Natural Channel Design: Fundamental Concepts, Assumptions, and Methods

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The natural channel design (NCD) approach to river restoration emulates natural river systems and was initially developed to help redirect the manner in which past traditional river works have impacted natural river systems. The NCD approach integrates fluvial processes over temporal and spatial scales of self-formed and self-maintained natural rivers. Landscapes and stream systems must be observed in light of their evolution or successional states through various stages of adjustment. In doing so, the processes that produce a stable reference reach morphology can be inferred through time trends of river change. To understand the cause and consequence of change becomes a formidable yet essential phase in this NCD process; thus, rigorous protocols are necessary to document field observations and complete a consistent, quantitative, comparative assessment. NCD requires an understanding of process and form relations that must be formally quantified, tested, designed, and monitored. Over 67 form variables must be predicted in NCD that cannot be accurately predicted using current analytical models, which currently contain an incomplete system of equations. However, analog, empirical, and analytical methods are applied in NCD to determine and test the design variables. This chapter explains the underlying fundamental principles and concepts of NCD, definitions, assumptions, ecological integration, prediction methodologies, and minimum application requirements required for a sustainable design that strives to meet multiple objectives.

1. INTRODUCTION

To restore an impaired river is an admirable and rewarding venture; it also is one of the most challenging undertakings due to the inherent complexity, uncertainty, and risk. These circumstances should discourage most, but the cumulative anthropogenic impacts of impaired stream systems often makes the "do nothing" alternative unacceptable. Traditional river works have created unexpected major instability and environmental problems because of the unnatural conditions imposed on river systems by modifying the bankfull channel morphology associated with various streamflow and sediment regimes [*Hey*, 1997a]. The river engineering works carried out for single-purpose objectives, such as navigation, flood control, flood alleviation, and channel stabilization, have destroyed the conservation and amenity value of riverine areas [*Brookes*, 1988; *Purseglove*, 1988; *Hey*, 1997a]. Benthic and in-stream habitats and associated aquatic plant and invertebrate communities have consequently been destroyed [*Hey*, 1997a; *Brookes*, 1988]. Further consequences include downstream flooding, poor aesthetics, reduced recreation, slow natural recovery, and unsustainable maintenance [*Soar and Thorne*, 2001]. Rigid materials and methods (such as rock riprap, concrete, and gabion baskets) have also been widely applied to stabilize stream banks with limited opportunity to soften the environmental and aesthetic impacts [*Hemphill and Bramley*, 1989; *Hey et al.*, 1991]. These works have been driven by economic, social, and

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political pressures rather than the ecological health of the river.

However, people want their rivers back . . . therein lies a challenge . . . back to what? The boundary conditions and the driving variables (flow and sediment regimes) that influence channel morphology have changed from the pristine and undisturbed "pre-white settlement" conditions; thus, it is generally impractical and unsustainable to recreate the ideal pristine river channel. What can be done practically, however, is to emulate natural stable rivers that exist under the present boundary conditions and driving variables reflected in their watersheds. By designing with nature rather than against it, such approaches are more likely to be cost-effective, require less maintenance and minimize environmental impacts compared to traditional engineering solutions [*Hey*, 1997a; *Soar and Thorne*, 2001].

The natural channel design (NCD) approach to river restoration emulates natural river systems and was initially developed to help redirect the manner in which past traditional river works have impacted natural river systems [*Rosgen*, 2007]. The NCD approach integrates fluvial processes over temporal and spatial scales of self-formed and self-maintained natural rivers. Landscapes and stream systems must be observed in light of their evolution or successional states through various stages of adjustment. In doing so, the processes that produce a stable "reference reach" morphology can be inferred through time trends of river change. To understand the cause and consequence of change becomes a formidable, yet essential phase in this NCD process; thus, rigorous protocols are necessary to document field observations and complete a consistent, quantitative, and comparative watershed and channel stability assessment.

NCD involves procedures for three different reaches throughout the methodology: the "existing reach," the "reference reach," and the "proposed design reach." The "existing reach" represents the current impaired condition of the stream reach identified for potential restoration. The "reference reach" is a stable stream that represents the same "potential" stream type, valley type, flow regime, sediment regime, stream bank type, and riparian vegetation community as the existing reach. Reference reaches do not necessarily represent pristine systems [*Hughes et al.*, 1986] but have adjusted to the driving variables and boundary conditions in such a way as to be self-maintaining. The reference reach is used to establish dimensionless relations that represent the stable dimension, pattern, and profile (morphology) for a given stream type and valley type. Ranges of values are determined for each morphologic variable to represent the natural variability inherent in streams. These ranges are determined by surveying numerous cross sections and taking multiple pattern and profile measurements for each variable at the reference reach site. The values are converted to a dimensionless form by dividing by a normalization parameter, such as bankfull width, bankfull mean depth, or bankfull slope. The dimensionless relations are then extrapolated to the existing reach for scale comparisons. The dimensionless values are converted to dimensional values once the bankfull conditions are determined to obtain the "scaled" morphological characteristics for the proposed design reach. The "proposed design reach" is intended to emulate a natural stable channel that has the same stream type and valley type as the reference reach. Selection criteria and assessment procedures are described in subsequent sections.

Overall, the NCD procedure strives to put scientific principles into practice and involves detailed field measurements of the morphological, hydraulic, sedimentological, and biological characteristics of river channels. NCD requires an understanding of process and form relations that must be formally quantified, tested, designed, and monitored. Over 67 form variables must be predicted in NCD that cannot be accurately predicted using current analytical models, which currently contain an incomplete system of equations [*Hey*, 1978, 1988, 1997b, 2006; *Soar and Thorne*, 2001]. However, analog, empirical, and analytical methods are applied in NCD to establish and test the design variables. This chapter explains the underlying fundamental principles and concepts of NCD, definitions, assumptions, ecological integration, prediction methodologies, and minimum application requirements required for a sustainable design that strives to meet multiple objectives.

2. DEFINITIONS

"River restoration," as defined in this NCD approach, is to establish the physical, chemical, and biological functions of the river system that are self-regulating and emulate the natural stable form within the constraints imposed by the larger landscape conditions. A "river system" includes not only the river channel but also its related components, including adjacent floodplains, flood-prone areas (low terrace plus active floodplain), wetlands, and associated riparian communities. The "natural stable form" involves reestablishing a physical stability that integrates the processes responsible for creating and maintaining the dimension, pattern, and profile of river channels. Such form variables are based on the driving variables of flow and sediment as well as the boundary conditions of channel materials, riparian vegetation, boundary roughness, and the slope, width, and sinuosity of its valley. "River stability" is defined as a river or stream's ability in the present climate to transport the streamflows and sediment of its watershed, over time, in such a manner that the channel maintains its dimension, pattern, and profile without either aggrading or degrading [*Rosgen*, 1996, 2001b, 2006b, 2007].

The term "dynamic equilibrium" is defined by *Leopold et al.* [1964, p. 6], from the work by *Hack* [1960] extended from the work of *Gilbert* [1877], as a postulation "that there is at all times an approximate balance between the work done and imposed load and that as the landscape is lowered by erosion and solution, or is uplifted, or as processes alter with changing climate, adjustments occur that maintain this approximate balance." Dynamic equilibrium is synonymous with river stability as used in NCD. River stability is predicted and validated by field measurement and protocols presented in the assessment phase of NCD based on specific methods documented by *Rosgen* [2006b].

River stability in NCD does not mean that a river is "fixed" in place; "hardening" of the channel boundary including the streambed and stream banks is *not* an objective related to the NCD approach to river restoration. The NCD method assumes that there will be some postrestoration adjustment of the form variables over time and following floods. The allowable departure of dimension, pattern, and profile data within the range of the proposed design variables is determined by reference reach data sets that prescribe the allowable criteria. A certain amount of deposition is acceptable unless it leads to a raise of the local base level through aggradation processes. Conversely, channel scour is acceptable in a natural stable river; however, scour that over time leads to degradation or abandonment of floodplain surfaces through channel incision is not acceptable. Stream bank erosion is also expected in natural stable rivers, but concern exists when the stream bank erosion rates become accelerated.

3. NCD FUNDAMENTAL PRINCIPLES AND CONCEPTS

3.1. The Independent and Dependent Variables Related to Form and Process

Following disturbance, rivers have a central tendency to reestablish their stable form [*Mackin*, 1948; *Leopold*, 1994]. A stable channel's role is to transport the flows and sediment produced by its watershed. Underlying the complexities of river processes is an assortment of interrelated variables that determine the morphology of the present-day river. "The shape of the cross section of any river channel is a function of the flow, the quantity and character of the sediment in motion through the section, and the character or composition of the materials (including vegetation) that make up the bed and banks of the channel" [*Leopold*, 1994]. "Links between channel form and process have been the foundation of our understanding of fluvial geomorphology" [*Simon et al.*, 2007, p. 1119]. Thus, the mutual interdependence between channel process and form has been demonstrated in numerous works [e.g., *Leopold et al.*, 1964; *Schumm*, 1977; *Leopold*, 1994; *Knighton*, 1998; *Hey*, 1982]. It is a key assumption in NCD that river form and fluvial processes evolve simultaneously and operate through mutual adjustments toward self-stabilization [*Rosgen*, 1994].

Figure 1 depicts the independent driving variables of streamflow and sediment regime as the key controlling variables affecting the dependent variables of channel form. The independent controlling variables also include the boundary conditions that are associated with the form and processes of natural rivers (Figure 1). The riparian vegetation community, for example, is a boundary condition developed and maintained naturally through the integration of various valley features, soil types, soil moisture, and microclimate. Bank strength, flow resistance, and channel roughness elements (such as large woody debris) are influenced by the riparian community and are important to many of the form variables. Many of these independent variables cannot be changed (e.g., valley dimensions), and others may not practically be changed (e.g., the streambed and stream bank materials, the delivered bed load and suspended sediment, and streamflow regime). Although streamflow regime can change over time with climate or watershed recovery, NCD must facilitate a range of flows within the river system.

A total of 67 dependent form variables are obtained in NCD that relate to the driving variables and boundary conditions (Figure 1). These morphological variables are measured and analyzed to represent the range and mean values of the dimension, pattern, and profile variables for the existing and reference reach conditions. Typical dimension variables are associated with the bankfull discharge stage. Bankfull channel width and mean depth are used as normalization parameters for the morphological variables in NCD for extrapolation and comparison among rivers of various sizes. The various dimensions of bed features, including riffles, pools, runs, and glides, are measured for their unique morphology. Runs are transition features from riffles into pools, and glides are transition features from pools to riffles. Glides are typical spawning bed features where "redds" are found for salmonids associated with gentle slopes, shallow depths, and natural sorting of bed materials. The glides, being associated with adverse slopes, create a hyporheic exchange and upwelling forces. The channel dimensions also include the inner berm feature associated with the low-flow channel. Such river data is required to directly incorporate these various features into NCD.

