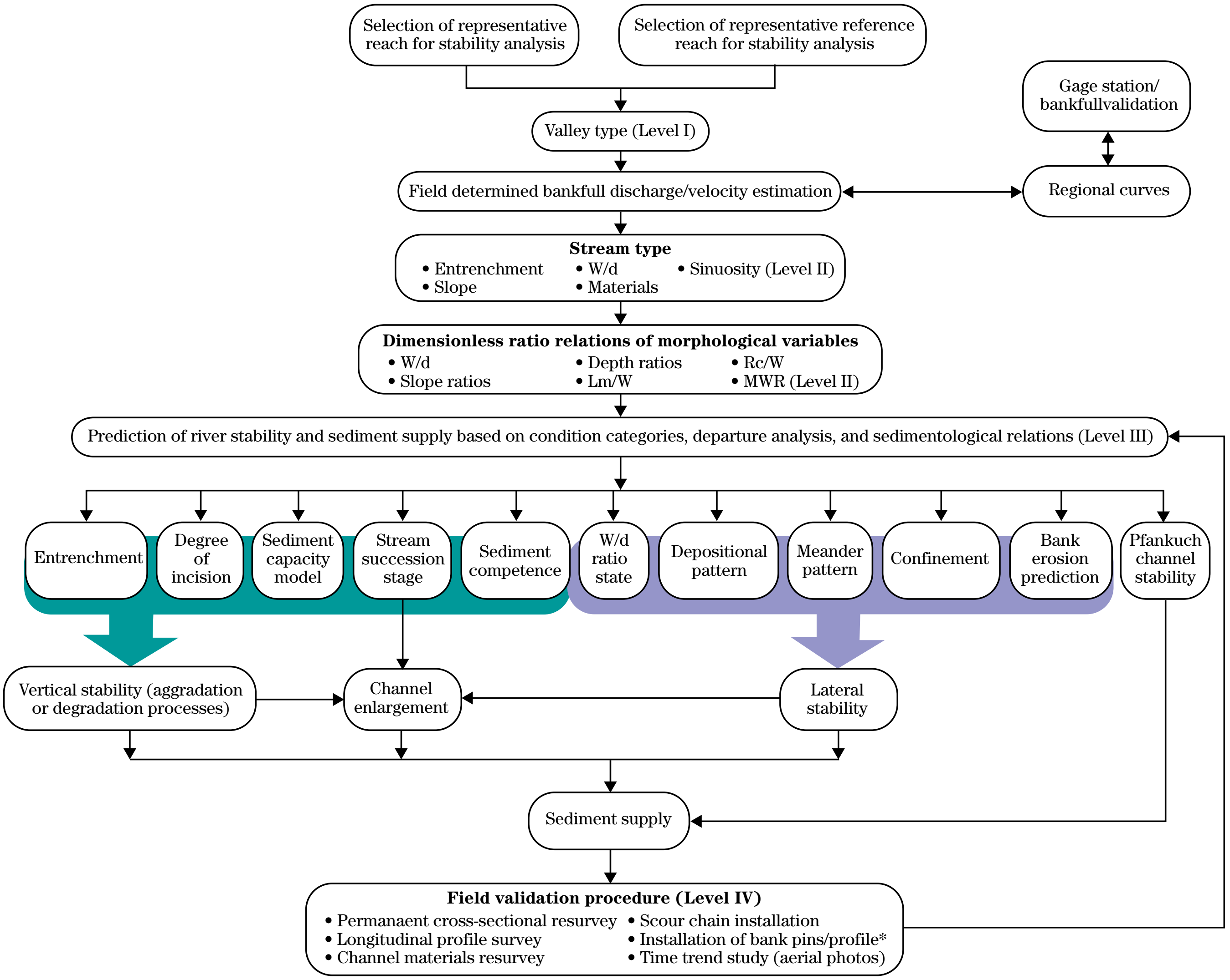


Streamflow change—Streamflow alteration (magnitude, duration, and timing) due to land use changes, such as percent impervious cover, must be determined at this phase. Streamflow models, such as the unit hydrograph approach, must be calibrated by back-calculating what precipitation probability generates bankfull discharge for various antecedent soil moisture and runoff curve numbers. It is critical to separate bankfull discharge from flood flows, as each flow category, including flood flow, has a separate dimension, pattern, and profile. This varies by stream type and the lateral and vertical constraints imposed within the valley (or urban “valley”).

Flow-duration curves by similar hydro-physiographic provinces from gaged stations are converted to bankfull dimensionless flow duration for use in the annual sediment yield calculation. Snowmelt watershed flow prediction output (Troendle, Swanson, and Nankervis 2005) is generally shown in flow-duration changes, rather than an annual hydrograph. Similar model outputs using flow-duration changes are shown in Water Resources Evaluation of Nonpoint Silvicultural Sources (U.S. Environmental Protection Agency (EPA) 1980).

Sediment competence—Sedimentological data are obtained by a field measurement of the size of bar and bed material, bed-load sediment transport, suspended sediment transport, and bankfull discharge measurements at the bankfull stage. Sediment relations are established by collecting energy slope, hydraulic radius, bed material, bar material, and the largest particle produced by the drainage immediately upstream of the assessment reach. Critical dimensionless shear stress is calculated from field data to determine *sediment competence* (ability to move the largest particle made available to the channel). Procedures for this field inventory are presented in Andrews (1984) and Rosgen (2001a, 2001d, 2005). Potential aggradation, degradation, and channel enlargement are predicted for the disturbed reach, comparing the required depth and slope necessary to transport the largest size sediment available. These calculations can be accomplished by hand, spreadsheet, or by commercially available computer programs.

Figure 11–10 Generalized flowchart of application of various assessment levels of channel morphology, stability ratings, and sediment supply



*Optional: sediment measurements (largest size moved at bankfull, D_i)

Changes in channel dimension, pattern, and profile are reflected in changes of velocity, depth, and slope. These changes in the hydraulic variables are reflected in values of shear stress. Shear stress is defined as:

$$\tau = \gamma RS \qquad \text{(eq. 11–2)}$$

where:
τ = bankfull shear stress (lb/ft^2)
γ = specific weight of water = 62.4 lb/ft^3
R = hydraulic radius of riffle cross section (ft)
S = average water surface slope (ft/ft)

Use the calculated value of τ (lb/ft^2) and the Shields diagram as revised with the Colorado data (fig. 11–11 (Rosgen and Silvey 2005)) to predict the moveable particle size (mm) at bankfull shear stress.

Another relationship used in assessment and in design is the use of dimensionless shear stress (τ^*_{ci}) to determine particle entrainment. Dimensionless shear stress is defined as:

$$\tau^* = 0.0834\left(\frac{D_{50}}{\hat{D}_{50}}\right)^{-0.872} \qquad \text{(eq. 11–3)}$$

where:
τ^* = dimensionless shear stress
D_{50} = median diameter of the riffle bed (from 100 count in the riffle or pavement sample)
$\hat{D}_{50}$ = median diameter of the bar sample (or subpavement sample)

If the ratio $\frac{D_{50}}{\hat{D}_{50}}$ is between the values of 3.0 and 7.0, calculate the critical dimensionless shear stress using equation 11–3 (modifications adapted from Andrews 1983, 1984; Andrews and Erman 1986).

If the ratio $\frac{D_{50}}{\hat{D}_{50}}$ is **not** between the values of 3.0 and 7.0, calculate the ratio $\frac{D_{max}}{D_{50}}$

where:
D_{max} = largest particle from the bar sample (or the subpavement sample)
D_{50} = median diameter of the riffle bed (from 100 count in the riffle or the pavement sample)

If the ratio $\frac{D_{max}}{D_{50}}$ is between the value of 1.3 and 3.0, calculate the critical dimensionless shear stress:

$$\tau^* = 0.0384\left(\frac{D_{max}}{D_{50}}\right)^{-0.887} \qquad \text{(eq. 11–4)}$$

Once the dimensionless shear stress is determined, the bankfull mean depth required for entrainment of the largest particle in the bar sample (or subpavement sample) is calculated using equation 11–5:

$$d_{bkf} = 1.65\tau^* \frac{D_{max}}{S} \qquad \text{(eq. 11–5)}$$

where:
d_{bkf} = required bankfull mean depth (ft)
1.65 = submerged specific weight of sediment
τ^* = dimensionless shear stress
D_{max} = largest particle from bar sample (or subpavement sample) (ft)
S = bankfull water surface slope (ft/ft)

The bankfull water surface slope required for entrainment of the largest particle can be calculated using equation 11–6:

$$S = 1.65\tau^* \frac{D_{max}}{d_{bkf}} \qquad \text{(eq. 11–6)}$$

Equations 11–5 and 11–6 are derived from the basic Shields relation.

If the protrusion ratios are out of the usable range as stated, another option is to calculate sediment entrainment using dimensional bankfull shear stress (eq. 11–2 and fig. 11–11).

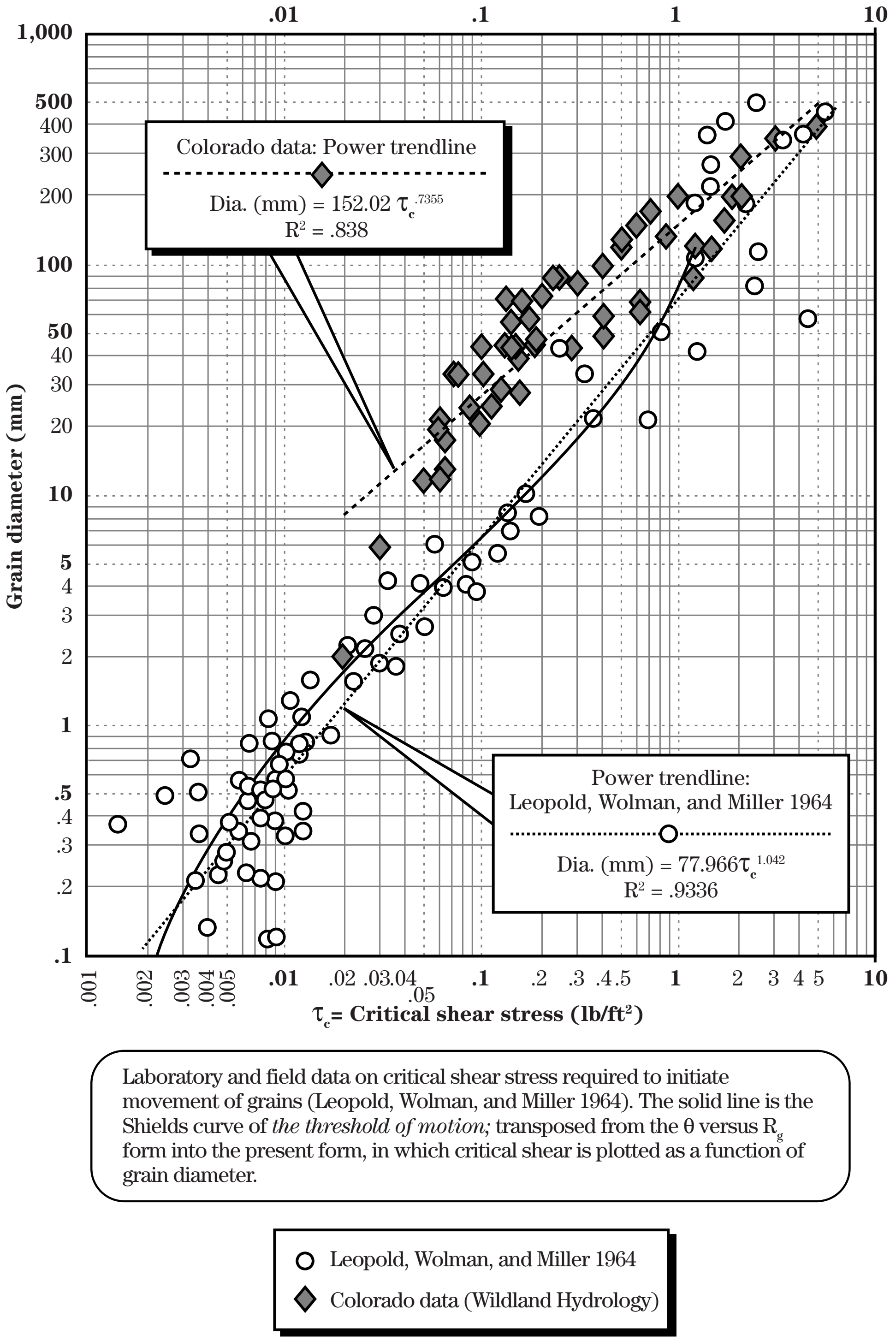
Sediment capacity—In addition to sediment competence, sediment capacity is important to predict river stability. Unit stream power is also utilized to determine the distribution of energy associated with changes in the dimension, pattern, profile, and materials of stream channels. Unit stream power is defined as shear stress times mean velocity:

$$\omega = \tau u \qquad \text{(eq. 11–7)}$$

where:
ω = unit stream power (lb/ft/s)
τ = shear stress (lb/ft^2)
u = mean velocity (ft/s)

Predicted sediment rating curves are converted to unit stream power for the same range of discharges by individual cells to demonstrate reduction or increase in coarse sediment transport.

Figure 11–11 Relation between grain diameter for entrainment and shear stress using Shields relations



Laboratory and field data on critical shear stress required to initiate movement of grains (Leopold, Wolman, and Miller 1964). The solid line is the Shields curve of *the threshold of motion;* transposed from the θ versus R_g form into the present form, in which critical shear is plotted as a function of grain diameter.

The use of reference dimensionless sediment rating curves by stream type and stability rating, (Troendle et al. 2001), as well as hydrology and hydraulic data, are all needed for the stability and design phases. Additional information will be presented in the respective sequential, analytical steps of each phase of the procedure. Local suspended sediment and bed-load data can be converted to regional sediment curves by plotting bankfull and suspended sediment data by drainage area. Examples of suspended sediment data plotted by 1.5-year recurrence interval discharge/drainage area for many regions of the United States as developed from USGS gage data by the U.S. Department of Agriculture (USDA), Agricultural Research Service (ARS) are presented in Simon, Dickerson, and Heins (2004). These relations can be used if a direct measurement of bankfull sediment cannot be obtained for subsequent analysis. Caution should be exercised in using an arbitrary bankfull value without field calibration of the bankfull discharge. The 1.5-year recurrence interval discharge is often greater than the actual bankfull value in wet climates and urban areas.

The disadvantage of using various suspended and bed load equations for the Rosgen geomorphic channel design methodology is the difficulty of determining sediment supply for sediment rating curves. It is common in the use of these models to have predicted values of many orders of magnitude different than observed values. The use of developed dimensionless ratio sediment rating curves for both suspended (less wash load) and bed load by stream type and stability is the improvement of predicted versus observed values. Results of an independent test of predicted versus observed values for a variety of USGS gage sites are shown in figures 11–12, 11–13, and 11–14. These figures show that predicted sediment rating curves match observed values for a wide range of flows. The model for bed-load transport reflects sediment transport based on changes in the channel hydraulics from a reference condition.

Validation of sediment competence or entrainment relations can also assist in the development and application of subsequent analysis. These data can be collected by installing scour chains and actual measurements of bed-load transport grain size for a given shear stress using Helley-Smith bed-load samplers. Plotting existing data collected by others in this manner can also help in developing a data base used in later analysis.

The use of reference dimensionless ratio sediment rating curves (bed load and suspended less wash load) requires field measured bankfull sediment and dis-

Figure 11–12 Comparison of predicted sediment rating curve to observed values from the Tanana River, AK, using the Pagosa Springs dimensionless ratio relation

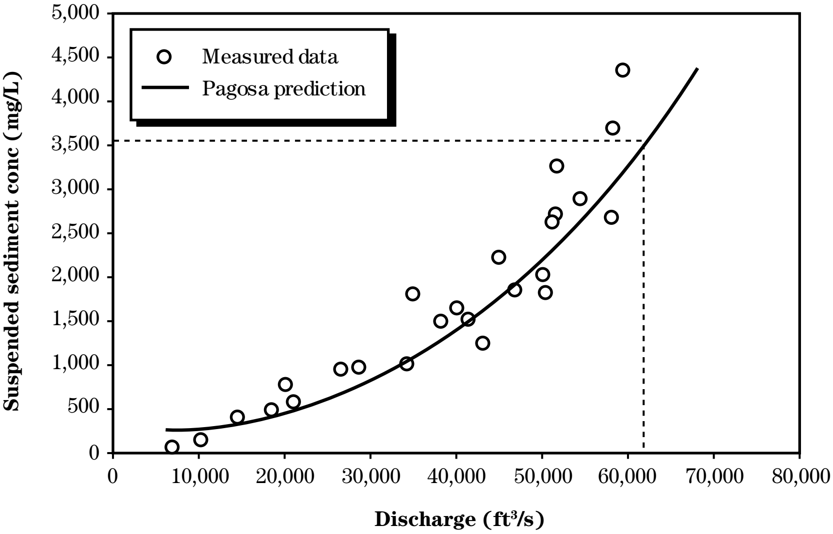
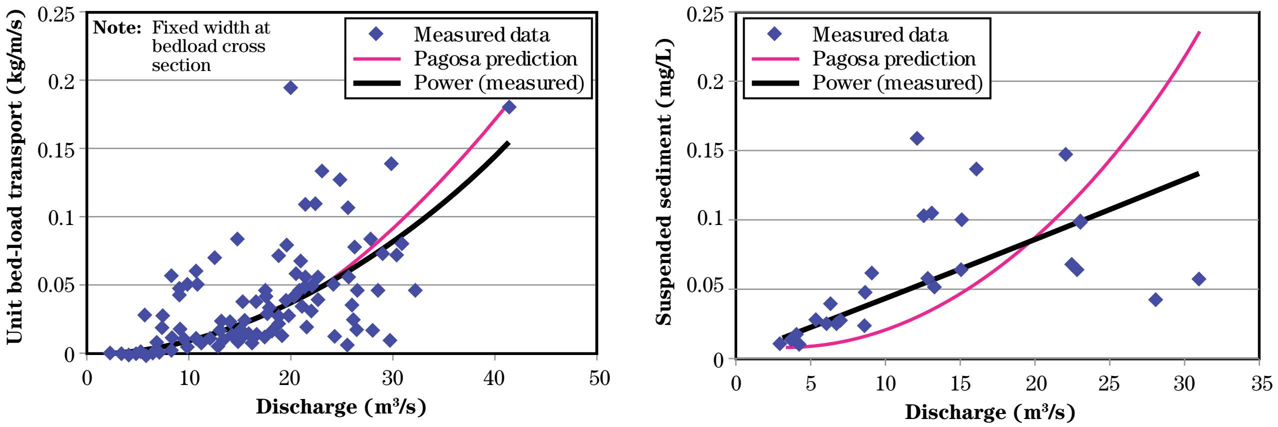
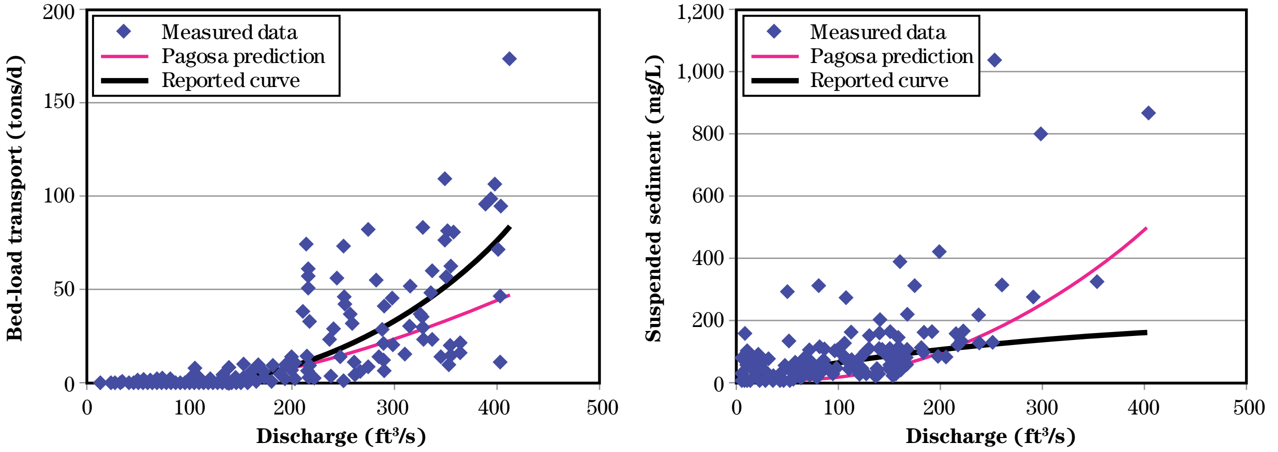


Figure 11–13 Predicted vs. measured sediment data using reference dimensionless rating curve (data from Leopold and Emmett 1997; Ryan and Emmett 2002)

East Fork River near Big Sandy, WY (from Leopold and Emmett 1997)



Little Granite Creek near Bondurant, WY (from Ryan and Emmett 2002)



