ELSEVIER

Catena 22 (1994) 169–199

CATENA

A classification of natural rivers

David L. Rosgen

Wildland Hydrology, 1 Steven's Lake Road, Pagosa Springs, CO 81147, USA

Abstract

A classification system for natural rivers is presented in which a morphological arrangement of stream characteristics is organized into relatively homogeneous stream types. This paper describes morphologically similar stream reaches that are divided into 7 major stream type categories that differ in entrenchment, gradient, width/depth ratio, and sinuosity in various landforms. Within each major category are six additional types delineated by dominate channel materials from bedrock to silt/clay along a continuum of gradient ranges. Recent stream type data used to further define classification interrelationships were derived from 450 rivers throughout the U.S, Canada, and New Zealand. Data used in the development of this classification involved a great diversity of hydro-physiographic/geomorphic provinces from small to large rivers and in catchments from headwater streams in the mountains to the coastal plains. A stream hierarchical inventory system is presented which utilizes the stream classification system. Examples for use of this stream classification system for engineering, fish habitat enhancement, restoration and water resource management applications are presented. Specific examples of these applications include hydraulic geometry relations, sediment supply/availability, fish habitat structure evaluation, flow resistance, critical shear stress estimates, shear stress/velocity relations, streambank erodibility potential, management interpretations, sequences of morphological evolution, and river restoration principles.

1. General statement

It has long been a goal of individuals working with rivers to define and understand the processes that influence the pattern and character of river systems. The differences in river systems, as well as their similarities under diverse settings, pose a real challenge for study. One axiom associated with rivers is that what initially appears complex is even more so upon further investigation. Underlying these complexities is an assortment of interrelated variables that determines the dimension, pattern, and profile of the present-day river. The resulting physical appearance and character of the river is a product of adjustment of its boundaries to the current streamflow and sediment regime.

SSDI 0341-8162(94)E0046-3

River form and fluvial process evolved simultaneously and operate through mutual adjustments toward self-stabilization. Obviously, a classification scheme risks over-simplification of a very complex system. While this may appear presumptuous, the effort to categorize river systems by channel morphology is justified in order to achieve, to some extent, the following objectives:

1. Predict a river's behavior from its appearance;
2. Develop specific hydraulic and sediment relations for a given morphological channel type and state;
3. Provide a mechanism to extrapolate site-specific data collected on a given stream reach to those of similar character;
4. Provide a consistent and reproducible frame of reference of communication for those working with river systems in a variety of professional disciplines.

2. Stream classification review

A definition of classification was offered by Platts (1980) where "classification in the strictest sense means ordering or arranging objects into groups or sets on the basis of their similarities or relationships." The effort to classify streams is not new. Davis (1899) first divided streams into three classes based on relative stage of adjustment: youthful, mature, and old age. Additional river classification systems based on qualitative and descriptive delineations were subsequently developed by Melton (1936) and Matthes (1956).

Straight, meandering, and braided patterns were described by Leopold and Wolman (1957). Lane (1957) developed quantitative slope-discharge relationships for braided, intermediate, and meandering streams. A classification based on descriptive and interpretive characteristics was developed by Schumm (1963) where delineation was partly based on channel stability (stable, eroding, or depositing) and mode of sediment transport (mixed load, suspended load, and bedload).

A descriptive classification was also developed by Culbertson et al. (1967) that utilized depositional features, vegetation, braiding patterns, sinuosity, meander scrolls, bank heights, levee formations, and floodplain types. Thornbury (1969) developed a system based on valley types. Patterns were described as antecedent, superposed, consequent, and subsequent. The delineative criteria of these early classification systems required qualitative geomorphic interpretations creating delineative inconsistencies. Khan (1971) developed a quantitative classification for sand-bed streams based on sinuosity, slope, and channel pattern.

To cover a wider range of stream morphologies, a descriptive classification scheme was developed for and applied on Canadian Rivers by Kellerhals et al. (1972, 1976), Galay et al. (1973), and Mollard (1973). The work of these Canadian researchers provides excellent description and interpretation of fluvial features. This scheme has utility both for aerial photo delineation and for describing gradual transitions between classical river types. and to date offers the most detailed and complete list of channel and valley features. The large number of possible interpretative delineations, however, makes this scheme quite complex for general planning objectives.

An attempt to classify rivers in the great plains region using sediment transport, channel stability, and measured channel dimensions was developed by Schumm (1977). Classifying stream systems on the basis of stability is often difficult because of the qualitative criteria can vary widely among observers leading to inconsistencies in the classification. Similarly, data on ratio of bedload to total sediment load as needed in this classification, while useful, often is not readily available to those who need to classify streams.

Brice and Blodgett (1978) described four channel types of: braided, braided point-bar, wide-bend point-bar, and equi-width point-bar. A descriptive inventory of alluvial river channels is well documented by Church and Rood (1983). This data set can be very useful for many purposes including the grouping of rivers based on similar morphological characteristics. Nanson and Croke (1992) presented a classification of flood plains that involved particle size, morphology of channels, and bank materials. This classification has some of the same criteria of channel type as presented in this paper, but is restricted to flood plains. Pickup (1984) describes the relation of sediment source and relative amounts of sediment to various aspects of river type, but is not a classification of channels. Recent documentation by Selby (1985) showed a relationship between the form and gradient of alluvial channels and the type, supply and dominant textures (particle sizes) of sediments. This relationship utilizes the Schumm (1977) classification in that an increase in the ratio of bed material load to total sediment load with a corresponding increase in channel gradient leads to a decrease in stability causing channel patterns to shift from a meandering to braided channel form. In his classification, Selby (1985) treats anastomosed and braided channel patterns similarly. However, the anastomosed rivers are not similar to braided rivers in slope, adjustment processes, stability, ratio of bed material to total load or width/depth ratios as shown by (Smith and Smith, 1980).

Typically, theoretically derived schemes, often do not match observations. To be useful for extrapolation purposes, restoration designs, and prediction, classification schemes should generally represent the physical characteristics of the river. With certain limitations, most of these classification and/or inventory systems met the objectives of their design. However, the requirement for more detailed, reproducible, quantitative applications at various levels of inventory over wide hydro-physiographic provinces has led to further development of classification schemes.

2. Stream classification concepts

The morphology of the present day channel is governed by the laws of physics through observable stream channel features and related fluvial processes. Stream pattern morphology is directly influenced by eight major variables including channel width, depth, velocity, discharge, channel slope, roughness of channel materials, sediment load, and sediment size (Leopold et al., 1964). A change in any one of these variables sets up a series of channel adjustments which lead to a change in

Table 1
Hierarchy of river inventories

Level of detail	Inventory description	Information required	Objectives
I	Broad morphological characterization	Landform, lithology, soils, climate, depositional history, basin relief, valley morphology, river profile morphology, general river pattern	To describe generalized fluvial features using remote sensing and existing inventories of geology, landform evolution, valley morphology, depositional history and associated river slopes, relief and patterns utilized for generalized categories of major stream types and associated interpretations.
II	Morphological description (stream types)	Channel patterns, entrenchment ratio, width/depth ratio, sinuosity, channel material, slope	This level delineates homogeneous stream types that describe specific slopes, channel materials, dimensions and patterns from "reference reach" measurements. Provides a more detailed level of interpretation and extrapolation than Level I.
III	Stream "state" or condition	Riparian vegetation, depositional patterns, meander patterns, confinement features, fish habitat indices, flow regime, river size category, debris occurrence, channel stability index, bank erodibility	The "state" of streams further describes existing conditions that influence the response of channels to imposed change and provide specific information for prediction methodologies (such as stream bank erosion calculations, etc.). Provides for very detailed descriptions and associated prediction/interpretation.
IV	Verification	Involves direct measurements/observations of sediment transport, bank erosion rates, aggradation/degradation processes, hydraulic geometry, biological data such as fish biomass, aquatic insects, riparian vegetation evaluations, etc.	Provides reach-specific information on channel processes. Used to evaluate prediction methodologies; to provide sediment, hydraulic and biological information related to specific stream types; and to evaluate effectiveness of mitigation and impact assessments for activities by stream type.

the others, resulting in channel pattern alteration. Because stream morphology is the product of this integrative process, the variables that are measurable should be used as stream classification criteria.

The directly measurable variables that appear from both theory and experience to govern channel morphology have been included in the present classification procedure. These "delineative criteria" interact with one another to produce a stream's dominant features.

The present classification system has evolved from field observation of hundreds of rivers of various sizes in all the climatic regions of North America, experience in stream restoration, extensive teaching, and practical applications of the classification system by many hydrologists, geomorphologists, fisheries experts, and plant ecologists. Initial efforts to develop the classification procedure began in 1973, and a preliminary version was presented to the scientific community (Rosgen, 1985). The present paper includes notational changes from the earlier publication.

3. Stream classification system

The classification of rivers is an organization of data on stream features into discreet combinations. The level of classification should be commensurate with the initial planning level objective. Because these objectives vary, a hierarchy of stream classification and inventories is desirable because it allows an organization of stream inventory data into levels of resolution from very broad morphological characterizations to discreet, measured, reach-specific descriptions. Each level should include appropriate interpretations that match the inventory specificity. Further, general descriptions and characteristics of stream types should be able to be divided into even more specific levels. The more specific levels should provide indications of stream potential, stability, existing "states", etc., to respond to higher resolution data and interpretations when planning needs change. A proposed stream inventory system, including an integrated stream classification, is shown in Table 1.

Current river "state" and influences on the modern channel by vegetation, flow regime, debris, depositional features, meander patterns, valley and channel confinement, streambank erodibility, channel stability, etc., comprise additional parameters that are considered critical to evaluate by stream type at a more detailed inventory level (Level III). However, for the sake of brevity and clarity, this paper will focus on the first two levels, the broad geomorphic characterization (Level I) and the morphological description (Level II) which incorporates the general character of channel form and related interpretations. Portions of the data used for detailed assessment levels are contained in the sub-type section of the earlier classification paper (Rosgen, 1985).

