

A Categorization of Approaches to Natural Channel Design

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Abstract

Presented herein is a categorization of commonly applied approaches to natural channel design. Approaches have been categorized as analog, empirical, or analytical. Methods and limitations of each approach and considerations for selection of an appropriate approach are discussed. Analog design replicates historic or adjacent channel characteristics and assumes equilibrium sediment and hydrologic conditions. Empirical design uses equations that relate various channel characteristics derived from regionalized or “universal” data sets, and also assumes equilibrium sediment and hydrologic conditions. Analytical design makes use of the continuity equation, roughness equations, hydraulic models, and a variety of sediment transport functions to derive equilibrium channel conditions, and thus is applicable to situations where historic or current channel conditions are not in equilibrium, or where applicable analogs or empirical equations are unavailable.

Analog, empirical and analytical approaches each have advantages and limitations. The advantage of the analog and empirical approaches is the intuitive simplicity of replicating desired channel and habitat characteristics from stable systems. Analog and empirical approaches require little or no consideration of sediment transport, as their application assumes equilibrium conditions. Analytical approaches are required when channel equilibrium is in question, and when no analog sites or empirical equations are applicable as a consequence of changing or differing hydrologic character and sediment inputs. The analytical approach often requires substantially more data, more time, and more highly trained personnel to apply.

Introduction

Design of natural channels for the purpose of restoration, rehabilitation, relocation, stabilization, or habitat enhancement is a developing science. Designing natural channels to meet both ecological and engineering criteria necessitates incorporating approaches and considerations from numerous scientific and engineering disciplines. However, most practitioners focus on approaches that emphasize their expertise, without adequately incorporating other components.

Because the developing industry of natural channel design lacks a standard approach to design (Miller and Skidmore in process), and indeed commonly embraces approaches that limit the integrity of channel design, a more comprehensive understanding of the spectrum of approaches to design is warranted. Contemporary research and development of channel design

methodologies (Federal Interagency Stream Restoration Working Group (FISRWG) 1998, Watson et al. 1999, Soar et al. 2001) indicate that no single approach is appropriate for all project conditions or objectives. While these studies imply recent convergence of common approaches, previous adoption of common practices has resulted more from effective marketing of techniques than from repeated success in implementation and universal applicability or acceptance.

Presented herein is a categorization of commonly applied approaches to channel design. Categorization is important to bring about an awareness of variable approaches and to facilitate discussion of the applicability of approaches to varying site conditions and data availability. This paper proposes the common terminology and categorization of approaches to natural channel design as analog, empirical, or analytical. Approaches to design have been similarly categorized in the literature (Shields 1996, FISRWG 1998, Watson et al. 1999, Inter-Fluve, Inc. 2000, Fripp et al. 2001).

Analog Approach - Adopts templates from historic or adjacent channel characteristics and assumes equilibrium between channel form and sediment and hydrologic inputs.

Empirical Approach - Uses equations that relate various channel characteristics derived from regionalized or “universal” data sets, and also assumes equilibrium conditions.

Analytical Approach - Makes use of hydraulic models and sediment transport functions to derive equilibrium conditions, and thus is applicable to situations where historic or current channel conditions are not in equilibrium with existing or predicted sediment and hydrologic inputs.

All channel design is based on the premise that “natural” channels tend toward equilibrium between channel form and sediment and hydrologic inputs (Leopold and Maddock 1953). Channel form is dictated by independent variables of hydrologic discharge, sediment supply, and character of boundary materials, including vegetation. Dependent variables are those physical characteristics that define channel form (width, depth, slope, and planform), which can be selected using various approaches to channel design. Analog approaches can be conducted without any quantification of independent variables. Empirical approaches require only dominant discharge and therefore can be conducted without any quantification or consideration of sediment supply. Analytical design methods require some quantification of independent variables in some instances, and can be used to quantify independent variables in other instances.

Analog Approach

An analog in its simplest form is a template for design. The template may exist in another location, or it may have existed previously in the same location. The analog approach is otherwise referred to as the reference reach method (Rosgen 1998), cognitive approach (FISRWG 1998), carbon copy approach (FISRWG 1998) or intuitive approach (Shields 1996). A distinction is made between a reference reach approach and carbon copy approach. A reference reach is defined as “a reach of stream outside the project that is used to develop design criteria for the project reach” (FISRWG 1998), whereas the carbon copy approach replicates pre-existing or historic conditions at the same site.

