Part II
The Biotic Environment

5

Biotic Stream Classification*

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Overview

- Stream classification implies that sets of observations or characteristics can be organized into meaningful groups based on measures of similarity or difference. Although this chapter focuses on biotic classification systems and management applications, it briefly reviews selected physical classification systems discussed by Montgomery and Buffington (Chapter 2) that are important for understanding biotic patterns.
- Early attempts at whole river classifications were generally unsuccessful because of the biophysical variability inherent over large spatial scales. At a smaller spatial scale, classification of river segments by stream order, linkage number, and drainage density has been useful because the scale is more appropriate for understanding patterns of biotic zonation either by using fish or invertebrates as indicators of segment types or by delineating zones where ecological processes (such as primary production or detrital dynamics) are occurring.
- Recent concepts emphasize multidisciplinary bases for classification related to increasingly small spatial units and hierarchical rankings of linkages between the geologic and climatic settings, stream habitat features, and biota. These are divided into ultimate (large spatial and long temporal scales) and proximate (small and short scales) controls on system characteristics. Classifications of physical features use either a single scale system (e.g., stream order, linkage number, or ecoregion) or a hierarchical system which nests characteristic features over a variety of spatial and temporal scales.
- Rosgen's (1994) classification system is used to illustrate the classification of present-day channels relative to their geologic setting and related fluvial processes such as water hydraulics and material transport.
- Most classification systems coupling biological and physical features employ vertebrate (mostly fish) and invertebrate (mostly insect) distributions. Occasionally, riparian and aquatic vegetation are utilized. Overall, these approaches usually sacrifice precision for generality. The usefulness of biologically based systems in stream management is diminished because of the intensive efforts demanded to measure and monitor community characteristics. However, the need for such a system remains great because of the significance of the biological community to regional ecological integrity.
- The best approach to stream classification depends on the scope and the nature of the question being asked. However, in general, the system chosen should have the ability to encompass broad spatial and temporal scales, to integrate structural and functional characteristics under different disturbance regimes, to convey information about mechanisms

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*This chapter is an updated version of Naiman et al. 1992 controlling stream features. and to accomplish the goal at low cost and at a high level of uniform understanding among resource managers.

Introduction

Classification systems have been used for centuries to organize information about ecological systems. Yet the classification of fluvial systems remains a difficult topic because running waters exhibit such dynamic changes with time and space. Each stream possesses a set of characteristics (e.g., morphology, hydrology, productivity, and so forth) which change in response to the local climate, geology, and disturbance regime.

The term "classification" implies that sets of observations or characteristics can be organized into meaningful groups based on measures of similarity or difference (Gauch 1982, Hawkins et al. 1993). Implicitly, relatively distinct boundaries exist and may be identified by a set of discrete variables. However, the classification of streams is complicated by both longitudinal and lateral linkages, by changes that occur in the physical features over time, and by boundaries between apparent patches that are often indistinct (Naiman et al. 1992, Rosgen 1994). For example, geomorphic and ecological characteristics of streams vary spatially from the headwaters to the sea (Langbein and Leopold 1966, Vannote et al. 1980), as well as temporally in response to disturbance patterns (Bisson et al. 1982, Wissmar and Swanson 1990).

Stream classification is essential for understanding the distribution of ecological patterns within drainage networks and for developing management strategies that are responsive to the ecological patterns. This chapter reviews the principles of stream classification through an analysis of conceptual approaches previously used to develop several contrasting schemes. Historic and extant classification systems, based on a variety of spatial scales (from microhabitats to ecoregions) incorporate several combinations of physical and biological components that are important to riverine systems. Chapter 2 provides a detailed discussion of some of the more useful physically based classifications while this chapter focuses on biotic classification systems and management applications. Nevertheless, it is prudent to briefly summarize the physical classification systems discussed by Montgomery and Buffington (Chapter 2) which are important for understanding biotic patterns.

Historical Concepts

The history of stream classification is reviewed comprehensively by Wasson (1989), Naiman et al. (1992) and Rosgen (1994). The dominant conceptual themes of the early efforts range from biological to physical features over spatial scales of a few meters to hundreds of square kilometers. At the larger scale, one of the original whole-river schemes was developed for New Jersey (USA) rivers (Davis 1890). Davis classified streams as young, mature, or old on the basis of observed erosion patterns. Later, Shelford (1911) attempted to produce a biological classification scheme for whole rivers in Michigan (USA) based on his idea of succession. However, because of longitudinal differences in physical and biological characteristics, whole-stream classification has been -of little use.

In contrast, basin-wide classification systems based on drainage network characteristics such as stream order, linkage number (total number of lst-order streams), and drainage density (Horton 1945, Strahler 1957) have proven useful, but too simplistic, for elucidating biotic patterns within drainage basins. Many became important tools-if only locally adapted— during the early part of the century. Early classifications generally were based on perceived patterns of biotic zonation using species of fish or invertebrates as indicators of segment types (Carpenter 1928, Ricker 1934, Huet 1954). In addition, numerous specialists of certain orders of stream invertebrates (e.g., Plecoptera, Ephemeroptera, Trichoptera) also utilized their data to propose organizational patterns (Macan 1961, Illies and Botosaneanu 1963). These early attempts at stream classification recognized that biotic zonation patterns generally were correlated with gradient or other abiotic features such as temperature or water chemistry, although Huet (1954) also recognized the importance of larger spatial scales by incorporating valley form. Later, classifications using stream order and linkage number were successful in describing patterns of ecological processes, such as primary production and detrital dynamics (Minshall et al. 1983, Naiman et al. 1987). In spite of widespread recognition of distinct biotic zones along rivers, there were many early critics because key physical parameters change gradually along the stream continuum (e.g., slope and width), and the biological characteristics change in a similar manner.

There are two general limitations to these historic systems. First, the reliance on species as indicators of ecological zones means that the biotic zonation schemes are only valid in basins with similar zoogeographic, geologic, and climatic histories. Despite relating physical factors to biotic patterns, these schemes failed to construct a conceptual framework for stream classification that could transcend regions. Second, for both physical and biological zonation systems there were no features relating geologic and climatic processes, which regulate the physical features of streams, to the classification system. Therefore, these efforts were ineffective at relating watershed-scale processes to dynamic changes in channel features (Naiman et al. 1992). However, the application of landscape ecology concepts (such as patches, boundaries, and connectivity) to rivers is now becoming a useful approach to overcome some of this difficulty (Décamps 1984, Ward and Stanford 1987, Rosgen 1994).

Recent Concepts

Ideally, a classification system should be based on a hierarchical ranking of linkages between the geologic and climatic settings, the stream habitat features and the biota (Hawkins et al. 1993). These-the geomorphic and climatic processes that shape the abiotic and biotic features of streams-provide a conceptual and practical foundation for understanding the structure and processes of fluvial systems (Chapter 2, Chapter 11). Furthermore, an understanding of process allows streams to be viewed in a larger spatial and temporal perspective, and to infer the direction and magnitude of potential changes due to natural and human disturbances. A stream classification system. based on patterns and processes and how they are expressed at different temporal and spatial scales, is the basis for successful management (Rosgen 1994).

Conceptually, individual stream classification units can be thought of as an integrated collection of ultimate and ***proximate*** controls on system characteristics. These terms generally correspond to higher and lower levels of a hierarchical ranking of controlling factors. Ultimate controls refer to a set of geologic factors that act over large areas (>1 km’), are stable over long time scales ($>10^4$ yr), and dictate the range of conditions possible in a drainage network. These include physical characteristics, such as regional geology and climate, and biotic characteristics, such as zoogeography (Moyle and Li 1979, Briggs et al. 1990). Proximate controls refer to local geomorphic and biotic processes important at small scales ($<10^2\,\mathrm{m}^2$), which can change stream characteristics over relatively short time periods ($<10^4$ yr). Proximate controls are constrained by ultimate controls and include such physical processes as discharge, temperature, hillslope erosion, channel migration, and sediment transport; and the biotic processes of reproduction, competition, disease, and predation-all of which may be influenced by an equally diverse array of human impacts. Within this conceptual framework, management strategies to effectively maintain important physical and ecological structures may be tailored to local conditions.

