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FLUVIAL GEOMORPHOLOGICAL METHODOLOGY FOR NATURAL STABLE CHANNEL DESIGN[1]

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ABSTRACT: A fluvial geomorphological methodology for designing natural stable channels is being widely applied for river restoration. It is an analogue procedure, as the W/d ratio and sinuosity from a reference reach are scaled to determine the restoration design. The choice of reference reach is crucial and published criteria specify that it should be stable, correspond to the stream type at the restoration site, have the same valley type, and be from the same hydrophysiographic region. For stable, meandering gravel cobble bed rivers flowing through alluvial flood plains (C3 and C4 stream types), UK regime equations are used to evaluate the procedure. Successful design requires particular combinations of the ratios of bankfull discharge, bed material size and load, valley slope, and bank vegetation category between the reference and restoration sites. These critical ratios, which are confirmed by U.S. field data, provide guidelines for selecting a suitable reference reach for C3-C4 stream types. They also indicate that the reference reach can be in any valley type or hydrophysiographic region. The geomorphological procedure will apply to all stable stream types, provided the reference reach is correctly identified. Specific guidelines for each stream type await the development of additional regime equations.

(KEY TERMS: fluvial geomorphology; river classification; reference reach; river restoration; natural stable channel design; regime equations; rational equations.)

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INTRODUCTION

Historically, many rivers have been widened, dredged, and/or straightened to develop water resources, reduce flood risk, improve land drainage, aid navigation, and generate power. They have also been indirectly impacted by land use changes and other developments that modify their flow and sediment transport regimes. Affected rivers have either been heavily engineered and/or managed to sustain an unnatural condition or, in the absence of any artificial intervention, become destabilized. Both can destroy the ecological, fisheries, and amenity value of riverine environments.

Increasing public concern regarding the sustainable development of river systems and the maintenance and enhancement of their biodiversity has resulted in the demand for the implementation of more environmentally sensitive and natural engineering works and for the restoration of unstable and degraded rivers. Consequently, there is an urgent need to develop more appropriate channel design procedures that will not only preserve the natural stability of rivers but, by maintaining habitat diversity, also their ecological and amenity value. By designing with nature, rather than imposing a solution on the river, such approaches are likely to be sustainable and, therefore, more cost effective than traditional engineering solutions.

The earliest attempt to develop stable channel design procedures were empirical and are referred to as regime equations. These establish relations between variables defining the dimension, pattern, and profile of the river and those defining the boundary conditions or causal variables that control their

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development, namely the flow and sediment transport regimes of the river, the bed and bank material, the vegetation on the banks, and the slope of the valley. Numerous equations have been developed over the years for canals since Kennedy's pioneering work in 1894 and, more recently, following Leopold and Maddock's (1953) work, for rivers. The earliest equations concentrated exclusively on the effect of discharge on channel form and are often referred to as hydraulic geometry relations.

In contrast, rational equations offer a theoretically based alternative to empirical regime equations for designing alluvial channels. If equations could be specified for each process that controls flow, sediment transport, and channel adjustment in alluvial channels, their simultaneous solution would enable the morphology of natural rivers to be prescribed given the boundary conditions (Hey, 1978, 1982).

Both regime and rational equations have limited application. As most of them are restricted to the design of straight channels in a particular river environment, it raises questions about their general utility for natural channel design. For many types of river, there are no relevant equations. Even if the equations are appropriate, there will still be some uncertainty in the predicted channel dimensions.

An alternative approach to natural channel design has recently been developed (Rosgen, 1994). It has variously been described as the 'Rosgen Method' after its initiator, or the 'river classification procedure' as the design process requires knowledge of river types. In reality, it is a fluvial geomorphological procedure (hereafter referred to as the "geomorphological procedure") because it uses the morphology of a natural, stable river as a reference analogue to scale the restoration design. Provided it applies to any type of river, it overcomes the restrictions with traditional engineering design approaches noted above.

This paper critically reviews the application of this geomorphological procedure for natural/stable channel design and identifies and verifies the critical criteria for selecting appropriate reference reaches for restoring meandering gravel and cobble bed rivers. Conclusions are made about the implications of these findings for other stream types.

RIVER CLASSIFICATION

Rivers vary considerably in their character, not only between source and mouth, but also between rivers reflecting local and regional variations in their controlling boundary conditions as they are influenced by the geology, terrain, climate, vegetation, and land use of their drainage basin. Various attempts have been made to rationalize this diversity by classifying them, principally on the basis of their morphology and substrate, into categories. The aim is to minimize the variability in the defining values within a category and to maximize it between them. Although it is generally considered that rivers vary continuously from source to mouth, both in terms of their physical and biological characteristics, it should be recognized that distinct streamwise breaks can occur in the values of the boundary conditions and associated flow processes that control channel form. Breaks occur below tributaries, in terms of discharge, sediment load, and, possibly, bed material calibre. They can also occur where there are distinct changes in lithology, which affect bed material size and valley gradient, and where there are abrupt differences in valley configuration and slope as, for example, where a river flows through a former glacial valley or through a former lacustrine reach. Channel morphology will vary downstream, reflecting local boundary conditions. Between abrupt breaks, relatively little change would be expected, which then constitutes a distinct river type.

The classification system developed by Rosgen (1994) is a comprehensive morphological system based on bankfull cross sectional and longitudinal profiles of the river and its plan form. At a more detailed level, bed material size is included, which enables the basic stream types to be further subdivided. With the exception of bed material size, the other variables that control channel form are not incorporated in the classification. Such information would, however, be redundant as their values are reflected in channel form. This arises because identical channels must have the same combination of their controlling variables. Any change in the latter may result in the river evolving to a new stable state depending on its sensitivity to change.

Based on the dimension, pattern and profile of the river, eight distinctly different stream types have been identified by Rosgen (1994). Each type is characterized by a range of entrenchment ratios, width/depth ratios, sinuosities, and slopes. This initial geomorphological characterization can be extended by field data on bed material size. This allows basic stream types to be subdivided, 1 through 6, respectively, for bedrock, boulders, cobbles, gravel, sand, and silt/clay. In total, 41 stream types have been identified (Rosgen 1994). Rosgen's classification underpins the geomorphological procedure for river restoration summarized in this paper.

FLUVIAL GEOMORPHOLOGICAL PROCEDURE FOR NATURAL CHANNEL DESIGN

This review of the application of geomorphological procedures for natural stable channel design does not consider each of the 40 steps proposed by Rosgen (1998). Instead, the key elements are assessed to determine whether there is any empirical or theoretical evidence to confirm, or invalidate, the scaling procedure used to generate stable natural channel designs for river restoration from reference reach data. It is emphasized that the assessment is restricted to mobile gravel and cobble bed meandering rivers that exhibit pool riffle sequences and have a connected floodplain, namely C3 and C4 stream types.

Establishing the Type and Cause of Instability and Restoration Options.

To restore an unstable river to a natural stable state, the first requirement with any type of design approach is to establish the nature of the instability and identify its cause (Hey, 1994). Failure to stabilize the boundary conditions would render any restoration works unsustainable. Restoration is not recommended on rivers that are naturally unstable (i.e., some D stream types) or where boundary conditions cannot readily be stabilized due to major and progressive land use or climate change.

Using the geomorphological procedure, it is necessary to identify the stream types in the unstable and, if available, adjacent stable reaches. As unstable channels undergo a sequence of changes in stream type while developing towards a new equilibrium (Rosgen 1994, 1996), the initial requirement is to establish the stage in the evolutionary process the river has attained. It is then necessary to decide whether (1) the original regime condition can be reinstated, (2) it is appropriate to allow the river to self-stabilize or, (3) it is preferable to create a channel that corresponds to the evolving stable state to prevent instability migrating further thus speeding up the stabilizing process. The decision depends on the stage of evolution of the river, particularly the entrenchment and lateral extent of the valley, because this influences energy dissipation during floods, as well as logistic, conservation, and economic considerations (Rosgen, 1998).

Identification of Reference Reach

The next stage in the geomorphological procedure involves the establishment of a reference reach. As this will be used to guide the restoration design, it is essential that it is the same stream type as that required for the restored reach. The procedure also requires that the reference reach is both vertically and laterally stable, is located in the same hydrophysiographic region, has a similar basin area, and has the same valley type as the restoration site. By being in the same hydrophysiographic region, it ensures they have the same climate, geology, topography, and vegetation and, thereby, comparable flow and sediment transport regimes (Rosgen, 1998).

Establishing Dimensionless Design Shape Ratios

The required dimensionless shape parameters for the restoration design are obtained from survey data from the reference reach. These data are used to establish the ratios of (1) bankfull width to mean depth and maximum depth to mean depth for the riffle cross section; (2) meander wavelength, radius of curvature, meander belt width, and bankfull pool width to the bankfull riffle width; and (3) the bankfull maximum pool depth to riffle mean depth. At low flow, riffle, run, pool, and glide slopes are surveyed to derive ratios relative to the average bankfull channel slope. These dimensionless ratios are the templates for designing the restoration scheme (Rosgen, 1998).

