# Design for Stream Restoration

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**Abstract:** Stream restoration, or more properly rehabilitation, is the return of a degraded stream ecosystem to a close approximation of its remaining natural potential. Many types of practices (dam removal, levee breaching, modified flow control, vegetative methods for streambank erosion control, etc.) are useful, but this paper focuses on channel reconstruction. A tension exists between restoring natural fluvial processes and ensuring stability of the completed project. Sedimentation analyses are a key aspect of design since many projects fail due to erosion or sedimentation. Existing design approaches range from relatively simple ones based on stream classification and regional hydraulic geometry relations to more complex two- and three-dimensional numerical models. Herein an intermediate approach featuring application of hydraulic engineering tools for assessment of watershed geomorphology, channel-forming discharge analysis, and hydraulic analysis in the form of one-dimensional flow and sediment transport computations is described.

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## Introduction

The term ''stream restoration'' is often erroneously used to refer to any type of stream corridor manipulation. In this paper, ''restoration'' refers to the return of a degraded ecosystem to a close approximation of its remaining natural potential [U.S. Environmental Protection Agency (USEPA) 2000]. Although this is more properly termed ''rehabilitation,'' we follow popular convention and use the term ''restoration'' here. Natural potential may be determined by life scientists using habitat assessment approaches (see below), although this determination is not free of subjective judgments. Ecosystem potential is typically gauged by indicators based on habitat quality, quantity, or species diversity. Alternatively, restoration may be thought of as an attempt to return an ecosystem to its historic (predegradation) trajectory (Society for Ecological Restoration 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intact ecosystems, information about regional environmental conditions, and analysis of other ecological, cultural, and historical reference information (Society for Ecological Restoration 2002). Large-scale projects, although not always economically or socially feasible, offer the greatest potential for effective restoration.

Clearly, effective restoration requires a broad-based interdisciplinary team [Federal Interagency Stream Restoration Working Group (FISRWG) 1998]. Project objectives, which usually include some type of habitat manipulation, should be set early on by team members working with other stakeholders. Hydraulic designers must then develop alternatives that meet these objectives subject to economic and other constraints. Sedimentation issues are often key constraints, since they have economic, institutional, and ecological ramifications. Below we outline the way that currently available tools may be applied in this context.

Strategies for restoration projects often include promoting higher levels of physical dynamism (e.g., flooding, erosion, and deposition) in streams that have been dammed, leveed, or channelized (e.g., Schmidt et al. 1998). 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 channel stability is often a key constraint in urban settings, and a tension often exists between the dynamism needed for ecological objectives and erosion and flood control interests. Risks associated with uncertain channel response can be reduced by the use of controls such as drop structures or sedimentation basins, implementation of the restoration in phases, and adaptive management.

Stream restoration is a growing area within hydraulic engineering practice encompassing a wide range of activities (Gore 1985; Brookes and Shields 1996; Hayes 2001a,b), but the remainder of this paper focuses on channel reconstruction. Channel design approaches include those based on stream classification and regional curves for hydraulic geometry (Rosgen 1996; Riley 1998), regime and tractive force equations (Ministry of Natural Resources 1994), reference reaches (Newbury and Gaboury 1993), and combinations of these approaches (Gillilan 2001). Although more sophisticated approaches based on two- and three-dimensional numerical models are available, the approach suggested below is based on assessment of watershed geomorphology (forms and processes), empirical tools (hydraulic geometry, critical velocities, or stresses), and hydraulic analysis in the form of one-dimensional flow and sediment transport compu-

