Sedimentation Engineering Design in River Restoration: System Stability Assessment for Design Guidance

F. Douglas Shields, Jr., Member, ASCE[1] *and Martin W. Doyle*[2]

Abstract

Since many river restoration projects involve manipulation of disturbed channels, the engineer should conduct an assessment of the present system to guide project planning and design. Four classes of stability assessment tools are identified and briefly reviewed: those based on Lane's relationship, channel reach classification, hydraulic geometry formulas, and relationships between sediment transport and hydraulic variables. Stability assessments require much professional judgment due to the qualitative nature of the tools available.

Introduction

The need for stability assessments

River channels selected for restoration projects are often unstable prior to restoration, i.e., they exhibit patterns of rapid bed or bank erosion or sedimentation relative to lightly degraded natural rivers in the same geologic and climatic region. These symptoms are driven by underlying imbalances in watershed sediment supply, transport, or storage (Sear 1996). An assessment of system stability should be performed early in the design process in order to select an appropriate level of effort for sedimentation engineering aspects of pre-design assessment, design, and post-project monitoring. In addition, since habitat degradation is often related to erosion or sedimentation, stability assessment is needed to develop restoration alternatives. The restoration project may itself affect channel stability, and this possibility must be explored in design.

---

[1] Research Hydraulic Engineer, USDA-ARS-National Sedimentation Laboratory, P.O. Box 1157, Oxford, MS 38655-1157, shields@sedlab.olemiss.edu.

[2] Graduate student, Department of Earth and Atmos. Sciences, Purdue Univ., West Lafayette, Indiana 47907.

What is a stability assessment?

A stability assessment consists of qualitative or quantitative analysis of a selected part of the fluvial system encompassing the restoration project to determine the direction and speed of morphologic changes. If possible, the dominant geomorphic processes influencing the channel and their root causes should be identified. The nature of the existing hydrologic response and the likelihood of future shifts in discharge and sediment load due to land use changes (e.g., urbanization or afforestation) should be considered. Existing instabilities in the channel system should be identified (Kondolf and Sale 1985; Kondolf 1990). The assessment provides a foundation for design and predictions of how the system will respond to the restoration project. An inadequate assessment may result in a restoration design that is obliterated by erosion or deposition within a short period of time, or one that degrades stream corridor resources or endangers floodplain assets.

The first step in performing a geomorphic assessment is to select the geographic boundaries for the analysis. The region included in the assessment should extend beyond the project reach, ideally to major geomorphic boundaries like watershed divides, reservoirs, or major confluences. However, resource limitations often dictate a smaller study area, and the engineer must exercise judgment in making tradeoffs between study quality and resource investment.

Types of stability assessments

Qualitative assessments are simple efforts requiring less than one week of effort for one person, consisting mostly of visual inspection. This type of assessment can be powerful when performed by someone with a high level of expertise. Large areas can be inspected from low-flying aircraft, with follow-up at selected sites on the ground. Quantitative assessments vary in methodology, but have in common the collation of data about the study area from a variety of sources to describe channel geometry, bed sediments, hydrology and land use in the past and present. One such assessment is the watershed-wide reconnaissance, which involves traversing all channels upstream of or adjacent to the project reach and visually assessing key parameters such as bed material types, channel morphology, and bank stability. Measurements such as channel width and depth, thickness of sediment deposits, and bank height and angle may also be collected. In some cases, tests may be run to determine the strength of bank soils and dendrological data may be collected from riparian trees to indirectly determine historical conditions.

Selecting a range of discharges to use for stability assessment

Use of most of the assessment procedures described below requires selection of a representative discharge or range of discharges. Full discussion of discharge selection for restoration assessment and design is beyond the scope of this paper, but a few observations will be made.

1. The term, "bankfull discharge" should be avoided in favor of other expressions such as "the range of channel-forming discharges." The literature abounds with confusing phrases like, "bankfull discharges are not bankfull in unstable channels."
2. Less precision is needed for discharges used in stability assessment than in design. Accordingly, less effort is required at this phase of the project. For design, Doyle et al. (1999) recommend computing an effective discharge using either flow data or computed flows and sediment discharges computed from flow using an appropriate sediment transport relationship. They found that the bankfull and two-year discharges were larger than the effective discharge for unstable reaches, and that capacity-return interval relations for channels with flashy hydrology were intrinsically different than those with relatively steady, snowmelt hydrology.