4.1. Geomorphic characterization (level I)

The purpose of delineation at this level is to provide a broad characterization that integrates the landform and fluvial features of valley morphology with channel relief,

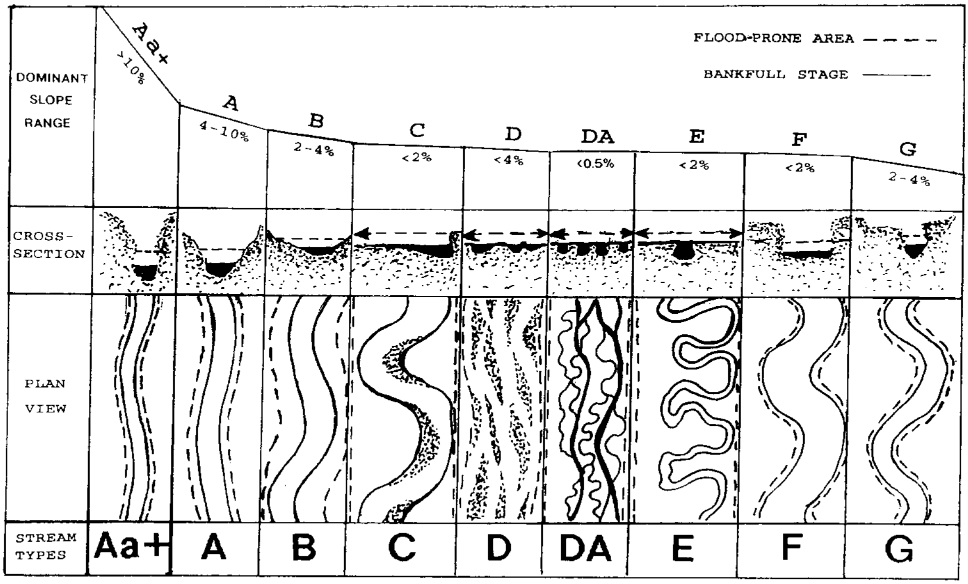


Fig. 1. Longitudinal, cross-sectional and plan views of major stream types.

pattern, shape, and dimension. Level I combines the influences of climate, depositional history, and life zones (desert shrub, alpine, etc.) on channel morphology.

The presence, description, and dimensions of floodplains, terraces, fans, deltas and outwash plains are a few examples of valley features identified. Depositional and erosional history overlay channel patterns at this level. Generalized categories of "stream types" initially can be delineated using broad descriptions of longitudinal profiles, valley and channel cross-sections, and plan-view patterns (see Fig. 1 and Table 2).

Longitudinal profiles

The longitudinal profile, which can be inferred from topographic maps, serves as the basis for breaking the stream reaches into slope categories that reflect profile morphology. For example, the stream types of Aa+ (Fig. 1) are very steep, (greater than 10%), with frequently spaced, vertical drop/scour-pool bed features. They tend to be high debris transport streams, waterfalls, etc. Type A streams are steep (4–10% slope), with steep, cascading, step/pool bed features. Type B streams are riffle-dominated types with "rapids" and infrequently spaced scour-pools at bends or areas of constriction. The C, DA, E and F stream types are gentle-gradient riffle/pool types. Type G streams are "gullies" that typically are step/pool channels. Finally, the D type streams are braided channels of convergence/divergence process that lead to localized, frequently spaced scour/depositional bed forms.

Bed features are consistently found to be related to channel slope. Grant et al. (1990) described bed features of pools, riffles, rapids, cascades, and steps as a function

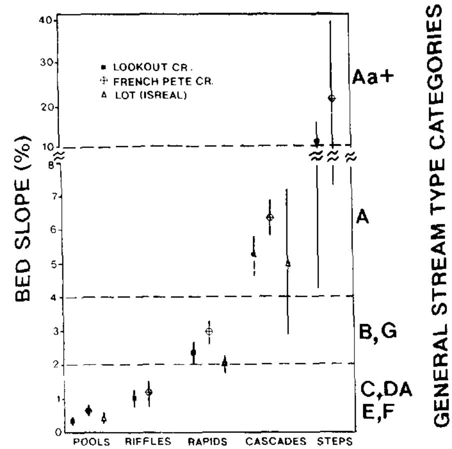


Fig. 2. Relationship of bed slope to bed forms for various stream types (from Grant et al., 1990).

of bed-slope gradient. Using their bed form descriptions, the above described stream types were plotted against the corresponding slope ranges reported by Grant et al. (1990). "Groupings", (Fig. 2), were apparent for riffle/pool stream types (C, E, and F) at less than 2%, rapids at 2–4% in "B" and "G", cascades in slopes 4–10% in type A streams, and steps for slopes 4–40% in types A and Aa+ streams. Because gradient and bed-feature relationships are integral to the delineation of stream type categories, "stream types" are more than just "arbitrary units". Bed morphology can be predicted from stream type by using bed-slope indices.

Cross-section morphology

The shape of the cross-section that would indicate a narrow and deep stream as opposed to a wide and shallow one can be inferred at this broad level. The manner in which the channel is incised in its valley can also be deduced at this level as well as information concerning floodplains, terraces, colluvial slopes, structural control features, confinement (lateral containment), entrenchment (vertical containment), and valley vs. channel dimension. For example, the type A streams are narrow, deep, confined, and, entrenched. The width of the channel and valley are similar. This contrasts with type C streams, where the channel is wider and shallower with a well-developed floodplain and a very broad valley. Type E streams have a narrow and deep channel (low width/depth ratio) but have a very wide and well developed floodplain. Type F streams have wide and shallow channels, but are an entrenched meandering channel type with little to no developed floodplain. Type G channels have low width/depth ratio channels similar to type E streams except they are well entrenched (no floodplain), are steeper, and less sinuous than type E streams (see Fig. 1).

Plan view morphology

The pattern of the river is classed as relatively straight (A stream types), low sinuosity (B stream types), meandering (C stream types), and tortuously meandering

Table 2
Summary of delineative criteria for broad-level classification

Stream type	General description	Entrenchment ratio	W/D ratio	Sinuosity	Slope	Landform/soils/features
Aa +	Very steep, deeply entrenched, debris transport 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 residual soils. Moderate entrenchment and W/D ratio. Narrow, gently sloping valleys. Rapids predominate with occasional pools.
C	Low gradient, meandering, point-bar, riffle/pool, alluvial channels with broad, well defined floodplains	> 2.2	> 12	> 1.4	< 0.02	Broad valleys with terraces, in association with floodplains, alluvial soils. Slightly entrenched with well-defined meandering channel. Riffle-pool bed morphology.

D	Braided channel with longitudinal and transverse bars. Very wide channel with eroding banks.	n/a	> 40	n/a	< 0.04	Broad valleys with alluvial and colluvial fans. Glacial debris and depositional features. Active lateral adjustment, with abundance of sediment supply.
DA	Anastomosing (multiple channels) narrow and deep with expansive well vegetated floodplain and associated wetlands. Very gentle relief with highly variable sinuosities. Stable streambanks.	> 4.0	< 40	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.
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 floodplain. Highly sinuous with stable, well vegetated banks. Riffle-pool morphology with very low width/depth ratio.
F	Entrenched meandering riffle/pool channel on low gradients with high width/depth ratio.	< 1.4	> 12	> 1.4	< 0.02	Entrenched in highly weathered material. Gentle gradients, with a high *W/D* ratio. Meandering, laterally unstable with high bank-erosion rates. Riffle-pool morphology.
G	Entrenched "gulley" step/pool and low width/depth ratio on moderate gradients.	< 1.4	< 12	> 1.2	0.02 to 0.039	Gulley, step-pool morphology with moderate slopes and low *W/D* 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.

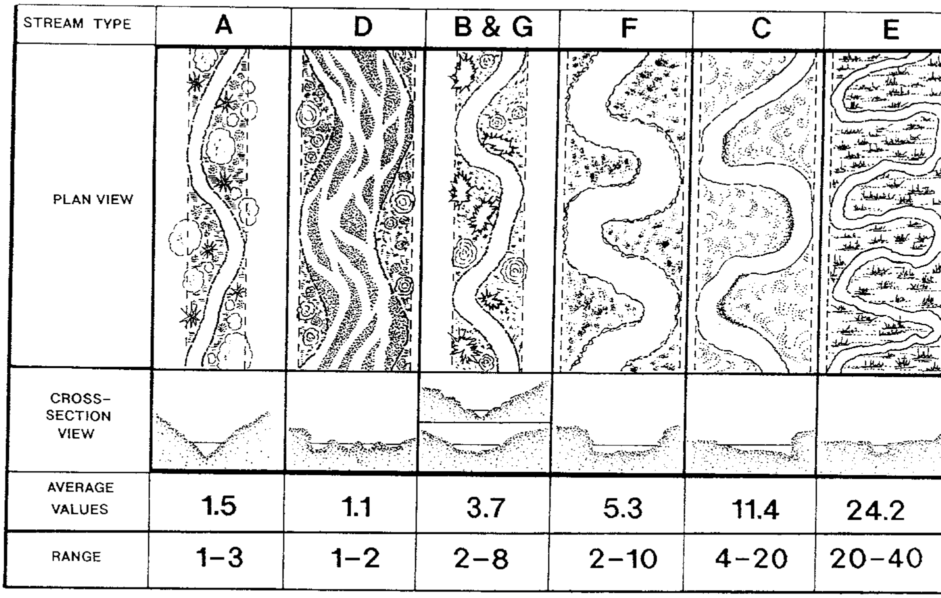


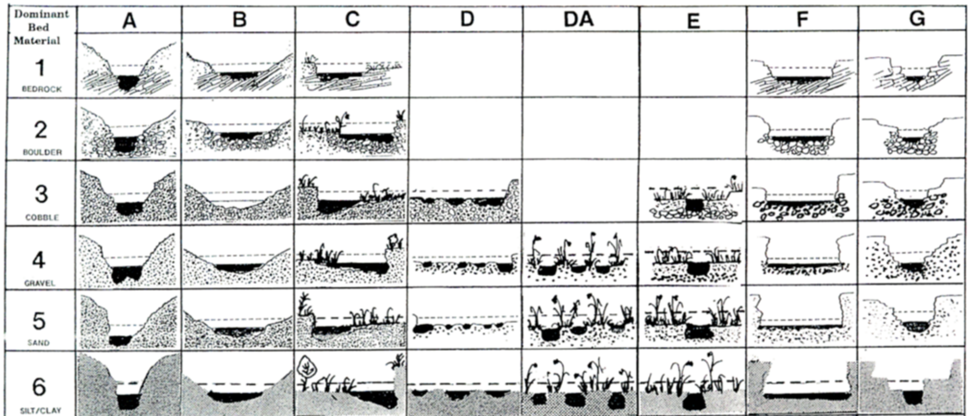
Fig. 3. Meander width ratio (belt width/bankfull width) by stream type categories.

