EMPIRICAL AND ANALYTICAL APPROACHES FOR STREAM CHANNEL DESIGN

F. Douglas Shields, Jr., Research Hydraulic Engineer, USDA-ARS National Sedimentation Laboratory, PO Box 1157, Oxford, MS 38655-1157, dshields@ars.usda.gov; Ronald R. Copeland, Principal Hydraulic Engineer, Mobile Boundary Hydraulics, PO Box 264, Clinton MS 39060, mbh2o@aol.com

Abstract Stream channel design has become a controversial topic, with different approaches favored by two main schools of thought. One approach, termed “natural channel design,” features the use of stream classification, design analogs (reference reaches) and empirical relations (regional curves). Natural channel design is intended to result in planforms and cross sections thought typical of undisturbed systems, with flow conveyance matched to a “bankfull” or dominant discharge. Explicit sediment transport analyses are typically limited to issues of competence and initiation of motion. Below, we refer to “natural channel design” as the empirical approach. The other approach, termed “analytical,” features the use of geomorphic assessments, process-based numerical models and sediment budgets. The analytical approach may be used to produce channel geometries that will accommodate any discharge. Varying amounts of erosion control and sediment management will be required. In fact, both approaches involve some empiricism and both contain certain analytical models. In this paper, differences and similarities between the two schools are further demonstrated in a case study of an alluvial channel carrying a significant load over a movable bed. In this case study the two approaches produce similar outcomes for channel base width and slope, but different channel depths and top widths. A sediment budget indicates adequate performance for the analytical design but likely failure through erosion for the empirically-based design.

INTRODUCTION

Thirty to forty years ago, widely-used hydraulic engineering texts (e.g. Chow 1959, Henderson 1966) and design manuals (USACE 1970, USDA 1977) contained very limited discussions of stable channel design, particularly with regard to fully alluvial channels, preferring to emphasize fixed-boundary hydraulics (MacBroom 2004). Some guidance was provided for matching the boundary shear stress (“tractive stress”) with channel boundary particle size so that the channel would not erode, but actual sediment transport computations and channel reach sediment budgeting were treated superficially. Further, aspects of then-current river geomorphology that were relevant, such as planform analyses and hydraulic geometry, were also covered lightly or not at all. Most analyses of channel stability assumed steady, uniform flow. As a consequence of ignoring the mobile boundaries of alluvial streams, many channelization projects experienced unforeseen instability, with long-lasting damage to stream corridor ecosystems, bridges and other riparian infrastructure (Brookes 1988, Wohl 2004). McCarley et al. (1990) reported results of a survey of flood control channel projects constructed by the U.S. Corps of Engineers: 39% of the reported post-construction problems were either vertical or horizontal channel instability and an additional 39% were classified as bank or toe failure. Biological effects of many of these projects were simply disastrous (Brookes 1988, National Academy of Sciences 1992). In fact, even channels that performed satisfactorily in terms of flood control or drainage often had extremely negative environmental effects because they featured uniform geometries (e.g., straight, prismoidal channels with trapezoidal cross sections) that departed strongly from natural stream morphologies that are necessary for quality aquatic habitat (Simpson et al. 1982).

In response to the unsatisfactory performance of many channels, new methods for channel design emerged. We arbitrarily categorize these approaches as empirical and analytical, combining the categories labeled “analog” and “empirical” by Skidmore et al. (2001) and “intuitive” and “empirical” by Shields (1997) into a single “empirical” category. Although the two approaches are contrasted below, others (Schwartz et al. 2003, MacBroom 2004) have noted that they are sometimes combined. Proponents of the empirical approach come from a wide variety of disciplinary backgrounds, education levels and professional affiliations, but include life scientists and hydrologists affiliated with consulting firms and public agencies. Proponents of the analytical approach include consulting engineers, fluvial geomorphologists, academics and researchers.

Empirical design approaches are based on form-based geomorphology (e.g., hydraulic geometry relations) as described by Leopold and Maddock (1953), Leopold and Wolman (1960) and others. In their original papers, these authors did not suggest that hydraulic geometry relationships be used to design channels, despite their similarity to older regime relations used for canal design. Rather they were advanced as indicators of fluvial channel form as a function of discharge. In the empirical approach, however, regional regression relations based on hydraulic geometry have been advanced as a design tool. These greatly simplify fluvial processes by assuming that channel form can be predicted as a function of a single geomorphic variable. Typical descriptions of empirical design approaches include Newbury and Gaboury (1993), Rosgen (1996, 1997, 1998, 2005), Brookes and Sear (1996), Riley (1998), Hey (2004) and RiverMorph (2005). An example of a project based on this approach is described by Doll et al. (2001). Although these methods sometimes include incipient motion analyses based on a characteristic bed material size and average hydraulic conditions at a selected design discharge, they ignore questions of sediment continuity (e.g., Will the design channel transport the sediment supplied to it from upstream reaches?), sometimes with negative results (Shields 1997, Smith 1997, Soar 2000, Kondolf et al. 2001). Despite the fact that the core of these approaches is based on an aspect of fluvial geomorphology, current workers in that field almost uniformly reject them as outmoded (Miller and Ritter 1996, Wilcock 1997, Doyle et al. 1999, Juracek and Fitzpatrick 2003, Committee on Applied Fluvial Geomorphology 2004, Malakoff 2004, Simon et al. 2005).