Scaling the Restoration Design

To scale the restoration design, the dimensionless shape ratios from the reference reach have to be multiplied by a known or predicted dimension of the restoration site. In practice, the bankfull cross sectional area for a stable riffle at the restoration site is used for this purpose.

For a site that is vertically unstable, either aggrading or degrading, it is impossible to define bankfull stage from morphological indicators. Even on rivers that are laterally unstable and an emergent bankfull level is identifiable, it does not follow that the associated cross sectional area corresponds to the final equilibrium value, as the river is still evolving to a new stable state. To circumvent this problem, the bankfull cross sectional area for a stable riffle immediately upstream from the restoration site is used provided no tributaries enter the river between the two reaches.

Should circumstances dictate that the upstream reach will remain unstable, for example due to different land ownership, or because it is of a different stream type to that required for the restoration, then an alternative approach is required. In this case, its value is predicted from a regional curve linking bankfull cross sectional area and basin area for that hydrophysiographic region (Rosgen, 1998). These regional curves are derived from field data obtained from both stable and unstable sites and from different stream types stratified by hydrophysiographic region. In the absence of such curves, the cross sectional area is derived from regional curves of bankfull discharge and estimated velocities obtained from locally calibrated values of Manning's n or Darcy-Weisbach friction factor (Rosgen, 1998).

The design bankfull riffle width, W (m), and mean depth, d (m), for the restored reach are obtained from the estimated bankfull cross sectional area for the restoration site, A (m^2), as outlined above, and the width/depth ratio, W/d, from the reference reach *viz*

$$\mathrm{W} = \sqrt{\mathrm{A} \cdot \left(\frac{W}{d}\right)} \tag{1}$$

from which the mean depth, d, can be determined (= A/W). Maximum riffle depth, d_m (m), is obtained by multiplying the ratio of the maximum depth to the mean depth for the riffle in the reference reach (d_m/d) by the calculated mean riffle depth (d) for the restoration site. The required plan form of the restored channel is obtained by first determining ratios of meander wavelength (λ), radius of curvature (r), meander belt width (W_{blt}), and riffle spacing (z) to bankfull riffle width (W) (mean and range) at the reference reach. Design values are then obtained by multiplying these ratios by the predicted bankfull riffle width (W) of the restored channel.

With the geomorphological approach, channel slope at the restoration site is obtained by dividing the local valley slope by the sinuosity derived from the predicted plan form. Variations in low flow slopes between pools and riffles are prescribed by scaling dimensionless ratios obtained from the reference reach. In more conventional engineering design procedures, bankfull channel slope is obtained directly via a specific regime or bed material transport equation. Both are notoriously inaccurate (Hey *et al.,* 1990; Gomez and Church, 1989). Sinuosity can subsequently be determined given the valley gradient. In contrast, this geomorphological procedure first determines sinuosity and then channel slope given the valley slope.

Design Evaluation

To assess the sustainability of the proposed design, checks are carried out to determine whether the shear stress at bankfull flow on the riffle will transmit the largest clast supplied from upstream (Rosgen, 1998). This has been found to be represented by the largest exposed clast on the lower third of a depositional bar in the affected reach (Rosgen, 1996). If it is indicated that the bankfull flow is not competent to transmit the largest exposed clast, or can transmit coarser material, then it is necessary to modify the bankfull depth. If the width/depth ratio remains within the observed range for that stream type following such a change, then the predicted bankfull width, plan form, and slope of the river are unaffected. Essentially, this mimics how a natural river would respond if its banks were nonerodible. If the width/depth ratio lies outside the range, then an adjustment would also need to be made to bankfull width and, hence, plan form and profile. This iterative process requires recalculation of the river's dimension, pattern, and profile before rechecking its competence to transmit the largest clast.

ASSESSMENT OF FLUVIAL GEOMORPHOLOGICAL PROCEDURE

It is evident that the fluvial geomorphological procedure will accurately prescribe the dimension, pattern, and profile of any stable river provided the shape parameters at the reference reach correspond to those required at the restoration reach and the scaling parameter is correctly determined.

United Kingdom regime equations (Hey and Thorne, 1986) for meandering gravel and cobble bed rivers, which flow through alluvial flood plains, namely C3 and C4 stream types, can be used to establish the criteria that enable these provisos to be met for these particular stream types. As both types of river exhibit small scale roughness and predominantly transport their bed material as bedload, the flow processes controlling their morphology are functionally identical. Therefore, one set of regime equations apply to both C3 and C4 stream types.

Determination of Design Cross Section

The first requirement is to determine the bankfull cross sectional area at the restoration site, as this underpins all scaling procedures. The use of regional curves assumes that there is no change in the bankfull cross sectional area of the river following periods of instability.

Regime equations can be used to evaluate this assumption for C3-C4 stream types. Their bankfull cross sectional area, A (m^2), is defined by

$$A = h\,Q^{0.87}\,D_{50}^{-0.11} \qquad (2)$$

where Q is the bankfull discharge (m^3/s), D_{50} the median grain size (m) of the surface armour (grid sample by number frequency), and the coefficient h varies with bank vegetation density (0.95 for less than 1 percent trees and shrubs, Category I; 0.73 for 1 through 5 percent, Category II; 0.60 for 5 through 50 percent, Category III; and 0.52 for greater than 50 percent, Category IV) (Hey and Thorne, 1986). For bankfull cross sectional area to remain constant following aggradation or degradation, there has to be no net change in any of these variables or, if any changes do occur, they must compensate each other.

Bankfull discharge, being equivalent to the flow transporting most bed material load (effective discharge), is prescribed by the flow and sediment transport regime of the river. Provided the river reestablishes a new stable state following destabilization without the flow and sediment transport regimes being affected, the bankfull discharge will not be altered. Equally, the bed material size will be unchanged if the sediment delivery from the catchment is maintained. Only if instability is severe enough to permanently alter the discharge and/or bed material load delivered by the upstream reach, for example through major climate and/or land use change or a change in base level, is it anticipated that there will be any systematic change in bankfull discharge and bed material size (Hey, 1979). Such changes have been shown to occur following extensive urbanization (Hammer, 1972) or downstream from dams (Gregory and Park, 1974). Differences in bankside vegetation before and after the destabilizing event are, however, very likely to occur. Provided restoration reestablishes an equivalent bank vegetation density (strength) through some form of bank stabilization, the original bankfull cross sectional area can be reinstated. However, if a different stream type is created, or the same stream type with a different bank vegetation density, then the bankfull cross sectional area would be expected to have a different value because a change in width/depth ratio will affect relative roughness and bankfull velocity.

Even assuming that the bankfull cross sectional area at a site does not change following instability, it has to be recognized that when it is assessed from regional curves, design errors can occur. To illustrate this problem, consider the North Carolina Piedmont regional curve (Harman *et al.,* 1999). Even though its coefficient of determination is a highly respectable 98.1 percent, the 95 percent confidence bands around the predicted cross sectional area are quite high. For example, for a basin area of 25.9 km^2 (10 square miles), the predicted area is 9.6 m^2 with upper and lower 95 percent confidence limits of 14.9 m^2 and 5.6 m^2. Assuming the restored stream has a width/depth ratio of 15, this gives a design width of 12 m. However, the 95 percent confidence limits are 14.9 m and 9.1 m, a variation of between +24.6 and -23.6 percent. Similarly, the predicted riffle mean depth is 0.8 m. As the 95 percent confidence limits are 0.6 and 1.0 m, predicted depths could be between -20 and +30 percent in error. This emphasizes the need to omit unstable sites from the regional curves and stratify the data by stream type and bank vegetation density. Streams with a low width/depth ratio will have a higher velocity and smaller cross sectional area, other factors being equal, because flow resistance is lower. This could minimize the variance around the predicted value.

The design procedure assumes that the width/depth ratio at the reference reach can be transferred to the restoration site (Equation 1). The circumstances that should enable this to be achieved for C3-C4 stream types can be predicted by the UK regime equations. These equations indicate that the reach average width/depth ratios are dependent on bankfull discharge, bed material size, and bank vegetation density.

$$\frac{W}{d} = kQ^{0.13}D_{50}^{\;0.11} \qquad (3)$$

The coefficient k varies with bank vegetation density category as defined for Equation (2) (19.68 for Category I, 15.14 for Category II, 12.41 for Category III, and 10.64 for Category IV). Bank material had no significant effect on width/depth ratios, despite the considerable range of their tensile strengths. This is probably due to the overriding influence of bank vegetation on bank strength. Riffle width/depth ratios were found to be 1.09 times reach average values.