Application of Analog Approach The analog approach is common among geomorphologists, fisheries biologists, ecologists and other practitioners in the natural sciences field, largely because it is an intuitive replication of desired natural condition. The probability of successful ecosystem recovery is directly related to how closely abiotic components of the system

approximate the targeted state. The method of replicating existing or historic conditions to achieve a desired condition within the project reach can be used on the reach scale, or for individual components of design. In the former, all channel characteristics from an entire reach are replicated in design. In the latter, specific components of a reach may be replicated at the project site to address site-specific desired conditions. An example is the construction of specific habitat elements, such as pools or woody debris jams, based on replication of similar habitat elements in adjacent reaches or other nearby channels.

Analog Approach Methods The analog approach is the simplest and most intuitive of approaches to channel design. The methods, in simplest form, require careful measurement of channel parameters, and adoption of these same measurements in design. Consequently, analysis required for design is minimal. Design can be conducted without regard to or analysis of hydrologic statistics or sediment transport. However, evaluation of watershed stability prior to adopting an analog methodology is essential and may require considerable effort and analysis.

Four methods of application of the analog approach include:

The reference reach approach is well documented in Rosgen (1996) and includes measurement and subsequent replication of a number of channel parameters, including width, depth, slope, bed material gradation, flood prone width, and sinuosity, among others. However, Rosgen (1998) further prescribes the intermediate step of classification in the design process, though the utility or importance of classification is questionable (Doyle and Harbor 2000). Reference reaches are classified, and subsequent design is based on dimensionless ratios prescribed by the selected stream class, rather than replicating actual reference reach parameters. In this sense, this classification-based approach is essentially an empirical approach, as the classification system is empirically derived.

The carbon copy approach relies on replication of previous or historic channel characteristics (FISRWG 1998). It is most commonly applied in the context of restoration of meander planform in channels that have been straightened. Historic channel alignment is often identified in the field, or in some cases from historic photos.

Target or component analogs, also termed reference reach methods by the Federal Interagency Stream Restoration Working Group (1998), are specific components of an existing channel that are used as templates for achieving desired conditions within a reach.

Cross-section analogs from stable reaches can be used to estimate dominant discharge and sediment transport character. Assuming that bankfull discharge is a fair indicator of dominant discharge (Andrews and Nankervis 1995), bankfull discharge can be estimated using any of a number of hydraulic analysis tools based on Manning's equation. Similarly, Fripp et al. (2001) describe application whereby a sediment rating curve is generated from an analog section and then applied to channel design at an adjacent location.

Limitations of Analog Approach Analog approaches to design are limited by the same assumptions that make the approach valid – identical watershed and boundary conditions must be assumed between analog and design condition. Natural channel process is dictated by three independent watershed and geographic variables – sediment supply (load and gradation), hydrology (timing and volume), and boundary conditions (bank cohesion and vegetation). Analog approaches for reach-scale design are not valid if these controlling variables are not

similar for the analog and the project site under post-construction conditions. Any discrepancy between analog and design reach conditions in these variables reduces the validity of approach.

Analog approaches further assume conditions of equilibrium among all independent and dependent variables. This required condition of equilibrium negates the applicability of analog techniques in actively changing watersheds (e.g., urban watersheds) or where unstable channel conditions exist (such as those altered by incision). Analogs are typically selected because of their apparent stability within a reach or watershed. However, unstable sections of the same reach, or unstable reaches within the same watershed, are often indicative of systemic disequilibrium, and therefore should be considered suspect in their eligibility for analog approaches. In such cases, where channel instability can be attributed to watershed factors, analog approaches are inappropriate. Similarly, the carbon copy approach, which uses historic channel form as an analog, may unintentionally replicate unstable reach conditions. For example, reinstatement of a meander, which was previously cutoff through natural process in an otherwise stable stream reach, will not necessarily address the sediment transport character that led to the cutoff.