(E stream types). Complex stream patterns are found in the multiple channel, braided (D) and anastomosed (DA) stream types. Sinuosity can be calculated from aerial photographs and often, like slope, serves as a good initial delineation of major stream types. These river patterns have integrated many processes in deriving their present form and thus, provide interpretations of their associated morphology.

Even at this broad level of delineation, consistency of dimension and associated pattern can be observed by broad stream types. Meander width ratio (belt width/bankfull surface width) was calculated by general categories of stream types for a wide variety of rivers. Measured mean values and ranges by stream type are shown in Fig. 3. Early work by Inglis (1942) and Lane (1957) discussed meander width ratio but the values were so divergent among rivers that the ratio appeared to have little value. When stratified by general stream types, however, the variability appears to be explained by the similarities of the morphological character of the various stream types. This has value not only for classification and broad-level delineations, but also for describing the most probable state of channel pattern in stream restoration work.

Discussion

Interpretations of mode of adjustment — either vertical, lateral, or both — and energy distribution can often be inferred in these broad types. Many variables that are not discrete delineative variables integrate at this level to produce an observable morphology. A good example of this is the influence of a deep sod-root mass on type E streams that produces a low width/depth ratio, low meander length, low radius of curvature, and a high meander width ratio. Vegetation is not singled out for mapping at this level, but is implicit in the resulting morphology. If this vegetation is changed, the width/depth ratio and other features will result in adjustments to the



	A	B	C	D	DA	E	F	G
ENTRH.	<1.4	1.4–2.2	>2.2	N/A	>2.2	>2.2	<1.4	<1.4
SIN.	<1.2	>1.2	>1.4	<1.1	1.1-1.6	>1.5	>1.4	>1.2
W/D	<12	>12	>12	>40	<40	<12	>12	<12
SLOPE	.04–.099	.02–.039	<.02	<.02	<.005	<.02	<.02	.02–.039

Fig. 4. Illustrative guide showing cross-sectional configuration, composition and delineative criteria of major stream types.

type C stream morphology. Detailed vegetative information, however, is obtained at the channel state level (Level III, Table 1).

Delineating broad stream types provides an initial sorting within large basins and allows a general level of interpretation. This leads to organization and prioritization for the next more detailed level of stream classification.

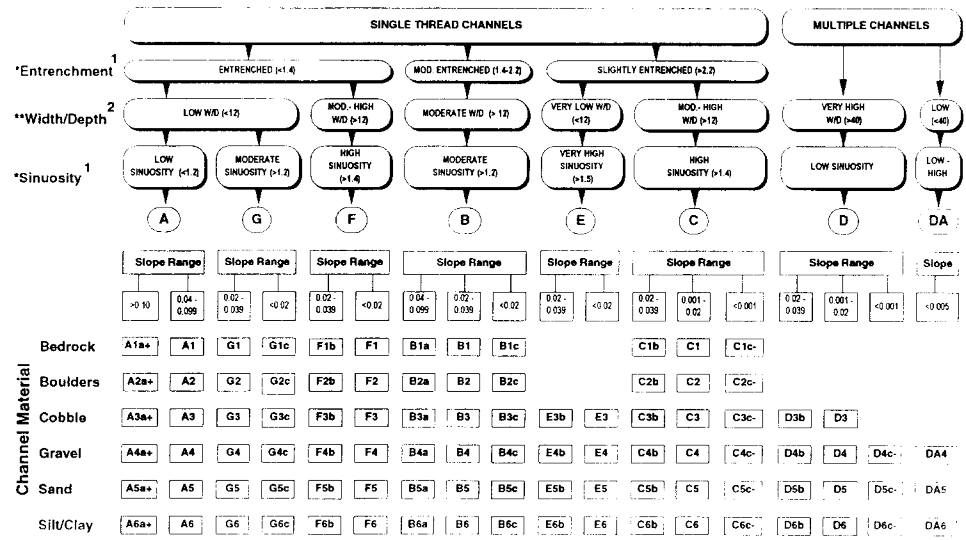
4.2. The morphological description (level II)

General description

This classification scheme is delineated initially into the major, broad, stream categories of A–G as shown in Fig. 1 and Table 2. The stream types are then broken into discreet slope ranges and dominant channel-material particle sizes. The stream types are given numbers related to the median particle size diameter of channel materials such that 1 is bedrock, 2 is boulder, 3 is cobble, 4 is gravel, 5 is sand, and 6 is silt/clay. This initially produces 42 major stream types as shown in (Fig. 4).

A range of values for each criterion is given in the key to classification for 42 major stream types (Fig. 5). The range of values chosen to represent each delineative criterion is based on data from a large assortment of streams throughout the United States, Canada and New Zealand. A recent data set of 450 rivers was statistically used to refine and test previous ranges of delineative criteria as described in the author's earlier publication (Rosgen, 1985).

Histograms were drawn of the distribution of values of each delineative criterion for each channel type. From the histograms of 5 criteria for 42 major stream types, the mean and "frequent range" of values were recorded. The most frequently observed values seemed to group into a recognizable "river form" or morphology. When values



[1] Values can vary by ± 0.2 units as a function of the continuum of physical variables within stream reaches.
[2] Values can vary by ± 2.0 units as a function of the continuum of physical variables within stream reaches.

Fig. 5. Key to classification of natural rivers.

were outside of the range of the "most frequently observed" condition, a distinctly different morphology was identified. As a result, the delineation of unique stream types representing a range of values amongst several variables were established. These variables and their ranges make up the current morphological description of stream types as shown in Figs. 4 and 5.

The classification can be applied to ephemeral as well as perennial channels with little modification. Bankfull stage can be identified in most perennial channels through observable field indicators. Although, these bankfull stage indicators, are often more elusive in ephemeral channels.

The morphological variables can and do change even in short distances along a river channel, due to such influences of change as geology and tributaries. Therefore, the morphological description level incorporates field measurements from selected reaches, so that the stream channel types used here apply only to individual reaches of channel. Data from individual reaches are not averaged over entire basins to describe stream systems. A category may apply to a reach only a few tens of meters or may be applicable to a reach of several kilometers.

Data is obtained from field measurements of representative or "reference reaches." The resultant stream type as delineated can then be extrapolated to other reaches where detailed data is not readily available. In similar valley and lithological types, stream types can often be delineated using these reference reaches through the use of aerial photos, topographic maps, etc.

Continuum concept

When the variables which make up the range of values within a stream type change, there is more often than not, a change in stream type. The ranges in slope, width/depth ratio, entrenchment ratio and sinuosity shown in Fig. 4 span the most frequently observed values. Exceptions occur infrequently, where values of one variable may be outside of the range for a given stream type.

This level recognizes and describes a continuum of river morphology within and between stream types. The continuum is applied where values outside the normal range are encountered but do not warrant a unique stream type. Often the general appearance of the stream and the associated dimensions and patterns of the stream do not change with a minor value change in one of the delineative criteria. For example, slope values as shown in Fig. 5, using the continuum concept, are not "lumped", but rather are sorted by sub-categories of: a + (steeper than 0.10), a (0.04–0.10), b (0.02–0.039), c (less than 0.02) and c- (less than 0.001).

The application of this concept allows an initial classification of a C4 stream type (a gravel bed, sinuous, high width/depth ratio channel with a well-developed floodplain. If the slope of this stream was less than 0.001, then the stream type would be a C4c−.

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, profile and pattern reflects on these adjustment processes which are presently responsible for the form of the river. The rate and direction of channel adjustment is a function of the nature and magnitude of the change and the stream type involved. Some streams change very rapidly, while others are very slow in their response.

Delineative criteria

At this level of inventory each reach is characterized by field measurements and validation of the classification. The delineation criteria and ranges for various stream types are shown in Fig. 5. This classification key also represents the sequential process for classification. The classification process starts at the top of the chart (single or multiple thread channels), and proceeds downward through channel materials and slope ranges.

Entrenchment

An important element of the delineation is the interrelationship of the river to its valley and/or landform features. This interrelationship determines whether the river is deeply incised or entrenched in the valley floor or in the deposit feature. Entrenchment is defined as the vertical containment of river and the degree to which it is incised in the valley floor (Kellerhals et al., 1972). This makes an important distinction of whether the flat adjacent to the channel is a frequent floodplain, a terrace (abandoned floodplain) or is outside of a flood-prone area. A quantitative expression of this feature, "entrenchment ratio" was developed by the author so that various mappers could obtain consistent values. The entrenchment ratio is the ratio of the width of the flood-prone area to the bankfull surface width of the channel. The flood-prone area is defined as the width measured at an elevation which is determined at twice the maximum bankfull depth. Field observation shows this elevation to be a frequent

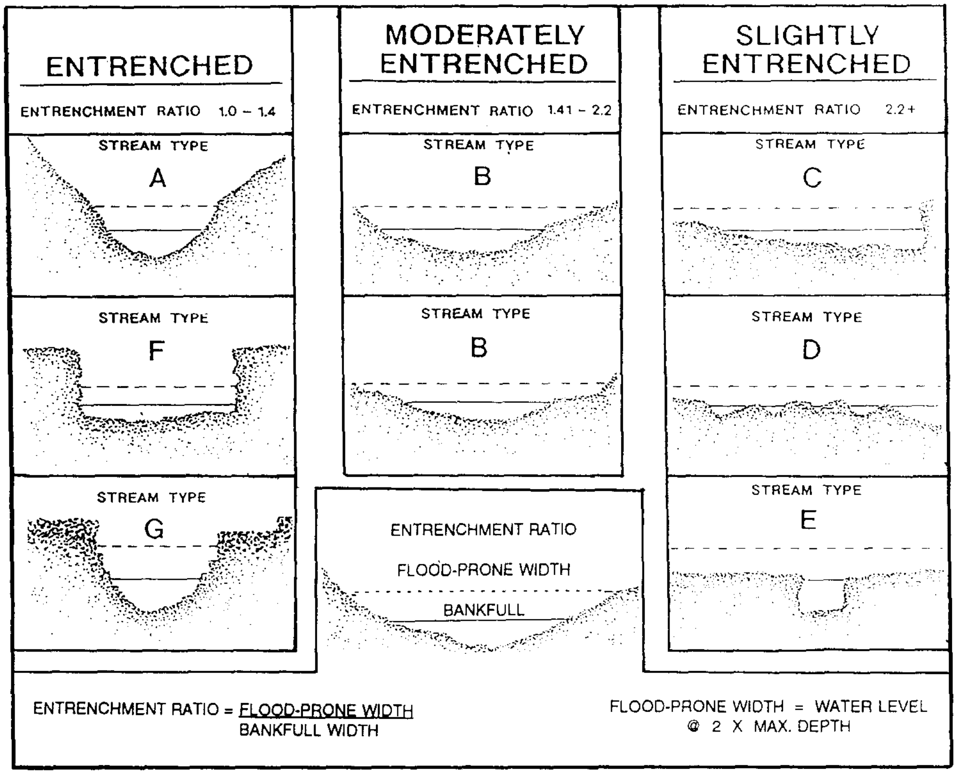


Fig. 6. Examples and calculations of channel entrenchment.

flood (50 year return period) or less, rather than a rare flood elevation. The categories are illustrated in Figs. 4, 5 and 6.