According to Equation (3), there are various combinations of the ratios of bank vegetation category (k_r), bed material size (D_r) and bankfull discharge (Q_r) between the riffle sections at the reference and restoration reaches which would result in no discrepancy between the width/depth ratios at the two sites. These are defined by the following equation.

$$Q_r = k_r^{-7.69} D_r^{-0.846} \qquad (4)$$

Figure 1 illustrates the relation between these ratios when the bank vegetation densities at the reference and restoration sites are equivalent (i.e., both are either I, II, III, or IV), and for various combinations of bank vegetation densities at the two sites. Plus and minus 10 percent limits are indicated for sites with equivalent bank vegetation densities. The same tolerance bands apply to sites with different

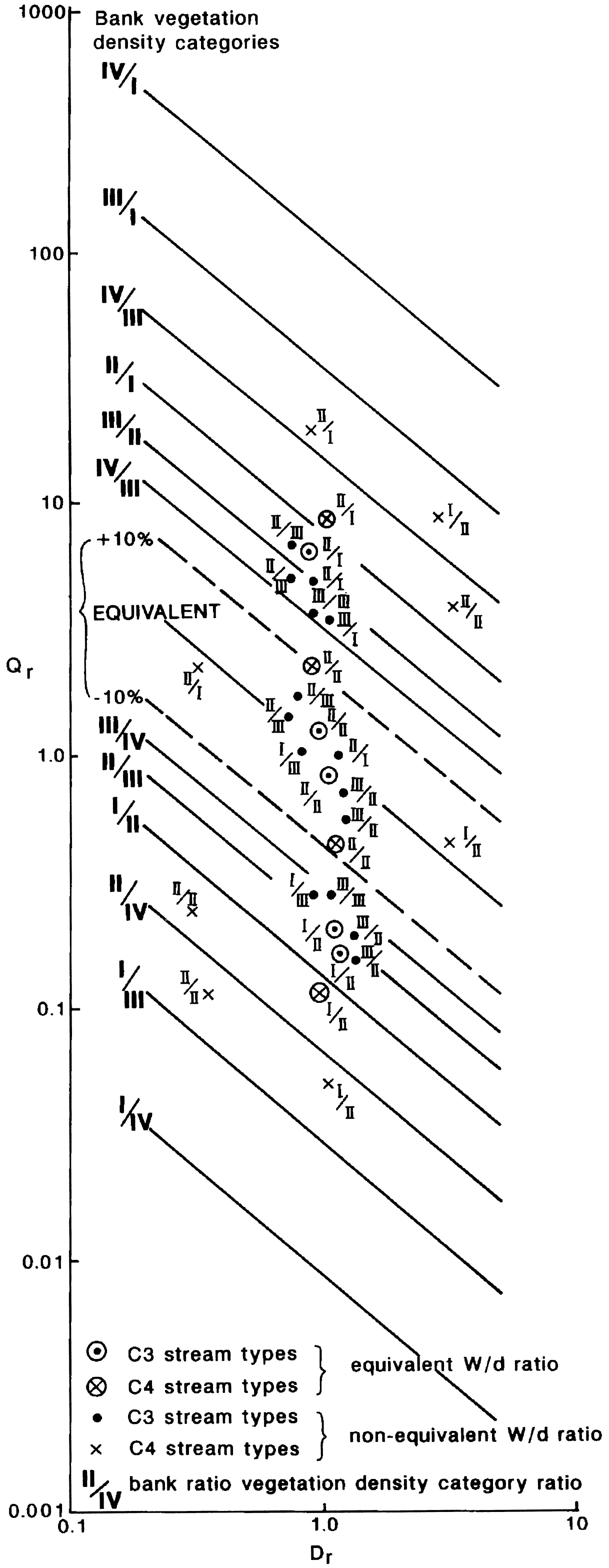

Figure 1. Equivalence of Width/Depth Ratios at Reference and Restoration Site for a Range of Bankfull Discharge, Bed Material Size, and Bank Vegetation Density Category Ratios Between the Two Sites Based on Hey and Thorne (1986) Regime Equations.

bank vegetation densities. Provided the boundary condition ratios lie within the bands, the UK regime equations indicate that the predicted bankfull widths and depths will be within ± 5 percent of the true values. Given that Equation (3) only provides point estimates of width/depth ratios, without specifying any confidence limits, and that a key boundary condition, bed material transport rate, is not explicitly included, it is apparent that the indicated 10 percent divergence boundaries are overly precise. Provided these critical ratios are achieved, it indicates there is no need for the reference reach to be in the same hydrophysiographic region or have the same valley type or the same basin area as the restoration reach.

As with the width/depth ratio, the transfer of the maximum depth to mean depth ratio from the reference to the restoration site is admissible provided that the boundary conditions at the two sites are comparable. The UK regime equations identify that equivalence of d_m/d ratios between reference and restoration sites can also occur when they have different boundary conditions. Given that

$$\frac{d_m}{d} = 0.91\,Q^{-0.01}\,D_{50}{}^{-0.45}\,D_{84}{}^{0.35} \tag{5}$$

it indicates that for these stream types the ratio is essentially independent of bankfull discharge and only varies with bed material size and gradation. Assuming that D_{84} (m) is $2D_{50}$ for the surface bed material, then the ratio d_m/d declines from 1.835 to 1.713 to 1.643 as D_{50} increases from 10 to 20 to 30 mm. Empirical evidence (D.L. Rosgen, pers. comm., March 17, 2002) corroborates these values, as the ratio has been observed to range from 1.5 for C3 streams, coarse gravel and cobble beds, to 1.8 for C4 streams composed of fine gravel. This confirms that for C3-C4 stream types the d_m/d ratio obtained from the reference reach can be replicated in the restoration design provided that they have a comparable bed material size frequency distribution. Equivalence of d_m/d ratios can also occur if the ratios of D_{50} and D_{84}, reference to restoration site, are related by $D_{50r} = D_{84r}{}^{0.555}$. Some error may still occur in predicted maximum depths if there is an overestimation or underestimation in the riffle mean depth.

Determination of Design Plan Form

The sinuosity (p) of the restored river, defined as the ratio of channel length to valley length, is derived directly from the plan form of the reference reach. Provided that the design riffle spacing, z (m), corresponds to the distance between inflexion points between bends, then 2z is the channel distance over one meander wavelength, λ (m). Hence, by definition,

$$p = \frac{2z}{\lambda} \tag{6}$$

As z is obtained from $\left(\frac{z}{W}\right)$W and λ from $\left(\frac{\lambda}{W}\right)$W, where the figures in italics refer to the reference reach, then

$$p = \frac{2(z/W)W}{(\lambda/W)W} = \frac{2z}{\lambda} \tag{7}$$

Therefore, the geomorphological approach ensures that the restoration reach has the same sinuosity as the reference reach.

As sinuosity is also equivalent to the ratio of valley to channel slope (Hey, 1976), then its value will depend on the gradient of the valley and the variables controlling channel slope, namely bankfull discharge and bed material calibre and load (Lane, 1955; Hey and Thorne, 1986). Bank vegetation is also likely to affect its value since tree lined rivers are observed to have a narrower width, greater depth and lower gradient, other factors being equal, than a river with nonvegetated banks (Hey, 1997). This is borne out by the fact that rational approaches to channel design based on continuity, flow resistance, and bed material transport equations indicate that for a particular bed material size there are a range of possible widths, depths, and slopes that will transmit a given discharge and bed material load. Consequently, any discrepancies in the values of any of these controlling variables between the reference and restoration reaches could result in their sinuosities being different. Even if a reference reach had the same discharge, load, bed material size, and bank vegetation, their sinuosities would be different if the valley slopes were not equivalent.

The potential error in the predicted design sinuosity that could result from nonequivalence of boundary conditions can be illustrated using the UK regime slope equation. This should be regarded as indicative given that its coefficient of determination was relatively low (62.9 percent) and that an independent estimate of bed material load had to be utilized when deriving the equation rather than a measured one. In spite of these caveats, the exponents in the equation are similar to those obtained by Kellerhals (1967) for rivers where bed material load was zero, suggesting that it has wider application.

Assuming that D_{84} (m) is approximated by twice the median size, then

$$p = \frac{S_v Q_b^{0.43}}{0.087 Q_s^{0.10} D_{50}^{0.75}} \tag{8}$$

where S_v is the valley slope and Q_s is the estimated bankfull bed material load (kg/s) predicted by the Parker *et al.* (1982) equation. The sinuosity at the restoration site will match that at the reference reach when boundary conditions are identical or when the ratios of the controlling variables compensate each other. For example, equivalence can result if bankfull discharge and bed material load at the reference reach exceed that at the restoration site while valley slope and bed material size are lower. There are numerous other possible combinations and these are defined by Equation (9) and illustrated in Figure 2.

$$Q_r = D_r^{1.744} S_{v_r}^{-2.326} Q_{s_r}^{0.233} \tag{9}$$

This shows combinations of bankfull discharge, bed material load, bed material size, and valley slope ratios, reference to restoration site, for equivalence of sinuosity. An increase in load at the reference site relative to the restoration site requires that the discharge ratio be higher and the bed material size ratio lower if the valley slope ratio remains the same. Consequently, provided these critical ratios are met, there is no restriction on the choice of reference reach.