3. If gauge data are available, the discharge which matches the event with a one-to-two year return interval is often assumed to be the dominant or effective discharge, and thus is of greatest interest. Less frequent events are likely to be more important in ephemeral channels and those in arid and subarid landscapes.
4. Caution should be used when data are limited to mean daily discharges and watershed size is less than say 100 km^2, because peak discharges can greatly exceed daily means in small watersheds. Unit values (data collected at 15-min intervals) are often available upon request from the U.S. Geological Survey.
5. Representative discharges may be estimated for ungauged reaches using regression formulas (Jennings et al. 1994, Wharton et. al 1989) developed using appropriate regional data sets.
6. Field indicators of channel-forming stage are often converted to discharge estimates, but these values vary widely depending on the reach analyzed, the method used and the observer (Williams 1978). Johnson and Heil (1996) suggest a simple approach for selecting a range of values using fuzzy numbers.

Tools for stability assessment

Lane relations

Four types of tools are usually employed in stability assessment. All are easily mis-used, and professional judgment is called for. The first group of tools are based on the Lane (1955) relationship, which states that stream power is proportional to the product of sediment discharge and bed material size ($QS \sim Q_s d_s$). This relationship has been extended to predict fluvial response to disturbance by many other workers (e.g., Sear 1996). Use of these and similar relations for stability assessment is discussed in standard texts (e.g., Chang 1988). The engineer should be aware of important limitations. First, anticipated adjustments may not occur because the system is currently responding to prior disturbance. Second, the channel system may not be free to adjust. For example, the bed may contain bedrock controls which limit changes in slope or bed material may not become coarser because gravel and cobble are not available for transport. Slope is governed by channel pattern (straight, braided, meandering, etc.) but channel pattern changes are very difficult to predict, and may be governed by discontinuous (threshold) relations rather than continuous relationships. Third, the Lane-type relations do not explicitly allow for complex response (Schumm 1977), in which fluvial systems exhibit unsteady, complex behaviors (e.g., a period of channel scour followed by aggradation or long lags in system response) in response to a single external influence.

The greatest limitation to application of Lane-type relations to assessment is that these relationships allow prediction of the direction of a change, but not its magnitude. Knowledge of the history of disturbance is needed to assess the current status of a system. For example, channel straightening increases slope and in some cases peak discharge. The basic Lane relationship indicates that channel response will be characterized by increasing sediment load and erosion (Parker and Andres 1976). Bed sediment size will also increase if larger sediments are available. In such a case, it is very helpful to know the extent and dates for prior channelization. Hammer (1972) quantified channel response to disturbances associated with watershed urbanization.

The discharge-slope product QS which forms the left side of the Lane relation is stream power. Various workers have noted that stream channel pattern (straight, meandering, or braided) is reflective of the balance between stream power and sediment grain size. A review is provided by van den Berg (1995), who proposes a relationship based on “potential” stream power, which is computed using the valley slope rather than the channel slope. These relattions may be useful in stability assessment, since systems which are near the threshold between meandering and braided may respond strongly to restoration actions.

Channel classification

A second approach for stability assessment is a qualitative approach that places all components of a fluvial system in one of three categories based upon their dominant function: sediment sources, sediment transportation zones, or sediment sinks (Schumm 1977). An even simpler classification is offered by Thorne et al. (1996), who suggests that all channels are either unstable or "moribund". Moribund channels are unable to alter their boundaries due to the presence of geologic or engineering controls on geometry or discharge. A specific example of application of the Schumm approach to disturbed fluvial systems involves the use of conceptual channel evolution models (CEMs) (Harvey and Watson 1986, Simon 1989) to describe watersheds experiencing channel incision. Though essentially qualitative, CEMs are powerful tools because they link channel forms to key processes in a rational way that allows post- and pre-diction of geomorphic trends. Following procedures described by Simon and Downs (1995) and Thorne et al. (1996), key sites throughout the channel network in a given watershed can be inspected, and each reach can be classified as one of six CEM stages. Results of the inspection can be recorded on a form and entered into a GIS or mapping software for a synoptic visualization of ongoing processes throughout the system. Typically real-world watersheds do not follow the CEM models perfectly, but the absence of a pattern in channel stages indicates that instabilities are the result of local phenomena rather than system-wide instability. Use of classification systems which are not process-based is not recommended.