Entrenchment ratios of 1–1.4 represent entrenched streams, 1.41–2.2 represent moderately entrenched streams and ratios greater than 2.2 are slightly entrenched (well-developed floodplain). These categories were empirically derived based on hundreds of streams. As with other criteria, the measured entrenchment ratio value may lie somewhat outside of the classification range. When this occurs, the author applies the continuum concept which allows for a category description where the entrenchment is either greater or less than the most frequently observed value for a given morphology. The continuum allows for a change of \pm 0.2 units where the corresponding delineative criteria still match the range of variables consistent for that type. In this case, all of the other attributes must be considered before assigning a stream type.

Width/depth ratio

The width/depth ratio describes the dimension and shape factor as the ratio of bankfull channel width to bankfull mean depth. Bankfull discharge is defined as the momentary maximum peak flow; one which occurs several days in a year and is often related to the 1.5 year recurrence interval discharge. Specific discussions on the delineation and significance of bankfull discharge are found in Leopold et al. (1964), Dunne and Leopold (1978), and Andrews (1980). Hydraulic geometry and sediment transport relations rely heavily on the frequency and magnitude of bankfull discharge.

Osborn and Stypula (1987) utilized width/depth ratio to characterize stream channels for hydraulic relations using channel boundary shear as a function of channel shape.

For this classification, values of low width/depth ratio are those less than 12. Values greater than 12 are moderate or high. Average values and ranges are shown in the stream type summaries. As in the continuum concept, applied to entrenchment ratio, there is an occasion where width/depth ratio values can vary by ± 2 units without showing a different morphology. This does not occur very frequently, but the continuum allows for some flexibility to fit the stream type into a "dominant" morphology.

Sinuosity

Sinuosity is the ratio of stream length to valley length. It can also be described as the ratio of valley slope to channel slope. Mapping sinuosity from aerial photos is often possible, and interpretations can often be made of slope, channel materials, and entrenchment once sinuosity is determined. Values of sinuosity appear to be modified by bedrock control, roads, channel confinement, specific vegetative types, etc. Generally speaking, as gradient and particle size decreases, there is a corresponding increase in sinuosity. The continuum as mentioned earlier also applies and adjustments of + or -0.2 can be applied to this delineative criteria. Meander geometry characteristics are directly related to sinuosity following minimum expenditure of energy concepts. Initial studies by Langbein and Leopold (1966) suggested that a sine generated curve describes symmetrical meander paths. From this observation they predicted the radius of curvature of meander bends from meander wavelength and channel sinuosity. In comparing observed versus predicted values of radius of curvature for 79 streams, Williams (1986) found this relation to be highly correlated when applied to an expanded data set. This demonstrates the interrelationship of sinuosity to meander geometry. Based on such relations and the relative ease of determination, sinuosity was selected as one of the delineative criteria for stream classification.

Channel materials

The bed and bank materials of the river is not only critical for sediment transport and hydraulic influences but also modifies the form, plan and profile of the river. Interpretations of biological function and stability also require this information. Often a good working knowledge of the soils associated with various landforms can predict the channel materials at the broad delineation level. Reliable estimates of the soil characteristics for glacial till, glacial outwash, alluvial fans, river terraces, lacustrine and eolian deposits, and residual soils can be derived from mapped lithology.

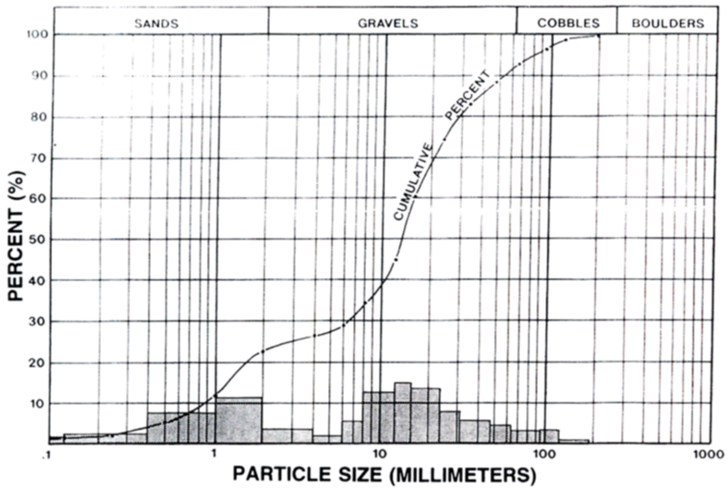


Fig. 7. Channel material sizes showing cumulative and percent distributions.

Field determination of channel materials for this classification system utilizes the "pebble count" method developed by Wolman (1954), with a few modifications to account for bank material and for sand and smaller sizes. This is a determination the frequency distribution of particle sizes that make up the channel. The pebble count data is plotted as cumulative percent and percent of total distribution (Fig. 7). The dominant particle size is identified in the cumulative percent curve as the median size of channel materials or size that 50% of the population is of the same size or finer (D_{50}). The percent distribution shown in Fig. 7 is often used to detect bimodal distributions that may be hidden in cumulative plots. This data is used in biological evaluation, sediment supply assessment, and other interpretative applications.

Slope

Water surface slope is of major importance to the morphological character of the channel and its sediment, hydraulic, and biological function. It is determined by measuring the difference in water surface elevation per unit stream length. Typically, slope is often measured through at least 20 channel widths or two meander wavelengths. As observed with the other delineative variables, slope values less or greater than the most frequently observed ranges can occur. These can occur without a significant change in the other delineative criteria for that stream type. The most frequently observed slope categories and applications of the continuum concept for slope is shown in Fig. 5.

In broad-level delineations, slopes can often be estimated by measuring sinuosity from aerial photos and measuring valley slope from topographic maps (valley slope/sinuosity = channel slope). The basin and associated landform relief can also be used to estimate stream slope ranges, as for example terraces and slopes of alluvial fans.

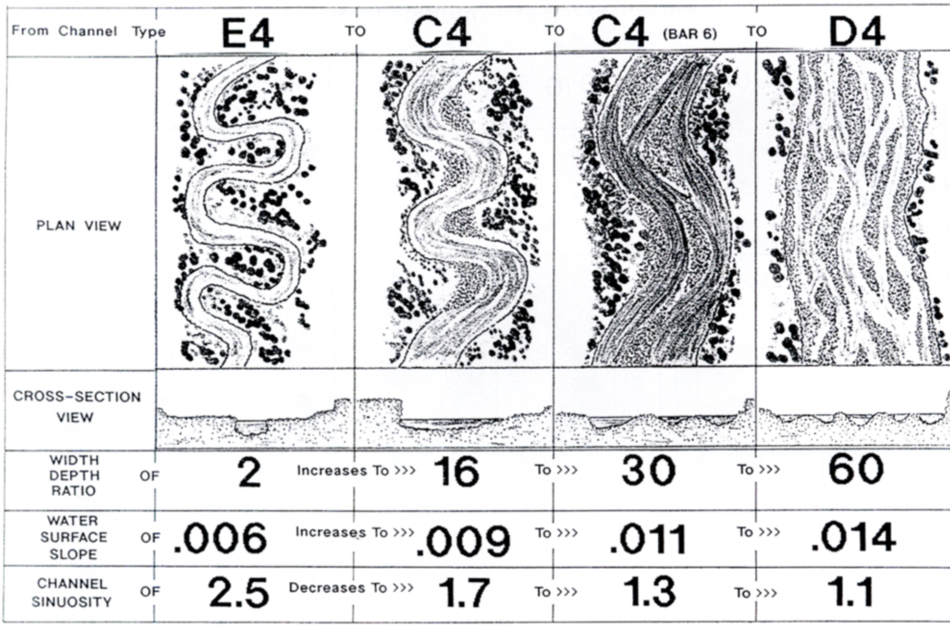


Fig. 8. Progressive stages of channel adjustment due to imposed stream bank instability.

5. Application

Past observations of adjustments of stream systems often provide insight into sensitivity and consequence of change. Stream system changes can be due to flow, sediment, or many of the interrelated variables that have produced the modern channel. If changes produces disequilibrium, similar streams types receiving similar impacts may be expected to respond the same. If the observer knows the stream type of the disturbed reach, and has cross-section, bank erosion, sediment data, riparian vegetation and fisheries data, this information can be used predictively to evaluate the risk and sensitivity to disturbance.