Although sinuosity is a key element in defining channel plan form, it is not sufficient to uniquely define the meander pattern (Hey, 1976, 1999). At least one other measure is required to specify its shape. In the geomorphological approach, the ratios $\frac{\lambda}{W}$ and $\frac{r}{W}$ at the reference site are scaled by the predicted bankfull width at the restoration reach to derive the design wavelength and radius of curvature (Rosgen, 1998). This ensures that the new channel has exactly the same shape as the reference reach and they only differ in terms of scale. It assumes that these ratios can be transferred to the restoration reach irrespective of any differences in boundary conditions at the two sites. Previous research has shown that these ratios depend on the degree of meandering (Hey, 1976), namely with meander arc angle, and that they are discharge dependent. Existing information does not enable the potential errors in design wavelengths and radii of curvature due to differences in boundary conditions between the reference and restoration reaches to be evaluated.

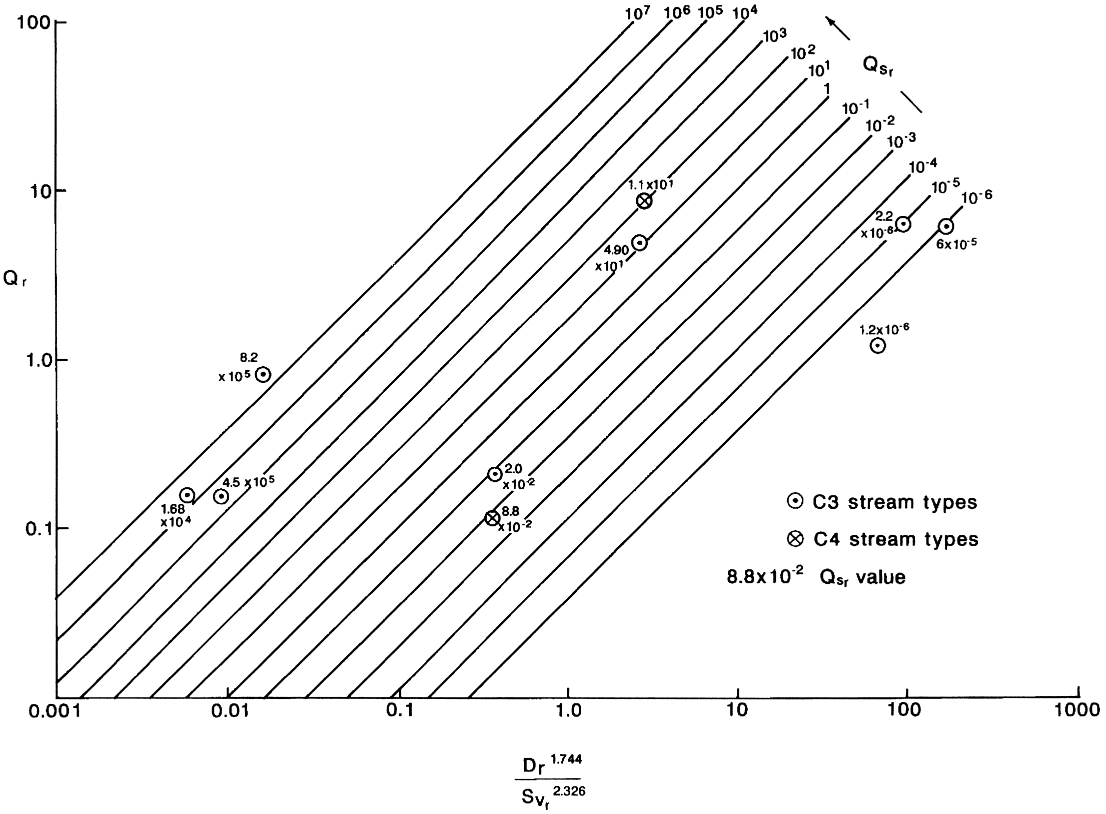

Figure 2. Equivalence of Sinuosity at Reference and Restoration Sites for a Range of Bankfull Discharge, Bed Material Size, Valley Slope, and Bed Material Load Ratios Based on Hey and Thorne (1986) Regime Equations.

Design Evaluation

Bed material load is clearly a key element in the design of a restoration scheme, as the river needs to transmit the incoming load without net erosion or deposition. By ensuring that the river is competent to transport the largest stone represented in the bed material load at bankfull flow, it is implied that it will just transmit the incoming bed material load up to and including this critical size.

Virtually all bed material load equations (bed and total load) rely on the concept that the transport rate is a function of an excess shear stress, stream power, or mobility function over an initial motion condition. By specifying a bankfull shear stress that can just transmit the largest clast supplied to the reach, it indicates that there will be an excess shear stress for smaller size fractions. Equations that use a representative grain diameter to specify the critical shear stress for initiation of transport and, hence, the excess shear stress for determining transport rates, calculate the transport rate per unit bed width. This implies that any increase in supply within that size range would be accommodated either by an increase in bed width, other factors being unchanged, or modification to the width, depth, and slope to satisfy the new condition. This is also borne out when bed material load equations are used in conjunction with continuity and flow resistance equations to predict the various combinations of width, depth, and slope for straight channels that would transmit a prescribed discharge and a load of a particular calibre. Any increase in bed material load, other things being equal, necessarily alters channel dimensions. Experiments (Needham and Hey, 1992) in a fixed width flume confirm this conclusion because an increase in bed material load at constant discharge was achieved by adjustment in flow depth and velocity with no change in water surface elevation or its slope. In natural channels with erodible banks, such changes would be expected to alter the river's dimension, pattern, and profile. Simply ensuring that the restored river has the competence to transport the largest clast supplied to it at bankfull flow would not appear to be a sufficient condition to achieve a sustainable solution, as the river's width also needs to be correctly dimensioned to transmit the bed material load. However, provided that the reference reach has similar boundary conditions to those required at the restoration reach, the channel width will be correctly sized to transmit the bed material load supplied from upstream. Any significant departure of the boundary conditions at the reference reach from those at the restoration section will jeopardize the integrity of the scheme, as the channel will probably be unstable.

ACTUAL AND PREDICTED CHANNEL DIMENSIONS

The foregoing suggests that for C3-C4 stream types, a reference reach can be successfully employed to design a restoration scheme provided that it is stable, of the same stream type, and that their boundary condition ratios have values prescribed by the UK regime equations.

To fully evaluate the geomorphological procedure for designing natural stable channels, comparisons were made between actual and predicted channel dimensions based on data for nine natural stable reaches of river (see Appendix). Although each site fulfills the requirements of a reference reach for restoration design, they were not specifically selected as being suitable candidates as reference reaches for each other. The main criteria were that they reflected a range of boundary conditions and, unlike most reference reaches, bankfull discharge information was available. All are meandering rivers flowing through an alluvial floodplain (C-type channels). Five have a cobble bed (C3) and four a gravel bed (C4). The sites are located on rivers in a number of different hydrophysiographic provinces and have a range of valley types and basin areas. This enabled the accuracy of the predicted dimension, pattern, and profile to be assessed and, in particular, their sensitivity to differences in boundary conditions at the designated reference and restoration reaches.

Each site was specified in turn as the restoration reach, with the remaining reaches used as the reference to predict its morphology. Initially, the actual cross-sectional area of the restoration reach was used in combination with the width/depth ratio from the reference reach to predict the design width and depth (Tables 1 and 2). This isolates the error due to differences in width/depth ratios between the two sites and corresponds to the case where the bankfull cross-sectional area is measured at an adjacent upstream stable reach. It also facilitates comparison with regime equations developed for similar rivers in the UK.

At three of the C3 stream sites, Ganarska River (Ontario, Canada), English Run (Pennsylvania, USA) and Muncy Creek (Pennsylvania, USA), the width/depth ratios are essentially the same. All have the same valley type, glacial outwash valleys with glacial deposits that have been subsequently reworked by the river. Ganarska River and Muncy Creek have a comparable bed material size and bank vegetation category, while the latter has a slightly lower discharge. English Run has a much lower discharge and bank vegetation density and a coarser bed material than the other two sites. To compare these sites with the UK data, the ratios of bankfull discharge, median bed material size, and bank vegetation category between the designated reference and restoration reaches are plotted on the graphs for W/d equivalence based on the UK regime equation (Figure 1). These show excellent conformance, confirming the relative values of discharge, bed material size, and bank vegetation required to obtain comparable W/d ratios. At these sites, bankfull widths and depths are predicted to within ±6 percent, as W/d ratios are within ±12 percent.

