CHAPTER 9

Stream Restoration

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9.1 INTRODUCTION

9.1.1 Scope

This chapter describes the application of the principles described elsewhere in this manual to a special class of engineering problems: stream restoration. Basic concepts are presented first in a qualitative discussion of "big ideas" rather than technical "how-to" guidance. This is followed by a description of how to prepare and execute a sediment studies plan for a stream restoration project. The generic approach described here may be too elaborate for small-scale, simple projects, but is less complex than needed for systemic types of restoration that aim to promote fundamental shifts in fluvial characteristics. However, some sedimentation analysis is needed for all stream restoration projects. Analytical tools useful for restoration analysis range from empirical relationships many decades old to recently developed science. References are provided in lieu of a full description of some of the analytical tools.

9.1.2 Basic Concepts

9.1.2.1 Definitions The term "river restoration" is used to refer to a wide spectrum of activities (Table 9-1). Definition of terms is an essential starting point, because the engineer must be able to communicate clearly with project stakeholders to create realistic expectations for project outcomes. Stakeholders may prefer to call a project "restoration," when in fact it is something else (e.g., an effort to improve aesthetics). No harm is done if everyone understands that the project will not restore a preexisting ecosystem. Whereas restoration aims to return an ecosystem to a former condition, rehabilitation and reclamation imply putting a landscape to a new or altered use to serve a particular human purpose. Restoration is not preservation, which keeps conditions in their current state, nor is it naturalization, which targets socially desirable improvement, but not a preexisting state. True restoration may be thought of as an attempt to return an ecosystem to its historic (predegradation) trajectory (SER 2002). Although this "trajectory" may be impossible to determine with accuracy, the general direction and boundaries may be established through a combination of information about the system's previous state, studies on comparable intact ecosystems, information about regional environmental conditions, and analysis of other ecological, cultural, and historical reference information (SER 2002). In this chapter, "restoration" refers to restoration, rehabilitation, and components of the other activities listed in Table 9-1 that lead to partial recovery of predisturbance ecosystem functions and attributes.

- In practice, river restoration projects are either targeted at entire watersheds or at reaches of channel 20 to 100 channel widths long, or more local measures to control erosion of gullies, zero-order tributaries, or single bends (Shields et al. 1999). Smaller-scale local measures are nested within reach-scale projects, whereas watershed restoration projects include reach-scale efforts and/or activities and programs designed to fundamentally impact land use and management (Williams et al. 1997). Watershed-scale actions are generally preferred from an engineering and ecological perspective because they have the greatest potential to influence fundamental causes of degradation. Fluvial processes operating at landscape or watershed scale can govern system response at smaller scales. However, economic and political factors usually dictate smaller-scale strategies for restoration projects. Local measures often used for restoration include erosion control structures (e.g., bank protection measures or grade control structures), floodplain and streambank revegetation, and habitat

Table 9-1 Definitions for Terms often Associated with River Restoration (NRC 1992; Brookes and Shields 1996; FISRWG 1998)

Term	Definition	Remarks
Restoration	Reestablishment of the structure and function of ecosystems. Ecological restoration is the process of returning an ecosystem as closely as possible to predisturbance conditions and functions. In the United States "predisturbance" usually refers to pre-European settlement. Because ecosystems are dynamic, perfect replication of a previous condition is impossible.	The restoration process re-establishes the general structure, function, and dynamic but self-sustaining behavior of the ecosystem. It is a holistic process not achieved through the isolated manipulation of individual elements.
Rehabilitation	Partial recovery of ecosystem functions and processes. Rehabilitation projects include structural measures and "assisted recovery." Assisted recovery refers to removal of a basic perturbation or disturbance (e.g., excluding grazing livestock from a riparian zone) and allowing natural processes (e.g., regrowth of vegetation, fluvial processes) to operate, leading to recovery of ecosystem function.	Rehabilitation does not necessarily re-establish the predisturbance structure, but does establish geological and hydrologically stable landscapes that support the natural ecosystem mosaic.
Preservation	Activities to maintain current functions and characteristics of an ecosystem or to protect it from future damage or losses.	
Mitigation	An activity to compensate for or alleviate environmental damage. Mitigation may occur at the damaged site or elsewhere. It may restore a site to a socially acceptable condition, but not necessarily to a natural condition.	Mitigation is often a permit requirement as part of some nonrestoration type of action; it thus may form the basis for a restoration project.
Naturalization	Management aimed at establishing hydraulically and morphologically varied, yet dynamically stable fluvial systems that are capable of supporting healthy, biologically diverse aquatic ecosystems. Does not require reference to a certain preexisting state.	The naturalization concept (Rhoads and Herricks 1996; Rhoads et al. 1999) recognizes that naturalization strategies are socially determined and place-specific. In human-dominated environments recurring human management and manipulation may be a desired and even necessary ingredient in the dynamics of the "naturalized" system.
Creation	Forming a new system where one did not formerly exist (e.g., constructing a wetland).	Concepts similar to those used in restoration or rehabilitation are often applied to produce ecosystems consistent with contemporary hydrology and morphology.
Enhancement	Subjective term for activities undertaken to improve existing environmental quality.	Stream enhancement projects of the past often emphasized changing one or two physical attributes in expectation that biological populations would respond favorably. But monitoring data were typically limited.
Reclamation	A series of activities intended to change the biophysical capacity of an ecosystem. The resulting ecosystem is different from the ecosystem existing prior to recovery.	Historically used to refer to adapting wild or natural resources to serve a utilitarian purpose, such as draining wetlands for agriculture.

structures (Section 9.5.2). Reach-scale measures include local measures applied over long reaches plus fencing to exclude livestock from stream corridors, channel reconstruction (Section 9.5.1.1.2), floodplain reconnection, dam removal, and revision of reservoir release strategies. Watershed-scale efforts include widespread application of these local and reach strategies plus programs that address exotic species, land use management, best management practices for forestry and agriculture, and storm water management. Strategies for restoration projects often include activities to promote higher levels of physical dynamism (e.g., flooding, avulsion, island formation, braiding, channel migration) in streams that have been dammed, leveed, or channelized.

On the other hand, many stream systems have been so disturbed by human activities or natural events that they have levels of physical instability that far exceed natural levels to which plants and animals are adapted. Restoration activities in these systems involve recovering stability through flow regulation, revegetation, and building erosion control structures (Shields et al. 1999). A tension exists between restoring the dynamic character of fluvial systems and providing socially acceptable levels of channel stability. During the last 50 years, most efforts at stream manipulation have emphasized stabilization. The shift toward allowing dynamic behavior may be difficult for many stakeholders to accept—given their lack of experience with such approaches. This concept is explored further in Section 9.5.

9.1.2.2 River Dynamism Because restoration implies at least a partial return to naturally dynamic structure, processes, and functions, it is useful to consider the characteristics of unmodified or lightly impacted rivers. When viewed over several decades, natural fluvial systems appear to be complex physically and ecologically; well connectedw vertically between water and substrate, longitudinally between upstream and downstream zones, and laterally between channels and floodplains; and infrequently disturbed by large natural events that keep the system in a long-term state of adaptation to seek balance and stability (Vannote et al. 1980; Williamson et al. 1995a; Bella et al. 1996; Klingeman et al. 1998). The movement of water and the transport of sediment and large woody debris cause the physical features of rivers to change continually. Although channel slope, sinuosity, and floodplain elevation evolve gradually, smaller-scale features such as individual bends, bars, and short bank segments may change rapidly during high flows. Large flows cause extensive interactions between river channels and floodplains. Infrequent disruptive events such as floods, earthquakes, volcanic eruptions, and landslides often trigger systemwide fluvial response. Severe droughts also constitute a type of natural disturbance.

The response of a fluvial system to natural or manmade disturbance varies with the geomorphic context. For example, lightly altered stream systems in regions of mild relief and humid climate (e.g., the United Kingdom or the eastern coastal plain of the United States) approach a conceptual ideal referred to as dynamic equilibrium (Schumm 1977). Bank erosion and bank-line migration typically occur in such a stream, but over a period of, say, several decades, the reach-average channel width, depth, and slope do not change, and sediment outflow is equal to sediment inflow (Thorne et al. 1996a). Furthermore, the average dimensions of such stream channels appear to be power functions of discharge of a certain frequency (see Section 9.3.1). When perturbed, such systems tend to respond in a way that returns the channel dimensions to the equilibrium status or to a new set of equilibrium dimensions. In contrast, systems with high-variance flood-frequency regimes are governed by extreme floods and exhibit transient behavior without the development of "characteristic" geometries typical of systems in dynamic equilibrium. Such fluvial systems are common in arid, semiarid, and proglacial environments. Flood-dominated streams pose an especially difficult challenge for restoration because system dynamics are pulsed, episodic, and often catastrophic in nature. A single flood can radically reconfigure stream morphology for years, decades, or centuries (Baker et al. 1988).

Stream ecosystems are resilient and well adapted to natural disturbances (Pickett and White 1985). Removal of moderate disturbances causes progressive physical changes (e.g., infilling of pools by sediment) and reduces the ability of biological populations to recover from severe disturbances. Biological changes follow removal of disturbances. For example, the plant community in a large fresh-water marsh in an arid hydrologically closed basin was found to require significant interannual flow variation (Klingeman et al. 1971). In another case, an intermediate frequency of bed-mobilizing events was associated with maximum species richness in a gravel-bed stream (Townsend et al. 1997). Evidently a greater frequency of bed disturbance reduced richness by excluding taxa that could not quickly recolonize in the intervals between disturbances, whereas less frequent disturbance allowed competitive exclusion of species that were capable colonists but poor competitors.

9.1.3 Role of Sedimentation Engineering in Stream Restoration Projects

9.1.3.1 The Engineer as Part of a Team Comprehensive restoration activities influence the entire fluvial system—including the channel, banks, riparian zone, and floodplain—and address biological processes and functions as well as physical conditions and river flows. Thus, hydrology, hydraulics, sediment transport, and channel morphology must be evaluated for the restoration site and for other potentially impacted areas. Frequently the same engineer or engineering team assumes responsibility for hydrologic, hydraulic, and sedimentation analyses. For example, the same person may perform hydrologic simulation to generate design discharges; backwater computations to predict water surface elevation, depths, velocities, and shear stresses at design discharge; and sediment transport computations to assess potential for erosion and sedimentation. Regardless of the division of labor, the persons charged with sedimentation engineering analyses should be involved in project planning, design, construction, and postconstruction activities (monitoring, operation, maintenance, and management).

Stream channel restoration projects can succeed as engineering exercises but fail dismally as ecological resource recovery efforts. As noted above, the definitions for restoration-type activities imply that the bottom-line objective for these efforts is ecological. It is imperative, therefore, that the engineer obtain guidance and input from a multidisciplinary team including earth and natural scientists. Communication within such a team is often difficult, because each discipline has its own values, tacit assumptions, and jargon. FISRWG (1998) can be very helpful in cross training among disciplines and facilitating team communication. Successful team function depends upon members working within the confines of their areas of expertise but understanding and interacting with other team members. A hydraulic engineer with a short course in ecology is not qualified to set habitat objectives, whereas a fisheries biologist with a short course in fluvial geomorphology is similarly not qualified to perform geomorphic assessment or channel design. Although many hydraulic engineers have broad experience in river erosion and sedimentation, team participation by geomorphologists (persons with regional experience and advanced degrees) is often necessary if the project locale is characterized by dynamic landforms and channels.

9.1.3.2 Setting Objectives Restoration project objectives should be defined early and clearly by stakeholders. Support for a restoration project is usually related to broad social, political, and institutional goals (Smith and Klingeman 1998). For implementation, such goals require rephrasing in terms of achievable objectives with measurable outcomes. Thus, although project goals may be general, project objectives must be specific and quantified to allow clear communication and postproject appraisal. Facilitation by the project manager and by technical experts such as the sedimentation engineer may be needed to convert general goals into achievable objectives, as well as to build consensus among diverse stakeholder groups and to ensure that objectives are clearly stated and not contradictory. For example, some projects may inadvertently adopt mutually exclusive objectives such as (1) the elimination of stream bank erosion and (2) the restoration of riparian plant communities that depend on erosion and deposition. Setting objectives for restoring physical habitat value to degraded river corridors requires an assessment of current habitat quality and a description of the factors contributing to degradation. As planning and design proceed, additional social or natural constraints may become apparent, and the original objectives may need to be modified accordingly.

9.1.3.2.1 Habitat Assessment and Setting Objectives Restoration project objectives often are phrased in terms of habitat manipulation. River corridors are often a rich complex of plant and animal habitats. Each life stage of each species has its own habitat requirements, and these are often expressed as ranges of physical variables. However, because stream corridors contain many species, and because habitat requirements are normally not known with precision, assessing the current status of habitat quantity or quality is inexact and involves professional judgment. Many natural events and human activities degrade habitat (Table 9-2), but the nature and magnitude of the degradation is hard to quantify. The engineer must work closely with biologists or ecologists to obtain an adequate assessment of the current status of habitat quality and to define critical elements that should be addressed in the restoration project. A geomorphologist can assist by identifying the factors responsible for physical habitat characteristics. The engineer may provide expertise in obtaining and interpreting data and model simulations describing physical aspects of habitat such as discharge, bed material characteristics, flow width and depth, current velocity, temperature, turbidity, and dissolved oxygen concentration.

An introduction to quantitative habitat assessment tools including the instream flow incremental methodology and the habitat evaluation procedure is provided by Federal Interagency Stream Restoration Working Group (FISRWG

Table 9-2 Typical Forms of River Corridor Degradation (FISRWG 1998; SRSRT 1994)

Basic cause	Typical examples	Types of degradation
Natural events	Floods, landslides, earthquakes, other tectonic events	Alteration of habitat, blockage of access to habitat, change in water quality or quantity
Land use changes	Urbanization, logging, animal grazing, mining, road building	Direct: Damage to banks and bed from animals and machines, pollution. Indirect: Increase in sediment production, water pollution, reduction in shade and organic inputs (leaves and twigs) from riparian zone, perturbation of hydrologic patterns
Flow regulation, withdrawal, or diversion	Dams, irrigation withdrawals, interbasin transfers	Depletion of aquatic habitat, inundation of stream habitat, replacement of natural flow patterns with regulated flow, perturbation of sediment transport patterns
Channel modifications	Channelization, bank protection, clearing, and snagging	Replacement of natural boundaries and geometries, overall simplification of physical complexity and heterogeneity.

1998). Additional tools for evaluating stage, discharge, and other time series variables relative to a reference or undegraded condition are described by Richter et al. (1996; 1998).

9.1.3.2.2 Effects of Project Scale on Objectives Project scale is a major consideration for stakeholders and the design team in setting objectives (Smith and Klingeman 1998). Project scope and scale control the breadth of restoration options (Klingeman 1998; Smith and Klingeman 1998) as well as the role of sedimentation engineering. Early stream restoration projects were usually small-scale efforts to manipulate physical habitat (e.g., Thompson (2002b)). Similar efforts remain common today. These projects typically focus on local scour and deposition but often do not consider sediment transport beyond the immediate site. Initial successes and failures showed the need to develop approaches that would operate at watershed and ecosystem scales using concepts from physical and biological sciences. A larger-scale project may address major system processes such as channel meandering, ecosystem diversity, and ecosystem complexity.

9.1.3.2.3 Opportunities Offered by Large-Scale Projects A broad, integrated approach is usually needed to rehabilitate severely degraded streams. Project planning that addresses habitat collectively rather than for individual species is usually preferred. Such a collective approach ("whole system restoration") may necessitate actions that address riparian zones, floodplains, and watersheds. General objectives have been suggested for restoring large-scale natural riverine functions (NRC 1992; Williamson et al. 1995a; 1995b; Bella et al. 1996), including the following:

- Restore dynamic ecosystem processes and functions in channels, riparian zones, and floodplains, including flooding, erosion, deposition, and exchange of sediment and organic material between channels and floodplains.
- Restore habitat diversity and complexity, system connectivity, and natural disturbance regimes.
- Provide a means whereby natural processes will function with little human intervention.

As an example of large-scale restoration, consider a channelized stream with extremely degraded aquatic habitat. One restoration strategy might feature the reinstatement of the meandering planform that existed before channelization. Meanders could be restored using strategies that either limited or expanded natural processes. The new channel alignment could be (1) designed and constructed, (2) designed and then allowed to develop through fluvial processes with structural constraints at key points, or (3) allowed to develop without intervention or structural constraint. Comparing these alternatives may require extensive sedimentation engineering analysis. Clearly, option (1) could have the greatest initial cost and create the greatest disturbance of existing conditions but also pose the least risk of subsequent changes, whereas option (3) would tend to be just the opposite—having the least cost and least immediate disturbance but the highest uncertainty regarding the predictability of subsequent changes. The latter option would require the most challenging sedimentation analyses.

9.1.3.3 Specific Habitat Restoration Objectives Habitat goals should be based on the attributes of relatively unaltered aquatic ecosystems or the causes of habitat degradation. General goals (e.g., improve water quality for aquatic organisms) must be supported by more specific objectives (e.g., reduce mean daily maximum water temperature below 17°C) (SRSRT 1994; Williamson et al. 1995a). Specific objectives are often phrased in terms of the same quantities used for habitat evaluation, including the following:

- Streamflow quantity. For example, provide adequate streamflow to meet seasonal needs for particular life stages or particular species or to mirror patterns in a lightly degraded reference system (Richter et al. 1996).
- Water quality. For example, maintain dry-season pool depths to meet temperature criteria.
- Channel dimensions for spawning, rearing, or refuge. For example, modify riffle frequency, increase channel pool volume and maximum depth, or increase the availability of steep or undercut banks.
- Longitudinal channel conditions for movement of organisms. For example, remove barriers or eliminate dewatered reaches.
- Streambank conditions. For example, reduce soil exposure and erosion; increase shade, cover, and refuge; or improve general condition, maturity, and successional opportunities for riparian vegetation.
- Influx and movement of sediment. For example, allow sediment to enter reach from upstream or local sources, provide flows for periodic sediment transport and flushing of substrate, or allow lateral bar formation along channel margins.
- Conditions in spawning gravel. For example, maintain intra-gravel flows when gravel-spawning species are important, such as salmonids.
- Input of organic matter and nutrients. For example, provide healthy riparian zones to ensure direct sources for organic matter and insects or maintain longitudinal continuum of organic matter from upstream sources and to downstream zones.