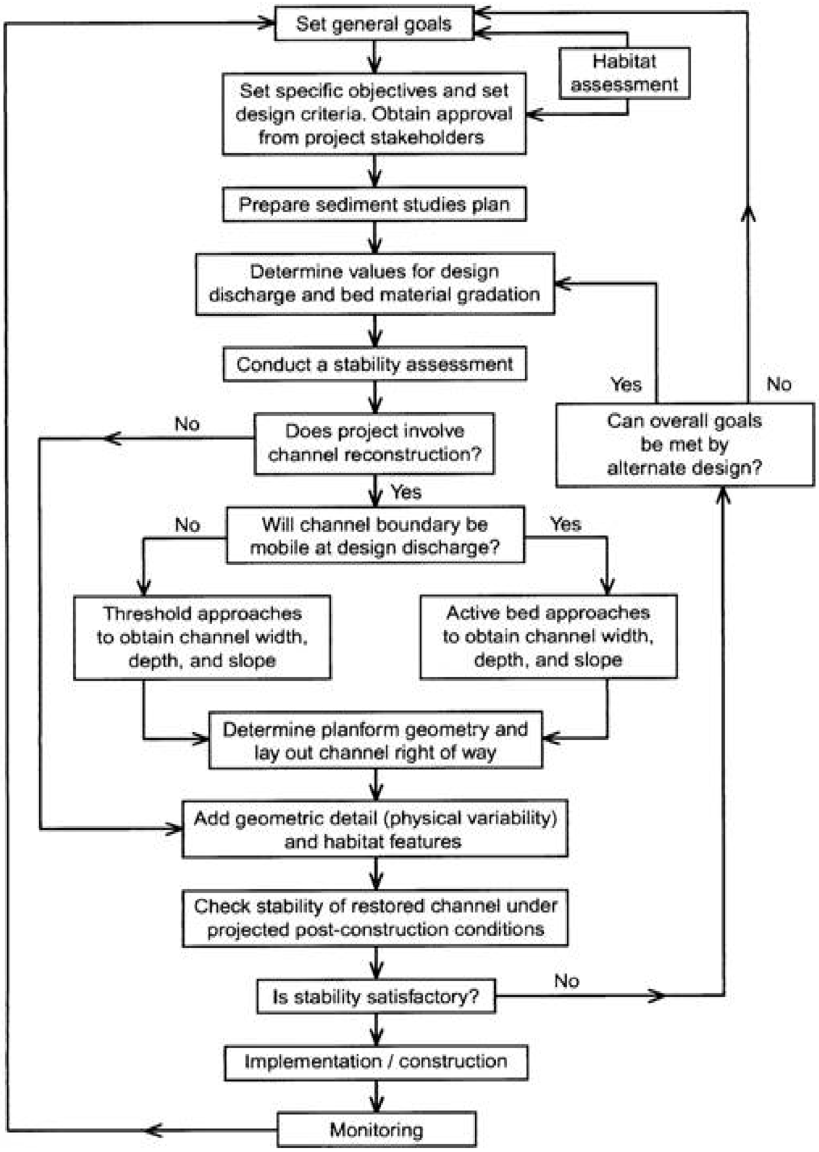

Figure 1 Analytical design approach for stream channel restoration projects from Shields et al. (2003).

Analytical approaches (e.g., Figure 1) involve more complex mathematical formulations to achieve joint solutions for water and sediment continuity and flow resistance, often using extremal hypotheses to achieve closure (Miller and Skidmore 2001). Analytical approaches are based on one- or two-dimensional representations of water flow and sometimes they include refinements such as sediment transport relations that handle a distribution of bed material grain sizes, unsteady flows, bank stability or flow-dependent flow resistance functions. Standard references with treatments of analytical alluvial channel design include Chang (1988), Millar and Quick (1998), Copeland et al. (2001), Eaton et al. (2004). Millar and MacVicar (1998), Schulte et al. (2000), Byars and Kelly (2001), Neary and Korte (2002), and Dierks et al. (2003) present examples of design using the analytical approach. Johnson and Niezgoda (2004) argue that the analytical approach produces cost savings in terms of reduced failure risk, even though the initial costs for design are higher. For restoration, users of the analytical approach must incorporate ecological criteria ("habitat assessment," Figure 1) and a stability assessment that includes the important step of placing the project reach within

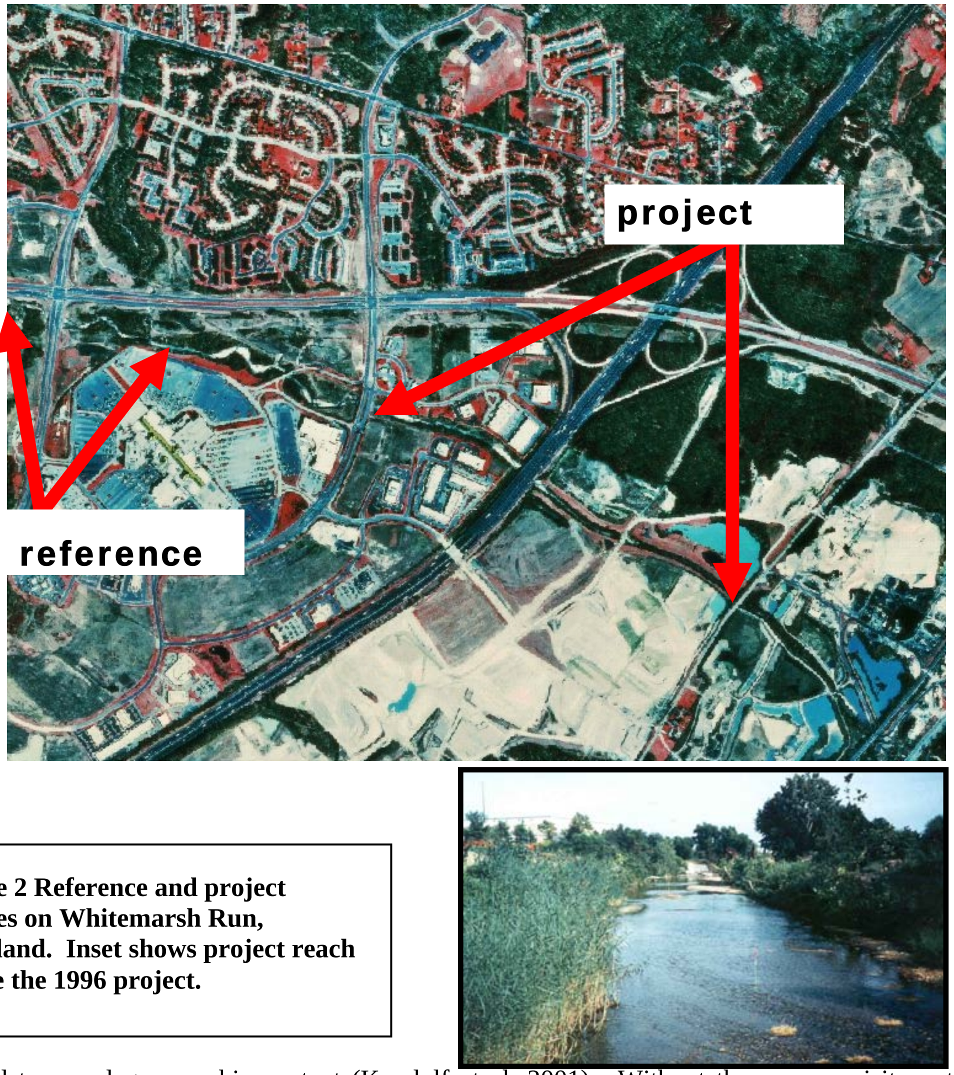

Figure 2 Reference and project reaches on Whitemarsh Run, Maryland. Inset shows project reach before the 1996 project.

its spatial and temporal geomorphic context (Kondolf et al. 2001). Without these prerequisites, stream channel modifications are likely to fall far short of the goal of ecological restoration (Shields et al. in press, Gillilan et al. 2005).

Both analytical and empirical approaches are now represented by software tools that facilitate design computations. Below we use these tools to solve a simple, hypothetical design problem partially based on a real-world alluvial channel in an urban watershed in metropolitan Baltimore, Maryland.