The remaining C3 stream types, Turkey Creek (Colorado, USA) and New Fork (North Carolina, USA) have had much lower width/depth ratios. The former is located in a valley influenced by glacial outwash and volcanic soils, while the latter is in a catchment underlain by sedimentary rock where there are no glacial influences. Not only are they located in different valley types to the other three sites but, more significantly, their boundary conditions differ in terms of bed material (coarser), and bank vegetation (higher densities). Use of either of these sites to predict channel morphology at Ganarska River, English Run, and Muncy Creek produced errors of up to ±40 percent for width and depth as their width/depth ratios are lower. Errors reduced to ±18 percent for predicted values at Turkey Creek based on New Fork and *vice versa*, reflecting the fact that their width/depth ratios are more comparable. Plotted Q_r/D_r bank vegetation category ratios exhibit considerable divergence from the curves (Figure 1) confirming the nonequivalence of their W/d ratios and the inappropriateness of the selected reference reach for predicting the width and depth of the restoration site.

For the C4 stream types, three sites have comparable width/depth ratios, namely East Fork San Juan River (Colorado, USA), Lake Fork Gunnison River (Colorado, USA), and Big Hole (Missouri, USA), while that for the fourth, South Fork Little Snake River (Colorado, USA), is significantly lower. The three former sites are located in the same valley type, fluvially reworked glacial outwash and glacial deposits with similar sized bed material, while the latter is in an alluvial valley with lacustrine bank sediment and much finer bed material.

For the sites on the East Fork San Juan, Lake Fork Gunnison, and Big Hole, predicted bankfull widths and depths when using the others as a reference, are in the range ±4 percent to ±10 percent of the observed

TABLE 1. C3 Stream Types: Predicted Values of Bankfull Riffle Widths, Mean Depths, Sinuosities, Channel Slopes, Wavelengths, and Radii of Curvature Compared to Actual Values Based on Actual Cross Sectional Area at Restoration Site.

Restoration Reach	Reference Reach	Predicted Bankfull Width (m)	Percent Error	Predicted Bankfull Depth (m)	Percent Error	Bankfull Cross Sectional Area at Restoration Reach (m^2)	Width/ Depth at Reference Reach	Percent Error	Sinuosity at Reference Reach	Percent Error	Predicted Channel Slope	Percent Error	Predicted Wave Length (m)	Percent Error	Predicted Radius of Curvature (m)	Percent Error
Ganarska	English Run	26.93	-2.43	1.333	2.55	35.90	20.2	-5.16	1.28	5.79	0.0018	-5.43	619.62	143.90	104.80	21.80
	Muncy	28.48	3.20	1.261	-3.04	35.90	22.6	6.10	1.24	2.48	0.0018	-2.38				
	New Fork	24.22	-12.25	1.482	14.02	35.90	16.3	-23.28	1.50	23.97	0.0015	-19.47	455.80	79.45	31.50	-63.40
	Turkey	20.51	-25.68	1.750	34.64	35.90	11.7	-44.98	1.20	-0.83	0.0019	0.87	184.80	-27.20	65.80	-23.40
English Run	Muncy	10.03	5.24	0.445	-5.79	4.46	22.6	11.88	1.24	-3.13	0.0185	3.04				
	New Fork	8.54	-10.51	0.522	10.65	4.46	16.3	-19.11	1.50	17.19	0.0153	-14.81	160.72	-26.77	11.10	-70.20
	Turkey	7.23	-24.21	0.617	30.69	4.46	11.7	-41.98	1.20	-6.25	0.0192	6.48	65.14	-70.32	23.20	-14.00
	Ganarska	9.75	2.17	0.457	-3.08	4.46	21.3	5.44	1.21	-5.47	0.0190	5.60	89.72	-59.12	30.38	-18.33
Muncy	New Fork	17.59	-15.03	1.077	17.87	18.95	16.3	-27.70	1.50	20.97	0.0093	-19.13				
	Turkey	14.90	-28.04	1.272	39.15	18.95	11.7	-48.14	1.20	-3.23	0.0117	1.45				
	Ganarska	20.09	-2.99	0.943	3.20	18.95	21.3	-5.75	1.21	-2.42	0.0116	0.61				
	English Run	19.56	-5.53	0.969	6.00	18.95	20.2	-10.62	1.28	3.23	0.0109	-4.89				
New Fork	Turkey	13.58	-14.81	1.155	18.42	15.68	11.7	-28.03	1.20	-20.00	0.0063	25.00	122.36	-59.21	43.59	110.28
	Ganarska	18.28	14.65	0.858	-12.02	15.68	21.3	30.35	1.21	-19.33	0.0062	23.97	168.18	-43.94	57.76	178.65
	English Run	17.80	11.65	0.881	-9.65	15.68	20.2	23.62	1.28	-14.67	0.0059	17.19	409.58	36.53	69.24	234.02
	Muncy	18.82	18.10	0.833	-14.55	15.68	22.6	38.31	1.24	-17.33	0.0060	20.97				
Turkey	Ganarska	12.04	34.87	0.566	-25.77	6.81	21.3	81.12	1.21	0.83	0.0179	-0.83	110.77	37.60	38.05	32.57
	English Run	11.72	31.34	0.581	-23.75	6.81	20.2	71.77	1.28	6.66	0.0169	-6.25	269.67	235.00	45.59	58.85
	Muncy	12.41	38.92	0.548	-27.99	6.81	22.6	92.18	1.24	3.33	0.0174	-3.23				
	New Fork	10.54	18.13	0.646	-15.21	6.81	16.3	38.95	1.50	25.00	0.0144	-20.0	198.38	146.41	13.70	-52.25

value. Best results were obtained between East Fork and Lake Fork, even though the bankfull discharge at the latter is twice that of the former. When using the South Fork Little Snake as the reference reach, predicted widths and depths are up to ±40 percent in error. Plotted ratios of Q_r to D_r and bank vegetation category indicate general conformance with the UK data both for equivalence and nonequivalence of width/depth ratios (Figure 1).

With regard to sinuosity, transferred values from the reference reach are within ±6.7 percent of those at the restoration site for all of the C3 stream types except for those involving New Fork. In contrast, for the C4 stream types, only South Fork, Little Snake, and Lake Fork Gunnison are similar. Plotted ratios of Q_r against $\left(\dfrac{D_r^{1.744}}{S_{v_r}^{2,326}}\right)$ (Figure 2) for these sites show general conformance with the UK equation (Equation 9) for equivalence of sinuosity (±6.7 percent) after allowance is made for differences in bed material load (Q_{s_r}). A more quantitative evaluation of the sites with equivalent sinuosities (±6.7 percent) was undertaken by comparing actual Q_r ratios with back calculated values obtained using Equation (9), given S_{v_r}, Q_{s_r}, and D_r. Errors ranged from +248 percent to -71 percent, with an average of +37 percent, which reflects the inherent inaccuracy of the regime slope equation. Better conformance would be expected with a slope equation, which is based on measured bed material load and which explicitly accounts for the influence of bank strength/vegetation.

Significant errors occurred in predicted wavelengths and radii of curvature for both stream types (Tables 1 and 2). This indicates that the dimensionless ratios used to define these parameters are more sensitive to differences in boundary conditions between the reference and restoration sites than is the case with the other dimensionless variables.

To evaluate the effect that error in the assessment of bankfull cross sectional area can have on the restoration design, the previous analysis was repeated using

TABLE 2. C4 Stream Types: Predicted Values of Bankfull Riffle Widths, Mean Depths, Sinuosities, Channel Slopes, Wavelengths, and Radii of Curvature Compared to Actual Values Based on Actual Cross Sectional Area at Restoration Site.