9.1.3.4 Scope of Sedimentation Analysis Stream restoration projects often change channel characteristics that impact sediment transport, including width, depth, slope, planform, bank erosion potential, hydraulic roughness, and bed material gradation. The sedimentation engineer may provide expertise in obtaining and interpreting data and model simulations describing physical aspects of habitat such as discharge, bed material characteristics, flow width and depth, current velocity, temperature, turbidity, and dissolved oxygen concentration. The engineer should also ensure that designs have acceptable outcomes with respect to erosion and sedimentation. Table 9-3 catalogs instability problems associated with various types of channel changes that are often key components of restoration projects.

Table 9-3 Potential Stability Problems Associated with Stream Restoration Projects

	Potential stability problems		
Modification	Project reach	Upstream	Downstream
Increase vegetation, woody debris, boulders, and other types of large-roughness elements	Aggradation	Aggradation	Degradation
Increase channel complexity (adding sinuosity or increasing the irregularity of cross-sectional shape and size)	Bank erosion, aggradation	Aggradation	Degradation
Remove of dams or weirs	Degradation upstream from structure, aggradation downstream.	Degradation	Aggradation or degradation, depending on impacts on flow and sediment discharge
Increase number of channel structures (e.g., weirs, spurs, bank covers, etc.)	Localized scour, bank erosion, aggradation	Aggradation	Degradation
Decrease bed slope	Aggradation	Aggradation	Degradation
Increase bed slope	Degradation	Degradation	Aggradation
Enlarge channel	Bank erosion, aggradation	Headcutting	Aggradation

Sedimentation analysis to support restoration design should predict the fluvial response to the project. For example, increasing channel width, increasing hydraulic roughness with vegetation or habitat structures, or decreasing channel slope by adding sinuosity will decrease sediment transport capacity and may lead to channel aggradation. On the other hand, if the restored channel is too steep, bed degradation may occur. Secondary responses may follow. For example, bank erosion may be triggered by bed aggradation or degradation. Even processes such as natural revegetation of a stream corridor can generate adjustments to the channel. Vegetation and in-channel woody debris can influence morphology of channels including the pool and riffle sequence, channel roughness, bank stability, locations of cutoffs, routing peak discharges, sediment routing and discharge, and the distribution of erosion. It follows that formulation of a sediment budget (Section 9.6.2) for the project reach using with- and without-project scenarios is one of the most basic sedimentation engineering tasks to support stream restoration.

9.1.3.5 Risk Evaluation Stream restoration projects that experience a significant imbalance between sediment supply and transport capacity either fail (do not deliver the desired benefits) or are not sustainable (have prohibitive maintenance requirements) (Brookes and Shields 1996). Because sediment transport analyses feature high levels of uncertainty, there are no standard approaches for determining what level of sediment transport imbalance is "significant." The designer must integrate knowledge gained from the stability assessment, preliminary design, and detailed design. The designer is responsible for making the client and other stakeholders aware of projected performance under various scenarios. For example, the project may experience unacceptable levels of erosion or sedimentation if discharges exceed a specified maximum peak or maximum average over some time period. Critical discharge levels may be lower during and shortly after project implementation. Nevertheless, sediment transport analyses are useful in reducing uncertainty (Johnson and Rinaldi 1998).

Restoration projects also experience failure when they do not generate the desired benefits. Even if the project performs perfectly with respect to water and sediment transport, the target species or communities may respond only weakly or may even decline. Biotic factors such as competition or predation, rather than physical habitat, may govern ecological response. In other cases, the linkages between habitat and ecological response may not be well understood enough to support reliable analysis. Biotic responses are heavily influenced by water quality, channel-floodplain interactions, and hydrologic variations. Some or all of these factors may not be altered by the restoration project. Inclusion of biotic factors into risk analysis must often be simply qualitative.

9.2 PREPARATION OF SEDIMENT STUDIES PLAN

A sediment studies plan (Fig. 9-1) is a critical early component of a stream restoration project. A good plan will ensure that significant sediment problems are identified and that analysis of alternatives is satisfactory. The schematic

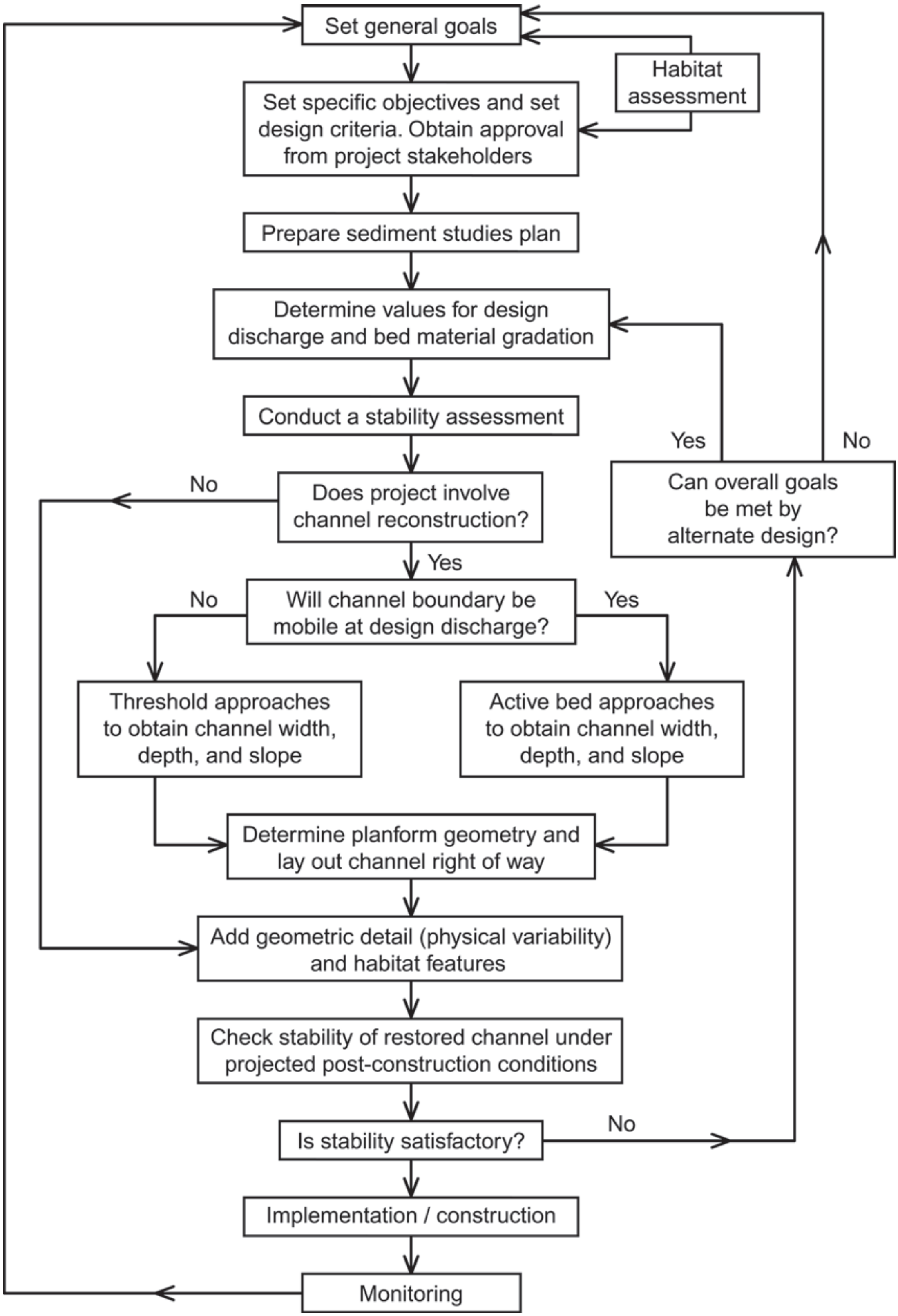

Fig. 9-1. Flow chart for sedimentation engineering aspects of stream restoration projects.

plan (Fig. 9-1) may be adjusted to fit a wide range of situations. For example, the stability assessment may be mainly qualitative for a simple project, but highly quantitative with multiple approaches to investigate the applicable variables for a complex project. As another example, the channel boundary may be constrained in urban areas, and therefore planform geometry will require little analysis.

9.2.1 Boundary of Study Area

The sediment studies plan should delineate the boundaries of the study area. Project impacts usually extend upstream and downstream beyond the project boundary. The region included in the assessment ideally should extend to major geomorphic boundaries such as 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.

9.2.2 Stability Assessment

The sediment studies plan should include an assessment of historic and current system stability as described in Section 9.4.

9.2.3 Identification of Potential Problem Areas

The sediment studies plan should identify the potential problems in the study area. Sediment problems are most likely to occur in conjunction with the following project features:

- Expansions
- Bridge crossings or other constrictions
- Abrupt changes in channel slope
- Cutoffs and changes in channel alignment
- The upstream approach to the project reach
- The transition from the project reach to the existing channel downstream
- Appurtenant structures in the channel such as dikes and weirs
- Tributary junctions
- Lower reaches of tributaries
- Water diversions
- Upstream from reservoirs and grade control structures
- Downstream from dams and grade control structures.

9.2.4 Data Inventory

The plan should include a catalog of available geometric, hydrologic, hydraulic, sedimentary, and land use data. Potential future watershed land use changes should be identified using zoning maps, GIS, study of sequential air photographs, and other approaches. The previously established boundaries and problem area identification will guide selection of gauge sites and justify data requirements. Watershed history and project life may be used to select time periods for trend evaluation.

9.2.5 Determination of Study Approach

The sediment studies plan should document the basis for the selection of methodology, such as time, cost, and data availability, as well as geomorphic factors. The current dynamism of the project reach and watershed should be considered, because the magnitude of sediment problems related to the restoration project will be in direct proportion to the scale of changes made to the channel geometry, boundary roughness, or discharge of a currently stable system. The level of study detail should ensure that major decisions about the project remain sound as more data become available during planning and design.

Sediment studies often include sediment budgets (Section 9.6.2) generated using various approaches. Because sediment budgets usually require extensive data sets (channel thalweg profile and cross sections, bed material gradations, flow duration curve, sediment inflows from upstream) and may involve substantial effort, an assessment based on the risk and consequences of project failure should be performed before a sediment budget analysis is launched. Many projects may require less elaborate analyses, but levels of uncertainty regarding project outcomes will be higher.

9.2.6 Data Collection

A data collection plan should be established and scheduled in the sediment studies plan if required data are not available. Standardized methods and equipment should be used to develop detailed and reliable sediment databases (e.g., Federal Interagency Sedimentation Project 2005). Chapter 5 in this volume and Edwards and Glysson (1988) describe approved samplers, standard sampling procedures, and laboratory analysis. Careful reduction and interpretation of the data is required in addition to the use of standardized data collection techniques. This is especially true when the data are collected over a relatively short time and at a relatively few sites within a large system. The engineer should advise the client regarding data collection needs and the levels of uncertainty that result from a lack of data.

9.2.7 Other Elements

The sediment studies plan should provide a reliable time and cost estimate for completion. A schedule of activities including preparation and review of end products should also be included. There should be a clear understanding among all participants in the planning and design processes about the scope of end products. An outline of the proposed final report may be helpful in this regard. A list of topics that may be included in such a report is provided in

Table 9-4 Topics to Include in a Sediment Studies Report

Topic	Remarks
Geography	Project and study area boundaries, current and projected future watershed land use
Data	Available data and sources Recommendations for data collection
History	Historic land use in the contributing watershed Hydrologic record Stream behavior in the study reach including aggrading and/or degrading trends, behavior of the system during flood events, and historical changes to and by the river system.
Bed and banks	Bed controls, bed material, bank heights, angles, vegetation, and stability
Channel stability	Existing channel and problems upstream and downstream from the proposed project area Knickpoints (headcuts) and knickzones
Physical habitat	Physical features that should be preserved or modified by a project
Project effects	Water-surface elevations and sediment transport capacity upstream of, within, and downstream of the project Tributaries (e.g., headcutting or induced deposition)
Recommendations	Project alternatives Future data collection and analyses to support design

Table 9-4. It should be clear how results of sediment studies will be used to affect decisions about overall project safety, efficiency, reliability, first cost, maintenance cost, environmental factors, social factors, and mitigation of adverse impacts resulting from sediment problems. Finally, the sediment studies plan and end products should be reviewed by scientists or engineers with expertise in sedimentation engineering and geomorphology to guard against costly oversights.

9.3 SELECTING VALUES FOR DESIGN DISCHARGE AND BED MATERIAL SIZE

9.3.1 Discharge

A representative discharge or discharge range is needed for many stability assessment tools (Section 9.4) and channel design (Section 9.5.1). The "channel-forming" or "dominant" discharge is often used as this representative value. The channel-forming discharge concept is based on the idea that for a given alluvial channel geometry, there exists a single steady discharge that, given enough time, would produce width, depth, and slope equivalent to those produced by the natural hydrograph. Although the channel-forming discharge concept is not universally accepted, most river engineers and scientists agree that the concept has merit, at least for perennial nonincised streams, particularly coarse-bed snowmelt-dominated streams in the montane west. See Soar and Thorne (2001) and Biedenharn et al. (2000) for a review of relevant literature. Producing a single value for channel-forming discharge, Q_{cf}, has proven difficult in many cases. In attempts to provide quantitative expressions for discharge values that are believed to approximate Q_{cf}, the following terms have been suggested:

- The effective discharge, or the discharge that, over time, transports the most sediment (Q_{eff}),
- The bank-full discharge (Q_{bf}), and
- A discharge based on statistical return intervals (Q_{ri}).

Of the three quantitative approaches to Q_{cf}, Q_{eff} generally requires the most data and effort (Table 9-5). Some workers have used sediment-discharge rating curves coupled with detailed geomorphic analysis to find Q_{eff} when historical hydrologic data were unavailable (Boyd et al. 1999). Additional comments dealing with ungauged sites are provided in Section 9.3.1.4.

9.3.1.1 Effective Discharge, Q_{eff}

9.3.1.1.1 Concept and Cautions Although discharge varies continuously, it is usually represented by a time series of discrete values measured at daily or shorter intervals. These data may be used to construct a frequency histogram by breaking the observed range into a finite number of increments. The mass of sediment transported by each discharge increment may be computed using a sediment rating curve or sediment transport formula if hydraulic and bed-material parameters are available. The effective discharge, Q_{eff}, is the increment of discharge that transports the largest sediment load over a period of years (Andrews 1980) (Fig. 9-2). Thus Q_{eff} integrates the magnitude and frequency of flow events (Wolman and Miller 1960) and is the best basis for channel restoration design. However, there are several problems associated with Q_{eff}:

- Computed values of Q_{eff} are sensitive to the number of increments used to build the discharge histogram.
- Computation of Q_{eff} has the same drawback as other methods in identifying one flow rather than a range of flows for channel formation (see Section 9.3.1.1.2 for details).
- Care must be exercised in applying the effective discharge procedure, particularly in unstable channels and those that have experienced catastrophic events during the period of record, because flow-frequency and sediment-transport relations may have changed or be changing with time as the channel adjusts. Results

Table 9-5 Quantitative Representations of Channel-Forming Discharge (Q_{cf})

Quantitative estimate of Q_{dom}	Data requirements	Recommended for	Limitations
Effective discharge (Q_{eff})	Historical hydrology for flow duration curve (10 years or more recommended) or synthetic flow duration curve; channel survey; hydraulic analysis; sediment gradation; sediment transport analysis and model calibration (if possible)	Channel design	Requires large data set
Bank-full discharge (Q_{bf})	Channel survey; hydraulic analysis and model calibration (if possible); identification of field indicators in a stable, alluvial reach.	Stability assessment; estimation of Q_{eff} in stable channels	Can be very dynamic in unstable channels/watersheds; field indicators can be misleading
Return interval discharge (Q_{ri})	Historical hydrology for flood frequency analysis, regional regression equations, or hydrologic model	First approximation of Q_{eff} and/or Q_{bf} in stable channels	No physical basis; relations to Q_{eff} and Q_{bf} inconsistent in literature

may therefore represent a transient average condition that does not accurately depict either the present flow and sediment-transport conditions or those prior to the event or disturbance.

The effective discharge is useful in comparing various channel geometries for competence to transport the incoming sediment load, facilitating study of project alternatives. Results of the effective discharge analysis are also useful when predicting the impact of alteration of watershed sediment loads (e.g., upstream dam removal) or hydrology (e.g., urbanization) on channel stability.

9.3.1.1.2 Determining Effective Discharge A three-phase process is involved in determining Q_{eff}:

1. Construct a frequency distribution (histogram) for discharge;
2. Construct a sediment-transport rating from either bed-material transport data or an analytical sediment transport relationship and reach hydraulics; and
3. Integrate the two relations by multiplying the sediment-transport rate for a specific discharge class by that discharge, with the maximum product being the effective discharge.

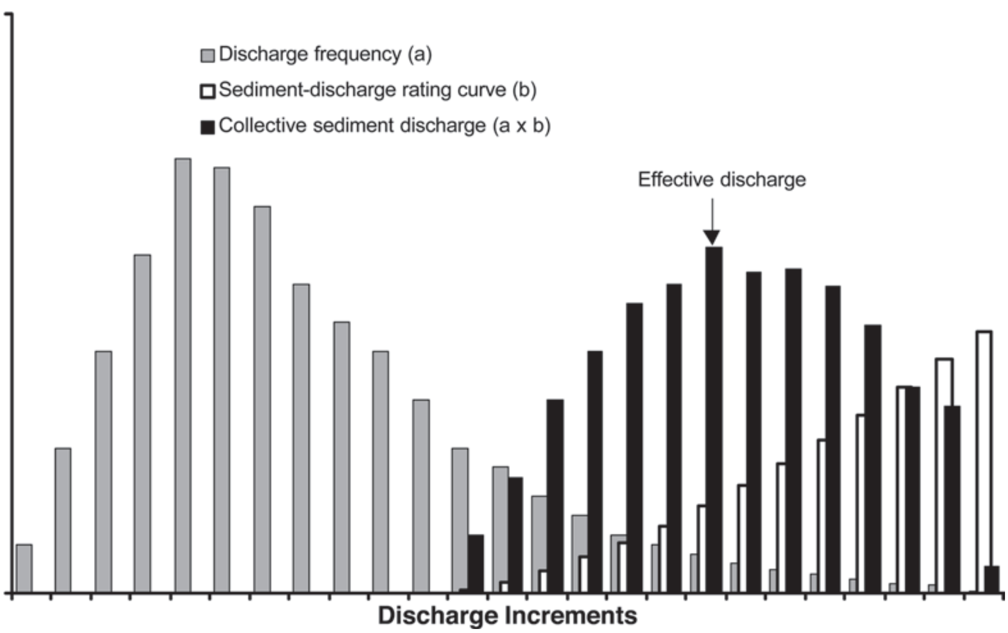

Fig. 9-2. Derivation of effective discharge by multiplying the discharge frequency histogram and the sediment rating curve to produce a collective sediment discharge histogram. Vertical axis represents frequency (percent of time), sediment discharge (mass per time), and collective sediment discharge (mass) for grey, white, and black bars, respectively.