The pattern variables reflect the boundary conditions and, similar to channel dimensions, are also related to the bankfull channel width. Pattern variables include the meander geometry relations of stream meander length, radius of curvature,

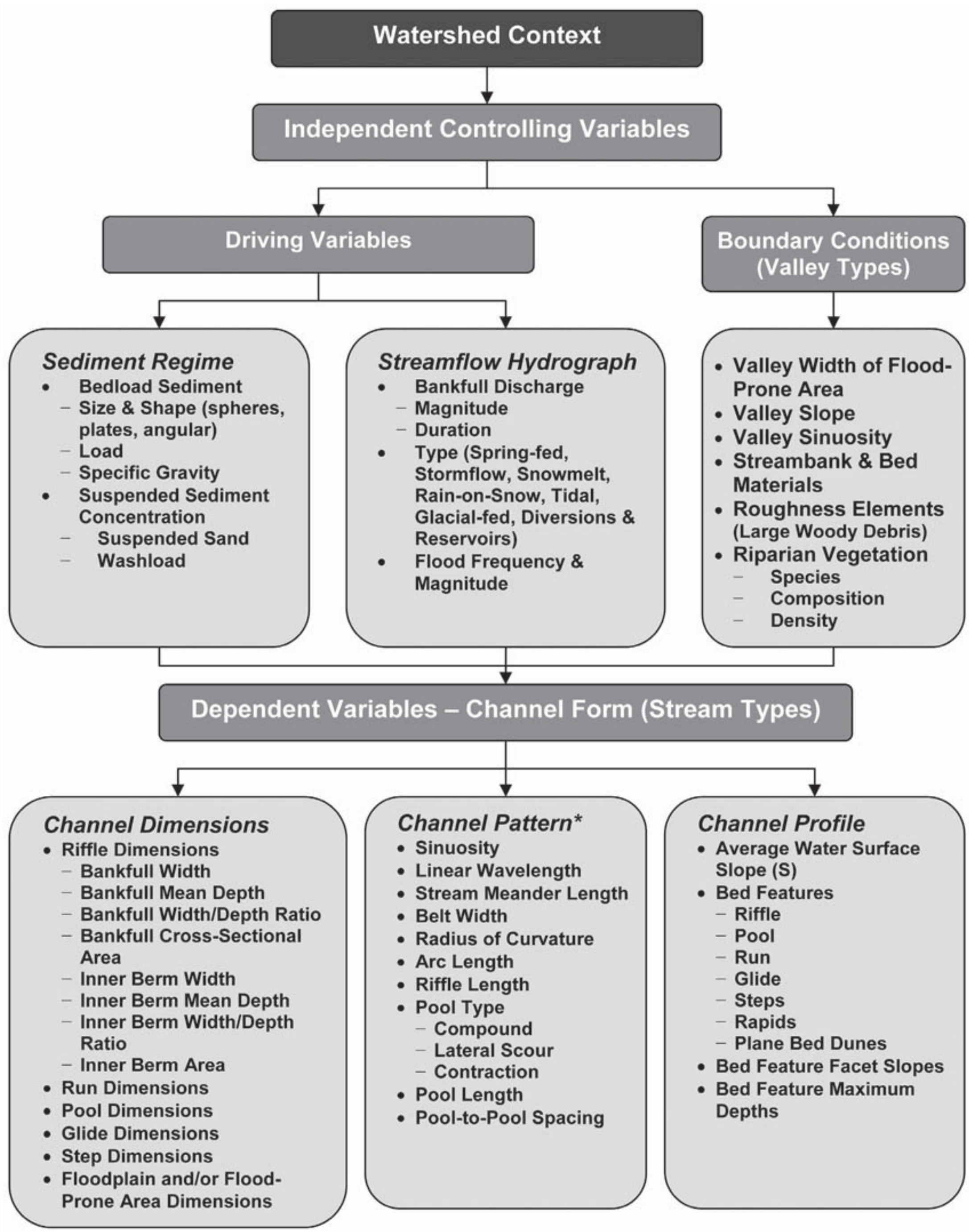

Figure 1. Independent and dependent variables that link the controlling variables and boundary conditions to the channel dimensions, pattern, and profile. *These channel pattern variables are representative of single-thread, meandering stream types; thus additional pattern recognition and description is required for bar-braided (D) and anastomosed (DA) stream types.

sinuosity, belt width, arc length, riffle and pool lengths, and pool-to-pool spacing (Figure 1). The channel profile includes slope measurements and an assortment of thalweg depths for the various bed features in addition to the depths measured at cross sections. Floodplain and/or flood-prone area dimensions and elevations are also measured.

The controlling variables for the existing and reference reaches are stratified (organized) by stream type and valley type with specific variables collected during the geomorphic characterization and assessment phases in the NCD methodology. Within each valley type is a unique characterization of flow regime, sediment regime, roughness elements, such as large woody debris, and riparian vegetation that influences the morphological character of the stream types contained in a valley. It is important to describe the flow regime (e.g., snowmelt, stormflow, spring fed, tidal influence, glacial fed, reservoir/diversion outflows, urban stormflow or rain-on-snow) to imply certain morphological conditions for a series of given channel form features. For example, spring-fed stream systems are associated with lower width/depth ratios due to flow resistance from dense riparian vegetation and low bed load sediment, compared to a snowmelt or rain-on-snow dominated flow regime. The sediment regime (size, type, and load or supply) that influences channel morphology is reflective of the depositional history of the valley type (e.g., terraced alluvial valley fills, glacial trough, lacustrine, alluvial fans, colluvial valleys, or deltas), including bar samples and stream bank and bed material inventories. The riparian vegetation type (overstory/understory, rooting character and ground cover type and density) also integrates the boundary conditions that influence the channel morphology.

Overall, an intimate relationship exists between process and form (Figures 1 and 2). Rivers having similar boundary conditions and driving variables of flow and sediment regime processes will have similar morphology, whereas any change in the controlling variables will alter channel morphology [*Schumm*, 2005]. Any sustainable solution in river restoration must properly replicate the form variables that represent the process integration of the independent, controlling variables with the dependent, form variables to maintain natural stability.

3.2. Applications of Form and Process Interrelations

The study of streams for any purpose involves form measurements of channel dimensions, pattern, profile, and materials. For any erosional, depositional, and equilibrium processes to be inferred, predicted, and validated, direct observations of river morphology are essential to obtain the stream's hydraulic, sedimentological, and biological character. From this information, the process interpretations are derived. For example, when a form variable changes due to imposed conditions, the corresponding hydraulic and sedimentological process relations are also influenced that result in "process changes" (e.g., aggradation, degradation, and lateral migration) and "channel consequences" (e.g., land loss, habitat changes, and shifts in stability) (Figure 2). An increase in the form variable of width/depth ratio from disturbance, for instance, without a change in the driving variable of bankfull discharge, results in an increase in flow resistance due to changes in relative roughness and friction factor because of reduced hydraulic mean depth. This results in a decrease of mean velocity and shear stress. The increase in width/depth ratio also creates a corresponding decrease in

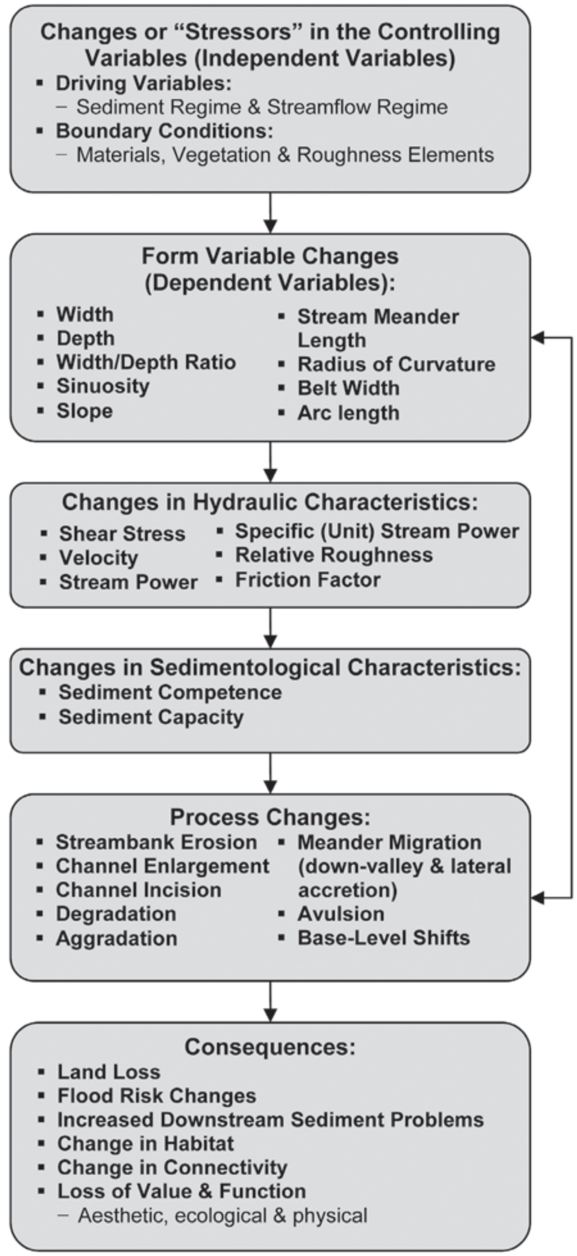

Figure 2. Linkage between form and process variable changes and the consequences due to changes in the controlling variables.

total stream power. Consequently, sediment transport competence and capacity are also decreased. Aggradation, accelerated stream bank erosion, chute cutoffs, and channel enlargement processes occur as a result of changes in the form variables. Additional form variables are subsequently adjusted including decreased sinuosity and increased slope. This form change, whether induced directly or indirectly, often results in a change in stream type from a meandering, riffle/pool, single-thread system to a multiple-thread, convergence/divergence bed-featured, bar/braided system. A change in both form and process can induce shifts in the geomorphic character of the river or a "threshold stream type" change.

3.3. Assumptions in Natural Channel Design

The primary assumptions in the NCD approach for river restoration are the following:

1. Form and process are interrelated.
2. Channel width is related to the bankfull discharge (normal high flow).
3. Assessments of river stability can be conducted to determine departure from a stable, reference condition.
4. Spatial and temporal changes of stream systems can be evaluated in watershed and river stability assessments through time trend studies and local validation using space for time substitution to select the appropriate stream succession scenarios and states.
5. Regional bankfull discharge and cross-sectional area can be determined from stream gauge sites and can be expressed as a function of drainage area within a hydrophysiographic area and can be extrapolated to ungauged sites within the same province; exceptions are associated with changes in streamflow and drainage area relations by diversions, reservoirs, and land use and must be determined from analysis and field studies from a watershed assessment rather than regional curves. The bankfull channel width and depth are not used for design from regional curves or hydraulic geometry unless such empirical relations are stratified by stream type and valley type.
6. A "reference reach" can be used to extrapolate dimensionless relations to determine the departure of the existing reach and for natural channel design. This assumption is based on the similarities in the boundary conditions and driving variables of the impaired existing reach and its potential stable stream type.
7. The dimensionless relations of the reference reach can be used to develop detailed dimensional values of dimension, pattern, and profile for the proposed design reach (e.g., bankfull maximum depths and facet slopes for riffles, runs, pools, glides, and steps).
8. Bar and bed samples and channel slope can be obtained to establish ratios to calculate critical dimensionless shear stress for the bankfull stage condition.
9. An entrainment relation using the Shields (or modified Shields [*Rosgen*, 2006b, 2007]) relation can be used to test for sediment competence for the existing, reference, and proposed design reaches.
10. Bankfull stage measurements of discharge, bed load, suspended sediment, and suspended sand sediment can be used to convert dimensionless relations of sediment rating curves to actual values of sediment rating curves (FLOWSED model [*Rosgen*, 2006a, 2006b, 2007]).
11. Regional bankfull bed load and suspended sediment curves can be established by major geology, stream stability, and drainage area in the interim absence of bankfull sediment data [*Rosgen*, 2006b, 2010].
12. Bankfull mean daily discharge can be obtained to develop dimensionless flow-duration curves at gauge stations. Mean daily bankfull discharge is then computed at ungauged sites and used to convert the dimensionless flow-duration curve to dimensional.
13. A sediment transport capacity model can be used to test for sediment continuity and channel stability for the existing, reference, and proposed design reaches.
14. Postrestoration stream adjustment of the dimension, pattern, and profile can appropriately occur within the range of natural variability of the reference reach data.