Restoration Reach	Reference Reach	Predicted Bankfull Width (m)	Percent Error	Predicted Bankfull Depth (m)	Percent Error	Bankfull Cross Sectional Area at Restoration Reach (m^2)	Width/ Depth at Reference Reach	Percent Error	Sinuosity at Reference Reach	Percent Error	Predicted Channel Slope	Percent Error	Predicted Wave Length (m)	Percent Error	Predicted Radius of Curvature (m)	Percent Error
East Fork	Lake Fork	19.03	4.09	0.733	-3.87	13.94	26.0	8.33	1.30	13.04	0.0124	-11.54	247.4	20.10	85.63	40.37
San Juan	South Fork	13.63	-25.47	1.023	34.22	13.94	13.3	-44.45	1.38	19.57	0.0117	-16.36	200.9	-2.47	52.47	-13.97
	Big Hole	17.51	-4.25	0.796	4.48	13.94	22.0	-8.33	1.60	39.13	0.0101	-28.13				
Lake Fork	South Fork	21.62	-28.83	1.633	41.00	35.30	13.3	-48.73	1.38	5.77	0.0113	-5.45	318.6	-19.57	83.24	-39.33
Gunnison	Big Hole	27.86	-8.57	1.267	9.42	35.30	22.0	-15.38	1.60	23.08	0.0098	-18.75				
	East Fork	29.11	-4.46	1.213	4.72	35.30	24.0	-7.69	1.15	-11.54	0.0136	13.04	328.8	-17.00	96.06	-29.98
South Fork	Big Hole	9.39	28.31	0.427	-22.21	4.01	22.0	65.04	1.60	16.36	0.0069	-14.06				
Little Snake	East Fork	9.81	34.01	0.409	-25.54	4.01	24.0	80.05	1.15	-16.36	0.0096	19.57	110.8	2.74	32.37	14.79
	Lake Fork	10.21	39.49	0.392	-28.46	4.01	26.0	95.05	1.30	-5.45	0.0085	5.77	132.7	23.01	45.94	62.93
Big Hole	East Fork	6.84	4.44	0.285	-4.33	1.95	24.0	9.09	1.15	-28.13	0.0183	40.46				
	Lake Fork	7.12	8.71	0.273	-8.10	1.95	26.0	18.18	1.30	-18.75	0.0162	24.26				
	South Fork	5.10	22.16	0.383	28.36	1.95	13.3	-39.41	1.38	-14.06	0.0153	17.48				

TABLE 3. C3 Stream Types: Predicted Values of Bankfull Riffle Widths, Mean Depths, Sinuosities, Channel Slope, Wavelengths, and Radii of Curvature Compared to Actual Values Based on Predicted Cross Sectional Area at Restoration Site From Regional Curves.

Restoration Reach	Reference Reach	Predicted Bankfull Width (m)	Percent Error	Predicted Bankfull Depth (m)	Percent Error	Bankfull Cross Sectional Area at Restoration Reach (m^2)	Percent Error	Width/ Depth at Reference Reach	Percent Error	Sinuosity at Reference Reach	Percent Error	Predicted Channel Slope	Percent Error	Predicted Wave Length (m)	Percent Error	Predicted Radius of Curvature (m)	Percent Error
Ganarska	English Run	23.82	-13.68	1.180	-10.20	28.10	-21.73	20.2	-5.16	1.28	5.79	0.0018	-5.43	547.90	115.70	92.60	7.74
	Muncy	25.20	-8.70	1.120	-14.22	28.10	-21.73	22.6	6.10	1.24	2.48	0.0018	-2.38				
	New Fork	21.43	-22.36	1.310	0.87	28.10	-21.73	16.3	-23.28	1.50	23.97	0.0015	-19.47	403.30	58.78	27.86	-67.61
	Turkey	18.14	-34.25	1.550	19.16	28.10	-21.73	11.7	-44.98	1.20	-0.83	0.0019	0.87	163.44	-35.65	58.23	-32.29
English Run	Muncy	10.74	12.64	0.476	0.80	5.11	14.57	22.6	11.88	1.24	-3.13	0.0185	3.04				
	New Fork	9.14	-4.22	0.559	18.45	5.11	14.57	16.3	-19.11	1.50	17.19	0.0153	-14.81	172.00	-21.63	11.88	-68.06
	Turkey	7.74	-18.88	0.660	39.87	5.11	14.57	11.7	-41.98	1.20	-6.25	0.0192	6.48	69.74	-68.23	24.85	-33.21
	Ganarska	10.43	9.36	0.490	3.80	5.11	14.57	21.3	5.44	1.21	-5.47	0.0190	5.60	95.96	-56.28	32.44	-12.80
Muncy	New Fork	12.92	-37.60	0.791	-13.45	10.22	-46.10	16.3	-22.70	1.50	20.97	0.0093	-19.13				
	Turkey	10.94	-47.20	0.934	2.21	10.22	-46.10	11.7	-48.11	1.20	-3.23	0.0117	1.45				
	Ganarska	14.75	-28.76	0.693	-24.19	10.22	-46.10	21.3	-5.75	1.21	-2.42	0.0116	0.61				
	English Run	14.37	-30.62	0.711	-22.19	10.22	-46.10	20.2	-10.62	1.28	3.23	0.0109	-4.89				
New Fork	Turkey	15.12	-5.13	1.290	32.34	19.51	24.43	11.7	-28.03	1.20	-20.00	0.0063	25.00	136.23	-54.59	48.53	134.13
	Ganarska	20.38	27.89	0.957	-1.80	19.51	24.43	21.3	30.35	1.21	-19.33	0.0062	23.97	187.50	-37.50	63.38	205.70
	English Run	19.85	24.54	0.983	0.81	19.51	24.43	20.2	23.62	1.28	-14.67	0.0059	17.19	456.55	52.18	77.21	272.50
	Muncy	21.00	31.73	0.929	-4.71	19.51	24.43	22.6	38.31	1.24	-17.33	0.0060	20.97				
Turkey	Ganarska	12.18	36.44	0.572	-24.90	6.97	2.35	21.3	81.12	1.21	0.83	0.0179	-0.83	112.06	39.20	37.88	31.98
	English Run	11.87	32.87	0.587	-22.94	6.97	2.35	20.2	71.77	1.28	6.66	0.0169	6.25	273.01	239.14	46.17	60.89
	Muncy	12.55	40.55	0.555	-27.12	6.97	2.35	22.6	92.18	1.24	3.33	0.0174	-3.23				
	New Fork	10.67	19.51	0.653	-14.27	6.97	2.35	16.3	38.95	1.50	25.00	0.0144	-20.0	200.81	149.45	13.87	-51.67

TABLE 4. C4 Stream Types: Predicted Values of Bankfull Riffle Widths, Mean Depths, Sinuosities, Channel Slope, Wavelengths, and Radii of Curvature Compared to Actual Values Based on Predicted Cross Sectional Area at Restoration Site From Regional Curve.

Restoration Reach	Reference Reach	Predicted Bankfull Width (m)	Percent Error	Predicted Bankfull Depth (m)	Percent Error	Bankfull Cross Sectional Area at Restoration Reach (m^2)	Percent Error	Width/ Depth at Reference Reach	Percent Error	Sinuosity at Reference Reach	Percent Error	Predicted Channel Slope	Percent Error	Predicted Wave Length (m)	Percent Error	Predicted Radius of Curvature (m)	Percent Error
East Fork	Lake Fork	19.03	4.09	0.733	-3.87	13.94	0	26.00	8.33	1.30	13.04	0.0124	-11.54	247.40	20.10	85.63	40.37
San Juan	South Fork	13.63	-25.47	1.023	34.22	13.94	0	13.33	-44.45	1.38	1.37	0.0117	-16.36	200.90	-2.47	52.47	-13.97
	Big Hole	17.51	-4.25	0.796	4.48	13.94	0	22.00	-8.33	1.60	39.13	0.0101	-28.13				
Lake Fork	South Fork	21.62	-28.83	1.633	41.00	35.30	0	13.33	-48.73	1.38	5.77	0.0113	-5.45	318.60	-19.57	83.24	-39.33
Gunnison	Big Hole	27.86	-8.57	1.267	9.42	35.30	0	22.00	-15.38	1.60	23.08	0.0098	-18.75				
	East Fork	29.11	-4.46	1.213	4.72	35.30	0	24.00	-7.69	1.15	-11.54	0.0136	13.04	328.83	-17.00	96.06	-29.98
South Fork	Big Hole	8.08	10.42	0.368	-33.05	2.97	-25.94	22.00	65.04	1.60	16.36						
Little Snake	East Fork	8.44	15.34	0.352	-35.90	2.97	-25.94	24.00	80.05	1.15	-16.36	0.0096	95.37	19.57	-11.61	27.85	-1.23
	Lake Fork	8.79	20.04	0.338	-38.43	2.97	-25.94	26.00	95.05	1.30	-5.45	0.0085	114.27	5.77	5.90	39.55	40.26
Big Hole	East Fork	7.17	9.41	0.298	0	2.14	9.74	24.00	9.09	1.15	-28.13	0.0183	40.46				
	Lake Fork	7.46	13.88	0.286	-3.74	2.14	9.74	26.00	18.18	1.30	-18.75	0.0162	24.26				
	South Fork	5.34	-18.46	0.401	34.47	2.14	9.74	13.33	-39.41	1.38	-14.06	0.0153	17.45				

the predicted bankfull cross sectional area at the restoration site from regional curves (Tables 3 and 4). Inevitably, there is the possibility that any discrepancy could either reduce or enhance the overall error in predicting the morphology of the designated restoration reach.