Frissell et al. (1986) discuss the topic of ultimate and proximate controls utilizing ideas from hierarchy theory to construct a continuum of habitat sensitivity to disturbance and recovery time (Figure 5.1). In their scenario, microhabitats are most sensitive to disturbance and watersheds are least sensitive. Furthermore,

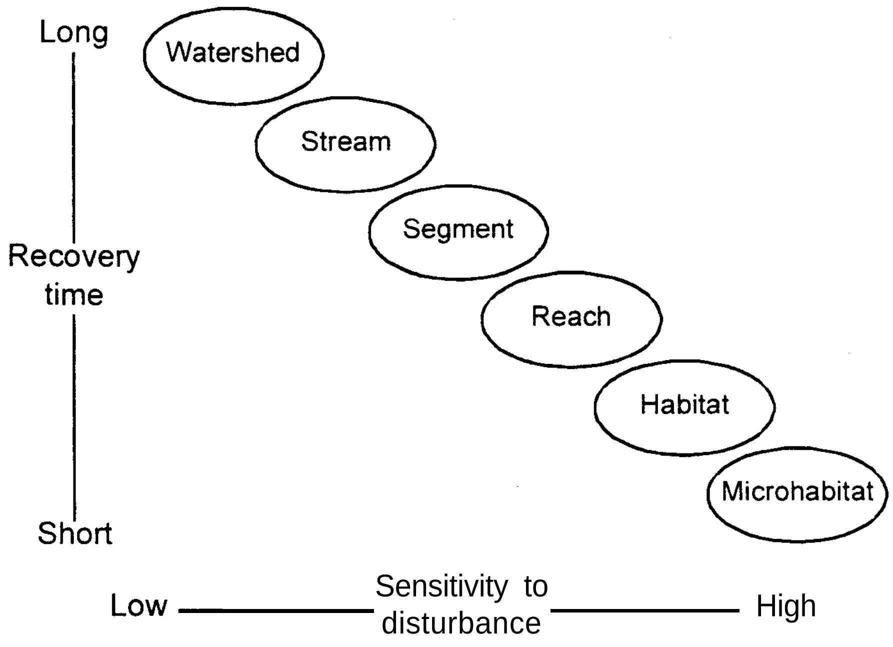

FIGURE 5.1. Relationship between recovery time and sensitivity to disturbance for different spatial scales associated with stream systems (After Frissell et al. 1986 and from Naiman et al. 1992. Reproduced with permission). See Table 5.1 for definition of spatial scales.

individual events that affect smaller-scale habitat characteristics generally do not affect larger-scale system characteristics (however, collectively they can have an impact). whereas large-scale disturbances directly influence smaller-scale features of streams. For example, on a small spatial scale, deposition at one site may be accompanied by scouring at another site nearby, and the reach or segment does not appear to change significantly. In contrast, a large-scale disturbance (such as a debris flow) is initiated at the segment level and reflected in all lower levels of the hierarchy (reach, habitat, microhabitat). On a temporal scale. siltation of microhabitats may disturb the biotic community over the short term. However, if the disturbance is of limited scope and intensity. the system may recover quickly to predisturbance levels.

Tailoring management strategies to stream types implies that the classification system includes the physical and biotic characteristics of the stream, as well as the disturbance regime creating and maintaining those characteristics. Successful classification systems are able to categorize the types and frequencies of disturbance that may impact the stream and predict adjustments in the physical and biotic characteristics.

Classification of Physical Watershed Features (a Summary)

River classification based on geomorphic characteristics came into prominence in the 1940s (Horton 1945, Leopold and Wolman 1957). This approach became important to fisheries biologists and land managers because geomorphic patterns are strongly linked to patterns of species distribution and abundance (Huet 19.54, Bisson et al. 1988, Morin and Naiman 1990). Almost all classification schemes based on physical habitat features have been founded on the perception that stream units (i.e., segment, reach, habitat) are discrete and can therefore be delineated. However, that is not always the case. Subtle gradations between segment types, reach types, and habitat types are common. Fortunately, dramatic and abrupt physical changes in stream width, depth, and velocity also are found (Frissell et al. 1986, Kellerhals and Church 1989). For example, Frissell et al. (1986) defined longitudinal boundaries of segment types by easily measured tributary junctions, major waterfalls, or other structural discontinuities, while reaches were defined less clearly by changes in channel gradient. Ultimately, however, the scope of the issue, or nature of the question being considered, should determine the appropriate scale(s) of resolution.

Single-Scale Classification

Observed patterns in drainage networks led to the development of the stream order concept (Horton 1945, Strahler 1957). Within geographic regions, this system has been correlated with physical and biotic features of streams (for example, see Minshall et al. 1983, Naiman et al. 1987). However, it is much less reliable at predicting patterns and behavior of stream characteristics across regions, or at microscales within regions. For example, major differences in stream size (Minshall et al. 1983) and response to disturbance (Resh et al. 1988) can be encountered for streams of the same order between regions because of variability in geology and hydrology. More importantly, stream order by itself provides little information on processes controlling longitudinal and lateral patterns, and therefore makes predictions of response to both natural and human disturbance imprecise. In spite of its almost universal usage in the United States, the value of the stream order classification scheme is only as an indicator of relative biotic and stream segment characteristics and position within a given drainage network. When properly used, however, it can be valuable as an ***accounting*** tool in categorizing biological and physical data.

Other more recent approaches to classification include large-scale schemes developed for their potential usefulness to regional water resource and fisheries managers. Bailey (1978) defined 11 ecoregions that delineated large areas ($>10^3\,\mathrm{km}^2$) of the United States based on climate. physiography, and vegetation. These were chosen because they were thought to be important in stratifying in-channel features (Rohm et al. 1987). The system has now been tested successfully in at least three areas (the upper Midwest, Arkansas, and Oregon, USA) with respect to chemical characteristics and fish species distribution (Larsen et al. 1986, Whittier et al. 1988). Rohm et al. (1987) were able to categorize fish assemblage, physical habitat (e.g., percentage riffle, pool) and water chemistry (e.g., alkalinity, conductivity) patterns into six ecoregions (Omernik 1987). The ecoregion concept is effective for grouping of streams where large-scale resolution is required (e.g., Rohm et al. 1987).

Hierarchical Classification

Recent stream classification systems in North America have been based on a hierarchical perspective linking large regional scales (ecoregions) with small microhabitat scales (Table 5.1). This approach is especially useful since stream processes occur at scales spanning 16 orders of magnitude (10^{-7}–$10^{8}\,\mathrm{m}$ spatially and 10^{-8}–$10^{7}\,\mathrm{yr}$ temporally; Minshall 1988). Several classification systems have been developed using nested landscape or channel features (Warren 1979, Frissell et al. 1986, Cupp 1989, Hawkins et al. 1993, Rosgen 1994, Chapter 2 this volume). The value of hierarchical stream classification is greatest when broadly applied (e.g., global, national, regional scales; Frissell et al. 1986). However, the approach is flexible enough to be modified for subregional purposes. Furthermore, it is important to understand the relative roles of controlling factors in determining the long-term and short-term characteristics of streams since the relative importance of the factors changes with spatial and temporal scales. Finally, a hierarchical approach requires fewer variables at any one level for classification. Within most geographic regions, managers and scientists need only one or two spatial and temporal scales to classify streams (Table 5.2).

One of the first hierarchical classification systems was developed by Warren (1979). He described 11 levels ranging from regional ($>10^2\,\mathrm{km}^2$) to microhabitat ($<1\,\mathrm{m}^2$) defined largely by four variables (substrate, climate, water chemistry, and biota). Warren did not propose a concrete classification system, but his

TABLE 5.1. Some events or processes controlling stream habitat on different spatio-temporal scales.