Qualitative reconnaissance for CEM classification of a reach 6 to 12 channel widths long can be done by an experienced person in 1 to 1.5 hours (Simon and Downs 1995). Selection of sites to inspect is critical—sites must form a sufficiently dense network throughout the watershed of interest, and additional attention must be paid to the most dynamic reaches. Local influences of bridge crossings should be avoided by inspecting reaches several hundred meters upstream from rather than at bridges. The quantity and quality of regional experience of the engineer is the key determinant of the quality of channel stability assessment based upon qualitative reconnaissance.

Johnson et al. (1999) reviewed and synthesized rapid stream channel stability assessment tools developed by Pfankuch (1978), the Federal Highway Administration ("Stream" 1995), and the aforementioned work by Simon and Downs (1995) and Thorne et al. (1996). The synthesized procedure is not limited to use in watersheds experiencing incision and results in a qualitative stability rating (excellent, good, fair, or poor) rather than a CEM stage. Effort and experience required is similar to that for the other methods, but estimates of average boundary shear stress and critical shear stress are required, and the effort required to generate these estimates varies widely based upon the availability of existing data, the size of bed sediments, and the confidence level required. Average boundary shear stress should be computed for a range of discharges bounding the effective or design discharge. Johnson et al. (1999) suggest computing critical shear stress using the Shields equation:

$$\tau_c = \theta(\gamma_s - \gamma_w) d_{critical}$$

Where θ = dimensionless Shields constant, varying from 0.01 for loosely packed sediments to 0.10 for tightly imbricated materials, τ_c is critical shear stress for movement of material of size $d_{critical}$, and γ_s and γ_w are specific weights for water and sediment.

The Johnson et al (1999) assessment method was developed specifically for road crossing stability, and may require some modification for reach stability assessment. In particular some of the indicators do not necessarily distinguish between local instability and natural channel processes (Doyle et al, In Press).

Both Johnson et al (1999) and Pfankuch (1978) equate channel stability with channel uniformity, associating local erosion caused by obstructions like woody debris with channel instability. While such features are causes of instability at road crossings, they are features common in natural channels and are critical for maintaining aquatic habitat.

Hydraulic geometry relationships

The third type of stability assessment tool involves application of hydraulic geometry relations, which are empirical formulas that predict channel width, depth, slope, etc. as a function of a selected discharge. Surrogates for discharge such as contributing drainage area have been used in modified versions these formulas. Although hydraulic geometry formulas and their predecessors, regime relations, are more than 50 years old (Leopold and Maddock 1953; Blench 1951), they remain popular due to their simplicity. Coverage of the use of these tools for restoration planning (Allen et al. 1994) and channel design (e.g., Shields 1996) is provided elsewhere, and here we focus exclusively on their use for stability assessment.

Essentially, the departure of a reach from a relationship based on data from adjacent lightly disturbed watersheds may be diagnostic of instability. For example, in their assessment of the Blackwater River in England, Thorne et al. (1996) found that mean width and depth were 47% and 42% larger, and mean velocity 233% smaller, respectively, than values predicted using applicable hydraulic geometry relationships (Hey and Thorne 1986). Although the computed stream power was 57% greater than predicted using the Hey and Thorne (1986) relationship, it remained low (~13 W m^{-2}) relative to unstable channels ($\geq$ ~35 W m^{-2}) (Brookes 1990). In contrast, meander wavelength and arc length were only 12 and 20% larger, respectively than predicted. Using this information and the results of a qualitative reconnaissance of a larger area, they concluded that the reach in question had been enlarged, but not straightened. The reach was assessed to be geomorphically active, but recovering its natural size only slowly due to low stream power and sediment availability.