3.4. The Ten Phases of Natural Channel Design

Any river restoration design must first identify the multiple specific objectives, goals, and anticipated benefits of the proposed restoration. Analytical calculations, regionalized validated relationships, and analogy are combined in a precise series of computational sequences [*Rosgen*, 2007]. The conceptual layout for the 10 phases of the NCD approach is shown in Figure 3. The flowchart is indicative of the full extent and complexity associated with this approach. The NCD approach is divided into 10 major sequential phases (Figure 3) that act as a fundamental design framework and guide users through the minimum requirements and specific design procedures that must be incorporated: phase I, define restoration objectives; phase II, develop local and regional relations; phase III, conduct watershed, river, and biological assessments; phase IV, consider passive recommendations for restoration; phase V, develop conceptual design plan; phase VI, develop and evaluate the preliminary natural channel design; phase VII, design stabilization and enhancement structures; phase VIII, finalize natural channel design; phase IX, implement natural channel design; and phase X, conduct monitoring and maintenance

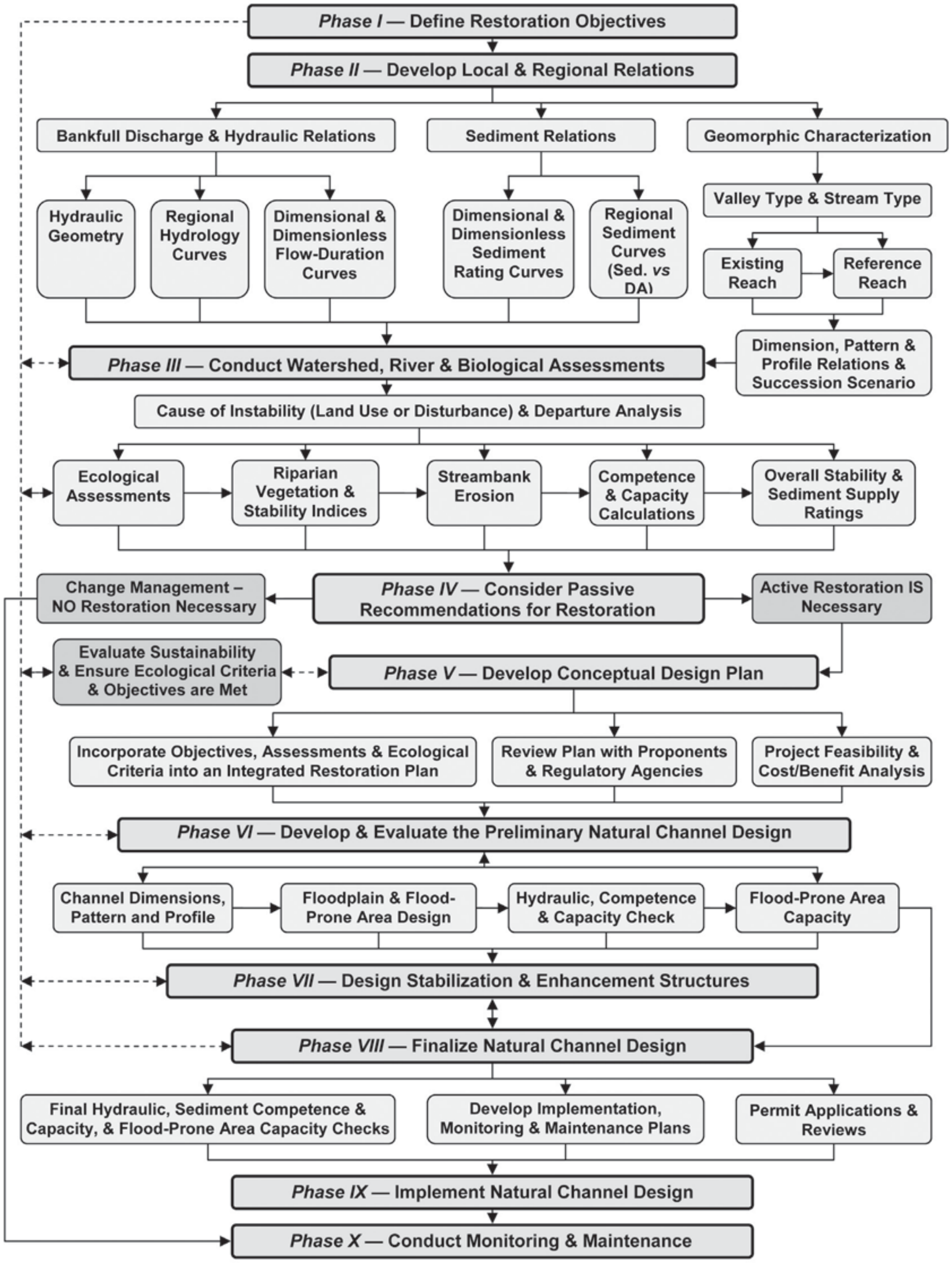

Figure 3. Ten phases in the natural channel design (NCD) approach to river restoration.

1. Phase I defines specific restoration objectives associated with physical, biological, and chemical processes. The restoration objectives must be stated clearly and concisely to appropriately design the solutions. It is essential to fully describe and understand all objectives, which also must be achievable and measureable. The goals or objectives of a river restoration design are often driven by an observed or perceived change over time resulting from impairment of uses and values. Common goals and objectives include enhancing water quality, managing riparian zones, improving in-stream habitat, allowing for fish passage, and stabilizing stream banks [*Bernhardt et al.*, 2005]. Creating terrestrial and off-channel aquatic habitats for mammals, birds, amphibians, and beaver; reducing flood levels, sediment supply, land loss, and attached nutrients; improving aesthetics (both visual and sound), recreational opportunities (e.g., trails, picnicking, camping, boating, fishing, and hunting), and wetlands; and allowing for self-maintenance and cost-effectiveness are also common objectives.

2. Phase II develops regional and localized specific information on the geomorphic characterization, sedimentology, hydrology, and hydraulics. Field data for the existing and reference reaches are collected and analyzed to define sedimentological, hydraulic, and morphological parameters in addition to biological and ecological studies, water quality data, and the riparian plant community. Phase II establishes the fundamental relations to determine the bankfull discharge and sediment supply (both bed load and suspended sediment) of the watershed and the reach in question.

Stream classification and valley type are also determined for the existing and reference reaches. The stable form and corresponding stream type from stream succession data must be determined for the existing reach to assist in selecting the correct reference reach to establish dimensionless relations of dimension, pattern, and profile data. Additionally, the recognition and matching of similar controlling variables and boundary conditions of the reference reach stream type and valley type with the impaired riparian ecosystem is crucial at this phase. Testing and evaluating the stability of the reference reach is conducted in phase III.

3. Phase III includes the watershed, river, and biological assessments to identify and understand causes of impairment and the nature, magnitude, direction, duration, and consequences of change. A cumulative watershed assessment is implemented utilizing the procedures given by *Rosgen* [2006b]. The relations among hillslope, hydrology, and channel processes are evaluated by location, land use, and erosional or depositional processes to help ascertain river impairment. The land use history and time trend analysis of river change are studied to provide insight into the cause of change. The morphological changes resulting in geomorphic thresholds that change stream types are documented.

The primary causes of instability or loss of physical and biological function must also be isolated and understood. Concurrent biological data (analysis of limiting factors) is obtained on a parallel track with the physical data. Ecological assessments compared to the potential state within the riparian ecosystem are necessary to establish criteria to integrate into the physical system for an appropriate assessment and design. Without such assessments and established criteria, the "vision" of ecological restoration objectives could be missed. The river and biological assessments are also conducted on the reference reach to ensure stability and to understand the physical and biological departure of the existing condition from the stable form.

4. Phase IV considers passive recommendations based on land use change in lieu of mechanical restoration. The causes of impairment should be understood from the assessment in phase III, and a passive restoration can be effective by influencing the drivers of the instability in a direction toward self-recovery. For example, riparian vegetation alterations of the boundary conditions can be reversed by better riparian management under high recovery potential. Changes in grazing strategy, land clearing, riparian management zone changes, flow regime changes from reservoirs or diversions, and changes in sediment budgets may be considered to initiate natural recovery of impaired rivers. If passive methods are reasonable to meet objectives, the procedure advances to the monitoring phase (phase X); otherwise, it is necessary to proceed with the subsequent phases in NCD for active restoration.

5. Phase V incorporates the objectives, assessments, and physical and ecological criteria into a resource-integrated conceptual natural channel design. The conceptual plan must address the multiple objectives and strive to meet the specific criteria identified in the assessments. True ecological restoration can only be accomplished if the conceptual design incorporates the limiting factors and critical criteria previously established in both phases I and III. The conceptual design provides a preliminary opportunity to properly integrate ecological criteria rather than "after the fact" add-ons. The conceptual design, however, must also be physically compatible with the fundamental central tendencies of the stable river form.

Project feasibility including physical and economic analyses are also conducted and discussed with the restoration sponsors in this phase. Following the sponsor review, the conceptual design is reviewed in the field with the regulatory agencies to share information, investigate various alternatives, and conduct an initial environmental evaluation. This provides the opportunity to include regulatory personnel at these early stages to investigate problem solving, resource enhancement, and how to direct mitigation to offset adverse effects.

6. Phase VI quantitatively develops and evaluates the preliminary natural channel design. The dimension, pattern, and profile variables of the proposed design reach are established and evaluated with subsequent analytical testing of hydraulic and sediment transport relations (competence and capacity). Also the floodplain and/or flood-prone area are designed and evaluated for flood discharge capacity along with the diversity, appropriateness, and compatibility of the proposed riparian habitats. The variability in natural rivers is incorporated into the design derived from the range of channel form features of the reference reach; this allows for an array of possible design solutions that incorporate multiple goals rather than a single, uniform design.

The multiple objectives are also reviewed and evaluated again in this phase for compatibility of both physical and ecological criteria. Water rights issues, diversions, habitat diversity (such as side channels, oxbow systems, rearing habitats, and wetlands), riparian plant assemblages (planned understory, midstory, and overstory composition and density), and specific aquatic and terrestrial habitats are tested against desired outcomes within existing or perceived physical, economic, and sociological constraints. Review of the preliminary design by professionals representing multiple disciplines and the restoration sponsors will help formulate and modify a potentially feasible, compatible, and sustainable design.

7. Phase VII incorporates stabilization and enhancement structures. River structures are designed to meet specific project requirements, such as energy dissipation, grade control, and lateral stability to buy time to establish the riparian plant community. A diversity of structures is required for fish habitat enhancement, recreational boating features, irrigation diversion structures, and specific habitat features. Common materials used in NCD structures include logs, root wads, woody debris, native boulders, and riparian vegetation, such as vegetation transplants and sod mats.

8. Phase VIII revises any preliminary design specifications following detailed computations (including final hydraulic, sediment competence and capacity, and flood-prone area capacity checks) and reviews by the planning team, sponsors, and regulatory agencies to finalize the natural channel design. Implementation, monitoring, and maintenance plans are also developed in this phase along with reviewing and incorporating regional requirements and submitting the necessary permit applications. Submitted plans for final review and approval should include the results of the previous phases including the watershed and ecological assessment tasks.

9. Phase IX is the implementation phase. The proposed design and stabilization measures are described and constructed. These measures involve contracting criteria, design layout, water quality control, field supervision, field methods, appropriate equipment recommendations, and construction staging.

10. Phase X is the final phase incorporating monitoring and maintenance. Implementation, validation, and effectiveness monitoring are required to evaluate project success. "Implementation monitoring" documents how well the design is actually constructed. "As-built" monitoring is often required to help ensure proper implementation and provide timely corrections for deficiencies identified during daily construction inspections. "Validation monitoring" evaluates the predicted versus observed system response related to river stability (e.g., lateral and vertical stability, channel enlargement, and lateral migration or bank erosion rates) where the prediction models are compared to observed response. "Effectiveness monitoring" evaluates the nature and extent of restoration response to meet stated objectives. The physical, biological, and chemical responses of the restoration, including terrestrial and aquatic habitat responses, are evaluated. Success criteria are documented to test and compare with postrestoration data. The acceptable post runoff departure from the "as built" data is based on the natural variability of the same parameters from the reference reach relations reflected in the ranges utilized in the design.

A maintenance plan is also implemented with established criteria that document when the nature and extent of change requires maintenance; reentry following restoration is recommended only if the morphological variables depart from the natural variability of the reference reach (stable river) used for design.

3.5. The Stream Classification System

An integral part of the NCD methodology involves the use of a stream classification system, which serves as the foundation of the assessment and design procedures. Due to the great variability in the fluvial landscape, various valley and stream types occur and represent a diverse range of morphologies. Their character and behavior is the result of past and present changes in the watershed: some are geologic or natural and some anthropogenic. Not all stream systems respond similarly to imposed change nor offer consistent interpretations. As a result, it becomes imperative that the various fluvial forms that represent river and valley types are described.