Lastly, analog approaches ignore the relative importance of various dependent and independent variables. As a result, slight differences between the design and the analog that are allowed to compensate for variances in site conditions or constraints may result in channel instability. For example, the use of Manning's roughness equation for derivation of a value for bankfull discharge from a reference reach illustrates the relative importance of the roughness coefficient (a variable which integrates both dependent and independent variables) in the equation (Inter-Fluve 2000). Because the roughness coefficient, 'n', is the only variable in the denominator of this equation, it has the greatest effect on the calculated values of discharge in the equation. For example: two identical stream cross sections with differing roughness values of 0.035 and 0.055, due to bank vegetation and bed substrate conditions, will result in bankfull discharges that differ by approximately 50%. Thus, analog design must carefully replicate roughness characteristics (e.g., vegetation, substrate, bedform diversity) to ensure equality between analog and design conditions.

Empirical Approach

Empirical refers to relationships based on experience or observation alone. Empirical equations represent average conditions by reducing the range of variables from many observations to predictive formulas. Empirical approaches are based on observed conditions, as are analog approaches, but they include a larger data set than a single analog. In this respect the empirical approach is an intuitive extension of the analog approach, in that designs are based on examples of stable conditions in similar environments, but based on larger, and therefore theoretically better, data sets.

The empirical approach is otherwise referred to as the "Hydraulic Geometry Method" (Copeland and Hall 1998, FISRWG 1998, Fripp et al. 2001). Historic geomorphologic studies of stable, natural channels resulted in what have been termed 'hydraulic geometry' formulas (Leopold and Maddock 1953), which quantified attributes of channels in regime. These formulas generally relate dependent variables such as width, depth, or slope to independent variables such as

discharge or bed material size (e.g., Parker 1979, Bray 1982, Hey and Thorne 1986, Williams 1986, FISRWG 1998), and are generated by regression of large, regional data sets.

Application of Empirical Approach Application of empirical approaches to channel design is well-documented. Design values for physical channel attributes can be generated, using empirical formulas, from relatively few known or constant values. In this respect, they are particularly applicable to determining multiple channel geometry variables from a single or few variables. There are four requirements for application of empirical equations to channel design:

1. The watershed within which design is to be implemented must be stable and unchanging;
2. The watershed and the channels from which the data were derived must have been stable and in equilibrium;
3. There must be similar watershed character and channel attributes between empirical data set and design channel; and
4. Confidence limits, or scatter within the data, of the values generated from the equations must be acceptable.

The Federal Interagency Stream Corridor Restoration Working Group manual (1998) presents a comprehensive review of available empirical equations and references. While equations exist relating virtually every channel attribute to other channel attributes, equations relating channel dimensions to discharge are most reliable for width, less reliable for depth, and least reliable as predictors of slope (Wharton 1995). Channel width, however, is strongly influenced by bank composition and vegetation (Hey and Thorne 1986, Millar and Quick 1998), and these are rarely included as input variables in empirical equations. Alternatively, empirical equations can be developed for a river, watershed, or group of regionally similar streams if they do not otherwise exist. However, generating equations represents a tremendous field data collection effort, and careful consideration of the stability of the channels and contributing watershed.

In addition to being used to design channel dimensions from known, or assumed, constants or single variables, empirical relationships, in the form of regional regression formulas, can be used to estimate discharge. Regional regression formulas based on watershed characteristics or channel width and discharge have been developed for numerous regions, generally by the USGS. These formulas can be valuable to channel design efforts in that they often represent the only reasonable estimate of design discharge (Inter-Fluve 2000). This application, however, is generally based upon the assumption that dominant discharge can be related to a specific return interval, such as the 2-year flow.

Empirical Approach Methods Empirical equations can be used to determine the primary variables (e.g., channel width), from which other components of design are derived, as well as values for virtually any other channel attribute. Equations are used to derive values for unknown variables from known, or assumed variables (Inter-Fluve, 2000). The applicability, details and intricacies of each set of equations can only be thoroughly evaluated from original sources that document the data sets used, and the statistical character of the equations and their resulting values. Any equations or empirical methodologies that do not detail their data sets and the statistical validity of their equations should be considered with skepticism. Comprehensive lists of valuable empirical relations and the regions from which their data sets were derived is

provided in the Federal Interagency Stream Restoration Working Group manual (1998) and Wharton (1995).