Hydraulic geometry formulas are easily and widely misused. Like all empirical regressions, they are limited in their predictive capacity to the domain of independent variables used in their derivation. Extrapolation of formulas developed using data from England to the Western U.S. or from the Rocky Mountains to the Eastern seaboard leads to erroneous results. For example, Rinaldi and Johnson (1997) found that meander geometry equations developed by Leopold and Wolman (1960) overpredicted meander dimensions for small streams in central Maryland by average factors of 2.67, 2.22, and 2.48 for meander wavelength, amplitude, and radius of curvature, respectively. Since hydraulic geometry formulas are continuous, deterministic functions free of time dependence, they overlook threshold behaviors, indeterminacy (equifinality), and long term dynamism common in many fluvial systems.

Relationships between sediment transport and hydraulic variables.

The fourth and largest suite of tools used in stability assessment are various types of relationships between sediment transport and hydraulic variables. These may be applied at the watershed level, or at a particular cross section.

Slope-drainage area relations. Data from reconnaissance surveys (described above) may be used to develop relationships between channel slope and channel-forming discharge for channel reaches 1 to 10 km long. Discharge is plotted against slope for each reach, and points are classified as representatives of stable or unstable reaches. Stability classification is based on subjective interpretation of field indicators of stability (Thorne et al. 1996) successive surveys and aerial photos, and specific gauge analyses. If discharge information is lacking, channel slope is plotted against contributing drainage area, and specific gauge analyses are omitted. For example, field reconnaissance and evaluation of the Coldwater River Watershed, Mississippi, indicated that stable reaches plotted close to a line defined by

$$S = 0.0042A^{-0.282}$$

Where S is the slope of the energy gradient and A is upstream drainage area in km^2. Steeper reaches were degradational, while those with more gradual slopes were aggradational (Shields et al. 1995). Nearly identical coefficients were derived for stage V reaches within the Yalobusha River Watershed, Mississippi by Simon (1998).

Stream power. Outputs from one-dimensional hydraulic models may be used to compute stream power or average boundary shear stress for project reaches and these values may be compared to those developed for nearby stable reaches. For example, the product of mean velocity and shear stress at channel forming discharge, which is equal to the stream power per unit bed area, may be used as a criterion for stability in stream restoration projects (Brookes 1990). Stream power data are plotted as squares, triangles, and circles for straightened, re-meandered channels in Figure 1. Based on experience with several restoration projects in Denmark and the U.K. with sandy banks, beds of glacial outwash sands, and a rather limited range of bankfull discharges (~0.4 to 2 $m^3 s^{-1}$), a stream power value of 35 W m^{-2} discriminated well between stable and unstable channels. Projects with stream powers less than about 15 W m^{-2} failed through deposition, while those with stream powers greater than about 50 W m^{-2} failed through erosion.