Maggie Creek (F4)—NV

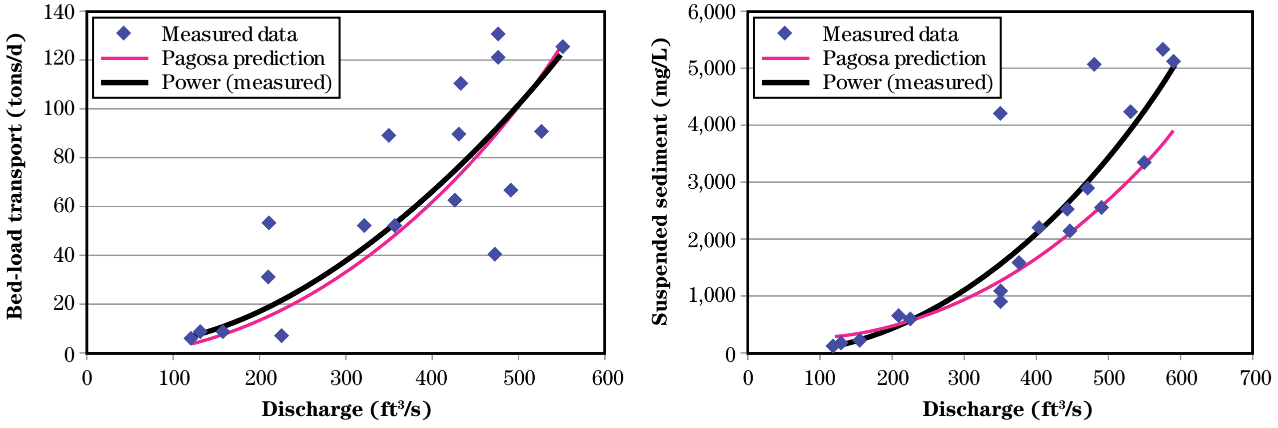
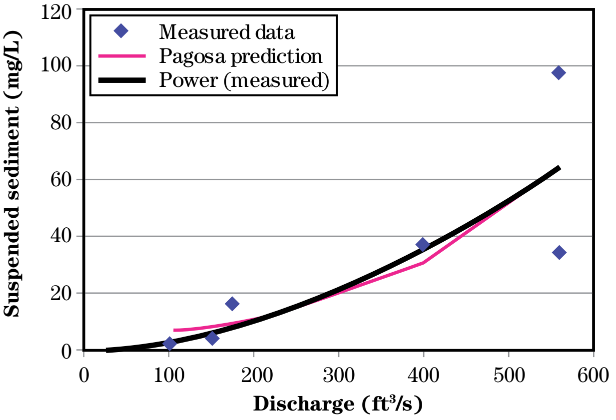
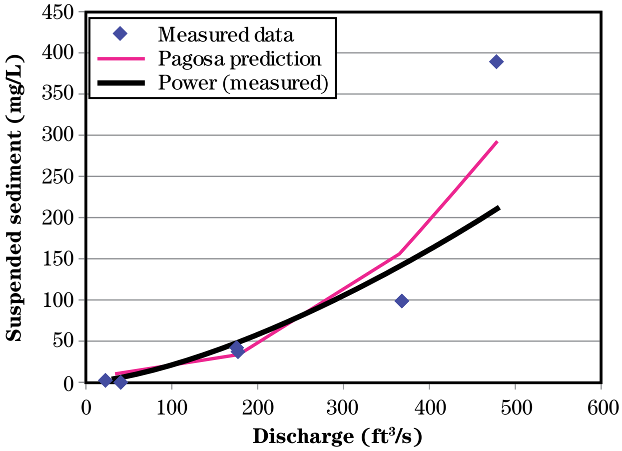


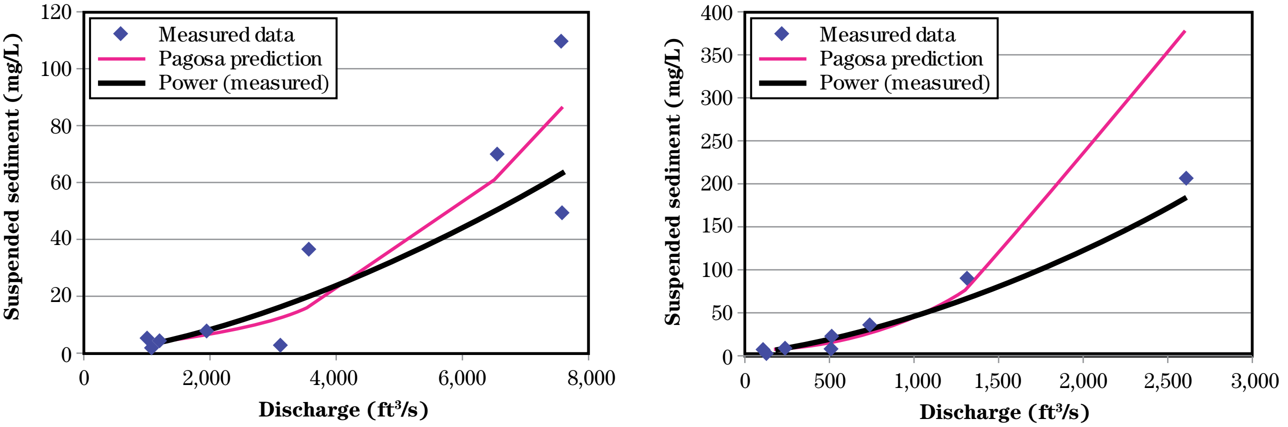
Figure 11–14 Predicted vs. measured suspended sediment data using dimensionless reference curve (data from Emmett 1975)


Warm Springs Creek near Clayton, ID 13297000

Upper Salmon Watershed 13297250

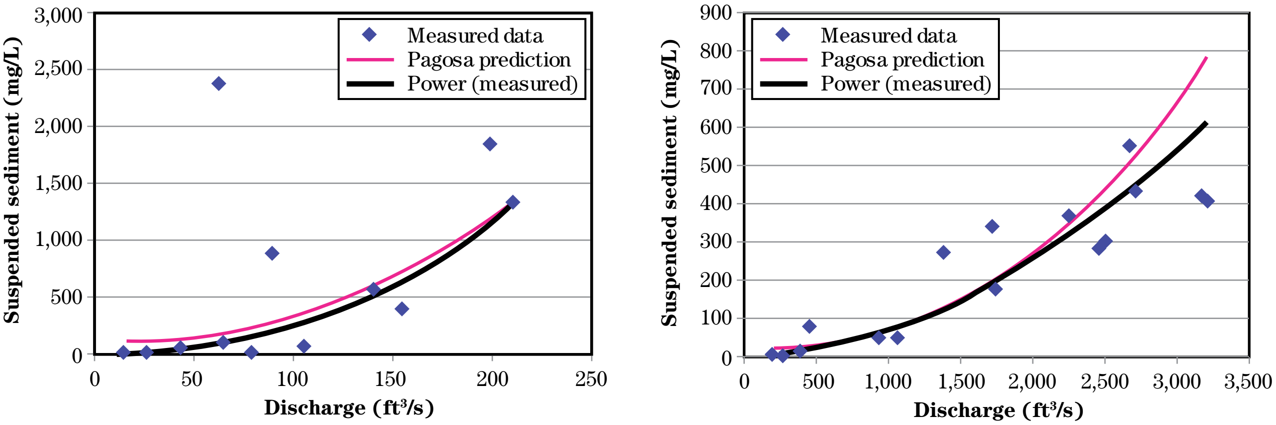

Upper Salmon Watershed 13297340

Upper Salmon Watershed 13297360

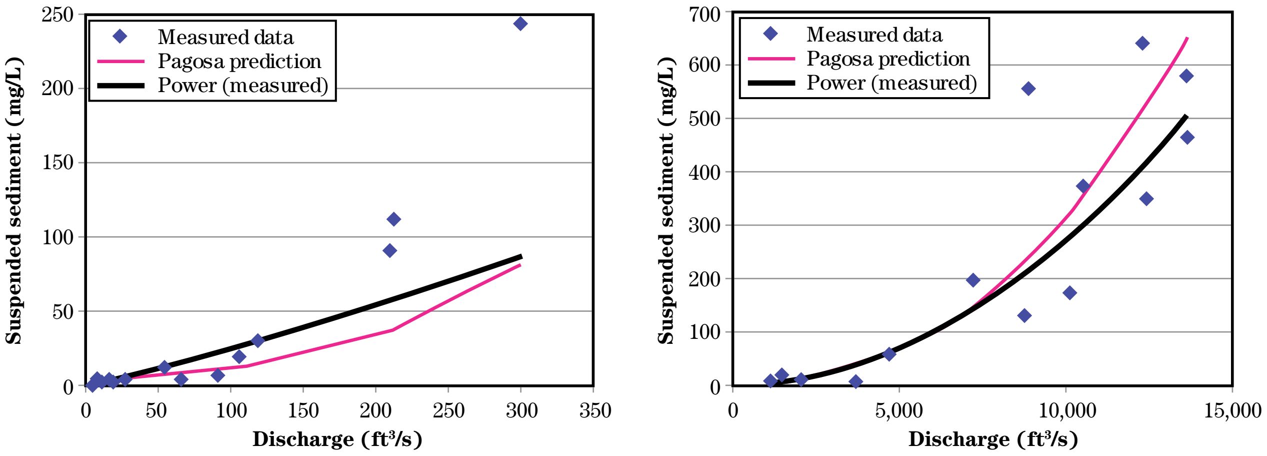

Upper Salmon Watershed 13297380

Upper Salmon Watershed 13297425

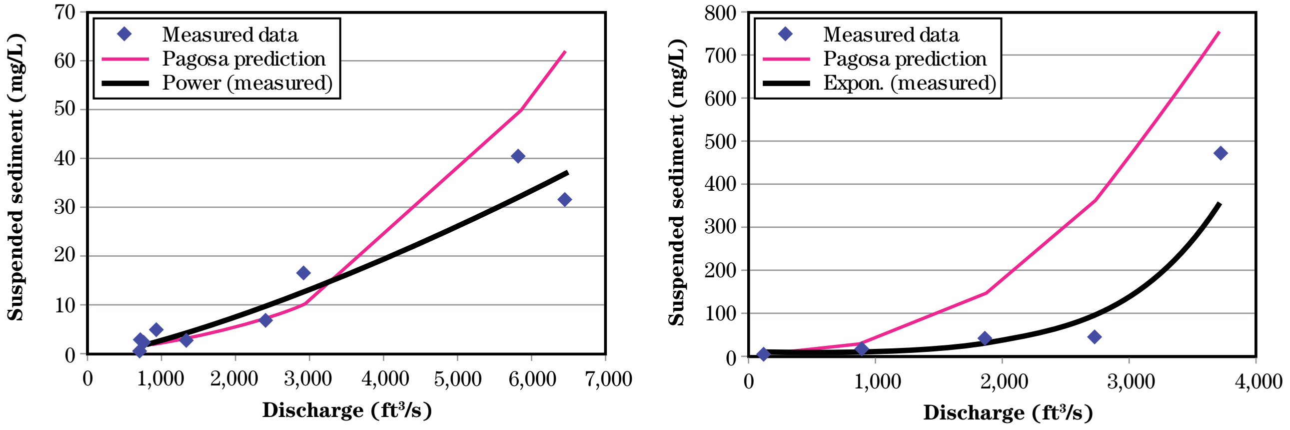
Figure 11–14 Examples of predicted vs. measured suspended sediment data using dimensionless reference curve (data from Emmett 1975)—Continued


Big Boulder Creek near Clayton, ID 13297500

East Fork Salmon River near Clayton, ID 13298000


Little Boulder Creek near Clayton, ID 13297450

Salmon River near Challis, ID 13298500


Salmon River below Yankee Fork 13296500

Yankee Fork Salmon River near Clayton, ID 1329600

charge. Regional bankfull sediment relations versus drainage area may be substituted if actual bankfull measurements are impossible to obtain, but must be extrapolated from streams of similar lithology, stream type, and stability. Examples of such relations using 1.5-year recurrence interval discharge for suspended sediment are shown in Simon, Dickerson, and Heins (2004). Dimensionless flow-duration curves are also used to produce total annual sediment yield once dimensionless ratio sediment and flow-duration curves are converted to dimensional relations. The examples of predicted sediment rating curves to observed values using a dimensionless sediment rating curve were presented in figures 11–12 to 11–14. Changes in unit stream power (eq. 11–7) are calculated to determine changes in transport rate due to change in depth, slope, and/or velocity. Dimensionless flow-duration curves are used to generate total annual sediment yield from the generated sediment rating curves and bed-load transport by unit stream power.

Streambank erosion—Streambank erosion rate (lateral erosion rate and sediment, tons/yr) is predicted as part of the river stability assessment. The influence of vegetative change, direct disturbance, and other causes of bank instability is quantitatively assessed. One of the major consequences of stream channel instability is accelerated streambank erosion and associated land loss. Fish habitat is adversely affected not only due to increased sediment supply but also by changes in pool quality, substrate materials, imbrication, and other physical habitat loss. Water temperatures are also adversely affected due to increases in width-to-depth ratio due to lateral accretion. The prediction methodology is presented in Rosgen (1996) and in Rosgen (2001d) utilizing a Bank Erodibility Hazard Index (BEHI) and Near Bank Stress (NBS) calculations.

Successional stages of channel evolution—A useful tool at this phase is the determination of various stream type scenarios and stages of channel evolution as depicted in figure 11–15. It is imperative to identify the present stage of the stream and predict the direction and consequence of change. The various stages and scenarios depicted in figure 11–15 assist the observer in this assessment. River channels undergo morphological change due to various disturbance and/or recovery (Rosgen 1996, 2001d, 2005). The assessment phase must identify current states and scenarios. For each state within a scenario, there are specific morphological, sedimentological, hydraulic, and biological relations depicted. The associated interpretations of these relations assist in river assessments.

River stability analysis—Additional stability variables are required for assessment, including the influence of large woody material, flow regime, depositional features, meander patterns, riparian vegetation, and channel stability ratings by stream type, and are summarized in the form shown in table 11–4.

Figure 11–15 Various stream type succession scenarios

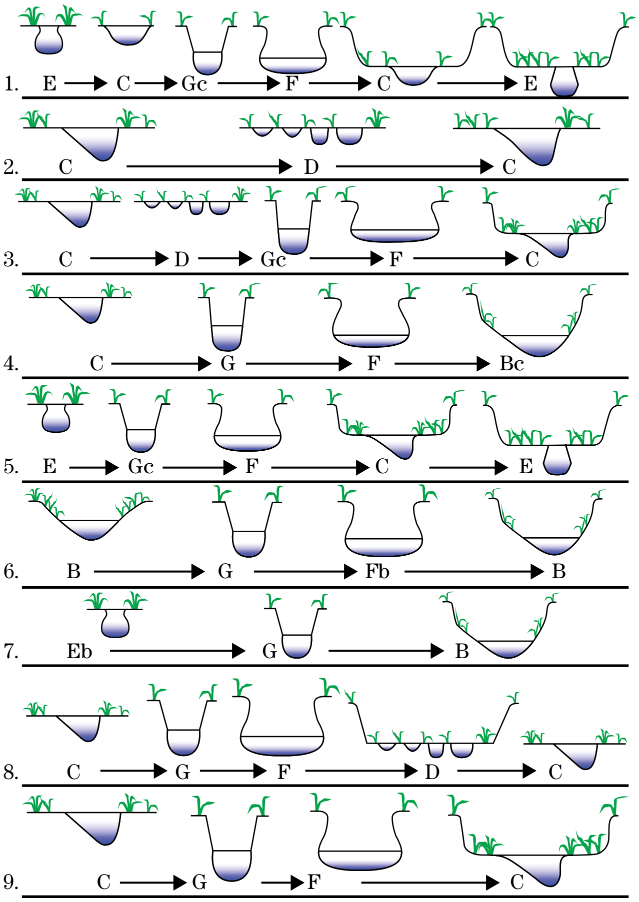


Table 11–4 Stream channel stability assessment summary form

Stream		**Stream**		**Date**		**Observers**									
Level III variables	Stream type		Flow regime		Stream size		Stream order		Meander pattern		Depositional pattern		Debris/channel blockage		
	Riparian vegetation	Current composition/density	Potential composition/density	Altered channel state (dimension, pattern, profile, materials)											
Channel dimension	Mean bankfull depth (ft)		Mean bankfull width (ft)		Cross section area (ft^2)		Remarks								
Channel dimension relationships	Width/depth ratio (W/D)		Reference condition width/depth ratio (W/D_{ref})		(W/D)/(W/D_{ref})		Circle	Stable	Moderately unstable	Unstable	Highly unstable				
Channel pattern	Mean (range)	MWR		Lm/W_{bkf}		Rc/W_{bkf}		Sinuosity							
River profile and bed features	Circle		Riffle/pool	Step/pool	Plane bed	Convergence/divergence	Dune/antidunes/smooth bed								
	Max bankfull depth (ft)	Riffle	Pool	Depth ratio (max/mean)	Riffle	Pool	Pool to pool spacing		Slope						
									Valley		Average bankfull				
Channel stability rating	Pfankuch rating		Pfankuch adjusted by stream type (use potential/reference reach)												
Bank erosion summary	Length of reach studied (ft)		Annual streambank erosion rate				Curved used	Remarks							
				(ton/yr)		ton/yr/ft									
Degree of confinement	Reference MWR		MWR/ Reference MWR		Unconfined (1.0–0.80)	Moderately confined (0.79–0.30)	Confined (0.29–0.1)	Severely confined (<0.1)							
Lateral stability	Circle		Stable		Moderately unstable		Unstable	Highly unstable (accelerated lateral erosion)							
Sediment capacity	Sufficient capacity		Insufficient capacity												
Stream channel scour/deposition	Largest particle-bar sample (mm)		τ_{ci}		Existing depth$_{bkf}$		Required depth$_{bkf}$		Existing slope$_{bkf}$		Required slope$_{bkf}$				
Degree of incision	Bank height ratio		Stable (no incision)	Slightly incised	Moderately incised	Deeply incised	Width of flood prone area (ft)		Entrenchment ratio						
Channel enlargement	Circle		Stable		Slight		Moderate		Extensive						
Stream successional stage		→		→		→		→		→		Existing stream state (type)		Potential stream state (type)	
Vertical stability	Circle		Stable		Aggradation		Degradation								
Sediment supply (channel source)	Circle		Very high	High	Moderate	Low	Score		Remarks/causes						

Base-level change—A key part of channel stability analysis. Degree of channel incision (lowering of local base level) is determined by the ratio of the lowest bank height divided by maximum bankfull depth, called the bank height ratio. A stream may not be entrenched (vertically constrained), but may be partially incised, leading to entrenchment. A grade-control structure requirement is often associated with partially incised channels (Rosgen 1997a).

Direct disturbance and riparian vegetation—The direct disturbance of stream channels must be offset by correcting dimension, pattern, profile, and often channel materials. Levees adjacent to both banks should be set back allowing room for a flood plain. Riparian vegetation change is not only a major cause of instability and loss of function, but is a key solution in restoration and natural channel design. Riparian vegetation reestablishment should contain the correct overstory and understory species to be compatible for a self-sustaining, long-term solution.

Biological assessments—Biological assessments that describe fish species, food chains, diversity with broad categories of ecoregions, and stream types (habitat units) are currently collected with the assessment level for identifying biological potential. Limiting factor analysis provides information that identifies specific problems that may be corrected by changed management and/or restoration.

It is readily apparent that this procedure involves extensive field observations and an extensive data base followed by a thorough and detailed analysis. All of this must be completed prior to restoration planning, as it forms much of the foundation for what follows.

It is important to understand the various causes of instability responsible for loss of physical and biological function and corresponding loss of value. Recommendations that follow are critically linked to land uses, disturbance regime, and other problem sources. The flowchart (fig. 11–10) depicts the assessment criteria of channel stability.

(d) Phase IV—Passive recommendations for restoration

A first priority in restoration is to seek a natural recovery solution based on changes in the variables causing the instability and/or loss of physical and biological function. Changes in land use management can influence riparian vegetation composition, density and vigor, flow modifications (diversions, storage, and reservoir release schedule modifications based on the operational hydrology), flood control measures, road closures/stabilization, hillslope erosional processes, and other process influences of river stability. Often, a change in management strategies can be very effective in securing stability and function. This often has to be determined based on the recovery potential of various stream types and the short- and long-term goals associated with the stated objectives (including costs). The alternative of self-stabilization is always a key consideration in any stability assessment. The time-trend aerial photography from phase III may help to provide insight into stream recovery potential following disturbance.

Successional stages of channel adjustment (fig. 11–15) can also assist at looking at natural recovery potential. It is very important to ensure that objectives are met through effectiveness monitoring required to provide the documentation on the nature, magnitude, rate, and consequences of natural recovery. If natural recovery potential is poor and/or does not meet specific objectives, phase V would be appropriate (Rosgen geomorphic channel design methodology).

(e) Phase V—The stream restoration and natural channel design using the Rosgen geomorphic channel design methodology

Phase V involves combining the results of the previous phases. A good design can only follow a good assessment. It is preferred not to patch symptoms, but rather provide solutions to restoration that will offset the cause of the problem and allow for the river to be self-maintaining. The practitioner must be very familiar with the processes involved in hydrology, hydraulics, sedimentology, geomorphology, soil science, aquatic habitat, and riparian vegetation. Due to the inherent complexity, it is usually necessary to obtain technical assistance for assessment and design, depending on the practitioner's experience and training.

The conceptual, generalized flowchart shown in figure 11–16 depicts the general sequence of the mixed use of analog, empirical, and analytical methods in this design procedure. The early sequence is required to determine the existing valley type and potential stream type of the stable form. The proposed channel type must be converted to a dimension, pattern, and profile to initially test whether the hydraulic and sediment relations associated with the watershed are compatible prior to advancing through all of the procedural steps.

The watershed and river assessment that predicts the consequence of streamflow, sediment supply, and channel change is reflected in figure 11–17. The procedure is incorporated into the following sequential analysis steps.