METHODS

Empirical and analytical approaches were used to determine reach-mean channel width, depth and slope for a reach of Whitemarsh Run, Maryland. For simplicity, a minor tributary (North Fork Whitemarsh Run) that entered Whitemarsh Run between the project reach and the reference reach was ignored. The empirical approach was essentially the same as that presented by RiverMorph (2005), while the analytical approach follows Shields et al. (2003). The empirical approach produces different channel widths and depths for pools, runs and riffles; riffle geometry was used for comparison with reach-mean values computed by the analytical technique.

Whitemarsh Run is located in the Chesapeake Bay watershed and flows eastwards from a suburban zone north of Baltimore, through the town of White Marsh. The headwaters are located in the Piedmont, but the majority of the system is found in the Western Coastal Plain. A USGS gage was located immediately downstream from the project reach. The channel regime was characterized by Soar (2000) as “dynamic” due to a “high sediment load of fine gravel material pulsed through the system by a flashy flow regime.” The channel was relatively straight and uniform

(Figure 2). An empirically-based project was designed and constructed in the study reach of Whitemarsh Run in 1996 (Brightwater, Inc. 1994, 1995, 1997) and was later evaluated by Soar (2000); this paper does not attempt to evaluate that project but merely uses some of the published data to furnish a hypothetical, simplified example. Results from this example should not be considered an actual design.

Empirical approach The basic steps for channel design using the empirical approach are (RiverMorph 2005):

1. Select a reference reach. The reference reach must be the same stream type (Rosgen 1994) as intended for the design project reach.

2. Compute bankfull discharge and associated channel dimensions for reference reach.

3. Compute bankfull discharge and associated channel cross-sectional area for the project reach.

4. Compute design channel geometry by scaling up reference reach geometry.

5. Check design channel for sediment-transport competency.

6. Lay out channel alignment.

Limitations of the empirical design approach have been identified by RiverMorph (2005):

1. The method is primarily applicable to gravel-bed, meandering streams.
2. The largest particles normally transported by the stream begin to mobilize at bankfull flows.

3. A suitable reference reach of appropriate stream type must be utilized and dimensionless ratios based on the size gradation of a sediment sample collected from a bar[1] must fall within specified ranges for competency checks based on Andrews and Erman (1986) or Andrews and Nankervis (1995). Rosgen (2005) has proposed use of a shear stress-grain size curve when bed material gradations produce ratios outside these ranges.

Additional limitations on reference reach characteristics have been published by Hey (2004).

We selected a stable reach upstream from the project reach as a reference (Figures 2 and 3). Project and reference reach dimensions (Table 1) were obtained from cross-section surveys provided by Brightwater, Inc. (1995 and 1997) and Soar (personal communication, 2005), respectively. Contributing drainage areas were obtained from applicable USGS gage descriptions. Valley slope was unavailable for the reference reach and was assumed equal to that reported for the project reach. Bed material gradations were from sieve analyses of samples collected in 1998 by Soar (2000). Dimensionless ratios for the reference reach were within tolerances prescribed by Hey (2004) (Table 2).

Figure 3 Conditions in reference/supply reach of Whitemarsh Run, Maryland, 1998.

---

[1] "The Rosgen modified procedure substitutes gradation parameters from a bar sample for the subpavement parameters used in the Andrews' equations. Typically, the bar sample is taken on the lower 1/3 of a point bar at an elevation halfway between the channel thalweg and bankfull elevation at the location of one of the largest particles on the bar. A good way to collect the sample is to scan the surface of the bar in this location for the largest particle and then place a plastic 5-gal bucket (with the bottom cut out) over the largest particle. The sample should be taken to a depth at least twice the size of the largest particle." RiverMorph (2005)

Table 1 Characteristics of Whitemarsh Run, Maryland, as of 1995. * = assumed quantity.

	Reference	Project
Location	Immediately upstream from North Fork confluence	Honeygo Rd. to State Route 7 neglecting North Fork tributary
Valley type	VIII	VIII
Valley slope	0.0043*	0.0043
Channel slope	0.0037	0.0038
Channel materials	Sand and gravel	Sand and gravel
Bed material D_{50}, mm	9.53*	9.53
Drainage area, km^2	14.0	16.2
Bankfull discharge, m^3/s	23.4	29.2
Annual sediment transport capacity, tonnes	7,680	12,500

Table 2 Reference reach evaluation using ratios proposed by Hey (2004). Subscript r denotes ratio of reference reach/design reach quantities. Q_s = bed material load estimated by the Parker et al. (1982) equation (kg/s), k_r = the ratio of bank vegetation factors (Hey and Thorne 1986). In this case k_r was assumed to be 1.0.

Quantity	Reference/ Design	Relationship (Hey 2004)	Recommended value for ratio
Bankfull Discharge, Q	1.16	$Q_r = k_r^{7.69} D_{50r}^{-0.846}$	1.00
D_{50}	1.00	$D_{50r} = D_{84r}^{0.555}$	1.00
Valley slope, S_v	1.00	$S_v = Q_r^{2.326} D_{50r}^{4.057} Q_{sr}^{0.542}$	1.75[2]

It is important to note that bankfull discharge does not directly enter design when using software produced by RiverMorph (2005). Instead, the bankfull cross-sectional geometry (area, width-to-depth ratio) is used to develop the design cross section. The first computational step in the empirical approach (Table 3) involves calculating the design channel width (W_{bkf}) based on the design channel cross-sectional area (A_{bkf}) and the reference width-to-depth ratio (w_{bkf} / d_{bkf}). Therefore a value of the design cross-sectional area at bankfull flow, A_{bkf}, must be generated using regional relations or by scaling up the value from the reference reach. RiverMorph (2005) advises that the reference reach cross section used as a template should be for "a stable riffle not under the effects of backwater other than the downstream stable pool." We generated the design A_{bkf} by multiplying the reference reach value by the ratio of project to reference reach drainage areas. Design channel geometry was then computed by substituting reference reach dimensions into the expressions given in Table 3 with the exception of meander amplitude and radius of curvature, which were based on a sine-generated curve function (RiverMorph 2005). RiverMorph (2005) produces a typical design cross section that may be modified by the user. Portions of the typical section higher than the bankfull discharge elevation are simply straight lines connecting the bankfull elevation with the existing ground surface (floodplain or channel banks) at an elevation 2 x bankfull depth higher than the thalweg. The slope of these lines is selected so that the entrenchment ratio (channel width at 2 x bankfull flow depth / bankfull width) equals the reference reach entrenchment ratio (Figure 4). For our design, we truncated the typical RiverMorph cross section where it intersected the existing ground surface, tying the new cross section into the current channel.

---

[2] Within limits suggested by Hey (2004) based on data from UK restoration sites.