Svstem level	Linear spatial scale” (m)	Evolutionary events[b]	Developmental processes‘	Time scale of continuous potential persistence” (yr)
Stream	10^3	Tectonic uplift subsidence: catastrophic volcanism: sea level changes; glaciation: climate shifts	Planation: denudation; drainage network development	10^6–10^5
Segment	10^2	Minor glaciation. volcanism: earthquakes: very large landslides; alluvial or colluvial valley intilling	Migration of tributary junctions and bedrock nick-points: channel floor incision; development of new 1st-order channels	10^4–10^3
Reach	10’	Debris torrents: landslides: log input or washout; channel shifts. cutoffs: channelization, diversion or damming by humans	Aggradation/degradation associated with large sediment-storing structures: bank erosion: riparian vegetation succession	10^2–10^1
Habitat or Channel Unit	IO”	Input or washout of wood. boulders etc.; small bank failures; flood scour or deposition: thalweg shifts; numerous human activities	Small-scale lateral or elevational changes in bedforms: minor bedload resorting	10^1–10^0
Microhabitat	10^{-1}	Annual sediment and organic matter transport; scour of stationary substrates: seasonal macrophyte growth and cropping	Seasonal depth and velocity changes: accumulation of fines: microbial breakdown of organics; periphyton growth	10^0–10^{-1}

[a] Space and time scales indicated are approximate for a 2nd- or 3rd-order mountain stream. Caution is advised in using absolute spatial scales for the hierarchy. Depending on the specific situation. for example, a channel reach may be tens to hundreds of meters long while a habitat unit may be less than one meter to several meters long. Perhaps a better spatial index that preserves geomorphic similitude is scaling by channel width (Chapter 2 this volume) because there is no absolute association of channel size with stream order.

[b] Evolutionary events change potential capacity: that is, extrinsic forces that create and destroy systems at that scale.

[c] Developmental processes are intrinsic, progressive changes following a system’s genesis in an evolutionary event.

From Frissell et al. 1986 with permission.

TABLE 5.2. Habitat spatial boundaries, conforming with the temporal scales of Table 5.1.

System level	Capacity time scale” (yr)	Vertical boundaries’	Longitudinal boundaries’	Lateral boundaries[d]	Linear spatial scale” (m)
Stream	10^6–10^5	Total initial basin relief; sea level or other base level	Drainage divides and sea coast, or chosen catchment area	Drainage divides: bedrock faults, joints controlling ridge valley development	10
Segment	10^4–10^3	Bedrock elevation: tributary junction or falls elevation	Tributary junctions: major falls. bedrock lithological or structural discontinuities	Valley sideslopes or bedrock outcrops lateral migration	10^2
Reach	10^2–10^1	Bedrock surface: relief of major sediment-storing structures	Slope breaks: structures capable of withstanding <50 year flood	Mean annual flood channel: mid-channel bars: other flow-splitting obstructions	10’
Habitat or Channel Unit	10^1–10^0	Depth of bedload subject to transport in <10-year flood: top of water surface	Water surface and bed profile slope breaks; location of genetic structures	Same as longitudinal	10^0
Microhabitat	10^0–10^{-1}	Depth to particles immovable in mean annual flood: water surface	Zones of differing substrate type, size, arrangement; water depth and velocity		10^{-1}

[a] Scaled to approximate a 2nd- or 3rd-order mountain stream. See cautions in Table 5.1, footnote a.

[b] Vertical dimension refers to upper and lower surfaces.

[c] Longitudinal dimension refers to upstream-downstream extent.

[d] Lateral dimension refers to cross-channel or equivalent horizontal extent.

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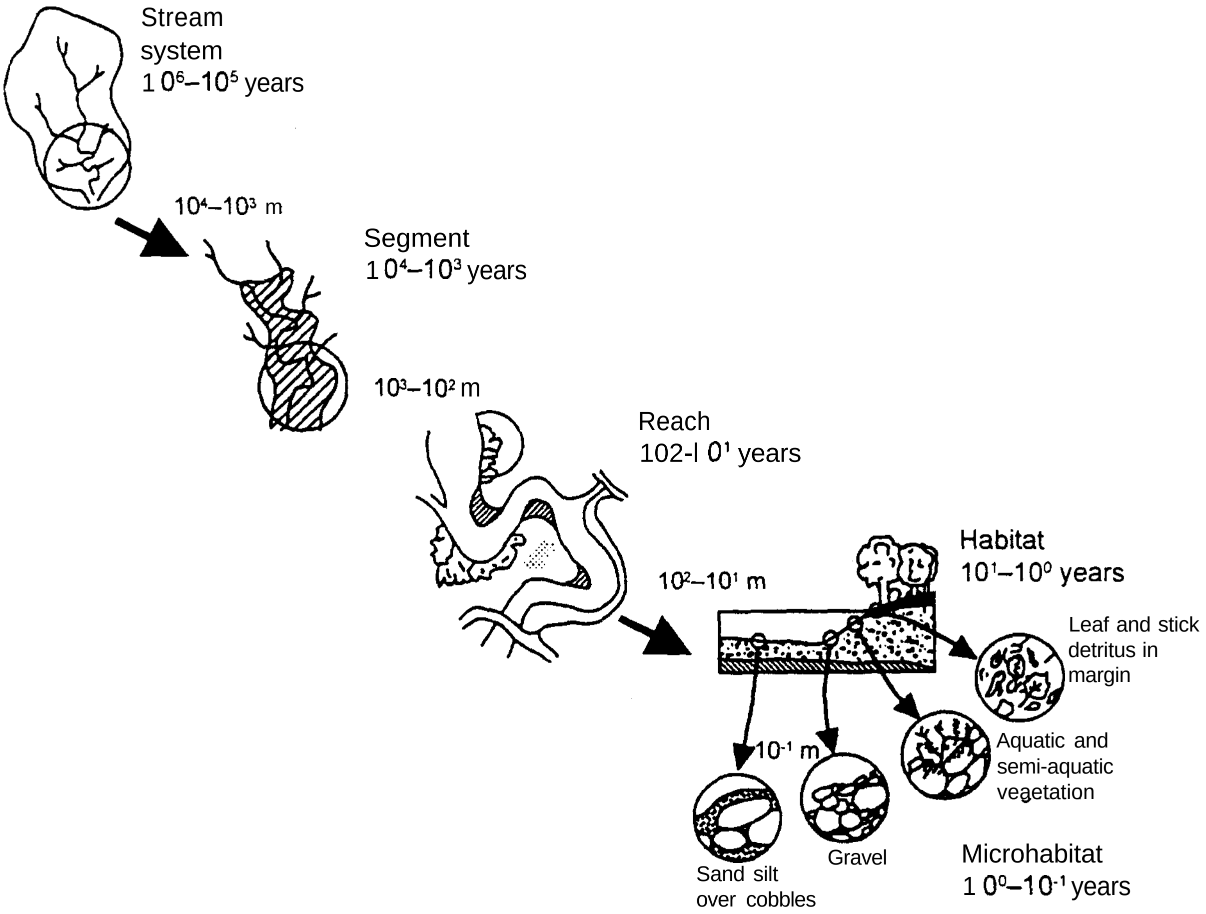

FIGURE 5.2. Hierarchical organizations of a stream system and its habitat subsystems. Linear spatial scale, approximated to 4th- to 6th-order mountain stream, is indicated as well as the temporal duration of existing channel features (modified from Frissell et al. 1986 with permission).

contribution to the conceptual evolution of stream classification is worth noting because he presented an explicit theoretical structure for a complex hierarchical system. He stressed the importance of assessing the potential of a stream (i.e., all possible developmental states and performances that a system may exhibit while still maintaining its integrity as a coherent unit) rather than its current condition. Evaluating potential states for a system assists in distinguishing natural variability from human disturbance.

Frissell et al. (1986) extended Warren's approach by incorporating spatially nested levels of resolution (e.g., watershed, stream, valley segment, reach, habitat unit (e.g., pool/riffle), and microhabitat) (Table 5.2, Figure 5.2). An important conceptual advancement, this system addressed form or pattern within each hierarchical level, as well as origins and processes of development. Nawa et al. (1990) used this approach to show that both fish species composition and the sensitivity of channels to disturbance varied between different valley segment types.