Limitations of Empirical Approach Wharton (1995), in a comprehensive review of channel geometry empirical relations, states that the most significant problem in application of empirical relations is that they are only applicable over the range of conditions from which they were derived. In Williams' much-referenced publication on empirical relations for river meanders (1986), he summarizes the suite of empirical equations as "represent(ing) problems more than they do conclusions" with respect to universal application. Even when the conditions for sites used to generate an empirical formula match the design condition, the wide range of confidence limits is a problem for designers. Confidence intervals for estimates from hydraulic geometry formulas often span an order of magnitude.

Form-based classification systems (as opposed to process-based classification), such as that presented by Rosgen (1996), are also fundamentally empirical relations, as they are based on observed conditions and imply universality in application. Such form-based classification systems, however, bear the additional danger of application without any reference to confidence limits or channel process. Published equations from classification systems report only the mean condition and do not detail the confidence limits or range of values for stable channel parameters. Furthermore, empirical methods, particularly those represented by classification systems, ignore the possibility of geomorphic convergence, when different processes lead to similar outcomes, or form (Schumm 1984). Because varying processes can result in the same channel form, methods relying on channel form ignore process, and therefore are not valuable predictive tools for determining equilibrium channel condition (Goodwin 1999).

Empirical equations and their application to natural channel design are inherently limited by their data sets. These limitations are expressed in a number of ways. A limited number of variables are included in development of empirical equations. Popular equations generally relate only channel geometry variables to one another, or relate discharge to geometry. Generally, empirical equations do not directly account for sediment supply, bed material gradation, bank cohesion, vegetative character, slope, or roughness, all of which influence natural channels. While many of these variables can be considered regionally consistent, they can vary tremendously within a watershed, and thereby affect the legitimacy of the equations applied. In contrast to the basis of many empirical relationships, Hey and Thorne (1986) included vegetation density and bank shear strength in developing empirical equations for gravel-bed rivers in the UK. They thereby accounted for important independent variables otherwise rarely considered in empirical studies. While regionalization may account for some missing variables, regional data sets can also ignore the importance of local controls, such as bedrock geology, cohesive bank materials, large woody debris, the effect of elevation on character of vegetation (species and density), or rapid changes in sediment character in mountainous regions.

In addition, empirical equations fundamentally rely on the selection of a representative dominant discharge, most commonly the bankfull discharge, although other values may be used (Doyle et al., 1999). Determination of dominant discharge can be non-trivial (Johnson and Heil 1996), and can be increasingly problematic in unstable channels, wherein its significance is questionable.

The use of empirical equations to design channel attributes is not appropriate under the following circumstances:

1. Aggrading, degrading, or otherwise unstable channels cannot be reasonably characterized using published empirical relationships (Shields 1996);
2. Site constraints identified that restrict planform amplitude;
3. Where property or infrastructure protection requirements preclude the free migration of channel planform over time; and
4. Equations that do not specifically incorporate sediment transport are applicable only to channels with relatively low bed load (USACE 1994).

Analytical Approach

Analytical approaches to channel design are gaining increasing popularity, particularly in constrained, urbanized and otherwise degraded environments, and are described in most recent comprehensive channel design guidelines (FISRWG 1998, Watson et al. 1999). Analytical approaches rely on the solution of physically based governing equations (Millar and MacVicar, 1998) and generally require quantification of one or more independent variables to determine channel parameters. Analytical approaches are also referred to as “process-based” (Soar et al. 2001).

Analytical approaches are based on the premise that channels can be described by a finite number of independent and dependent variables (Griffiths 1983, USACE 1994, Hey 1978, Hey 1988). The number of variables identified ranges in the literature to as many as 15 (Hey 1978, Hey 1988) necessary to fully describe channel geometry in natural channels. The majority of these are dependent variables that adjust to the independent variables and to each other. It is impossible to account for all variables, thus the analytical approach, like the analog and empirical approaches, must rely on assumptions about variables, and must rely on values for variables derived by non-analytical means (analog or empirical). To compute the unknown variables, only three suites of equations are available: the continuity equation, flow resistance equations, and sediment transport equations (Shields 1996).