Because of the great diversity of morphological features among rivers, a stream classification system was developed to stratify and describe various river types [*Rosgen*, 1994, 1996]. The nature and range of the dependent form variables of river channels were delineated to help describe the variety of morphological stream types that do occur in nature. These types were not determined arbitrarily but rather were organized by measured data representing hundreds of rivers between 1969 and 1994 [*Rosgen*, 1994, 1996]. Resultant stream types are a reflection of mutually adjusting variables that describe their unique sedimentological, hydraulic, morphological, and biological characteristics. "The classification is based on parameters of form and pattern but has the advantage of implying channel behavior [*Leopold*, 1994, p. 20]."

Stream classification is based primarily on the measured bankfull stage morphology of the river because it is the bankfull stage that is responsible for shaping and maintaining the channel dimensions over time. Channel widths and other dimensions of alluvial river systems are more consistent with the more frequent, but lower magnitude (bankfull) discharge [*Wolman and Miller*, 1960; *Leopold*, 1994; *Rosgen*, 1994]. The bankfull discharge is also responsible for the long-term cumulative sediment transport, which also influences the channel boundary [*Wolman and Miller*, 1960; *Dunne and Leopold*, 1978]. However, rather than using the measured values of dimension, pattern, and profile to define a stream type, the classification system is based on dimensionless morphological parameters required for scaling purposes (Table 1). Study streams are seldom located immediately upstream or downstream of reference stream types; thus, scaling of the morphological relations is necessary.

Specific objectives of the stream classification system [*Rosgen*, 1994, 1996, 2003] are to (1) predict a river's behavior from its morphological appearance based on documentation of similar response from similar types for imposed conditions; (2) stratify empirical hydraulic, sedimentological, and biological relations by stream type by state (condition) to minimize variance; (3) provide a mechanism to extrapolate site-specific morphological data; (4) describe physical stream relations to complement biological and riparian ecosystem inventories and assist in establishing potential and departure states; and (5) provide a consistent, reproducible frame of reference for communicating stream morphology and condition among a variety of professional disciplines.

The stream classification system consists of a hierarchical assessment of channel morphology that includes four levels of assessment [*Rosgen*, 1994, 1996]. The four levels provide the physical, hydrologic, sedimentological, and geomorphic context for linking the driving forces and response variables at all scales of inquiry. The detail required at each level of assessment varies with the degree of resolution necessary to achieve the specific objectives previously stated.

Level I of the hierarchical assessment is the geomorphic characterization where streams are classified at a broad level on the basis of valley landforms and observable channel dimensions. Eight major morphological stream types can be identified (A, B, C, D, DA, E, F, and G) using five initial definitive criteria: channel pattern (multiple-thread versus single-thread channels), entrenchment ratio, width/depth ratio, sinuosity, and slope (Table 1) [*Rosgen*, 1994, 1996]. "Entrenchment ratio" is a measure of vertical containment described as the ratio of the flood-prone area width to bankfull width. The flood-prone area width is obtained at an elevation at two times the maximum bankfull depth. If the entrenchment ratio is less than 1.4 (±0.2 to allow for the continuum of channel form), the stream is classified as entrenched or vertically contained (A, G, and F stream types) (Table 1). If the entrenchment ratio is between 1.4 and 2.2, (+ or −0.2), the stream is moderately entrenched (B stream types). If the ratio is greater than 2.2, the stream is not entrenched (C, E, and DA stream types). Additionally, some stream types are associated with valley types that have well-developed floodplains (C, D, E, and DA stream types), while other stream types are associated with valley types with no floodplains (A, B, certain D, G, and F stream types). Table 1 describes the additional criteria (channel pattern, width/depth ratio, sinuosity, and slope) for each major stream type.

Because stream morphology is invariably fixed to the landscape position, prior to the broad-level stream classification, level I also identifies valley types that integrate structural controls, fluvial process, depositional history, climate, and broad life zones. Valley types are stratified into 11 broad geologic categories that reflect their origin and represent the independent boundary conditions that influence channel morphology [*Rosgen*, 1994, 1996]. Table 2 summarizes the valley types and their associated characteristics, separated by historic erosional or depositional processes, and corresponding differences in valley slope, channel materials, and width. Valley types and related landforms are the initial stratification of stream types (Table 2). For example, highly dissected fluvial slopes (valley type VII) are indicative of steep, narrow, deeply incised, erosional A and G stream types. Narrow, low-gradient streams in confined canyons and deep gorges (valley type IV) are characteristic of the entrenched F stream types.

In addition to valley types, stream types must also be stratified by the driving process variables of flow and sediment regime to help minimize the variance of the integrated form variables. For example, stable C4 stream types (gravel-dominated C type) in terraced alluvial fill valleys (valley type VIII) with river widths between 3 and 15 m characteristically average width/depth ratios between 12 and 14. However, the width/depth ratios average between 18 and 24 for C4 stream types in U-shaped, glacial trough valleys (valley type V). The width/depth ratios for the C4 stream type in valley type V are larger because of higher ratios of bed load to total sediment

Table 1. General Stream Type Descriptions and Definitive Criteria for Broad-Level Classification[a]

Stream Type	General Description	Entrenchment Ratio	*W*/*d* Ratio	Sinuosity	Slope	Landform/Soils/Features
Aa+	Very steep, deeply entrenched, debris transport, torrent streams.	<1.4	<12	1.0 to 1.1	>0.10	Very high relief. Erosional, bedrock, or depositional features; debris flow potential. Deeply entrenched streams. Vertical steps with deep scour pools; waterfalls.
A	Steep, entrenched, cascading, step/pool streams. High energy/debris transport associated with depositional soils. Very stable if bedrock- or boulder-dominated channel.	<1.4	<12	1.0 to 1.2	0.04 to 0.10	High relief. Erosional or depositional and bedrock forms. Entrenched and confined streams with cascading reaches. Frequently spaced, deep pools in associated step/pool bed morphology.
B	Moderately entrenched, moderate gradient, riffle-dominated channel, with infrequently spaced pools. Very stable plan and profile. Stable banks.	1.4 to 2.2	>12	>1.2	0.02 to 0.039	Moderate relief, colluvial deposition and/or structural. Moderate entrenchment and width/depth ratio. Narrow, gently sloping valleys. Rapids predominate with scour pools.
C	Low gradient, meandering, point bar, riffle/pool, alluvial channels with broad, well-defined floodplains.	>2.2	>12	>1.2	<0.02	Broad valleys with terraces in association with floodplains, alluvial soils. Slightly entrenched with well-defined meandering channels. Riffle/pool bed morphology.
D	Braided channel with longitudinal and transverse bars. Very wide channel with eroding banks.	NA	>40	NA	<0.04	Broad valleys with alluvium, steeper fans. Glacial debris and depositional features. Active lateral adjustment with abundance of sediment supply. Convergence/divergence of bed features, aggradational processes, high bed load and bank erosion.
DA	Anastomosing (multiple channels) narrow and deep with extensive, well-vegetated floodplains and associated wetlands. Very gentle relief with highly variable sinuosities and width/depth ratios. Very stable stream banks.	>2.2	highly variable	highly variable	<0.005	Broad, low-gradient valleys with fine alluvium and/or lacustrine soils. Anastomosed (multiple channel) geologic control creating fine deposition with well-vegetated bars that are laterally stable with broad wetland floodplains. Very low bed load, high wash load sediment.
E	Low gradient, meandering riffle/pool stream with low width/depth ratio and little deposition. Very efficient and stable. High meander width ratio.	>2.2	<12	>1.5	<0.02	Broad valley/meadows. Alluvial materials with floodplains. Highly sinuous with stable, well-vegetated banks. Riffle/pool morphology with very low width/depth ratios.
F	Entrenched meandering riffle/pool channel on low gradients with high width/depth ratio.	<1.4	>12	>1.2	<0.02	Entrenched in highly weathered material. Gentle gradients with a high width/depth ratio. Meandering, laterally unstable with high bank erosion rates. Riffle/pool morphology.
G	Entrenched "gully" step/pool and low width/depth ratio on moderate gradients.	<1.4	<12	>1.2	<0.039	Gullies, step/pool morphology with moderate slopes and low width/depth ratio. Narrow valleys or deeply incised in alluvial or colluvial materials, i.e., fans or deltas. Unstable, with grade control problems and high bank erosion rates.

[a]See *Rosgen* [1994, 1996, 2006b] for more information. From *Rosgen* [2006b].

Table 2. Valley Types Used in the Geomorphic Characterization and Their Associated Stream Types[a]

Valley Types	Summary Description of Valley Types	Stream Types
I	Steep, confined, V-notched canyons, rejuvenated side slopes	Aa+, A, G
II	Moderately steep, gentle-sloping side slopes often in colluvial valleys	B, G
III	Alluvial fans and debris cones	A, B, F, G, D
IV	Canyons, gorges, and confined alluvial and bedrock-controlled valleys with gentle valley slopes	C, F
V	Moderately steep, U-shaped glacial-trough valleys	C, D, F, G
VI	Moderately steep, fault-, joint-, or bedrock-controlled valleys	Aa+, A, B, C, F, G
VII	Steep, fluvial dissected, high-drainage density alluvial slopes	Aa+, A, G
VIII	Alluvial valley fills either narrow or wide with moderate to gentle valley slope with well-developed floodplain adjacent to river, and river terraces, glacial terraces, or colluvial slopes adjacent to the alluvial valley	C, D, E, F, G
IX	Broad, moderate to gentle slopes associated with glacial outwash or Eolian sand dunes	C, D, F
X	Very broad and gentle valley slopes associated with glacio- and nonglaciolacustrine deposits	C, DA, D, E, F, G
XI	Deltas	C, D, DA, E

[a]See *Rosgen* [1996, 2006b] for more information. From *Rosgen* [2006b].

load, steeper valley slopes than the valley type VIII, higher sediment supply, and unconsolidated, noncohesive bank material. Pattern and profile variables also differ, such as sinuosity (greater in valley type VIII) and radius of curvature (larger in valley type V). Regardless of valley type, these are still C stream types with meanders, riffle/pool bed features on slopes less than 0.02 with floodplain connectivity. When developing "reference reach" relations, it is essential to stratify stream types by valley type and the corresponding flow and sediment regimes [*Rosgen*, 1998, 2006b, 2007].

Level II is the morphological description that classifies stream types within certain valley types using field measurements of the same criteria necessary for the broad-level classification from specific channel reaches and fluvial features [*Rosgen*, 1994, 1996]. In addition, the initial stream type is further subdivided by its dominant channel material size: 1, bedrock; 2, boulder; 3, cobble; 4, gravel; 5, sand; and 6, silt/clay. In total, 41 primary stream types exist. Subcategories of slope are also utilized along a slope continuum where the combined morphological variables are consistent for a stream type. However, for a particular stream reach that is steeper or flatter than the normal range of that type, a small letter subcategory is used to best reflect actual variables [*Rosgen*, 1994, p. 181]: a+ (steeper than 0.10), a (0.04–0.10; slopes typical of A stream types), b (0.02–0.04; slopes typical of B stream types), c (0.001–0.02; slopes typical of C stream types), and c− (less than 0.001).

The various categories and threshold ranges were obtained from field data representing over 800 rivers using frequency distributions from each major stream type grouping to establish the interrelations of morphological data. The parameter ranges are described by the frequency distributions summarized by *Rosgen* [1996, chapter 5]. In addition, Rosgen also describes the process-integration and interrelated morphologic, hydraulic, and sedimentological characteristics of each primary stream type.

Due to the continuum of channel form and shifts in stream types along river reaches, the definitive criteria values can depart from the typical ranges for a given stream type. These instances are indicative of (1) a transition between stream types and valley types that occurs when changing from an upstream reach into a downstream reach (spatial variability), (2) a shift in stability or condition influenced by variables described in level III (temporal variability), and/or (3) an equilibrium threshold shift trending toward a new stream type (temporal and spatial variability). In these instances, the variables that best represent the dominant morphological type must be determined.