Figure 11–16 Generalized flowchart representing Rosgen geomorphic channel design utilizing analog, analytical, and empirical methodologies

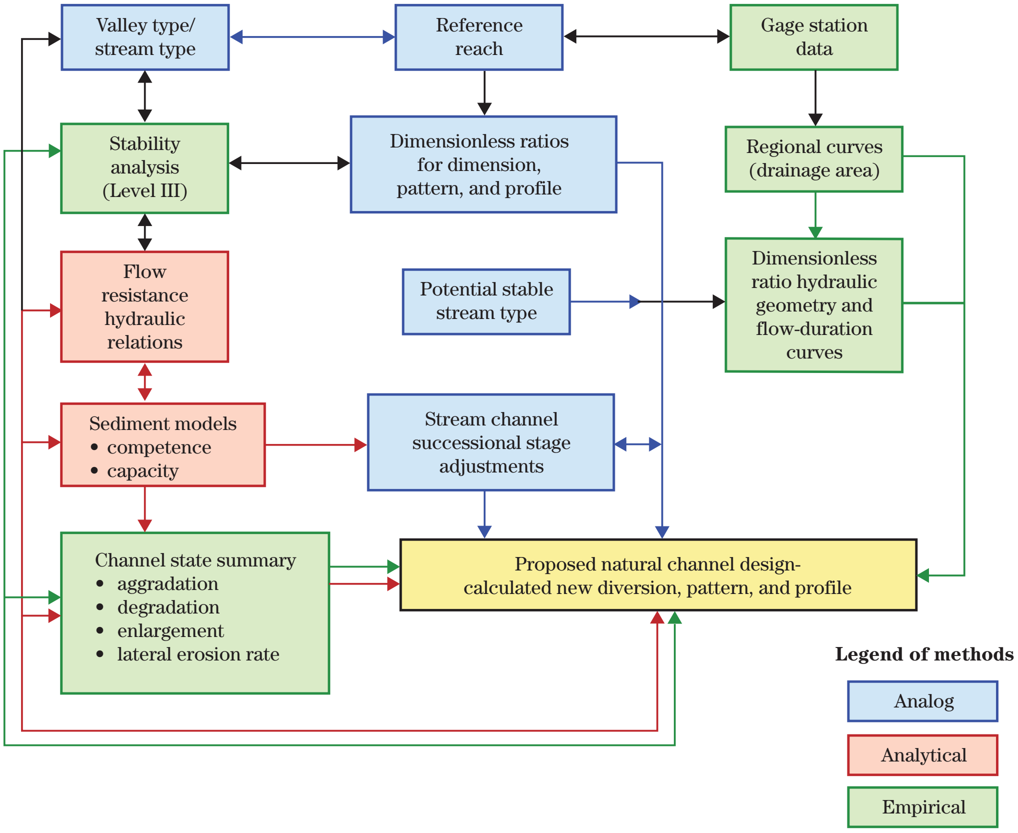
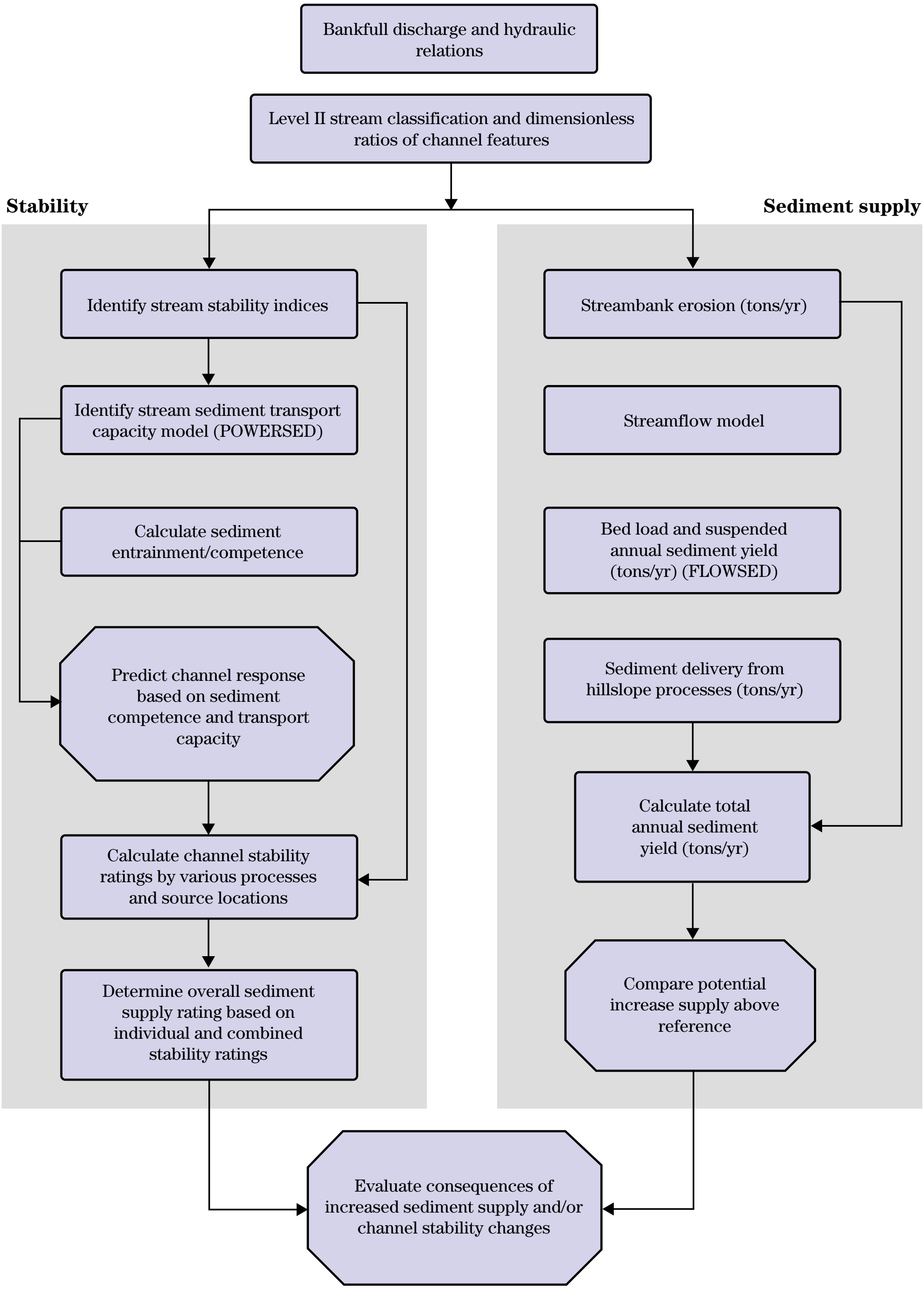


Figure 11–17 Flowchart for determining sediment supply and stability consequences for river assessment



The procedural sequence utilized in the Rosgen geomorphic channel design methodology is shown in the following operational steps:

Step 1 Obtain and/or verify regional curves (bankfull discharge, cross-sectional area, width and depth versus drainage area). The regional curves must be located in the same hydro-physiographic province as that of the restoration reach.

Step 2 Obtain hydraulic geometry (USGS 9–207 forms, summary of current meter measurements) from the gage station stratified by stream type and bed features.

Step 3 Create dimensionless hydraulic geometry by dividing all values by the bankfull value.

Step 4 Obtain flow-duration curves from the gage station for a representative hydro-physiographic region.

Step 5 Create dimensionless flow-duration curve by dividing all flow values by the bankfull discharge.

Step 6 Identify the valley type for the restoration reach(s). Identify stream type(s) of the restoration reach.

Step 7 Obtain corresponding reference reach data for the same valley and stream type. The reference reach is not required to be located within the same watershed or hydro-physiographic province. Examples of the dimensionless ratio and other reference reach data by stream type/valley type are presented in table 11–3.

Step 8 Complete and/or review the stability examination data for the restoration reach (fig. 11–10 and table 11–4). Evaluate variables/states that represent instability relations (width, depth, and slope values that do not meet sediment transport requirements).

Step 9 Select appropriate scenario of successional stages of channel adjustment for channel evolution scenario (fig. 11–15). This determines the stream type of the current state and the potential state to match the valley type. (This step is completed in the stability phase, phase III).

Step 10 Obtain drainage area (mi^2) for the restoration reach.

Step 11 Obtain bankfull cross-sectional area (A_{bkf}) from the regional curves (step 1).

Step 12 Obtain reference reach width-to-depth ratio associated with the stable design stream type commensurate with the valley type (step 7).

Step 13 Calculate design bankfull channel width of riffle reach:

$$W_{bkf} = \left[\left(\frac{W_{bkf}}{d_{bkf}}\right)_{ref} A_{bkf}\right]^{\frac{1}{2}} \qquad \text{(eq. 11– 8)}$$

Step 14 Calculate mean riffle depth:

$$d_{bkf} = \frac{A_{bkf}}{W_{bkf}} \quad \text{or} \quad \left[\frac{W_{bkf}}{\left(\frac{W_{bkf}}{d_{bkf}}\right)_{ref}}\right] \qquad \text{(eq. 11–9)}$$

Step 15 Calculate meander wavelength (Lm) for average and range of values. Obtain meander length ratio average and range of values, where:

$$MLR = \left[\left(\frac{Lm}{W_{bkf}}\right)_{ref}\right] \text{ from reference reach data (step 7, table 11–3).}$$

$$Lm = \left[\left(MLR_{ref}\right)\right] W_{bkf} \text{ (from step 13)} \qquad \text{(eq. 11–10)}$$

Step 16 Calculate belt width (W_{blt}) for average and range of values from meander width ratios (MWR).

$$MWR = \left[\left(\frac{W_{blt}}{W_{bkf}}\right)_{ref}\right] \quad \text{(step 7, table 11–3).}$$

$$W_{blt} = [(MWR)_{ref}]\, W_{bkf} \qquad \text{(eq. 11–11)}$$

Step 17 Calculate radius of curvature (Rc) for average and a range of values from ratio of radius of curvature ratio. (step 7, table 11–3).

$$Rc = \left[\left(\frac{Rc}{W_{bkf}}\right)_{ref}\right] W_{bkf} \qquad \text{(eq. 11–12)}$$

Step 18 Obtain an aerial photo depicting vegetation, channel features and terrain character. Layout the range of values for meander length (Lm), belt width (W_{blt}) and radius of curvature (Rc) on aerial photo or detailed topographic map. Adjust pattern to utilize terrain features and existing vegetation where possible within the range of the pattern variables. Once the preliminary layout is complete, measure stream length (SL) of the proposed channel. Measure valley length (VL) by following the fall line of the valley, rather than straight line segments between meanders.

Step 19 Calculate sinuosity (k) of the proposed channel where:

$$k = \frac{SL}{VL} \qquad \text{(eq. 11–13)}$$

Step 20 Calculate valley slope (S_{val}). Measure the water surface elevation difference (DE) between the same bed features along the fall line of the valley using valley length (VL), where:

$$S_{val} = \frac{DE}{VL} \qquad \text{(eq. 11–14)}$$

Step 21 Calculate proposed channel average slope (S):

$$S = \frac{S_{val}}{k} \qquad \text{(eq. 11–15)}$$

Step 22 Calculate bankfull channel velocity (u_{bkf}) and check design bankfull discharge with velocity, cross-sectional area (continuity) regional curves:

$$uA = Q \qquad \text{(eq. 11–16)}$$

$$\frac{Q}{A} = u \quad \text{Compare to regional curve (step 1)} \qquad \text{(eq. 11–17)}$$

Steps 23 through 26 Predict stream competence (entrainment) by utilizing particle entrainment computations. A general flowchart depicting the procedural steps is shown in figure 11–18.

First, obtain bar sample gradation from field sampling and sieving procedure upstream of the proposed restoration (Rosgen 1996). A field procedure for bar sampling, pavement/subpavement sample and wet-sieving onsite is presented in tables 11–5 and 11–6. The user is advised to review additional details of particle size sampling by Bunte and Abt (2001). Sediment sampling is also addressed in NEH654 TS13A. Bar samples are field-sieved and recorded in the entrainment worksheet (table 11–7).

The sediment competence computations that determine bed stability (aggradation/degradation) are completed and summarized in table 11–8. This method has shown consistency when actual bed-load/scour chain data are compared to predicted values. Use the value of the largest particle in the bar sample (or subpavement sample), D_{max} in millimeters, and the revised Shields diagram to predict the shear stress required to initiate movement of the largest particle in the bar and/or subpavement (fig. 11–11).

If the protrusion ratios described in equations 11–3 or 11–4 are outside the ranges indicated in table 11–8, the user should use the shear stress equation (eq. 11–2) and apply it with a revised Shields relation using Colorado data or local data if available (fig. 11–11).

$$\tau^* = 0.0834\left(\frac{D_{50}}{\hat{D}_{50}}\right)^{-0.872} \qquad \text{(eq. 11–3)}$$

$$\tau^* = 0.0384\left(\frac{D_{max}}{D_{50}}\right)^{-0.887} \qquad \text{(eq. 11–4)}$$

$$\tau = \gamma RS \qquad \text{(eq. 11–2)}$$

A grain size corresponding with shear stress is selected to determine what sizes the river can potentially move. Based on measured bed-load sizes, in a heterogeneous mixture of bed material comprised of a mixture of sand to gravel and cobble, the previously published Shields relation generally underestimates particle sizes of heterogeneous bed material in the shear stress range of 0.05 pounds per square foot to 1.5 pounds per square foot. The Shields relationship is appropriately used for entrainment sizes below and/or above this value range. Without this adjustment, most computations underestimate the largest sizes of heterogeneous bed material moved during bankfull discharge. The measured data in figure 11–11 indicate the magnitude of the underestimate of particle size entrainment from comparing published relations to measured values.

To determine the ability of the existing stream reach to transport the largest clast size of the bed-load sediment, it is necessary to calculate the bankfull dimensionless shear stress (τ^*). This calculation determines the depth and slope necessary to mobilize and transport the largest particle made available to the channel. The dimensionless shear stress at bankfull stage is used in the entrainment

Figure 11–18 Generalized flowchart depicting procedural steps for sediment competence calculations

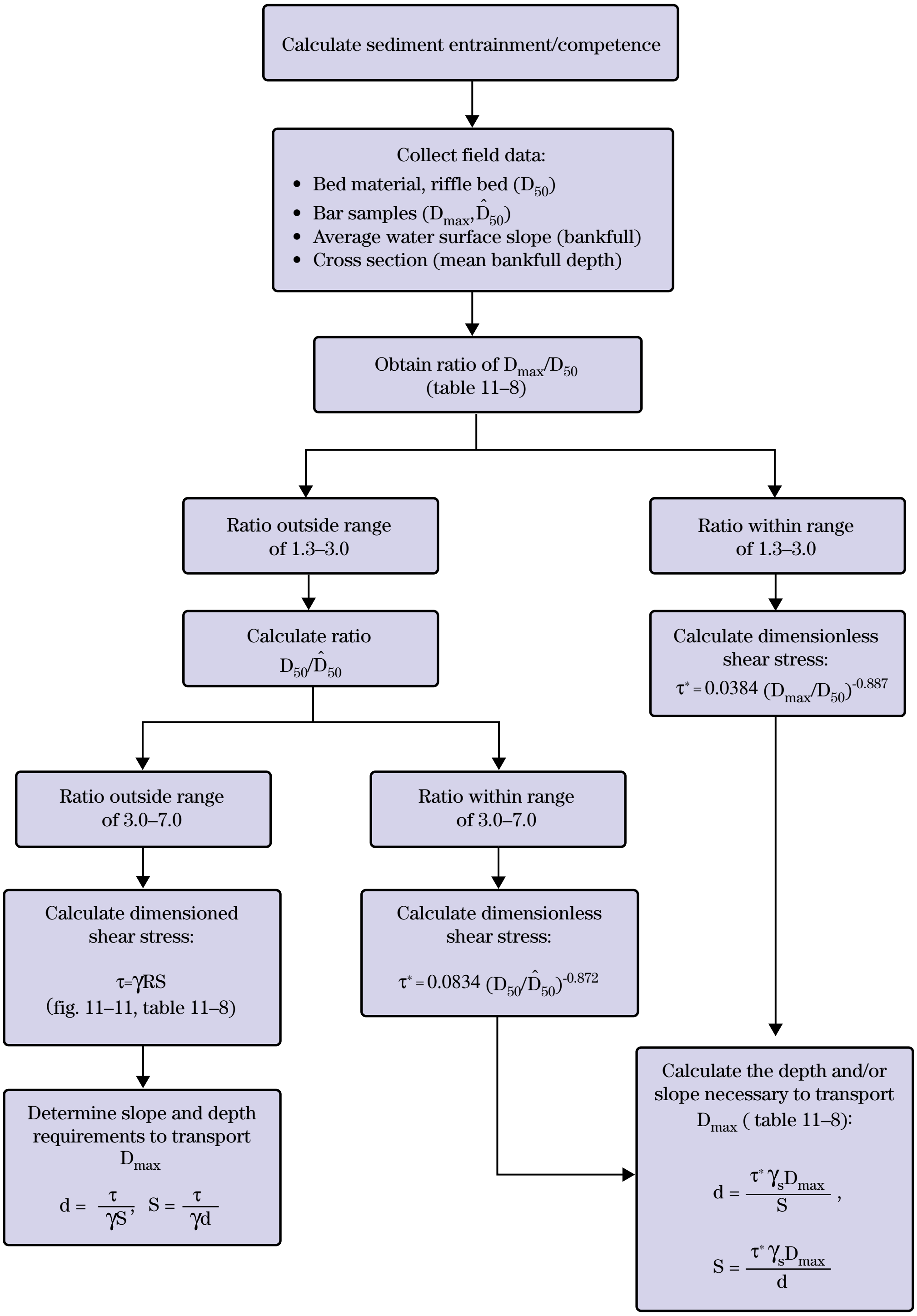


Table 11–5 Field procedure for bar samples*

Bar sample field procedure
Collect sediment core samples from point bars along the project and reference reaches. At least one sample should be collected from each reach associated with a change in stream type. Conduct a critical shear stress analysis using the following procedures:
Locate a sampling point on the downstream a third of a meander bend. The sample location on the point bar is halfway between the thalweg elevation (the point of maximum depth) and the bankfull stage elevation. Scan the point bar in this area to determine the sampling location by observing the maximum particles on the surface of the bar.
Place a 5-gallon bottomless bucket at the sampling location over one of the representative larger particles that are observed on the lower third of the point bar. Remove the two largest particles from the surface covered by the bottomless bucket. Measure the intermediate axis for each particle and individually weigh the particles. Record these values. The largest particle obtained is D_{max}, the largest particle from the bar sample. Push the bottomless bucket into the bar material. Excavate the materials from the bottomless bucket to a depth that is equal to twice the intermediate axis width of the largest surface particle. Place these materials in a bucket or bag for sieving and weighing.
For fine bar materials, follow the directions above, except that when the bottomless bucket is pushed into the bar material, excavate materials from the bucket to a depth of 4 to 6 inches. Place these materials in a bucket or bag for sieving and weighing.
Wet-sieve the collected bar materials using water and a standard sieve set with a 2-millimeter screen size for the bottom sieve. Weigh the bucket with sand after draining off as much water as possible. Subtract the tare weight of the bucket to obtain the net weight of the sand.
Weigh the sieved materials and record weights (less tare weight) by size class. Be sure to include the intermediate axis measurements and individual weights of the two largest particles that were collected.
Determine a material size class distribution for all of the collected materials. The data represents the range of channel materials subject to movement or transport as bed-load sediment materials at bankfull discharge.
Plot data; determine size-class indices, D_{16}, D_{35}, D_{50}, D_{84}, D_{95}. The D_{100} should represent the actual intermediate axis width and weight (not the tray size) when plotted. The largest size measured will be plotted at the D_{100} point (Note: $D_{100} = D_{max}$). The intermediate axis measurement of the second largest particle will be the top end of the catch range for the last sieve that retains material (use the record data in the entrainment worksheet, table 11–7).
Survey a typical cross section of a riffle reach at a location where the stream is free to adjust its boundaries. Plot the survey data. Determine the hydraulic radius of the cross section.
Conduct a Wolman Pebble Count (100 count in riffle) of the bed material in the coarsest portion of the wetted riffle area (active channel). The pebble count should be conducted at multiple transects that represent the riffle. Plot data and determine the size-class indices.

*Sediment sampling is also addressed in NEH654 TS13A.

Table 11–6 Field procedure for pavement/sub-pavement samples

Pavement/subpavement sample field procedure (alternate procedures for obtaining a pavement/sub-pavement sample if you are unable to collect a bar sample)
Locate a sampling point in the same riffle where cross-sectional survey was conducted. The sampling point should be to the left or right of the thalweg, not in the thalweg, in a coarse-grain size portion of the riffle.
Push a 5-gallon bottomless bucket into the riffle at the sampling location to cut off the streamflow. The diameter of the bucket (sample size) should be at least twice the diameter of the largest rock on the bed of the riffle.
Remove the pavement material (surface layer only) by removing the smallest to the coarsest particles. Measure the intermediate axis and weight of the largest and second largest particles. Record these values. Place the remaining pavement materials into a bucket or bag for sieving and weighing.
Remove the sub-pavement material to a depth that is equal to twice the intermediate axis width of the largest particle in the pavement layer, or at least 150-millimeter depth. Caution: if a coarser bed material persists under the sub-pavement, it generally is material remnant of the previous bed. Stop at this condition and do not excavate deeper, even if the depth is not at twice the maximum pavement particle diameter. This residual layer is generally not associated with the size distribution of bed load transported at the bankfull stage. Collect the sub-pavement materials into a separate bucket or a bag. Measure the intermediate axis and weight of the two largest particles in the sub-pavement sample. Record these values. Sieve and weigh the remaining sub-pavement materials. The sub-pavement sample is the equivalent of the bar sample; therefore, use the largest particle from the sub-pavement sample in lieu of the largest particle from a bar sample in the entrainment calculations. Note: If the largest particle collected from the sub-pavement is larger than the pavement layer, the largest rock should be discarded from the sub-pavement layer. Drop back to the next largest particle size to determine the largest particle size to be used in the entrainment calculation.
Wet-sieve the collected pavement materials and then the subpavement materials using water and a standard sieve set with a 2-millimeter screen size for the bottom sieve. Weigh the bucket with sand after draining off as much water as possible. Subtract the tare weight of the bucket to obtain the net weight of the sand.
Weigh the sieved materials and record weights (less tare weight) by size class for both the pavement and sub-pavement samples. Be sure to include the mean intermediate axis width and individual net weights of the two largest particles that were collected (table 11–7).
Determine a material size-class distribution for the materials. The subpavement data represent the range of channel materials subject to movement or transport as bed-load sediment materials at bankfull discharge.
Plot data; determine size-class indices, D_{16}, D_{35}, D_{50}, D_{84}, D_{95}. The D_{100}, should represent the actual intermediate axis width and weight (not the tray size) when plotted. The largest size measured will be plotted at the D_{100} point. (Note: $D_{100} = D_{max}$). The intermediate axis measurement of the second largest particle will be the top end of the catch range for the last sieve that retains material.
The pavement material size class distribution may be used to determine the D_{50} of the riffle bed instead of doing the 100 count in the riffle bed.
Determine the average bankfull slope (approximated by the average water surface slope) for the study reach from the longitudinal profile.
Calculate the bankfull dimensionless shear stress required to mobilize and transport the largest particle from the bar sample (or sub-pavement sample). Use the equations and record the data in the entrainment worksheet (table 11–8).

Table 11–7 Bar sample data collection and sieve analysis form

Point / Side BAR-BULK MATERIALS SAMPLE DATA: Size Distribution Analysis		Party:
Location:	Date:	Notes:

SUBSAMPLES	Sieve SIZE		Sieve SIZE		Sieve SIZE		Sieve SIZE		Sieve SIZE		Sieve SIZE		Sieve SIZE		Sieve SIZE		Sieve SIZE	
	Tare Weight		Tare Weight		Tare Weight		Tare Weight		Tare Weight		Tare Weight		Tare Weight		Tare Weight		Tare Weight	
	Sample Weights		Sample Weights		Sample Weights		Sample Weights		Sample Weights		Sample Weights		Sample Weights		Sample Weights		Sample Weights	
	Total	Net	Total	Net	Total	Net	Total	Net	Total	Net	Total	Net	Total	Net	Total	Net	Total	Net
1																		
2																		
3																		
4																		
5																		
6																		
7																		
8																		
9																		
10																		
11																		
12																		
13																		
14																		
15																		
Net Wt. Total																		
% Grand Tot.																		
Accum. % =<																		

SURFACE
MATERIALS
DATA
(Two Largest Particles)

No.	Dia.	WT.
1		
2		

Bucket
+ Materials
Weight___________

Bucket
Tare
Weight___________

Materials
Weight___________
(Materials less than:
___________mm.)