The first phase involves selecting the type of discharge data to be used and a method for subdividing the observed range of discharge into classes to produce a frequency histogram. The period of record should be at least 10 to 15 years. In many cases, mean daily discharges are used because these data are readily available from the USGS and others. However, except for large rivers, mean daily flows tend to be underestimators of sediment transport because they mask the effects of short-duration peak flows. Discharges representing time periods shorter than a day, such as the 15-min data collected by the USGS, provide a more accurate means of establishing a sediment-transport rating relation. These data, although superior for a broader size range of streams and rivers, are not readily available, but may sometimes be obtained via special request.

There are no definite rules for selecting the most appropriate interval and number of classes (Thorne et al. 1998). The reader should note that the outcome of an effective discharge analysis is sensitive to the method used to derive the flow histogram. Yevjevich (1972) stated that the class interval should not be larger than 25% of the standard deviation of the sample. Hey (1997) found that 25 classes with equal arithmetic intervals produced a relatively continuous flow-frequency distribution and a smooth sediment load histogram with a well-defined peak, indicating an effective discharge that corresponded exactly with bank-full flow. Biedenharn et al. (2000) recommend setting the interval size equal to the discharge range (maximum observed discharge minus the minimum observed discharge) divided by 25. The first interval should begin at zero for suspended-load channels and at the critical discharge for initiation of bed load movement for gravel-bed rivers. Experience has shown that in some cases 25 classes produce unsatisfactory results, and a larger number of classes may be required. However, class size should be large enough so that some discharges occur in each class. In cases where the hydrologic response is extremely flashy, use of constant increments for the flow histogram may result in an extremely high relative frequency for the lowest interval, biasing Q_{eff} downward (Fig. 9-3). Soar and Thorne (2001) advocate using a continuous probability density function based on very small discharge intervals to avoid the problems associated with histogram development. If the frequency distribution is based on real data, it will exhibit a "noisy" appearance, but this may be addressed by using a moving average approach in phase 3, described below.

The second phase of the procedure involves developing a rating curve showing sediment concentration as a function of water discharge. Only sediment size classes that form the channel boundary should be used in the rating curve (Kuhnle et al. 2000). Typically, this range corresponds to the bed material sediment, but it may include finer sizes if significant material is being deposited on top of the banks (e.g., to form natural levees). The use of total-load transport data separated into suspended-, wash-, and bed-load components is ideal, but data in such detail are usually not available. Suspended sediment data are generally most readily available, and these data represent the sum of wash load and bed-material load moving

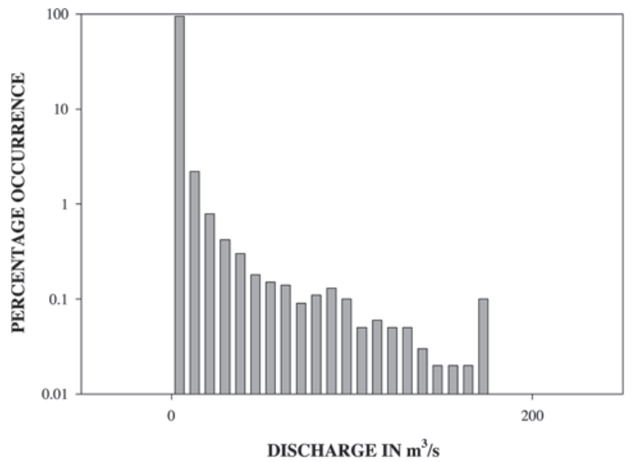

Figure 9.3a. 25 Equal arithmetic class intervals.

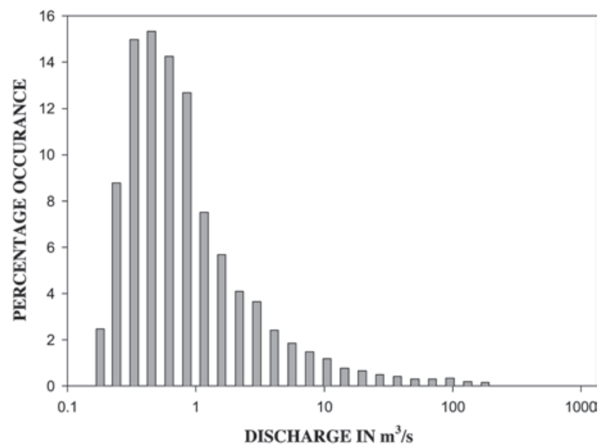

Figure 9.3b. 25 Logarithmic classes

Fig. 9-3. Effects of using (a) 25 equal ("arithmetic") class intervals and (b) 25 "logarithmic" class intervals for developing the flow-frequency histogram. The large number of discharges in the first class interval may bias the resulting value of Q_{eff} downward.

in suspension. Bed material moving as bed load is usually not measured. The transport of bed material load can be classified as bed-load-dominant, mixed-load-dominant, or suspended-load-dominant on the basis of the ratio of shear velocity to fall velocity (Julien 1995). If sediment data are not available, bed-material load transport rates can be derived from a variety of transport functions, as described in Chapter 2 and elsewhere (Stevens and Yang 1989; Andrews and Nankervis 1995). Generally, sediment concentrations are plotted against discharge in log-log space and regressed to create a simple rating relation (Fig. 9-4a). However, power functions derived in this way are often inadequate to define the transport relation because they overestimate transport at high flows. In addition, transport can also be overestimated at low discharges because

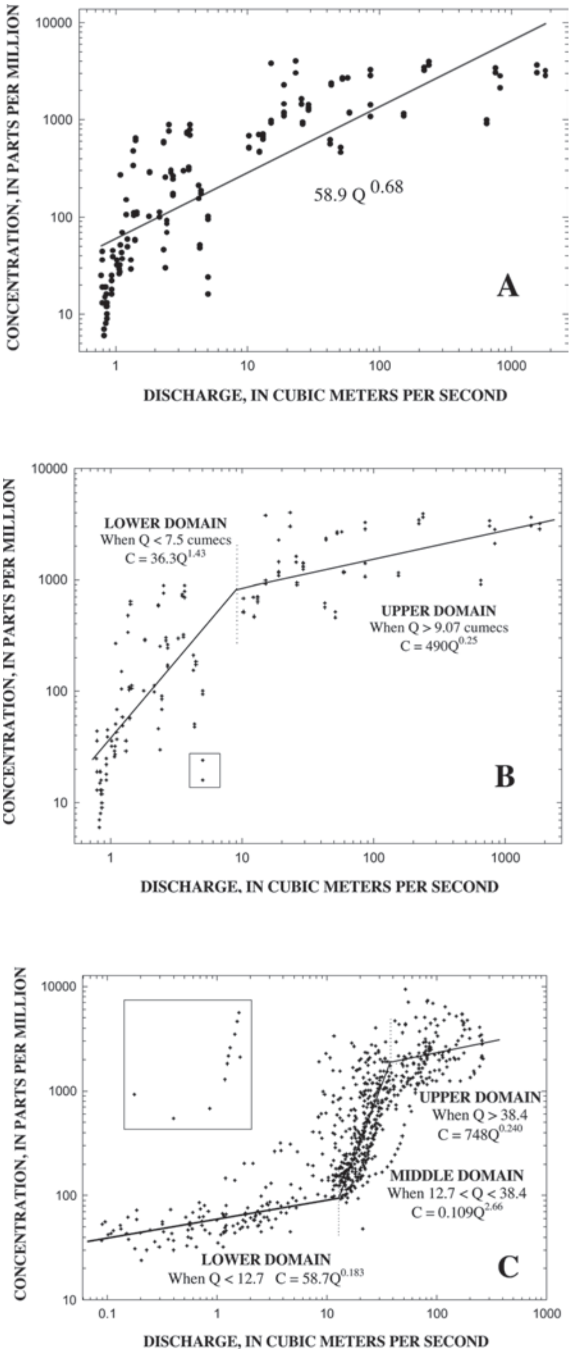

Fig. 9-4. Sediment rating curve derivation. (A) Use of simple power function relation. (B) Use of two linear segments. Points inside rectangular box were regarded as anomalies and were not included in regression. (C) Use of three linear segments. Points inside rectangular box were regarded as anomalies and were not included in regression.

of the sensitivity of transport relations to bed-material gradations, which sometimes vary with discharge. This necessitates using two or three linear segments or a curved rating (Glysson 1987; Simon et al. 2004; Fig. 9-4b and c). In gravel-bed rivers, surface armoring and incipient motion flow requirements (Parker and Klingeman 1982) also suggest the use of more than one segment for the bed load relation.

Phase three of the procedure is accomplished by multiplying the frequency (in percent) of each discharge class by the sediment load corresponding to the discharge at the center of the class interval. The resulting values represent the average transport rate for each discharge class. The center of the class interval with the greatest transport rate is Q_{eff} (Andrews 1980) (see Fig. 9-2). In some cases, however, there may not be a single class interval representing a maximum. Instead, the peak average transport rate may spread across a range of classes, indicating that there is no single effective discharge but that significant geomorphic work is performed by a wide range of flows (e.g., Biedenharn and Thorne 1994). There is considerable support for this concept in the literature, and such a situation calls for considerable professional judgment in selecting design discharge capacity for the restored channel.

9.3.1.2 Bank-Full Discharge, Q_{bf} The bank-full discharge is the maximum discharge that a channel can convey without overflow. Theoretically, Q_{bf} and Q_{eff} are generally equivalent in channels that have remained stable for a period of time, thus allowing the channel morphology to adjust to the current hydrologic and sediment regime of the watershed (e.g., Andrews 1980). However, in an unstable channel that is adjusting its morphology to changes in the hydrologic or sediment regime, Q_{bf} can vary markedly from Q_{eff}. Therefore, the expression "bank-full discharge" should never be used to refer to Q_{ri} or Q_{eff}. The relationship of Q_{bf} to Q_{ri} and Q_{eff} is useful as an indicator of channel stability and sheds light on morphologic changes to be expected locally as well as up- and downstream (Schumm et al. 1984; Simon 1989; Thorne et al. 1996a). The Q_{bf} from "template" or "reference" reaches (stable reaches from similar reaches/watersheds) has been used as a guideline for relevant dimensions of the restored channel (Rosgen 1996). Three problems should be noted in regard to Q_{bf}:

- Identifying the relevant features in the field that define the stage associated with Q_{bf} can be problematic. Many field indicators have been proposed, but none appear to be universally applicable or free from subjectivity (Williams 1978). Similar statements hold for the methods developed for selecting appropriate ranges of Q_{bf} values based on these indicators (Johnson and Heil 1996). Field methods presented by Harrelson et al. (1994) should be considered in Q_{bf} determination.
- Channel restoration is most often (if not always) practiced in unstable channels (instability is often the reason for restoration), and hence, unstable watersheds. Other candidates for restoration include channels that have stable boundaries but that have been greatly enlarged for flood control. In such cases Q_{bf} can be highly dynamic and very different from Q_{cf} (Doyle et al. 1999) and should not be assumed to be the same as Q_{cf}.

- In certain instances, the current Q_{bf} may be a poor choice for future channel performance. For example, an apparently stable channel may overflow frequently due to upstream urbanization. Urbanization typically increases the amount of impervious area, decreasing infiltration and increasing runoff peaks and quantities. Urbanization has the greatest impact on small, frequent events (Hollis 1975), and there may be a threshold level of watershed imperviousness (approximately 15%) beyond which effects significantly increase (Moscrip and Montgomery 1997). As another example, streams in arid landscapes may adjust to large, infrequent events and have very large values for Q_{bf}. Additional discussion is provided in numerous references, including FISRWG (1998).

9.3.1.3 Discharge for a Specific Return Interval, Q_{ri} If gauge data are available, the discharge equivalent to the event with a given return interval is often assumed to be the channel-forming discharge; for example, $Q_{cf} = Q_2$ (where Q_2 is the two-year event). Similarities exist between certain recurrence interval discharges, Q_{eff}, and Q_{bf}. In general, Q_{bf} in stable channels corresponds to a flood recurrence interval of approximately 1 to 2.5 years in the partial duration series (Simon et al. 2004), although intervals outside this range are not uncommon. Recurrence interval relations for channels with flashy hydrology are intrinsically different from those for channels with less variable flows. Because of such discrepancies, many studies have concluded that recurrence interval approaches tend to generate poor estimates of Q_{bf} (Williams 1978) and of Q_{eff} (Pickup 1976; Doyle et al. 1999). Hence, assuming a priori that Q_{ri} is related to either Q_{bf} or Q_{eff} should be avoided in channel design, although it may be useful at times to take Q_{ri} as a first estimate of Q_{eff} and/or Q_{bf} in stable channels, particularly those with snowmelt hydrology (Doyle et al. 1999). Watershed urbanization typically causes greater runoff amounts and larger peak discharges for similar storms, increasing the frequency of higher discharges. Channel enlargement may result. This makes the recurrence interval approach tenuous, because it is commonly based on events that have occurred over the full historical record.

9.3.1.4 Ungauged Sites When gauge records are not available, estimates of Q_{ri} can be based on similar gauged watersheds or on regression formulas (Wharton et al. 1989; Jennings et al. 1994; Ries and Crouse 2002) developed using appropriate regional data sets. Calculation of Q_{eff} will require synthesis of a flow duration curve. Two methods are described by Biedenharn et al. (2000; 2001): the drainage area-flow duration curve method (Hey 1975) and the regionalized duration curve method. It should be noted that both methods simply provide an approximation to the true flow duration curve for the site because perfect hydrologic similarity never occurs. Accordingly, caution is advised.

9.3.1.4.1 Drainage Area-Flow Duration Curve Graphs of Q_{ri} versus drainage area are developed for a number of sites on the same river or within hydrologically similar portions of the same drainage basin as the ungauged location. If data are reasonably homogenous, power functions may be fit using regression and used to generate a flow duration curve for the ungauged location.

9.3.1.4.2 Regionalized Duration Curve A nondimensional flow duration curve is developed for a hydrologically similar gauged site by dividing discharge by Q_{bf} or Q_2. Then Q_2 is computed for the ungauged site using the aforementioned regression equations. Finally the flow duration curve for the ungauged site is derived by multiplying the dimensionless flows (Q/Q_2) from the nondimensional curve by the site Q_2.

9.3.1.5 Checking Computed and Estimated Channel-Forming Discharges The quantities Q_{eff}, Q_{bf}, and Q_{ri} are all hypothetical estimates of Q_{cf}. Their equivalence to the theoretical single discharge that would produce the same channel geometry as the natural runoff sequence is based on observations and judgment. For this reason it is important that more than one estimator for the channel-forming discharge be considered. Computed effective and bank-full discharges outside the range between the 1- and 3-year recurrence intervals should be questioned. The computed effective and recurrence interval discharges should be compared with field evidence to ascertain if these discharges have geomorphic significance.

9.3.1.6 A Range of Discharges The quantities Q_{eff}, Q_{bf}, and Q_{ri} provide single values for a design discharge. However, inspection of a natural channel reveals the inherent variability present in natural fluvial systems. Hence, in designing channels that are intended to replicate natural channel features, but also remain stable over long periods of time, it is important to establish an acceptable range of design discharges. In addition, channel flow resistance may change appreciably with discharge, producing major effects on stage, sediment transport, and channel stability. Acceptable discharge capacity ranges may also be needed to guide channel sizing. For example, to incorporate natural variability, specifications could allow a range of channel widths and depths. If Q_{bf} is used for design discharge, then an appropriate range of discharges should be selected based on the range of Q_{bf} observed in the reference reaches. If Q_{eff} is used as the design tool, then the range of discharges should correspond to the effective discharge increment.

After a preliminary design is prepared, channel stability checks (Fig. 9-1 and Section 9.6) may include simulation of sediment transport either for selected hydrologic events or a flow duration curve. This type of analysis will indicate if the channel will experience unacceptable levels of scour or deposition during discharges above and below the design flow.

The discussion above deals with selection of discharges for channel design. Other types of stream restoration design problems may require selection of different discharges. For example, structural or vegetative bank treatments may be designed to withstand events with a certain probability of annual occurrence. Riparian vegetation may require limited periods of inundation during certain seasons. Riffles and other zones with coarse bed material may be designed to allow disturbance for removal of fines ("flushing") at a certain frequency (see Section 9.5.4).

9.3.2 Bed Material Size Distribution

A description of the bed material size distribution that is planned or anticipated under project conditions is needed for stability assessment and restoration design. Supplemental information will also be needed on bank material characteristics, particularly if banks are noncohesive. Information about the streambed and banks may be gathered at the same time using suitable sampling methods (cores, bulk samples, or layer samples, as appropriate) and sample processing techniques (sieving or sedimentation tests, as appropriate) for the sizes of material present. Although the bed material and bank material sizes may be visually estimated for rough preliminary estimates, careful sampling is required for quantitative analyses.

Bed material is characteristically heterogeneous. Bed material sampling techniques should vary with the bed type and the purpose for sampling. For example, floodplain boring may be needed to determine bed sediment size when a new channel is to be excavated. In other cases, bed material may be sampled from the existing channel or from a reference reach that serves as a restoration template. The resulting data may be used for sediment transport and channel stability computations, habitat assessment, or design of habitat features (e.g., flow regimes for periodically flushing coarse beds; stability of aquatic habitat structures).

Bed material sampling should provide estimates of representative sizes as well as information regarding spatial variability in the channel. Coarse beds pose greater difficulties than sand beds. Techniques applicable to coarse-bed rivers have been described by Bunte and Abt (2001), whereas techniques for sands and smaller materials are described by USACE (1995), and Ferguson and Paola (1997). If a coarse bed is rarely mobilized, then a surface hand-sampling technique (e.g., a Wolman (1954) pebble-count procedure) may be sufficient. If sediment transport is expected at a coarse bed, then sieve analysis of bulk sample is needed to include smaller subsurface particles. Relationships between gradations of bulk samples representing surface and subsurface sediments are presented by Parker (1990).

