A Hierarchical Approach to Classifying Stream Habitat Features

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ABSTRACT

We propose a hierarchical system of classifying stream habitats based on three increasingly fine descriptions of the morphological and hydraulic properties of channel geomorphic units. We define channel geomorphic units as areas of relatively homogeneous depth and flow that are bounded by sharp gradients in both depth and flow. Differences among these units provide a natural basis for habitat classification that is independent of spatial scale. At the most general level of resolution, we divide channel units into fast- and slow-water categories that approximately correspond to the commonly used terms "riffle" and "pool." Within the fast-water category, we identify two subcategories of habitats, those that are highly turbulent (falls, cascades, chutes, rapids and riffles) and those with low turbulence (sheets and runs). Slow-water habitats include pools formed by channel scour (eddy pools, trench pools, mid-channel pools, convergence pools, lateral scour pools and plunge pools) and those formed behind dams. Dammed pools include those obstructed by debris dams, beaver dams, landslides and abandoned channels. We consider backwaters as a type of dammed pool. Fishes and other stream organisms distinguish among these habitats at one or more levels of hierarchy. Habitats defined in this way represent an important habitat templet on which patterns of biological diversity and production form. We believe that a hierarchical system of classification will facilitate understanding of biotic-habitat relationships in streams and lead to more effective methods of evaluating the effects of environmental change on stream ecosystems. Refining the criteria by which habitats are distinguished, quantifying how different species use different habitats, and integrating the ways biota respond to habitat variation should facilitate the emergence of a theory of stream habitat organization.

"It is not the nomenclature that matters but the clear definitions of the contents given to terms, a truism most frequently misunderstood." E. Balon (1982).

Development of a logical and consistent system of stream habitat classification has challenged both stream researchers and fisheries managers for many years (e.g., Platts 1980; Bisson et al. 1982; review by Mosley 1987). Although there is a clear need for classification, no single approach has been generally accepted. A general system of habitat classification has been hindered because

1. stream environments consist of so many independent and interacting factors known to influence biota that distinguishing habitats based on a single criterion is impractical;
2. environmental heterogeneity varies considerably both within and among streams, which makes the number of habitat classes required for adequate description of a given stream unclear;
3. environmental variation is often gradual rather than discrete at several different spatial and temporal scales, further confounding identification of habitat classes; and
4. the type and resolution of classification needed may vary with specific research or management objectives.

A general classification system of stream habitats should serve several purposes (Pennak 1979; Warren 1979; Platts 1980). The system should provide a standard frame of reference that facilitates communication among researchers and managers. Habitat classes should be defined in an ecologically meaningful way that can be easily recognized by both researchers and managers. These classes should be based on measurable variation in environmental attributes at spatial scales important to the activities of stream biota. It should also be possible to extrapolate biotic-habitat relationships from one stream to another. Furthermore, the system should be flexible

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enough that it can be used to address a variety of research and management objectives.

The need for a general, workable classification is especially acute for small streams (< 4th order), which exhibit considerable heterogeneity in both morphological and hydraulic features (Beschta and Platts 1986; Sullivan et al. 1987; Robinson and Beschta 1990). Environmental variation in small streams is conspicuous at the spatial scale of channel geomorphic units, hereafter referred to as "channel units." Channel units are quasi-discrete areas of relatively homogeneous depth and flow

It seems especially important that hypotheses regarding the effects of individual habitat features (e.g., food or cover) be tested while controlling for the effects of other habitat factors.

that are bounded by sharp physical gradients (e.g., riffles and pools). Individual units are formed by interactions among discharge, sediment load and channel resistance to flow (e.g., Leopold et al. 1964; Richards 1982). Different types of units are usually in close enough proximity to one another that mobile stream organisms can select the type of unit that provides the most suitable habitat.

Variation in the structure and dynamics of the physical environment are primary factors affecting production and diversity of stream biota (e.g., Hynes 1970; Vannote et al. 1980; Minshall 1988). This spatial and temporal heterogeneity represents an important habitat templet (e.g., Southwood 1977) for stream biota. Although important environmental variation exists at all levels of spatial resolution, many research and management objectives are best addressed at the spatial scale of channel units (e.g., Sullivan et al. 1987). At the channel unit of resolution, both abundance of biota and rates of ecosystem processes often exhibit marked patchiness, presumably as a consequence of high variation in habitat suitability or quality. Differences in habitat quality among channel units are often associated with differences in morphology (e.g., depth, width, shape), current velocity (hydraulics) and bed roughness (substrate size). For example, nutrient uptake (Aumen et al. 1990), algal abundance (Tett et al. 1978), invertebrate production (Huryn and Wallace 1987) and diversity (Hawkins 1984), and fish abundance (Bisson et al. 1988) are all known to exhibit significant variation at this spatial scale.