Be Sure to Add Separate Material Weights to Grand Total

GRAND TOTAL
SAMPLE WEIGHT

NOTES

Table 11–8 Sediment competence calculation form to assess bed stability (steps 23–26)

Stream:			Reach:		
Observers:				Date:	
Enter required information					
	D_{50}	Riffle bed material D_{50} (mm)			
	$\hat{D}_{50}$	Bar sample D_{50} (mm)			
	D_{max}	Largest particle from bar sample (ft)		**(mm)**	304.8 mm/ft
	S	Existing bankfull water surface slope (ft/ft)			
	d	Existing bankfull mean depth (ft)			
1.65	γ_s	Submerged specific weight of sediment			

Select the appropriate equation and calculate critical dimensionless shear stress				
	$D_{50} / \hat{D}_{50}$	Range: 3 – 7	Use equation 1:	$\tau^* = 0.0834\left(\frac{D_{50}}{\hat{D}_{50}}\right)^{-0.872}$
	D_{max} / D_{50}	Range: 1.3 – 3.0	Use equation 2:	$\tau^* = 0.0384\left(\frac{D_{max}}{D_{50}}\right)^{-0.887}$
	τ^*	Bankfull dimensionless shear stress	Equation used:	

Calculate bankfull mean depth required for entrainment of largest particle in bar sample			
	d	Required bankfull mean depth (ft)	$d = \frac{\tau^* \gamma_s D_{max}}{S}$
	Circle:	Stable Aggrading Degrading	

Calculate bankfull water surface slope required for entrainment of largest particle in bar sample			
	S	Required bankfull water surface slope (ft/ft)	$s = \frac{\tau^* \gamma_s D_{max}}{d}$
	Circle:	Stable Aggrading Degrading	

Sediment competence using dimensional shear stress	
	Bankfull shear stress $\tau = \gamma d S$ (lb/ft^2) (substitute hydraulic radius, R, with mean depth, d)
	Moveable particle size (mm) at bankfull shear stress **(**fig. 11-11**)**
	Predicted shear stress required to initiate movement of D_{max} (mm) (figure 11-11)
	Predicted mean depth required to initiate movement of D_{max} (mm) $d = \frac{\tau}{\gamma S}$
	Predicted slope required to initiate movement of D_{max} (mm) $S = \frac{\tau}{\gamma d}$

analysis for both the reference reach and project reach. This analysis of the reference, stable condition is compared to the potentially disturbed reach. To maintain stability, a stream must be competent to transport the largest size of sediment and have the capacity to transport the load (volume) on an annual basis. These calculations provide a prediction of sediment competence as required in steps 23 through 26.

Step 27 Compute sediment transport capacity. Following this analysis, the depth and/or slope may need to be adjusted by recalculating steps 14 through 27.

FLOWSED and POWERSED are sediment supply/sediment transport models that predict the following:

- total annual suspended sediment yield
- total annual suspended sand sediment yield
- total annual bed-load sediment yield
- potential aggradation and/or degradation
- flow-related annual sediment yield due to changes in streamflow magnitude and duration

The models are based on the use of dimensionless reference sediment rating and flow-duration curves. The normalization parameters include:

- bankfull discharge
- bankfull stage bed load
- suspended and suspended sand sediment

The appropriate dimensionless sediment curves are selected for representative stream types and stability ratings. The dimensionless flow-duration curves are developed from representative hydrophysiographic province data from USGS stream gage data.

The FLOWSED model reflects sediment supply and generates the total annual sediment yield for both suspended and bed load. Changes in flow are also reflected in flow-duration curves and corresponding sediment yield. To determine annual sediment yield, near-bankfull stage values must be field measured to convert dimensionless sediment and flow-duration curves to actual values.

The POWERSED model compares sediment transport capacity from a stable, reference condition by predicting transport rate change due to channel hydraulics. The hydraulics reflect potential change in morphological variables such as channel width, depth, and slope. The corresponding changes in flow resistance are used to predict velocity, shear stress, and unit stream power (velocity multiplied by shear stress). Sediment rating curves from the FLOWSED model are converted from discharge to unit stream power for a wide range of flows. Revised values of annual sediment transport can then be compared to the reference condition from the subsequent change in the hydraulic geometry of the stream channel and corresponding response in sediment transport. Any flow modifications can also be simulated by revised flow-duration curves.

Detailed descriptions and model tests are provided for FLOWSED/POWERSED in Rosgen (2006). This analysis is complicated and detailed. However, it can be computed by spreadsheet or commercially available computer programs (RIVERMorph® 4.0). The basis of the calculations and model descriptions, however, are described to better understand how the models work. Table 11–9 lists the data required to run the FLOWSED and POWERSED models. With these data, the user can generate average annual sediment yields (tons/yr).

Table 11–9 Data required to run the FLOWSED and POWERSED supply/sediment transport models

Data requirements for FLOWSED/POWERSED
• Background reference data (flow and sediment) – Dimensionless suspended sediment rating curves by stream type or stability – Dimensionless bed-load rating curves by stream type or stability – Dimensionless flow duration (from local or representative hydro-physiographic province) – Momentary maximum bankfull discharge – Mean daily bankfull discharge (the mean daily discharge the day bankfull occurs at a gage station) – Flow-duration curves indicating change in flow regime (increase and/or decrease)
• Field measured values (for both reference and impaired condition) – Cross section – Longitudinal profile – Pebble count on active riffle bed to obtain D_{50} and D_{84} of bed material – Stream classification (level II) – Pfankuch channel stability rating – Measured bankfull discharge (ft^3/s) – Measured suspended sediment (mg/L) – Measured suspended sand sediment (mg/L) – Measured bed-load sediment (kg/s) (Helley-Smith bed-load sampler)

FLOWSED

The FLOWSED model is graphically depicted in figures 11–19 and 11–20. The procedure in table 11–10 and accompanying worksheet depicted in table 11–11 provide a more detailed understanding of the model. The following provides insight into the basis of the model.

Predict runoff response—Several applicable models for runoff exist, including TR–55, WRENSS (EPA 1980), the unit hydrograph approach (U.S. Army Corps of Engineers (USACE) 1998b), and others (EPA 1980; Troendle, Swanson, and Nankervis 2005). This step also considers operational hydrology from reservoirs, diversions, and other flow modifications that influence the magnitude, duration, and timing of streamflow. The input variables for most models are precipitation data, a vegetation alteration map by aspect and elevation, drainage area computations, percent of drainage area in impervious condition, and similar data specified based on the specific model being selected. The output from these models needs to be in the form of flow-duration curves. Flow-duration curves must represent reference conditions (full hydrologic utilization or recovery) and existing departures from reference. Because few stream gages are located on smaller watersheds, dimensionless ratio procedures become essential for data extrapolation in flow models. The data are entered into the flow-duration portion of the FLOWSED worksheet (table 11–11).

Develop dimensionless flow-duration curves—If a water yield model or operational hydrology data with actual flow-duration curve data are not available, it will be necessary to utilize dimensionless flow-duration curves. This information is obtained from gage station data and made dimensionless by dividing the mean daily discharge data by bankfull discharge. Bankfull discharge data are divided into all of the ranges of mean daily discharge and then plotted; see figures 11–9 and 11–21 as an example of the application for Weminuche Creek. The user must develop dimensionless flow-duration curves from gaging stations that represent a hydro-physiographic region similar to the impaired stream being assessed. If the user is applying these relations to a stormflow-generated hydrograph, rather than snowmelt (as in the case of Weminuche Creek), the following changes are recommended:

- Convert bankfull discharge (momentary maximum discharge in ft^3/s) to mean daily bankfull. This is accomplished by obtaining the mean daily discharge on the day during which bankfull discharge occurs. This ratio of mean daily discharge divided by momentary maximum discharge is used to develop the dimensionless flow-duration curves for a stormflow-dominated region. For example, if the mean daily discharge from a gage in a stormflow-dominated hydrograph was 125 cubic feet per second, but bankfull was 550 cubic feet per second, the ratio is 0.227. This ratio would be multiplied by the bankfull discharge from the regional curves or from a flood-frequency curve relation to convert bankfull discharge from a momentary maximum to a mean daily discharge value.

- Divide the mean daily discharge values by mean daily bankfull to establish the dimensionless relations similar to those in figures 11–9 and 11–21.

- Convert from dimensionless to dimensioned mean daily bankfull values. The momentary maximum value must be adjusted by the appropriate ratio, then multiplied by the appropriate ratio value in the dimensionless flow-duration curve. The dimensioned flow-duration curve data are entered into the FLOWSED worksheet (table 11–11). This would be done separately for reference or baseline conditions, and then would be compared to impaired or impacted watershed conditions to calculate annual streamflow and sediment yield.

FLOWSED—Continued

Collect bankfull discharge, suspended sediment, and bed-load sediment—This step is eventually used to convert the reference dimensionless sediment rating curves to actual values. It is very important to capture the bankfull discharge and have several data points to compute an average of the flow and sediment values due to the high spatial and temporal variability of sediment movement. Field methods and equipment used should follow the procedures outlined in book 3, chapter C2 of Field Methods for Measurement of Fluvial Sediment (USGS 1999).

It may be necessary to separate the wash load (silt/clay fraction) from the total suspended sediment load for calculation and interpretation. For channel stability purposes, the silt/clay fraction is not energy limited or hydraulically controlled, and in some settings, it can be subtracted from the suspended sediment yield data for the prediction of potential aggradation. This would not be the case, however, if there were concerns over accelerated fine sediment deposition into extremely low-gradient streams, deltas, reservoirs, lakes, marshes, or estuaries. Colloidal sediments can present problems for impaired waters; thus, wash load may need to be retained in suspended sediment analysis. Enter these measurements in the FLOWSED worksheet (table 11–11).

Obtain or establish reference dimensionless suspended and bed-load rating curves—These curves should be developed for stable reference reach sites representing stable streams. A similar relation can be stratified for poor stability or unstable streams. These reference curves are used to establish sediment rating curves for the calculation of flow-related sediment increases and to establish an annual sediment yield estimate for proportioning contributing sediment sources. The equations for these curve relations are used in the FLOWSED worksheet (table 11–11).

Convert dimensionless suspended and bed-load sediment rating curves to actual (dimensioned) values—Convert dimensionless values by multiplying the field-measured bankfull discharge and sediment values by each of the ratios appropriate for the relation selected. Dimensionless ratio bed-load and suspended rating curves are used to convert data to dimensioned rating curves (fig. 11–20). Examples of dimensioned bed-load and suspended sediment rating curves are shown in figures 11–22 and 11–23 for the Weminuche Creek in Colorado. Tests of this relation are reported in the text in figures 11–13, 11–14, and 11–15, where reference dimensionless rating curves were used to establish sediment rating curves.

If it is not possible to obtain measured bankfull discharge, suspended sediment, and bed-load sediment data to convert dimensionless sediment rating curves to actual values, regional curves can be temporarily substituted. The user must obtain drainage area in square miles to calculate bankfull discharge from a similar hydro-physiographic province. The bankfull flow is used to convert the dimensionless flow-duration to dimensioned flow duration. The bankfull discharge is also used to convert the dimensionless discharge portion of the dimensionless bed-load and suspended rating curve to actual values. The sediment data obtained from the drainage area must be derived from existing measured bankfull suspended sediment and bed-load sediment data, then converted to unit area sediment values from the corresponding drainage area. These data need to represent the same lithology, stream type and stability condition of the stream being evaluated. These data are entered in the FLOWSED worksheet (table 11–11).

An example of unit area suspended sediment data from USGS sites throughout the United States is shown in Simon, Dickerson, and Heins (2004). These measured sediment values were separated by evolutionary stages. Additional stability or stream type data may help to identify appropriate relations for extrapolation. This drainage area extrapolation procedure represents only an interim procedure until measured bankfull values can be obtained.

FLOWSED—Continued

Convert dimensionless flow duration to dimensioned flow duration—The bankfull discharge is multiplied by each of the ratios to convert dimensionless data to actual discharge values representing mean daily discharge for each percentile. An example of a dimensioned flow-duration curve using bankfull discharge to convert from the dimensionless relation (fig. 11–21) is shown in figure 11–24.

Calculate annual sediment yield for both suspended and bed-load sediment—This is accomplished by taking the dimensioned flow-duration curve and multiplying flow increments for duration of time in days by the sediment yield associated with that flow. Enter these calculations in the FLOWSED worksheet (table 11–11).

Calculate flow-related sediment yield—This calculation is accomplished using the output of the flow-duration curves showing the increase in magnitude and duration of flow. The post-treatment flows are routed through the calculation in the FLOWSED worksheet (table 11–11). The excess water calculation output from the WRENSS snowmelt model (EPA 1980) or a similar model integrates the flow with flow-duration changes. Dimensionless flow-duration curves are also converted to dimensioned values by multiplication of the bankfull discharge value. Reference conditions for watersheds in relative hydrologic recovery are compared to watersheds where streamflow has been increased or decreased by change in vegetation or by reservoirs and/or diversions.

Stormflow models, such as TR–55, need to be used to compute new bankfull values, converting dimensionless values to new dimensioned flow durations. It is important to calibrate the bankfull discharge, as the precipitation probability for a given antecedent moisture content and runoff curve number that generates the bankfull discharge needs to be determined. Any greater flow will be distributed on flood plains or a flood-prone area if the stream is not entrenched. Thus, flow-related sediment changes are determined by the use of dimensionless sediment rating curves and dimensionless flow-duration curves. Other appropriate models can also be used for this step, based on the user's familiarity with the various models selected. The output required, regardless of the model, is bankfull discharge and pre- and post-treatment flow-duration curves.

Figure 11–19 General overview of the FLOWSED model

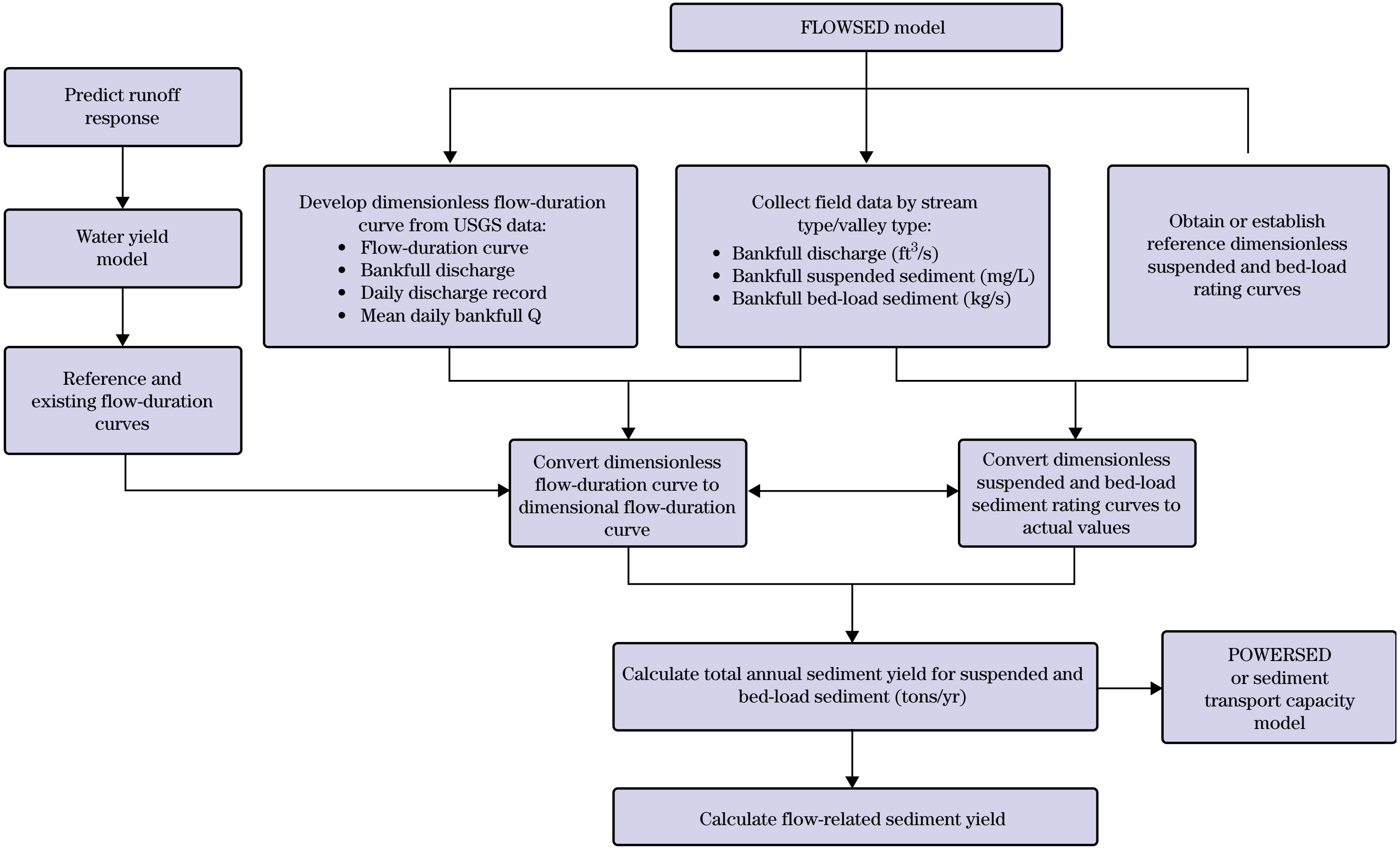


Figure 11–20 Graphical depiction of the FLOWSED model

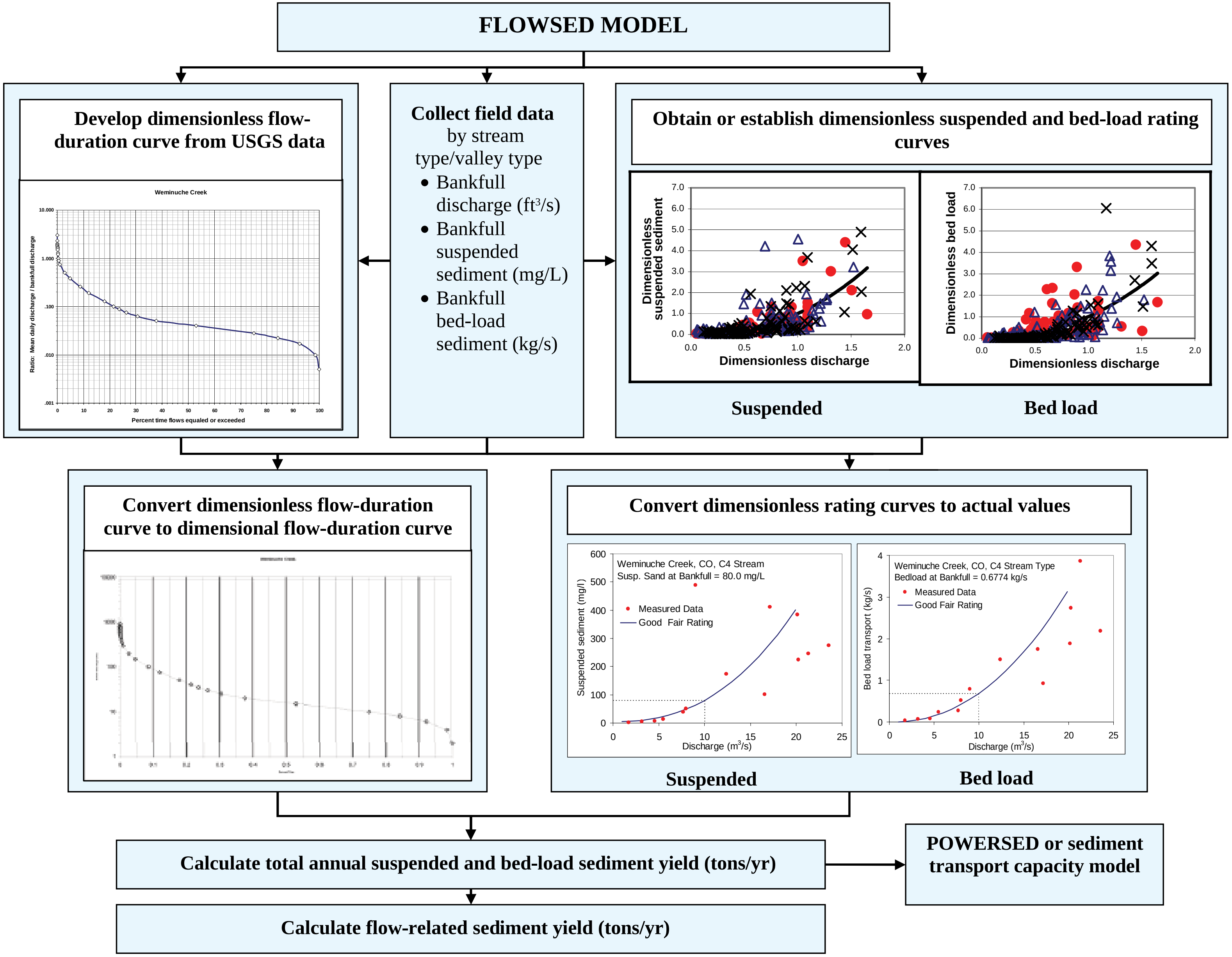


Table 11–10 FLOWSED model procedure to calculate annual bed-load and suspended sediment yield

FLOWSED procedure	
FS–1	Measure stream cross section (on riffle), profile, pattern, and materials.
FS–2	Measure bankfull width, mean depth, and velocity, and compute discharge.
FS–3	Measure suspended sediment at the bankfull stage; separate wash load in lab
FS–4	Measure bed-load sediment at the bankfull stage, sieve particle sizes, and measure largest size.
FS–5	Compute average water surface slope.
FS–6	Collect point bar sample, weigh by size fraction and record D_{50} and largest size (D_{max}).
FS–7	Collect pebble count on active riffle bed: obtain D_{50}, D_{84} sizes (mm).
FS–8	Determine stream type.
FS–9	Conduct channel stability assessment procedure, including Pfankuch channel stability rating.
FS–10	Obtain reference dimensionless bed-load sediment rating curve for appropriate stream type/stability rating.
FS–11	Obtain reference dimensionless suspended sediment rating curve for appropriate stream type/stability rating.
FS–12	Determine ratio of wash load/suspended sediment by Q/Q_{bkf} relation.
FS–13	Construct a bed-load rating curve (enter range of Q/Q_{bkf} ratios into the reference bed-load relation from step 10 and multiply by the measured bankfull bed load from step 4).
FS–14	Construct suspended sediment rating curve in the same manner as in step 13 using reference dimensionless sediment relations (step 11) and bankfull suspended sediment (step 3).
FS–15	Construct a suspended sediment rating curve less wash load (silt/clay) for potential settleable sediment by multiplying ratio of wash load/suspended sediment for appropriate Q/Q_{bkf}.
FS–16	Convert suspended sediment less wash load from mg/L to tons/day on rating curve: tons/d = $0.0027 \times ft^3/s \times mg/L$.
FS–17	Convert suspended sediment less wash load from mg/L to tons/d as in step 16.
FS–18	Convert bed load in lb/s to tons/d, where tons/d = (lb×86,400)/2000 (if metric, convert kg/s to lb/s by multiplying by 2.205).
FS–19	Obtain dimensionless flow-duration curve from either water yield model or regionalized relation.
FS–20	Develop the dimensionless flow-duration curves using the normalization parameter of mean daily bankfull discharge, rather than momentary maximum values from flood-frequency data. Divide the mean daily discharge (the day bankfull discharge occurs) by the momentary maximum value to determine the appropriate conversion ratio.
FS–21	Convert dimensionless flow-duration curve to actual flow by multiplying bankfull discharge (step 2) times the Q/Q_{bkf} ratios from dimensionless flow-duration curve (step 19).
FS–22	Calculate total annual sediment yield for suspended sediment, suspended sediment less wash load, and bed load from sediment rating curve/flow-duration curve procedure (table 11–11). Obtain flow from the water yield model for hydraulically recovered condition to compare departure from existing/proposed condition (step 22). This represents the pre-treatment flow duration/sediment relation.
FS–23	To determine flow-related increase in sediment, multiply post-treatment flow-duration curve times appropriate sediment rating curves for suspended, bed-load and total sediment rating curves to calculate total annual sediment yield using the same procedure as step 21 (table 11–11).