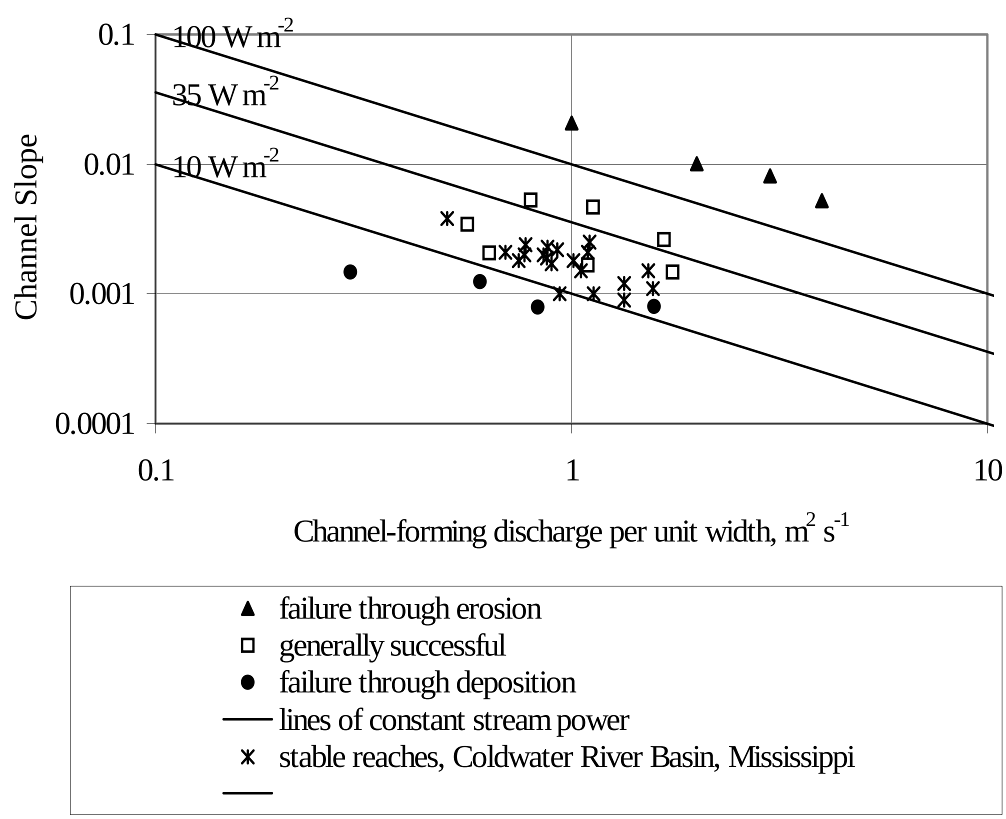

Figure 1. Brookes' stream power stability criteria.

Since these criteria are based on observation of a limited number of sites, application to different stream types (e.g., cobble-bed rivers) should be avoided. However, similar criteria may be developed for basins of interest. For example, data points representing stable reaches in the Coldwater River watershed of northwestern Mississippi are shown in the adjacent figure as stars. This watershed is characterized by incised, straight (channelized) sand-bed channels with cohesive banks. Slopes for stable reaches shown were measured in the field, and 2-year discharges were computed using a watershed model (HEC-1) (U.S. Army Corps of Engineers 1993). Downs (1995) developed stability criteria for channel reaches in the Thames Basin of the U.K. based entirely on slope: channels straightened during the 20th century were depositional if slopes were less than 0.005, and erosional if slopes were greater.

Incipient motion. Incipient motion analyses offer a quick check of bed stability in channels with beds coarser than sand (Pemberton and Lara 1984). These approaches indicate whether or not the bed will move when subjected to certain hydraulic conditions, but do not directly tell anything about channel stability. For example, shear stress may exceed the level needed to move a representative particle size, but since there is a supply of sediments from upstream, bed elevation may remain stable or aggrade. Most incipient motion relations indicate that critical bed size in mm is about 20 times the average velocity or about 10,000 times product of depth and slope. A list of five procedures useful for gravel or cobble beds is presented in Table 1. These five relationships predicted a critical sediment size of 20 to 31 mm for a hypothetical example where Q = 14.2 $m^3 s^{-1}$, channel width = 18.3 m, mean depth = 1.2 m, mean velocity = 1.0 m s^{-1}, slope = 0.0021, D_{90} = 34 mm, and Manning n based on bed material size = 0.03 (Pemberton and Lara 1984). Typically, the engineer computes the bed material sizes that are at the threshold of motion for the upper and lower bounds of the discharge range of interest, but the relationships in Table 1 may also be solved for slope or discharge given the other variables.

Table 1. Incipient Motion Stability Checks for Coarse, Noncohesive Beds Solved for Critical Bed Material Size, $d_{critical}$ (from Pemberton and Lara 1984). V_m= mean velocity, ω=terminal fall velocity, τ_c = critical bed shear stress, n_s = Manning coefficient for bed roughness, d_{90} = 90th percentile of bed sediment size.