The median particle size, D_{50} (the size for which 50% of the bed material by weight is smaller), is the parameter most commonly used in sediment transport calculations. Less common descriptors include D_{90}, D_{84}, D_{75}, D_{65}, D_{35}, and D_{16} (for use in bed load, incipient motion, and flow resistance equations) and D_{60}, D_{25} and D_{10} (e.g., to describe particle sorting). For some types of aquatic habitat work (e.g., habitats for fish that spawn in gravel) it is also important to know the proportion of particles finer than gravel ($<$2 mm) found within the coarse matrix. Some streams have beds composed of mixtures of sand and larger sediments that have bimodal particle size distributions. Bimodality can also have a major impact on incipient motion and sediment transport (Chapter 2 of this volume and Wilcock 1998). Specific gravity of bed material can be quite important if it departs from standard values between 2.6 and 2.7.

Streamwise and lateral variations in bed material sizes occur along point bars, at lateral bars, and between pools and riffles, as well as for straight reaches with little thalweg variability. Bed particles near an eroding bank containing gravel or coarser materials are likely to be similar in size to the coarse component of bank material, rather than to upriver bed material. Therefore, if a restoration project for a coarse-bed stream emphasizes benthic habitats, it will be necessary to consider the spatial variability of bed material in detail. But if the restoration project emphasizes sediment transport and continuity of sediment supply from upstream to downstream reaches, the bed material size available for transport is of greatest interest.

Clearly, site-specific factors should be considered. Bed material along a mid-channel bar or other obvious depositional surface indicates the size of sediment transported by recent events. However, care should be taken that long-term stable morphologic features are not assumed to be representative of short-term channel dynamics. For example, channels with relict glacial outwash material often have riffles that are not mobilized by any but extreme events. Material in such features is not representative of normal bed material load.

9.4 STABILITY ASSESSMENT

9.4.1 Purpose and Scope

Stability assessment and analysis are a key aspect of planning and design for restoration of dynamic stream corridors. River channels are often perturbed by imbalances in watershed sediment supply, transport, or storage (Sear 1996) triggered by large floods (Stevens et al. 1975), channelization (Schumm et al. 1984; Simon 1989), upstream reservoirs (Simons and Senturk 1976), urbanization (Hammer 1972; Moscrip and Montgomery 1997), or other watershed land use changes. Using results of a system stability assessment, the project manager can select an appropriate level of effort for sedimentation engineering aspects of predesign assessment, design, and postproject monitoring. In addition, because habitat degradation is often related to erosion or sedimentation, stability assessment is needed to develop restoration alternatives. Furthermore, the restoration project may itself affect channel stability (Table 9-3), and this possibility must be evaluated during design. More detailed guidance for performing stream channel stability assessments is provided by the U.S. Army Corps of Engineers (USACE 1994) and by Lagasse et al. (2001). A template for geomorphic investigations is provided in Chapter 6 of this volume.

A stability assessment consists of examination of a selected part of the fluvial system encompassing the restoration project to determine the direction and speed of morphologic changes. The assessment provides a foundation for design and predictions of how the system will respond to the restoration project. 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. If possible, the dominant geomorphic processes influencing the channel and their root causes should be identified. Relative magnitudes are emphasized rather than quantification during assessment. 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).

If significant sedimentation problems are identified, more detailed engineering analysis will be required during design. Stream channel performance includes both conveyance and geometric stability, especially as they relate to long-term maintenance. Stability impacts are generally determined by comparing bed-material sediment transport for existing and anticipated project conditions. The stability assessment also provides an inventory of available data and may include recommendations for additional data collection programs and more detailed studies.

The first step in conducting the stability assessment is to determine the spatial domain for the investigation. Usually, this area will coincide with the project boundaries identified in the sediment studies plan (Section 9.2).

The second step is to formulate a statement describing acceptable rates of morphologic change. Current and projected channel stability may be assessed relative to these levels. From a strictly pragmatic standpoint, a reach is unstable when morphologic change (i.e., erosion or deposition) is rapid enough to generate public concern (Brice 1982). From a more scientific perspective, a stream is unstable only if it exhibits abrupt, episodic, or progressive changes in location, geometry, gradient, or pattern because of changes in water or sediment inputs or outputs (Rhoads 1995; Thorne et al. 1996b). In other words, a stream may be highly dynamic but considered geomorphically stable (i.e., in a state of dynamic equilibrium, Section 9.1.2.2) if its long-term temporal average properties (channel width and sediment input and output) are stationary. Such a stream may have relatively rapid rates of lateral migration and thus bank retreat. Thus the statement defining acceptable rates of change should provide a clear rationale.

The scale of observed instabilities should also be considered in setting criteria. Short segments of channels may be locally stable or unstable due to structures, vegetation, or geological conditions, but the reach or watershed that surrounds them may exhibit different patterns. For example, reaches upstream of headcuts in incising channel networks are often quite stable, but downstream zones are extremely disturbed (Simon 1989). If headcuts migrate upstream, stable reaches may quickly shift to unstable. Local flow constrictions (e.g., bridge crossings) may produce serious local scour in an otherwise stable stream. An assessment should differentiate between local, reach, and systemwide instabilities. Clearly, systemic instability is most serious and is usually not amenable to purely local treatment. Spatial patterns of channel form and process are best understood when stability assessment results are placed on a watershed map or within a geographic information system.

9.4.2 Types of Stability Assessments

9.4.2.1 Qualitative Stability Assessments Qualitative assessments are simple efforts requiring less than 1 week of effort for one person, and consist 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 on the ground. On-the-ground reconnaissance should include the project reach and adjoining upstream and downstream reaches. Spatial trends in channel conditions should be examined. If the downstream reach is degrading, it is possible that disturbance could move upstream into the project reach in the form of a headcut or knickzone. Instability upstream could increased sediment supply to the project reach.

Qualitative assessments should also include a review of the available information regarding the geological and physiographic setting for the project, as well as its temporal context. The engineer should develop a timeline or table showing major disturbances (e.g., large floods, avulsions, dam closure, channelization, deforestation) affecting the project reach. Review of historic maps and air photo coverage can be a powerful tool (Rhoads and Urban 1997). Sear (1996) provides an excellent overview of factors to be considered in qualitative stability assessments for river restoration projects. Additional guides are provided by Biedenharn et al. (1998) and USACE (1995, Appendix E).

9.4.2.2 Quantitative Stability Assessments Quantitative assessments vary in methodology, but have in common the collation of numerical 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. Five types of tools are commonly used in stability assessment: (1) Lane relations, (2) channel classification, (3) hydraulic geometry relationships, (4) relationships between sediment transport and hydraulic variables, and (5) bank stability. All five are easily misused, so professional judgment is required. These tools are discussed in the following section, and comments are made regarding tool selection.

9.4.3 Tools for Stability Assessment

9.4.3.1 Lane Relations The first group of tools is based on the Lane (1955a) relationship (also due to Gilbert 1914), which states that stream power is proportional to the product of sediment discharge (Q_s) and bed material size (D_s) in an alluvial stream in a state of dynamic equilibrium:

$$Q_w S \sim Q_s D_s$$

Note that $Q_w S$, the product of water discharge (Q_w) and stream gradient (S) is a reduced form of stream power, dimensionally corresponding to power per unit weight of fluid per unit length of channel. In this relationship and the others that follow the water discharge of interest is a fluvially significant (e.g., channel-forming) discharge. Other investigators have combined the original proportionality with others (e.g., H = flow depth, B = channel width) to form a set of relationships useful for characterizing fluvial behavior:

$$S \sim BD_{50} / Q_w \tag{9-1}$$

$$B/H \sim Q_w Q_s \tag{9-2}$$

$$\text{Channel sinuosity} \sim 1/Q_s \tag{9-3}$$

Many other workers (e.g., Schumm 1969; Nunnally 1985; Sear 1996; Hooke 1997) have extended these relationships to predict fluvial response to disturbance. In the following relations, a superscript of + indicates increase, 0 indicates no change, − indicates decrease, and ± indicates unpredictable shifts.

Increase of water discharge, for example, diversion of water into a reach:

$$Q_s^0 \; Q_w^+ \sim S^-, D_{50}^+, H^+, B^+ \tag{9-4}$$

Decrease of water discharge, for example, extraction of water from a reach resulting in a narrower channel:

$$Q_s^0 \; Q_w^- \sim S^+, D_{50}^-, H^-, B^- \tag{9-5}$$

Increased sediment supply, for example due to hydraulic mining:

$$Q_s^+ \; Q_w^0 \sim S^+, D_{50}^-, H^-, B^- \tag{9-6}$$

Decrease in bed material load as water discharge increases, for example in later stages of urbanization as paved area increases:

$$Q_s^- \; Q_w^+ \sim S^-, D_{50}^+, H^+, B^{\pm} \tag{9-7}$$

Decrease in bed material load and water discharge, following dam construction, for example:

$$Q_s^- \; Q_w^- \sim S^{\pm}, D_{50}^{\pm}, H^{\pm}, B^- \tag{9-8}$$

Bed material and water discharge both increase, but water discharge increases more. For example, in long-term urbanization, the frequency and magnitude of discharge increase, triggering channel erosion (increasing width and depth):

$$Q_s^+ \; Q_w^{++} - S^- D_{50}^+, H^+, B^+ \tag{9-9}$$

Sediment supply and water discharge both increase, but sediment supply increases more. For example, when forest is converted to row crop production, gravel beds tend to change to sand, and channels become wider and shallower:

$$Q_s^{++} \; Q_w^+ \sim S^+, D_{50}^-, H^-, B^+ \tag{9-10}$$

Use of these and similar relations for stability assessment is discussed in standard texts (e.g., Chang 1988; USACE 1995, Appendix D). The engineer should be aware of important limitations:

- Anticipated adjustments may not occur because the system is currently responding to prior disturbance. Accordingly, a review of watershed history for events creating channel system disturbance is an important part of stability assessment.
- The channel system may not comply with the relation because it is not free to adjust. For example, the bed may contain bedrock controls that limit changes in slope, or bed material may not become coarser because gravel and cobble are not available for transport or because fine sediment contributions from eroding banks and tributaries overwhelm main channel processes. 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.
- 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.
- Lane-type relations allow prediction of the direction of a change, but not its magnitude.

Despite these limitations, the Lane-relation approach may be quite powerful when the history of disturbance is known. For example, a straightened stream experiencing accelerated bed and bank erosion may be responding to the increased slope by increasing sediment load (e.g., Parker and Andres 1976).

The discharge-slope product QS that forms the left side of the Lane relation is one representation of 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 of the numerous resultant equations for planform prediction is provided by Thorne (1997). These relations may be useful in stability assessment, because systems that are near the threshold between meandering and braided may respond strongly to restoration actions. Further, the engineer should avoid designing a channel with a slope that is too small or too great for the selected planform. One of the more recent contributions is 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. A data set representing observations from 228 streams was used to produce a formula defining the threshold between single-thread meandering rivers with sinuosities greater than 1.5 and less-sinuous braided rivers:

$$\omega_{vt} = 843\, D_{50}^{0.41} \tag{9-11}$$

where

ω_{vt} = the specific stream power at the transition between meandering and braided planforms in W m^{-2}.

Specific stream power, or stream power per unit bed area, is defined by

$$\omega_v = CS_v Q_{bf}^{0.5} \tag{9-12}$$

where

C = 2.1 for sand-bed rivers and 3.3 for gravel-bed rivers, and
S_v = valley (not channel) slope.

Channel width, which appears in the conventional definition of unit stream power ($\omega = \gamma Q\, S/B$, power per unit bed area), does not appear in the relationship because it is assumed to be a function of Q_{bf}. Streams with values of specific stream power greater than the threshold will braid, whereas those with lower values will meander, as shown in Fig. 9-5. Limits for the function are $Q_{bf} > 10\ m^3\ s^{-1}$ and 0.1 mm $< D_{50} <$ 100 mm. Dade (2000) produced a more qualitative planform discriminator based on channel slope, median bed material size, and discharge.

9.4.3.2 Channel Classification Channel classification is a primarily qualitative approach for stability analysis in which the engineer divides the channel network in the study area into reaches and assigns each channel reach to a class or type based on visual inspection or measurement of key variables (Chapter 6). The quantity and quality of regional

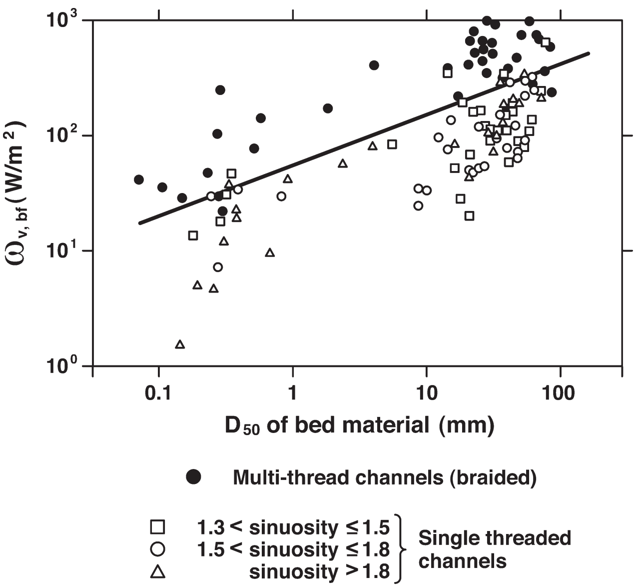

Fig. 9-5. Planform prediction diagram developed by van den Berg (1995) after Thorne (1997).

experience of the engineer is the key determinant of the quality of channel stability assessment based upon qualitative reconnaissance. Ideally, results from reconnaissance should be verified using tools that examine recent trends such as specific gauge analyses, comparison of thalweg profiles, and comparison of channel width, depth, and bed elevation depicted on successive surveys of several cross sections through time (USACE 1994; Biedenharn et al. 1998). Examination of historical photographs (aerial and ground) and maps and interviews with landowners and other observers can also be particularly valuable.

Results of inspection and salient data can be recorded on a form for each reach and entered into a GIS or mapping software for synoptic visualization of ongoing processes throughout the system. It is critical to view results of classifications within the context of the entire watershed, because changes and modifications within a reach may be propagated through the system. Systemwide trends should be clearly identified. Presentation of classification results in map format can be extremely useful for communication with funding agencies or local landowners involved with or impacted by channel modifications.

Classification schemes generally fall into two broad groups, descriptive and process-based. Among the former is the scheme proposed by Rosgen (1994, 1996). Using this scheme, a reach can be assigned an alphanumeric taxonomic code based on its appearance and rough estimates of channel dimensions. For instance, a channel classified as "C4" is a single-thread meandering gravel-bed channel with a width-to-depth ratio greater than 1.4 and a slope less than 0.02, whereas a "D3" channel is a braided cobble-bed channel with a width-to-depth ratio greater than 40 and a slope less than 0.02. Codes in this classification scheme range from A1 to G6 and ostensibly cover all river conditions. The widespread adoption of the Rosgen method is an indicator of its ease of use. However, simple descriptive classifications do not allow the user to infer what processes control channel form and future response. The Rosgen method has drawn severe criticism for its use beyond description and communication (Miller and Ritter 1996; Doyle and Harbor 2000).

In contrast to descriptive schemes, process-based classifications can be used as preliminary indicators of channel stability. However, because these schemes describe processes in addition to form, they require more expertise to use. In particular, process-based schemes require the user to relate processes occurring at the watershed scale to the reach of interest. For example, Schumm (1977) proposed placing of components of a fluvial system in one of three classes based on their current dominant geomorphic function: sediment sources, sediment transportation zones, or sediment sinks, and a similar approach was proposed by Montgomery (1999). Thorne et al. (1996b) suggested that all channels are either unstable (active morphological changes), dynamically stable (no characteristic change over engineering time scales), or "moribund" (unable to alter morphology 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). Though essentially qualitative, CEMs are powerful tools because they link channel forms to key geomorphic processes in a rational way that allows post- and prediction. However, their use is limited to channel systems experiencing adjustment by channel incision. Typically real-world watersheds do not follow the CEM models perfectly, but the absence of a distinct longitudinal progression in channel stages indicates that instabilities are the result of local phenomena rather than systemwide instability. In other words, classification systems can be used to indicate channel stability either directly or indirectly.

Simon and Downs (1995) and Thorne et al. (1996b) provide rough guidelines on inspecting key sites throughout a channel network in a given watershed to assess channel stability via reach classification. Inspection includes 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. Inspection of a single reach (6–12 channel widths long) can be done by an experienced person in 1 to 1.5 h (Simon and Downs 1995). These inspections should be conducted at key sites throughout the watershed. Selection of reaches to inspect is critical—sites must form a sufficiently dense network, and additional attention must be paid to the most dynamic reaches. Local influence of bridge crossings should be avoided by inspecting reaches several hundred meters upstream from, rather than at, bridges.

Johnson et al. (1999) reviewed and synthesized rapid stream channel stability assessment tools developed by Pfankuch (1978), the Federal Highway Administration (FHA 1995), and the previously noted work of Simon and Downs (1995) and Thorne et al. (1996b). A key component of the Johnson procedure is computation of the ratio of average boundary shear stress to critical shear stress. In gravel-bed rivers, as a rule of thumb, bed motion begins when this shear stress ratio exceeds 1. When the ratio exceeds about 2, most of the bed is in motion, and when it exceeds 3, the entire bed is in motion. However, Parker and Klingeman (1982) noted that bed shear stresses in gravel-bed streams rarely exceed more than two or three times the critical value even during severe floods. The Johnson procedure is not limited to use in watersheds experiencing incision, and it results in a qualitative stability rating (excellent, good, fair, or poor) rather than a CEM stage. The effort and experience required to use this assessment method are similar to that for the other methods. However, 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 (1936) equation,

$$\tau_c = \theta(\gamma_s - \gamma_w)D_{\text{critical}} \tag{9–13}$$

where

θ = dimensionless critical shear stress (Shields constant);
τ_c = critical shear stress for movement of material of size D_{critical}; and
γ_s and γ_w = specific weights for water and sediment.

Modification of τ_c for the effects of sediment mixtures when bed sediments are mixtures of sand and gravel may be in order. Critical shear τ_c may also be modified for the effect of gravity on bank slopes, if banks are comprised of granular, noncohesive sediments. See Chapter 2 in this volume for a full discussion of the Shields constant. A useful compilation of reported values for θ is provided by Buffington and Montgomery (1997). A compilation of data from natural rivers showed that θ exhibits modal values of approximately 10, 1, and 0.04 for rivers characterized by suspended-load, mixed-load, and bed-load regimes (Dade and Friend 1998).