Table 11–11 FLOWSED calculation of total annual sediment yield

Stream: **Notes:**

From flow-duration curve						**From sediment rating curves**					**Calculate**	**Calculate daily mean sediment yield**				
Flow exceedance	**Daily mean discharge**	**Mid-ordinate streamflow**	**Increment**	**Mid-ordinate streamflow**	**Dimensionless streamflow**	**Dimensionless suspended sediment discharge**	**Suspended sediment discharge**	**Suspended sediment minus wash load**	**Dimensionless bed-load discharge**	**Bed load**	**Time adjusted streamflow**	**Suspended sediment**	**Suspended sediment minus wash load**	**Bed load**	**Bed load plus suspended**	**Bed load plus suspended minus wash load**
(%)	**(ft^3/s)**	**(%)**	**(%)**	**(ft^3/s)**	**(Q/Q_{bkf})**	**(S/S_{bkf})**	**(tons/d)**	**(tons/d)**	**(b_s/b_{bkf})**	**(tons/d)**	**(ft^3/s)**	**(tons/d)**	**(tons/d)**	**(tons/d)**	**(tons/d)**	**(tons/d)**
									Annual totals:		**(acre-ft)**	**tons/yr)**	**(tons/yr)**	**(tons/yr)**	**(tons/yr)**	**(tons/yr)**

Bankfull discharge (ft^3/s)	
Bankfull bed load (kg/s)	
Bankfull suspended (mg/L)	

Dimensionless sediment rating curve used

Type	**Intercept**	**Coefficient**	**Exponent**	**X**	**Y**	**Form**	**Notes**
Bed load							
Suspended							

Figure 11–21 Dimensionless flow-duration curve for Weminuche Creek, CO

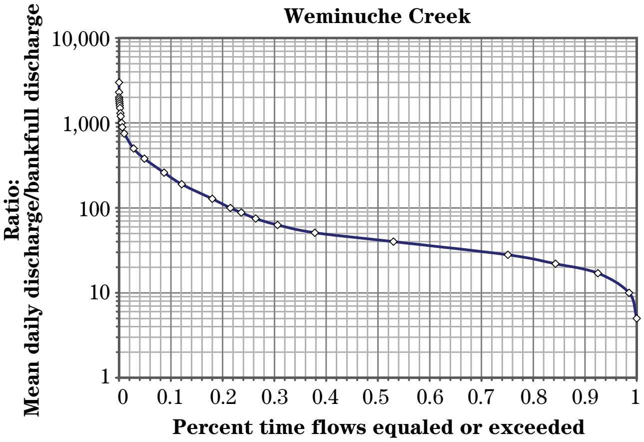


Figure 11–22 Bed-load sediment rating curve for Weminuche Creek, CO

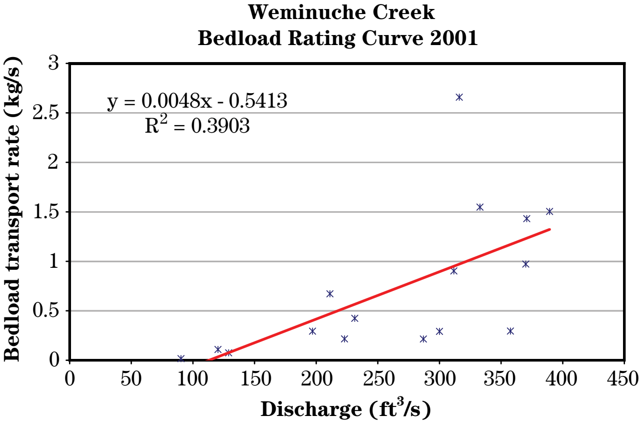


Figure 11–23 Suspended sediment rating curve for Weminuche Creek, CO

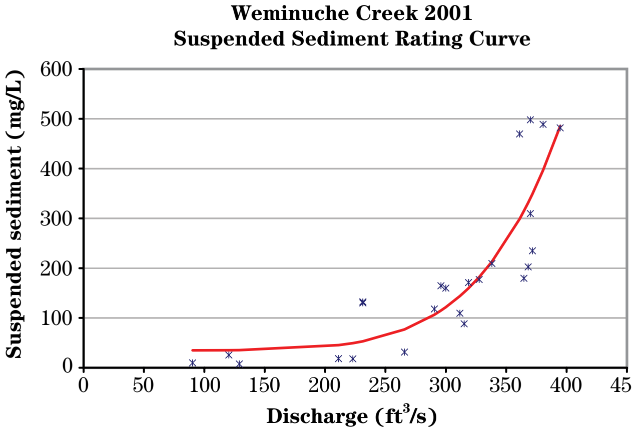
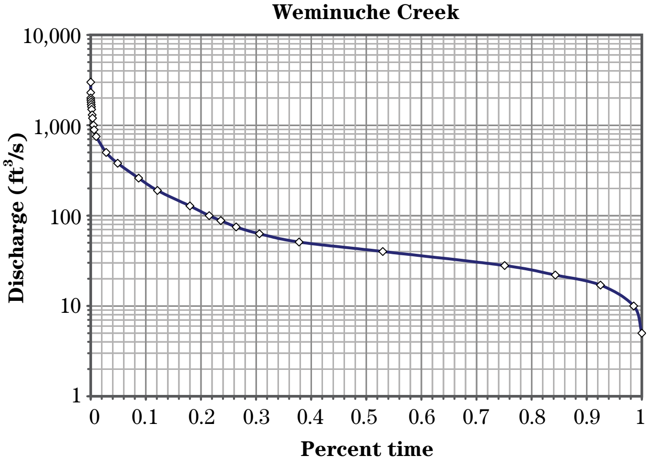


Figure 11–24 Dimensioned flow-duration curve for Weminuche Creek, CO



POWERSED

A generalized flowchart depicting the POWERSED model is shown in figure 11–25, and a graphical depiction of the model is shown in figure 11–26.

Evaluate channel characteristics that change hydraulic and morphological variables—Changes in the cross section and/or pattern (slope) for potentially impaired reaches are measured to determine width, depth, slope and calculated velocity. Comparisons are made between hydraulic characteristics of the reference versus the impaired reach. This analysis is used in the bed-load transport model (POWERSED) or in a comparable bed-load model selected by the user. Shear stress and unit stream power are calculated using equations 11–2 and 11–7:

$$\tau = \gamma d S \qquad \text{(eq. 11–2)}$$

where:
γ = specific weight of the fluid
d = mean depth
S = water surface slope

Unit stream power or power per unit of streambed area (ω_a) is defined as:

$$\omega_a = \tau u \qquad \text{(eq. 11–7)}$$

where:
τ = bankfull shear stress (lb/ft^2)
u = mean velocity

POWERSED can be used to simulate hydraulic geometry (width, depth, slope, velocity, and discharge) for a wide range of stages for reference and impaired reach hydraulic evaluations. POWERSED can also be used to compute changes in hydraulic character due to modified channel dimension, pattern, profile or materials. This information is used to determine changes in unit stream power for increased or decreased discharge. This model predicts channel stability response to imposed sediment load, change in flow, and/or change in distribution of energy due to channel change. The model determines sediment transport and predicts aggradation, stability, or degradation, depending on the nature and extent of the channel and/or flow change. The hydraulic/sediment departure is compared to the corresponding reference or stable condition. A recent comparison of predicted to observed values on an independent data set was shown in Rosgen (2006) where predicted annual sediment yield values were predicted within 3 percent of measured values for a C4 stream type and within 6 percent of measured values for a D4 stream type on Weminuche Creek, Colorado.

Calculate bed-load and suspended sand-bedmaterial load transport (stream power)—Bed load and suspended sand-bed material load transport calculations may use various equations, such as the Bagnold equation. The POWERSED model (figs. 11–25, 11–26 and tables 11–12 and 11–13) assists in the analysis of sediment transport and channel response. This model was developed to predict the effects of channel instability and sediment supply changes in sediment transport. Other bed-load and suspended sand-bed material load transport models can be employed by the user, based on familiarity with and calibration/validation of the model for application to the particular stream types being analyzed.

The POWERSED model applies the suspended sand-bed material and bed-load sediment rating curves/flow duration/revised unit stream power-transport curves or a comparable model selected by the user to predict sediment transport and channel stability. The prediction includes river stability and total annual bed-load sediment yield in tons/year. The equations or computer program generates a change in coarse bed-load transport that will be influenced by changes in channel cross section and/or slope. Changes in streamflow, velocity, unit stream power, critical dimensionless shear stress, and other variables due to land use changes predict changes

POWERSED—Continued

in river stability and total annual bed-load sediment yield. The sediment supply component is predicted using the FLOWSED model and is derived from dimensionless bed-load and suspended sediment rating curves for corresponding stream and stability types. These changes are compared to stable reference conditions for a departure comparison.

Procedural steps for computations of the POWERSED model are presented in table 11–12. Bed-load transport and suspended sand-bed material load is calculated using the POWERSED worksheet (table 11–13).

The POWERSED model is used to predict the transport rate and capacity for each reach independently. Reaches may be stable (sediment in versus sediment out), aggrading, or degrading. The model identifies reaches that may have serious instabilities due to changes in sediment supply and/or hydraulic characteristics. The analysis assists in pinpointing various river reaches for mitigation. The sediment transport changes reflect the sediment supply of the existing condition compared to the reference condition. Annual streambank erosion rates and other sources are compared to the total annual sediment yield.

Figure 11–25 POWERSED model to predict bed-load and suspended sand-bed-material load transport

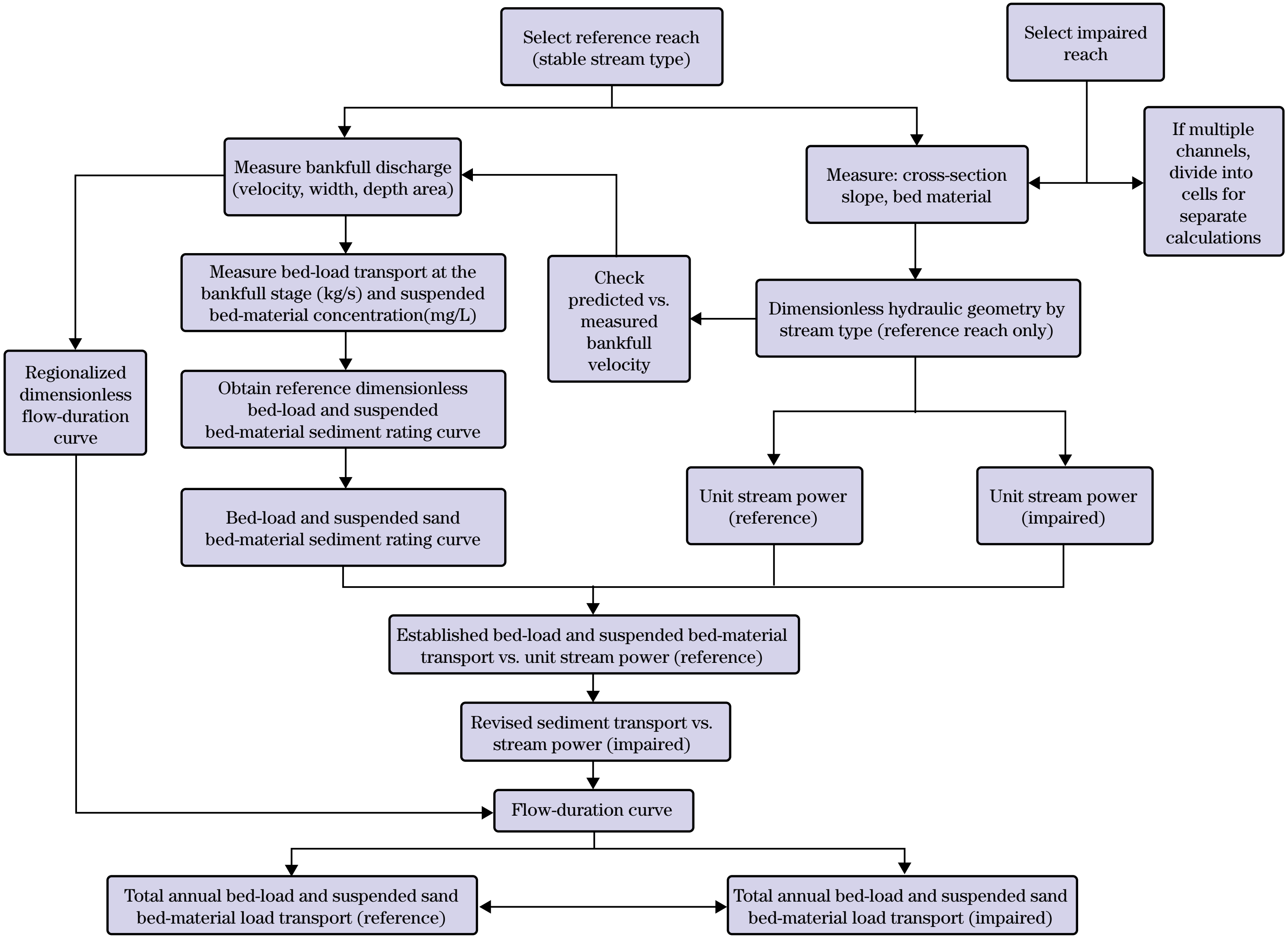


Figure 11–26 Graphical depiction of POWERSED model

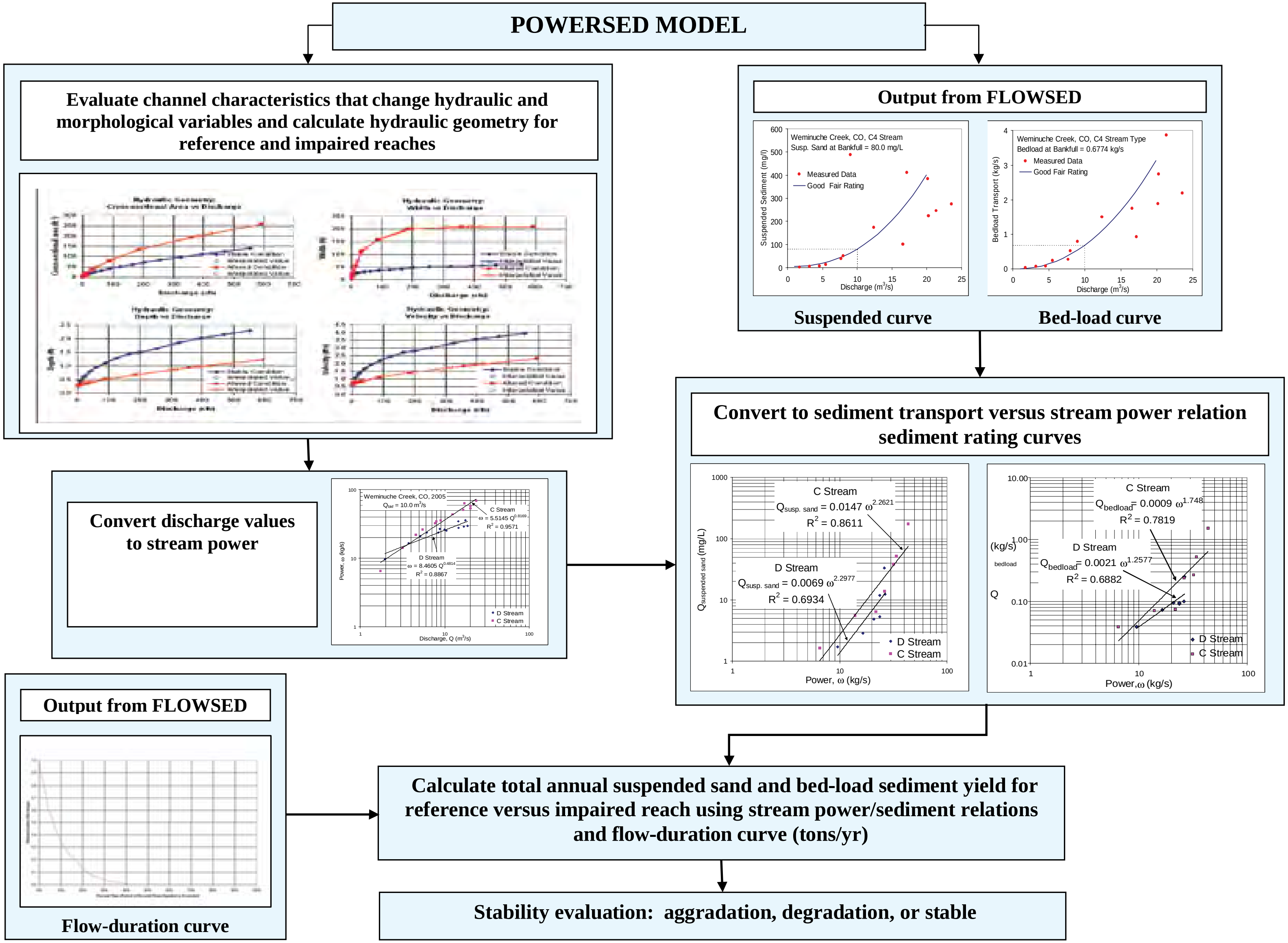


Table 11–12 POWERSED procedural steps of predicted bed-load and suspended sand-bed material transport changes due to alterations of channel dimension or slope (same stream with different bankfull discharges)

POWERSED procedure	
PS–1	Select a reference reach: a. Survey a stable cross section; measure the stream gradient and bed material. b. Measure bankfull discharge (ft^3/s). c. Measure bankfull bed load (kg/s).
PS–2	Obtain an appropriate dimensionless bed load and suspended sand sediment rating curve: a. Construct a dimensional bed load and suspended sand sediment rating curve for the defined range of flow using the measured bankfull discharge, bankfull bed load transport and suspended sand-bed material load.
PS–3	Obtain the drainage area of the reference reach: a. Predict bankfull discharge and cross-sectional dimensions using regional curves. b. Validate the regional curves using the measured bankfull discharge and cross-sectional dimensions.
PS–4	Use dimensionless hydraulic geometry by stream type to predict the hydraulic geometry of the stable cross section for a full range of discharge (baseflow to above bankfull): a. Construct hydraulic geometry curves. b. Check predicted versus measured bankfull velocity. c. Obtain hydraulic geometry for each discharge value within the defined range of flow. d. Calculate unit stream power for each discharge value within the defined range of flow.
PS–5	Select an impaired reach on the same stream: a. Obtain the drainage area. b. Predict bankfull discharge from the validated regional curve. c. Survey the cross section, and measure the stream gradient and bed material.
PS–6	Obtain the stable (potential) dimension, pattern, and profile for the impaired reach. If reference reach is not immediately upstream and/or is of different size or drainage area, complete the following procedure: a. Slope = valley slope/sinuosity. b. Obtain appropriate cross-sectional area from regional curve. c. Obtain width-to-depth ratio (W/d) from reference dimensionless ratios by stream type. d. Calculate appropriate width.
PS–7	Use the RIVERMorph® procedure or applicable spreadsheet calculations to predict the hydraulic geometry of the impaired and potential cross sections for a full range of discharge (baseflow to above bankfull). Follow the step below for the impaired and potential cross sections: a. Construct hydraulic geometry curves. b. Obtain hydraulic geometry for each discharge value within the defined range of flow. * If channel has multiple channels, divide the channels into thirds and treat as a separate channel c. Calculate unit stream power for each discharge value within the defined range of flow.
PS–8	Plot unit stream power vs. bed load and suspended sand-bed material transport for the stable cross section.
PS–9	Construct a unit stream power versus bed-load transport curve for the impaired and potential cross sections using the relationship constructed in step 8.
PS–10	Obtain a dimensionless flow-duration curve for the appropriate region: a. Create a dimensional flow-duration curve using the bankfull discharge for the stable reach. b. Create a dimensional flow-duration curve using the bankfull discharge for the impaired reach.