Even though the bankfull discharge is not used to determine design geometry, it may be used to check the sediment competency of the design. Bankfull discharge for the reference reach (Table 1) was determined using cross-section indicators of bankfull stage and the Limerinos (1970) formula for Manning n. The bankfull discharge for the project reach was obtained by multiplying the discharge for the reference reach by the ratio of contributing drainage areas. Resulting discharges were much greater than those shown on regional curves for nonurban watersheds (White 2001), but within 19% of those for urban areas in North Carolina (Doll et al. 2002). Sediment transport competency was checked and found adequate using D_{90} from the bed sediment gradation and modified Shields curves provided by Rosgen (2005).

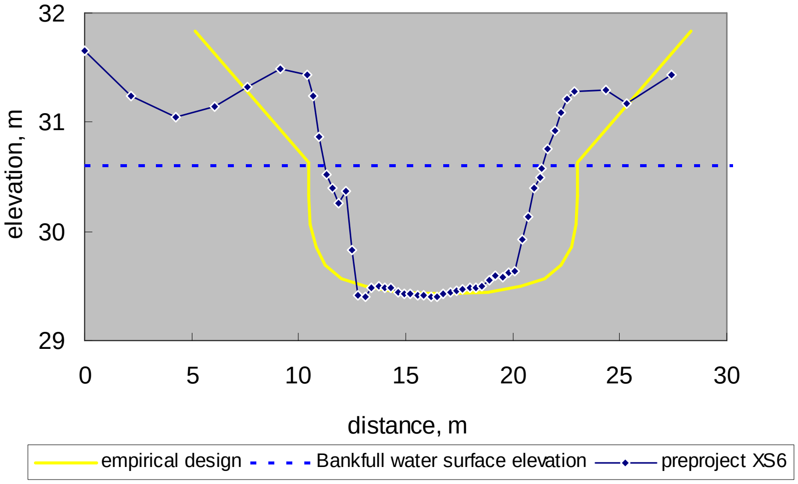

Figure 4 Typical empirical design cross section superimposed on typical preproject cross section.

Analytical approach The basic steps in the analytical approach for sizing alluvial channels are

1. Locate stable supply reach and determine bed gradation and roughness (Manning) coefficients for bed and banks.
2. Determine channel-forming discharge and flow duration curve.
3. Calculate bed-material sediment inflow for the project reach.
4. Develop a family of slope-width solutions that satisfy resistance and sediment transport equations.
5. Reduce the range of solutions to meet site constraints such as maximum slope, width, or depth.
6. Conduct sediment budget analysis to ensure sediment transport continuity for full range of discharges.

It is very important that the supply reach be stable with no signs of active widening, degradation or aggradation since the analytical approach produces a design that transports the same quantity of sediment as the supply reach. The supply reach was the same as the reference reach used for the empirical design (Figure 3). A rating curve for water surface elevation in the supply reach was calculated using the equal velocity method (Chow 1959) to composite bed and bank roughness. The Limerinos (1970) equation was used to calculate bed roughness and a Manning roughness coefficient of 0.085 was selected for the banks and overbanks based on evaluation of photographs. Using this procedure allowed the composite roughness to vary with depth. The Meyer-Peter and Muller (1948) equation was selected based on the bed material size and used to calculate a sediment transport rating curve. The rating curves were used to calculate bankfull discharge, effective discharge and average annual sediment load.

A flow duration curve for the supply reach was developed using the regionalized duration curve method described in Copeland et al. (2001). Discharges from the gaged watershed were reduced by a constant (0.9) equal to the ratio of the two-year annual peak discharges. This ratio was developed using two-year annual peak flows calculated from regional regression equations presented by Dillow (1996) for the Western Coastal Plain of Maryland.

A preliminary or initial geometry for the project reach was selected to accommodate the channel-forming discharge.

Three methods were used to estimate the channel-forming discharge. The effective discharge for the supply reach was determined by integrating the supply reach flow duration curve with the supply reach sediment transport rating curve. The midpoint of the discharge increment with the greatest sediment transport (27.5 m^3/s) was selected as the effective discharge (Figure 5). The effective discharge for the project reach was determined by increasing the supply reach effective discharge by the ratio of two-year annual peak flows. The project reach effective discharge was therefore 31.1 m^3/s, which corresponds to a return interval of 1.5 years. The supply reach bankfull discharge determined using field indicators of bankfull stage was 23.4 m^3/s (Table 1) and had a return interval of 1.3 years. The effective discharge was selected for use as the channel-forming discharge because its return interval was closer to that generally accepted for channel-forming discharge and because field indicators may be misleading in urban stream channels.

The next step in the analytical method is to determine a representative trapezoidal cross-sectional geometry with a combination of width, depth and slope for which the resultant hydraulic conditions are able to transport the incoming bed-material load without aggradation or degradation. The initial estimate for these dimensions was made for the channel-forming discharge in the project reach.

Table 3 Empirical Design for Whitemarsh Run, Maryland

	Relationship[3]	Reference C5	Preproject F4	Design C5
Width, m	$W_{bkf} = \sqrt{A_{bkf} \cdot (w_{bkf} / d_{bkf})}$	12.2	9.8	13.1
Depth, m	$D_{bkf} = W_{bkf} / (w_{bkf} / d_{bkf})$	0.8	0.8	0.8
Entrenchment ratio	$ER_d = ER_{ref}$	1.84	1.27	1.33[4]
Sinuosity	$K_d = K_{ref}$	1.17	1.13	1.17
Slope	$S_{bkf} = S_v / K$	0.0037	0.0038	0.0037
Wavelength, m	$L_m = W_{bkf} \cdot (l_m / w_{bkf})$	116	-	124
Amplitude, m	$W_{blt} = W_{bkf} \cdot (w_{blt} / w_{bkf})$	34	-	33
Radius of curvature, m	$R_c = W_{bkf} \cdot (r_c / w_{bkf})$	28	-	32

---

[3] Upper case letters are bankfull channel dimensions for the design channel, while lowercase letters are for the reference reach channel. All dimensions shown here are for riffles; the RiverMorph software also produces dimensions for pools and runs. W = channel width, D = channel depth, A = cross sectional-area, K = sinuosity, S_{bkf} = channel slope, S_v = valley slope, L_m = meander wavelength, W_{blt} = meander belt width or amplitude, R_c = meander radius of curvature.

[4] The design entrenchment ratio does not follow the prescribed relationship because the project reach is deeply incised, and when the design cross section is superimposed on the existing topography, it is not possible to attain the reference reach entrenchment ratio without prohibitive amounts of excavation and fill.