Level III assesses stream condition to predict river stability (e.g., aggradation, degradation, sediment supply, stream bank erosion, and channel enlargement). The stream classification system was developed with an understanding that a stability evaluation must be conducted at a higher degree of resolution (level III assessment) than morphological groupings (level II). Channel stability assessments, however, must be stratified by stream type and valley type for extrapolation purposes. Additional form variables are identified by stream type and their definitive criteria to determine a state or condition. Various processes and stream channel response to imposed changes in the controlling variables can then be inferred using time trend aerial photo analysis and detailed field measurements [*Rosgen*, 1994, 1996, 2006b]. Variables assessed and introduced in this level include bank-height ratio (a measure of degree of channel incision determined as the lowest bank height divided by the bankfull maximum depth), meander width ratio (lateral containment or confinement measured by channel belt width divided by bankfull width), shear stress, shear velocity, and total stream power. Prediction of stream bank erosion (BANCS model

[*Rosgen*, 1996, 2001a, 2006b]), hydraulic analysis [*Rosgen*, 1996, 2006b], sediment competence and transport capacity [*Rosgen*, 2006a, 2006b], and quantitative indices for river stability are also collected at this level [*Rosgen*, 1996, 2001b, 2006b].

Critical, but often difficult, in the stability assessments and interpretations is an understanding of what constitutes a natural process versus an acceleration of a natural process as streams can be stable, yet dynamic. It is essential to distinguish if the methods used in the river stability assessment predict the differences between natural, stable rates versus accelerated rates that may exceed a geomorphic threshold. The assessment phase in NCD requires a departure analysis of the existing reach from the reference reach condition to assist with these interpretations. Without such stability assessments for the reference and existing reaches, it is often difficult to understand the cause and consequence of change related to certain land uses that are the agents of disequilibrium.

Level IV is conducted to validate process-based assessments of stream condition, potential, and stability as predicted from levels I–III. Prediction of river system process is complex and uncertain; thus, validation of the procedure is essential, since restoration designs are based upon such predictions. Validation procedures include annual dimension, pattern, profile, and material resurveys; annual stream bank erosion studies; sediment competence validation; hydraulic relations using gauging stations or current meter measurements; and direct measurements of bed load and suspended sediment for the accurate estimate of sediment transport capacity. After reach conditions are verified, the validation data are used to establish empirical relationships for testing, validating, and improving the prediction methods. In fact, the basic foundation of the stream classification system was developed from the author's level IV field data collected over many years that were used to develop the prediction methodologies and for the interpretation and extrapolation of the basic relations. The field data involve sediment transport, stream bank erosion rates, hydraulics, and corresponding changes in the channel form variables, all of which are time-consuming and expensive to collect. It is necessary to validate the procedures for both the existing and reference reaches. In this manner, it is possible to measure natural stream bank erosion rates and to obtain a wide range of natural variability of the dimensions, pattern, and profile to determine acceptable rates and tolerances.

Levels III and IV of the stream classification system are often overlooked in the published literature when discussing how stream classification can be used to infer process and how it applies to river restoration [e.g., *Miller and Ritter*, 1996; *Simon et al.*, 2007; *Juracek and Fitzpatrick*, 2003]. The importance of conducting a watershed and river stability assessment should not be underestimated. Level III is performed specifically to assess the processes occurring in river systems, and the process predictions are followed by validation procedures in level IV. The following stream succession scenarios are used as part of the level III analysis to infer channel succession over time and space using historical evidence and current geomorphic conditions to predict future response.

3.6. Stream Channel Succession

Predicting a river's behavioral response to geologic and anthropogenic disturbances is necessary for those working with river systems. The observations of the past and an understanding of form and process interactions create the basis to predict future channel response and erosional or depositional processes associated with similar impacts. It is paramount to first look back in time using time trend aerial photographs, historic records, dendrochronology, paleochannel analysis, carbon dating, and other methods to understand channel change over time and space. Parallel with such analysis is an understanding of the change in the controlling process variables that influence river morphology.

Rivers do not always change instantaneously under a geomorphic exceedance or "threshold." Rather, they undergo a series of channel adjustments over time to accommodate change in the driving variables. Their dimensions, pattern, and profile reflect on these adjustment processes that are presently responsible for the form of the river. The nature, rate, and direction of channel adjustments are unique to the stream type involved. Some streams change very rapidly, while others are slow in their response [*Rosgen*, 1994, 1996].

Understanding the central tendency and the characteristics of the stable form and the processes of river adjustment that shape the landscapes and river systems over time lends the observer an insight into the processes of the past. These processes can then be projected to interpret future conditions under similar boundary conditions or driving variables. Furthermore, landforms and rivers equilibriate with different endpoint features of their morphology due to the variation in the erosional or depositional processes under a wide spectrum and great variation of the independent variables. Due to changes in the driving variables and boundary conditions, not every stream returns to its original or predisturbance form.

Stream succession is a central element to predict a river's behavior from its morphological characteristics, which are directly related to the stream type's corresponding hydraulic and sedimentological relations. Stream channel succession is the result of adverse consequences of excess sediment supply;

accelerated bank erosion rates; degradation, aggradation, and channel enlargement from channel disturbance; streamflow changes; and/or sediment budget changes that lead to channel change. These changes result in stability shifts and adjustments leading to channel morphological changes and eventual stream type changes over time. Classification of stream type [*Rosgen*, 1994, 1996] is used to establish the links between channel process, form, and stability [*Thorne*, 1997]. It is essential that the field observer ascertain the cause, direction, and trend of river change as well as the stable equilibrium form in NCD.

Twelve various scenarios are illustrated in Figure 4 representing successional scenarios of stream type shifts, each representing various sequences from actual rivers. These scenarios represent morphological shifts and their tendencies toward stable endpoints (additional scenarios are possible). Each stage of the individual scenarios is associated with unique relations of morphological, hydrological, sedimentological, and biological functions. Adverse adjustments due to disequilibrium can result in accelerated sediment yields, loss of land, lowering of the water table, decreased land productivity, loss of aquatic habitat, and diminished recreational and visual values.

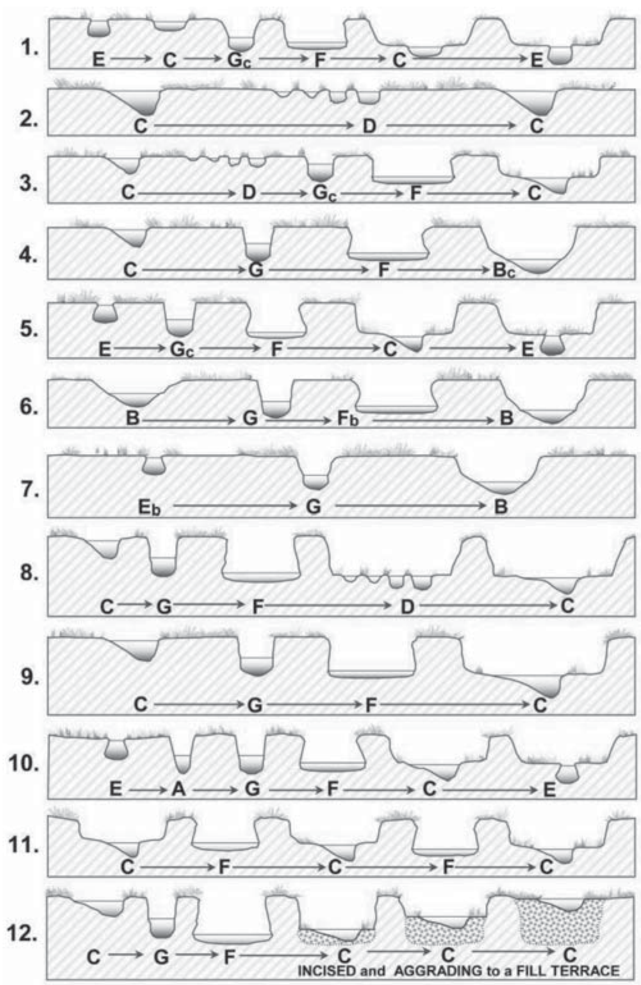

Figure 4. Various stream succession scenarios of stream type shifts over time (for letter codes see Table 1). Note that these various scenarios represent actual rivers (i.e., they are not hypothetical) and do not represent the only possible scenarios. Adapted from *Rosgen* [1999, 2001b, 2006b, 2007].

The "existing reach" in NCD is often associated with a stream type that is not stable or is in disequilibrium. Referring to Figure 4, these stream types represent the intermediate or transitional stages of each succession scenario. The following must be determined for the existing reach: (1) the appropriate morphological scenario (scenarios 1–12 in Figure 4), (2) within a scenario, the current successional stage of the existing stream type, (3) the various stages leading up to a succession endpoint, (4) the series of natural changes that occur prior to reaching stability, and (5) the potential stable form of the channel type. Selecting the appropriate stream succession scenario and sequence is aided by time trend aerial photography, dendrochronology, paleochannel evaluation, and other historical evidence. The potential stream type of the existing reach is an important criterion necessary to select the appropriate reference reach.

Restoration direction is aided by understanding the present successional stage within a specific scenario and the starting and endpoints. In some cases, restoration involves returning the stream to its predisturbance state on previously abandoned surfaces (priority IV [*Rosgen*, 1997]). Knowing the direction and rate of change and recovery potential also assists to prescribe management changes for potential passive restoration recommendations. Boundary condition changes from predisturbance, such as channel confinement (lateral containment), for example, promote stream types with low meander width ratios (stream belt width divided by bankfull width) typical of Bc stream types [*Rosgen*, 1996].

3.7. The Reference Reach and Proposed Design Reach

The reference reach selection is a critical step in NCD. The reference reach must be stratified based on identified geomorphic characteristics, boundary conditions, and driving variables of the existing and proposed design reaches (Figure 5). A reference reach is required for each identified existing reach that has a different valley type or potential stream type. As stated previously, a geomorphic characterization is then completed for the reference reach followed by an assessment to ensure stability and to determine the departure of the existing stream stability from the reference reach

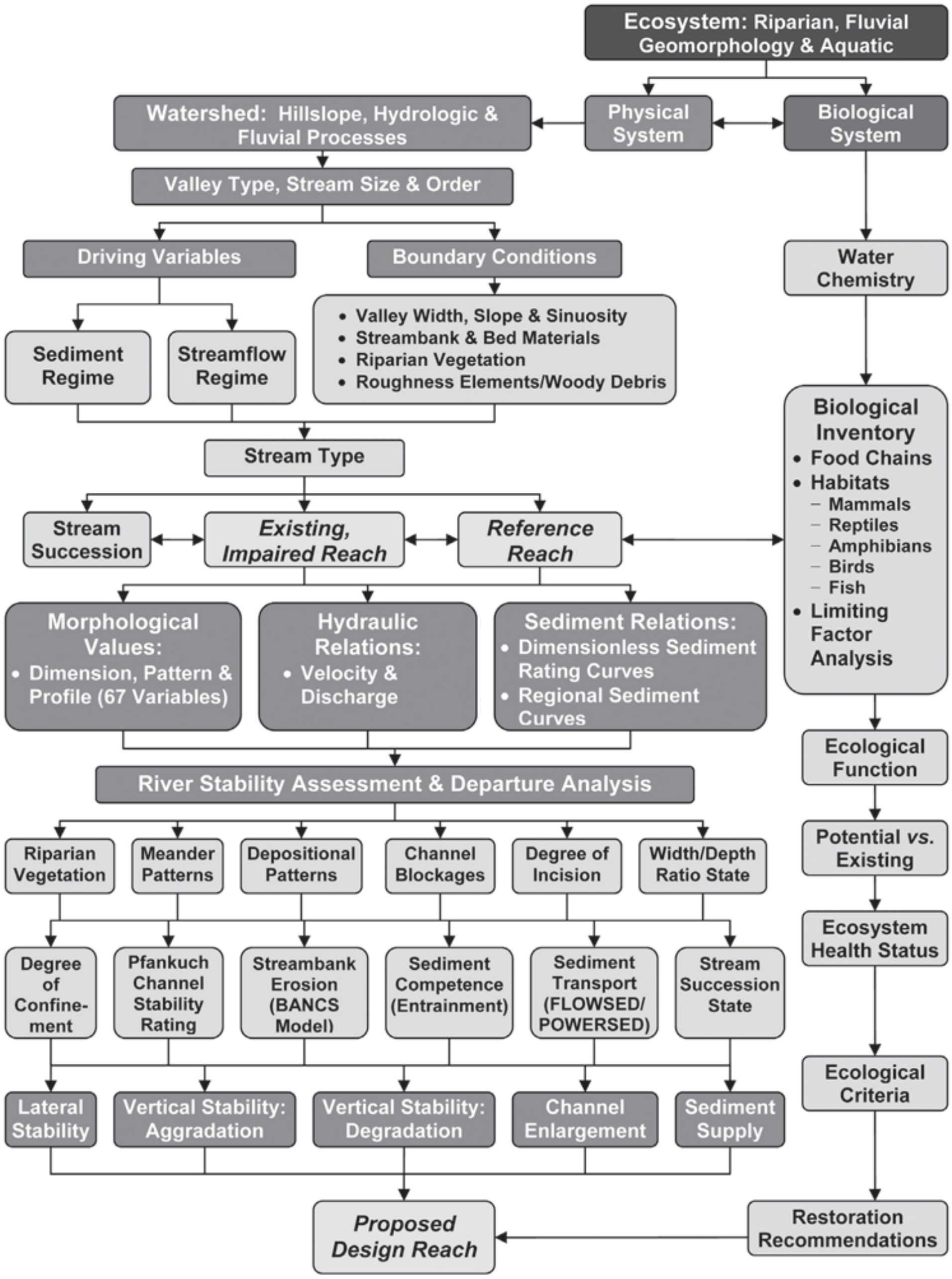

Figure 5. Watershed variables integrated into the development of physical and biological relations in NCD.