Table 11–12 POWERSED procedural steps of predicted bed-load and suspended sand-bed material transport changes due to alterations of channel dimension or slope (same stream with different bankfull discharges)—Continued

POWERSED procedure	
PS–11	Calculate total annual sediment yield (bed-load and suspended sand-bed-material load) in tons/yr for all three (stable, impaired, potential) cross sections using the appropriate flow-duration curve: a. Convert the predicted bed-load transport for each discharge value within the defined range of flow from kg/s to tons/d by multiplying kg/s by 95.24. Convert values of suspended sand-bed material load in mg/L to tons/d by multiplying (mg/L)(.0027)(ft^3/s). b. Multiply the predicted bed-load and suspended sand-bed material load transport (tons/d) by the percent time factor from flow-duration curve. c. Sum the time adjusted bed-load transport and multiply by 365 days to obtain annual bed load yield in tons/yr. d. Divide the annual yield for both bed-load and suspended sand-bed material load by the drainage area to obtain the annual unit area bed-load and suspended sand-bed material load yield (tons/yr/mi^2). e. Compare the annual unit area bed-load and suspended sand-bed material load yield predicted for all three conditions (stable, impaired and potential).
PS–12	Record data for impacted and reference condition (separately) in POWERSED worksheet (table 11–13).

Table 11–13 POWERSED model to predict bed-load and suspended sand and bed-material load transport*

Stream: **Gage station#:** **Date:**

Equation type	**B0**	**B1**	**B2**	**Form**	**Equation name**	**Enter equation number (1 or 2)**	**Bankfull discharge (ft^3/s)**	**Bankfull bed load (lb/s)**	**Suspended bed-material load (mg/L)**
1 Dimensional									
2 Dimensionless									
3 Bed load									
4 Suspended sand-bed concentration									

Flow-duration curve		**Calculate**	**Hydraulic geometry**				**Measure**	**Calculate**								
Exceedance probability	**Daily mean discharge**	**Mid-ordinate stream-flow**	**Area**	**Width**	**Depth**	**Velocity**	**Slope**	**Shear stress**	**Stream power**	**Unit power**	**Time increment**	**Daily mean bed-load transport**	**Time adjusted bed-load transport**	**Daily mean suspended transport**	**Time adjusted suspended transport**	**Time adjusted total transport**
(%)	**(ft^3/s)**	**(ft^3/s)**	**(ft^2)**	**(ft)**	**(ft)**	**(ft/s)**	**(ft/ft)**	**(lb/ft^2)**	**(lb/s)**	**(lb/ft/s)**	**(%)**	**(tons/d)**	**(tons)**	**(tons/d)**	**(tons)**	**(tons)**
											Annual total sediment yield (tons/yr):					

*Use this model for both reference and impaired conditions separately. Calculate bed load separately from suspended bed-material load.

Step 28 Obtain maximum bankfull riffle depth (d_{max}) from ratio of maximum riffle depth divided by mean bankfull depth from dimensionless ratios of reference reach data (step 7) (table 11–3).

$$d_{mbkf} = \left[\left(\frac{d_{mbkf}}{d_{bkf}}\right)_{ref}\right] d_{bkf} \qquad \text{(eq. 11–18)}$$

Step 29 Determine entrenchment ratio of proposed channel by measuring the width of the flood-prone area at an elevation of twice the maximum bankfull depth ($d_{max\ bkf}$). Entrenchment ratio is calculated by:

$$ER = \frac{W_{fpa}}{W_{bkf}} \qquad \text{(eq. 11–19)}$$

Step 30 Calculate flood-prone area capacity. This involves estimating velocity associated with the cross-sectional area and slope of the stream channel and flood-prone area. Determine cross-sectional area of the flood-prone area. Plot the bankfull cross-section and flood-prone area elevation ($2 \times d_{max\ bkf}$) and width. Use valley slope for hydraulic calculations for the flood-prone area. Estimate roughness from Manning's equation based on vegetative cover and other roughness elements. HEC–2, HEC–RAS, or other models can be used to obtain the corresponding discharge of the flood-prone area. Calculate the 50- and 100-year flood levels based on the proposed design. Use the bankfull channel capacity from step 22.

Step 31 Calculate depth of pool (ratios from table 11–3):

$$d_{mbkfp} = \left[\left(\frac{d_{mbkfp}}{d_{bkf}}\right)_{ref}\right] d_{bkf} \qquad \text{(eq. 11–20)}$$

Step 32 Calculate depth of glide (ratios from table 11–3):

$$d_g = \left[\left(\frac{d_g}{d_{bkf}}\right)_{ref}\right] (d_{bkf}) \qquad \text{(eq. 11–21)}$$

Step 33 Calculate depth of run (ratios from table 11–3):

$$d_{run} = \left[\left(\frac{d_{run}}{d_{bkf}}\right)_{ref}\right] (d_{bkf}) \qquad \text{(eq. 11–22)}$$

Step 34 Calculate slope of pool (ratios from table 11–3):

$$S_p = \left[\left(\frac{S_p}{S}\right)_{ref}\right] S \qquad \text{(eq. 11–23)}$$

Step 35 Calculate slope of glide (ratios from table 11–3):

$$S_g = \left[\left(\frac{S_g}{S}\right)_{ref}\right] S \qquad \text{(eq. 11–24)}$$

Step 36 Calculate slope of run (ratios from table 11–3):

$$S_{run} = \left[\left(\frac{S_{run}}{S}\right)_{ref}\right] S \qquad \text{(eq. 11–25)}$$

Step 37 Calculate pool-pool spacing (from plan view and profile layout).

Step 38 Design stabilization/fish habitat enhancement measures (grade control, energy dissipation, bank stability, holding cover). See phase VI.

Step 39 Prepare revegetation plan compatible with native plants, soil, and site conditions. Make recommendations on vegetative maintenance and management for long-term solutions.

Step 40 Design a monitoring plan including effectiveness, validation, and implementation monitoring. Prepare maintenance plan to ensure long-term success.

The variables associated with existing, proposed, gage station, and reference reach data are summarized in the form as demonstrated in table 11–14 (Rosgen 1998). The variables used in table 11–14 and forms used in field data collection are in the Reference Reach Field Book (Rosgen, Leopold, and Silvey 1998; Rosgen and Silvey 2005).

Table 11–14 Morphological characteristics of the existing and proposed channel with gage station and reference reach data

Restoration site (name of stream and location):
Reference reach (name of stream and location):

Variables		Existing channel	Proposed reach	USGS station	Reference reach
1	Stream type				
2	Drainage area, mi^2				
3	Mean riffle depth, ft (d_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
4	Riffle width, ft (W_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
5	Width-to-depth ratio (W_{bkf}/d_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
6	Riffle cross-sectional area, ft^2 (A_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
7	Max riffle depth (d_{mbkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
8	Max riffle depth/mean riffle depth (d_{mbkf}/d_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
9	Mean pool depth, ft (d_{bkfp})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
10	Mean pool depth/mean riffle depth	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
11	Pool width, ft (W_{bkfp})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
12	Pool width/riffle width	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
13	Pool cross-sectional area, ft^2 (A_{bkfp})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
14	Pool area/riffle area	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
15	Max pool depth (d_{mbkfp})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
16	Max pool depth/mean riffle depth (d_{mbkfp}/d_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:

Table 11–14 Morphological characteristics of the existing and proposed channel with gage station and reference reach data—Continued

Variables		Existing channel	Proposed reach	USGS station	Reference reach
17	Low bank height (LBH)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
18	Low bank height to max riffle depth (LBH/d_{mbkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
19	Width of flood-prone area, ft (W_{fpa})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
20	Entrenchment ratio (W_{fpa}/W_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
21	Point bar slope	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
22	Bankfull mean velocity, ft/s (u_{bkf})				
23	Bankfull discharge, ft^3/s (Q_{bkf})				
24	Meander length, ft (Lm)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
25	Meander length ratio (Lm/W_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
26	Radius of curvature, ft (Rc)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
27	Ratio of radius of curvature to bankfull width (Rc/W_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
28	Belt width, ft (W_{blt})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
29	Meander width ratio ($W_{b/t}/W_{bkf}$)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
30	Individual pool length, ft	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
31	Pool length/riffle width	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
32	Pool to pool spacing (based on pattern), ft (p-p)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:

Table 11–14 Morphological characteristics of the existing and proposed channel with gage station and reference reach data—Continued

Variables		Existing channel	Proposed reach	USGS station	Reference reach
33	Ratio of p-p spacing to bankfull width (p-p/W_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
34	Stream length (SL)				
35	Valley length (VL)				
36	Valley slope (VS)				
37	Average water surface slope (S)		S = VS/k		
38	Sinuosity (k)	SL/VL:	SL/VL:	SL/VL:	SL/VL:
		VS/S:		VS/S:	VS/S:
39	Riffle slope (water surface facet slope) (S_{rif})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
40	Ratio riffle slope to average water surface slope (S_{rif}/S)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
41	Run slope (water surface facet slope) (S_{run})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
42	Ratio run slope/average water surface slope (S_{run}/S)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
43	Pool slope (water surface facet slope) (S_p)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
44	Ratio of pool slope/average water surface slope (S_p/S)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
45	Glide slope (water surface facet slope) (S_g)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
46	Ratio glide slope/average water surface slope (S_g/S)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
47	Max run depth, ft (d_{run})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
48	Ratio max run depth/ bankfull mean depth (d_{run}/d_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
49	Max glide depth, ft (d_g)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:

Table 11–14 Morphological characteristics of the existing and proposed channel with gage station and reference reach data—Continued

Variables		**Existing channel**	**Proposed reach**	**USGS station**	**Reference reach**
50	Ratio max glide depth/ bankfull mean depth (d_g/d_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:

Materials					
51	Particle size distribution of channel material (active bed)				
	D_{16} (mm)				
	D_{35} (mm)				
	D_{50} (mm)				
	D_{84} (mm)				
	D_{95} (mm)				
52	Particle size distribution of bar material				
	D_{16} (mm)				
	D_{35} (mm)				
	D_{50} (mm)				
	D_{84} (mm)				
	D_{95} (mm)				
	Largest size particle at the toe (lower third) of bar (mm)				

Sediment transport validation (Based on Bankfull Shear Stress)		**Existing**	**Proposed**
Calculated shear stress value (lb/ft^2) from curve			
Size from Shields diagram - Original data (mm)			
Size from Shields diagram - Colorado data (mm)			
Largest size (mm) to be moved (D_{max})			
Dimensionless shear stress (τ^*)			
Mean d_{bkf} (ft) calculated using dimensionless shear stress equations for given slope			

Remarks:

(f) Phase VI—Selection and design of stabilization and enhancement structures/methodologies

The objectives of river structures are often primarily designed to:

- buy time to protect the new channel from excess erosion until significant riparian vegetation can become established
- reduce accelerated streambank erosion
- provide grade control
- provide recreational boating
- obtain stable flow diversions
- enhance fish habitat including instream cover, holding cover, spawning habitat, and habitat diversity
- reintroduce and stabilize large wood for fishery, stability, and aesthetic purposes
- protect infrastructure adjacent to streams
- protect bridges, culverts, and drainageway crossings
- reduce flood levels
- transport sediment
- provide energy dissipation

River stabilization and enhancement structures are numerous and continue to be improved and developed. The effort here will not be to make a complete listing, but rather present methods used in the Rosgen geomorphic channel design methodology consistent with the objectives. The structures and methods primarily utilize native materials such as natural boulders, logs, rootwads, and vegetative transplants.

Design objectives will be presented to provide the user with alternatives to standard or traditional structures.

Grade control

Often cross-channel check dams are used for grade control. NRCS has successfully used many types of channel grade control structures, but streams with high sediment loads have experienced some adverse channel adjustment in some case. The adjustments are associated with aggradation, lateral erosion, flood stage increase, migration barriers for fish, increased recreational boating risk, land loss, channel incision through lateral migration and channel avulsion. To prevent these stability problems, the cross vane was developed (fig.11–27 (Rosgen 2001e)).

Application of this design is also very effective for bridge pier scour reduction (Johnson, Hey, et al. 2002). A photograph depicting the structure as constructed on the lower Blanco River, Colorado, is shown in figure 11–28. The structure also decreases near-bank shear stress, minimizing streambank erosion.

The photographs in figures 11–29 and 11–30 demonstrate the use of cross vanes in river restoration. In this example, a reconstructed river project on the East Fork Piedra River, Colorado, in a valley type V (glacial trough), converted a braided (D4) stream type to a meandering (C4) stream type. The use of the cross vane structure was effective at maintaining grade control, transporting excessive coarse bed load, reducing bank erosion, buying time for riparian vegetation colonization, and providing trout habitat. The structures located along 3 miles of this project withstood floods at twice the bankfull discharge magnitude in 2004. Logs and rootwads can also be utilized in this structure as designed in Rosgen (2001e) and as shown in figure 11–31. The use of large wood in this structure assists in the visual, as well as biological enhancement objectives. The step in the upper third of the structure dissipates energy, reduces footer scour, and minimizes risk for recreational boating and fish passage.

A structure designed for larger rivers for grade control and streambank protection is the W-weir. This structure can also be effectively used for irrigation diversions, protection of central piers and approach sections on bridges, bed-load transport, recreational boating, and fish habitat. Visually, it is improved over a line of rock often used in grade control. It resembles natural bedrock features in stream channels. Figure 11–32 depicts the design (Rosgen 2001e), and figure 11–33 shows a typical W-weir structure as installed on the Uncompahgre River in Colorado.

Streambank stabilization

Most stream restoration projects require some degree of streambank stabilization. Often the stabilization involves riparian vegetation reestablishment or change in management. Regardless, there is a time element that is needed to establish rooting depth, density, and

Figure 11–27 Cross section, profile, and plan view of a cross vane

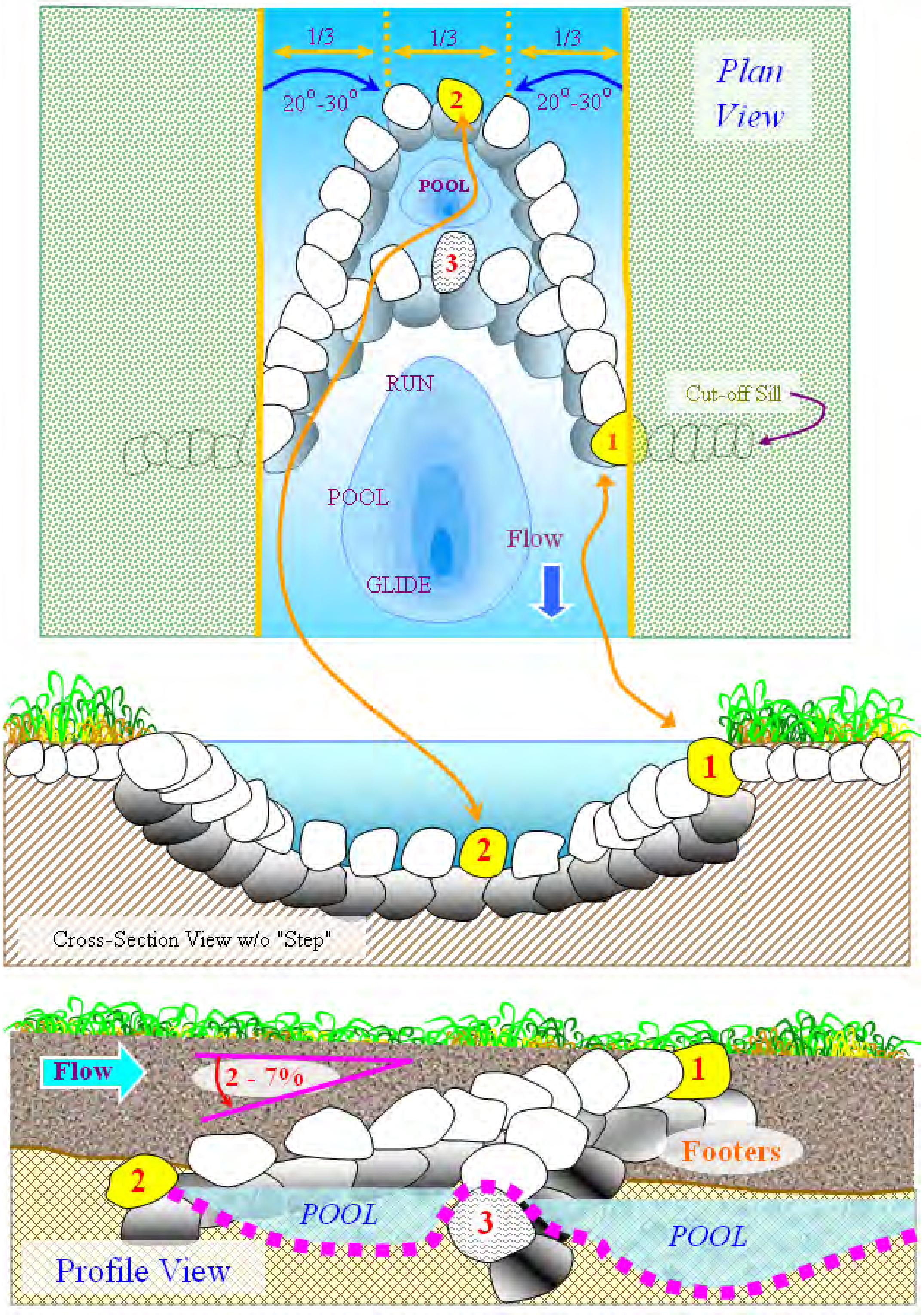


Figure 11–28 Cross vane installed on the lower Blanco River, CO

Figure 11–29 Cross vane structure with step on the East Fork Piedra River, CO

Figure 11–30 Cross vane/step-pool on the East Fork Piedra River, CO

Figure 11–31 Cross vane/rootwad/log vane step-pool, converting a braided D4→C4 stream type on the East Fork Piedra River, CO