In using this (Johnson et al. 1999) method, as well as other assessment methods, the user should bear in mind the conditions and purposes of the original tool. The Johnson 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. 2000). Both Johnson et al. (1999) and Pfankuch (1978) equate channel stability with channel uniformity, associating local erosion caused by flow obstructions like woody debris with channel instability. Although such features may be causes of instability at road crossings, they are common in natural channels and are critical for maintaining aquatic habitat and overall fluvial system stability. Hence, the method provides an estimate of stability, but each case should be treated individually due to local effects and inherent variability between sites.

9.4.3.3 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 characteristic discharge, Q_{cf}, Q_{bf}, Q_{eff}, or Q_{ri}. Use of hydraulic geometry relations for restoration planning (Allen et al. 1994) and channel design (e.g., Shields 1996) is discussed elsewhere; here we focus on their use for stability assessment. These relationships are sometimes referred to as "downstream" hydraulic geometry formulas to differentiate them from formulas that describe how flow width and depth change at a given location as discharge increases ("at-a-station" formulas) (Leopold and Maddock 1953; Dunne and Leopold 1978). Surrogates for discharge, such as contributing drainage area, have been used in modified versions of these formulas, although this may introduce additional error. Hydraulic geometry relationships have also been applied to other dependent variables such as depth, slope, and velocity. Hydraulic geometry relations are sometimes stratified according to bed material size or other factors.

Hydraulic geometry relations can be developed for a specific river or watershed, or for streams with similar physiographic characteristics. River reaches that are judged to be in a state of dynamic equilibrium are selected for data collection. Use of field indicators rather than gauge data to determine channel-forming discharge is usually unwise (Williams 1978). Data scatter about the developed curves is expected even in the same river reach. The more dissimilar the stream and watershed characteristics are, the greater the expected data scatter. So-called "regional curves" would be expected to have data scatter across a full log cycle. It is important to recognize that this scatter represents a valid range of stable channel configurations due to variables such as geology, vegetation, land use, sediment load and gradation, and runoff characteristics. The composition of banks is very important in the determination of stable channel width. It has been shown that the percentage of cohesive material (Schumm 1977) and the type and amount of bank vegetation (Hey and Thorne 1986; Trimble 1997) significantly affect channel width.

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. (1996b) 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, eroding channels in the United Kingdom and Denmark (≥ ~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 limited sediment availability. This case study highlights the importance of professional judgment and field observations in interpreting results of stability analysis.

Hydraulic geometry formulas are easily and widely misused in river restoration. 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 United States 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. Because hydraulic geometry formulas are continuous, deterministic functions free of time dependence, they overlook threshold behaviors, indeterminacy (equifinality), and long-term dynamism, which are common in many fluvial systems (Schumm 1977). Analytical tools (discussed below) coupled with modern geomorphic analyses are required for more reliable assessments.

9.4.3.4 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.

9.4.3.4.1 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. 1996a; 1996b), 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 Yalobusha River Watershed, Mississippi, indicated that stable reaches could be plotted close to a line defined by

$$S = 0.0028A^{-0.433} \tag{9.14}$$

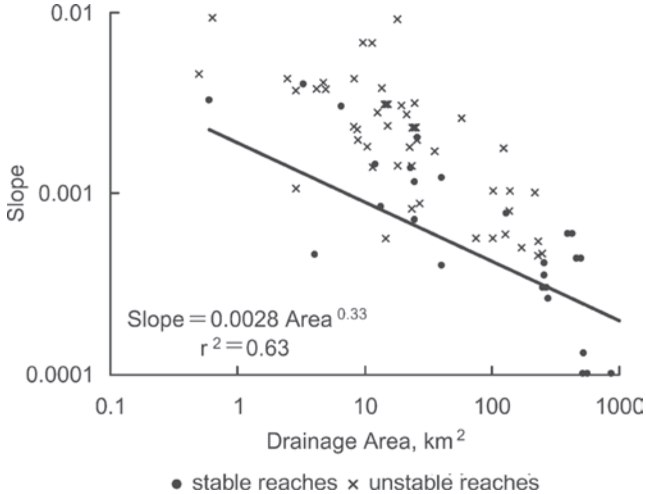

Fig. 9-6. Example of channel bed slope-drainage area relation used for reach stability assessment. Solid line represents the power function shown on the plot, which was obtained from regression of data from stable reaches (Simon and Thomas 2002). Unstable reaches generally plot above the line.

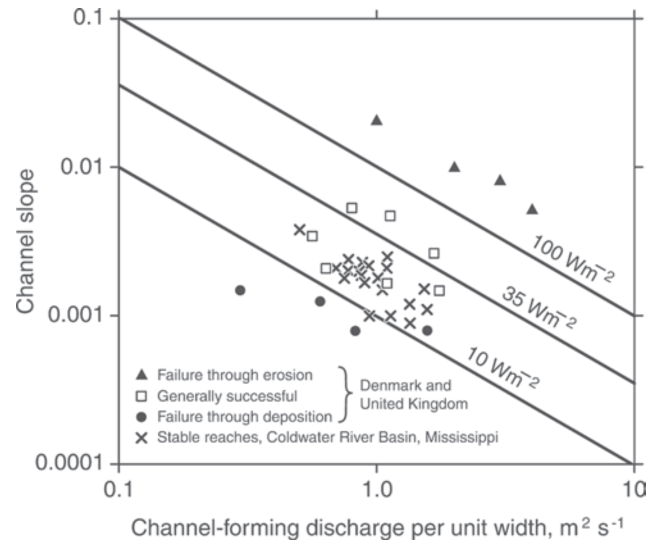

Fig. 9-7. Stream power stability criteria (Brookes 1990). Squares, triangles, and circles represent straightened, re-meandered channels in Denmark and the United Kingdom with sandy banks and beds of glacial outwash sands. Stars represent stable reaches in the Coldwater River watershed of northwestern Mississippi. 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 channel-forming discharges were assumed equal to Q_{2yr}, computed using a watershed model (HEC-1) (USACE 1993).

where

S = slope of the energy gradient and
A = upstream drainage area in km^2

(Simon and Thomas 2002, Fig. 9-6). Steeper reaches tended to be unstable.

9.4.3.4.2 Stream Power Outputs from one-dimensional hydraulic models may be used to compute stream power or average boundary shear stress, 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 one form of the stream power per unit bed area, may be used as a criterion for stability in stream restoration projects (Brookes 1990). Unit stream power data are plotted as squares, triangles, and circles for initially straightened channels that were restored by meander reconstruction in Fig. 9-7. Based on experience with several restoration projects in Denmark and the United Kingdom with sandy banks, beds of glacial outwash sands, and a rather limited range of Q_{bf} (~0.4−2 m^3 s^{-1}); a unit stream power value of 35 W m^{-2} discriminated well between stable and unstable re-meandered channels. Projects with unit stream powers less than about 15 W m^{-2} failed through deposition, whereas those with unit stream powers greater than about 50 W m^{-2} failed through erosion.

Because these criteria are based on observation of a limited number of sites in specific geographical areas and with small bed sediment sizes, application to different situations (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 Fig. 9-7 as x's. 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) (USACE 1993). Downs (1995) developed stability criteria for channel reaches in the Thames Basin of the United Kingdom based entirely on slope: channels straightened during the twentieth century were depositional if slopes were less than 0.005, and erosional if slopes were greater.

9.4.3.4.3 Incipient Motion Fundamental principles regarding incipient motion of sediments on channel bed and banks are presented in Chapter 2 in this volume. 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 because there is a supply of sediments from upstream, bed elevation may remain stable or even aggrade. Use of incipient motion relationships is further complicated by the fact that there is no true threshold condition where all the particles of a given size begin to move. Most critical shear stress relationships were developed by extrapolation of sediment transport rate versus shear stress curves to zero transport. This process results in critical shear stresses

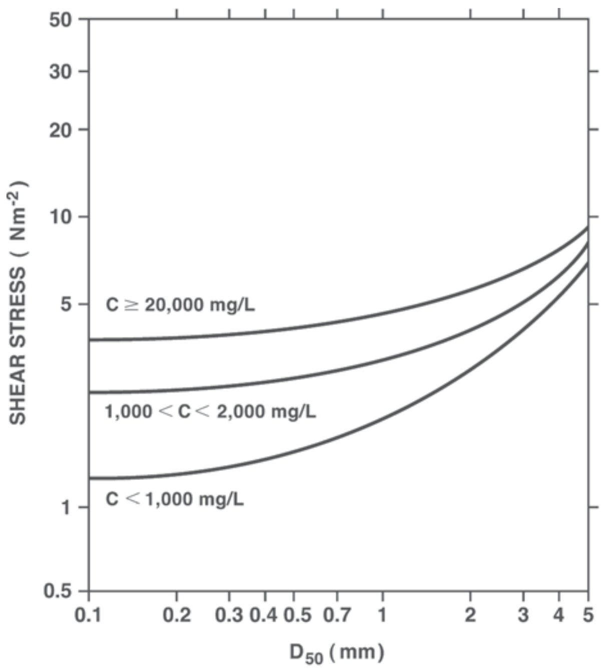

Fig. 9-8. Allowable mean shear stress for channels with boundaries of noncohesive material smaller than 5 mm carrying negligible bed-material load (after Lane 1955b in USDA 1977). "Allowable" stresses may be tolerated without causing serious erosion or endangering channel stability. Average shear stress may be adjusted for trapezoidal channel side slopes and width-depth ratio. Details are provided by Chang (1988) and USDA (1977). Values are for straight channels, and should be reduced approximately 10%, 25%, and 40% for slightly, moderately, and very sinuous channels, respectively.

that may be significantly higher than those at which sediment actually begins to move (Gessler 1971; Paintal 1971).

Some incipient motion relations indicate that critical bed size in mm is about 20 times the average velocity in m s^{-1} or about 10,000 times the product of depth in meters and slope. Typically, the median grain size, D_{50}, is used for the critical bed size in assessing the stability of a particular slope-width-depth-discharge combination (Pemberton and Lara 1984). A guideline used by the U.S. Department of Agriculture (USDA 1977) is shown in Fig. 9-8. It should be noted that the curves in Fig. 9-8 were drawn based on observations from straight canals, which have much more steady, uniform flows than most natural streams. In addition, the original source (Lane 1955b) for these curves states that "where much sand is carried, this method of analysis is not applicable," and "for crooked canals, lower values [of critical shear stress] must be used."

A list of five procedures useful for gravel or cobble beds is presented in Table 9-6. These five relationships predict 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 9-6 may also be solved for slope or discharge given the other variables.

The relationships in Table 9-6 involve varying amounts of theory and empiricism, and the engineer should be familiar with the underlying assumptions before interpreting their results. However, for ease of use we have omitted the details and simply reduced the equations to simplest form to yield

Table 9-6 Incipient Motion Stability Checks for Coarse, Noncohesive Beds Solved for Critical Bed Material Size, D_{critical} (from Pemberton and Lara 1984)

Basic relationship	D_{critical} (mm)	Remarks	Source
$D_{\text{critical}} = 20.2\, V_m^{\,2}$	$20.2\, V_m^{\,2}$	Based on assumption that velocity near bed is 0.7 V_m.	Mavis and Laushey (1949)
$V_m / V_f = 2.05$	$21.6\, V_m^{\,2}$ ($D_{\text{critical}} > 2$ mm)	V_f is the terminal fall velocity, approximated by the settling velocity formula of Rubey (1933)	Yang (1973)
$\tau_c = \gamma_w HS$	13,000 HS ($D_{\text{critical}} > 6$ mm)	Fig. 9-8 gives range of values for τ_c	Lane (1955b)
$\theta = \tau_c/[(\gamma_s - \gamma_w)\, D_{\text{crit}}]$	10,000 HS ($D_{\text{critical}} > 1$ mm)	Assumes Shields constant = 0.06	Shields (1936)
$D_{\text{crit}} = HS / [0.058\, (n_s / D_{90}^{\,1/6})^{3/2}]$	$17.2\, HS\, D_{90}^{\,0.25}\, n_s^{\,-1.5}$	Reduces to form similar to Lane and Shields when Strickler equation is used for n_s	Meyer-Peter and Muller (1948)

Note: V_m = mean velocity, V_f = terminal fall velocity.

ALLOWABLE VELOCITIES FOR UNPROTECTED EARTH CHANNELS		
CHANNEL BOUNDARY MATERIALS		ALLOWABLE VELOCITY
DISCRETE PARTICLES	SEDIMENT LADEN FLOW $D_{75} > 0.4$ mm	$v_b \times D \times A \times B$
	$D_{75} < 0.4$ mm	0.6 ms^{-1}
	SEDIMENT FREE FLOW $D_{75} > 2.0$ mm	$v_b \times D \times A \times B$
	$D_{75} < 2.0$ mm	0.6 ms^{-1}
COHERENT EARTH MATERIALS	PI > 10	$v_b \times D \times A \times F \times C$
	PI < 10	0.6 ms^{-1}

NOTE: In no case should the allowable velocity be exceeded when the 10% chance discharge occurs, regardless of the design flow frequency

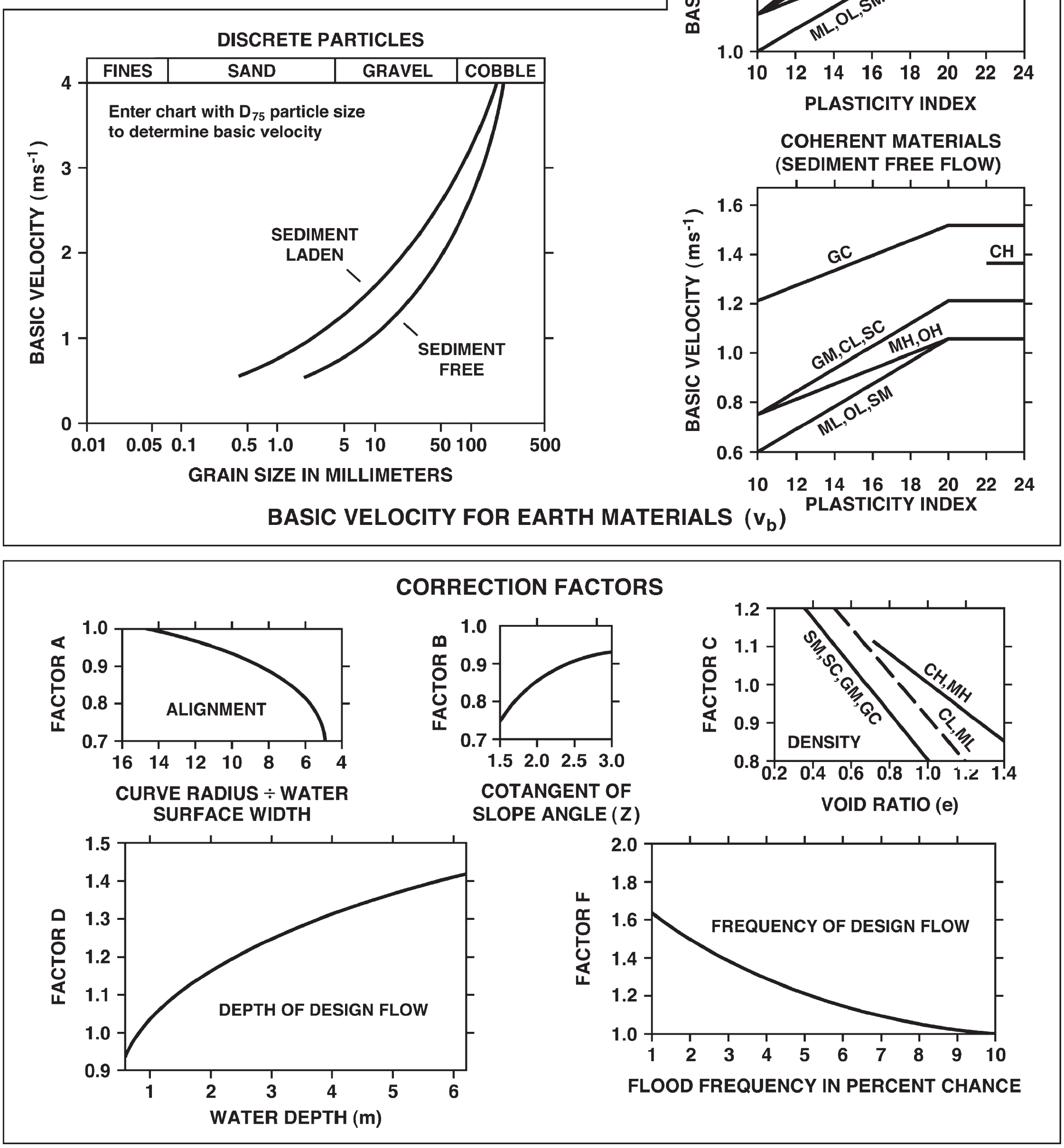

Fig. 9-9. USDA (1977) allowable-velocity charts for "unprotected earth channels." "Allowable velocities" are the maximum cross-sectional average flow velocities that do not cause serious boundary erosion. Allowable velocity for a given channel is determined using the formula in the box at the top left. The basic velocity, v_b, is given by one of the group of three plots at the top of the figure, whereas correction factors A, B, C, D, and F are obtained from the five plots in the bottom group. The letters PI = plasticity index, and the abbreviations GC, SC, CH, CL, GM, MH, OH, ML, OL, SM, etc. refer to the type of boundary as classified using the Unified Soil Classification System.

Table 9-7 Suggested Maximum Permissible Mean Channel Velocities (after USACE 1991)

Channel material	Mean channel velocity m s^{-1}
Fine sand	0.6
Coarse sand	1.0
Fine gravel[a]	2.0
Earth	
Sandy silt	0.6
Silt clay	1.0
Clay	2.0
Grass-lined earth[b]	
Bermuda grass	
Sandy silt	2.0
Silt clay	2.0
Kentucky blue grass	
Sandy silt	2.0
Silt clay	2.0
Poor rock (usually sedimentary)	3.0
Soft sandstone	2.0
Soft shale	1.0
Good rock (usually igneous or hard metamorphic)	6.0

[a]For particles larger than about 20 mm.

[b]For slopes less than 5%. Keep velocities less than 1.5 m s^{-1} unless good cover and proper maintenance can be obtained.

bed material size in mm. 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.

Incipient motion approaches based on velocity rather than shear stress are also available. Because channels with identical average velocities can experience different bed shear stresses, correction factors for variation in flow depth, sediment load, channel curvature, and so forth have been developed (USDA 1977). A series of charts for determining allowable velocity is presented in Fig. 9-9, and a commonly used set of values based on experience is presented in Table 9-7. The allowable-velocity approach is not recommended for channels transporting a significant load of material larger than 1 mm.

