The Reference Reach - a Blueprint for Natural Channel Design

by

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Abstract

The reference reach is used to develop natural channel design criteria based upon measured morphological relations associated with the bankfull stage for a specific stable stream type. Specific data on stream channel dimension, pattern and profile are collected and presented by dimensionless ratios by stream type. The reference reach is a portion of a river segment that represents a stable channel within a particular valley morphology. The morphological data collected is used for extrapolation to disturbed or unstable reaches in similar valley types for the purposes of restoration, stream enhancement, stabilization, and stream naturalization schemes. Bankfull discharge and dimensions from streamgage stations for particular hydro-physiographic provinces are correlated with drainage area to develop regional curves for extrapolation to non-gaged reaches.

Regime equations often used for river restoration design represent data developed empirically from a range of stream types. If the streams where the regime equations are being implemented are not similar to the streams from which the equations were developed, resultant designs can be incompatible with natural channel morphology. This problem can be offset if the source of the empirical equations can be identified and published by specific stream type. Reference reach data can be used to validate and sort appropriate regime equations by stream type prior to implementation. Examples of field methods, analytical procedures, and applications in natural channel design are presented

Introduction

To understand, predict and describe each complex process of the mutual integration of the independent and dependent variables that shape and maintain the stream channel in the present climate has challenged the river engineer for centuries. The requirements of modern civilizations have placed great stress on rivers and even greater demands on river engineers. The activities of river control, floodplain encroachment, channelization, levee construction, and stabilization with concrete, rip-rap, interlocking blocks, and other "hard" control measures have made canals out of natural rivers. The loss of physical and biological function in these altered river systems have induced large-scale adverse response by the general public throughout North America and portions of Europe…they want their rivers back. However, they also want their rivers to be stable and their homes to be protected from flooding. These new questions have put the river engineer in a real dilemma due to the often, conflicting and competing objectives.

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A majority of river engineering designs are based on clear water discharge, rigid boundary theory, uniform flow, smooth beds, and uniform channel materials (Chow, 1959). These underlying assumptions are often violated in natural rivers, thus their validity for use in natural channel design needs to be tested. Empirically derived regime equations, often used to establish channel dimensions and slope, can be very appropriate if the stream being restored is similar to the stream from which the relations have been developed. In design manuals, however, it is difficult to determine the source of the relation and/or the stream type(s) that a model represents. It is desirable then, to stratify regime equations associated with the stream types from which they were derived.

Morphologically described stream types based on field measurements are described in Rosgen (1994). An assortment of stream types are presented that are delineated by slope, channel materials, width/depth ratio, sinuosity and entrenchment ratio. The stream types are described at the morphological description level (level II) of the hierarchical system for classification. At this level of inventory, the existing dimension, pattern, profile, and materials are described. The descriptions however, do not necessarily represent a stable form or describe the potential of the stream. An assessment of condition or state is determined in level III and verified in level IV (Rosgen, 1994,1996).

The use of a reference reach data base, characteristic of the stable channel morphology for a similar valley type can provide an integrative approach which has the stable dimension, pattern and profile to keep the stream from aggrading or degrading. Morphological measurements must be obtained by unique stream types in order to extrapolate these data. The use of a classification system for this purpose is essential in order to group variables by morphological similarity and to reduce statistical variance between the groups.

If the condition of the river being restored is extremely unstable, a dilemma often exists in the selection of the potential stream type and the associated morphological characteristics for a given flow and sediment regime, valley slope, and channel materials. Reference reach data using dimensionless ratios can be used to establish design values as long as the reference reach is representative of the same valley type and sediment regime (see valley type descriptions, Rosgen, 1996). The reference reach data is not to be confused with stream type data from level II analysis, since this data summarized from various streams of the same type, does not always represent the stable form.

Other approaches to restoration design involve modeling sediment transport to then back-calculate the corresponding effective discharge, depth and slope (Thomas, et al, 1994). Any significant errors in the sediment transport model, however, can be directly transferred to the corresponding design discharge, directly influencing the dimensions and corresponding meander pattern and slope of the restored channel.