Figure 11–32 Plan, cross section, and profile views of a W-weir structure

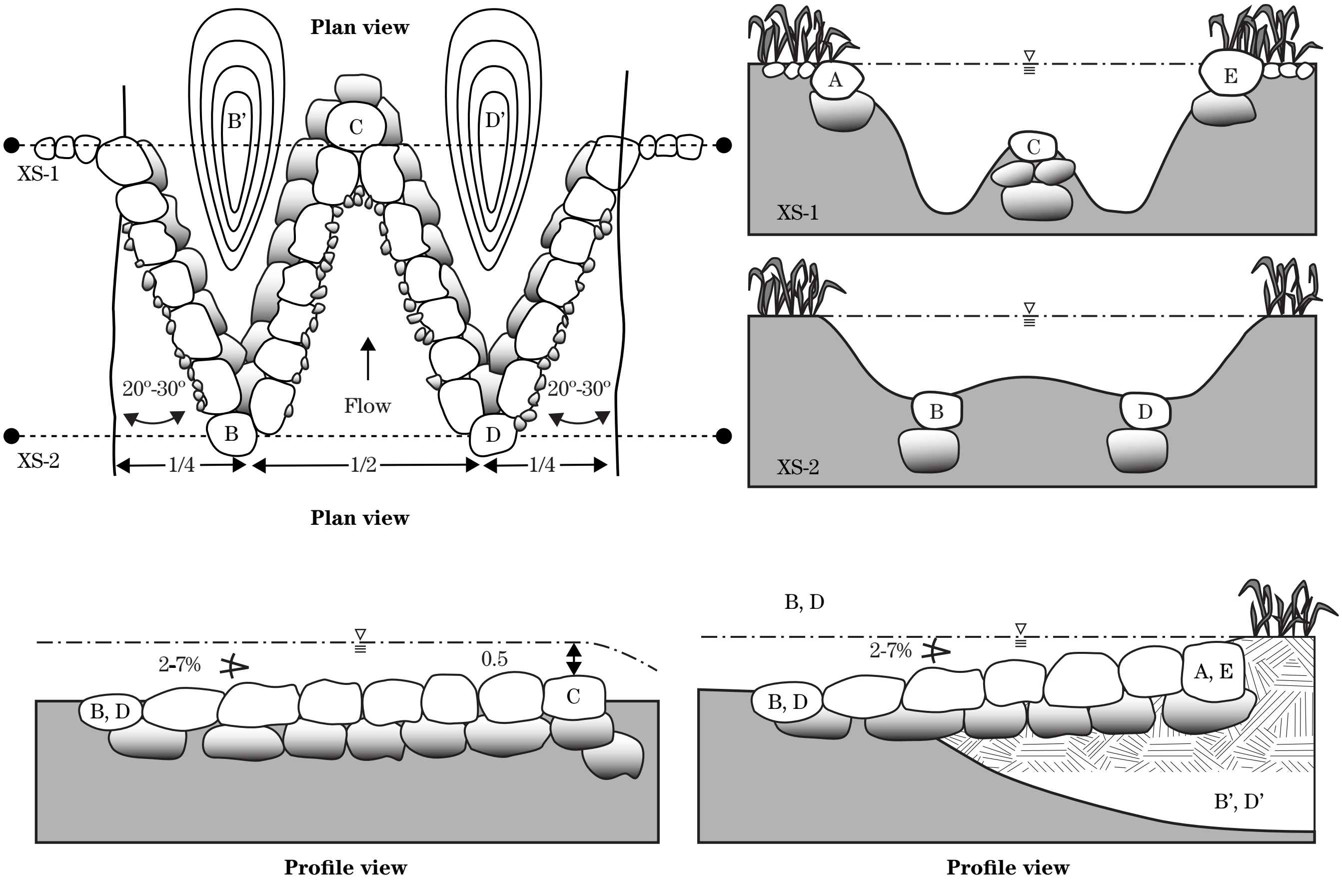


Figure 11–33 W-weir installed on the Uncompahgre River, CO

Figure 11–34 Plan, profile, and section views of the J-hook vane structure

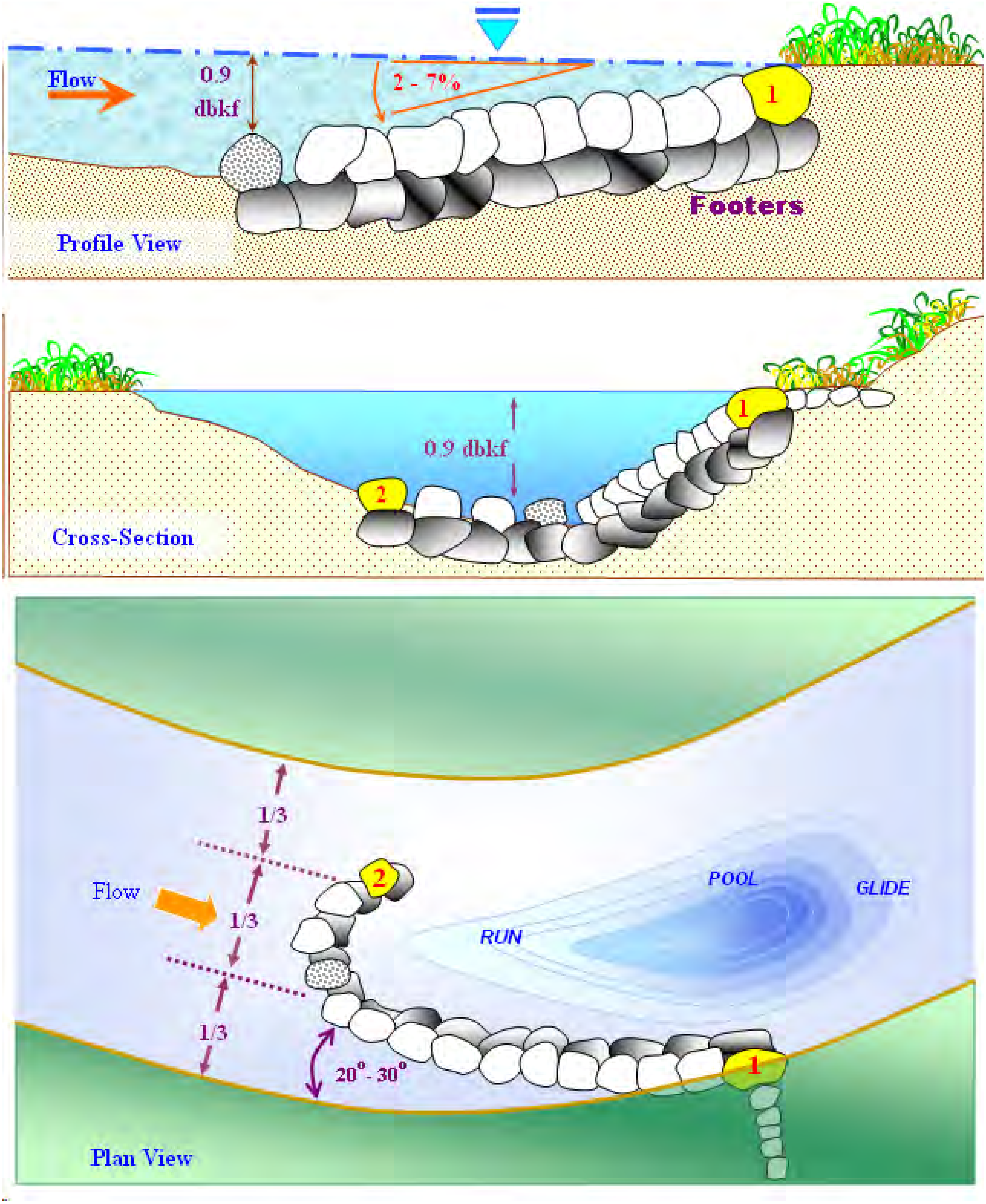


Figure 11–35 Log vane/J-hook combo with rootwad structure

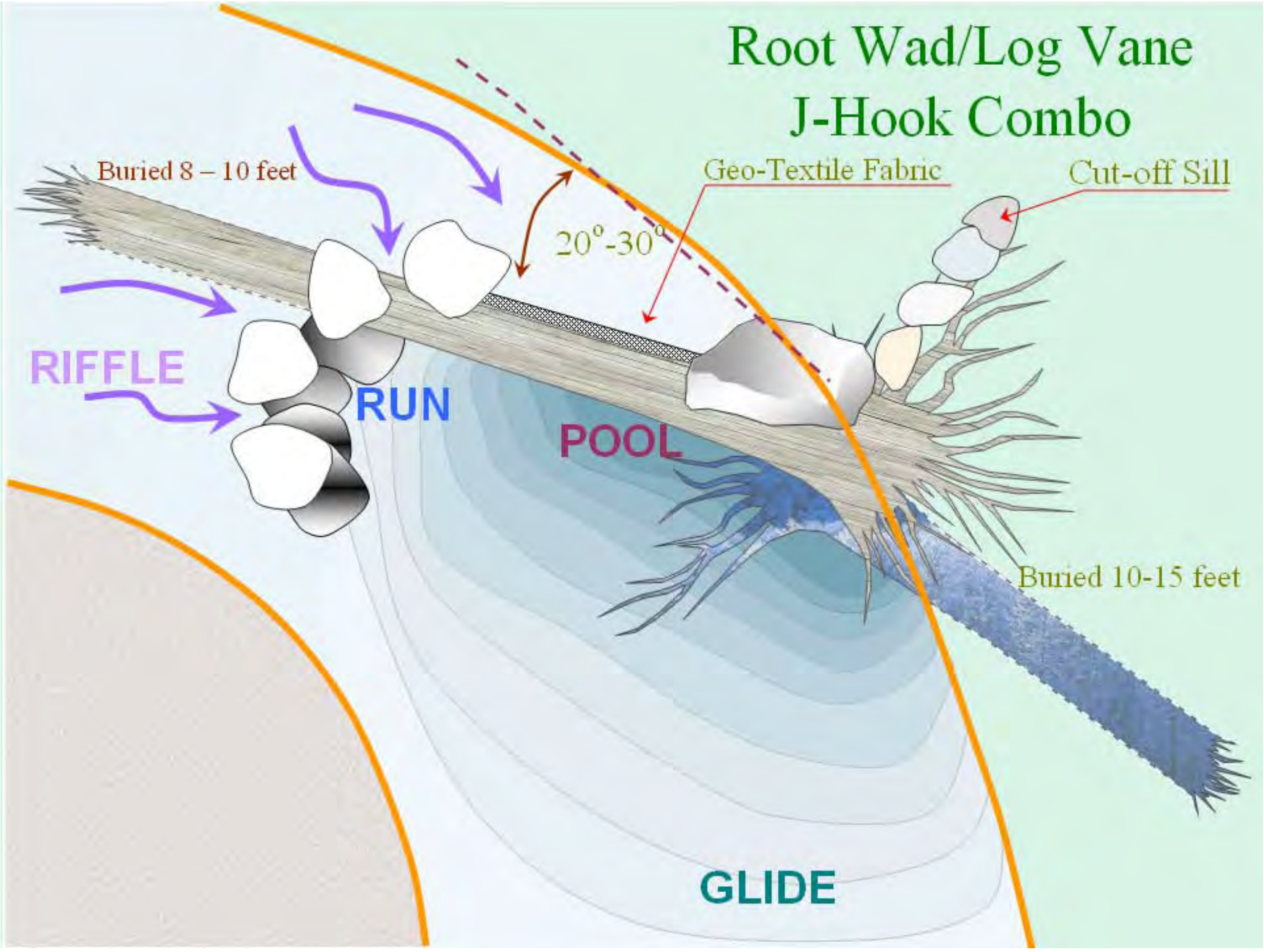


Figure 11–36 Rock vane/J-hook combo with rootwad and log vane footer

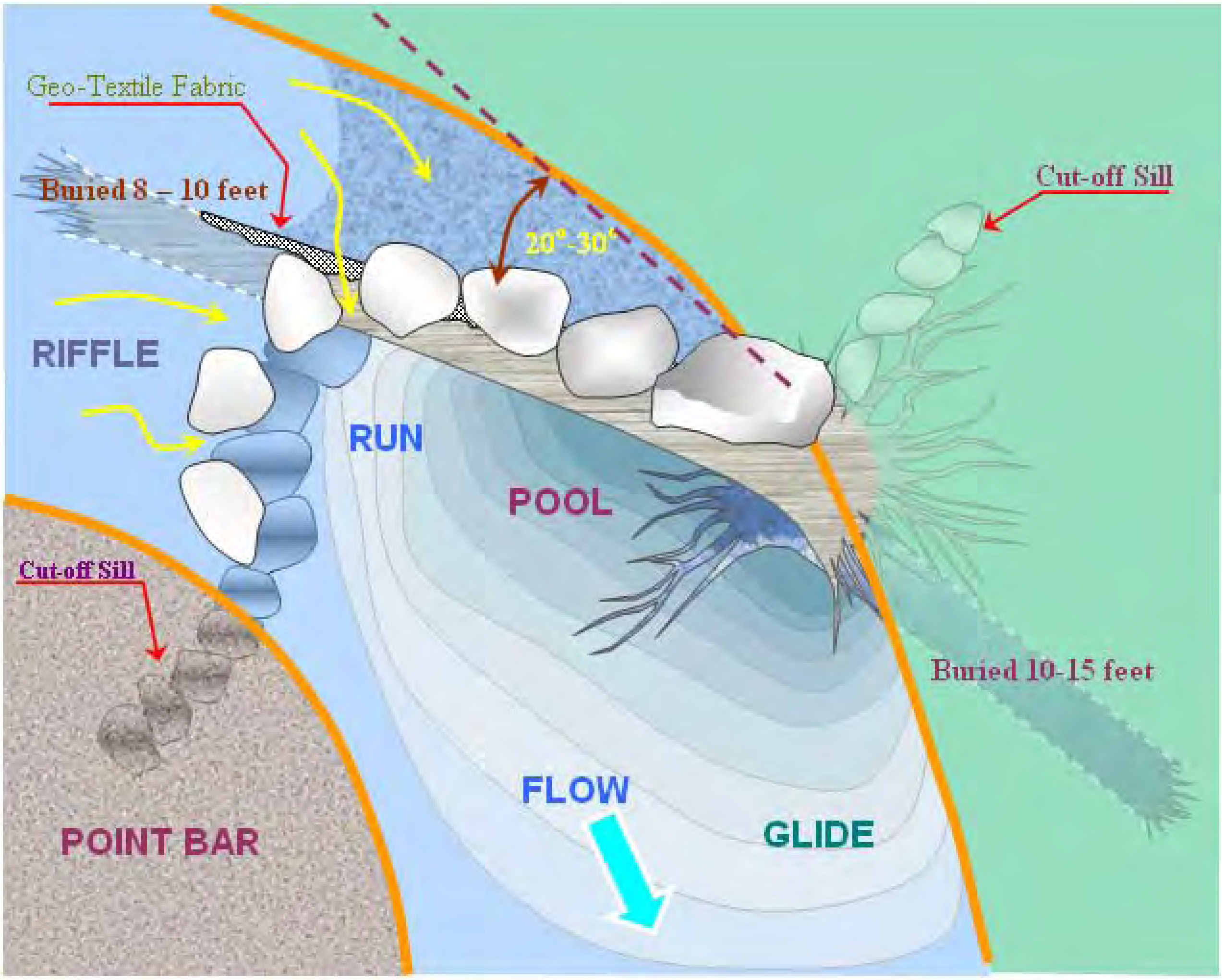
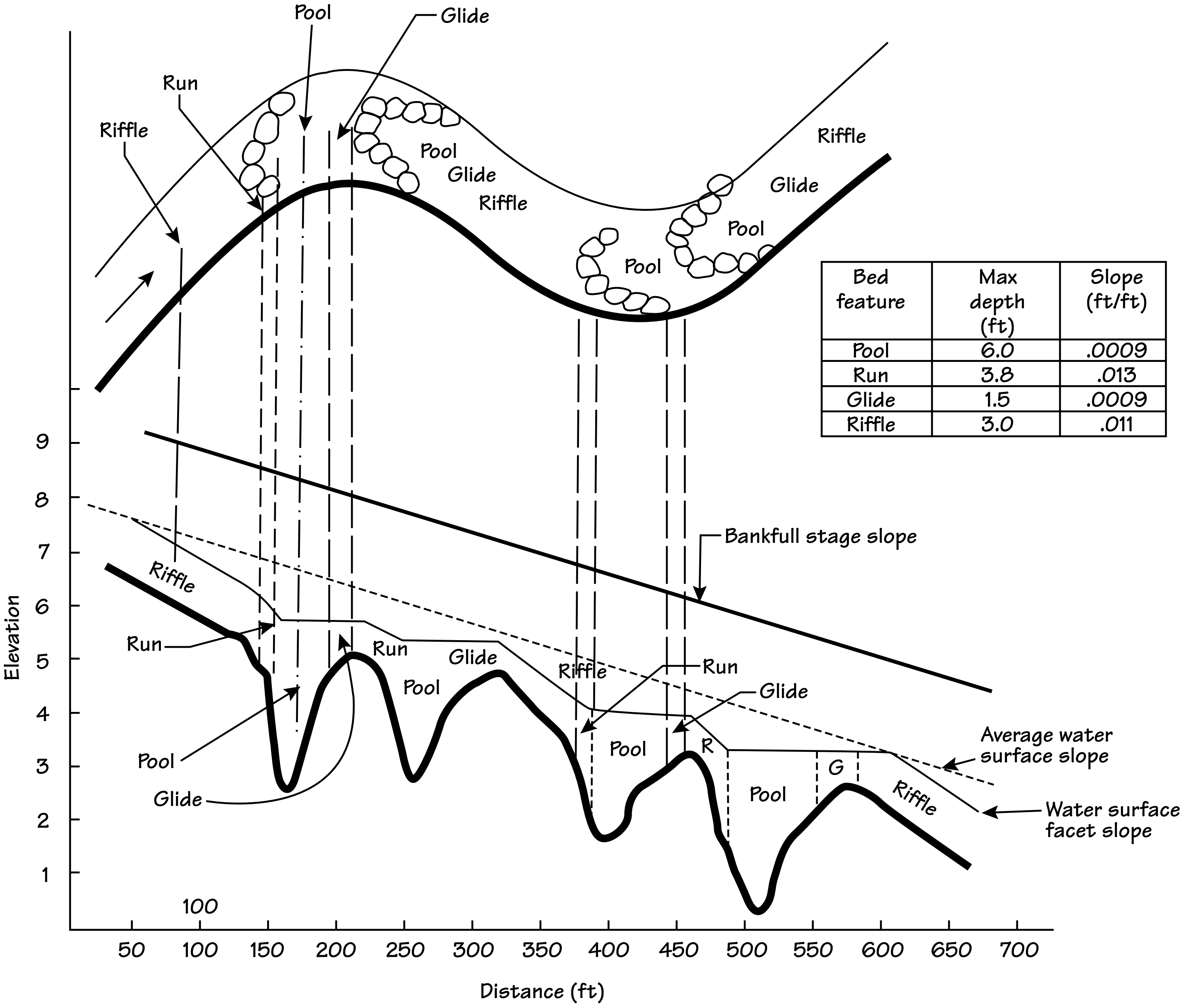


Figure 11–37 Native boulder J-hook with cut-off sill, East Fork Piedra River, CO

Figure 11–38 Rootwad/log vane/J-hook structure, East Fork Piedra River, CO

Figure 11–39 J-hook/log vane/log step with cut-off sill, East Fork Piedra River, CO

Figure 11–40 Longitudinal profile of proposed C4 stream type showing bed features in relation to structure location



Bed feature	Max depth (ft)	Slope (ft/ft)
Pool	6.0	.0009
Run	3.8	.013
Glide	1.5	.0009
Riffle	3.0	.011

Figure 11–41 Boulder cross vane and constructed bankfull bench

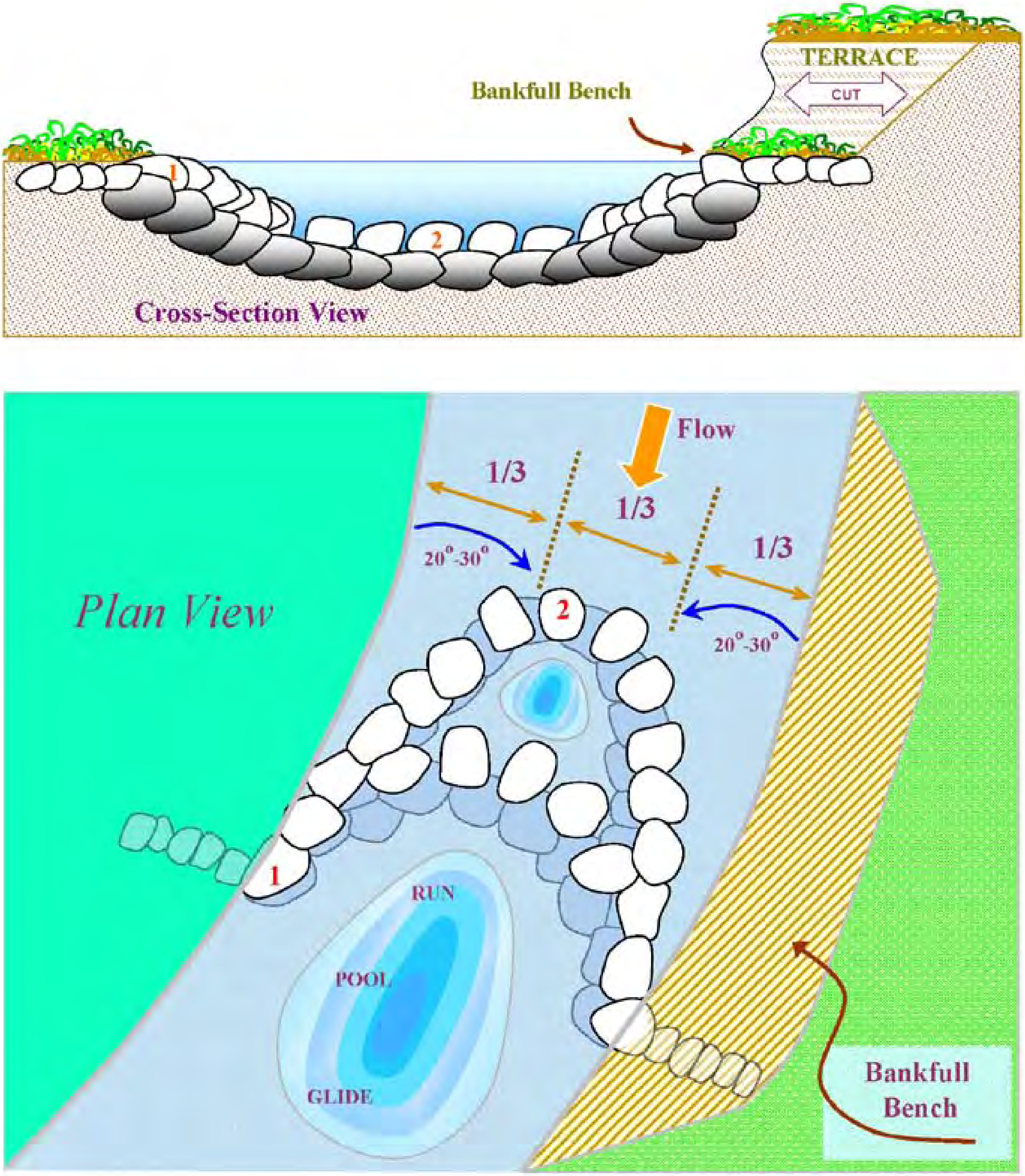
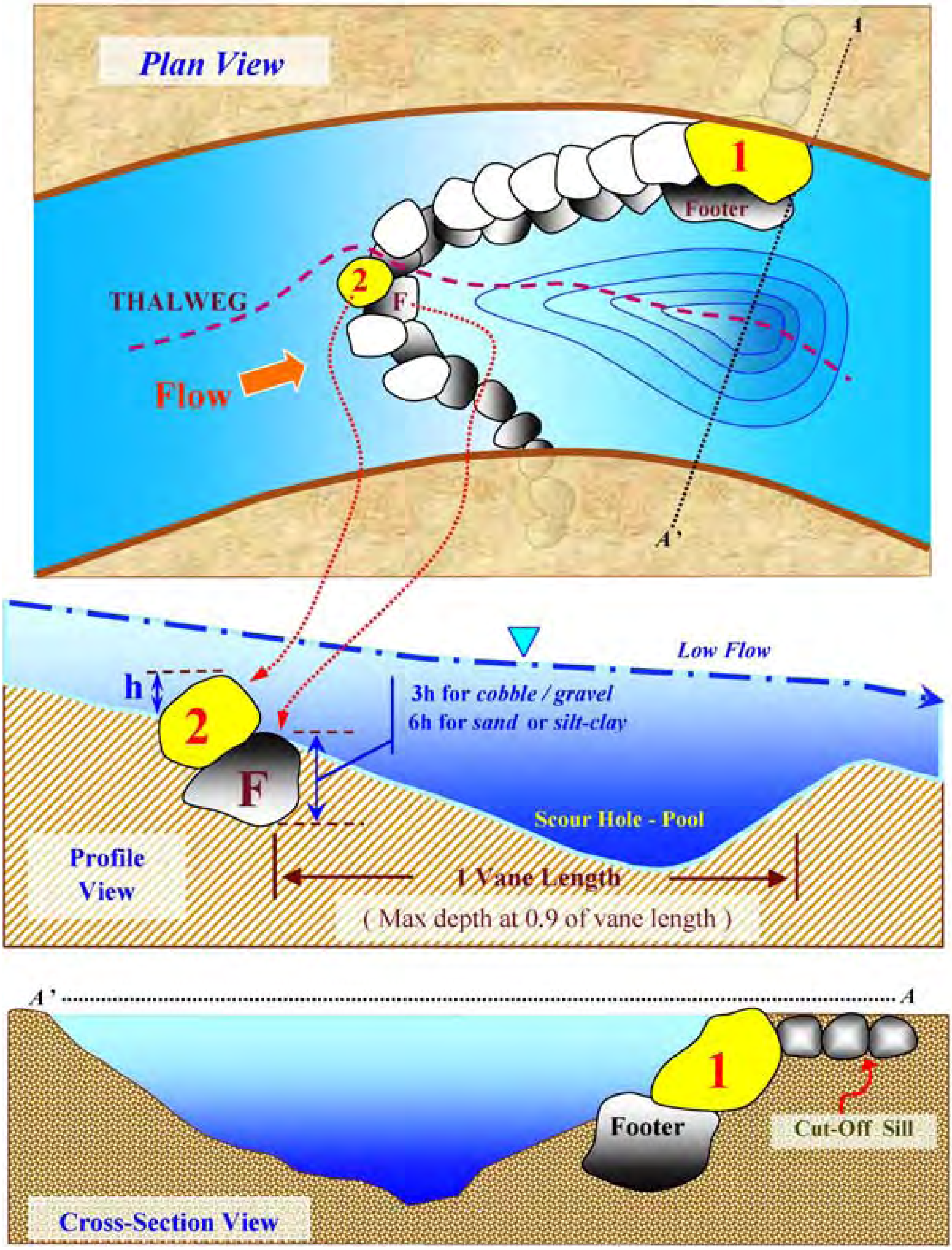


Figure 11–42 Locations/positions of rocks and footers in relation to channel shape and depths



strength to help maintain bank stability. The use of the J–hook (or fish hook) vane was developed to reduce near-bank stress to buy time for root development. The design is shown in figure 11–34 (Rosgen 2001e). Materials other than boulder are used in the J–hook vane. Logs and rootwads can be effectively used for multiple objectives (fig. 11–35 (Rosgen 2001e)). Variations in the use of materials are shown in figure 11–36 (Rosgen 2001e). An example of a J–hook vane is shown in figure 11–37, as constructed out of native boulders located in a reconstructed East Fork Piedra River. The structure also provides fish habitat, energy dissipation, bed-load transport, and provides protection of developments along streambanks. The use of a J–hook vane reduces the need for toe rock stabilization or a surfacing or hardening of the bank with riprap or other resistant structure. The length of bank protected is approximately two and a half to three times the length of the vane. The J–hook vane also is used to protect bridges and structures (Johnson, Hey, et al. 2001). Figures 11–38 and 11–39 provide examples of a J–hook vane using logs, rootwads, and log steps, as well as native boulders.