condition. Table 3 lists the major criteria to select a reference reach that must match or be similar to the proposed design reach. This table also identifies the range of variability and scaling criteria for extrapolation purposes. Table 4 is a priority list of reference reach selection scenarios in relation to the proposed design reach.

The “proposed design reach” enters the NCD methodology after the existing and reference reaches have been identified, the geomorphic characterization conducted, and the watershed, river, and biological assessments are completed (phases II and III) (Figure 5). If passive recommendations (phase IV) are insufficient to address the cause of impairment and active restoration is necessary, a conceptual channel design is developed (phase V) to emulate a natural stable channel for the proposed design reach followed by the preliminary natural channel design (phase VI) with the proposed

Table 3. Reference Reach Selection Criteria

Reference Reach Selection Criteria	Relation to Proposed Design Reach
Valley type	same
Stream type	same
Scaling (bankfull width)	within one order of magnitude for bankfull widths less than 50 ft within one-half order of magnitude for bankfull widths greater than 50 ft
Stream order	within one stream order
Boundary conditions	similar
Valley slope	
Valley sinuosity	
Valley width of flood-prone area	
Stream bank and bed material	
Riparian vegetation	
Driving variables	similar
Sediment regime and sediment sizes	
Flow regime	

dimension, pattern, profile, and floodplain/flood-prone area relations. A proposed design reach is required for each existing reach identified. The procedures must be completed for each proposed design reach utilizing the appropriate reference reach data. The required restoration variables for the existing, reference, and proposed design reaches are organized and recorded in an extensive multipage master table [*Rosgen*, 2007].

While designing the physical variables of the proposed design reach, the concurrent integration of the physical and biological components is necessary to help meet the design objectives and work toward sustainability. Figure 5 illustrates the integration of the biological and ecological objectives and functions into the natural channel design, which is not solely limited to stream channels. Floodplains, terraces, riparian community types, wetlands, oxbow channels, and off-channel ponds are all part of river systems and are important to restoring the physical, chemical, and biological functions. Ecology includes the organism and its associated habitats; thus, physical alterations of river systems are essential habitat components for various species, age classes, and functions. Changes to habitats should be designed with an understanding of the benefits from specific criteria that create the needed conditions to offset the limiting factors. Overall, the ecosystem complexity and diversity must satisfy site- and community-specific objectives involving the interactions between animal and plant communities for mammals, reptiles, amphibians, birds, and fish. To accomplish these ecological objectives, a multidisciplinary team is required to provide: (1) specific objectives; (2) an assessment of the existing conditions, including limiting factors for specific animal communities, age classes, life stages, and food chains, in relation to their habitats; (3) guidance criteria to the restoration effort; (4) an integration and assessment of conflict resolution due to potential conflicting and competing uses and objectives; (5) evaluation and monitoring criteria; (6) advice on project implementation and critical seasons to reduce conflict with existing and proposed habitats; and (7) reasonable alternatives to accommodate multiple plant and animal communities.

Table 4. Priorities of Reference Reach Locations in Relation to the Proposed Design Reach[a]

Priority	Reference Reach Locations in Relation to Proposed Design Reach
First	immediately upstream (carbon copy)
Second	immediately downstream (carbon copy)
Third	same stream but not immediately upstream or downstream (scale variation)
Fourth	within the same watershed
Fifth	outside of watershed and similar in size and scale
Sixth	outside of watershed and much smaller or larger in size and scale[b]

[a]Assuming similar valley type, stream type, boundary conditions, and driving variables.

[b]Must be tested against a smaller or larger reference condition to determine variability of dimensionless relations.

Ecological restoration is currently seen as a top priority for society and as a good investment [*Aronson et al.*, 2010; *Rey Benayas et al.*, 2009]. However, criteria for ecological restoration are noticeably absent in the published literature and in practice and must be established. Currently, site-, species- and habitat-specific criteria must be developed for each project.

Figure 5 is the culmination of the physical and biological assessments that help identify specific reaches and proposed actions based on the ecological and physical limitations.

4. THE NATURAL CHANNEL DESIGN APPROACH

4.1. NCD Prediction Methodologies

NCD incorporates analog, empirical, and analytical methods for assessment and design (Figure 6) to predict the channel morphology for natural river systems [*Rosgen*, 2007]. There are 67 form variables representing the dimension, pattern, and profile of natural, stable channels required for NCD prediction and implementation. The current analytical, numeric, rational, and empirical models used in non-

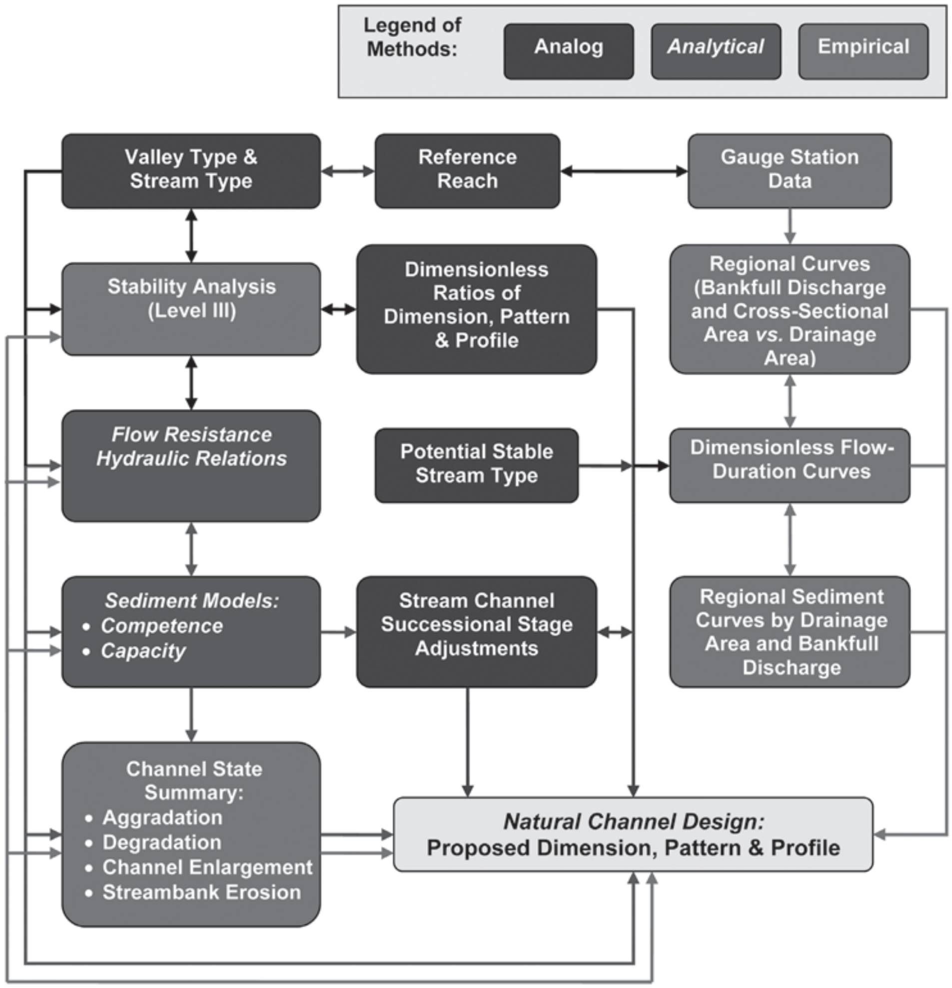

Figure 6. Generalized NCD flowchart utilizing analog, analytical, and empirical approaches [*Rosgen*, 2007].

NCD approaches to river restoration cannot provide this required output. For example, there are no known analytical or process-based models that predict the depth and slope of runs and glides, point bar slopes, meander geometry, and other features of riffle/pool, meandering stream types. To design and construct such features, form-based calculations using analog methods from reference reach data by stream type and valley type, and integrated by the driving variables and boundary conditions, have proven to be an appropriate method to consistently provide the morphology of the restored river [*Hey*, 2006; *Kondolf and Downs*, 1996].

Soar and Thorne [2001, p. 112] discuss that the analog approach "is preferred over more analytical methods based on the application of sediment transport equations which often yield significant errors in estimates of the design discharge and supply load that could affect the design specification." As so many unknown variables are involved to describe the channel configuration, "the river is the best model of itself" [*Shields*, 1996, p. 26] and "is ultimately the best channel restoration designer" [*Soar and Thorne*, 2001, p. 49]. Reference reaches can also serve to estimate attainable conditions, to evaluate temporal and spatial changes in ecological integrity, to classify attainable uses of streams, and to set biological and environmental criteria [*Hughes et al.*, 1986].

The empirical approach in NCD uses equations associated with various similar basins and channel boundary characteristics derived from regionalized or universal data. Empirical relations are used in the hydraulic and sedimentological evaluations for the existing, reference, and proposed design reaches [*Rosgen*, 2007]. Empirical relations for relative roughness and friction factor relations are used for velocity prediction [*Rosgen*, 2006b, 2007]. Tractive force relations including dimensional and dimensionless shear stress relations for particle entrainment and sediment competence calculations are used as well as dimensionless sediment rating curves for both suspended sediment and bed load [*Rosgen*, 1998, 2006b, 2007]. Empirical relations are also developed for regional bankfull discharge and cross-sectional area versus drainage area by hydrophysiographic provinces [*Rosgen*, 2006b, 2007]; these values are validated using the velocity calculations and requirements. Regional bankfull suspended and bed load sediment relations by dominant geologic type and river stability versus drainage area or bankfull discharge are also useful [*Rosgen*, 2010].

The analytical approach makes use of hydraulic and sediment transport models to derive relations for the existing and proposed stability conditions. The POWERSED model utilizes flow resistance, unit stream power, and sediment transport relations by flow stage to simulate sediment transport capacity computations for various dimension, pattern, and profile relations [*Rosgen*, 2006a, 2006b, 2007]. This model is run on the existing, reference, and proposed design reaches. The FLOWSED and POWERSED models are programmed and available in the RIVERMorph™ software program. Validation and applications of these models in restoration and engineering are described by *Rosgen* [2006a, 2010] and *Athanasakes and Rosgen* [2010].

4.2. The Multistage Channel Design for Specified Streamflows

NCD incorporates a multistage channel design as displayed in natural rivers to accommodate a wide range of streamflows, including base flow and bankfull discharge, and the floods are designed at a stage above the stream channel in floodplains and flood-prone areas to accommodate the frequent and the infrequent or rare floods. Rather than overwiden the active channel to accommodate flood flows, NCD generally designs toward the minimum width/depth ratio values of the active bankfull channel. However, the floodplain and flood-prone area features are commonly overwidened to accommodate the large floods. Setback terraces outside of the floodplain can be used to protect certain critical areas from flooding while providing river system function. Such stream restoration involving interconnection of stream channels and floodplains add to ecological function and species richness [*Paillex et al.*, 2009].