9.4.3.4.4 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, the preceding discussion regarding critical values of stream power and slope offers some guidance. Erosion of cohesive materials is affected by water quality, by material history (weathering and saturation), and by macroscale phenomena (e.g., zones of weakness between cohesive blocks). A review is provided in Chapter 4 of this volume. Current research emphasizes the importance of positive and negative pore water pressure in cohesive beds (Simon and Collison 2001) and banks (Simon et al. 2000). A field test for measuring cohesive bed erodibility is available, but many replications are required to characterize a channel reach, because of local variations (Hanson and Simon 2001).

At present, most guidance for stability of cohesive material is based on scattered observations. 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 of 1.5 m, and 0.8 to 2.6 m s^{-1} for flow depth of 15 m. Fortier and Scobey (1926, in French 1985) suggested a maximum permissible mean velocity of 1.1 m s^{-1} for alluvial silts and stiff clay and a value of 1.8 m s^{-1} for shales and hardpans. These values correspond to mean bed shear stresses of 12 and 32 N m^{-2}, respectively. Values are

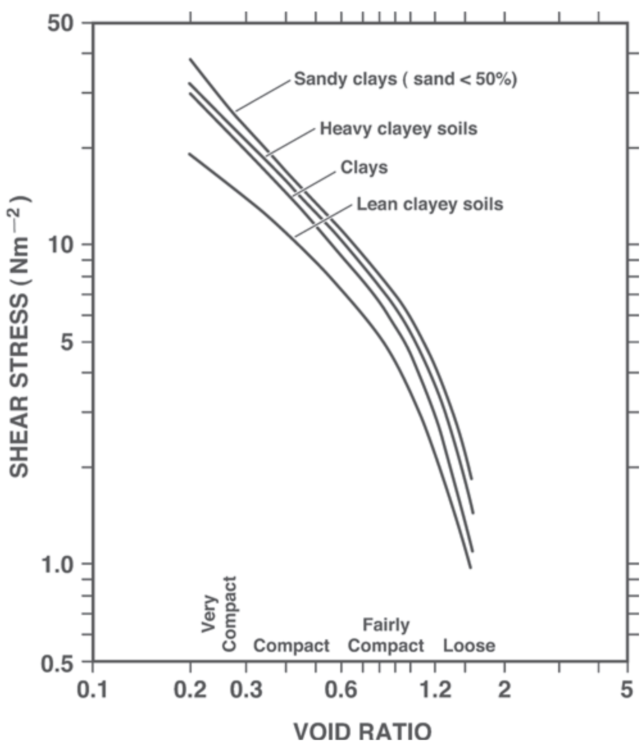

Fig. 9-10. Allowable shear stresses for cohesive materials based on conversion by Chow (1959) of permissible velocities published by "The maximum"(1936) to boundary shear stresses. "Allowable" stresses may be tolerated without causing serious erosion or endangering channel stability. Curves represent the maximum allowable boundary shear stress for cohesive soils with void ratios as given on the x-axis and soil properties shown on the curve labels. Values are for straight channels, and should be reduced approximately 10%, 25%, and 40% for slightly, moderately, and very sinuous channels, respectively.

for "straight channels of small slope after aging" and depths of flow less than 0.9 m. The Fortier and Scobey values should be reduced 25% for sinuous channels, increased by 0.15 m s^{-1} when depth exceeds 0.9 m, and increased 0.3 to 0.6 m s^{-1} for streams carrying high sediment loads (French 1985). Data presented by Chow (1959) regarding allowable shear stresses for cohesive materials are shown in Fig. 9-10, and additional empirical data are presented by Julien (1995). Empirical data such as those shown in Fig. 9-10 should be used with extreme caution, because they represent a limited data set and do not allow for inclusion of macroscale phenomena that may be most important.

9.4.3.4.5 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. The purpose of a sediment budget analysis is to determine if a specific channel reach has the capacity to transport the sediment load delivered to it by upstream channels. If significant differences are found between the inflowing sediment rating curve and a rating curve for the specific channel reach, then a condition of channel instability has been identified. Detailed computations must necessarily be postponed until the design stage, because project dimensions and boundaries may not yet be known. Nevertheless, assumed channel properties may be used to good effect within the bounds of normal sediment transport relationship accuracy. Sediment budgets are discussed in greater detail in Section 9.6.2.2.

9.4.3.5 Bank Stability Streambank erosion may be classified as fluvial erosion of material from a bank face (generally analyzed using incipient motion approaches described above) or collapse of large masses of bank material. These masses are removed from the bank toe ("basal cleanout"), resteepening the bank profile and creating conditions conducive to another failure. Mass failure of steep, cohesive banks is related to bank height, bank angle, and soil properties (Simon et al. 2000). If bank heights are greater than about 3 m and angles greater than about 45º, 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). Software packages may prove helpful in simulating effects of stage and groundwater table fluctuations on banks of various height and angle (e.g., Simon et al. 2000; 2003). If bank soil properties are not known, a tabulation of stable and unstable bank heights derived from the watershed qualitative reconnaissance may prove helpful, particularly when coupled with forecasts of future channel degradation or aggradation.

9.4.4 Assessment Tool Selection

Normally a stability assessment proceeds by dividing the channel network into reaches displaying consistent fluvial properties and applying a set of assessment tools to each reach. A greatly simplified example is provided in Table 9-8.

Table 9-8 Summary of Simplified Hypothetical Stability Assessment

	Reach					
Assessment tool	1	2	3	4	Value required for stability	Reference
Bed slope from a slope-drainage area relationship [a]	0.002	0.00018	0.0022	0.0024	0.0006–0.0008	Simon and Thomas (2002)
Unit stream power, W m^{-2}	29	43	33	52	<35	Brookes (1990)
Potential specific unit stream power, W m^{-2} [b]	24	32	38	45	≤ 30 for meandering planform	Van den Berg (1995)
Channel evolution model	Stage V	Stage V	Stage IV	Stage II	Stage V or VI	Simon (1989), reconnaissance per Thorne et al. (1996b)
Average bed shear stress, N m^{-2}	24	26	30	29	20–25 [c]	Regional observations
Height of near-vertical banks, m	5.1	4.7	4.3	2.2	3.8	Bank stability analysis per Thorne (1999) and Simon et al. (2003)

Note: Consensus of assessment indicates incision (and instability) is proceeding upstream through reach 3 to reach 4. Reaches 1 and 2 are slightly aggradational, but accelerated lateral channel migration likely continues there.

[a] $S = 0.0028\ A^{-0.33}$.

[b] $2.1\ S_v\ Q_{bf}^{0.5} < 843\ D_{50}^{0.41}$.

[c] Larger than value based on incipient motion (12 N m^{-2}) due to significant bed material load.

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 with lightly perturbed alluvial channels in dynamic equilibrium for which extensive data sets are available. Incipient motion type analyses including Shields parameters are usually limited to channels with beds dominated by material coarser than sand, whereas 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.

9.5 RIVER RESTORATION DESIGN

Following stability assessment, the restoration project enters the design phase (Fig. 9-1). Although not shown in Fig. 9-1, preliminary analyses may be performed for several alternatives, and detailed design may be reserved for subsequent iterations using the selected alternative. The complexity of design studies should be related to project scale, but an understanding of likely impacts on sediment transport and channel morphology is needed for all restoration projects. Techniques used for design borrow principles from the engineering topics of stable channel design and channel stability analyses and the science of fluvial geomorphology (Chapter 6).

The adaptive, dynamic quality of river systems gives them a certain capacity for recovery (self-restoration). Some stream ecosystems may respond more favorably to assisted recovery (e.g., creating conditions that allow natural revegetation of riparian zones) than strategies featuring aggressive intervention. Generally, strategies that involve the greatest structural modification hold potential for the greatest project-induced adverse environmental impacts, but may prove most beneficial in the long run. Reconstruction of a meandering or braided channel with appropriate width, depth, bed texture, and sinuosity may be necessary to restore a drastically altered stream.

9.5.1 Channel Design

9.5.1.1 Channel Design for Restoration Projects If the existing stream is stable (Thorne et al. 1996b), a good rule of thumb is to modify the channel as little as possible. However, in some cases it may be necessary to modify a stable channel to meet overall project objectives (e.g., restoring some of the functional attributes of the ecosystem). When the existing stream is unstable, significant intervention may be necessary for restoration. In reach-scale projects consideration should be given to isolating the restored reach from the disturbed channel (e.g., through the use of grade controls or sediment traps).

Analytical equations are preferred for design over empirical formulas. Many empirical relations (e.g., hydraulic geometry formulas) are based on limited, regional data sets, and the influence of variables that become important in application may be hidden. For example, a relationship between discharge and velocity based only on data from streams with engineered bank protection would not be applicable to a natural stream with unprotected banks. When design variables are related to a single independent variable such as discharge, the reliability of the relationship is limited.

9.5.1.1.1 Acceptable Levels of Dynamism Conventional flood control, navigation, and channel stabilization projects have focused on increasing the stability of channel position, geometry, and flow conditions. A premium has been placed on high levels of certainty regarding performance and fluvial response. In contrast, restoration projects often seek to enhance the dynamic behavior of fluvial systems, often by relaxing constraints when past activities have led to highly regulated flows or uniform, fixed boundaries. System restoration may involve restoration of processes such as flooding, meander migration, channel avulsion, formation and destruction of large woody debris jams, and backwater sedimentation. For example, high flows may be ecologically beneficial in a number of ways: flushing fine sediments from coarse deposits and thus maintaining conditions that allow intra-gravel movement of water and oxygen, recharging floodplain water tables, depositing nutrient-laden silt on floodplain lands, and temporarily creating extensive “lakes” and feeding areas for migratory waterfowl, fish, and other organisms. Removing or changing the operational strategy for flood control structures may restore high-flow regimes. Experiments by the U.S. Bureau of Reclamation in 1996 and 2004 that produced artificial floods of preset magnitude and duration on the Colorado River in the Grand Canyon downstream from Glen Canyon Dam provide an example of flood restoration. The artificial floods were designed to restore beaches, bars, and wildlife habitat impacted by decades of reservoir operation. Immediate results of the 1996 event showed that morphologic response occurred rapidly—changes were observed after only a few days of high flow (Vaselaar 1997; Schmidt et al. 1998), but longer-term outcomes were less satisfactory, driving plans for the second experiment (Pennisi 2004).

Restoring natural fluvial processes present challenges to engineers because it requires changing streams from an understood present condition to an uncertain, more dynamic future situation. Human systems tend to call for stability, reliability, and predictability; natural systems tend to be dynamic and unpredictable. The reluctance to venture into unknown outcomes may be addressed in at least three ways:

- Incorporating new physical controls into project design. For example, if meandering processes are to be restored or enhanced, then meander belt boundaries could be established. These may be geologic controls, existing structural controls, or new structural controls installed either during project construction or at a later date if and when needed. Similarly, longitudinal limits for re-meandering (e.g., at bridges) might be established at existing or constructed controls such as drop structures.
- Developing the restoration project in stages. If each stage is well conceived and fits into the ultimate restoration condition, this allows the uncertainties to be reduced with each stage and the dynamism and instabilities to be somewhat restricted.
- Providing sediment sinks or sources as needed to maintain sediment continuity and channel stability. These measures will generally require costly operation or maintenance programs.

Restoring a channel to a state of dynamic equilibrium may not be a socially acceptable outcome if the resulting situation poses threats to riparian resources or infrastructure. The need for a relatively high level of channel stability is often a driving factor in urban settings, where tolerance for channel adjustments is low. Clearly, human factors may force design tradeoffs that lead to less than full restoration of channel dynamics and dependent ecosystem attributes. Although these tradeoffs were common in historical river engineering projects, they usually reduce the value of restoration projects. Regardless of strategy, the consequences for channel stability of design alternatives under various scenarios may be evaluated using approaches described in Section 9.6.

9.5.1.1.2 Channel Reconstruction Design analyses should attempt to ensure that the reconstructed channel is not rapidly damaged or destroyed by erosion or sedimentation. The approaches described in Sections 9.5.1.2 and 9.5.1.3 may be used to select the channel width, depth, and slope required for an acceptable level of stability given water and sediment inflows anticipated for the future with-project condition. However, it should be noted that the analytical approaches described in these sections are applicable only to fluvial systems that, given enough time, develop characteristic forms (equilibrium morphologies) in response to an unchanging hydrologic regime. Usually these are perennial, moderate-to-low-energy, single-thread, meandering streams. In these systems, channel width, depth, slope, and bed material grain size eventually adjust to the channel-forming discharge and the input bed-material sediment load. The restoration designer seeks to assist this adjustment by computing and selecting appropriate values for channel geometry. When the computed channel geometry is not feasible due to site or project constraints, the resulting maintenance requirements (erosion controls or sediment removal requirements) may be computed. However, it is important to understand that many fluvial systems are not responsive to a channel-forming discharge of a given average frequency (see Section 9.3.1). Special analyses (Section 9.5.2) may be appropriate when hydraulic structures or habitat enhancement features will be used within the channel, in adjacent backwaters, or on the floodplain.

9.5.1.1.3 Design Variables and Approaches The engineer must select average channel width, depth, slope, and hydraulic roughness and lay out a planform so that the channel will pass the incoming sediment load without significant degradation or aggradation. These design variables are functions of the independent variables of water discharge, sediment inflow, and streambed and stream bank characteristics. In some cases, channel dimensions may be based on a preexisting condition, but this set of dimensions may not be stable if watershed land use or climate has changed. The design process is most challenging when the project reach is unstable due to straightening, channelization, or changing hydrologic or sediment inflow conditions, as is the case in most urban areas. The effects of urbanization on hydrologic response (e.g., increasing flow quantities and peaks) can trigger rapid bed and bank erosion, particularly when these effects are coupled with declining watershed sediment yield as development proceeds.

Channel design approaches may be classified as threshold or active-bed methods. These approaches are discussed in the following sections. The engineer should select an approach based on boundary mobility at design discharge conditions (Fig. 9-1).

9.5.1.2 Design Procedure for Threshold Channels

9.5.1.2.1 When to Use the Threshold Approach Threshold methods are appropriate in cases where bed-material inflow is negligible and the channel boundary is immobile even at high flows. For example, streambeds that are composed of very coarse material or that contain numerous bedrock controls may be immobile even during bank-full flows. Channels with bed material derived from events or processes not currently operative, such as glaciation, may also be candidates for threshold analyses. It should be noted, however, that unmodified channels generally transport significant quantities of material composing their boundaries. Because restoration projects usually are intended to promote natural processes and functions, use of threshold approaches is rarely appropriate. An example of an appropriate use of threshold methods is provided by Newbury and Gaboury (1993), who used tractive-force analysis to size stone used to construct permanent artificial spawning riffles in a channelized stream.

Threshold channels are designed so that a selected fraction of the bed material will be at the threshold of motion (see Section 2.4) at design discharge. Clearly, selection of the design bed material size is crucial. Guidance for sampling bed material is provided in Section 9.3.2. If fine material is moved as throughput over a pavement of coarser sediment, the pavement material should be used to determine the sediment size for design. However, an active-bed analysis may be necessary to ensure that the throughput transport rate is maintained. Threshold methods do not provide unique solutions for channel geometry, and geomorphic principles may be used to finalize selection of reasonable design variables.

9.5.1.2.2 Allowable Velocity and Tractive Force Threshold-of-motion channel design procedures have been widely used for many years (e.g., Lane 1955b). The allowable-velocity approach of USDA (1977) is reviewed in Section 9.4.3.4.3, and graphs are provided in Fig. 9-9. Allowable velocity values are based on experience and various observations. The tractive-force approach (also known as the tractive-stress approach) is a more scientific method based on an analysis of the forces acting on sediment particles on channel boundaries. The basic derivation of equations used in the tractive-force approach assumes that channel cross sections and slopes are uniform, beds are flat, and bed-material transport is negligible. These conditions are rarely found in nature, particularly in lightly degraded streams. Therefore this approach has limited applicability to restoration design.

9.5.1.2.3 Step-by-Step Approach Although design should include reiteration to refine values based on preliminary estimates, a threshold approach may proceed as follows:

- Determine design bed material gradation and water discharge as described above. Note that the use of Q_{eff} is inappropriate for most cases of threshold channel design, because the boundary of the channel will be immobile under design discharge conditions. The discharge selected for sizing a threshold channel should be less than the channel-forming discharge, which, by definition, "does the most work on the channel." Accordingly, the discharge used for design will usually be Q_{ri} or Q_{bf} and will be smaller than Q_{eff}, unless Q_{eff} is determined based on transport of sediments finer than the boundary materials.
- Use hydraulic geometry or regime formulas (see above) to compute a preliminary average flow width.
- Using the design bed material size gradation, estimate critical bed shear stress. The compilation of data presented by Buffington and Montgomery (1997) may prove helpful, because it includes many values from natural streams (as opposed to laboratory flumes) and extensive information regarding the collection and derivation of each value of dimensionless critical shear stress.
- Use bed material size, estimated channel sinuosity, bank vegetation, and flow depth to estimate a flow resistance coefficient. Normally resistance due to bars and bed forms will not be important in threshold channels flowing full, so formulas such as those proposed by Limerinos (1970) or Hey (1979) may be used to compute resistance coefficients. Bathurst (1997) provides a review of flow resistance equations and their proper application.
- Using the continuity equation and a uniform flow equation (e.g., Manning or Chezy), compute the average depth and bed slope needed to pass the design discharge. Sinuosity may be computed by dividing the valley slope by the bed slope. Adjustment of the flow resistance coefficient for sinuosity and reiteration may be required.

9.5.1.2.4 Example An example of a preliminary design developed using the above step-by-step process is provided in Table 9-9. The hydraulic geometry formula chosen for flow width corresponds to bank-full discharge in gravel-bed streams with armor layers and "5 to 50% tree and shrub cover" on the banks. A Shields constant of 0.042 was computed and used to define threshold conditions, but other approaches such as maximum permissible velocity or tractive stress could also be used. The value of the flow resistance coefficient (Darcy-Weisbach f) computed using the formula by Hey (1979) was not modified to account for head losses due to bends, because bend losses would be a relatively small fraction of total loss in such a channel (Onishi et al. 1976). Bend losses are more important for channels with finer bed material and more pronounced bars and bed forms. Channel sinuosity, planform, and alignment were designed as described in Section 9.5.1.4.

9.5.1.2.5 Refinements Additional refinements to shear-stress-based threshold design approaches to allow for the effects of the angle of repose of noncohesive materials, channel side slopes, and bend flow are explained in textbooks (e.g., French 1985; Chang 1988; Julien 1995). For channels with bottom widths greater than twice the flow depth and with side slopes steeper than 1V:2H, the maximum boundary shear stress at a point on the bed or banks may be approximated by 1.5 $\gamma_w HS$ (Chang 1988). Information on the cross-sectional distribution of velocity and shear stress in bends is provided by the USACE (1991).