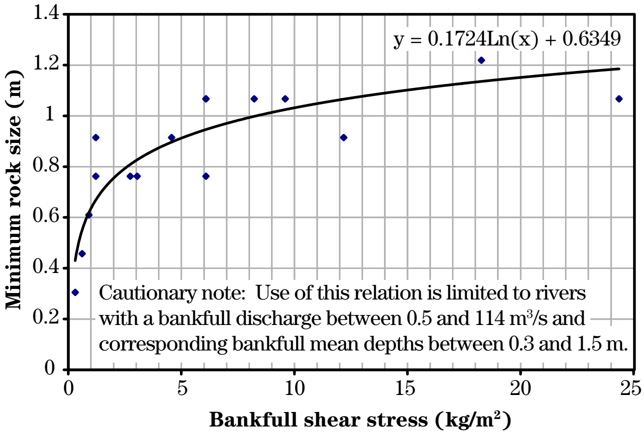
An example of the use of structure location forming compound pools consistent with meander curvature and bed features is shown in figure 11–40. The accompanying data indicate the slope and depth of the corresponding bed features. Regardless of structures, riparian vegetation establishment and management must be an active part of Rosgen geomorphic channel design.

Vane design specifications

The use of structures must be compatible with curvature and bed features of natural rivers. Figures 11–41 and 11–42 illustrate the use of rock for cross vanes, as well as for footers. Figure 11–43 provides guidance on rock sizing.

Vane slope—The slope of the vane extending from the bankfull stage bank should vary between 2 to 7 percent. Vane slope is defined by the ratio of bank height/vane length. For installation in meander bends, ratios of J-hook vane length/bankfull width is calculated as a function of the ratio of radius of curvature/bankfull width and departure angle (table 11–15). Equations for predicting ratios of J-hook vane spacing/bankfull width on meander bends based on ratio of radius of curvature/bankfull width and departure angle are shown in table 11–16. Vane length is the distance measured from the bankfull bank to the intercept with

Figure 11–43 Rock size



Cautionary note: Use of this relation is limited to rivers with a bankfull discharge between 0.5 and 114 m³/s and corresponding bankfull mean depths between 0.3 and 1.5 m.

Table 11–15 Equations for predicting ratio of vane length/bankfull width (V_L) as a function of ratio of radius of curvature/width and departure angle, where W = bankfull width (SI units)

Rc/W	Departure angle (degrees)	Equation
3	20	$V_L = 0.0057\ W+0.9462$
3	30	$V_L = 0.0089\ W+0.5933$
5	20	$V_L = 0.0057\ W+1.0462$
5	30	$V_L = 0.0057\ W+0.8462$

Table 11–16 Equations for predicting ratio of vane spacing/width (V_s) as a function of ratio of radius of curvature/width and departure angle, where W = bankfull width (SI units)

Rc/W	Departure angle (degrees)	Equation
3	20	$V_s = -0.006\ W+2.4781$
3	30	$V_s = -0.0114\ W+1.9077$
5	20	$V_s = -0.0057\ W+2.5538$
5	30	$V_s = -0.0089\ W+2.2067$

the invert elevation of the streambed at a third of the bankfull channel width for either cross vanes or J-hook vanes. For very large rivers, where it is impractical to extend the vane length to a third of the bankfull width, vane slope is calculated based on the specified angle of departure and the ratio of bank height/vane length where the vane arm intercepts the proposed invert of the structure.

The spacing of J-hook vanes can be increased by 0.40W for a low BEHI of less than 30 (Rosgen 1996, 2001b).

Bank height—The structure should only extend to the bankfull stage elevation. If the bank is higher, a bankfull bench is constructed adjacent to the higher bank, and the structure is integrated into the bench. The use of a cross vane is shown in figure 11–41 where a bankfull bench is created adjacent to a terrace bank.

Footers—The minimum footer depth at the invert for cobble and gravel-bed streams is associated with a ratio of three times the protrusion height of the invert rock. This is applicable to all three structures and is shown in figure 11–41 for a J-hook vane. For sand-bed streams, the minimum depth is doubled due to the deeper scour depths that occur. All rocks for all three structures require footers. If spaces are left between the invert rocks for cross vane and W-weirs, the top of the footer rocks becomes the invert elevation for grade control. If no gaps are left, the top of the surface rock becomes the base level of the stream.

Rock size—The relationship of bankfull shear stress to minimum rock size used for all three structures is shown in figure 11–43. The application of this empirical relation is limited to size of rivers whose bankfull discharge varies from 0.56 cubic meters per second (20 ft^3/s) to 113.3 cubic meters per second (4,000 ft^3/s). For example, appropriate minimum rock sizes for values of bankfull shear stress less than 1.7 kilograms per square meter (0.35 lb/ft^2) are associated only with stream channel bankfull depths from 0.26 to 1.5 meters (2–5 ft). This relation would not be appropriate for applications outside the limits of the data for a river slope of 0.0003 and a mean depth of 6.1 meters, even though a similar shear stress results, as in the example presented.

(g) Phase VII—Design implementation

A key requirement at this phase is to correctly implement the proposed design. This involves the layout, construction supervision, and water quality controls during construction.

Layout

It is necessary to pre-stake the alignment of the channel and to provide for protection of existing vegetation outside of the construction alignment. The layout involves making necessary onsite adjustments to the design based on constraints that may have been previously overlooked. Terrain irregularities, vegetation, property boundaries, and channel changes since the field data were collected can all require local modifications to placement. Staging areas for materials must be located for both the collection and temporary storage of materials. Stockpile areas, vegetative donor sites, and boundary references/facilities requiring special identification must be flagged. Locations of structure placement and type must be flagged.

Construction supervision (oversight)

Without exception, it is critical to have daily onsite inspection and construction coordination. It is essential to check grades, dimensions, structure placement, slopes, angles, and footers as an on-going requirement. It is most effective to coordinate this work during construction, rather than wait and provide a postconstruction inspection and find problems after the work is completed. The daily field review and documentation at this phase is very helpful to properly implement the design.

Water quality controls

As part of the layout, sediment detention basins, diversions, silt fences, and pump sites must be located to prevent onsite and downstream sediment problems and as required by Federal, state, and local ordinances. Staging of construction should also be conducted in such a manner to minimize sedimentation problems. Monitoring of water quality during construction may be required; thus, preventative measures will reduce future potential problems.

(h) Phase VIII—Monitoring and maintenance

Monitoring

The key to a successful monitoring program is the focus on the question or the specific objectives of monitoring. Monitoring is generally recommended to:

- measure the response of a system from combined process interaction due to imposed change
- document or observe the response of a specific process and compare to predicted response for a prescribed treatment
- define short-term versus long-term changes
- document spatial variability of process and system response
- ease the anxiety of uncertainty of prediction
- provide confidence in specific management practice modifications or mitigation recommendations to offset adverse water resource impacts
- evaluate effectiveness of stabilization or restoration approaches
- reduce risk once predictions and/or practices are assessed
- build a data base to extrapolate for similar applications
- determine specific maintenance requirements

Watershed and river assessments leading to restoration involve complex process interactions, making accurate predictions somewhat precarious. Measured data reflecting specific processes will continually improve understanding and prediction of sedimentological, hydrological, morphological, and biological process relations. Another great benefit resulting from monitoring is the demonstration of the effectiveness of reduced sediment problems and improved river stability due to management/mitigation—the central purpose of watershed and sediment assessments and restoration.

The state of the science cannot be advanced, nor can the understanding of complex processes be improved without monitoring. This phase is divided into three major categories:

- implementation monitoring to ensure restoration designs were laid out and constructed correctly
- validation monitoring (matching predicted to observed response, including model calibration and model validation)
- effectiveness monitoring (response of a process or system to imposed change)

Field methods/procedures are also addressed.

Implementation monitoring—Often the best-laid design plans are not implemented correctly due to various reasons. Response of a process and/or system must first address the question or possible variable of potential problem in instituting the design and stabilization/enhancement structures correctly. Riparian vegetation response may be ineffective if heavy grazing of livestock occurred. Exclusion fence maintenance can also be a key in vegetative recovery. If restoration designs were correct, but the contractor installed structures at the wrong angle, slope, or position on the bank, then near-bank stress reduction or erosion rate would not be a correct design implementation related to the effectiveness of the mitigation structure.

As-built measurements of dimension, pattern, and profile are essential to compare to design plans. Documentation of exact locations and types of stabilization and/or enhancement structures is also required. Many failures observed in monitoring are due to poor structure placement locations, construction problems, as well as inability to implement correct design specifications.

Vegetation establishment problems are often traced to establishing the wrong plant associations (species), planting at the wrong time of year and at the wrong elevations on the bank (water table), using the wrong techniques in transplanting and/or cutting plantings, and lacking an irrigation plan, if needed. This monitoring leads the designer to be very thorough in the vegetative planning and implementation phase of restoration.

Validation monitoring—For every prediction methodology, there is a procedure to validate the model. Some methods are more difficult and time consuming to validate than others, while some results can be determined on a short-term, rather than a long-term basis.

The monitoring will improve predictive capability for the future and potentially reduce mitigation measures that would not be effective for continued implementation. Conversely, if management practices indicate that sediment and/or stability conditions create obvious impairment, revised practices or specific process-based mitigation such as restoration may be recommended. The restoration specialist will gain the most confidence in the procedure only by field measurements, which not only validate a prediction, but determine if the initial assessment objectives were met. The various categories of validation monitoring include calibration and validation.

- **Validation**—Model validation involves testing of a model with a data set representing local field data. This data set represents an independent source (different from the data used to develop the relation). Often these data are used to extend the range of conditions for which the model was developed. Due to the uncertainty of prediction, this step is very important prior to widespread application of model output. Models can be extremely helpful in comparative analysis, even if observed values depart from measured. It is important, however, to be aware of the variability in the prediction. Often this monitoring outcome develops tighter relations or subsets of the initial relation, improving the understanding of the processes being predicted. An example of this type of monitoring would be similar to the effectiveness monitoring of streambank erosion rates presented previously. However, beyond measuring bank erosion rate, the observer is additionally required to measure the same parameters used to predict streambank erosion. The streambank prediction involves calculating a bank erosion hazard index (BEHI) and near-bank stress (NBS) (Rosgen 1996, 2001b). The analysis involves plotting the observed values with the predicted values for the same prediction variables. In many cases (with sufficient numbers of observations), this monitoring can lead to improved local or regional models, adapted for unique soil types and vegetation. Validation modeling provides documentation not only on how well the mitigation performed but also on the performance of the model.

  Validation modeling is designed to answer specific questions at specific sites/reaches. Design must be matched with a strong understanding of the prediction model. Validation modeling for the dimensionless ratio sediment rating curves would involve sampling sediment over the full range of streamflows to compare predicted to observed values. The measurements would need to be stratified by the same stream type and stability rating used for the prediction.

- **Calibration**—Models are often used to predict potential impairment. Model calibration is the initial testing of a model and tuning it to a set of field data. Field data are necessary to guide the modeler in choosing the empirical coefficients used to predict the effect of management techniques. An example of this is the data set of measured suspended sediment and bed-load sediment by stream type and stability to establish dimensionless ratio sediment rating curves used for design. These data were not collected in all areas where the model would potentially be applied; thus, another type of monitoring (validation) is helpful to determine if the model is appropriate for extrapolation to a particular region.

Effectiveness monitoring—The specific restoration design and implementation needs to be monitored. Monitoring will determine the appropriateness or effectiveness of specific designs and is implemented to reduce potential adverse sediment and/or river stability effects. Since monitoring requires site-specific measurements, temporal, spatial, scale, streamflow variation, and site/reach, monitoring is required to properly represent such variability and extrapolate findings of a process and/or system response to imposed change. Such variability factors are summarized as:

- **Temporal**—To isolate the variability of season and/or annual change, designs of monitoring should include monitoring over time scales. For example, measuring annual lateral erosion rates should include measurements once per year at the same time of year. If the objectives are to identify seasons where disproportionate erosion occurs, measurements may be obtained during snowmelt runoff, later post stormflow runoff, ice-off, and other periods of time associated with a given erosional process. Annual replicate surveys of particle size gradation of bed material under a permanent glide cross section will provide valuable information of magnitude, direction, and consequence of annual shifts. Temporal measurements must also cover a range of time during bed-load sampling as surges occur or slugs of bed load often appear as discontinuities of time. Sampling over recommended time periods for a given flow (generally 20 minutes) helps the probability of observing this variability (as opposed to an instantaneous point sample). Short-term versus long-term monitoring must also be considered based on the probability of change, the severity and consequence of effects, and the likelihood of variation. Sampling over many years, although costly, may be warranted to cover changes in wet/dry periods.

- **Spatial**—Variability of change/response involving spatial considerations can be identified by measurements of the same process at more than one site (cross section) or even more intense on the same site. For example, a longitudinal profile measured over a couple of meander wavelengths will indicate changes in the maximum depth and/or slope of pools, rather than just monitoring one pool at one location. Identifying more than one reach of the same morphological type can also be used to understand response trends. Sampling the spatial variability (both vertically and laterally) within a cross section of velocity and sediment helps identify or at least integrate such variability into a documented observation.
- **Scale**—Monitoring streams of various sizes and/or stream orders, but of the same morphological type and condition, will help identify variability in system response for proper extrapolation of results. For example, vertical stability measurements should be made on river reaches of the same condition and the same type, but at locations that reflect various stream widths (size) and stream order.
- **Streamflow variation**—Measurements of channel process relations need to be stratified over a range of seasonal and annual flows. For example, both suspended and bed-load sediment should be measured over a wide range of flows during the freshet, low-elevation snowmelt, high-elevation snowmelt, rising versus recession stages, stormflow runoff, and baseflow. This stratification for streamflow allows the field observer to plot a sediment rating curve that represents the widest range of seasonal flows where changes in sediment supply can vary.
- **Site or reach variation**—Monitoring a site for soil loss should include a soil type designation for potential extrapolation for similar conditions on similar soil types. The same is true for stream types. Sediment, hydraulic, and stability monitoring need to be stratified by stream type since such data will naturally vary for the reference (stable) reach between stream types. This information is helpful to be able to readily detect departure from a reference stream type, rather than differences between stream types.
- **Design concepts for effectiveness monitoring**—The key information summary from the assessments used to identify impairment and resultant restoration designs are as follows:
  - Summarize the causes of land use impacts responsible for the impairment.
  - Understand the processes affected.
  - Identify specific locations and reaches associated with adverse impacts.
  - Determine the time trends of impacts (potential recovery periods).
  - Identify the specific nature of impairment (direction, magnitude, and trend of change).
  - Evaluate the consequence of change.
  - Determine the nature, location, extent and quality of mitigation (implementation).

The information supplied in the following list leads the observer to identify the locations, nature of processes affected, the extent of the impact, and quality of the mitigation implementation. For example, if the dominant process impacted by a land use is causing disproportionate sediment supply, land loss and river instability, and is determined to be accelerated streambank erosion, then the lateral stability monitoring would emulate the following design:

- Locate reaches of the same stream type that represent an unstable bank.
- Locate reaches of the same stream type that represent a stable bank.

- Install permanent cross sections on each set of reaches.
- Install bank pins (if conditions warrant) and/or toe pins (see monitoring methods).
- Inventory vegetation, bank material, and slope for each site (see monitoring methods).
- Resurvey both streambanks at least once per year to measure soil loss (lateral erosion) and total volume (in cubic feet and tons/year).
- Compare annual lateral erosion rates over time to the stable reach and document rate of recovery based on the nature of the mitigation.

Vertical stability and enlargement rates and direction can also be monitored using permanent cross sections in a similar stratification procedure (comparison to reference reach, above versus below, before versus after).

Physical and biological monitoring—The sediment and river stability changes associated with assessment and design are primarily related to physical changes. However, the consequences of such physical changes are directly related to potential impairment of the biological function. Changes in river stability, such as aggradation, degradation, enlargement, and stream type changes, are also related to habitat and food chains. Limiting factor analyses assesses habitat loss due to river instability and/or excess sediment such as relations of holding cover, instream/overhead cover, water temperature, dissolved oxygen, and benthics. A range of information associated with stream condition can be stratified by stream type by stream stability including diversity index, population dynamics, age class distribution, spawning, rearing habitat, and many more attributes related to stream health. Biological monitoring should follow similar rules of inventory stratification based on the diverse nature of streams and their natural variability.

If a biologist is studying only the biological parameters within a specific ecoregion, the natural stable differences between reference reach stream types cannot be identified if the stratification of the inventory does not include stream types. In other words, a stable C4 stream type will not have the attributes of a stable E4 or B4 stream type, even though they are all gravel-bed streams. If the biological inventory is not stratified by stream type or stream stability, departure of habitat conditions between a stable C4 and an unstable C4 cannot be easily identified. Reference conditions that reflect biological potential must be stratified as a minimum by stream type and stream stability for adequate departure analysis to identify degree, direction, and magnitude of impairment. Companion biological inventories of assessment and monitoring can be very compatible with the monitoring methods of the physical system described.

Once this information is analyzed, the monitoring design can proceed. The next step is to identify a strategy of monitoring. Effectiveness monitoring should always be conducted near the activity responsible for the initial impairment. Four primary design strategies often utilized are as follows:

- Measurements obtained before versus after the initiation of a management change in the land use activity, mitigation, restoration, and enhancement. This can be very effective as it establishes a precalibration period that identifies premitigation variability of the measured parameters. Following mitigation, departure can be readily determined, assuming measurements take into consideration the aforementioned variability factors.
- Measurements or observations taken above versus below impact areas related to specific land uses and specific mitigation. For example, if two different grazing strategies are implemented, measurements of effectiveness can be observed above versus below fence line contrasts. This can also be implemented where a mitigation may only influence the lower reach of a river compared to the upper reach (assuming the same stream type).
- Measurements obtained determining departure from a paired watershed are often helpful as similar climatic events similarly impact both watersheds. The pairing would contrast a watershed that had extensive mitigation or land management change with one that had not been changed. This also assumes variability of scale, temporal, and spatial variability and comparisons of similar landscapes and stream types have been identified.

- Measurements obtained of a disturbed reach or site, receiving mitigation compared to a reference condition. This type of monitoring can occur at locations far removed from the reference reach. The reference condition, however, must be of the same soil type, stream type, valley type, lithology, and vegetative type.

Maintenance plan

To ensure that the implemented design is successful, it is key to have a maintenance plan. The maintenance plan must ensure the following:

- Survival of the riparian vegetation reestablishment—This could involve an irrigation supply or replanting/interplanting.
- Structure stability—Post-runoff inspections must be conducted of structures for grade control, bank stabilization and/or fish habitat enhancement. Maintenance needs are assessed and implemented to prevent future failures and to secure proper function.
- The dimension, pattern, and profile must stay within the natural variability or range as depicted in table 11–5 for each variable. Maintenance of these variables is recommended only if the values exceed the design channel ranges.
- The biological maintenance may involve reestablishment of described populations of various age classes and/or species of fish and/or food sources.

654.1103 Conclusion

The individual(s) responsible for the project should also become experienced by being involved in all phases of this methodology. If the same individual conducts the assessment and also completes the design, implementation, and monitoring, the desired objectives of restoration are the most likely to be accomplished. The complexity of this method requires great attention to detail, training, and an understanding of processes. The monitoring of the project, including the implementation, validation and effectiveness procedures, is the best approach to become experienced and knowledgeable about the Rosgen geomorphic channel design methodology.

Mathematical definitions

Variables	
Riffle cross-sectional area at bankfull	A_{bkf}
Pool cross-sectional area at bankfull	A_{bkfp}
Mean riffle depth at bankfull	d_{bkf}
Mean pool depth at bankfull	d_{bkfp}
Maximum glide depth at bankfull	d_g
Maximum riffle depth at bankfull	d_{mbkf}
Maximum pool depth at bankfull	d_{mbkfp}
Maximum run depth at bankfull	d_{run}
Diameter of riffle particle at 50% finer than size	D_{50}
Diameter of bar sample particle at 50% finer than size	$\hat{D}_{50}$
Diameter of riffle particle at 84% finer than size	D_{84}
Maximum size of particle on bar	D_{max}
Gravitational acceleration	g
Weight density of water	γ
Sinuosity	k
Low bank height	LBH
Meander length	Lm
Meander-length ratio	(Lm/W_{bkf})
Manning's *n*	n
Pool-to-pool spacing (based on pattern)	(p-p)
Bankfull discharge	Q_{bkf}
Hydraulic radius	R
Radius of curvature of meander	Rc
Average water surface slope (bankfull slope)	S
Slope of glide (water surface facet slope)	S_g
Stream length	SL
Slope of pool (water surface facet slope)	S_p
Slope of riffle (water surface facet slope)	S_{rif}
Slope of run (water surface facet slope)	S_{run}
Bankfull shear stress	τ
Dimensionless bankfull shear stress	τ^*
Bankfull mean velocity	u_{bkf}
Shear velocity	u^*

Variables	
Valley length	V_L
Valley slope	V_S
Riffle width at bankfull	W_{bkf}
Width-to-depth ratio at bankfull	(W_{bkf}/d_{bkf})
Width-to-depth ratio at bankfull of reference reach	$(W_{bkf}/d_{bkf})_{ref}$
Pool width at bankfull	W_{bkfp}
Belt width	W_{blt}
Meander-width ratio	(W_{blt}/W_{bkf})
Width of flood-prone area	W_{fpa}
Entrenchment ratio	(W_{fpa}/W_{bkf})
Stream power	ω

Subscripts	
Bankfull	bkf
Meander belt	blt
Flood-prone area	fpa
Glide	g
Maximum at bankfull	mbkf
Maximum at bankfull in pool	mbkfp
Pool	p
Reference reach	ref
Riffle	rif
Run	run