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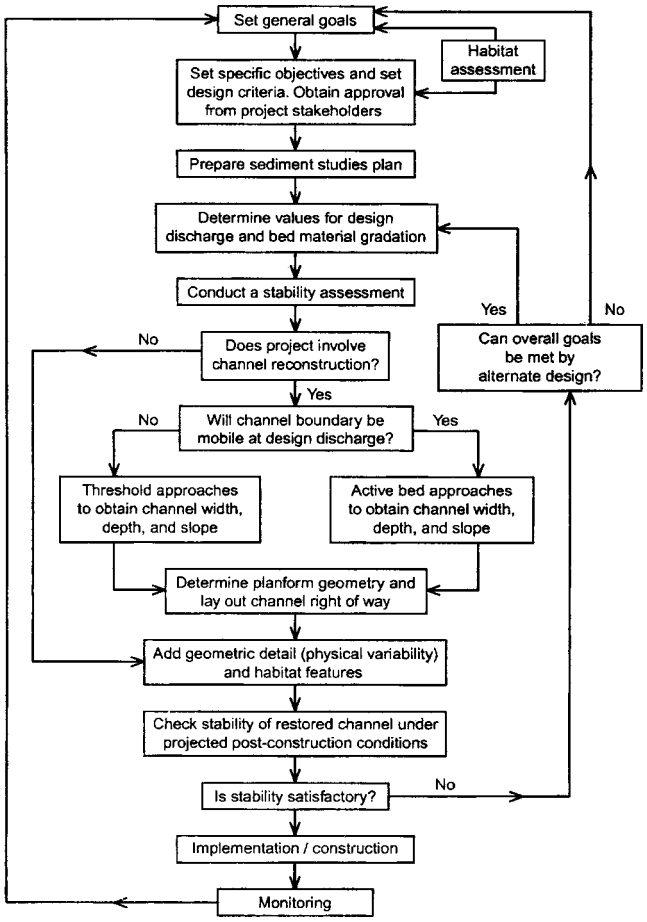


**Fig. 1.** Flow chart for hydraulic engineering aspects of stream restoration projects

tations. This approach uses many of the same tools as the aforementioned guides, but differs from them in that balancing sediment supply and transport is a key consideration. Application to specific cases supports the wisdom of this approach relative to others (Copeland 1994; Copeland et al. 2001, Appendix G; Soar and Thorne 2001, Chapter 8). Uncertainties involved in channel restoration design are rather high, and sediment transport analyses are useful in reducing uncertainty (Johnson and Rinaldi 1998).

## Planning

### *Setting Objectives and Habitat Assessment*

Initial project phases must include definition of measurable project objectives by project stakeholders (Fig. 1) (FISRWG 1998; Copeland et al. 2001). This process often requires an assessment of current habitat quality and identification of the factors contributing to degradation (Society for Ecological Restoration 2002). An introduction to quantitative habitat assessment tools including the instream flow incremental methodology and the habitat evaluation procedure is provided by FISRWG (1998). Additional tools for evaluating stage, discharge, and other time series variables relative to a reference condition are described by Richter et al. (1996).

### *Stability Assessment*

Since habitat degradation is often driven by instability, stability assessment is needed to develop restoration alternatives. A stability assessment consists of examination of a selected part of the fluvial system encompassing the restoration project to determine the causes, direction, and speed of morphologic changes [Kondolf and Sale 1985; Kondolf et al. 1990; U.S. Army Corps of Engineers (USACE) 1994; Lagasse et al. 2001]. The assessment provides a foundation for design and basis for prediction of system response. Inadequate assessment may result in a project that is obliterated by erosion or deposition within a short period of time, or one that degrades stream corridor resources or endangers floodplain assets.

Initial steps in performing a stability assessment include selecting an appropriate spatial domain (certainly more than the project reach, but economic constraints may prevent inclusion of the entire watershed) and defining levels of dynamism that constitute instability. Current and projected channel stability may be assessed relative to these levels. From a strictly pragmatic standpoint, a reach (a section longer than, say, 20 channel widths) is unstable when morphologic change (i.e., erosion or deposition) is rapid enough to generate public concern (Brice 1982) or excessive maintenance requirements (USACE 1994). 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) if its long-term (say 10 years or more) temporal average properties (channel width, depth, slope, sediment input and output) are stationary. Such a stream may have relatively rapid rates of lateral migration and thus bank retreat but still have a very healthy ecosystem. Thus the statement defining acceptable rates of change should provide a clear rationale.

*Qualitative* assessments typically require less than one week of effort for one person, and consist mostly of visual inspection from aircraft or on the ground and review of readily available historical information (Sear 1996; Biedenharn et al. 1998). Such assessments can be powerful when performed by someone with a high level of expertise. Review of historic maps and air photo coverage can be a powerful tool (Rhoads and Urban 1997; Kondolf et al. 2001). *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. Six types of tools are commonly used in stability assessment (Table 1). A watershed assessment normally proceeds by dividing the channel network into reaches displaying consistent fluvial properties and applying a set of assessment tools to each reach. A simplified example is provided in Table 2.