Stream stability

A “stable” stream, as used in this paper, is defined as: the ability of a stream, over time (in the present climate), to transport the flows and sediment produced by its watershed in such a manner that the dimension, pattern and profile are maintained without either aggrading, nor degrading (Rosgen, 1996). The reference reach characterizes the stable morphology, but does not necessarily require “pristine” or “relic” reaches that are very rare to find. Verification of the stability of the reference reach is done by procedures included in Level IV of the hierarchical river inventory (Rosgen, 1996). Aerial photographs can be used to provide additional evidence of stability by depicting time-trends in comparing the morphological state prior to and following floods. For example, a major flood estimated at a 10,000 year return period, occurred on Fall River, in Rocky Mountain National Park, resulting from the breach of Lawn Lake. The C4 stream type in Horseshoe Park was stable prior to the flood, and the author observed this river the following day of the flood. The stream channel maintained the same pre-flood dimension, pattern and profile. The channel did not aggrade nor degrade which met the criteria of a stable channel. The width of the stream did not reflect the rare, large flood, but maintained the width associated with the bankfull discharge. Fall River, thus makes a good candidate for the reference reach database for a stable C4 stream type.

The Bankfull discharge

The use of bankfull discharge is similar to effective, dominant, and channel forming streamflows. It is imperative that the selection of a reference discharge be consistent among rivers in order to: a) classify streams; b) extrapolate morphological relations from similar stream types but of different size; and c) to develop dimensionless ratios from these relations. A design that emulates natural, stable channels, associated with self-formed and self-maintained reference reaches, allows a determination of dimension, pattern and profile using dimensionless ratios. Measurements of width and depth to obtain width/depth ratio are associated with the dimensions corresponding to the bankfull stage. Without a consistent reference discharge, dimensionless ratios for a variety of stream types, could provide confusion among river engineers.

The bankfull discharge or the discharge associated with the stage at the incipient point of flooding is a frequently occurring flow of moderate magnitude. The author for a period of the last 12 years has visited approximately 10 USGS gage sites/year throughout North America. The average return period from field calibration using bankfull field indicators is 1.1 to 1.8 years. This includes ephemeral streams in Arizona, spring-fed streams in Eastern Oregon, Streams in Delaware, Alabama, Maryland, Montana, California, Wisconsin, Minnesota, North and South Dakota and many other vastly different hydro-physiographic provinces. The field determination of bankfull discharge using morphological indicators needs to be calibrated with measured values at gaged sites. Once this is done, regional curves are developed using drainage area to predict bankfull discharge and bankfull dimensions for each hydro-physiographic region where precipitation/runoff relations vary. These curves are used to assist in bankfull discharge determination in highly unstable systems where field evidence of bankfull is extremely difficult to detect. Regional curves for bankfull discharge and bankfull cross-sectional area versus drainage area have been recently developed by a diverse group of field observers in various agencies and universities (Table 1). The excellent correlation coefficients in these studies show the apparent application of using drainage area for estimating bankfull discharge on unstable reaches and un-gaged rivers.

Table 1. Correlation coefficients for regional curve development using morphologically determined bankfull stage for various hydro-physiographic provinces throughout the United States.

Location/source of data	Variable correlated with drainage area	Correlation coefficient (r^2)
Upper San Juan River, Colorado, (Rosgen, 1997, research in progress)	Bankfull discharge vs drainage area	0.988
	Bankfull cross-section area	0.977
	Bankfull width	0.885
	Bankfull depth	0.599
Maryland Piedmont,1998, (USFWS, R.Everitt and T. McCandless, in progress)	Bankfull discharge	0.905
	Cross-section area	0.914
	Bankfull width	0.837
	Bankfull depth	0.779
North Central Kansas, 1997, (Phil Balch, in progress)	Bankfull discharge	0.911
Delaware, 1997 (R. Smith, in progress)	Bankfull cross-section area	0.956
	Bankfull width	0.823
	Bankfull depth	0.698
Arizona, Northern Arizona Univ.,1998, (T.Moody and W. Odem, in progress)	Bankfull discharge	0.954
Central Oklahoma, 1997 lowlands,USDA,NRCS (R.Riley,et al, in progress)	Bankfull discharge	0.99
	Bankfull cross-section area	0.989
	Bankfull width	0.841
	Bankfull depth	0.884
Wisconsin, 1997, USDA,NRCS (L. Steffen)	Bankfull cross-section area	0.866
	Bankfull width	0.913
	Bankfull depth	0.798

The regional curves assist in providing a closer "bracket" for consistency of the design discharge determination using bankfull discharge in the absence of gaged data, inexperienced observers, and/or lack of visible bankfull indicators.