Other significant hierarchical classification systems for broad scales of resolution include that of Lotspeich (1980) and Brussock et al. (1985). Brussock et al. (1985) developed a hierarchical system for large rivers based primarily on predictable patterns of variation in channel form. Channel form is an important parameter because it overlays in-channel features (e.g., relief, lithology, and discharge) controlling the physical state of the stream (e.g., temperature, depth, substrate, and velocity) which, in turn, influences the character of biotic resources. Variations in channel form are believed to be related to lithology, gradient, and climate (state factors), as they act on substrate particle size,

TABLE 5.3. Valley bottom and sideslope geomorphic characteristics used to identify the five valley segment types in Figure 5.3.

Valley segment type[a]	Average Channel gradient[b]	Sideslope gradient[c]	Valley bottom width[d]	Channel patterns	Stream order[e]	Landform and geomorphic features
F2 Alluviated lowlands	≤1%	>5%	>5X	Unconstrained: highly sinuous	Any	Wide floodplains typically formed by present or historic large rivers within flat to gently rolling lowland landforms: sloughs. oxbows, and abandoned channels commonly associated with mainstream rivers
VI V-shaped. moderate-gradient bottom	*2-6* %	30–70%	<2X	Constrained	≥2	Deeply incised channels with steep competent sideslopes: very common in uplifted mountainous topography: less commonly associated with marine or glacial outwash terraces in lowlands and foothills
V4 Alluviated mountain valley	1–4%	Channel adjacent slopes <10%; increase to ≥30%+	*2-4X*	Unconstrained: high sinuosity with braids and side-channels common	*2-5*	Deeply incised channels with relatively wide floodplains; distinguished as “alluvial Rats” in otherwise steeply dissected mountainous terrain
U4 Active glacial out-wash valley	1–7%	Initially <5%, increasing to >60%	<4X	Unconstrained; highly sinuous and braided	*1-3*	Stream corridors directly below active alpine glaciers; channel braiding and shifting common; active channel nearly as wide as valley bottom
H3 Very high-gradient valley wall/head-water	11%+	>60%	<2X	Constrained: stair-stepped	*1-2*	Small channels moderately entrenched into high-gradient mountain slopes or headwater basins; bedrock exposures and outcrops common; localized alluvial/colluvial terrace deposition

[a] Valley segment type names include alphanumeric mapping codes in italic (from Cupp, 1989a, b).

[b] Valley bottom gradient is measured in lengths of *ca. 300* m or more.

[c] Sideslope gradient characterizes the hillslopes within 1.000 horizontal and ***ca.*** 100 m vertical distance from the active channel.

[d] Valley bottom width is a ratio of the valley bottom width to active channel width.

[e] Stream order defined by Strahler (1957).

bed load, and competence. Examining streams throughout the United States, they described seven regions based on differences in state factors. They related channel form to community structure and confirmed L.B. Leopold’s assertion that stream channel form can be predicted along the length of the river within geographic regions (Leopold et al. 1964).

In the Pacific Northwest, three hierarchical classification systems are widely used in resource management (Cupp 1989, Hawkins et al. 1993, Rosgen 1994) while the system described by Montgomery and Buffington (Chapter 2) is gaining acceptance. Cupp (1989) adapted the hierarchical concept of Frissell et al. (1986) to small forested streams in Washington using eight hierarchical levels ranging from ecoregion to microhabitat. Valley segments are distinguished by average channel gradient and valley form (Table 5.3, Figure 5.3). Initial field tests show that stream segment types are correlated with habitat (Beechie and Sibley 1990). Hawkins et al. (1993) refined the Bisson et al. (1982) system of salmonid habitat classification by first identifying which physical characteristics were needed to describe specific channel units and then ranking their importance as descriptive features useful in defining and discriminating among different types of channel units. They recommend a three-level hierarchy

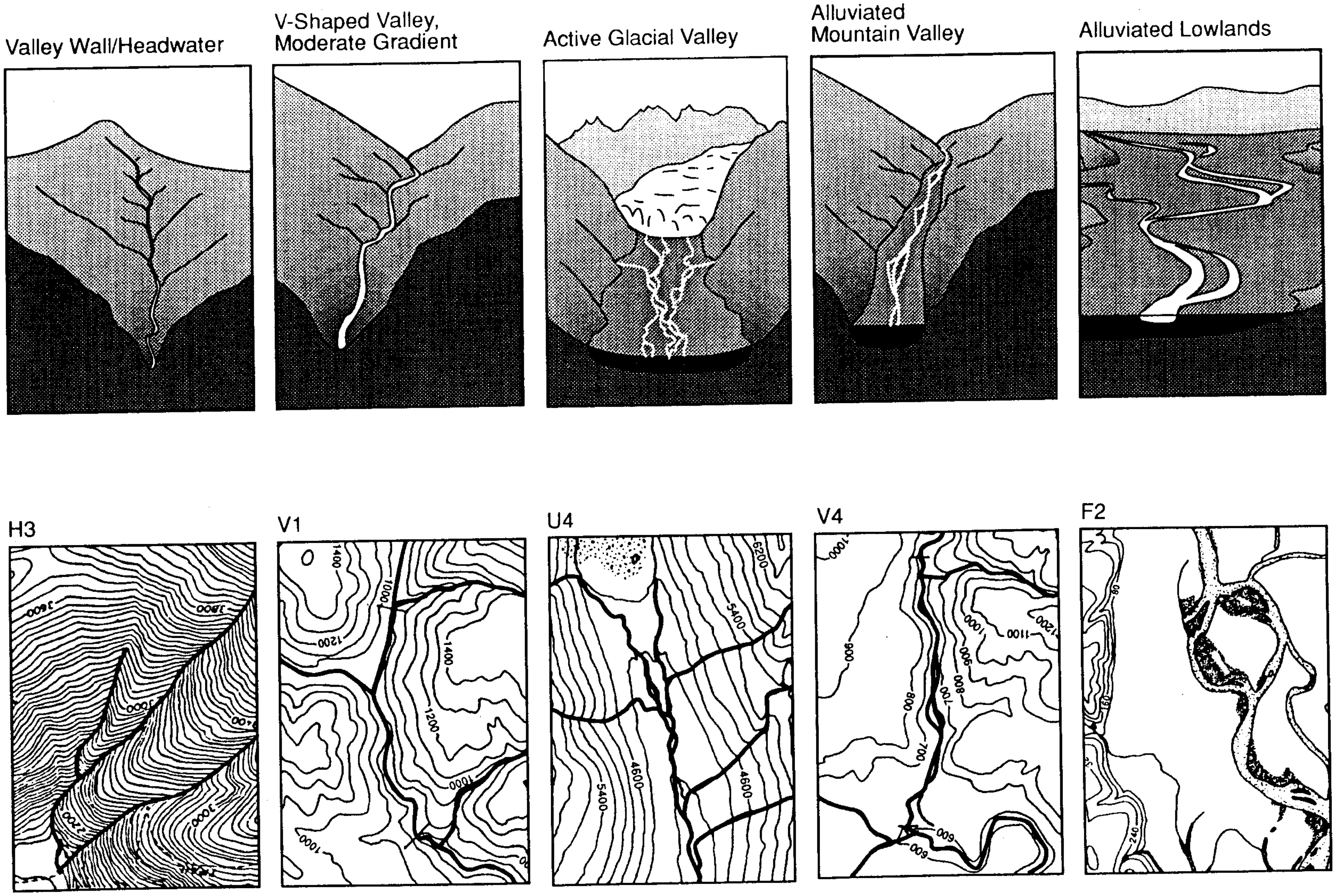

Figure 5.3. Three-dimensional projections made from topographic maps assist in determining segment type. See Table 5.3 for physical characteristics of each stream type (Naiman et al. 1992 reproduced with permission).