5.1. Evolution of stream types

In reviewing historical aerial photos, observations can be made of progressive stages in channel adjustment. These adjustments occur partially as a result of change in stream-flow magnitude and/or timing, sediment supply and/or size, direct disturbance, and vegetation changes. These observed changes in channel morphology over time can be communicated in terms of stream type changes. For example, due to streambank instability, and a resultant increase in bank erosion rate, the stream increased it's width/depth ratio; decreased sinuosity; increased slope; established a bimodal particle size distribution; increased bar deposition; accelerated bank erosion; and decreased the meander width ratio. These changes can be described more simply

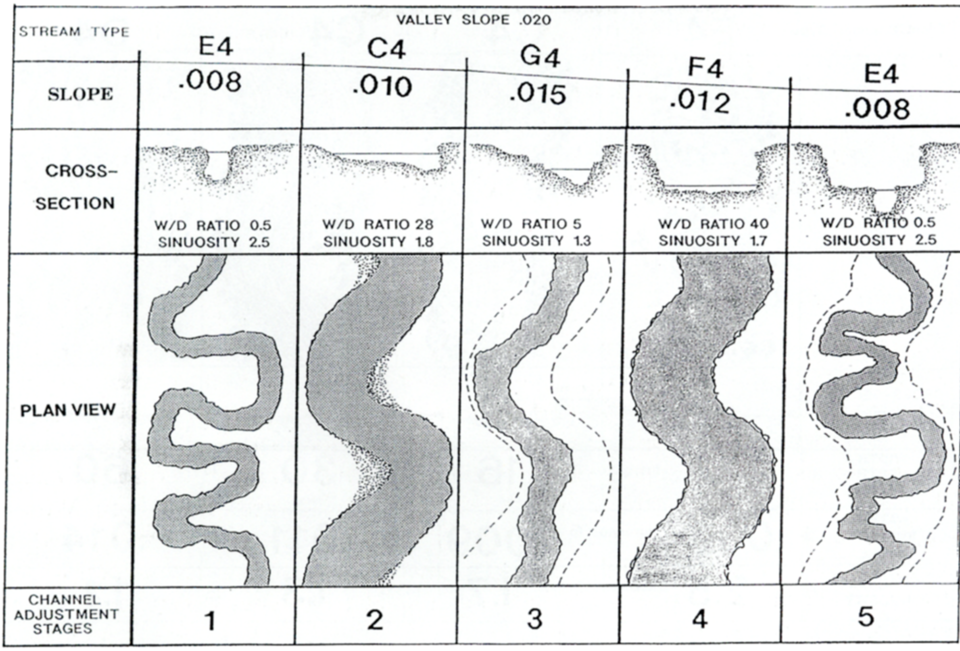


Fig. 9. Evolutionary stages of channel adjustment.

as a series of progressive changes of channel adjustment in stream type from an E4 to C4 to C4 (bar-braided) to D4 (Fig. 8).

Another example of channel adjustment where morphological patterns are changed sufficient to indicate a shift in stream type is shown in Fig. 9. In this scenario, a change in streambank stability led to an increase in width/depth ratio and slope, and a decrease in sinuosity and meander width ratio. As the slope steepened along with a high width/depth ratio, chute cutoffs occurred across large point bars creating a gulley. The stream abandoned its floodplain, decreased the width/depth ratio, steepened the slope and decreased sinuosity. This resulted in a change in base level as all of the tributaries draining into this stream were over-steepened. Sediment from both channel degradation and bank erosion was increased. As the banks continued to erode, the width/depth ratio and sinuosity both increased with a corresponding decrease in slope. The channel was still deeply entrenched, but eventually started to develop a floodplain at a new elevation. This stream eventually evolved under a changed sediment and flow regime into a sinuous, low gradient, low width/depth ratio channel with a well developed floodplain which matched the original morphology, except now exists at a lower elevation in the valley. This case is shown more simply in Fig. 9 as a shift from an E4 stream type to C4 to G4 to F4 and back to an E4 type.

These changes have been well documented throughout western North America due to various reasons including climate change and adverse watershed impacts. The knowledge provided by observing these historical adjustments and the understanding of the tendency of rivers to regain their own stability can assist those restoring disturbed river systems. Often the works of man try to "restore" streams back to a state that does not match the dimension, pattern and slope of the natural, stable form. As stream types change, there are a large number of interpretations associated with these "morphological shifts". Stream types can imply much more than what is initially described in it's alphanumeric title.

5.2. Fish habitat

When physical structures are installed in channels to improve the fish habitat, the adjustment processes that occur sometimes create more damage than habitat. For example, Trail Creek in southeast Colorado, a C4 stream type, had a gabion check dam installed at 80% of the bankfull stage to create a plunge pool for fish. The results were; decreased upstream gradient; width/depth ratio increase; decreased mean bed particle diameter; and decreased competence of the stream to move its own sediment. The longitudinal profile of the river changed creating headward aggradation. With a decrease in slope, there was a corresponding increase in sinuosity that resulted in accelerated lateral channel migration and increased bank erosion. Subsequently, the stream abandoned the original channel and created a "headcut gulley" with a gradient that was twice the valley slope. This converted the C4 stream type to a G4 type in a period of approximately two years. The "new" stream type has abandoned its floodplain, is rejuvenating tributaries headward and creating excess sediment from stream degradation and bank erosion. This disequilibrium caused by the check dam is long-term and has deteriorated the habitat that the structure was initially designed to improve. Unfortunately, structures like this continue to be installed by well-meaning individuals without a clear understanding of channel adjustment processes.

To prevent similar problems and to assist biologists in the selection and evaluation of commonly used in-channel structures, guidelines by stream type were developed (Rosgen and Fittante, 1986). In the development of these guidelines hundreds of fish habitat improvement structures were evaluated for effectiveness and channel response. A stream classification was made for each reach containing a structure. From this data, the authors rated various structures from "excellent" to "poor" for an extensive range of stream types. These guidelines provide "warning flags" of potential adverse adjustments to the river so that technical assistance may be obtained. In this manner, structures may be better designed to not only meet their objectives, but help maintain the stability and function of the river. Fisheries habitat surveys presently integrate this stream classification system (USDA, 1989). The objective for this integration is to determine the potential of the stream reach, current state, and a variety of hydraulic and sediment relations that can be utilized for habitat and biological interpretations.

5.3. Flow resistance

Application of the Manning's equation and the selection of a roughness coefficient N value to predict mean velocity is a common methodology used by engineers and

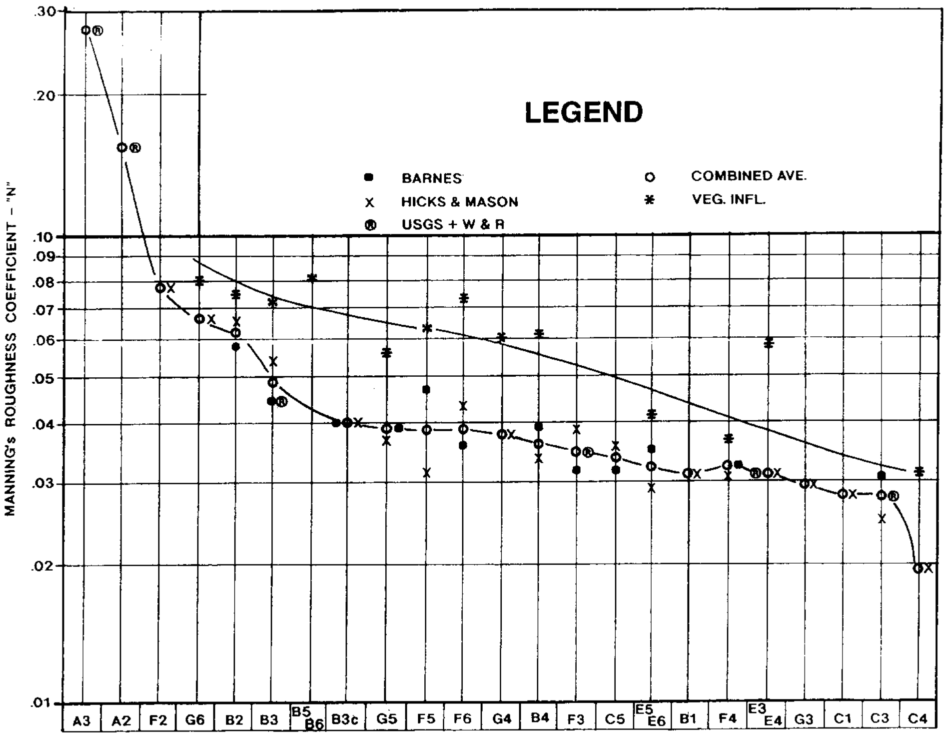


Fig. 10. Bankfull stage roughness coefficients ("*N*" values) by stream type for 140 streams from the United States and New Zealand.

hydrologists. The lack of consistent criteria for selection of the correct *N* values, however, creates great variability in the subsequent estimate of flow velocity. Barnes (1967), and Hicks and Mason (1991) produced photographs and a variety of stream data which was primarily a visual comparison approach for the selection of roughness coefficients. However, using these books for a visual estimate of roughness, actually involves looking at various stream types. The author classified each of the 128 streams described in both publications, noted the occurrence of vegetation influence, and plotted the bankfull stage *N* values by stream type (Fig. 10). The remarkable similarity of *N* values by stream type for two data bases from two countries revealed another application for estimating a bankfull stage roughness coefficient using stream classification. This may help in developing more consistent roughness estimates and provide an approach for improving stream discharge estimates by using the manning's equation. Roughness values increase as stage decreases, thus, the *N* values shown in Fig. 10 are for bankfull conditions only. The Hicks and Mason (1991) work is exemplary in terms of evaluating and displaying variations in *N* with changes in stream discharge. These variations can potentially be developed as a rate of change index for changes in stage by stream type. The influence of vegetation is shown to cause a marked adjustment in values by stream type. As would be expected, this relationship suggests the vegetation influence on roughness is diminished as channel gradient and bed material particle size increase. Stream types essentially integrate those variables affecting roughness, such as; gradient, shape and form resistance, particle size, and relative depth of bankfull discharge to the diameter of the larger particles in the channel. Rather than looking at discrete predictors, stream types integrate the many variables that influence resistance. Another recommended application to roughness estimation is to develop specific relations of roughness and associated velocity as recently developed for "mountain streams" by Jarrett (1984, 1990). In this method, equations were stratified for steeper slopes and cobble/boulder channel materials, using hydraulic radius and slope in the equations. Jarrett's results were valuable in that they produced values much different from most published equations. This work could be even more effective if the stream data were further stratified into stream types and size of stream. In this manner, much like the Manning's N values, equations could be developed using the integrating effects of stream types and thereby advance the state of the art of applications.