The multistage channel provides the alternative of design complexity under a changing flow regime, typical of expanding urban development, operational hydrology of reservoirs and diversions, and climate change. The multistage channel also allows for the greatest diversity and complexity of both aquatic and terrestrial habitats and appropriate riparian systems. Extreme flows of both floods and droughts are common and are best accommodated in the multiple-stage scenarios. The wide range of streamflows can be accommodated in four stages (Figure 7) (most common in C stream types (Table 1) in a terraced, alluvial valley type VIII (Table 2)): stage 1, the low-flow or "inner-berm" channel; stage 2, the bankfull stage channel; stage 3, the active floodplain at the incipient point of flooding; and stage 4, the infrequent but highest flood-level stage.

The multistage channel allows for a range of shifts in flows but an option of placing these flows on various levels. This design concept, which is found in natural reference reach systems, is superior to the overwidened, trapezoidal-shaped channel prevalent in many traditional river designs. The advantages of the four-stage channel, as compared to the "one-size-fits-all flows" channel, include the following:

1. Vegetation is established on the banks of stages 2, 3, and 4 (Figure 7) due to favorable soil moisture.

2. Stream bank erosion rates are decreased, and rooting depth and density are increased due to lower bank heights and favorable riparian vegetation conditions at the various benches and flats.

3. Stream bank erosion is also reduced due to reductions in near-bank stress as the flows onto the next highest level are

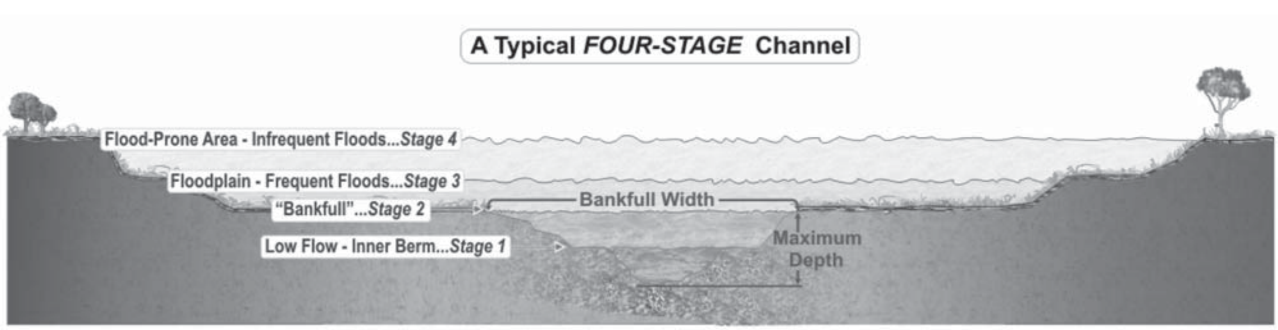

Figure 7. A four-stage channel design typical for a C4 stream type in a valley type VIII.

spread out rather than being vertically and laterally constrained by a greater stream bank height.

4. During drought, the low-flow channel (stage 1) can provide sufficient depth for fish habitat.

5. During high flows, the low-flow channel (stage 1) helps maintain the sediment transport capacity.

6. Increases in the magnitude and frequency of flood peaks due to watershed development or climate changes can be dispersed out of channel and onto a floodplain or flood-prone area.

7. Recreational activities and trails can be created on the floodplain (stage 3) and flood-prone area (stage 4).

8. There is a more natural, visually pleasing river setting.

9. There is a decrease in flood stages for the same magnitude flood due to improved hydraulic and sediment transport efficiency.

10. Habitat is improved, and ecological diversity is increased.

In some situations involving colluvial valley type II (Table 2) or for confined, laterally contained streams in alluvial valleys with meander width ratios (belt width divided by bankfull width) less than 2.0, a flood-prone area exists, which includes the area above the bankfull stage (e.g., B stream types (Table 1) in a colluvial valley type II). Under these conditions, a three-stage channel (Figure 8) exists and is associated with stage 1, the low-flow or "inner-berm" channel; stage 2, the bankfull stage channel; and stage 3, the flood-prone area.

A two-stage channel exists in E stream types (Table 1) in a lacustrine or glaciolacustrine valley type X (Table 2) due to the absence of an inner berm (low flow) channel and a low terrace. The stages involve the bankfull channel and the floodplain/flood-prone area. The two-stage channel is also associated with A stream types in a V-notched valley type I and also with A, B, C, F, and G stream types that are bedrock- or boulder-dominated in a bedrock-controlled valley type VI.

4.3. Channel Dimension, Pattern, and Profile Design

The dimensions and profile of the design channel in traditional river works are often derived from relations developed for clear water discharge, uniform flow, rigid boundary theory, uniform channel materials, and regime relations not stratified by distinct, identifiable river types. Unfortunately, the assumptions are not appropriate for most natural stream channels that are self-formed and self-maintained under much different controlling variables. Hence, traditional river works have typically designed single-thread, "one-size-fits-all flows" in a trapezoidal, flat-bottomed channel [*Soar and Thorne*, 2001]. These channels are often relatively straight and often "hardened" to prevent channel erosion and to increase velocity for major flood stage reduction. Many of these channels have required frequent and expensive dredging as the design did not account for sediment transport capacity. If empirical or regime equations are used to derive channel dimensions (with the understanding of the river types and conditions used to develop the relations), the values should be checked against reference reach data. Accordingly, *Shields* [1996, p. 37] states that "after initial selection of average channel width and depth, designers should consider the compatibility of these dimensions with other factors using guidance provided by *Rosgen* [1994] or their own experience with nearby stable reaches."

In NCD, the cross section involves a multiple-stage channel design as described in the previous section that is required to transport sediment and to provide aquatic habitats and address water quality issues during a range of flows. The design bankfull discharge and the corresponding cross-sectional area are obtained first when developing the proposed channel dimensions by using validated regional curves [*Rosgen*, 2007]. Regional curves of bankfull cross-sectional area versus drainage area generally have an excellent correlation coefficient and low variance making it acceptable to determine the

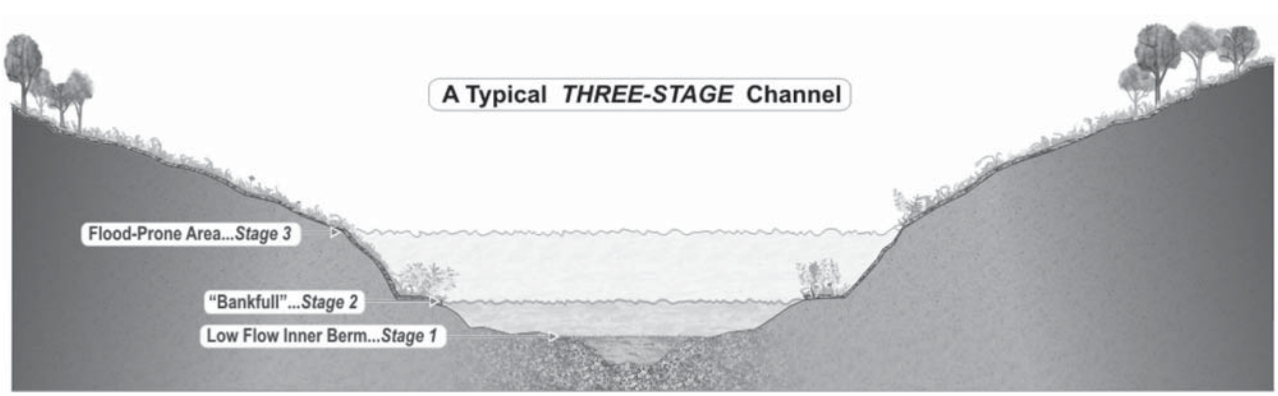

Figure 8. A three-stage channel design typical for B stream types in a colluvial valley type II.

proposed channel's cross-sectional area. However, predicting bankfull width and bankfull depth from regional curves is discouraged due to the consistent higher error term in the relation and because the regional curves are not stratified by stream type (reflecting the variation in width/depth ratio). In scenarios where regional curves are not available or cannot be used (e.g., when project location is below a reservoir), bankfull cross-sectional area can also be calculated from continuity ($A_{bkf} = Q_{bkf} / u_{bkf}$) by knowing bankfull discharge and either knowing or estimating the bankfull mean velocity (u_{bkf}). The bankfull width is then calculated as:

$$W_{bkf} = (A_{bkf} * W/d_{ref})^{1/2},$$

where W_{bkf} = bankfull width, A_{bkf} = bankfull cross-sectional area from regional curves or continuity, W/d_{ref} = bankfull width/depth ratio from the reference reach.

Bankfull mean depth can then be computed by $d_{bkf} = A_{bkf} / W_{bkf}$. Bankfull maximum depth and inner berm channel dimensions are then calculated using dimensionless data from the reference reach and scaled using the bankfull width of the proposed design reach. The mean, minimum, and maximum values for all dimensions must be computed from the ranges specified in the reference reach data. Dimensions are required for all bed features (e.g., riffles, runs, pools, glides, and steps) and also for the floodplain, low terrace, and/or flood-prone areas.

The typical longitudinal profile for NCD involves a range of depths, slopes, and bed feature shapes designed specifically to quantitatively describe bed features. A range of pattern data is also obtained from the dimensionless ratios from a reference reach. Sinuosity is not simply a ratio of valley slope to channel slope but rather is generated from a channel layout incorporating the range of multiple pattern variables that represent natural planform variability, including linear wavelength, stream meander length, belt width, arc length, radius of curvature, riffle length, and pool length ratios. The resulting sinuosity is then determined by dividing the proposed design stream length by the valley length. The meandering pattern determined in NCD (as opposed to straightened, channelized rivers) and the heterogeneity of bed features (e.g., riffles, pools, and glides) are important to dissipate energy and to promote a hyporheic exchange function [*Kasahara and Wondzell*, 2003; *Boulton*, 2007; *Cardenas*, 2009].

The initial channel slope of the proposed design reach is determined by dividing the valley slope by the design sinuosity. This analog method does not rely on an empirical equation but requires compatibility among valley and stream types of the reference reach dimensionless relations and the proposed bankfull width (used as the normalization parameter for pattern). This approach also accounts for any boundary constraints (e.g., terrain and vegetation) within the valley. The final design slope and dimensions are determined following verification of sediment transport capacity and competence.

5. MINIMUM NATURAL CHANNEL DESIGN REQUIREMENTS

Proper implementation of the NCD approach to river restoration must encompass all phases and procedures as outlined in Figure 3. It is also strongly advised that the practitioner be involved in *all* phases. Completing only partial phases or skipping a phase in the NCD method is not an acceptable river restoration practice and will add to the risk of failure and potentially may not meet stated objectives. NCD involves, as a minimum, experience, knowledge, and unique abilities to carry out the following 20 requirements:

1. Be observant and respectful of the complexity of the assignment.
2. Clearly understand and incorporate multiple objectives, including physical, biological, chemical, aesthetic, social, and economical considerations, into restoration designs.
3. Integrate multiple disciplines into the design schemes, including plant science, fisheries, soils, fluvial geomorphology, hydrology, engineering, terrestrial and aquatic biology, and ecology to provide a sustainable design solution that meets the multiple objectives.
4. Seek out ecological criteria and require an analysis of limiting factors for various organisms and their habitats.
5. Obtain and verify the "bankfull discharge" for assessment and design purposes; this includes developing and calibrating regional curves of bankfull discharge versus drainage area. (Note that it is critical that the design discharge not be a flood flow; however, flood flows must be designed and accommodated.) Avoid a "one-size-fits-all flows" and design multistage channels for specific flows including base flow, bankfull, and floods.
6. Identify the driving variables and boundary conditions that influence the channel dimensions, pattern and profile (Figures 1 and 2).
7. Identify the stream succession sequence and the current state of a given river reach (Figure 4) and study and verify the potential, natural stable stream type for the proposed design reach for the given valley type incorporating space for time substitution and recovery potential and direction.
8. Select the appropriate reference reach that meets the controlling variable criteria to establish a range of dimensionless ratios and morphological relations to calculate the

stable dimension, pattern, and profile variables for the natural channel design; do *not* rely on stream structures to create the morphological features over time.