### *Discharge for Assessment and Design*

The ''channel-forming'' or ''dominant'' discharge $Q_{cf}$ is often used as the representative value for stability assessment or channel design. The channel-forming discharge concept is that, for a given alluvial channel geometry, there exists a single discharge that given enough time would produce width, depth, and slope equivalent to those produced by the natural hydrograph. This discharge therefore dominates channel form and process, at least for streams in humid regions and for perennial streams in semiarid environments (Biedenharn et al. 2001; Soar and Thorne 2001). At least three approaches are available for determining $Q_{cf}$: effective discharge ($Q_{eff}$), bank-full discharge ($Q_{bf}$), or the discharge that corresponds to a given return interval, $Q_{ri}$ (Table 3).

**Table 1.** Overview of Channel Stability Assessment Tools

| Type of Tool | Best applied to | Weaknesses | References |
|---|---|---|---|
| Lane relations | Quick preliminary assessments when system disturbance is dominated by a shift in one variable | Limited to fully alluvial systems. Does not allow for complex response. Predicts direction of response, but not magnitude. | USACE (1995, Appendix D)<br>Sear (1996)<br>Hooke (1997) |
| Channel classification | Fluvial systems disturbed by influences leading to rapid incision or aggradation. Can be mapped on GIS for synoptic visualization of watershed processes. | Form-based systems do not provide indication of future response. Process-based classification systems require considerable expertise to use properly; easily misapplied by inexperienced personnel. | Simon and Downs (1995)<br>Thorne et al. (1996b)<br>Johnson et al. (1999)<br>Doyle and Harbor (2000)<br>Kondolf et al. (2001) |
| Hydraulic geometry relations and planform predictors | Regions with lightly perturbed alluvial channels in dynamic equilibrium for which extensive data sets are available | Can give misleading results when applied outside domain of the underlying data | Allen et al. (1994)<br>van den Berg (1995)<br>Shields (1996, pp. 37–41)<br>Thorne et al. (1996b) |
| Relationships between sediment transport and hydraulic variables | Incipient motion type analyses including Shields parameters are usually limited to channels with beds dominated by material coarser than sand, while sediment budgets are best for sand bed streams prone to aggradation. | Sediment inflows to the project reach are usually unknown. Most sediment transport relations are imprecise. | USACE (1994, Chapter 5) |
| Regional relationships | Channel networks with large data sets that include stable sites | Purely empirical approach assumes future hydrology will be similar to past | Simon (1998) |
| Bank stability analyses | Channels with cohesive banks higher than about 3 m | Requires considerable field data | Thorne (1999) |

### Effective Discharge

If available, a time series of discharge records may be used to construct a frequency histogram. The mass of sediment transported by each discharge increment may be computed using a sediment rating curve or sediment transport formula. The effective discharge $Q_{\text{eff}}$ is the increment of discharge that transports the largest sediment load over a period of years (Wolman and Miller 1960; Andrews 1980; Emmett and Wolman 2001). Thus $Q_{\text{eff}}$ integrates the magnitude and frequency of flow events, and is the best starting point for design because it links sediment load with channel geometry. However, there are several problems associated with $Q_{\text{eff}}$ (Biedenharn et al. 2001; Soar and Thorne 2001). Key among these is the high level of uncertainty in sediment transport computations. The effective discharge is useful in

**Table 2.** Summary of Simplified Hypothetical Stability Assessment

| Type of tool (Table 1) | Assessment tool | Reach 1 | Reach 2 | Reach 3 | Reach 4 | Value required for stability[a] | Reference |
|---|---|---|---|---|---|---|---|
| Channel classification | Channel evolution model | Stage V | Stage V | Stage IV | Stage II | Stage V or VI | Simon (1989), reconnaissance per Thorne et al. (1996b) |
| Planform predictor | Potential specific stream power per unit bed area, $2.1S_v\ Q_{\text{bf}}{}^{0.5}$ $(\text{W}\cdot\text{m}^{-2})$ | 24 | 32 | 38 | 45 | $<843D_{50}^{0.41}=30$ for meandering planform | van den Berg (1995) |
| Regional relationship | Slope–drainage area relationship $S=0.00454A^{-0.322}$ | 0.002 | 0.00018 | 0.0022 | 0.0024 | 0.0011–0.0014 | Simon (1998) |
| Regional relationship | Unit stream power $\gamma_w Q_{\text{cf}} S/B$ $(\text{W}\cdot\text{m}^{-2})$ | 29 | 43 | 33 | 52 | $< 35$ | Brookes (1990) |
| Bank stability analyses | Height of near-vertical banks (m) | 5.1 | 4.7 | 4.3 | 2.2 | 3.8 | Thorne (1999) |