5.4. Hydraulic geometry relations

The original work of Leopold and Maddock (1953) made a significant contribution to the applied science in the development of hydraulic geometry relations. The variables of; depth, velocity, and cross-sectional area were quantitatively related to discharge as simple power functions for a given river cross-section. Their findings prompted numerous research efforts over the years. To refine average values of exponents, and to demonstrate the potential for applications of hydraulic geometry relations by stream types, this author assembled stream dimensions, slopes, and hydraulic data for six different stream types having the same discharge and channel materials. The objective was to demonstrate how the shape (width/depth ratio), profile (gradient), plan view (sinuosity), and meander geometry affect the hydraulic geometry relations. For example channel width increases faster than mean depth, with increasing discharge in high width/depth ratio channels. The opposite is true in low width/depth ratio channels. Streamflow values from baseflow of approximately 4 cfs up to bankfull values of 40 cfs were compared for each cross-section, and the corresponding widths, depths, velocities, and cross-sectional area for each stream type were computed. The A3, B3, C3, D3, E3 and F3 stream types selected for comparisons all had a cobble dominated bed-material size. The resultant hydraulic geometry relations for the selected array of stream types at the described flow ranges are shown in Fig. 11. Except for the E3 stream type for the plot of width/discharge, the slope of the plotted relations did not significantly change nearly as much as the intercept values.

6. Shear stress/velocity relations

Using the same data from the six stream types described previously, a "lumped" data base for all stream types from low to high flow was made for the corresponding shear stress ($\tau = \gamma RS$) (Shields, 1936) vs. mean velocity, where; $\tau =$ shear stress,

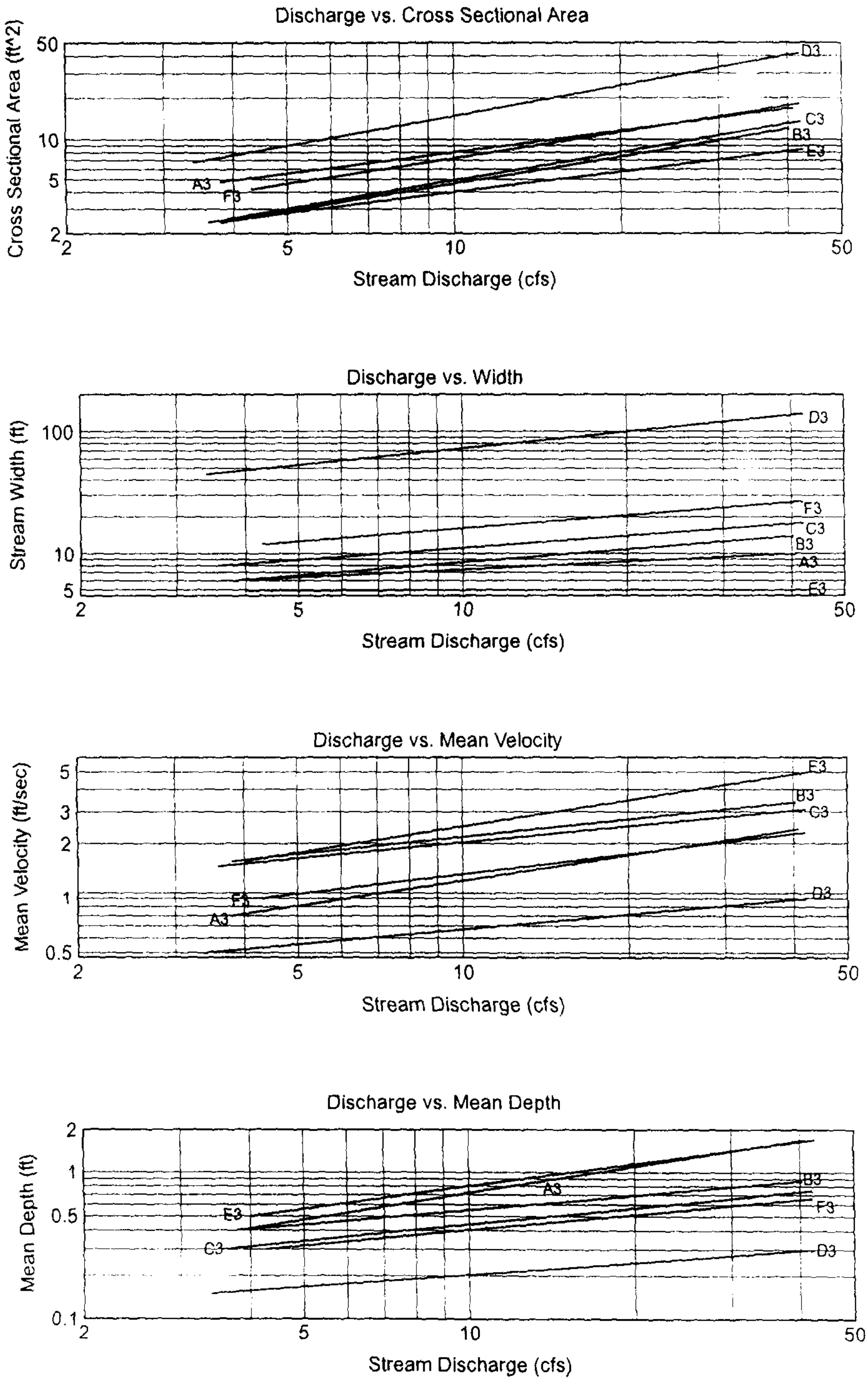


Fig. 11. Hydraulic geometry relations for selected stream types of uniform size.

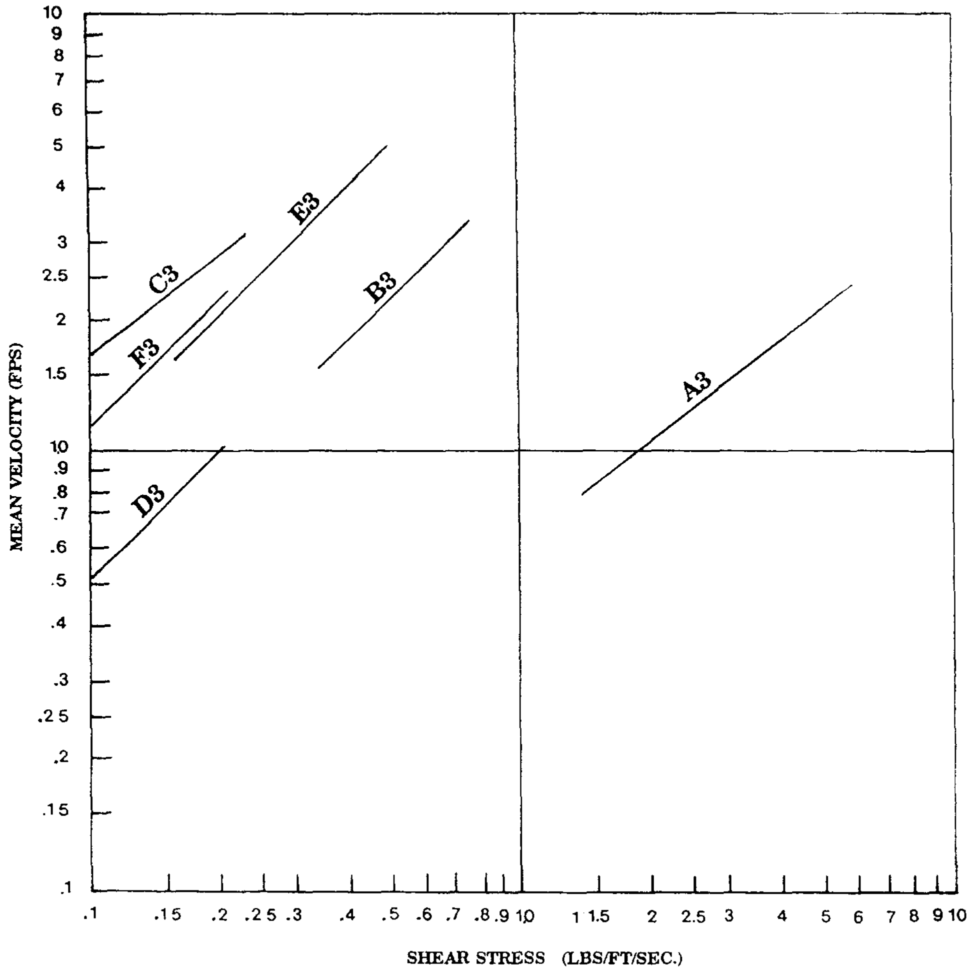


Fig. 12. Relationship of mean velocity vs. shear stress for six stream types from base flow (3-4 cfs) to bankfull discharge (40-41 cfs).

γ = density of water, R = hydraulic radius, and S = channel slope. As expected, a meaningful relation was not found. However, plotting shear stress and velocity stratification by stream type provided a trend that did shows promise (Fig. 12). While more data are needed to establish mathematical and statistical relationships, the comparisons arranged by stream type may have potential for future applications.

6.1. Critical shear stress estimates

Previous investigations of the magnitude of shear stress required to entrain various particle diameters from the stream-bed material have produced a wide range of values. A number of investigators have assumed the critical dimensionless shear

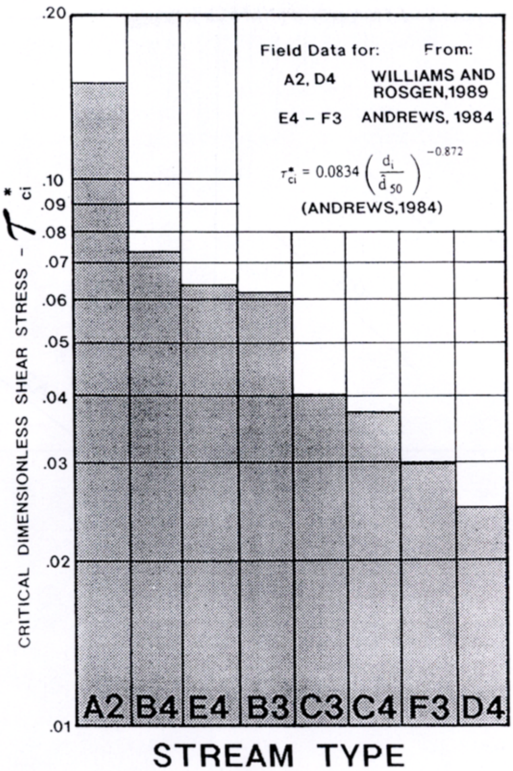


Fig. 13. Relationship of field verification of critical dimensionless shear stress values for various stream types.

stress values of 0.06 for computations of bedload transport using Shield's (1936) criteria (Baker, 1974; Baker and Ritter, 1975; Church, 1978; Bradley and Mears, 1980; Simons and Senturk, 1977; Simons and Li, 1982). In addition, critical dimensionless shear stress values computed from data compiled by Fahnestock (1963), Ritter (1967), and Church (1978) for the entrainment of gravels and cobbles from a natural river-bed, as reported by Andrews (1983) showed a range of approximately 0.02 to 0.25. The mean of the computed values was 0.06, which is the value suggested by Shields (1936).