Application of Analytical Approach Analytical methods are perhaps most valuable in their ability to estimate independent variables and to predict or determine resultant dependent variables when analogs and empirical relations are non-existent or inappropriate. Most equations and methods apply only to alluvial channels, not cohesive or bedrock channels, or those dominated by large woody debris (FISRWG 1998). Analytical methods may be used to determine the following variables:

- Sediment load (if alluvial) and computation of sediment budget;
- Discharge durations or discharge return intervals, using continuous flow simulation models; and
- Channel geometry dimensions.

In addition to determination of variables, analytical design can be applied to test long term vertical stability of design conditions and allowable shear and velocity. These analyses can be useful for cross checking design developed using analog or empirical approaches to account for assumed conditions of equilibrium.

Analytical Approach Methods Numerous analytical methods are described in the literature (Shields 1996, FISRWG 1998, Copeland and Hall 1998, Millar and Quick 1998, Fripp et al. 2001, Soar et al. 2001) addressing varying components of channel design, from deriving hydrologic statistics and sediment load to testing sediment continuity in empirical or analog designs. Shields (1996) categorizes analytical methods as belonging to one of three governing sets of equations – continuity, flow resistance, and sediment transport. Specific equations from these sets are selected based on assumptions made, variables or characteristics known or quantified, site constraints, and bed materials. Analytical design requires careful consideration of the applicability of selected methodology to the project site. For example, twenty sediment transport functions are available in SAM (Thomas et al. 2000), each of which is suitable only under specific conditions and for limited ranges of sediment grain size.

Alternatively, analytical methods can be categorized according to the specific component of design that they address: hydraulic, geometric, or sediment character. Analytical methods can be used to determine hydraulic and hydrologic design components, such as: water surface elevations for flood control related design; shear for bed and bank design; or extent and duration of inundation for revegetation design. Similarly, geometric components of design solved using analytical methods may include appropriate channel geometry dimensions of width and depth for given slope, or planform character. Sediment components of design include sizing of bed substrate, if imported or installed, and integrating sediment transport analysis with channel geometry iterations to ensure sediment continuity.

Various computational models (HEC-6, GSTARS 2.0, FLUVIAL-12, etc.) can be valuable for some elements of iterative design, or to check the validity of proposed designs in light of sediment continuity. FISRWG (1998) lists characteristics of 8 computational models that, with few exceptions, compute the aggradation or degradation potential of a design channel, and provides references for comprehensive reviews of the capabilities and performance of the models.

Limitations of Analytical Approach Analytical methods are inherently limited by data quality and quantity used in the equations or models. Furthermore, as analytical approaches often address multiple unknown variables, equations and models generally assume constant values for a number of variables, such as cross-section geometry (assumed trapezoidal), bed sediment size distribution (Shields 1996), and ignore other variables such as channel planform. Most channel sediment transport models do not simulate bank erosion, although recently developed models provide this capability (e.g., CONCEPTS), but at a significant cost in terms of data needed and modeling expertise. Even correctly applied sediment transport relations may produce results that differ from actual conditions by $\pm 100\%$. Analytical approaches may require numerous assumptions that cannot be adequately verified or calibrated. Similarly, the output typically creates absolute values, rather than ranges of acceptable values for channel attributes, such as channel width and planform, which in natural streams vary considerably. Channel attribute values derived analytically may deviate considerably from any basis in natural or existing conditions. For example, planform generated using an analytical approach may be non-variable, if using a sine-generated curve as suggested by Langbein and Leopold (1966). Lack of variability in planform greatly reduces hydraulic variability, sediment sorting, and consequently, limits habitat variability.

The level of analysis (and related data requirements) of some analytical methods make them impractical for application except in well funded applied and research arenas. The efficacy of many analytical approaches depends on ability to estimate sediment load, which can require an expensive and intensive effort. Furthermore, most analytical methods require considerable ability to understand and interpret complex mathematical and computation processes, as well as a background in engineering. Consequently, practitioners with limited backgrounds (or those with solely natural science backgrounds) may be inadequately qualified to conduct analytical methods.

Selecting an Approach

Analog, empirical and analytical approaches all have strengths and weaknesses, as well as limited application. A given project may require elements of each approach. For example, Soar et al. (2001) present a methodology for restoration design of meandering rivers which begins with determination of effective discharge from an analog reach, continues with selection of channel width from empirical data sets which relate effective (bankfull) discharge to channel width, and then applies analytical or process-based equations in the SAM package (Thomas et al. 2000) to account for channel hydraulics and sediment transport. Soar et al. (2001) further suggests that meander wavelength be determined empirically after Leopold and Wolman (1957), and that meander shape be determined analytically using a sine-generated curve after Langbein and Leopold (1966). This approach is founded on the assumption that the analog reach is in equilibrium with its hydrologic condition and sediment supply, as effective discharge is originally estimated from an analog reach.