The similarity of bankfull and effective discharge, as originally proposed by Wolman and Miller (1960), has been verified by Andrews (1980), Andrews and Nankervis (1995) and, Batalla and Sala, (1995). The calculation of effective discharge involves flow duration and sediment rating curves, however, effective discharge, using this calculation would have a greater magnitude than the bankfull discharge in incising channels due to a shift upward of the intercept and slope values of the sediment rating curve. The authors field observations associated with incised channels show an increase in sediment supply reflected in the sediment rating curve shift, due to accelerated stream bank and bed erosion. Calculating a larger magnitude discharge than bankfull for design purposes in the incising channel will result in increased shear stress, stream power and localized boundary stress. If the source of the increased sediment is from upstream supply, then routing (sediment transport capacity) versus stream bank and bed erosion needs to be distinguished. If an effective discharge calculation using a "steeper" sediment rating curve in an incised river is much larger than the bankfull discharge, the design flow can result in accelerated channel erosion. Incised rivers often make it difficult for field observers to detect bankfull indicators, thus regional curves, calibrated for the appropriate hydro-physiographic province, are recommended to obtain the bankfull discharge.

Development of design criteria

One group of regime equations are the hydraulic geometry relations, (Leopold and Maddock, 1953). Hydraulic geometry relations have been very useful in describing width, depth cross-sectional area and velocity as power functions of stream discharge. Where the stream types associated with a bankfull width/depth ratio, slope, and channel materials are similar to the streams from which the hydraulic geometry were derived, extrapolation of these relations is appropriate for design purposes. If stream types vary significantly from the empirical relations, the reference reach method that integrates morphological variables into dimensionless ratios for unique sets of stream types can help reduce errors. An example of this application compares bankfull width, depth, and slope for the same discharge for an E4 stream type (an alluvial, gravel bed, highly sinuous, meandering stream with a width/depth ratio of 3, with a well developed floodplain) compared to a C4 stream type (an alluvial, gravel bed, meandering stream with a width/depth ratio of 20 with a well developed floodplain). For a discharge of 3 cms (100 cfs), the corresponding dimensions for the two alluvial, gravel bed stream types are shown in Table 2. The contrasting dimensions for the same discharge for these two, stable, meandering gravel bed streams would not be correctly identified using hydraulic geometry relations, unless initially stratified by stream type. Additional examples are shown in Rosgen, (1994).

Some regime equations predict slope, width, and depth using discharge and dominant channel materials (USACOE, 1994). In the example of the C4 and E4 stream types, both of which have gravel beds, the dimensions for the C4 stream type would have been correctly predicted using these regime equations. The E4 stream type, however, would not have been correctly predicted due to its' low width/depth ratio. Regime equations can be stratified by individual stream types to avoid this problem.

Selection criteria for reference reaches involves characterization from a representative segment of a valley type similar to the disturbed design reach. Valley types are similar in basin relief, depositional materials and features of the stream to be restored. Quantitative morphological data is collected for the reference reach, then converted to dimensionless ratios by dividing the dimension, pattern and profile variables by the bankfull values of the same feature. The purpose of the dimensionless ratios are to calculate actual design values for width, depth, meander length, radius of curvature, pool depth, pool slope, cross-sectional area of riffles and pools, riffle slope, maximum riffle depth and many other channel properties.

Table 2. Relations of width, depth, velocity and cross-sectional area to discharge for two different gravel bed streams for a bankfull discharge of 3.0 cubic meters/sec (100 cfs).

Variables	**E4 stream type**	**C4 stream type**
Bankfull surface width	2.2 meters (7.1 ft.)	7.3 meters (23.9 ft.)
Bankfull mean depth (meters)	0.73 (2.4 ft.)	0.37 meters (1.2 ft.)
Width/depth ratio	3	20
Bankfull mean velocity (meters/sec.)	1.8 meters/sec (6 ft./sec.)	1.1 meters/sec (3.5 ft./sec.)
Bankfull cross-sectional area (square meters)	1.5 square meters (16.7 $ft.^2$)	2.7 square meters (28.6 $ft.^2$)
Valley slope	.010	.010
Channel sinuosity	1.4	2.5
Channel slope	.007	.004

The dimensionless ratio values (Table 3) can be obtained directly and applied to streams of various sizes and bankfull discharge, but of the same stream type. For example, the bankfull width for a stable C4 stream type is calculated by the square root of the product of width/depth ratio of the stable reference reach stream type times the cross-sectional area at the bankfull stage. Mean bankfull depth is calculated by dividing bankfull surface width by width/depth ratio. Additional examples of the data collected and variables computed from reference reach data are shown in Table 3.