9.5.1.3 Design Procedure for Active-Bed Channels Active-bed approaches should be used for channels with beds that are mobilized during all high-flow events (at least several times a year). These systems are much more sensitive to relationships between channel geometry and sediment inflow than threshold channels, and design requires more attention. The method described here is applicable for hydraulic design of channels for single-thread streams with mobile beds. Design of braided channel networks is beyond the scope of this chapter. The active-bed design procedure is intended to produce a channel that will transport the sediment supplied to the reach from upstream. Selecting

Table 9-9 Example of Preliminary Channel Design Using Threshold Approach

Quantity	Relationship	Source	Value
Valley slope		Survey or topographic map	0.007
Downvalley distance, km		Survey or topographic map	1.5
D_{50} of bed material, mm		Samples and sieve analysis	45
D_{84} of bed material, mm		Samples and sieve analysis	60
Design discharge, $m^3\ s^{-1}$	$Q_{1.5\ yr}$	Flood-frequency curve	6.7
Width, B, m	$2.73\ Q^{0.5}$	Hey and Thorne (1986)	7.1
Shields constant, θ	Appropriate value or relationship[a]	Buffington and Montgomery (1997)	0.042
Depth-slope product, RS, m[b]	$1.65\ D_s\theta$		0.0031
Variation in depth at a section	R/H_{max}	Assumed based on reference reach	0.75
Channel shape coefficient, a	$11.1\ [R/H_{max}]^{-0.314}$	Hey (1979)	12.15
Darcy-Weisbach flow resistance coefficient, f[c]	$\dfrac{8}{\left[5.75\log\left(\dfrac{aR}{3.5D_{84}}\right)\right]^2}$	Hey (1979)	0.10
Hydraulic radius, R, m[d]	$\sqrt{\dfrac{fQ^2}{8gP^2(RS)}}$	Simultaneous solution of continuity and uniform flow equations for depth.	0.6
Bed slope, S	RS/R		0.005
Sinuosity	Valley slope/channel slope		1.3
Channel length, km	Sinuosity × downvalley distance		2.0

[a]Many of the relations tabulated by Buffington and Montgomery (1997) require an entire gradation curve for both surface (armor) and subsurface bed sediments.

[b]Assumes that average flow depth = hydraulic radius.

[c]Assume a trial value for R. Numerous other relationships are available. For example, the equation due to Limerinos (1970) leads to a Manning n of 0.032, which is equivalent to a Darcy-Weisbach f of 0.10.

[d]Assume wetted perimeter P = width, B. Check R computed with this formula against trial value assumed for computation of Darcy f. Iterate as needed.

channel geometry based on preexisting conditions or threshold approaches without regard to sediment continuity can produce channels that are competent to transport only a fraction of the supplied sediment (Shields 1997). Rapid sedimentation, instability, and high maintenance requirements may result.

The reader should note that the approach described below is based on one-dimensional models, and the highly three-dimensional nature of fluid motion in meanders, which is closely coupled with complex bed topography, is poorly represented. In most cases, two- and three-dimensional effects (e.g., bends) must be incorporated into design computations by professional judgment. The overall approach described could be used with more sophisticated numerical models of flow and sediment movement, but input requirements are often prohibitive for application to smaller projects. Future advances in the state of the art of hydrodynamic modeling may address these issues.

9.5.1.3.1 Width Determination When channel width is not constrained by right-of-way limitations, design width may be determined using the analogy method, hydraulic geometry formulas, and analytical methods (in order of preference). Each is discussed briefly here.

Analogy Method The width may be set equal to the average of measured widths from a reference reach. The reference reach must be in a state of dynamic equilibrium and have the same channel-forming discharge as the project reach. The reference reach may be in the project reach itself, upstream and/or downstream from the project reach, or in a physiographically similar watershed. Streambanks and streambeds in the project and reference reaches must be composed of similar material, and there should be no significant hydrologic, hydraulic, or sediment differences in the reaches.

Hydraulic Geometry Hydraulic geometry formulas (described in Section 9.4.3.3) for width generally display less scatter (residual error) than those for depth or slope. Appropriate formulas, wisely applied, can therefore be used to generate initial values for reach-average channel width.

Analytical Methods If a reliable width versus channel-forming discharge relationship cannot be determined from field data, or if there is significant sediment transport, analytical methods may be employed to obtain a range of feasible solutions, as described below.

9.5.1.3.2 Average Slope and Depth Depth and slope should be calculated using analytical techniques. Analytical techniques are based on physical laws and limited empiricism, and therefore are preferred to empirical hydraulic geometry relationships. In addition to depth and slope, analytical methods may also be used to calculate width in lieu of an empirical method. The design variables of width, slope, and depth may be calculated from the independent variables of water discharge, sediment inflow, and bed-material composition. Three equations are required for a unique solution of the three dependent variables. Flow resistance and sediment transport equations are readily available. Several investigators propose using the extremal hypothesis to supply the third equation (Chang 1980; White et al. 1982; Millar and Quick 1993). However, extensive field experience demonstrates that channels can be stable with widths, depths, and slopes different from extremal conditions.

The stable-channel design routine in the hydraulic design software SAM (Copeland 1994; Thomas et al. 1995; "SAM Hydraulic" 2005) and also found within HEC-RAS 3.1 and higher may be used to determine channel depth and slope. This method is based on a typical trapezoidal cross section and assumes steady uniform flow. The method is especially applicable to small streams because it accounts for sediment transport, bed form and grain roughness, and bank roughness. The first step in using an analytical method for channel dimensions is to determine the sediment inflow into the project reach. 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. Supply reach computations are important in restoration projects, because restoration almost never extends to the upper limits of disturbance. Therefore the designer must develop features (such as sediment traps) that allow a transition from the sediment supply typical of the disturbance regime to the regime provided by the restored reach. Many urban areas are built on alluvial fans or other aggradational features with channels supplied by relatively steep headwaters. Historically, the downstream reaches maintained equilibrium by periodically avulsing. However, once floodplains are developed, such channel changes are typically prevented, thus exacerbating channel aggradation (personal communication, D. Simons).

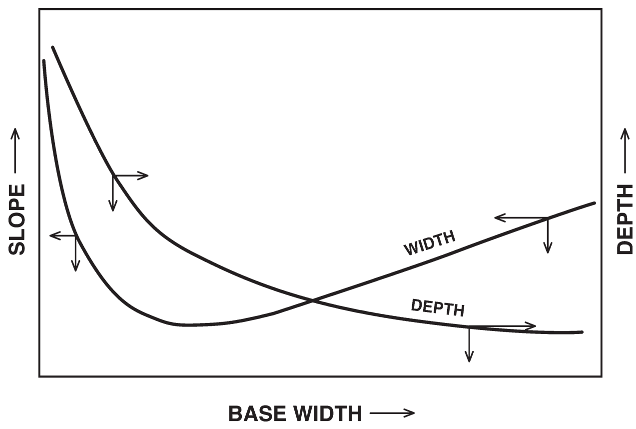

Fig. 9-11. Stable channel design chart showing family of solutions yielding a stable channel for a given design discharge.

The second step in active-bed analytical channel design is to develop a family of slope-width solutions that satisfy the resistance and sediment transport equations. For each combination of slope and base width, a unique value of depth is calculated. The engineer may select any appropriate flow resistance and sediment transport relations to generate the family of slope-width solutions. Shiono et al. (1999) present a simple equation useful for computing flow resistance of a two-stage channel with a meandering low-flow channel, but the equation is based on data from a physical model with uniformly smooth floodplains and main channel. The stable channel design routine in SAM uses either resistance and sediment transport equations by Brownlie (1981; 1983) or a combination of the Meyer-Peter and Muller (1948) sediment transport equation and the Limerinos (1970) resistance equation to calculate bed resistance and sediment transport. The routine may also be used to assess the stability of an existing channel.

An example stability curve is shown in Fig. 9-11. Any combination of slope and base width from this curve will be stable for the prescribed stable channel design discharge. Using the width from a hydraulic geometry predictor or from a reference reach, a unique slope and depth are determined. Width could also be obtained from the minimum slope. Other possible stable channel width and slope combinations can be found from the stability curve. Depth is specified by a given slope and width (or width by a given slope and depth). Constraints on this wide range of solutions may result from a maximum possible slope or a width constraint due to right-of-way. Maximum allowable depth could also be a constraint. With constraints, the range of solutions is reduced. Combinations of width, depth, and slope above the stability curve will result in degradation, and combinations below the curve will result in aggradation. The greater the distance from the curve, the more severe the instability will be. The relationship between sediment transport in the restoration project reach and in downstream reaches must also be investigated. The same general discussion applies, except that the restoration reach becomes the sediment supply reach and the downstream reach is evaluated for an imbalance between bed material transport capacity and sediment supply.

9.5.1.3.3 Example A preliminary design for a hypothetical channel reconstruction for rehabilitation of a sand-bed stream in an urban area with actively eroding banks was developed using the process described above (Table 9-10). Reaches upstream and downstream from the project are relatively stable, except for a few bend locations where bank failure is occurring.

The effective discharge was found by developing a flow-duration curve using data from a downstream gauge. The flow-duration curve was then integrated with a sediment-discharge-rating curve calculated using the Brownlie (1981) equation and channel geometry upstream from the project reach. An hydraulic geometry formula was developed for flow width using appropriate regional data (Table 9-10). Use of the inflowing sediment load to solve for depth and slope ensures that the restoration design will be competent to transport the supplied load.

9.5.1.4 Design of Channel Alignment and Geometric Detail Designing the reconstructed channel alignment involves selecting a channel right-of-way that produces appropriate bed slope and, for single-thread meandering channels, meander geometry. Procedures are similar for threshold and active-bed channel designs. In some cases, preexisting channel alignments determined from maps, aerial photos, or soil surveys may be used if the resulting channel slope is adequate. Channel alignment may be designed by arranging a curve of fixed length (=channel length) on a map of the site. The channel length is simply the downvalley distance times the reach sinuosity, which is the ratio of valley slope to channel slope. Reach sinuosity may be

Table 9-10 Example of Preliminary Channel Design Using Active-Bed Approach

Quantity	Relationship	Source	Value
Valley slope		Survey or topographic map	0.001
Downvalley distance, km		Survey or topographic map	10
Median bed material size, mm		Samples and sieve analysis	0.6
D_{84} of bed material, mm		Samples and sieve analysis	1.0
Design discharge, $m^3\ s^{-1}$		Effective discharge analysis	68
Sediment load at design discharge, $kg\ s^{-1}$	Sediment transport equation and channel geometry from upstream reach	Brownlie (1981)	25
Channel side slope		Assumed	1V:1.5H
Manning n value for side slopes		Estimated	0.05
Top width B, m	$3.6Q^{0.5}$	Developed from stable reaches within watershed	30
Depth, m and bed slope	Simultaneous solution of sediment transport and uniform flow equations	Brownlie (1983) for bed resistance	2.4 (depth) 0.00061 (slope)
	Bed resistance composited with assumed Manning n-value for side slopes	Equal-velocity approach (Chow 1959) for compositing	
Sinuosity	Valley slope/channel slope		1.6
Channel length, km	Sinuosity × downvalley distance		16

checked against values for reference reaches in nearby, similar watersheds.

Meander wavelengths resulting from channel right-of-way layout may be checked against values obtained from hydraulic geometry formulas (e.g., Leopold et al. 1964; Ackers and Charlton 1970) or analytical functions (Langbein and Leopold 1966), but care should be taken to ensure that the data sets used to generate the formulas are from geomorphically similar regions and streams (Rinaldi and Johnson 1997). In general, hydraulic geometry formulas that give wavelength as a function of width are preferred. Uniform geometries (e.g., constant bend length and radius) should not be used. Values derived from formulas may be taken as averages, but bend-to-bend variation should occur. Constant dimensions for channel width, depth, slope, and meander radius and wavelength should not be used for design. Instead, design should capture the spatial variability typical of lightly degraded systems. For example, meandering channels tend to be wider and shallower at riffles, which are often found at meander inflection points, and narrower and deeper at bend apices (Richards 1978; Hey and Thorne 1986). The dimensions computed as described in Sections 9.5.12 and 9.5.1.3 should be used only as averages. Excavation and fill are generally less effective than flow constriction and expansion in producing and maintaining bed features such as pools and riffles. Well-designed projects will develop higher levels of physical heterogeneity with time as vegetation develops, bed material is sorted, large woody debris is trapped, and patterns of local scour and deposition replace uniform dimensions with those typical of natural, lightly degraded streams. Physical response tends to be most favorable for sinuous channels.

As an example, the design outlined in Table 9-10 has a valley slope of 0.001 and a channel slope of 0.00061. Thus a channel sinuosity of 1.6 is feasible. Using a hydraulic geometry formula ($L = 61.21\ Q_{bf}^{0.467}$) curve for meander wavelength (Ackers and Charlton 1970), an approximate meander wavelength of 439 m was selected. Using GIS or mapping software, a mildly sinuous planform channel of fixed length was laid out on a digital topographic map of the project reach.

9.5.2 Habitat Structures

In addition to varying channel geometry, additional physical heterogeneity may be introduced into a reconstructed channel by constructing various types of in-channel habitat structures. Many river restoration projects consist entirely of placing habitat structures and planting riparian vegetation. In some cases, structures are intended to control erosion and enhance habitat (e.g., Shields et al. 1995a). Some workers have questioned the philosophy of using structures to restore habitat, reasoning that if natural fluvial forms and processes are restored, artificial structural elements will be unnecessary or even detrimental. In all types of aquatic habitat planning and design, it is best to let natural processes guide choices for actions. Wherever natural conditions can be used to advantage, the actions are likely to become most compatible with the habitat needs in the ecosystem. Structures not in harmony with the geomorphic processes controlling channel form and physical aquatic habitat are at best a waste of resources, and may damage the stream corridor ecosystem. Conversely, when watershed and riparian conditions are restored to predisturbance status, there is generally little need for habitat structure (except to produce rapid change, which may be desired by stakeholders).

Many types of structural measures have been used for in-channel aquatic habitat improvement, but most fall into four categories (Shields 1983): sills, deflectors, random rocks, and covers. An overview of these categories is provided in Table 9-11. Some structures are essentially erosion control structures (e.g., irregularly shaped revetments and intermittently spaced spur dikes), whereas others are designed to cause bed or bank erosion. Materials used for construction may be natural or artificial, but materials occurring naturally in the stream corridor prior to degradation are preferred.

9.5.2.1 Design of Habitat Structures The design of aquatic habitat structures is a combination of hydraulic engineering concepts and experience. Care should be used to ensure that structures do not induce unwanted erosion or sedimentation that adversely impacts riparian structures. Shields (1983) provides a review of several habitat structure design case studies. Additional case studies of use of deflectors (Shields et al. 1995a) and sills (Shields et al. 1995b) in small sand- and gravel-bed streams are also available. Long-term case studies are provided by Thompson (2002b). Unfortunately, there have been many failures (Table 9-11). Gabion structures often fail because of poor anchorage or because abrasion from cobbles transported by large flows causes breaks in wire meshes and loss of fill material. Various structures have been damaged during floods by debris or by being moved out of position. Other structures have succeeded in providing the intended physical effects, but have not produced measurable biological responses. Given these difficulties, the designer must proceed with caution. A step-by-step approach is provided by Shields (1983) and FISRWG (1998). In addition to the design guides referenced in Table 9-11, information useful for designing large woody debris structures is given by Shields and Gippel (1995), Hilderbrand et al. (1998), D'Aoust and Millar (2000), and Shields et al. (2004).

9.5.2.2 Spawning Gravel and Fish Passage Habitat structures are used to provide pool habitat, cover, and overall physical heterogeneity in many types of stream ecosystems, but additional issues arise in streams that support gravel-spawners and migratory species.

9.5.2.2.1 Spawning Gravel Design of habitat measures to trap and hold gravel for fish spawning beds involves competing constraints: bed sediment stability is needed to protect eggs while incubating, but periodic sediment transport

Table 9-11 Typical Characteristics of In-Channel Habitat Structures

Structure type	Intended effects	Typical location	Materials	Common problems	Design guidance
Sills	Increase scour away from banks	Extending across channel from bank to bank	Stone, gabion, or log weirs with uniform, sloping, or notched crests	Flanking. Fish passage. Undermined by downstream scour hole. Erosion of crest. Abrasion and failure of gabion wire.	Klingeman et al. (1984). "Simple bed control structures," in Biedenharn et al. (1998). Artificial riffles described by Newbury and Gaboury (1993)
Deflectors	Increase surface flow disturbance along banks; deflect flow away from banks	Along banks	Irregularly shaped revetments, intermittently spaced short spurs or groins, boulders, or root wads	Erosion of crest. Structure subsidence in fine-bed channels. Erosion of opposite bank. Scour holes too small. Covered by deposition. Flanking.	Klingeman et al. (1984). "Dikes and retards," in Biedenharn et al. (1998). Kuhnle et al. (1999b; 2002), Thompson (2002a)
		Extending out from river bank	Cabled (anchored) trees; longer spur dikes, groins, or jetties		
Random rocks	Induce scour, create zones of low velocity in wake	Isolated midchannel flow obstructions	Boulders, boulder clusters (groups), root wads, vanes, or sills detached from banks	Fall or roll into downstream scour hole.	
Covers	Little impact on flow or sediment; primarily intended to provide shade and hiding places	Along undercut banks	Lumber piers, trees, brush, rafts, and features that cause local turbulence and thus reduce water transparency	Habitat protected by cover may be eliminated by sedimentation.	

is needed to prevent fine sediment from depositing in the upper portions of the gravel matrix. Hydraulic analysis is required to select appropriate bed material gradations and flow regimes (Reiser et al. 1989; Reiser 1998; Wu and Chou 2003).

9.5.2.2.2 Migratory Barrier Removal Removal of passage blockages has been undertaken in many tributary streams in order to expand the range of habitat use for migratory fish. Blockages have also been removed on larger rivers, usually older dams or weirs or landslides that have blocked channels that once allowed fish to pass. A full discussion of the subject of dam removal is beyond the scope of this chapter (see HCSEE 2002), but recent studies have begun to document the physical (Doyle et al. 2003) and ecological (Stanley et al. 2002) changes associated with removing dams, and other studies provide specific guidance for dam decommissioning and removal (ASCE Task Committee 1997). Bedrock outcrops have been modified by drilling or blasting to carve steps or pools. Artificial structures have also been built to bypass blockages and older dams and weirs have been removed or rebuilt to provide passage. Large hydraulic structures have been constructed to allow fish passage past hydroelectric dams, and voluminous literature is available (e.g., Bell 1986; Jungwirth et al. 1998). Information is also available regarding fish passage over simple rock ramps or weirs (Harris et al. 1998).