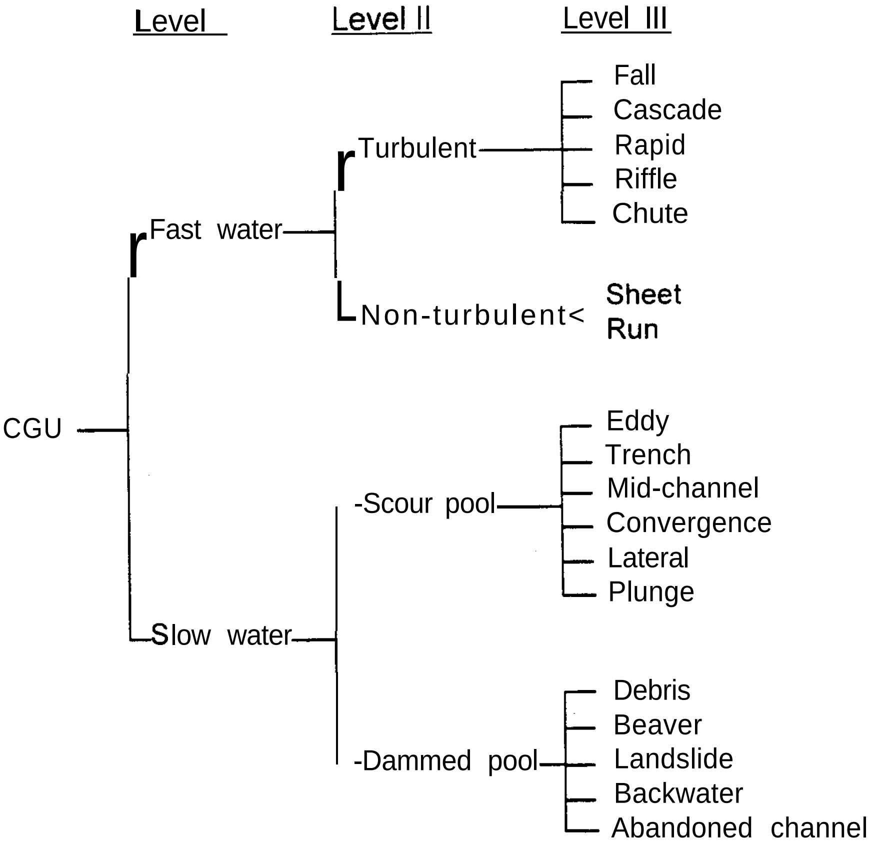

FIGURE 5.4. Similarity dendrogram illustrating how channel geomorphic units (CGU) can be classified with increasing levels of resolution. Three levels of resolution are shown that can be used to distinguish classes (Hawkins et al. 1993 with permission).

(Figure 5.4): (A) At the coarsest level of resolution are pool and riffles; (B) at base flows riffles are either turbulent or not, and pools are created by either scour or material deposition in the channel: (C) the fast- and slow-water classes are further subdivided based on other physical criteria related to specific fish-habitat considerations. Fishes and other stream organisms appear to distinguish among these habitats at one or more levels of the hierarchy but, unfortunately, there are few published data available for empirical tests of the system. Rosgen (1994) developed a classification system based on geomorphic and in-channel characteristics, including channel gradient, sinuosity, width-to-depth ratio, bed material, entrenchment, channel confinement, soil erodibility, and stability. It also includes subcategories that may change over short temporal scales and are characterized by riparian vegetation, channel width, organic debris, flow regime, meander patterns, depositional features, and sediment supply. Rosgen's stream-type classification system has been used widely for site-specific riparian forest and fisheries management, and for predicting geomorphic and hydrologic processes.

Rosgen's (1994) classification system requires further explanation because of its wide use. It is based on a morphological arrangement of the aforementioned stream characteristics organized into relatively homogeneous stream types. He correctly assumes that contemporary channel morphology is governed by physical laws resulting in observable stream features and fluvial processes (such as water hydraulics and transported materials). A change in any one of the fluvial (i.e., physical) processes causes channel adjustments which lead to changes in other fluvial processes, resulting in new channel features.

Rosgen (1994) recognizes four hierarchical aspects to classification: (I) broad geomorphological characterization, (II) morphological description of the channel, (III) stream condition, and (IV) verification (Table 5.4). The first two aspects address the character of the channel, forming the basis of his system, and are discussed below. Aspect III addresses the state of the stream further describing existing conditions that influence the response of channels to imposed change and provides specific information for prediction. Aspect IV addresses verification of reach-specific information on channel processes which is used to evaluate predictions. Interested readers are referred to the original publication for additional information on Aspects III and IV.

Geomorphologic Characterization (Aspect I). The purpose of Aspect I is to provide a broad characterization that integrates the landform and fluvial features of valley morphology with channel relief, pattern, shape, and dimension. Aspect I combines the influences of climate, depositional history, and vegetative life zones on channel morphology. Generalized categories of stream types are initially delineated using descriptions of dominant slope range, valley and channel cross-sections, and plan-view patterns (Figure 5.5 and Table 5.5).

The longitudinal profile serves to identify slope categories for stream reaches. For example, streams of type Aa+ have channel gradients greater than 10% with frequently spaced, vertical drop scour-pools (Figure 5.5 and Table 5.5). The cross-sectional profile also can be inferred at this broad level as well as information concerning floodplains,

TABLE 5.4. Hierarchy of river inventories.

Level of detail	Inventory description	Information required	Objectives
I	Broad geomorphological 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 used for generalized categories of major stream types and associated interpretations
II	Morphological description (channel types)	Channel patterns: entrenchment ratio; width-to-depth ratio: sinuosity; channel material: slope	To delineate 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" of condition	Riparian vegetation; depositional patterns: meander patterns; confinement features; fish habitat indices; flow regime: river size category; debris occurrence; channel stability index; bank erodibility	To further describe existing conditions that influence the response of channels to imposed change and provide specific information for prediction methodologies (such as stream bank erosion calculations); provides for very detailed descriptions and associated prediction/ interpretation
IV	Verification	Involves direct measurements and 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

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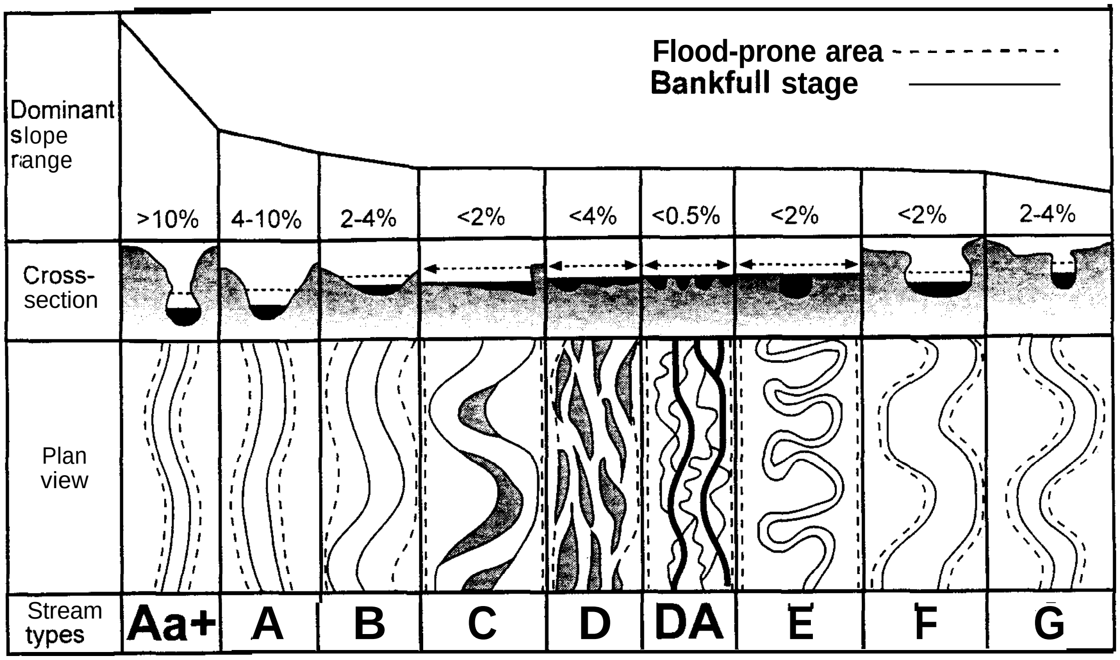

FIGURE 5.5. Longitudinal, cross-sectional, and plan views of major stream types (reprinted from Rosgen 1994 with kind permission of Elsevier Science-NL, Sara Burgerhartstrmt 25, 1055 KV Amsterdam, The Netherlands).

terraces, structural control features, confinement, entrenchment, and valley versus channel dimensions. For example, the type A streams are narrow, deep, confined, and entrenched while the width of the channel and the valley are similar (Figure 5.5 and Table 5.5). The plan view morphology is simply the pattern of the river from above. For example, type A streams are relatively straight while type C streams are meandering (Figure 5.5).