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 continues there. $S_v$ = valley slope, $Q_{\text{bf}}$ = bank-full discharge, $S$ = energy slope, $A$ = contributing drainage area, $\gamma_w$ = specific weight of water, $Q_{\text{cf}}$ = channel-forming discharge, $B$ = flow width, $R$ = hydraulic radius. Numerical values in table based on this case; for application users must consult references.

[a]Assuming $D_{50}=0.3$ mm, 39 km$^2$ $<A<$ 82 km$^2$.

**Table 3.** Quantitative Representations of Channel-Forming Discharge ($Q_{cf}$)

| Quantitative estimate of $Q_{cf}$ | 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 using observed stage-discharge relation (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 |

comparing the competence of alternative channel geometries to transport the incoming sediment load. Results of effective discharge analysis are also useful when predicting the impact of alteration of watershed conditions with respect to sediment loads (e.g., upstream dam removal) or hydrology (e.g., urbanization) on channel stability.

**Bank-full Discharge**

Herein the bank-full discharge $Q_{bf}$ refers to the maximum discharge that the channel can convey without overflow onto the floodplain (Copeland et al. 2001). Although this definition differs from that used by others (e.g., Rosgen 1996), it eliminates confusion. 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., Pickup 1976; Andrews 1980; Soar 2000; but see Emmett and Wolman 2001). 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 evolution (Schumm et al. 1984; Simon 1989; Thorne et al. 1996a). Field indicators of $Q_{bf}$ are often unreliable (Williams 1978). Problems associated with basing design on $Q_{bf}$ are discussed by FISRWG (1998) and Biedenharn et al. (2001).

**Discharge for Specific Return Interval**

If gauge data are available, the discharge with a given return interval is often assumed to be the channel-forming discharge, e.g., $Q_{cf}=Q_2$, where $Q_2$ is the two-year return interval discharge (e.g., Hey 1994; Ministry of Natural Resources 1994; Riley 1998). 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 (Leopold et al. 1964; Andrews 1980), although intervals outside this range are not uncommon. Recurrence interval relations are intrinsically different for channels with flashy hydrology than for those 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; Kondolf et al. 2001) 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, although it may be useful at times to serve as a *first estimate* of $Q_{eff}$ and/or $Q_{bf}$ in stable channels, particularly those with snowmelt hydrology (Doyle et al. 1999). The $Q_{ri}$ approach is based on the assumption of stationary hydrologic conditions and thus is weak when applied to situations such as urbanizing watersheds where land use changes are forcing changes in hydrology and geomorphology.

**Ungauged Sites**

When gauge records are not available, estimates of $Q_{ri}$ can be based on similar gauged watersheds or obtained from regression formulas (Wharton et al. 1989; 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. (2001): the drainage area–flow duration curve method (Hey 1975) and the regionalized duration curve method (Watson et al. 1997). 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. 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. 2000).

**Range of Discharges**

The quantities $Q_{eff}$, $Q_{bf}$, and $Q_{ri}$ are estimates of $Q_{cf}$, and thus more than one of these should be considered (Biedenharn et al. 2001). Values of $Q_{eff}$ and $Q_{bf}$ outside the range bounded by the one- and three-year recurrence intervals should be questioned. Stages for estimates of $Q_{cf}$ should be compared with field evidence of geomorphic significance. Channel performance should be examined for a range of discharges that represent key levels for aquatic habitat, riparian vegetation, channel stability, or flow conveyance (Copeland et al. 2001).