9.5.3 Channel-Floodplain Connectivity

Past engineering activities have included placing streambank protection to control channel migration and constructing levees to eliminate floodplain inundation. These actions have often altered and degraded ecosystems. Because hydrologic interaction between the floodplain and channel is so ecologically important, reestablishment of floodplain functions is often a goal of river restoration projects.

9.5.3.1 Floodplain Reconnection Issues Floodplain reconnection may simply involve levee breaching to allow pastures or gravel pits to flood during high-water periods. More generally, reconnection is a major undertaking, particularly where extensive floodplain development has occurred. It involves full or partial restoration of large-scale flow and sediment transport conditions. It may be necessary to limit floodplain reconnection projects to elementary bank-line alterations that result in most of the water and all of the bed load remaining in the prerestoration channel and only minor diversions of water and suspended sediments. In other cases it may be possible to introduce major alterations that allow limited re-meandering between set-back levees or within a low-elevation floodplain.

Channel stability and flooding are primary concerns when floodplain reconnections are considered. Breaching or removing dikes and revetments may trigger channel destabilization. Hence, economic, physical, and environmental impacts of various levels of confinement of flow, sediment load, and meandering processes must be assessed. Hydrologic conditions (river flows, floods, droughts) and physical space (channels, riparian zones, floodplains) are key elements for working with these concepts (Williamson et al. 1995a; 1995b; Bella et al. 1996).

9.5.3.2 Longitudinal Variation in Floodplain Confinement In projects where there is significant longitudinal variation in floodplain confinement, sediment transport continuity during high flows should be carefully considered. For example, when the project reach is located in a relatively broad valley just downstream from the mouth of a steep-walled canyon, deposition is likely in the project reach during flows that exceed bank-full in the project channel but remain confined to the upstream channel. A similar situation may occur in developed areas where the upstream floodplain has been encroached upon by levees. In such a situation, simulation of sediment transport for large single events or long-term flow records including such events will allow determination of the magnitude of the sediment transport imbalance. It may be necessary to increase the channel capacity in the project reach. Designs featuring excavation to lower berms or terraces, in order to increase the frequency of overbank flooding, may be especially vulnerable to aggradation in this type of situation (Fullerton and Baird 1999).

A contrasting situation occurs when the proposed restoration reach has incised, but upstream reaches have not. Because the incised channel is larger, high flows are generally confined to the channel, and sediment transport rates and erosive forces are elevated relative to the upstream reaches. Reestablishment of the hydraulic connectivity between the channel and floodplain is often desirable in such a situation. Two approaches are possible: the incised channel may be filled to preincision elevations, or a berm (an artificial floodplain) may be excavated along and adjacent to the incised channel (Shields et al. 1999). Filling may be done during construction or gradually by sedimentation in response to low weirs or roughness elements placed in the incised reach, thus accelerating natural incised channel evolution. Hydraulic and sediment transport analysis can assist in determining the most feasible approach and the appropriate geometry for the restored channel cross section. Impacts of incised channel filling on flooding may be important in some situations.

9.5.4 Channel Bottom Habitats

Sediment size and gradation are key aspects of riverine aquatic habitats. The ASCE Task Committee (1992) developed a bed-material-based stream-reach classification (Table 9-12) and reviewed literature dealing with biological functions of bed sediments within each stream type. Interstitial voids are an important component of habitat in gravel and cobble beds for some fish (e.g., salmonid reproduction) and many invertebrates. Some cobble- or gravel-bed streams are impaired due to deposition of fine sediments within the coarse matrix as a result of flow stabilization by

Table 9-12 Bed-Material-Based Stream Reach Classification (after ASCE Task Committee 1992)

Bed type	Particle size (mm)	Relative frequency of bed movement	Typical benthic macroinvertebrate density/diversity	Fish use of bed sediments
Boulder-cobble	≥64	Rare	High/high	Cover, spawning, feeding
Cobble-gravel	2–256	Rare to periodic	Moderate/moderate	Spawning, feeding
Sand	0.062–2	Continual	Low/low	Silt and clay bed deposits in off-channel backwaters are used for feeding
Fine material	<0.062	Continual or rare	High/low	Feeding

upstream dams or sediment-producing watershed activities (Reiser 1998). Rehabilitation activities include control of sediment sources and techniques to mobilize the fine sediment trapped in the bed using mechanical flushing, scour-producing structures, and the release of "flushing flows" from upstream reservoirs. Design of a flushing flow regime requires considerable analysis (Reiser et al. 1989; Reiser 1998) to define flows adequate to winnow fines away from the matrix without destroying it.

9.5.5 Backwater Protection

River development activities have routinely led to closing secondary channels, sloughs, and other backwater zones (Gore and Shields 1995; Klingeman et al. 1998). They have been used for disposal of dredged or excavated material. In other cases they have been deepened to provide dock access or storage of vessels. Unaltered backwaters (e.g., secondary channels, sloughs, and floodplain lakes) support local ecosystems directly connected to the main channel on a continuous, perennial, or seasonal basis. For example, backwaters sustain organisms that would not otherwise survive or thrive in the stream because they provide low-velocity habitats and critical refuge zones, especially during floods. Because backwater areas are depositional zones, they are relatively transient features. Because many rivers have been stabilized, the creation of new backwaters by channel migration, avulsion and other processes has been slowed or eliminated. As a result, backwater habitats are declining along many rivers (ASCE Task Committee 1992). Backwater zones primarily receive suspended sediment through connecting channels that introduce flow from the mainstem or by flooding. During floods, coarse material may be swept into backwater channels from the tops of intervening bars. The mouths of connecting channels are susceptible to bed load deposition and eventual closure, thus degrading ecological and recreational values (Shields and Abt 1989).

True restoration would involve restoration of processes responsible for backwater creation (e.g., avulsions). Although this strategy is preferred, it is often not feasible, particularly along larger rivers. Instead, strategies intended to reverse or retard sedimentation in existing backwaters and to create new backwaters (e.g., dredging or excavation) are often pursued. Backwater projects include development of connecting channels and protection of existing backwaters using weirs, blocks, or river training structures. Effects of these measures may be short-lived without maintenance. Sedimentation in zones adjacent to river training dikes is complex, but appears to be inversely related to dike crest elevation relative to annual flood stage (Shields 1984 and 1995). Typical sediment transport calculations (e.g., one-dimensional models) may not replicate phenomena in the vicinity of channel margins where backwaters connect to the main channel. Backwater protection may require more elaborate sedimentation analyses (e.g., Barkdoll et al. 1999).

9.6 STABILITY CHECKS

Because of the uncertainties involved in channel design, a series of stability checks should be performed. Stability checks include simple approaches such as those discussed in Section 9.4 as well as more detailed analyses of bank stability and sediment transport capacity.

9.6.1 Bed and Bank Stability

Bank erosion is difficult to predict and simulate, and thus the outer banks of bends and other locations subjected to potentially erosive flows should be protected if the consequences of bank erosion are unacceptable. Mass failure of steep, cohesive banks is related to bank height, bank angle, and soil properties. Stability assessment analyses that incorporate these variables are described in Thorne (1999) and numerical models (e.g., Simon et al. 2000; 2003) are available. In general, cohesive banks over 3 m high should be analyzed for slope stability. Because bank stability is sensitive to bank height, impacts of channel aggradation and degradation on bank stability should be considered. Bank protection of any type (vegetation or structure) is usually ineffective if bed erosion (degradation) is occurring. If the aim of the project is a partial return to a less disturbed stream condition, then usually some bank erosion is desirable because many ecosystems have key species that depend on habitats created by lateral channel migration.

Restoration projects often feature the use of vegetation to protect banks. A full discussion of vegetation for streambank protection is beyond the scope of this chapter, but engineers should bear in mind that bank erosion is often governed by erosion of the toe of the bank, which cannot be stabilized by vegetation in channels with perennial flow. With adequate structural toe protection, woody vegetation has been used to stabilize banks along channels experiencing mean velocities as great as 2 to 3 m s^{-1} (Nunnally and Sotir 1997). Limited information is available regarding critical levels of hydraulic loading for plant materials (e.g., Hoitsma and Payson 1998; Fischenich 2001). Newly constructed banks are more readily eroded than those that have become well vegetated, and may require protection with temporary measures such as biodegradable fabric during the period of plant establishment. The rate of the fabric degradation should be analyzed in tandem with the expected growth rate of the planted vegetation in order to ensure that the protection is not compromised through time. Miller and Skidmore (1998) describe a bank protection design featuring vegetation on the upper bank and toe protection with cobbles wrapped in a biodegradable fabric (coir). The fabric decays as plants become established, gradually leading to a well-vegetated, but deformable bank. Additional useful information regarding bed and bank stabilization is provided by Biedenharn et al. (1998), FISRWG (1998), and Gray and Sotir (1996), and science underpinning interactions between channels and vegetation is reviewed in Bennett and Simon (2004).

9.6.2 Sediment Budgets

A sediment budget is a tool for assessing the long-term stability of a restored reach and estimating maintenance requirements. Average annual bed-material yields of the design channel and either the existing channel (if it is stable) or the upstream reach (if the existing channel is unstable) are compared. Large differences in bed-material yields indicate potential channel instability. The level of confidence that can be assigned to the sediment budget is a function of the reliability of the available data. In many restoration projects, the absence of relevant flow data will require the use of synthetic or extrapolated flow data, greatly reducing the confidence level.

9.6.2.1 Tools Effects of alternative designs with different reach-average widths, depths, and slopes on sediment continuity may be analyzed using spreadsheets, but the most reliable way to determine the long-term effects of changes in a complex mobile-bed channel system is to use a numerical model such as HEC-6 (e.g., Copeland 1986) or HEC-RAS, one-dimensional models based on a series of channel cross sections, which may vary in shape and are available at Hydrologic Engineering Center (2005). A simpler treatment is provided by SAM, which simulates steady, uniform flow at a single cross section. SAM is described in Section 9.5.1.3.2. The SAM approach is appropriate if longitudinal changes in cross-sectional shape and bed-material gradation are small, because it does not account for hydraulic sorting or bed armoring.

It should be noted that most numerical models suitable for design work do not simulate bank erosion, and few simulate washload transport or effects of unsteady flows. In addition, one- and two-dimensional models do not simulate flow phenomena that are three-dimensional. A full discussion of sediment transport models is provided in Chapters 14 and 15.

9.6.2.2 Step-by-Step Approach The following steps are recommended for conducting a sediment budget analysis:

- Calculate hydraulic parameters for a typical or average reach for a range of discharges. This range should extend from the average annual low flow to the peak of the design discharge. If restoration channel design is based on a single discharge value (e.g., the channel-forming discharge), sediment budget analysis for the entire range of discharges that will affect the stability of the project should be performed as a check on design.
- Select an appropriate sediment transport function for the study reach. This can be done by comparing calculated sediment transport to measured data, taking care to ensure that bed-material load is being compared. When no data are available, one may rely on experience with similar streams in choosing an equation.
- Calculate bed-material sediment transport rating curves for the existing channel in the project reach and upstream and downstream from the project reach. Sediment transport curves should also be calculated for the alternative project design channels. Pre- and post-project sediment transport rating curves should also be determined for tributaries that might be affected by the proposed design.
- Calculate bed-material yield for the existing and project channels using the flow duration sediment discharge rating curve method as described by USACE (1995, pp. 3-4 through 3-10). Average annual bed-material yield should be calculated using the flow duration curve. This provides an estimate of average annual deposition

or degradation. Performance of the project during a design flood event should be evaluated using the design flood hydrograph. If the project will affect the flow duration curve or the flood hydrograph, then this should be reflected in the analysis.

- Calculate trap efficiency by comparing the pre- and postproject bed-material yields. The reach trap efficiency, E, in percent is expressed by the equation

$$E = \frac{100\,(Y_{s_{in}} - Y_{s_{out}})}{Y_{s_{in}}} \tag{9-15}$$

where

Y_s = annual bed-material yield,

and subscripts "in" and "out" refer to inflow and outflow, respectively. Negative trap efficiency implies that bed material sediment will be eroded from the project reach. A positive value means that bed material sediment will be deposited in the project reach. Forecast stability is highest for trap efficiency of zero.

9.6.2.3 Interpretation Consider a reach that contains three-dimensional features and longitudinal differences that require repeated basic sediment transport calculations at successive cross sections along the length of the channel. Assuming that a reliable formula is used or that accurate field measurements are made, it is quite likely that bed-material yield at adjacent cross sections may be unequal. The engineer must resist the temptation to quickly dismiss differences in sediment transport at opposite ends of a reach as the product of formula limitations or measurement errors (or to immediately accept agreement in sediment transport at opposite ends of the reach). Local hydraulic conditions may well lead to local deposition or erosion. Hence the analysis must include consideration of spatial and temporal sources and sinks for sediment within the reach. Otherwise, a situation where sediment is placed into or removed from local storage may be treated as one where sediment merely passes through a reach. Given enough time or a large enough sediment transport event, the consequences could be surprising and damaging.

9.6.2.4 Example Using the example channel geometry described in Section 9.5.1.3.3 and Table 9-10, a new sediment-rating curve was developed and integrated with the flow duration curve to determine the effect of the new geometry on the sediment budget. By comparing the calculated annual design channel sediment transport with the bed-material yield from the supply reach, it was found that about 83% of the annual bed-material load would be transported through the reach. Higher levels of bed-material transport could be obtained by increasing the channel slope, but it was determined that decreasing sinuosity would adversely affect habitat quality. In order to retain sinuosity, the preliminary design planform was adopted for the final design, and plans for periodic sediment removal were included in the operation and maintenance plan.

9.7 IMPLEMENTATION AND CONSTRUCTION

In general, disturbance of a river and its riparian corridor should be minimized during construction. Standard practices for sediment and erosion control should be employed. These require design, careful installation, and repeated inspection and maintenance. Complicated projects may require sequenced measures, including site dewatering. Unexpected site conditions may require fit-in-field adjustments. Contingency plans should include scenarios involving extreme floods or droughts during and shortly after construction. Features involving live vegetation require special considerations for selecting, handling, installing, and caring for plant materials. FISRWG (1998) provides an introduction to these topics.

Projects involving only minor changes to channel systems with negligible sedimentation problems are good candidates for design-build contracts. In simple low-cost projects for which consequences of failure are acceptable, a low-level or conceptual design may be used with a higher-than-normal level of on-site construction oversight. With such conceptual designs, it is relatively easy to incorporate habitat variability and diversity, as adherence to specified dimensions may be relaxed. Detailed plans and specifications, which are necessary for complex projects, often feature strict adherence to design criteria, and the resulting habitat is too uniform. When possible, contract specifications should be written in terms of maximum and minimum values for key parameters (e.g., "channel top width shall be no less than 16 m and no greater than 18 m"), and because contractors will tend to employ the limit of tolerance to achieve lowest cost (e.g., a constant width = 16 m), construction oversight must be employed to provide suitable physical irregularity. Personnel assigned to oversee construction must have an understanding of fluvial systems and project objectives to effectively translate the design into reality.

9.8 MONITORING AND POSTCONSTRUCTION ADJUSTMENT

Fluvial system response to restoration projects cannot be precisely predicted, and dynamic watershed land use, extreme weather events, and changing project objectives add more uncertainty. Accordingly, project plans should provide for adaptive management after initial construction. Information from monitoring project performance is required for adaptive management decisions. Monitoring efforts are normally tightly constrained by economic factors. A standard suite of variables for monitoring includes stage, discharge, and sediment concentration and periodic determinations of bed material size and channel geometry. Evaluation of hydraulic performance may include determination of changes in flow resistance due to changes in bank and floodplain vegetation, bed material size, and channel planform. Because project objectives usually focus on ecosystem response, it may be important to monitor water quality, biological populations, or social variables. Clearly, it is not possible to monitor every project fully. Even projects that have monitoring programs may produce little useful information if monitoring data are not combined into well-defined metrics reflective of overall system response. In addition, monitoring results must be disseminated so that future restoration projects are responsive to new knowledge gained. Feedback should be provided to project designers and to those charged with program management. Restoration projects should be viewed within a landscape context. Individual restoration projects should be viewed as staged components of overall, long-term ecosystem management schemes for the larger river system and watershed (Seal et al. 1999).

No simple rules exist for setting the length of a monitoring program, but several seasonal cycles should be included. Monitoring intensity may be greatest during the first two or three years, when greatest response is anticipated, and less frequent in subsequent years except after extreme events. The life cycles for key species should also be considered. The impact of physical habitat improvements on plant and animal communities may not become apparent rapidly. Vegetative growth and fluvial response take time. For example, it may take many years for riparian zone revegetation to supply large woody debris for instream recruitment. Furthermore, the physical recovery of degraded stream banks requires more time than is needed only for the recovery of plant community composition (Clary and Webster 1989). Similarly, structures may require high flows to produce the intended effects.

9.9 CONCLUSIONS

Stream restoration is a term often used to refer to stream corridor manipulation. True restoration, however, seeks to return the status of an ecosystem to a former, less degraded state with recovery of function and processes. Large-scale projects, though not always economically or socially feasible, offer the greatest potential for true restoration. All stream restoration projects require some level of sedimentation engineering to reduce the risk of undesirable outcomes. Often the basic task for the engineer is to formulate a sediment budget for the project and to determine how alternatives and various sequences of hydrologic events will impact the quantity and size of sediments within the reach. The outcome of this analysis provides a foundation for a projection of the sustainability of the project. Due to the unorthodox nature and relatively high level of uncertainty surrounding stream restoration projects, involvement of the sedimentation engineer should continue through the implementation phase, and a monitoring program should be included in project plans.

ACKNOWLEDGMENTS

Meg Jonas, Bruce Rhoads, Peter Downs, and Darryl Simons read an earlier version of this paper and made many helpful comments, leading to substantial improvement. Chester Watson, Colin Thorne, Philip Soar, and David Biedenharn provided useful insights in the discussion of channel-forming discharge. The authors also acknowledge contributions by other control and corresponding members of the Task Committee on River Restoration in the form of conference papers and oral discussions at committee meetings. Among these members are Rebecca Soileau, William Fullerton, Richard Hey, and Drew Baird.

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