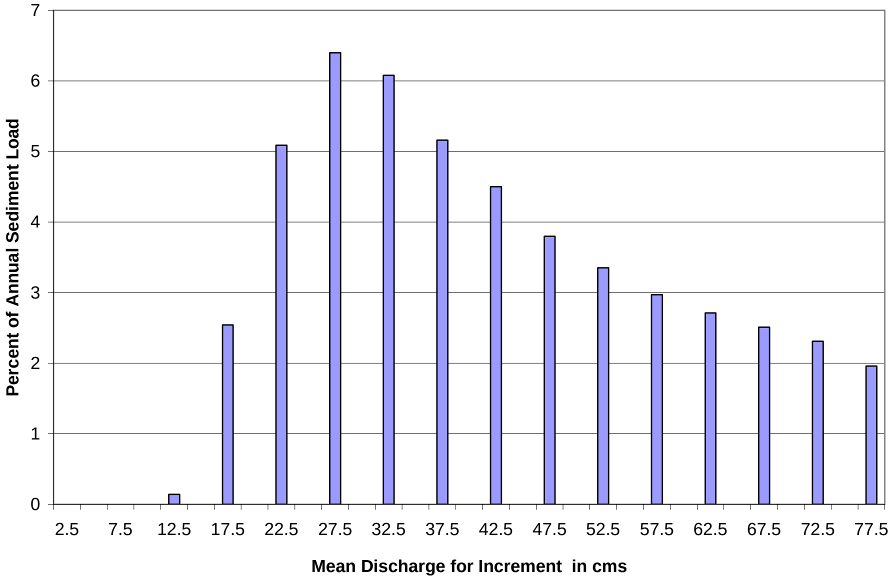

Figure 5 Effective discharge analysis for Whitemarsh Run, Maryland.

The design geometry was checked using the full range of expected discharges. One method for calculating the channel geometry with the channel-forming discharge is the Stable Channel Analytical Method in SAM (Thomas et al. 2002) and HEC-RAS (USACE-HEC 2002). This method solves sediment transport and resistance equations simultaneously, providing a family of width-depth-slope solutions that will pass the incoming bed-material sediment load. In this case, the incoming sediment load from the supply reach was calculated for a discharge of 27.5 m^3/s. The calculated stability curves are shown in Figure 6. These curves were calculated by assigning a channel side slope of 2.5 (a first estimate of slope needed for geotechnical stability) and a bank roughness of 0.085. Theoretically, any geometry represented by a point on the stability curve represents a stable design solution. Selected dimensions (Table 4) featured a slightly higher sinuosity than present in the existing channel to improve habitat characteristics.

Flow duration curves were developed for the project reach and the supply reach. The flow duration curve for the project reach was calculated directly from 39 years of mean daily flow records from the USGS gage located just downstream from the project reach. An annual peak-flow frequency curve was also developed from gage data. Since the stability curve ensures sediment transport stability for only the channel-forming discharge, the next step in the design process is to compute a sediment budget using the entire range of expected discharges. This is done by integrating the flow duration and the sediment transport curves for the supply reach and the project reaches to obtain average annual sediment loads for both reaches. If necessary, channel dimensions may be modified to ensure sediment loads are practically equal.

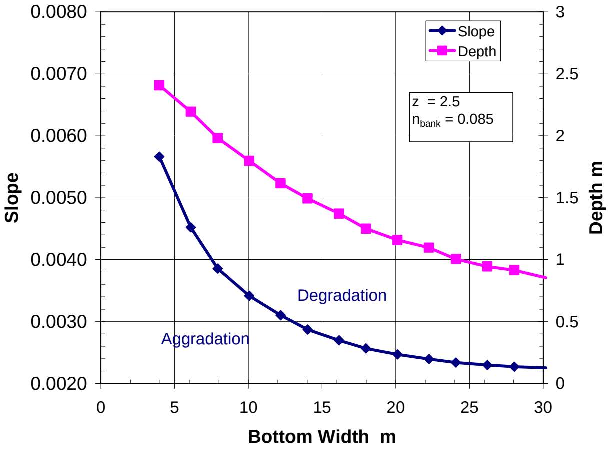

Figure 6 Slope-width-depth family of curves for project

RESULTS

Empirical and analytical approaches differ in selection of design discharge. The effective discharge for the reference/supply reach (27.5 m^3/s) was 18% higher than the estimated bankfull discharge (23.4 m^3/s), probably due to the effects of urbanization-driven channel incision on cross-sectional morphology. Disturbed channels, such as those draining urban watersheds like this one, exhibit inconsistent relationships between bankfull and channel forming discharge and field indicators are subject to operator error (Williams 1978). Griffin (1998) measured bed material and bed material load gradations for storms spanning a range of peak discharges in the project reach during 1996 and found that channel forming discharge was about three times as great as bankfull discharge estimated from field indicators by others.

Table 4 Comparison of Design Outcomes, White Marsh Run, Maryland

	Empirical	Analytical
Top Width, m	14.9[5]	18.5
Bottom Width, m	9.5	10.7
Flow Depth at Design Q, m	0.82	1.8
Channel Slope	0.0037	0.0034
Design Q, m^3/s	27.2	31.1
Design Manning n	0.025	0.059
Mean annual sediment transport capacity, tonnes	10,800	8,360
Trap efficiency, %	-41	-9

The empirical design discharge was smaller and a lower Manning n-value was used to compute this discharge (Table 4). The Manning n value used for the reference reach in the empirical approach (0.025) was simply based on the application of the Limerinos formula to the observed bed sediment gradation without increases for bends, bars, bank vegetation, or other boundary irregularities. This was justified based on the fact that the reference reach was rather straight and uniform and the analysis was limited to the lower part of the channel cross section that was unlikely to support woody vegetation. A single n-value was used for the entire cross section since sophisticated techniques for compositing different bed and bank roughness values were not available within tools normally used for empirical design. The higher n-value used for the supply reach within the analytical approach (0.059) was derived by compositing Limerinos-based values for the bed and a much higher value (0.085) assumed for the heavily vegetated banks.

Sediment budgets for the empirical and analytical designs were compared by computing their trap efficiencies:

$$TE = 100 \quad \frac{Y_{Supply} - Y_{Project}}{Y_{Supply}}$$

Where *TE* = trap efficiency, %, and *Y* = mean annual sediment load for the supply and project reaches, as indicated by the subscripts.

For sediment load computations, composite roughness values were computed for both design cross sections using the Limerinos equation for the bed and 0.085 for the banks. The resulting trap efficiencies were fair for the analytical design (-9%), but very poor (-41%) for the empirical design, indicating excessive degradation potential. The degradation predicted for the empirical design reflects the effect of the steeper, narrower channel geometry on sediment transport at flows above bankfull. Similar analyses with Yang and Laursen-Madden sediment transport

---

[5] Width of channel at water surface elevation for analytical design discharge.

relations, which allow computation of transport by size class but do not consider armoring at low flows produced trap efficiencies of +12% for the analytical channel and -18% to -14% for the empirical channel. Interestingly, the empirical design project actually constructed at this site in 1994 suffered failure through excessive aggradation because the project design slope (0.0025) was much lower than required to transport the supplied load (Soar 2000). This slope was selected based on adoption of planform characteristics of the target stream type for the design channel without consideration of reference reach properties (Brightwater 1994). A reanalysis (Brightwater 1997) included data from a reference reach described as unstable by Soar (2000).