Andrews (1983) described a relationship where to the ratio of surface (pavement) bed particles to sub-surface (sub-pavement) particles that yielded an estimate of critical dimensionless shear stress values (τ_{ci}*) from 0.02 to 0.28. Additional work using the same equation was applied to several Colorado gravel-bed streams with similar results (Andrews, 1984).

It is sometimes difficult for many engineers to obtain pavement and sub-pavement data along with the required channel hydraulics information to refine critical dimensionless shear stress estimates using the Andrews (1983, 1984) equation. The use of stream types to help bridge this gap of estimating the critical dimensionless shear stress value (τc) has potential where these study streams have been analyzed and classified. The study streams by Andrews (1984) were classified, data compiled and the values of $\tau_c{}^*$ (critical dimensionless shear stress) were plotted (Fig. 13). A2 and D4 stream types were obtained from field measurements of bedload sediment and bed-material size distribution for those types (Williams and Rosgen, 1989). Stream types and their morphologic/hydraulic characteristics do not substitute for detailed on-site investigations as described by Andrews (1983, 1984); however, calculations of $\tau_{ci}{}^*$ are often made without the benefit of site-specific investigation. Based on the great variability in the estimate of $\tau_{ci}{}^*$, sediment transport prediction errors can be from one to several orders of magnitude. A closer approximation of $\tau_{ci}{}^*$ for stream reaches that cannot be investigated in detail, is possible using the extrapolation approach shown in Fig. 13.

A similar analysis has been made but not included here using unit stream power rather than critical shear stress. This analysis again demonstrated that stratification by stream type improved sediment transport/stream power relations as an integrative function of the supply/energy distribution/resistance factors for specific stream types.

6.2. Sediment relations

Stream types have been used to characterize sediment rating curves that reflect sediment supply in relation to stream discharge. For example, a sediment rating curve regression relation for an A2 stream type would have a characteristic low slope and intercept. The sediment rating curve for the C4 stream type, however, has a higher intercept and steeper slope. The author has used this procedure for both suspended and bedload rating curves. These relationships were initially plotted as a function of channel stability ratings as developed by Pfankuch (1975). Applications for cumulative effects analysis for non-point sediment sources utilized this approach (USEPA, 1980). Subsequent comparisons of data with stream type delineations indicated similar relations.

The ratio of bedload to total sediment load can also be stratified by stream type where measured data is available. Ranges of less than 5% bedload to total sediment load for C3 stream types have been reported, but values greater than 75% bedload to total load for G4 stream types have also been measured (Williams and Rosgen, 1989). The "high ratio" bedload streams are the A3, A4, A5, D3, D4, D5, F4, F5, G3, G4, and G5 stream types.

6.3. Management interpretations

The ability to predict a river's behavior from its appearance and to extrapolate information from similar stream types helps in applying the interpretive information in Table 3. These interpretations evaluate various stream types in terms of; sensitivity to disturbance, recovery potential, sediment supply, vegetation controlling influence, and streambank erosion potential. Application of these interpretations can be used for; potential impact assessment, risk analysis, and management direction by stream type. For example, livestock grazing effects were related to stream stability and

Table 3
Management interpretations of various stream types

Stream type	Sensitivity to disturbance [a]	Recovery potential [b]	Sediment supply [c]	Streambank erosion potential	Vegetation controlling influence [d]
A1	very low	excellent	very low	very low	negligible
A2	very low	excellent	very low	very low	negligible
A3	very high	very poor	very high	high	negligible
A4	extreme	very poor	very high	very high	negligible
A5	extreme	very poor	very high	very high	negligible
A6	high	poor	high	high	negligible
B1	very low	excellent	very low	very low	negligible
B2	very low	excellent	very low	very low	negligible
B3	low	excellent	low	low	moderate
B4	moderate	excellent	moderate	low	moderate
B5	moderate	excellent	moderate	moderate	moderate
B6	moderate	excellent	moderate	low	moderate
C1	low	very good	very low	low	moderate
C2	low	very good	low	low	moderate
C3	moderate	good	moderate	moderate	very high
C4	very high	good	high	very high	very high
C5	very high	fair	very high	very high	very high
C6	very high	good	high	high	very high
D3	very high	poor	very high	very high	moderate
D4	very high	poor	very high	very high	moderate
D5	very high	poor	very high	very high	moderate
D6	high	poor	high	high	moderate
DA4	moderate	good	very low	low	very high
DA5	moderate	good	low	low	very high
DA6	moderate	good	very low	very low	very high
E3	high	good	low	moderate	very high
E4	very high	good	moderate	high	very high
E5	very high	good	moderate	high	very high
E6	very high	good	low	moderate	very high
F1	low	fair	low	moderate	low
F2	low	fair	moderate	moderate	low
F3	moderate	poor	very high	very high	moderate
F4	extreme	poor	very high	very high	moderate
F5	very high	poor	very high	very high	moderate
F6	very high	fair	high	very high	moderate
G1	low	good	low	low	low
G2	moderate	fair	moderate	moderate	low
G3	very high	poor	very high	very high	high
G4	extreme	very poor	very high	very high	high
G5	extreme	very poor	very high	very high	high
G6	very high	poor	high	high	high

[a] Includes increases in streamflow magnitude and timing and/or sediment increases.
[b] Assumes natural recovery once cause of instability is corrected.
[c] Includes suspended and bedload from channel derived sources and/or from stream adjacent slopes.
[d] Vegetation that influences width/depth ratio-stability.

sensitivity using stream types (Meyers and Swanson, 1992). They summarized their study results on streams in northern Nevada that "... range managers should consider the stream type when setting local standards, writing management objectives, or determining riparian grazing management strategies."

This interpretive information by stream type can also apply to establishment of watershed and streamside management guidelines dealing with; silvicultural standards, surface disturbance activities, surface disturbance activities, gravel and surface mining activities, riparian management guidelines, debris management, floodplain management, cumulative effects analysis, flow regulation from reservoirs/ diversions, etc. An example of the implementation of these guidelines by stream type are shown in the Land and Resource Management Plan (USDA, 1984).

Applications for riparian areas (USDA, 1992), have utilized the stream classification system into their recently developed "Integrated Riparian Evaluation Guide" — Intermountain Region. The classification system was used to help stratify and classify riparian areas based on natural characteristics and existing conditions. It is also used to evaluate the potential risks and sensitivities of riparian areas.

6.4. Restoration

The morphologic variables that interact to form the dimensions, profile and patterns of modern rivers are often the same variables that have been adversely impacted by development and land use activities. To restore the "disturbed" river, the natural stable tendencies must be understood to predict the most probable form. Those who undertake to restore the "disturbed" river must have knowledge of fluvial process, morphology, channel and meander geometry, and the natural tendencies of adjustment toward stability in order to predict the most effective design for long-term stability and function. If one works against these tendencies, restoration is generally not successful. Restoration applications using stream classification and the previously discussed principles are documented in the "Blanco River" case study (National Research Council, 1992).

7. Summary

Rivers are complex natural systems. A necessary and critical task towards the understanding of these complex systems is to continue the river systems research. In the interim, water resource managers must often make decisions and timely predictions without the luxury of a complex and thorough data base. Therefore, a goal for researchers and managers is to properly integrate what has been learned about rivers into a management decision process that can effectively utilize such knowledge. There is often more data collected and available on rivers than is ever applied. Part of the problem is the large number of "pieces" that this data comprises and the difficulty of putting these pieces into meaningful form.

The objective of this stream classification system presented here is to assist in bringing together these "pieces" and the many disciplines working with rivers under a common format — a central theme for comparison, a basis for extrapolation, prediction, and communication. The stream classification system can assist in organizing the observations of river data and of molding the many pieces together into a logical, useable, and reproducible system.

With the recent emphasis on "natural" river restoration or "naturalization" throughout Europe and North America, understanding the potential versus the existing stream type is always a challenge. The dimension of rivers related to the flow, and the patterns, which in turn are related to the dimensions, have to be further stratified by discrete stream types. In this way, the arrangement of the variables that make up the plan, profile and section views of stable stream types that are integrated within their valley's can be emulated. This also involves re-creation of the corresponding appropriate bed morphology associated with individual stream types with the observed sequence of step/pool and/or riffle pool bed features as a function of the bankfull width. The use of meander width ratios by stream type helps to establish the minimum, average and ranges of lateral containment of rivers. This often helps the design engineer/hydrologist determine appropriate widths that need to be accommodated when natural, stable rivers are re-constructed within their valleys. River and floodplain elevations, which need to be constructed, can be often determined by the used of the entrenchment ratio, which depicts the vertical containment of rivers in the landform. Using these integrative, morphological relations by stream type, can avoid the problematic "works" done on streams which create changes in the dimensions, pattern and profile of rivers which are not compatible with the tendencies of the natural stable form.

A classification system is particularly needed to stratify river reaches into groups that may be logically compared. Such stratification reduces scatter that might appear to come from random variation, whereas the scatter often results from attempting to compare items generically different. For example, data developed from empirical relations associated with process oriented research in natural channels such as tractive force relations, resistance and sediment transport equations, etc., can be stratified by stream type. This can help reduce the scatter when applied to stream types different than those from which the relations were developed.

Utilizing quantitative channel morphological indices for a classification procedure insures for consistency in defining stream types among observers for a great diversity of potential applications. The classification presented here may be the first approximation of a system that undoubtedly will be refined over the years with continued experience and knowledge. This stream classification system hopefully can be a vehicle to provide better communication among those studying river systems and promote a better understanding of river processes, helping put principles into practice.