Procedural rules for data collection and documentation of the reference reach

- verify bankfull discharge with regional curves from gage station data
- stratify by representative valley type (width, valley slope, same channel materials, landform/landtype association)
- stratify by morphological stream type
- be stable (in equilibrium or in regime) but not required to be pristine
- have at least two full meander wavelengths, or 20 widths of length of consistency for measurements
- be free to adjust channel boundaries for the frequent high flows
- select cross-sections and long. Profile to represent typical bed features
- establish range of values as well as average for “natural variance”
- if located at gage station, work up hydraulic geometry by stream type
- complete a level III, (Rosgen, 1996) condition assessment of stream type

Table 3. Reference reach data and example computations for design.

Morphological Variables	**Morphological Variables**	**Morphological Variables**	**Morphological Variables**	**Morphological Variables**
1}Bankfull width	10)Channel materials:D15 D35,D50,D84,D95, D100	19)Riffle slope	28) Glide slope	37) Ratio of run depth/mean depth
2)Bankfull mean depth	11)Bar material: D15, D35,D50, D84, D95, D100	20) Ratio riffle slope/ave. slope	29) Ratio of glide slope/ave. slope	38) Run w/d
3)Width/depth ratio (1)/(2)	12} Stream type	21) Riffle max. depth ratio (4)/(2)	30) Glide depth	39) Ratio of run w/d/ave. w/d
4)Bankfull max. depth	13) Bankfull cross-section area (1)x(2)	22) Pool slope	31) Ratio glide depth/mean depth	40)Meander length (Lm)
5)Width of floodprone area	14) Drainage area	23) Ratio of pool slope/ave. slope	32) Glide w/d ratio	41) Ratio of Lm/bankfull width
6)Entrenchment ratio (5)/(1)	15) wetted perimeter (P)	24) Max. pool depth	33) Ratio of glide w/d/riffle w/d	42) Radius of curvature (Rc)
7) valley slope	16) Hydraulic radius (13)/(15)	25) Ratio of max. depth/mean depth	34) Run slope	43) Ratio of Rc/ bankfull width
8) Average water surface slope	17) Bankfull velocity	26) W/D ratio of pool	35) Ratio of run slope/ave. slope	44) Belt width
9) Sinuosity (7)/(8) chan.Length/valley L	18) Bankfull discharge	27) Ratio pool w/d/riffle w/d	36) Run depth	45) Meander width ratio (Wblt/Wbkf)

Restoration Concepts

Restoration of natural stable channels, as used in this paper, is defined as the establishment of the dimension, pattern and profile of the appropriate stable stream type in order to restore it's physical and biological function. Observations are necessary of the cause of the instability, and the current state of the existing stream type. Knowing where the stream is in the evolutionary sequence of channel adjustment, often helps in selecting the appropriate stable stream type. The evolution model proposed by Hupp and Simon (1991) can be compared to the quantitative, morphological relations by stream type shown in association with the various phases of channel evolution (Rosgen, 1996). Restoration often helps "speed up" the process of evolution, toward a faster recovery to the stable form. Channel form as described using dimensionless ratios of the reference reach has evolved over time, resultant of an integration of a channel forming discharge (bankfull) and sediment regime. The basis for this type of natural channel design utilizes this assumption

Summary

The morphological variables used to establish design dimensions, patterns and the profile for natural channel design can be developed from stable reference reaches. Due to the large number of variables and their wide variability, stratification by stream type assists in the extrapolation of dimensionless ratios to streams being restored. Caution should be used in applying regime equations, unless the empirical relations have been stratified by the various stream types that the restoration represents.

The advantage of using the stable reference reach for design criteria is the integration of the dependent variables of the streams dimension, pattern and profile with the independent variables of streamflow, sediment regime, channel materials and valley slope. The stream has evolved, over time, to have just the slope, width, depth and other morphological features to transport the flows and sediment produced by its' watershed without either aggrading or degrading. The design engineer must be able to "read the river" and select design specifications compatible with the natural stable channel.

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