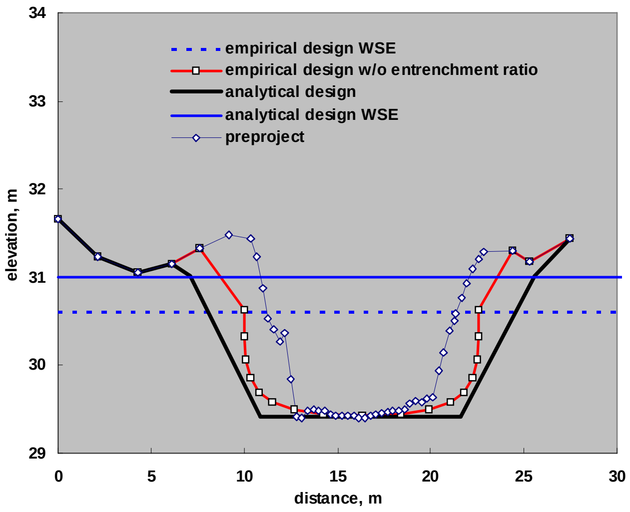

Figure 7 Cross sections for preproject conditions and empirical and analytical designs, White Marsh Run, Maryland.

Both designs produced cross sections larger than the preproject channel, but the analytical cross section was larger, consistent with a larger design discharge and larger Manning n-value (Figure 7). In Figure 7, preproject topography is used for overbank portions of both design cross sections. Although the empirical design flow depth at design discharge was only about half of the corresponding analytical depth, similar channel depths resulted when the design cross sections were superimposed on a typical preproject cross section. The analytical channel was about 5% wider at the bottom and 28% wider at the top. The empirical design channel, with a slope of 0.0037, had significantly more sediment transport potential than the analytical channel. The design slope for the empirical channel was taken directly from the reference reach where annual flows were about 10% less than the project reach. The analytical method allowed the designer to slightly reduce the slope and increase the sinuosity while retaining sediment continuity, which is attractive from aesthetic and habitat quality standpoints. The analytical design channel had a slope of 0.0034, which was chosen from the stability curve and had a corresponding base width of 10.7 m. If a design slope of 0.0037 had been selected, the channel base width for the analytical channel would have been 9.0 m. The narrower channel would have an increased composite roughness and due to the influence of the vegetated banks.

Neither approach addresses complex properties of natural channels such as the effects of meandering; bank geometry, soils, and vegetation on bank stability and flow resistance; cohesive sediments; or armoring (MacBroom 2004). Changes in bed roughness due to bedform changes were not considered. Analytical approaches are based on sediment transport computations which have high levels of uncertainty (Dierks et al. 2003), but this problem may be addressed by using field observations to refine transport estimates or by simply using relative transport rates as a basis for design (Wilcock 2004).

CONCLUSIONS

Design of stream channels for restoration purposes involves many critical decisions, regardless of the approach involved. Design outcomes are sensitive to input parameters such as bed material size, design discharge, hydraulic roughness and cross-sectional shape. Even with new software to facilitate computation, an experienced, well-educated (rather than a trained) designer is needed.

Selection of the reference or supply reach has major effects on the outcome of both design approaches. Empirical design sediment continuity problems associated with inappropriate reference reach selection were minimized in this case by using the sediment supply reach as the reference reach. Selection of channel forming discharge should include all three methods: determination of bankfull discharge based on field indicators of bankfull stage, analysis of flow frequency and effective discharge analysis. Calculation of hydraulic parameters in deep, narrow channels must account for the effects of bank roughness. When bank roughness differs strongly from bed roughness, channel hydraulics are very sensitive to cross-sectional shape.

The underlying philosophy of the empirical approach lends itself to habitat restoration, but it does not allow for designs where conveyance (flood control) issues act as constraints. It tends to be computationally less difficult and less process-based than analytical approaches. The empirical approach is targeted at coarse-bed streams and produces suspect results for streams with beds that are frequently mobile. The empirical approach, as currently practiced, contains checks for sediment competence, but not sediment continuity. Therefore even though a design may produce a channel that is competent to transport the larger bed material sizes found in samples from the pre-project reach, it may fail through aggradation or degradation.

ACKNOWLEDGMENTS

RiverMorph, LLC provided a copy of RiverMorph 3.1 and associated technical support. Inset of Fig. 2 furnished by Phil Soar. Sean Bennett, Munsell McPhillips and Andrew Simon read an earlier version of this paper and made many helpful comments.

REFERENCES

Andrews, E.D. and Erman, D.C. (1986). “Persistence in the Size Distribution of Surficial Bed Material During an Extreme Snowmelt Flood,” *Water Resources Research*, 22(2), pp 191-197.

Andrews, E.D. and Nankervis, J. M. (1995). “Effective Discharge and the Design of Channel Maintenance Flows for Gravel-Bed Rivers,” *Natural and Anthropogenic Influences in Fluvial Geomorphology*, Geophysical Monograph 89. American Geophysical Union. pp. 151-164.

Brightwater, Inc. (1994). “White Marsh Run.” Report on establishing design discharge and criteria for stream restoration and wetland hydrology, Brightwater, Inc., Ellicott City, MD.

Brightwater, Inc. (1995). “White Marsh Run.” Report on establishing design discharge and criteria for stream restoration and wetland hydrology, 1994 Revision, Brightwater, Inc. Ellicott City, MD.

Brightwater, Inc. (1997). “White Marsh Run.” Report on concept design modifications to stream restoration construction project between Honeygo Blvd. and Route 7, Brightwater, Inc., Ellicott City, MD.

Brookes, A. (1988). *Channelized Rivers: Perspectives for Environmental Management*. John-Wiley & Sons, Chichester, U. K.

Brookes, A. and Sear, D. A. (1996). “Geomorphological principles for restoring channels,” in *River Channel Restoration: Guiding Principles for Sustainable Projects.* John Wiley & Sons, New York.

Byars, M.S. and Kelly M. (2001). “Sediment transport in urban stream restoration design,” *Proc. 2001 Wetlands Engineering and River Restoration Conference*, American Society of Civil Engineers, Reston, VA, pp.17-28.

Chang, H.H. (1988). *Fluvial Processes in River Engineering*. John Wiley & Sons, New York.

Chow, V. T. (1959). *Open Channel Hydraulics*, McGraw Hill, New York.