Factors that should be used to select an approach include:

1. Watershed stability and channel stability;
2. Availability of applicable analog and empirical equations; and
3. Degree to which independent variables of hydrology and sediment supply can be quantified.

Advantages and limitations of each approach should be carefully considered when applied to design of natural channels. The advantage of the analog approach is the intuitive simplicity of replicating desired channel and habitat characteristics. Similarly, the empirical approach offers the simplicity of deriving design-channel characteristics from measured relationships among physical channel attributes from other channels. Both analog and empirical approaches require little or no consideration of sediment transport, as their application assumes equilibrium conditions. These approaches are popular among designers and regulators with minimal funding and little specialization.

Analytical approaches are required when channel equilibrium is in question, and when no analog templates or empirical equations are appropriate as a consequence of changing or differing hydrologic character and sediment inputs. Further, analytical approaches are often necessary to perform details of analog and empirical design when specific design components are not addressed by analog data or empirical equations. The reliability of analytical methods is dependent upon the accuracy of input variables and the applicability of the models. The analytical approach often requires more data, more time, and more highly trained personnel to

apply. However, there is additional benefit to the greater quantification of design components. Quantification of design relative to process ultimately enables managers to evaluate project success and failure relative to quantifiable processes. In a field that commonly fails to conduct post-project appraisals, analytical approaches to design will provide greater avenues for evaluation of designs relative to objectives.

Project cost is also a factor in selection of design methods. In an ideal world the best design methodology will be selected, regardless of cost. However, there are practical limits to the benefits gained from additional design analyses. Once the limitations of various design approaches have been identified, these approaches can be evaluated relative to their costs. By evaluating cost *after* evaluating the benefits of various methods, budget can guide choice with the understanding of the consequences of that choice.

Resources Providing Design Methodologies

A number of publications describing methods, and selection of methods, for natural channel design have become available in recent years. Those listed below describe analog, empirical and analytical techniques and their application, though with varying terminology.

1. Shields, F. D. Jr. (1996) Hydraulic and hydrologic stability. In: *River Channel Restoration: Guiding Principles for Sustainable Projects*. A. Brookes and F.D. Shields, Jr. (eds.) John Wiley & Sons Ltd.
2. Federal Interagency Stream Restoration Working Group (1998) *Stream Corridor Restoration: Principles, Processes, and Practices*. National Technical Information Service, U.S. Department of Commerce, Springfield, VA.
3. NHI (National Highway Institute) (2001) *Stream Stability at Highway Structures*, Third Edition. Publication no. NHI 01-002, Hydraulic Engineering Circular No. 20. March 2001.

Summary

Channel design typically focuses on quantification of dependent variables and assumes, consciously or unconsciously, constancy and stability of independent variables. All approaches can be used to determine any of the dependent variables, but only analytical design approaches directly account for independent variables. Analog and empirical approaches both assume constancy and equivalence of independent variables between observed conditions (analog or empirical data set) and site conditions. Application of analog or empirical approaches increases the risk of project instability and failure (and thus designer liability) when inappropriately applied. Application of the analytical approach, however, does not increase the risk of failure when it is applied to projects where a simpler method would work. Thus, application of the analytical approach to natural channel design is more likely to result in project success than application of other approaches.

While this paper assigns approaches to channel design to three distinct categories, the methods applied in progressive modern projects are perhaps best viewed as falling along a continuum, with geomorphic/analog approaches on one end of the spectrum, and analytical/engineered on the other. Practical, functional design occurs somewhere in the middle ground (Soar et. al. 2001). Millar and MacVicar (1998) applied the term “semi-theoretical relations” to certain

analytical methods or assumptions developed from empirical data sets. And indeed, all but the simplest methodologies typically require elements of analog, empirical and analytical approaches. Contemporary methods for channel design, therefore, acknowledge the limitations, and embrace the value, of the three distinct approaches presented.

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