### *Bed Material Size Distribution*

Most stability assessment tools require a representative bed sediment size, and size distributions are needed for sediment transport computations, habitat assessment, and design of habitat features (e.g., flow regimes for periodically flushing coarse beds or stability of aquatic habitat structures). Bed material sampling techniques should vary with the bed type and the purpose for sampling (USACE 1995; Bunte and Abt 2001). For example,

floodplain borings 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. Bed material sampling should provide estimates of representative sizes as well as information regarding spatial variability. The computations described below are extremely sensitive to sediment size, and bed texture can change quickly in channels draining disturbed watersheds with eroding tributaries (Doyle and Shields 2000). A sensitivity analysis using a range of sediment sizes may be advisable.

### Design

Although not shown in Fig. 1, preliminary analyses may be performed for several alternatives, and detailed design may be reserved for subsequent iterations using the selected alternative. 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 generally better than empirical formulas based on channel-forming discharge or stream classification (Copeland 1994; Kondolf et al. 2001; Downs and Kondolf 2002). However, use of these equations involves a good bit of judgment (e.g., selection of resistance coefficients or appropriate sediment transport relations), and satisfactory performance depends on the user's expertise and familiarity with the stream system in question (Copeland 1994).

### Design Variables and Approaches

The analytical approaches described below are strictly applicable only for alluvial systems approaching a state of dynamic equilibrium; judgment and modification is required when streams deviate from these conditions. The approaches described here are suited for perennial, moderate to low-energy 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, erosion control features may be designed or sediment removal requirements may be computed.

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. The engineer should select an approach based on boundary mobility at design discharge conditions (Fig. 1).

### Threshold Channels

Threshold methods are appropriate in cases where bed material inflow is negligible and the channel boundary is immobile even at high flows (e.g., streambeds composed of very coarse material or that contain numerous bedrock controls). Channels with bed material derived from events or processes not currently operative, such as glaciation, may also be candidates for threshold analyses. Threshold-of-motion channel design procedures have been widely used for many years (e.g., Lane 1955; USDA 1977). Allowable velocity values are based on experience and various observations. The ''tractive force'' or ''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 slightly degraded streams. Therefore this approach is rarely appropriate for projects intended to promote natural processes and functions. 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 riffles in a channelized stream. Threshold methods are poorly suited for channels with significant amounts of cohesive material in the bed because of the complex nature of cohesive bed erosion (Simon and Thomas 2002).

Threshold methods are so called because the dimensions are set so that a selected fraction of the bed material will be at the threshold of motion at design discharge. Clearly, selection of the design bed material size is crucial. If fine material is moved as throughput over a pavement of coarser sediment, the pavement material should be used for determining 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. Design should include reiteration of the steps found in Table 4 to refine values based on preliminary estimates:

An example of threshold design for channel reconstruction is provided by Beck et al. (2000). Additional refinements to shear-stress-based threshold design approaches to allow for the effects the angle of repose of noncohesive materials, channel side slopes, and bend flow are explained in textbooks (e.g., Chang 1988). More recent work on meander hydraulics is presented by Lyness et al. (2001). 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 $1.5\gamma_w HS$, where $\gamma_w$=specific weight of water; $H$=flow depth; and $S$=energy slope (Chang 1988). Information on the cross-sectional distribution of velocity and shear stress in bends is provided by USACE (1991).

### Active-Bed Channels

Active-bed approaches (Table 5) should be used for channels with beds that are mobilized during all high flow events (at least sev-

**Table 4.** Basic Steps in Channel Design, Threshold Approach

| Step | Task | Notes | Resources |
|---|---|---|---|
| 1 | Determine design bed material gradation and discharge as described above | Using $Q_{eff}$ is inappropriate here, since the boundary of the channel will be immobile under design discharge conditions. Accordingly, the design $Q$ will usually be $Q_{ri}$ or $Q_{bf}$ and will be smaller than $Q_{eff}$ unless $Q_{eff}$ is based on transport of sediments finer than the boundary materials | See above |
| 2 | Compute a preliminary average flow width | Hydraulic geometry or regime formulas may be used | Shields (1996, pp. 36–41); Copeland et al. (2001, pp. 71–79) |
| 3 | Using the design bed material size gradation, estimate critical bed shear stress | Consider sediment gradation and local conditions | Komar (1987); Buffington and Montgomery (1997); Wilcock (1998); Fischenich (2001) |
| 4 | Use bed material size, estimated channel sinuosity, bank vegetation, and flow depth to estimate a flow resistance coefficient | Normally resistance due to bars and bedforms will not be important in threshold channels flowing full, so formulas based on grain size may be used to compute resistance coefficients | Limerinos (1970); Bathurst (1997) |
| 5 | Using the continuity equation and a uniform flow equation (e.g., Manning, Chezy, etc.), 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. In addition, the resulting form (width/depth) ratio should be checked against relationships that include bank materials and vegetation. | Knighton (1998, pp. 174–177) |