Morphological Description (Aspect 11). After streams are separated into the major categories of A through G (Figure 5.5 and Table 5.5), Aspect II is applied separating them into discreet slope ranges and dominant substrate particle sizes. This results in 42 subcategories of stream types (Figure 5.6). In reality, however, there is a normal range of values for each criterion and this important observation is incorporated into Rosgen's classification system. This aspect recognizes and describes a morphological continuum within and among stream types. The continuum is applied where values outside the normal range are encountered but do not warrant a unique stream type. For example, selected channel slopes in Figure 5.6 are sorted by subcategories of: a+ (>10%), a (4–10%), b (2–3.9%), c (<2%), and c– (<0.01%).

The emphasis on channel materials is equally important, as they are critical not only for sediment transport and hydraulic influences (such as channel roughness) but also for the modification of the river's form, plan, and profile. Interpretation of biological function and stability also require this information. Using the "pebble count" method of Wolman (1954), with a few modifications for large bank materials and sand (Rosgen 1994), the particle size distribution of channel materials can be determined easily in the field.

Although the classification systems developed by Cupp (1989) and Rosgen (1985, 1994) are both based on geomorphic and geologic landscape features, they illustrate two fundamentally different approaches in classification. Rosgen's system is based on present stream characteristics (e.g., channel width, sinuosity). Cupp's system is based on the presumed potential states of the stream (i.e., all possible natural states that may occur in stream features within given segment types). Therefore, Rosgen's method is responsive to the effects of natural and human-induced disturbance as manifested

TABLE 5.5. Summarv of delineative criteria for broad-level classification.

Stream type	General description	Entrenchment ratio	Width-to-depth ratio	Sinuosity	Slope	Landform/soils/features
Aa+	Very steep. deeply entrenched. debris transport streams	<1.4	<12	1.0-1.1	>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	1.0–1.2	4-10%	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	1.4-2.2	>12	>1.2	2-3.9%	Moderate relief, colluvial deposition and/or residual soils: moderate entrenchment and width-to-depth 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	<2%	Broad valleys with terraces in association with floodplains and 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	nia	<4%	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	<0.05%	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-to-depth ratio and little deposition; very efficient and stable; high meander width ratio	>2.2	<12	>1.5	<2%	Broad valley/meadow; alluvial materials with floodplain; highly sinuous with stable, well-vegetated banks: riffle-pool morphology with very low width-to-depth ratio
F	Entrenched meandering riffle-pool channel on low gradients with high width-to-depth ratio	<1.4	>12	>1.4	<2%	Entrenched in highly weathered material; gentle gradients, with a high width-to-depth ratio; meandering, laterally unstable with bank-erosion rates; riffle-pool morphology
G	Entrenched ‘gully" step-pool and low width-to-depth ratio on moderate gradients	<1.4	<12	>1.2	2-3.9%	Gully, step-pool morphology with moderate slopes and low width-to-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

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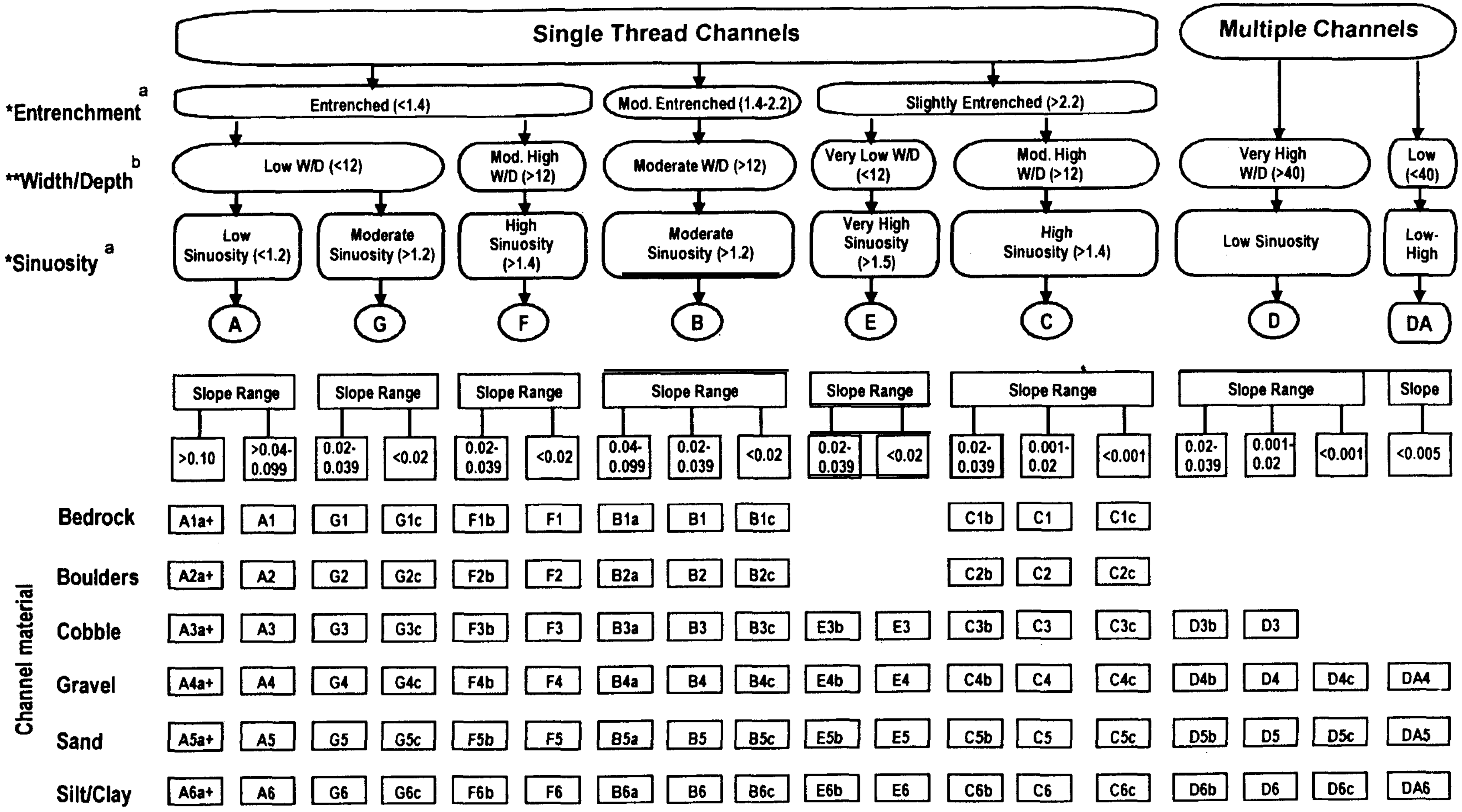

[a] Values can vary by ±0.2 units as a function of the continuum of physical variables within stream reaches.
[b] Values can vary by ±2.0 units as a function of the continuum of physical variables within stream reaches.

FIGURE 5.6. Key to classification of natural rivers (reprinted from Rosgen 1994 with kind permission of Elsevier Science-NL, Sara Burgerhartstrmt 25, 1055 KV Amsterdam, The Netherlands).

by variations in width-to-depth ratio or changes in riparian vegetation, whereas Cupp's approach is responsive to disturbances only at the large segment scale, or to severe small-scale disturbances, such as debris flows or hillslope failures, that cause channel features to deviate outside some predicted range or alter the mean state of the system.