Basic Relationship	**$d_{critical}$ mm**	**Remarks**	**Source (as cited by Pemberton and Lara 1984)**
$d_{critical} = 20.2\ V_m^2$	$20.2\ V_m^{\ 2}$	Based on assumption that velocity near bed is 0.7 V_m.	Mavis and Laushey (1948)
$V_m / \omega = 2.05$	$21.6\ V_m^{\ 2}$ ($d_{critical}$ > 2mm)		Yang (1973)
$\tau_c = \gamma_w\ DS$	13,000 DS ($d_{critical}$ > 6mm)	See Lane (1952) for graph which gives range of values	Lane (1952)
$\theta = \tau_c /[(\gamma_s - \gamma_w)\ d_{crit}]$	10,000 DS ($d_{critical}$ > 1mm)	Assumes Shields constant = 0.06	Shields (1936)
$d_{crit} = DS / [0.058\ (n_s/d_{90}^{1/6})^{3/2}]$	$17.2\ DS\ d_{90}^{0.25}\ n_s^{-1.5}$	Reduces to form similar to Lane and Shields when Strickler equation is used for n_s .	Meyer-Peter, Muller (1948)

The relationships in Table 1 involve varying amounts of theory and empiricism, and the engineer should be familiar with the underlying assumptions before interpreting their results. However, we have omitted the details and simply reduced the equations to simplest form to yield bed material size in mm for ease of use. It is important to note that incipient motion analyses are invalid for sand channels or gravel beds in motion at the discharge of interest because they presume zero transport of the critical bed size at the selected discharge. Some observers suggest the Shields constant θ = 1.5 to 1.8 for stable, moving-bed sand channels at channel-forming discharge (Parker, personal communication), which would yield a critical sediment size in mm = (330 to 400 times the product of depth (in m) and slope.

Silt and clay beds. For beds finer than sand, few tools exist and much uncertainty arises due to the complexity of cohesive bed erosion. However, see above regarding critical values of stream power and slope. Erosion of cohesive materials is affected by water quality, material history (weathering and saturation), and by macroscale phenomena (e.g., zones of weakness between cohesive blocks). Current research emphasizes the importance of positive and negative pore water pressure in cohesive beds and banks (Simon and Hanson 1999). Neill (1973, in Pemberton and Lara 1984) published competent velocities for erosion of cohesive materials ranging from 0.6 to 1.8 m s^{-1} for flow depth = 1.5 m, and 0.8 to 2.6 m s^{-1} for flow depth = 15 m.

Sediment budgets. Sediment budgets for channel reaches are at the upper end of a continuous scale of complexity and effort for stability assessments, and at the lower end of the scale for design. Detailed computations must necessarily be postponed until the design stage, as project dimensions and boundaries are required. Nevertheless, assumed channel properties may be used to good effect within the bounds of normal sediment transport relationship accuracy. SAM, a software package developed by the U.S. Army Engineer Waterways Experiment Station (Copeland 1994) may prove useful in selecting an appropriate sediment transport relationship and in computing sediment budgets for steady, uniform flow at single cross sections. The user may select from 19 sediment transport relations. SAM requires that the user either provide the bed material discharge input to the design reach, or specify the discharge, channel geometry, and bed sediment size for a “supply reach” upstream from the design reach. SAM computes sediment discharge for the supply reach assuming that it is transporting bed material at full capacity. SAM then computes a family of stable geometries for the design reach, including one for which stream power is a minimum. A warning is issued if there is no geometry for the design reach competent to transport the supplied load.

Bank stability. Bed stability does not ensure bank stability. Bank erosion is difficult to predict and simulate, and designers may find it necessary to protect the outer banks of bends and other locations subjected to potentially erosive flows if the consequences of bank erosion are unacceptable. Newly constructed banks are more readily eroded than those that have become well-vegetated. If the aim of the project is a partial return to a less-disturbed stream condition, then usually some additional bank erosion is desirable, and many ecosystems have key species that depend on habitats created by lateral channel migration. Mass failure of steep, cohesive banks is related to bank height, bank angle, and soil properties. If bank heights are greater than about 3 m and angles greater than about 45 degrees, a stability analysis may allow assessment of the severity of bank instability and the need for remedial measures. A stability chart may be prepared for a given set of bank soil properties, as described by Thorne (1999). However, if bank soil properties are not known, a tabulation of stable and unstable bank heights may be derived from the watershed qualitative reconnaissance.