9. Collect and inventory the geomorphic characterization and stream morphology data for the existing and reference reaches.

10. Conduct watershed, river stability, and biological assessments on both the existing reach and reference reach to understand the cause and consequence of past actions that led to river impairment and loss of physical and biological function; this includes time trend assessments, streamflow changes, and erosional or depositional process relations of aggradation, degradation, channel migration, stream bank erosion rates, down-valley channel migration rates, channel enlargement, and sediment supply.

11. Document the exact cause, nature, and extent of the erosional or depositional processes related to instability or disequilibrium (e.g., base-level change due to aggradation, degradation, incision, channel enlargement, accelerated lateral erosion and/or down-valley meander migration).

12. Incorporate hydraulic relations using resistance relations or appropriate prediction methods.

13. Calculate and validate sediment competence and sediment transport capacity for bed load, suspended sand sediment, and total suspended sediment.

14. Maintain consistency for assessment, design, implementation, and monitoring to meet stated objectives, offset the cause of the problems and incorporate the natural variability determined by the reference reach data for layout and the criteria for postrestoration monitoring.

15. Understand the uncertainty of prediction, validate all models, and place controls that document the various process responses from detailed postrestoration monitoring.

16. Recognize the economic and social constraints, prepare reasonable budgets, and present design alternatives to the public and restoration sponsors.

17. Communicate all phases of design to contractors, the public, restoration sponsors, and regulatory personnel.

18. Provide field supervision and training of construction personnel to ensure proper implementation of the design, staging, water quality control, and specification of appropriate equipment and materials needed.

19. Establish success criteria that incorporate meeting specific objectives within the natural variability and dynamic nature of river systems and their ecological function.

20. Monitor to determine the consequence of on-site implementation, evaluate effectiveness of design, validate predictions, assess how well the design met stated objectives, and determine if the stream is self-maintaining within the acceptable range of natural variability; utilize data for future restorations.

This list was developed from field experience over time based on reviews of implemented NCD projects and should alert the stream restoration practitioner to the extensive requirements and challenges involved in the design and implementation of river restoration projects. This is not a complete or exhaustive list. It does indicate, however, that unique skills and experience are required. It is strongly advised not to undertake river restoration without the following: (1) field experience, (2) a strong academic and practical applied science background, (3) incorporating multiple disciplines as necessary, and (4) specific training, mentoring, and peer review.

5.1. Increasing the Risk of Failure

The highest risk of failure comes from not correctly implementing all 10 phases of the NCD methodology and the corresponding 20 minimum NCD requirements. It has been this author's experience that risks are needlessly increased by shortcutting river restoration details and implementation. In addition to not meeting the 20 minimum NCD requirements, the following list documents reasons that increase the likelihood of project failure: (1) insufficient project funding where, unfortunately, completion of projects is encouraged by taking "shortcuts"; (2) implementing designs during poor weather conditions, such as saturated soils, moderate to high flow stages, snow, ice, and frozen ground; (3) utilizing inappropriate materials and stabilization methods, including rock sizes, gabions, fabrics, wrong plant materials, concrete, riprap, and "Jacks"; (4) political and social constraints, such as boundaries of construction limits that are not compatible with minimum river boundaries; (5) using equipment not matched to site conditions or that is inefficient to properly complete the design; (6) not providing irrigation or methods to establish riparian vegetation in a timely manner; (7) not designing floodplain grading of meandering, riffle/pool channels (C stream types, Table 1) in terraced alluvial fill valleys (valley type VIII, Table 2) to ensure that the "flood wave" is opposite of the sine wave of the meander to prevent erosion and gully development in the newly created floodplain surfaces (accomplished by grading from the floodplain height on the inside bend to the low terrace height on the outside bend to allow flood flows to shift opposite of the sine wave of the channel meanders); (8) field supervision during construction is not consistently provided resulting in poorly implemented design; (9) construction given to the lowest bidder regardless of experience in river restoration projects; and (10) disconnects among the individuals doing assessment, design, implementation, and monitoring; the same individuals should be involved in all stages.

5.2. Case Examples

Many projects have failed as the result of problems stemming from the aforementioned list as well as not adequately completing the 10 phases and the 20 minimum requirements. The following are case examples where project failures and nonsustainable project designs increased the risk for failure and where specific minimum requirements (MR) were not met.

The first example is a project in Maryland (White Marsh Run) that failed because the bankfull discharge was not validated (MR 5), and no sediment transport capacity computation was conducted (MR 13). The river was designed and constructed with too high of a bankfull discharge resulting in a high width/depth ratio. The first runoff caused major stream aggradation, although multiple rock structures were used. A misguided concept is that designing and implementing large, dominant stabilization structures will offset the need to correctly design the bankfull discharge and the associated dimension, pattern, and profile of the river (MR 8). This common misconception has led to multiple, yet predictable and preventable failures.

Another common oversight that can lead to failures is designing the wrong stream type for the given valley type (MR 6). This occurred in Virginia following a major hurricane-driven flood where the postflood rehabilitation created a single-thread, straight trapezoidal channel with levees (F3 stream type, Table 1) on an actively building, steep alluvial fan (valley type III, Table 2). The fan was located below a debris flow/debris torrent stream type (A3a+). This transported small boulders, large cobble, gravel, and sand from the A3a+ stream type directly into the Rapidan River resulting in aggradation of the main stem river reach with subsequent hurricane floods. The stable stream type for such actively building alluvial fans is a bar-braided, D3 stream type. This stream type's function is to naturally deposit the coarse erosional debris on the fan surface rather than route it to the main stem reach of the valley floor. The constructed stream type did not follow the geomorphically stable form for this fluvial landform and caused accelerated disequilibrium of the receiving stream.

Projects that are proposed that do not control the cause of instability (MR 10 and MR 13) are often rejected (or should be rejected) for restoration design. One example was on the Swift Current River in Montana where the regulated main stem below a reservoir reduced the flow release during the snowmelt runoff season. This change in the timing and flow reduction caused downstream aggradation and braiding due to the unregulated tributary of Boulder Creek that transported large quantities and sizes of bed load into the regulated main stem reach. The proponent's design was to convert the braided reach (D3 stream type) to a meandering pattern (C3 stream type) reach. However, the cause of the braiding was due to flow regulation and the high bed load that came from an undisturbed watershed; a C3 stream type conversion would have promoted both a high risk and a probability of failure without addressing the flow releases. If the operational hydrology of the dam had been modified to release a bankfull discharge timed with the sediment transport flows of the unregulated tributary, the designed C3 stream type would potentially be sustainable.

Other common project failures have occurred due to constructing "incised" river channels. Degree of incision is a measure of a local reduction in base level and abandonment of an active floodplain as determined by bank-height ratio (the lowest bank height divided by the maximum depth at bankfull stage). If the bankfull discharge or depth is incorrect for the designed dimensions, an incised channel results (MR 5 and MR 8). Flood flows greater than the bankfull stage create excess shear stress and unit stream power in incised channels resulting in accelerated streambed and stream bank erosion. Bankfull discharge, slope, and width/depth ratio are critical design requirements in NCD.

Furthermore, traditional computations for river design are often not appropriate for natural channels and are conservative in nature. The tendency to design a "one-size-fits-all-flows" channel creates oversized widths of stream channels to increase channel capacity to handle floods, reduce velocities within the "minimum" allowable velocities, and reduce shear stress for critical depth computations so as not to entrain D_{50} bed particles (MR 5). Such traditional designs promote high width/depth ratios and sediment deposition or channel aggradation. If validated sediment transport models were applied, these high width/depth ratio channels would indicate the channel process of aggradation (MR 13). Aggrading channels are not only unstable but require high maintenance, add to flood stage problems, and contribute to poor aquatic habitat.

6. DISCUSSION AND SUMMARY

NCD is based on the fundamental principles of form and process integration. Selection of the appropriate form is based on recognition of the controlling processes. In the absence of reasonable time periods to validate prediction methodologies required for design, the reference reach is required to represent the channel process and form relations. There are 67 dependent variables developed from the reference reach and extrapolated to existing impaired reaches for NCD. Critical for proper extrapolation is the inherent stratification of such morphological variables by valley type and stream type. In addition, each stream type within its valley type must further be described by the controlling variables representing the boundary conditions and driving variables. For example, high bed load streams in glacial trough valleys (valley type V, Table 2) with rain-on-snow-dominated hydrographs for their attendant forcing condition will exhibit unique morphology. In contrast, spring-fed systems in lacustrine valley types (valley type X) have cohesive banks, lower bed load, and lower gradients and are associated with meandering, low width/depth ratio, riffle/pool channels with floodplain connectivity (E and C stream types, Table 1).

In addition to the reference reach approach, the NCD method also uses analytical and empirical methods to develop the proposed channel design. Hydraulic and sedimentological relations are predicted and validated. This approach is utilized for river restoration rather than applying an incomplete system of equations prevalent in traditional river design approaches. The major differences between the NCD approach to river restoration and traditional river design works are that NCD (1) integrates multiple disciplines; (2) assumes a higher risk as the design allows for channel adjustment within a stable range and does not "fix" a river in place; (3) generally uses "softer" stabilization materials, such as native materials that include wood and riparian vegetation; (4) often requires a larger watershed perspective to identify the cause of impairment beyond the reach scale; (5) designs a multiple-stage channel to match a range of flows including floods that create floodplain connectivity and function compared to traditional river works that often involve the calculation of flood discharge and trapezoidal channels that accommodate the design flood; and (6) derives the dimension, pattern, and profile variables based on an analog method that integrates process and form relations associated with the controlling variables rather than using analytical models.

The NCD approach, if implemented correctly, will offset many of the adverse consequences and problems identified from past traditional river works. The incorporation of NCD procedures provides for more sustainable designs that are intended to work in harmony with the river. The method requires rigor in field observations. The NCD method has been successfully implemented on hundreds of river restoration projects by this author and many others since its inception [e.g., *Berger*, 1992; *National Research Council*, 1992, pp. 217–228; *Klein et al.*, 2007; *Hammersmark et al.*, 2008, 2010; *Ernst et al.*, 2010; *Pierce et al.*, 2008; *Baldigo et al.*, 2008, 2010].

Less than 5% of the multiple and large-scale restoration projects constructed by the author have required any maintenance. A 5 year postrestoration monitoring project was conducted by the Colorado State University on a 19 mi restoration project designed and constructed by the author (Little Snake River, Three Forks Ranch in Colorado, and Wyoming). The results of this monitoring verified that very little maintenance was required and that the project met the restoration objectives [*Bledsoe and Meyer*, 2005; *Meyer*, 2007]. This project involved channel relocation and reconstruction of the dimension, pattern, and profile that incorporated a variety of river structures and reestablishment of the riparian vegetation community. The design also reconnected the floodplain and involved a rise in the water table with oxbow lakes, an improvement in aquatic, terrestrial, and waterfowl habitat, as well as a change in the livestock grazing system (the cause of impairment). "NCD has proven to have enormous practical and economic utility for the growing stream restoration field [*Lave*, 2009, p. 1529]." Success or failure of this method is closely linked to the 10 phases and the 20 minimum requirements in addition to the experience of the restoration practitioner and the required attention to detail.

As in any science, river restoration involves multiple processes and forms whose predictions are not only complex but require extensive field validation over time. Integrating the combined experience from river studies to develop classifications and fundamental relations form the basis of the NCD method. Due to the recognized uncertainty of prediction, continued validation is not only encouraged but essential to provide confidence in the method. It has been this validation and testing that has modified and improved the NCD approach over four decades. As restoration objectives continue to expand, the tools required to meet such demands will continue to be updated. Regardless, the basic tenet for this work should be to continue to monitor in a manner that helps us direct our future work: for the answers are to be found in the river.

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