There is disagreement about whether the principal units of classification should be temporally stable (e.g., valley segment) or dynamic (e.g., stream types). Arguments for temporal stability suggest that a reach, once classified, is of little management value if it changes naturally over the time scale of land-use practices (Frissell et al. 1986). In contrast, a dynamic classification based on smaller, evolving units provides a more accurate description of present conditions in the reach (e.g., active channel width, riffle/pool ratio). Both perspectives may be useful for management assessments depending on the specific objectives of the assessment.

Classification Coupling Biological and Physical Features

Coupling biotic resources with the physical features of streams has practical value for both science and management. Existing systems have been based on patterns of species distribution, community structure, and biotic function. Biotic communities serve as integrators of ecological conditions expressed over different time and space scales and, therefore, can be sensitive indicators of environmental vitality. Most classification systems have been based on fish (e.g., Huet 1954, Karr 1981) or invertebrate assemblages (e.g., Illies and Botosaneanu 1963, Cummins 1974, Wright et al. 1984). However, several recent systems have been based on patterns of riparian vegetation (Harris 1988) and aquatic plants (Holmes 1989). In general, all biotic classification schemes assume a predictable relationship between stream biota and geomorphic and hydrologic controlling factors acting on the system.

Vertebrate Community Classification

Fish have formed the basis for stream classification systems for several biological and political reasons. Hawkes (1975) argued that fish probably best reflect the general ecological conditions of rivers because they are presumed to be at the top of the aquatic food chain and, therefore, are integrative of the condition of the entire environmental system. In addition, because many commercial, recreational, and endangered fish species inhabit rivers, there has been continued need to categorize and manage their habitat. Fisheries managers and scientists have the growing responsibility of identifying fish community associations, their ecological requirements, and designing suitable ways of maintaining their integrity in the face of continued habitat deterioration (Naiman et al. 1995, Stouder et al. 1996). Despite the merits of this type of classification, there are limitations that often impede widespread application.

In general, models coupling biological and physical features usually sacrifice precision for generality and assume that fish populations are limited by habitat rather than intra- or interspecific competition, extrinsic factors (e.g., fishing mortality or disease), or natural disturbance (Bisson et al. 1982, Fausch et al. 1988). Although there is inherent value in using sensitive fish species in stream habitat models, individual species often show high yearly variability in production independent of physical habitat conditions (Hall and Knight 1981). In contrast, the entire fish community may provide a more accurate indication of habitat conditions, especially if community parameters are more stable over time than population parameters, and relate predictably to habitat features (e.g., complexity, size) and habitat change (Gorman and Karr 1978, Berkman and Rabeni 1987, Hughes et al. 1987) (Table 5.4).

Ultimately, zoogeographic factors restrict the geographic scope of classification schemes based on the structure of fish assemblages. However, spatial variability in physical and biotic factors shaping community dynamics also can limit geographic scope. Environmental disturbance regimes vary with climate and geology (Poff and Ward 1989). In streams where seasonal flow patterns are predictable. communities may be persistent and resilient (Moyle and Vondracek 198.5). However, in streams with highly variable and unpredictable flow patterns. communities can exhibit sharp temporal fluctuations in structure (Matthews 1982), and this is especially so in the Pacific coastal ecoregion where so many of the fish populations are anadromous (Chapter 9 this volume, Stouder et al. 1996). Anadromous fish often out-compete resident species and, where spawning salmonid populations are large, excavation of the streambed during spawning significantly alters the invertebrate community (which also is used in classification, see below). Furthermore, within climatic regions, the influence of floods can vary depending on channel form and substrate (Resh et al. 1988).

Biotic factors further compound species-habitat relationships. In stream segments where competition and predation are important factors, fluctuations in physicochemical conditions can alter the intensity and direction of competitive and predator-prey interactions (Fraser and Cerri 1982, Reeves et al. 1987, Chapter 9 this volume). Further, variability in productivity between streams may also contribute to wide ranging diversity patterns (Bunn and Davies 1990, Morin and Naiman 1990, Chapter 17 this volume). Moreover, there are various human activities which produce major alterations in fish community composition (e.g., species introductions, chemical pollution, harvest) without altering physical habitat structure.

Many recent investigations have examined spatial patterns, both within and between streams of functional characteristics in fish communities (Gorman and Karr 1978, Moyle and Li 1979, Schlosser 1982 and 1987, Berkman and Rabeni 1987). Moyle and Li (1979) speculated that, while species composition may often be unstable, there may be stability in trophic structure in given habitat settings. Furthermore, Schlosser (1987) hypothesized that there is a predictable longitudinal pattern in characteristics of fish communities (e.g., trophic diversity, demography, seasonal stability) in warm-water streams.

The literature on the ecology of stream fish communities is replete with empirical support for stochastic and deterministic structure (Grossman et al. 1982, Moyle and Vondracek 1985, Matthews 1986) as well as strong (Gorman and Karr 1978) and weak species-habitat relationships (Schlosser 1982). Such disparity is ultimately a consequence of the physicochemical features of the drainage basin (i.e., geology, climate), channel (i.e., substrate, depth-to-width ratio), and habitats (i.e., depth, velocity, large organic debris). These are the primary determinants of the physical template influencing the life history attributes, population dynamics, and community structure and function of stream fishes.

For both scientific and management purposes, it is particularly important to characterize community patterns and controlling processes under different physical conditions. Zalewski and Naiman (1985) speculated that the relative importance of biotic and abiotic controls over fish community characteristics varies along a continuum from upstream to the mouth. Poff and Ward (1989) described a conceptual model relating factors of community regulation to characteristics of the flow regime. Site-specific management can be applied on the basis of understanding community patterns and controlling processes.

Invertebrate Community Classification

Classification schemes based on patterns in benthic invertebrate community structure also have been important tools. Hawkes (1975) discussed the value of developing biotic classification schemes which couple the macroinvertebrate distribution with physicochemical stream features. Macroinvertebrates are good indicators of both short- and long-term change, as well as local and large-scale disturbances because they exhibit diverse life history strategies (Minshall 1988). However, factors limiting the utility of fish classification (e.g., zoogeography, disturbance regimes, biotic interactions, and productivity) also restrict the utility of invertebrate-based classification systems by altering species-habitat relationships.

In Britain, for example, invertebrate assemblages form the basis for the classification of unpolluted rivers and are used to develop procedures for predicting faunal assemblages at given sites from a small set of physicochemical variables (Wright et al. 1989). This particular invertebrate classification system was developed following an intensive biological and physicochemical survey of rivers. Environmental variables measured are those suspected of playing major roles in determining the distribution of the invertebrate fauna, and those which are altered by chemical and thermal pollution and regulation of river discharge regimes (Armitage 1984). As a predictive model it is valuable in detecting environmental stress and identifying species-rich communities, both important elements in stream management (Wright et al. 1989). This type of predictive system, coupling the invertebrate classification scheme to environmental variables, is largely successful because it employs a small set of variables regulating invertebrate distribution which change with direct impacts on water quality. However, the ability to link this approach to larger landscape features of the watershed (e.g., hierarchical classification) is diminished because the human-induced alterations are considered to be on water quality and in-channel (on-site) physical features rather than larger-scale changes. Other potential drawbacks to this approach are the influence of larger-scale geologic features on water quality changes (Armitage 1984) and the demand for exhaustive field monitoring of invertebrate assemblages or in-channel physicochemical variables to establish such a system.

Another approach is based on the functional attributes of invertebrates (Chapter 8). For two decades there has been an emphasis on organizing species into ecologically meaningful trophic guilds and elucidating changes in the functional role of assemblages along the length of rivers (Cummins 1974). This approach takes advantage of changes in trophic diversity that occur naturally along the longitudinal profile of rivers (Chapter 15). Like fish community classification schemes, the value of classifying streams by invertebrate functional groups is the independence from taxonomic structure, which enables comparisons of different basins over larger regions. Minshall (1988), however, argued against relying on such a trophic group classification. using evidence of Hawkins et al. (1983), who were unable to find shifts in functional groups in habitats degraded by logging. An added drawback to such a classification is the difficulty of categorizing diverse species into realistic functional feeding groups for all life-history stages.