**Table 5.** Basic Steps in Channel Design, Active-Bed Approach

| Step | Task | Notes | Resources |
|---|---|---|---|
| 1 | Determine sediment inflow for the project reach | Sediment discharge for upstream ''supply reach'' may be computed based on hydraulics and appropriate sediment transport relation. Transitions such as sediment traps may be required | Thomas et al. (1995) |
| 2 | Develop a family of slope-width solutions that satisfy resistance and sediment transport equations (e.g., Fig. 2) | Width-depth ratios should be checked against empirical relations that include effects of bank materials and vegetation | Knighton (1998, pp. 174–177); Shiono et al. (1999) |
| 3 | Reduce the range of solutions to meet site constraints such as maximum slope, width, or depth | Combinations of width, slope and depth above the curve (Fig. 2) will lead to degradation, while those below will lead to aggradation | Copeland et al. (2001) |
| 4 | Compute sediment transport capacity for reaches downstream from the project | Transitions and controls (e.g., drop structures) may be required | |

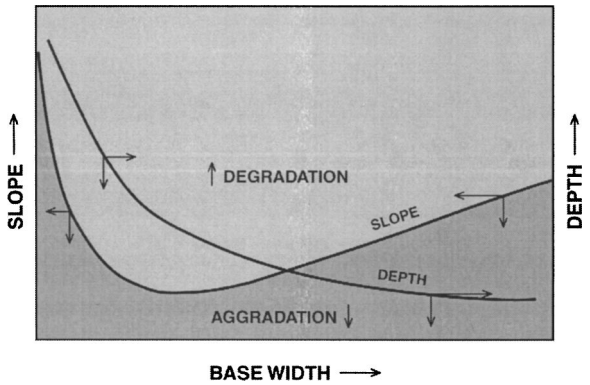


**Fig. 2.** Conceptual stable channel design chart showing family of solutions yielding stable channel for given design discharge. Arrows emanating from curves indicate appropriate axes.

eral times a year). These systems are much more sensitive to relationships between channel geometry and sediment inflow than threshold channels. Selecting 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) and thus quickly fail (Keller 1978, Chap. 8; Kondolf et al. 2001; Soar and Thorne 2001). The method described here is applicable for single-thread channels with mobile beds, and design of braided channel networks is beyond the scope of this paper. The approach described below is based on one-dimensional models, and the highly three-dimensional nature of fluid motion in meanders that 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 below could be used with more sophisticated numerical models of flow and sediment movement, but most of these models are too costly and require too much calibration data for application to small to medium stream restoration projects. Future advances in the state of the art of hydrodynamic modeling may address these issues.

The basic philosophy of the approach was stated by Thomas (1990) and by Copeland and Hall (1998), and several examples are available (Copeland 1990, 1994; Copeland et al. 2001, Appendix G; Soar and Thorne 2001, Chap. 8). 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, and several investigators propose using the extremal hypothesis to supply the third equation (e.g., Millar and Quick 1993). However, extensive field experience demonstrates that channels can be stable with widths, depths, and slopes different from extremal conditions. An alternative to the extremal hypothesis is to use a hydraulic geometry width predictor as the third equation or to use a reference reach to determine width. 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 between the reaches.

The stable-channel design routine in the hydraulic design software *SAM* (Copeland 1994; Thomas et al. 1995; ⟨http://chl.wes.army.mil/software/sam/⟩) may be used to determine channel depth and slope. The stable channel design routine in *SAM* uses either the resistance and sediment transport equations by Brownlie (1983) or a combination of the Meyer-Peter and Mueller (1948) sediment transport equation and the Limerinos (1970) resistance equation to calculate bed resistance and sediment transport (e.g., Soar and Thorne 2001, Chap. 8). *SAM* is based on representation of the channel cross section by a typical trapezoidal shape and the assumption of 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. Use of *SAM* is limited to cases where longitudinal changes in bed material gradation may be neglected, since it does not account for hydraulic sorting or bed armoring.