For the C3 stream types, errors in the predicted bankfull cross sectional area varied from +2.4 percent for Turkey Creek to -46.1 percent for Muncy Creek. This was strongly influenced by the robustness of the regional curve. For example, the northeastern Pennsylvanian regional curve, used for the latter, is still provisional and is based on only four data points. In general, the greater the error in the predicted cross sectional area, the greater the error in the design bankfull widths and depths, Muncy Creek. Where the error was minimal (i.e., Turkey Creek), there was little change in predicted widths and depths. Where there were negative errors in both the predicted cross sectional area and width/depth ratio, errors in width increased, while those for depth decreased (Muncy from Turkey). Where both were overpredicted, the error in the design width increased further, while that for depth declined (English Run from Muncy). In situations where negative errors in cross sectional area were balanced by positive errors in width/depth ratio (New Fork from Turkey), errors in width reduced, while those for depth increased. With the reverse (Muncy from Turkey), errors in width increased and those for depth declined.

Although the design sinuosity and channel slope were unaffected by the use of predicted bankfull cross sectional area, it influenced calculated values of wavelength and radius of curvature, as they are derived from the design bankfull width. Whether or not this increased or decreased errors depends on the disparity in the wavelength and radius of curvature to width ratios at the two sites.

For the C4 stream sites, there were no errors in the estimation of bankfull cross sectional area on the East Fork San Juan and on the Lake Fork of the Gunnison, whereas there were errors of +9.7 percent and -25.9 percent on the

Big Hole and South Fork Little Snake, respectively. As for the C3 streams, the effect of these errors on predicted bankfull widths and depths at these sites also depended on the sign and degree of error in the value of the width/depth ratio at the designated reference reach relative to that at the restoration site. Channel wavelength and radius of curvature were also affected as noted previously.

IMPLICATIONS FOR RESTORATION DESIGN

Choice of Reference Reach

This analysis indicates that reference reach data can be successfully used to predict the design bankfull width, depth, sinuosity, and slope for restoration design. However, considerable care has to be exercised to choose an appropriate reference reach to achieve it. Not only must it be of the same stream type as that required for the restoration site and to be laterally as well as vertically stable, it also needs to have either identical boundary conditions or compensating combinations of boundary condition ratios to minimize design errors. The latter are expected to vary with stream type. Unfortunately, the choice of reference reach is often limited due to the prevalence of unnatural conditions or inappropriate stream types with the result that the boundary conditions at potential reference sites could differ from those at the restoration reach. Although there may be a number of possible options for the choice of reference reach, it is a question of identifying the one that will minimize errors in the scaling of the restoration design. Three options for selecting an appropriate reference reach for restoration design are prioritized below. They apply to all stable stream types.

Priority 1: Reference Reach Adjacent to Restoration Reach and All Boundary Condition Ratios Are Unity. Reference reach is located immediately up or downstream from the restoration reach, depending on the direction instability is migrating, and the bed material size, valley slope, bankfull discharge, and associated bed material load ratios are unity. Although the latter two values are unlikely to be known, and are probably indeterminate in the case of the unstable reach, their values will be closely comparable provided no tributaries enter the river between the reference and restoration reaches. Even though the above ratios are unity, it is apparent that the bankfull cross sectional area, width/depth ratio, and sinuosity can only be transferred to the restoration site provided the new channel is constructed with an equivalent bank vegetation density to that at the reference reach. Although tree lined channels are often preferred as a reference reach, because they have lower width/depth ratios, it is not a requirement. Nontree lined channels will generally be wider and shallower with larger cross-sectional areas. Constructing the restored channel with the same cross sectional area as the reference reach means that the reference reach represents a blue print for the restoration design and can be copied. To sustain the restoration design, some form of bank protection will normally be required, particularly if the natural floodplain alluvium has been regraded. This will need to maintain the dimension, pattern, and profile of the river either permanently or until the developing riparian vegetation is sufficiently resilient to prevent bank failure.

Priority 2: Reference Reach Remote From Restoration Reach and All Boundary Condition Ratios Are Unity. Often, the reference reach has to be located at some distance from the restoration site, possibly in a different catchment. If the bed material size and valley slope at the reference reach match those at the restoration site and the bankfull discharge and bed material load correspond to those in the stable reach immediately upstream from the restoration site, then the W/d ratio and sinuosity at the reference reach can be transferred. Should there be no information available on bankfull discharge or load at one or both sites, these scaling parameters can still be transferred provided the reference reach experiences the same flow and sediment transport regime as the restoration site. This can be achieved by ensuring that the reference reach is in the same hydrophysiographic region and has the same valley type and basin area. As before, the reference reach can be copied for the restoration design, as their cross sectional areas would be identical given the same basin area and provided that the restored river is constructed with a bank vegetation density equivalent to that at the reference reach. To maintain the restored channel, the banks would need to be stabilized.

Priority 3: Reference Reach Remote From Restoration Reach and Boundary Conditions Not Necessarily Unity. If any of the boundary condition ratios are not unity, then it would be necessary to assess whether their W/d ratio and sinuosity at the reference reach could be transferred for the restoration design using regime equations specific to the required stream type. With this approach it is not a requirement that the reference reach be in the same hydrophysiographic region as the restoration site or have the same valley type and basin area.

Using regime equations for C3-C4 rivers to illustrate the approach, the following evaluation steps need to be undertaken to ensure that the reference reach is appropriate for defining the shape of the restored river. More precise guidance awaits the development of more comprehensive sets of equations based on measured bed material loads and that fully account for effect of bank vegetation on channel morphology.

1. Sinuosity Equivalence – Define D_r, S_{v_r}, and Q_r and estimate Q_{s_r}. Using Equation (9), calculate the Q_r required for equivalence of sinuosity, given D_r, S_{v_r}, and Q_{s_r}, and compare the calculated and actual Q_r values. The foregoing analysis suggests that for acceptable equivalence of sinuosity, the error should lie within +250 percent. Reject the site as a reference reach if the error exceeds these limits, as the imposed sinuosity could diverge significantly from the required natural value.

Provided the banks of the restored river are protected from erosion, it is apparent that a wide range of sinuosities and gradients could be imposed and maintained. Indeed, rivers have historically been sustained in an artificial, straightened state using either heavy engineering works or by lining the riverbanks with trees. The river accommodates the imposed pattern and profile by adjusting its depth. To achieve the most natural solution, the departure between the required and predicted sinuosities should be minimized. This will ensure that the pool riffle sequence and associated bar forms are in phase with the meander pattern.

2. W/d Equivalence – Use Equation (4) to establish whether Q_r, D_r, and bank vegetation density ratios lie within the ±10 percent limits for equivalence of W/d ratio. If not, reject as a reference reach. A key element in this assessment is the equivalent bank vegetation density to be implemented at the restoration reach, as this strongly influences the calculation. By protecting the banks of the restored river from erosion they not only can sustain the lowest W/d ratio associated with bank vegetation Type IV, but also progressively higher ratios that correspond to Types III through I. Consequently, the effective bank vegetation at the restoration site can be ascribed any value and this increases design possibilities. If the preference is to minimize the W/d ratio at the restored site to increase sinuosity, as lower gradients are possible to satisfy flow and sediment continuity, then equivalence is required when the restoration reach is ascribed a bank vegetation density of IV.

3. Design Cross Sectional Area – The cross sectional area for the restoration site should, ideally, be obtained from a section immediately upstream provided it is of the requisite stream type. Failing that, it would need to be obtained from an appropriate regional curve stratified by stream type and bank vegetation density. Should the bankfull cross sectional area at the restoration site correspond to that at the reference reach, then the latter represents the design blueprint and can be copied without being scaled. If it is larger, then the dimensions of the reference reach are scaled up and *vice versa* if it is smaller.

Design Evaluations

To check the stability of the restoration design, the simplest procedure is to ensure that the bankfull discharge and associated bed material load in the approach reach can be transmitted through the restored section and delivered downstream (Hey and Heritage, 1993).

It is vital that the equations used to estimate discharge and bed material load are appropriate for the local conditions: the design reach and both upstream and downstream. Although there may be absolute errors in the calculated values, this does not constitute a major problem, as the requirement is to ensure that there are no relative differences along the river. Any adjustments to maintain continuity should be restricted to changes in flow depth provided the width/depth ratio remains within the range for that streamtype.

A more comprehensive assessment involves calculating the average annual bed material load transported by the river to ensure that the longstream continuity is maintained (Hey and Heritage, 1993). This involves integrating the long term daily flow duration curves and bed material load rating curves for various locations along the river. Based on these curves, the average annual bed load transported by the river can be calculated and compared. As with the previous method, the equations used to derive the bed material load rating curve must be appropriate for the type of river in question. Adjustments to the design would need to be made if erosion or deposition was predicted.

CONCLUSIONS

The fluvial geomorphological approach to natural stable channel design differs somewhat from the more traditional engineering procedures. While the latter directly use the controlling boundary conditions to predict channel morphology, either through empirical regime equations or governing process equations, with the geomorphological procedure it is more implicit.