Plant Classification

Various classification systems based on riparian vegetation patterns have also been developed (Harris 1988, Swanson et al. 1988, Baker 1989). This has considerable potential for stream management because riparian forests are active boundaries at the interface between upland and aquatic systems, and therefore may be sensitive indicators of environmental change (Naiman and Décamps 1990, Chapter 12 this volume).

The fundamental classification unit of riparian zones is the community type. This is defined either by present vegetative composition or potential climax vegetation (Swanson et al. 1988). Inferences are drawn regarding environmental gradients and successional relationships between community types. Stratification of community types is based on overstory or understory vegetation. The understory (herbs and shrubs), because of its higher turnover rate, is a better indicator of current soil and hydrologic conditions, whereas the canopy is a better integrator of longer temporal patterns. As with other biotic classification systems, the most valuable riparian classification schemes center on relationships to physical factors associated with the river environment.

Many authors have addressed the need for ranking riparian zones with respect to conservation value or ecological potential (Slater et al. 1987, Harris 1988, Swanson et al. 1988, Baker 1989, Gregory et al. 1991, Gurnell et al. 1994). Slater et al. (1987) used species richness, rarity, and frequency-of-occurrence to formulate the conservation value of different stream segments. Although these biotic variables were independent of taxonomic structure, the value of this classification system was diminished by the absence of a relationship between riparian habitat variables and the aquatic biota.

Harris (1988) classified riparian vegetation (i.e.. species composition) in relation to six geomorphic valley types in the Sierra Nevada mountains of California. Incorporating concepts from landscape ecology and hierarchical relationships of different landscape elements, he limited classification units to the stream segment scale and addressed the importance of larger-scale factors in determining smaller-scale patterns. His geomorphic-vegetation units differed in their sensitivity to management, yet were useful for purposes of resource inventory, detailed ecological studies, and prediction of human-induced alterations. Although Harris suggested several reasons for the stream segment-vegetation relationships, processes governing the observed patterns could not be determined. Nonetheless, the classification system developed by Harris was an important step forward in coupling different landscape processes to biotic resources and in attempting to predict the sensitivity of stream segments to disturbance.

Another approach undertaken in the late 1970s in Britain classifies rivers from the distribution of aquatic plant assemblages (Holmes 1989). The basis for this system is that plants integrate short- and long-term conditions in the river, and that they play an important role in the ecology of stream fish and invertebrates as food and shelter. This approach requires an extensive survey of rivers, including a complete documentation of plant species diversity and habitat variables. A computer-aided classification system is essential to stratify rivers and river segments hierarchically. This approach has been successful largely because rivers in Britain do not exhibit the strong longitudinal shifts in physical features seen in western North America (Holmes 1989).

An Evaluation of the Biological–Physical Approach

The usefulness of biologically based stream classification systems in stream management may be diminished because such approaches demand, at least initially, intensive efforts to measure and monitor community characteristics (Chapter 18). This is especially true for invertebrates, somewhat less so for fish and vegetation. Furthermore, species-habitat relationships are often confounded by such factors as zoogeography, disturbance, biotic interactions, and productivity. If biotic classification systems are to have broad application, they must be related to physical features of the watershed in order to make inferences on the effects of land-use changes. In this regard Harris (1988) comes closest to accomplishing this objective. Yet disturbances to different watershed elements (e.g., habitat, riparian zone, hillslope) can produce similar impacts on the stream biota. In the absence of information on the cause of stream degradation and the linkage between the physical and biotic components of the system, it remains difficult to gauge the recovery potential of stream biota.

Management Based on Stream Classification

Although the number and diversity of specific stream classification systems are large, there appears to be a consensus developing on the fundamental attributes of an enduring classification system. These attributes relate to the ability to encompass broad spatial and temporal scales, to integrate structural and functional characteristics under various disturbance regimes, to convey information about underlying mechanisms controlling in-stream features, and to accomplish this at low cost and at a high level of uniform understanding among resource managers (Naiman et al. 1992, Hawkins et al. 1993). No existing classification system adequately meets all of the model attributes. Even though the concepts of Frissell et al. (1986), Cupp (1989), Hawkins et al. (1993), and Rosgen (1994) are regarded as important intellectual advancements, they do not provide the level of understanding of channel processes needed to predict channel responses to specific types of watershed disturbances (such as debris flows or hillslope failures). Consequently, specific links between physical and biological processes within these classification systems remain poorly defined. Physical, process-based approaches that offer more promise in meeting these attributes, discussed by Montgomery and Buffington (Chapter 2 this volume and 1997), are currently being used to address a wide variety of stream-related management issues in the Pacific Northwest. Nevertheless, the generally narrow perspective provided by all existing classification systems limits their effectiveness. For example, all current stream classifications for regulating forest practices in the Pacific coastal ecoregion rely simply on the presence or absence of salmonids coupled with some index of stream size (e.g., channel width, mean annual discharge, or stream order). The relative degree of regulatory protection decreases with decreasing stream size and is virtually nonexistent in streams without salmon or trout. Generally, there is no explicit consideration of the underlying geomorphic context or the potential response of the channel segment to disturbance. A similar case could be made for the classification schemes applied by the water quality regulatory agencies which classify streams based on a comparison of physiochemical characteristics with a region-wide set of “desired” criteria. Such classifications are narrowly focused only on the properties of the system which fall under the legal jurisdiction of the regulatory agency.

Despite these caveats, the hierarchical classification system has been useful in making resource managers in the Pacific Northwest aware of the diversity of stream types and the need for a variety of management prescriptions for habitat protection and conservation. This is especially important in a region with approximately forty subcategories of stream segments, and where nearly 80% of the ancient forests have been cut in the last century to sustain a US $9.0 billion /yr forest products industry employing more than 60,000 people. The evolving stream classification system currently used as part of the Washington Forest Practices Regulations (Chapter 2), for example, allows resource managers and scientists to consider, in some cases, alternative forestry practices (e.g., silvicultural techniques, cutting patterns) that are tailored to specific stream and valley bottom configurations rather than using narrowly defined techniques and regulations applied across a few stream sizes and types. Simple prescriptive management, such as riparian zones of fixed width, is less effective than management techniques adapted to local topography and natural disturbance regimes.

This has been effectively demonstrated by Benda et al. (1992), who showed how the zonation of geomorphic surfaces in a 260 km^2 montane valley could be used to focus attention on streams where salmonid habitat value was highest. The valley was stratified at a large scale ($>50\,\text{km}^2$) by geologic structure and associated geomorphology, and at a smaller scale ($<10\,\text{km}^2$) by older lacustrine clay terraces and the more recent floodplain of the main river. Additionally they quantified differences in the habitat characteristics (channel width, large organic debris, and spawning gravel) of streams on the various geomorphic surfaces. The valley was then partitioned into areas of high and low risk based on the physical habitat characteristics of the streams.

This is only one example of an emerging perspective for streams and riparian zones which uses classification as a basis for designing new approaches for resource management. The placement of logging access roads, decisions on when, where, and how much tree harvest should occur, and development of silvicultural restoration techniques and of system models all require adherence to stream type. The most effective stream and riparian models include aquatic and terrestrial disturbance regimes, unique species mixtures, spatial and temporal heterogeneity, and microclimate gradients-all of which vary by stream type. Further, emerging silvicultural techniques for riparian tree species account for genetic vitality, stand development, and system complexity-factors that are specific to stream types (Berg 1995).

Even though the search for an ideal classification system is not complete, the fundamental principles of an ideal system are reasonably well articulated. However, it will be necessary for resource managers to adapt guiding principles using an adaptive management approach for specific situations (Holling 1978, Chapter 27 this volume). The task is difficult and requires a holistic. long-term perspective, but once in place, it provides a solid foundation for making resource decisions that affect the environmental quality of streams for decades.

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