Committee on Applied Fluvial Geomorphology. (2004). Position statement on Applied Fluvial Geomorphology, Committee on Applied Fluvial Geomorphology, Quaternary Geology and Geomorphology Division, Geological Society of America. http://www.geo.wvu.edu/%7Ekite/QG&GFluvGeomPositionStatement22March2004.html

Copeland, R.R., McComas, D.N., Thorne, C.R., Soar, P. J., Jonas, M.M. and Fripp, J.B. (2001).“Hydraulic Design of Stream Restoration Projects,” ERDC/CHL-TR-01-28, U.S. Army Corps of Engineers Engineer Research and Development Center, Vicksburg, MS.

Dierks, S., Gustavson, K., Schneider, J., Wilson, S. (2003). “Stream Restoration Design using the Stable Channel Analytical Model (SAM),” *Proc. Protection and Restoration of Urban and Rural Streams Symposium 2003*. Philadelphia, Pennsylvania. American Society of Civil Engineers, Reston, VA. (doi:10.1061/40695(2004)32)

Dillow, J.A. (1996). “Technique for Estimating Magnitude and Frequency of Peak Flows in Maryland,” USGS Water Resources Investigations Report 95-4154, Towson, MD.

Doll, B.A., Clinton, D.R., Jenkins, J.W., Jr., Patterson, J.M., Coleman, N.J. (2001). “Urban Stream Restoration Using a Natural Channel Design Approach,” *Proc. Wetlands and River Restoration* 2001. Reno, Nevada. American Society of Civil Engineers, Reston, VA (doi:10.1061/40581(2001)2).

Doll, B.A., Wise-Frederick, D.E., Buckner, C.M., Wilkerson. S.D., Harman, W.A., Smith, R.E. and Spooner, J. (2002). “Hydraulic Geometry Relationships for Urban Streams throughout the Piedmont of North Carolina.” *Journal of the American Water Resources Association*. 38(3), pp. 641-651.

Doyle, M. W., Boyd, K.F. and Skidmore, P.B. (1999). “River Restoration Channel Design: Back to the Basics of Dominant Discharge.” *Proceedings, Second International Conference on Natural Channel Systems*. Watershed Science Centre, Trent University, Peterborough, Ontario.

Eaton, B. C. Church, M. and Millar, R. G. (2004). “Rational regime model of alluvial channel morphology and response,” Earth Surface Processes and Landforms 29:4, 511-529, doi: 10.1002/esp.1062

Gillilan, S., Hoitsma, B. T. and Kauffman, M. (2005). “Challenges in developing and implementing ecological standards for geomorphic river restoration projects: a practitioner’s response to Palmer et al. (2005),” *Journal of Applied Ecology* (2005)42, pp. 223-227.

Griffin, D. (1998). “Channel Restoration Using Indicators of Bankfull.” “Engineering Approaches to Ecosystem Restoration, Wetlands Engineering and River Restoration Conference 1998,” Conf. Proc. 100, American Society of Civil Engineers Reston, VA. (doi 10.1061/40382(1998)178.)

Henderson, F. M. (1966). *Open Channel Flow*. New York: The MacMillan Company.

Hey. R.D. (2004). “Applicability of Geomorphological procedures for river restoration” *Proc. Critical Transitions in Water and Environmental Resources Management*, June 27-July 1, 2004, Salt Lake City, Utah, American Society of Civil Engineers, Reston, VA. (doi:10.1061/40737(2004)409).

Hey, R. D. and Thorne, C. R. (1986). “Stable channels with mobile gravel beds,” *Journal of Hydraulic Engineering* 112(9), pp. 671-689.

Johnson, P. A. and Niezgoda, S. L. (2004). “Risk-based method for selecting bridge scour countermeasures.” *Journal of Hydraulic Engineering* 130(2), pp.121-128.

Juracek, K. E. and Fitzpatrick, F. A. (2003). “Limitations and implications of stream restoration,” *Journal of the American Water Resources Association* 39(3) pp 659-670.

Kondolf, G.M., Smeltzer, M.W. and Railsback, S.F. (2001). “Design and performance of a channel reconstruction project in a coastal California gravel-bed stream.” *Environmental Management* 28(6), pg. 761.

Leopold, L. B. and Maddock, T., Jr. (1953). “The Hydraulic Geometry of Stream Channels and Some Physiographic Implications.” *U. S. Geological Survey Professional Paper 252*, U.S. Government Printing Office, Washington, D. C., (252), pp 117-127.

Leopold, L. B. and Wolman, M. G. (1960). “River meanders.” *Bulletin of the Geological Society of America* 71, pp. 769-794.

Limerinos, J. T. (1970). “Determination of the Manning Coefficient from Measured Bed Roughness in Natural Channels,” Water Supply Paper 1898B, US Geological Survey, Washington, DC.

MacBroom, J.G. (2004). “Merging River Mechanics and Fluvial Morphology for River Management,” *Proc. World Water and Environmental Congress* 2004. Salt Lake City, Utah. American Society of Civil Engineers, Reston, VA. (doi:10.1061/40737(2004)408).

Malakof, D. (2004). The River Doctor. *Science* 305(5686), pp. 937-939 [DOI: 10.1126/science.305.5686.937].

Meyer-Peter, E., and Müller, R. (1948). “Formulas for bed-load transport,” Proc. 2nd Meeting of the IAHR, Stockholm, Sweden, pp 39–64.

McCarley, R.W., Ingram, J.J., and Brown, B.J. (1990). “Flood-Control Channel National Inventory,” Miscellaneous Paper HL-90-10. U.S. Army Engineer Waterways Experiment Station.

Millar, R.G. and MacVicar, B.J. (1998). “An Analytical Method for Natural Channel Design,” *Proc. Wetlands Engineering and River Restoration Conference 1998*. Denver, Colorado. American Society of Civil Engineers, Reston, VA. (doi:10.1061/40382(1998)65).

Millar, R. G. and Quick, M. C. (1998). “Stable width and depth of gravel-bed rivers with cohesive banks.” *Journal of Hydraulic Engineering* 124(10), pp. 1005-1013.

Miller, J.R. and Ritter, J.B. (1996). “An Examination of the Rosgen classification of natural rivers.” *Catena* 27, pp. 295-299.

Miller, D.E. and Skidmore, P.B. (2001). “Natural channel design: How does Rosgen classification-based design compare with other methods?” *Proc. Wetlands and River Restoration* 2001. American Society of Civil Engineers, Reston, VA. CD-ROM.

National Research Council, Committee on Restoration of Aquatic Ecosystems. (1992). *Restoration of Aquatic Ecosystems: Science, Technology and Public Policy*. National Academy Press, Washington, D. C.

Neary, V.S. and Korte, N. (2002). “Preliminary Channel Design: Blue River Reach Enhancement in Kansas City." *Proc., 9th International Conf. on Urban Drainage*. Portland, Oregon, September 8-13, 2002.