As natural channel morphology reflects the boundary conditions and associated flow processes, it follows that identical channels must have the same boundary conditions. In contrast, similar channels, namely those of the same stream type and shape (width/depth ratio, sinuosities, radius of curvature to width ratios, etc.), which differ only in terms of scale, have different boundary conditions.

This investigation indicates that successful restoration design can be achieved using the geomorphological procedure given the correct choice of reference reach. It is not simply a question of choosing any stable reach of the requisite streamtype. For C3-C4 stream types, regime equations provide general guidance on the critical boundary condition ratios between the reference and restoration reaches to ensure equivalence of width/depth ratios and sinuosities. More precise guidance awaits the development of improved regime equations.

Although the foregoing analysis is specifically for C3-C4 stream types, the geomorphological procedure will apply for all types of stable natural channels provided the chosen reference reach is similar to that required for the restoration design. The critical boundary condition ratios for ensuring morphological similarity between reference and restoration sites will differ between stream types, reflecting variations in the operation of the processes that control their morphology. For example, resistance to flow will change between boulder and cobble/gravel bed rivers as the roughness changes from large scale to small scale. Flow resistance is further complicated by bedform development in sand bed rivers. Differences also occur between modes of bed material transport. For boulder, cobble, and gravel bed rivers, this will be predominately as bedload, whereas in sand bed channels it will be in suspension.

In the absence of regime equations for other than C3-C4 stream types, recourse has to be made to alternative procedures for identifying suitable reference reaches. In the light of this investigation, current advice (D.L. Rosgen pers. comm., November 12, 2003) no longer requires the reference reach to be in the same hydrophysiographic region as the restorative site. The main criteria, in addition to being stable and of the same stream type, are that it should be in the same valley type (width, slope, depositional materials, landform/landtype association) and that the river has a dense riparian vegetation (i.e., bank vegetation density IV). Given these constraints, the range of possible W/d ratios and sinuosities is limited. Any slight error in the design bankfull cross sectional area will be accommodated by slight bed scour or deposition provided that the design planform is maintained by bank protection measures.

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LITERATURE CITED

Gomez, B. and M. Church, 1989. An Assessment of Bed Load Transport Formulae for Gravel-Bed Rivers. Water Resources Research 25(6):1161-1186.

Gregory, K.J. and C.C. Park, 1974. Adjustment of River Channel Capacity Downstream From a Reservoir. Water Resources Research 10(4):870-873.

Hammer, T.R., 1972. Stream Channel Enlargement Due to Urbanization. Water Resources Research 8(6):1530-1540.

Harman, W., J.D. Jennings, J.M. Patterson, D.R. Clinton, L.O. Slate, A.G. Jessup, J.R. Everhart, and R.E. Smith, 1999. Bankfull Hydraulic Geometry Relationships for North Carolina Streams. *In:* Wildland Hydrology, D.S. Olsen and J.P. Potyondo (Editors). American Water Resources Association, Middleburg, Virginia, TPS-99-3, pp. 401-408.

Hey, R.D., 1976. Geometry of River Meanders. Nature 262:482-484.

Hey, R.D., 1978. Determinate Hydraulic Geometry of River Channels. Jour. Hydraulics Division, ASCE 104 (HY6):869-885.

Hey, R.D., 1979. Dynamic Process-Response Model of River Channel Development. Earth Surface Processes 4:59-72.

Hey, R.D., 1982. Gravel-Bed Rivers: Processes and Form. *In:* Gravel-Bed Rivers, R.D. Hey, J.C. Bathurst, and C.R. Thorne (Editors). Wiley, Chichester, United Kingdom, pp. 1-10.

Hey, R.D., 1994. Restoration of Gravel-Bed Rivers: Principles and Practice. *In:* Natural Channel Design: Perspectives and Practice, D. Shrubsole (Editor). Canadian Water Resources Assoc., Cambridge, Ontario, Canada, pp. 157-173.

Hey, R.D., 1997. Channel Response and Channel Forming Discharge, Final Report. U.S. Army Corps of Engineers, R&D6871-EN-01, European Research Office, London, United Kingdom, 108 pp.

Hey, R.D., 1999. Characterization of Stream Meanders for Stream Restoration: Discussion. Jour. Hydr. Eng. ASCE 125(2):214-216.

Hey, R.D. and G.L. Heritage, 1993. Draft Guidelines for the Design and Restoration of Flood Alleviation Schemes. National Rivers Authority R&D Note 154, Bristol, United Kingdom, 98 pp.

Hey, R.D., G.L. Heritage, and M. Patteson, 1990. Design of Flood Alleviation Schemes: Engineering and the Environment. Ministry of Agriculture, Fisheries and Food, London, United Kingdom, 176 pp

Hey, R.D. and C.R. Thorne, 1986. Stable Channels With Mobile Gravel-Beds. Jour. Hydraulic Eng. ASCE 112(8):671-689.

Kellerhals, R., 1967. Stable Channels With Gravel-Paved Beds. Jour. Waterways and Harbours Division, ASCE 93:63-84.

Kennedy, R.G., 1894. The Prevention of Silting in Irrigation Canals in India. Proc. Inst. Civil Eng. 119:281-295.

Lane, E.W., 1955. The Importance of Fluvial Morphology in River Engineering. Proc. ASCE, Paper 745:1-17.

Leopold, L.B. and T. Maddock, 1953. The Hydraulic Geometry of Stream Channels and Some Physiographic Implications. U.S. Geological Survey Professional Paper 252, Washington, D.C.

Needham, D.J. and R.D. Hey, 1992. Dynamic Modelling of Bed Waves. *In:* Dynamics of Gravel-Bed River, P. Billi, R.D. Hey, C.R. Thorne, and P. Tacconi (Editors). Wiley, Chichester, United Kingdom, pp. 404-414.

Parker, G., P.C. Klingeman, and D.G. McClean, 1982. Bedload and Size Distribution in Paved Gravel-Bed Streams. J. Hydraulic Division, ASCE 103(HY4):544-571.

Rosgen, D.L., 1994. A Classification of Natural Rivers. Catena 22:169-199.

Rosgen, D.L., 1996. Applied River Morphology. Wildland Hydrology, Pagosa Springs, Colorado.

Rosgen, D.L., 1998. The Reference Reach – A Blueprint for Natural Channel Design. *In:* Proc. Wetland Engineering and River Restoration Conf., ASCE, CDROM.

APPENDIX
REFERENCE REACH MORPHOLOGY AND BOUNDARY CONDITIONS

Site	Bankfull Width (m)	Mean Depth (m)	Channel Slope (S)	Sinuosity (P)	Wavelength λ (m)	Radii of Curvature (m)	Cross Sectional Area A (m^2)	Bankfull Discharge Q (m^3/s)	Median Bed Material D_{50} (mm)	D_{84} Bed Material Size (mm)	Valley Slope S_v	Bankfull Bed Material Load⁺ (Kg/S)	Width/ Depth	Cross Sectional Area (Regional Curve) A (m^2)	Bank Vegetation Category (Hey and Thorne, 1986)	Basin Area (km^2)
C3 STREAM TYPES																
Ganarska Ontario	27.6	1.300	0.0019	1.21	254.0	86.0	35.90	49.8	64	96	0.0023	2.78×10^{-4}	21.3	28.10	II	262.0
English Run Pennsylvania	9.54	0.472	0.018	1.28	219.5	37.2	4.46	8.15	73	143	0.0230	4.66	20.2	5.11	I	21.5
Muncy Creek Pennsylvania	20.71	0.914	0.0115	1.24	–	–	18.95	40.19	66	181	0.0140	2.28×10^{2}	22.6	10.22	II	61.6
New Fork North Carolina	15.94	0.975	0.0050	1.50	300.0	20.73	15.68	28.32	80	362	0.0075	2.92	16.34	19.51	III	75.1
Turkey Creek Colorado	8.93	0.762	0.0180	1.20	80.5	28.70	6.81	7.92	87	208	0.0216	1.25×10^{2}	11.72	6.97	III	59.6
C4 STREAM TYPES																
East Fork San Juan Colorado	18.29	0.762	0.014	1.15	206.0	61.0	13.94	21.22	56	180	0.0161	2.79×10^{2}	24.0	13.94	II	47.4
Lake Fork Gunnison Colorado	30.48	1.158	0.012	1.30	396.2	137.2	35.30	48.11	50	190	0.0156	1.11×10^{3}	26.0	35.30	II	78.9
South Fork Little Snake Colorado	7.32	0.549	0.008	1.38	107.9	28.2	4.01	5.38*	17	56	0.0110	9.73×10^{1}	13.33	2.97	II	19.0
Big Hole Missouri	6.55	0.298	0.013	1.60	–	–	1.95	2.43*	54	185*	0.0210	1.80×10^{-1}	22.0	2.14	I	17.0

*Estimated value.

⁺Estimated using Parker *et al.* (1982) equation.