Acknowledgements

I would like to thank the many individuals who have contributed in data collection, analysis, thought, and spirit towards this classification. The individuals are too numerous to mention, but in particular I would like to mention my river companions, Dr. Luna Leopold, Hilton "Lee" Silvey, Dale Pfankuch, Owen Williams, Alice Johns, Jim Nankervis and Steve Belz. Their contributions to consultation, analysis, and review are much appreciated. The majority of the illustrations were drawn by H. Lee Silvey. Appreciation of the fine work of word processing is acknowledged to Kay McElwain.

References

Andrews, E.D., 1980. Effective and bankfull discharges of streams in the Yampa River Basin, Colorado and Wyoming. J. Hydrol., 46: 311–330.

Andrews, E.D., 1983. Entrainment of gravel from natural sorted riverbed material. Geol. Soc. Am. Bull., 94: 1225–1231.

Andrews, E.D., 1984. Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado. Geol. Soc. Am. Bull., 95: 371–378.

Baker, V.R., 1974. Paleohydraulic interpretation of Quaternary alluvium near Golden, Colorado. Quat. Res., 4: 94–112.

Baker, V.R. and Ritter, D.F., 1975. Competence of rivers to transport coarse bedload material. Geol. Soc. Am. Bull., 86: 975–978.

Barnes, H.H., 1967. Roughness characteristics of natural channels. U.S. Geol. Survey, Water Supply Paper 1849, 213 pp.

Bradley, W.C. and Mears, A.I., 1980. Calculations of flows needed to transport coarse fraction of Boulder Creek alluvium at Boulder, Colorado. Geol. Soc. Am. Bull., Part II, 91: 1057–1090.

Brice, J.C. and Blodgett, J.C., 1978. Counter Measures for Hydraulic Problems at Bridges. Vol. 1, Analysis and Assessment. Report No. FHWA-RD-78-162, Fed. Highway Admin., Washington, DC, 169 pp.

Church, M., 1978. Paleohydrological reconstructions from a Holocene valley. In: A.D. Miall (Editor.), Fluvial Sedimentology. Can. Soc. Pet. Geol. Mem., 5: 743–772.

Church, M. and Rood, K., 1983. Catalogue of alluvial river channel regime data. Natural Sciences and Engineering Research Council of Canada. Dept. Geology Univ. British Columbia, Vancouver, B.C., Edition 1.0.

Culbertson, D.M., Young, L.E. and Brice, J.C., 1967. Scour and fill in alluvial channels. U.S. Geological Survey, Open File Report, 58 pp.

Davis, W.M., 1899. The geographical cycle. Geogr. J., 14: 481–504.

Dunne, T. and Leopold, L.B., 1978. Water in Environmental Planning. Freeman, San Francisco, CA, 818 pp.

Fahnestock, R.K., 1963. Morphology and hydrology of a glacial stream — White River. Mount Rainier, Washington. U.S. Geol. Survey Prof. Paper 422-A, 70 pp.

Galay, V.J., Kellerhals, R. and Bray, D.I., 1973. Diversity of river types in Canada. In: Fluvial Process and Sedimentation. Proceedings of Hydrology Symposium. National Research Council of Canada, pp. 217–250.

Grant, G.E., Swanson, F.J. and Wolman, M.G., 1990. Pattern and origin of stepped-bed morphology in high-gradient streams, Western Cascades, Oregon. Geol. Soc. Am. Bull., 102: 340–352.

Hicks, D.M. and P.D. Mason, 1991. Roughness characteristics of New Zealand rivers. New Zealand Dept. of Scientific and Industrial Research, Marine and Freshwater, Natural Resources Survey, Wellington, 329 pp.

Inglis, C.C., 1942. Rapid westerly movement of the Kosi River. Central Board of Irrigation, India (Technical), Poona, Bombay, pp. 7 and 8.

Jarrett, R.D., 1984. Hydraulics of high-gradient streams. J. Hydraul. Eng., 110(11): 1519–1539.

Jarrett, R.D., 1990. Hydrologic and hydraulic research in mountain rivers. Water Res. Bull. WARBAQ, 26(3): 419-429.

Kellerhals, R., Neill, C.R. and Bray, D.I., 1972. Hydraulic and geomorphic characteristics of rivers in Alberta. Research Council of Alberta, River Engineering and Surface Hydrology Report 72-1, p. 52.

Kellerhals, R., Church, M. and Bray, D.I., 1976. Classification and analysis of river processes. J. Hydraul. Div., ASCE, 102(HY7): 813-829.

Khan, H.R., 1971. Laboratory studies of alluvial river channel patterns. Ph.D. Dissertation, Dept. of Civil Engineering Department, Colorado State University, Fort Collins, CO.

Lane, E.W., 1957. A study of the shape of channels formed by natural streams flowing in erodible material. Missouri River Division Sediment Series No. 9, U.S. Army Engineer Division, Missouri River, Corps of Engineers, Omaha, NE.

Langbein, W.B. and Leopold, L.B., 1966. River meanders — Theory of minimum variance. U.S. Geol. Survey Prof. Paper No. 422-H, 15 pp.

Leopold, L.B. and Maddock, T., 1953. The hydraulic geometry of stream channels and some physiographic implications. U.S. Geol. Survey Prof. Paper No. 252. Supt. of Docs, U.S. Government Printing Office, Washington, DC, 57 pp.

Leopold, L.B. and Wolman, M.G., 1957. River channel patterns: braided, meandering, and straight. U.S. Geological Survey Prof. Paper 282-B.

Leopold, L.B., Wolman, M.G. and Miller, J.P., 1964. Fluvial processes in geomorphology. Freeman, San Francisco, CA, 522 pp.

Matthes, G., 1956. River engineering. In: P.O. Abbott (Editor), American Civil Engineering Practice. Wiley, New York, Vol. II, pp. 15-56.

Melton, F.A., 1936. An empirical classification of flood-plain streams. Geogr. Rev., 26.

Mollard, J.D., 1973. Air photo interpretation of fluvial features. In: Fluvial Processes and Sedimentation. Research Council of Canada, pp. 341-380.

Meyers, T.J. and Swanson, S., 1992. Variation of stream stability with stream type and livestock bank damage in Northern Nevada. Water Resources Bull. AWRA, 28(4): 743-754.

Nanson, G.C. and Croke, J.C., 1992. A genetic classification of floodplains. In: G.R. Brakenridge and J. Hagedorn (Editors), Floodplain Evolution. Geomorphology, 4: 459-486.

National Research Council, 1992. Restoration of aquatic ecosystems. Restoration case studies. National Academy Press, Washington, DC, pp. 470-477.

Osborn, J.F. and Stypula, J.M., 1987. New models of hydrological and stream channel relationships. In: Erosion and sedimentation in the Pacific Rim. IAHS Publ. No. 165, Oregon State Univ., Corvallis, OR.

Pfankuch, D.J., 1975. Stream reach inventory and channel stability evaluation. USDA Forest Service, R1-75-002. Government Printing Office #696-260/200, Washington DC, 26 pp.

Pickup, G., 1984. Geomorphology of tropical rivers. 1. Landforms, hydrology and sedimentation in the fly and lower Purari, Papua New Guinea. In: A.P. Schick (Editor), Channel Processes, Water, Sediment, Catchment Controls. Catena Suppl., 5: 1-17.

Platts, W.S., 1980. A plea for fishery habitat classification. Fisheries, 5(1): 1-6.

Ritter, J.R., 1967. Bed-material movement. Middle Fork Eel River, California. U.S. Geol. Survey Prof. Paper 575-C, pp. C219-C221.

Rosgen, D.L., 1985. A stream classification system. In: Riparian Ecosystems and Their Management. First North American Riparian Conference. Rocky Mountain Forest and Range Experiment Station, RM-120, pp. 91-95.

Rosgen, D.L. and Fittante, B.L., 1986. Fish habitat structures — A selection guide using stream classification. In: J.G. Miller, J.A. Arway and R.F. Carline (Editors), 5th Trout Stream Habitat Improvement Workshop, Lock Haven Univ., Lock Haven, PA. Penn. Fish Comm. Publics, Hamsburg, PA, pp. 163-179.

Schumm, S.A., 1963. A tentative classification of alluvial river channels. U.S. Geological Survey Circular 477. Washington, DC.

Schumm, S.A., 1977. The Fluvial System. Wiley, New York, 338 pp.

Selby, M.J., 1985. Earth's Changing Surface: an Introduction to Geomorphology. Oxford University Press, Oxford.

Shields, A., 1936. Application of similarity principles and turbulence research to bed-load movement. In: W.P. Ott and J.C. Uchelen (translators), Mitt. Preuss. Verschsanst., Berlin. Wasserbau Schiffbau. California Institute of Technology, Pasadena, CA, Report No. 167, 43 pp.

Simons, D.B. and Senturk, F., 1977. Sediment Transport Technology. Water Resource Publications, Fort Collins, CO, 807 pp.

Simons, D.B. and Li, R.M., 1982. Engineering Analysis of Fluvial Systems. SLA, P.O. Box 1816, Fort Collins, CO.

Smith, D.G. and Smith, N.D., 1980. Sedimentation in anastomosing river systems: examples from alluvial valleys near Banff, Alberta. J. Sediment. Petrol., 50: 157–164.

Thornbury, W.D., 1969. Principles of Geomorphology. 2nd Edition. Wiley, New York.

USDA (U.S. Department of Agriculture), Forest Service, 1984. Land and Resource Management Plan — Arapaho and Roosevelt National Forests and Pawnee Grassland. Fort Collins, CO.

USDA (U.S. Department of Agriculture), Forest Service, 1989. Fisheries Habitat Surveys Handbook. Region 4 — FSH 2609.23. Ogden, UT.

USDA (U.S. Department of Agriculture), Forest Service, 1992. Integrated Riparian Evaluation Guide. Intermountain Region — Ogden, UT.

USEPA (U.S. Environmental Protection Agency), 1980. An approach to water resources evaluation of non-point silvicultural sources. Chap. VI, Total Potential Sediment, D. Rosgen. EPA-600/8-80-012, Athens, GA, pp. 39–41.

Williams, G.W., 1986. River meanders and channel size. J. Hydrol., 88: 147–164.

Williams, G.P. and Rosgen, D.L., 1989. Measured total sediment loads (suspended loads and bedloads) for 93 United States streams. Open File Report 89-67. U.S. Geol. Survey, Denver, CO, 128 pp.

Wolman, M.G., 1954. A method of sampling coarse river-bed material. Trans. Am. Geophys. Union, 35: 951–956.