### *Channel Alignment and Geometric Detail*

Designing the reconstructed channel alignment involves selecting a channel right of way that produces appropriate bed slope and 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 routing a curve of fixed length across a hardcopy or digital (electronic) 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 checked against values for reference reaches in nearby, similar watersheds. If the right of way is confined by topographic features or manmade structures, the desired level of sinuosity may be higher than allowed by site constraints. Grade controls such as weirs or bed sills may be needed to reduce slope or prevent bed erosion.

Meander wavelengths resulting from channel right of way layout may be checked against values obtained from hydraulic geometry formulas (e.g., Ackers and Charlton 1970; Soar and Thorne 2001) 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 discharge or width are most effective (USACE 1994; Copeland et al. 2001). Uniform geometries (e.g., constant bend length and radius) should not be used. Values derived from formulas may be used as averages, but bend-to-bend variation should occur, as shown in data compilations presented by Copeland et al. (2001, Fig. 46). Such variation presents an opportunity to work around right-of-way constraints.

Constant dimensions for channel width, depth, and slope should also be avoided. Instead, values computed as described above should be used as averages, and detailed design should capture the spatial variability typical of lightly degraded systems (Richards 1978; Hey and Thorne 1986; Knighton 1998; Soar and Thorne 2001). Of course, movable bed channels constructed with nonuniform geometry and roughness will develop natural, heterogeneous patterns in response to fluvial processes. Physical heterogeneity may also be increased by constructing various types of in-channel habitat structures (Shields 1983; Shields et al. 2001). 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 (Th-

ompson 2002). 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).

### Stability Checks

Due to the uncertainties involved in channel design, a series of stability checks should be run for any design. Stability checks include simple approaches such as those discussed above for predesign assessment, as well as more involved analyses of bank stability and sediment transport capacity. For example, sediment transport may be simulated for selected hydrologic events or typical annual hydrographs in order to determine if the channel will experience unacceptable levels of scour or deposition during discharges greater and less than the design flow. Bed or bank stabilization, either permanent or temporary, may be necessary to ensure project success (Gray and Sotir 1996; Biedenharn et al. 1998). 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 (e.g., Johnson 1998).

Effects of alternative designs with different reach average widths, depths, and slopes on sediment continuity (budgets) 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 *SAM* or *HEC-6*. *HEC-6* is a one-dimensional model based on a series of channel cross sections and is available at ⟨http://www.wrc-hec.usace.army.mil/software/⟩. It should be noted that most numerical models that are practical tools 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, and one-dimensional models do not capture two-dimensional phenomena. Accurate simulation of sediment transport in gravel bed rivers is particularly difficult, and evaluations of *HEC-6* for gravel bed simulation are guarded, though generally positive (e.g., Havis et al. 1996; Bradley et al. 1998).

### Discussion and Conclusions

Although the number and scope of stream restoration projects are increasing, designs for these projects are often weak in hydraulic engineering. This paper represents an attempt to outline acceptable standards for hydraulic design for channel reconstructions. All stream restoration projects require some level of sedimentation analysis to reduce the risk of undesirable outcomes. More powerful, user-friendly software tools are needed for this type of work. Sensitivity analysis and expert advice should be integral parts of such software. More accurate and robust flow resistance and sediment transport relations are needed. Ideally, tools for analyzing habitat issues should smoothly interface with those for flow and sediment transport. Due to the unorthodox nature and relatively high level of uncertainty surrounding stream restoration projects, involvement by the hydraulic designer should continue through the implementation phase, and a monitoring program should be included in project plans.


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## Notation

*The following symbols are used in this paper:*

$A$ = contributing drainage area;
$B$ = flow width;
$D_{50}$ = median bed material size;
$H$ = depth of flow;
$n$ = Manning flow resistance coefficient;
$Q_{bf}$ = bank-full discharge;
$Q_{cf}$ = channel-forming discharge;
$Q_{eff}$ = effective discharge;
$Q_{ri}$ = discharge with given return interval;
$R$ = hydraulic radius;
$S$ = channel bed slope=energy slope for uniform flow;
$S_v$ = valley slope; and
$\gamma_w$ = specific weight of water.

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