Newbury, R.W. and Gaboury, M.N. (1993). *Stream Analysis and Fish Habitat Design: A Field Manual*. Newbury Hydraulics Ltd., Gibsons, British Columbia.

Parker, G., Klingeman, P. C. and McClean, D. G. (1982). “Bedload and size distribution in paved gravel-bed streams,” *Journal of the Hydraulics Division*, American Society of Civil Engineers, 103(HY4), pp. 544-571.

Riley, A. L. (1998). *Restoring Streams in Cities: A Guide for Planners, Policymakers and Citizens*. Island Press, Washington, D. C.

RiverMORPH (2005). *RiverMORPH User’s Manual Version 3.1*. RiverMORPH, LLC, Louisville, Kentucky.

Rosgen, D.L. (1994). *Applied River Morphology*. Wildland Hydrology Books, Pagosa Springs, Colo.

Rosgen, D. L. (1997). “A geomorphological approach to restoration of incised rivers.” In Wang, S.Y., Langendoen, E. and Shields, F. D. Jr., (eds.) *Management of Landscapes Disturbed by Channel Incision, Stabilization, Rehabilitation and Restoration*. Center for Computational Hydroscience and Engineering, University of Mississippi, University, Mississippi. pp 12-22.

Rosgen, D.L. (1998). “The Reference Reach – A Blueprint for Natural Channel Design,” *Proc. Wetlands Engineering and River Restoration Conference*, Denver, Colorado, American Society of Civil Engineers, Reston VA., pp. 1009-1016. (doi: 10.1016/40382(1998)166)

Rosgen, D. L. (2005). “The Rosgen Geomorphic Approach for Natural Channel Design,” Appendix 7-C, NRCS Draft Stream Design Guide, USDA-NRCS, Washington, D. C.

Schulte, M. A., Forman, S. M., Williams, D. T., Mashburn, G. and Vermeeren, R. (2000). A stable channel design approach for the Rio Salado, Salt River, Arizona,” *Proc. Building Partnerships - 2000 Joint Conference on Water Resource Engineering and Water Resources Planning & Management*, American Society of Civil Engineers, Reston VA., CD-ROM, (doi:10.1061/40517(2000)362).

Schwartz, J.S., Carpenter, D.D., Slate, L.O., Sinha, S.K., Brennen, K. and MacBroom, J. (2003). “Research needs for improvement of principles and practices in urban stream restoration.” *Proc. Protection and Restoration of Urban and Rural Streams Symposium 2003*. Philadelphia, Pennsylvania. American Society of Civil Engineers, Reston, VA. pp. 15-28.

Shields, F. D., Jr. (1997). “Reach-average dimensions for channel reconstruction.” In Wang, S. Y., Carstens, T. (eds.) *Environmental and Coastal Hydraulics: Protecting the Aquatic Habitat*. Proceedings Theme B, Vol. 1, XXVII Congress of the International Association for Hydraulic Research, American Society of Civil Engineers, New York, pp. 388-393.

Shields, F. D., Jr., Copeland, R. R., Klingeman, P. C., Doyle, M. W. and Simon, A. In press. Stream restoration. Chapter 9 in *Sedimentation Engineering*, Volume 2, Manual 54, American Society of Civil Engineers, Reston, Virginia.

Shields, F. D., Jr., Copeland, R. R., Klingeman, P. C., Doyle, M. W. and Simon, A. (2003). "Design for stream restoration." *Journal of Hydraulic Engineering* 129(3), pp.575-584.

Simon, A., Doyle, M., Kondolf, M. Shields, F.D., Jr., Rhoads, B., Grant, G., Fitzpatrick, F., Juracek, K., McPhillips, M. and MacBroom, J. (2005). "How Well do the Rosgen Classification and Associated 'Natural Channel Design' Methods Integrate and Quantify Fluvial Processes and Channel Response?" *Proc. World Water and Environmental Resources Congress*. Anchorage, Alaska. American Society of Civil Engineers, Reston, VA. (doi: 10.1061/40792(173)584)

Simpson, P.W. (1982). "Manual of Channelization Impacts on Fish and Wildlife." Contract No. 14-16-0009-80-006. U. S. Fish and Wildlife Service, U.S. Department of the Interior, Washington, D. C.

Skidmore, P. B., Shields, F. D., Jr., Doyle, M. W. and Miller, D. E. (2001). "A categorization of approaches to natural channel design." *Proc. Wetlands and River Restoration* 2001. American Society of Civil Engineers, Reston, VA, CD-ROM.

Soar, P. J. (2000). "Channel restoration design for meandering rivers." Thesis submitted to the University of Nottingham for the degree of Doctor of Philosophy, Nottingham, U. K.

Soar, P.J. and Thorne, C.R.. (2001). "Channel Restoration Design for Meandering Rivers," ERDC/CHL CR-01-1. U.S. Army Corps of Engineers, Washington, D.C.

Smith, S.M. (1997). "Changes in the hydraulic and morphological characteristics of a relocated stream channel." MS thesis, University of Maryland, College Park.

Thomas, W.A., Copeland, R.R. and McComas, D.N. (2002). "SAM –Hydraulic Design Package for Channels," U.S. Army Corps of Engineers Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg MS.

U.S. Army Corps of Engineers (USACE). (1970). "Hydraulic Design of Flood Control Channels," EM 1110-2-1601, Office of the Chief of Engineers, Washington, D.C.

U.S. Army Corps of Engineer Hydrologic Engineering Center (USACE-HEC) (2002). "HEC-RAS River Analysis System*,"* Users Manual, Version 3.1, Davis CA.

U.S. Department of Agriculture (USDA) (1977). "Design of Open Channels," Technical Release No. 25, Soil Conservation Service, Washington, D.C.

White, K. E. (2001). "Regional curve development and selection of a reference reach in the non-urban, lowland sections of the piedmont physiographic province, Pennsylvania and Maryland," U.S. Department of the Interior, U.S. Geological Survey Water-Resources Investigations Report 01-4146, USGS, New Cumberland, PA.

Wilcock, P.R. (1997). "Friction between Science and Practice: The Case of River Restoration." Eos, *Transactions, Am. Geophysical Union* 78(41), pg 454

Wilcock, P.R. (2004). "Sediment Transport in the Restoration of Gravel-bed Rivers," *Proc. Critical Transitions in Water and Environmental Resources Management*. Salt Lake City, Utah. American Society of Civil Engineers, Reston, VA. (doi:10.1061/40737(2004)433).

Williams, G.P. (1978). "Bankfull Discharge of Rivers," *Water Resources Research* 14(6), pp 1141-1154.

Wohl, E. (2004). *Disconnected rivers: linking rivers to landscapes.* Yale University Press. New Haven, Conn.