Assessment Tool Selection

Selection of a suite of tools for a particular project involves considerable judgment, and is strongly influenced by the availability of existing data sets, the experience of responsible personnel, and economic factors. However, some generalizations can be made. Lane-type relations are good for quick preliminary assessments, particularly where system disturbance is dominated by a shift in one of the main variables. Process-based classification schemes are most highly developed for fluvial systems disturbed by influences leading to rapid incision or aggradation. Hydraulic geometry approaches are limited to projects located in regions for which extensive data sets are available. Inicipient motion type analyses including Shields parameters are usually limited to channels with beds dominated by material coarser than sand, while sediment budgets are best for sand bed streams prone to aggradation. Cohesive boundary channels are most difficult to analyze, and empirical tools such as slope-area relations, regional stream power indices or shear stress thresholds are often applied. Channels with cohesive banks higher than about 3 m usually call for some type of bank stability analysis.

APPENDIX. REFERENCES

Allen, P. M., Arnold, J.G., and Byars, B.W. (1994). Downstream channel geometry for use in planning-level models. *Water Resources Bulletin* 30(4), 663-70.

Blench, T. (1951). Regime Theory for Self-Formed Sediment-Bearing Channels. *American Sociey of Civil Engineers: Transactions, Paper No. 2499* : 383-408.

Brookes, A. and Shields, F. D., Jr. (Eds.) (1996). *River Channel Restoration*. John Wiley & Sons, Chichester, U.K.,

Brookes, A. (1990). Restoration and Enhancement of Engineered River Channels: Some European Experiences. *Regulated Rivers: Research & Management* 5, no. 1: 45-56.

Buffington, J.M. and Montgomery, D.R. 1997. A Systematic Analysis of Eight Decades of Incipient Motion Studies, with Special Reference to Gravel-Bedded Rivers. *Water Resources Bulletin* 33(8): 1993-2029.

Chang, H.H. (1988). *Fluvial processes in river engineering*. John Wiley & Sons, New York.

Copeland, R.R. (1994). *Application of Channel Stability Methods-Case Studies*. Technical Report HL-94-11, US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, USA.

Downs, P.W. (1995). Estimating the Probability of River Channel Adjustment. *Earth Surface Processes and Landforms* 20, 687-705.

Doyle, M.W., Boyd, K. F. and Skidmore , P. B. (1999). River Restoration Channel Design: Back to the Basics of Dominant Discharge. *Second International Conference on National Channel Systems*, Niagra Falls, Canada.

Doyle, M.W., Rich, C., Harbor, J. M., and Spacie, A. (In Press). Geomorphic stability assessment in urbanized streams. *Physical Geography,* Special Issue on Human Impacts in Geomorphology.

Hammer, T.R. (1972). "Stream channel enlargement due to urbanization", *Water Resources Research*, 8, 1530-40.

Harvey, M. D., and Watson, C.C. (1986). Fluvial Processes and Morphological Thresholds in Incised Channel Restoration. *Water Resources Bulletin: American Water Resources Association* ,22(3), 359-68.

Hey, R.D., and Thorne, C.R. (1986). Stable Channels with Mobile Gravel Beds. *Journal of Hydraulic Engineering* 112(8), 671-689.

Jennings, M. E., Thomas, W. O., Jr., and Riggs, H. C., (1994). Nationwide summary of U.S. Geolgocal Survey regional regression equations for estimating magnitude and frequency of floods for ungaged sites, 1993: *U.S. Geological Survey Water-Resources Investigations Report 94-4002*, 196 pp.

Johnson, P., and Heil, T. (1996). Uncertainty in Estimating Bankfull Conditions. *Water Resources Bulletin* ,32(6), 1283-1291.

Johnson, P.A., Gleason, G.L., and Hey, R.D. (1999). "Rapid Assessment of Channel Stability in Vicinity of Road Crossing." *Journal of Hydraulic Engineering*, 125(6), 645-651.

Kondolf, G. M. (1990). Hydrologic and channel stability considerations in stream habitat restoration. *Environmental Restoration: Science and Strategies for Restoring the Earth.*, 214-227. Covelo, California: Island Press.

Kondolf, G. M., and Sale, M.J. (1985). Application of Historical Channel Stability Analysis to Instream Flow Studies, Publication No. 2527, Environmental Sciences Division, Oak Ridge National Laboratory. *Proceedings of* *the Symposium on Small Hydropower and Fisheries*, Bethesda, Maryland: American Fisheries Society, 184-194..

Lane, E.W. (1955). The Importance of Fluvial Morphology in Hydraulic Engineering. *Proceedings: American Society of Civil Engineers* 81, no. 745: 745-1 - 745-17.

Leopold, L.B., and Maddock, T., Jr. (1953). The Hydraulic Geometry of Stream Channels and Some Physiographic Implications. *United States Government Printing Office*, no. 252: 117-27.

Leopold, L.B., and Wolman, M.G. (1960). "River meanders", *Bulletin of the Geological Society of America*, 71, 769-94.

Neill, C.R. (1973), "Guide to Bridge Hydraulics", Published for Roads and Transportation Assosciation of Canada.

Parker, Gary, and David Andres. (1976). Detrimental Effects of River Channelization. *American Society of Civil Engineers From the Proceedings of the Symposium on Inland Waters for Navigation, Flood Control & Water Diversions*: 1248-66. Colorado State University, Fort Collins.

Pemberton, E. L., and Lara, J.M. (1984). *Computing Degradation and Local Scour: Technical Guideline for Bureau of Reclamation*, Denver, CO.

Pfankuch, D.J. (1978). "Stream reach inventory and channel stability evaluation." *Rep.*, U.S. Department of Agriculture, Forest Service, Northern Region.

Rinaldi, M., and Johnson, P.A. (1997). Characterization of stream meanders for stream restoration. *Journal of Hydraulic Engineering*, 123(6), 567-70.

Schumm, S. A. (1977). *The Fluvial System.* New York: John Wiley and Sons, Inc.

Sear, D. A. (1996). The Sediment System and Channel Stability. *River Channel Restoration: Guiding Principles for Sustainable Projects*, A. Brookes and F.D. Shields, Jr., eds., Chichester,U.K.: John Wiley and Sons, Ltd., 149-99.

Shields, F. D., Jr., Knight, S. S., and Cooper, C. M. (1995). Rehabilitation of watersheds with incising channels in Mississippi. *Water Resources Bulletin* **31**(6):971-982.

Simon, A. (1989). A Model of Channel Response in Disturbed Alluvial Channels. *Earth Surface Processes and Landforms*, 14(1), 11-26.

Simon, A. (1998). *Processes and forms of the Yalobusha River system: a detailed geomorphic evaluation*. Vicksburg, MS: U.S. Army Corps of Engineers.

Simon, A., and Downs, P.W. (1995). An interdisciplinary approach to evaluation of potential instability in alluvial channels. *Geomorphology* 12: 215-32.

Simon, A., and Hanson, G.J. (1999). "Pore Pressure Effects on the Entrainment and Erosion of Cohesive Sediments in Incised Channels: Positive Pressure and Matric Suction," Abstracts, International Conference on Drainage Dynamics and Morphology, Jerusalem.

"Stream stability at highway structures." (1995). *Hydr. Engrg.* Circular No. 20: FHWA-IP-90-014, 2nd ed., Office of Engineering, Bridge Division Federal Highway Administration, Washington, D.C.

Thorne, C. R., Reed, S. and Doornkamp, J. C. (1996). *A Procedure for Assessing River Bank Erosion Problems and Solutions*. Almondsbury: National Rivers Authority.

Thorne, C.R. (1999). Bank Processes and Channel Evolution in the Incised Rivers of North-Central Mississippi. *Incised River Channels*, S.E. Darby and A. Simon, eds., Chichester, U.K.: John Wiley and Sons, 97-121.

Van den Berg (1995). Prediction of channel pattern of alluvial rivers. *Geomorphology* 12(1995):259-279.

Wharton, G., Arnell, N.W., Gergory, K.J., and Gurnell, A.M. (1989). River Discharge estimated from Channel Dimensions. *Journal of Hydrology* 106, 365-76.

Williams, G. P. (1978). Bankfull discharge of rivers. *Water Resources Research* 14(6):1141-1480.