Bisson et al. (1982) based a system of salmonid habitat classification on naturally occurring channel

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The Upper Smith River near Mount St. Helens, Washington, illustrates the heterogeneous nature of physical habitats in many small stream ecosystems. A standardized classification system for habitats at the channel unit spatial scale should lead to better defined habitat relationships for stream biota.

units and the hydraulic processes that formed them. They suggested that several distinct channel units occur at summer, base-flow conditions that could be easily recognized and had ecological relevance to salmonids. The American Fisheries Society has since adopted much of their habitat nomenclature (Helm 1985), and this classification system has been successfully applied to both research and management purposes. For example, by classifying habitats in this manner, Bisson et al. (1982, 1988) and Sullivan (1986) discovered important ecological associations among habitat characteristics, species abundance and body form for the juvenile stages of three species of salmonids. Coho salmon (*Oncorhynchus kisutch*), steelhead trout (*Oncorhynchus mykiss*), and cutthroat trout (*Oncorhynchus clarkii*) segregated within stream segments by using different types of channel units. In these studies, fish distinguished between riffles and pools as well as subclasses of pools defined by channel unit position, forming constraint and flow. Benthic invertebrates also appear to use different types of channel units

(e.g., Hawkins 1984; Statzner and Higler 1986). In these cases, the basis for differential use of units appears to be related to differences in either substrate size or hydraulic characteristics. Kershner and Snider (1992) refined the predictions of instream flow models by weighting output by channel unit type thereby more accurately predicting changes in habitat availability with changing flow.

After nearly 10 years of use, we are now aware of several obstacles that limit the original version of the Bisson et al. (1982) system as a general classification tool. First, aquatic ecologists have often assigned habitats into different numbers of habitat classes based on a real or perceived need for more, and sometimes fewer, habitat classes than originally described. As a consequence, there has been a tendency for "habitat-type proliferation" to occur (e.g., McCain et al. 1989). Although such modifications often may be needed to address specific objectives, use of different sets of habitat classes can potentially confound comparisons among streams, if the basis for discriminating habitat units in each case is not clear. Second, we have sometimes used similar terms to describe dissimilar habitats, thereby further confounding among-stream comparisons. Third, we are aware of several instances in which the system has been used without clear consideration of either research or management objectives. In the following section, we suggest that a hierarchical classification scheme can provide both a logical and ecologically relevant foundation on which to base classification of channel units and a means of standardizing descriptions of channel units.

Needs for Consistent Systems of Classification

Stream management depends on a solid understanding of biota-habitat relationships and, as such, refinement of ecologically sound ways to describe and classify habitats is a critical component of stream science and management. For example, managers often rely on empirical descriptions of habitat use to make inferences about factors that limit a species' growth or abundance. Habitat classification can therefore aid in determining the factors that may limit populations, if habitat classes are based on differences in factors known to influence biota, and habitat classification is used in a consistent manner.

Quantification of habitat use provides a basis for predicting biotic response to changes in habitat availability. If the availability of different habitat types and habitat-specific abundances is known, selectivity indices can be calculated. These calculations assume that different habitat types are discrete, are equally accessible, and recognizable by the organism(s) of interest. Where these assumptions are valid, such analyses provide the type of data fundamental to understanding patterns of habitat use by different species and form a basis for predicting biotic response to changes in habitat availability.

Much of our understanding of habitat relationships in streams has emerged from comparative studies that describe statistical relationships between habitat variables and abundance. These studies have yielded important insights regarding the factors that influence abundance, but general quantitative models with high predictive power have not yet emerged (see Fausch et al. 1988; Marcus et al. 1990 for reviews). In fact, some habitat-based models produce conflicting results (see Binns and Eiserman 1979 and Bowlby and Roff 1986). In hindsight, the present status of habitat modelling may not be surprising. The perceived relative importance of different environmental factors may depend strongly on the spatial scale of observation (e.g., Lanka et al. 1987; Crowl and Schnell 1990). Furthermore, comparison of studies conducted at the same spatial scale may be confounded if the relative importance of different micro-spatial factors varies with habitat type. It seems especially important that hypotheses regarding the effects of individual habitat features (e.g., food or cover) be tested while controlling for the effects of other habitat factors. Ideally such analyses would be conducted within a single habitat type in which only the habitat component of interest varied and other habitat variables were constant or nearly so. Truly general models must ultimately integrate responses biota exhibit to environmental variation at several spatial and temporal scales, and we have not progressed far in this respect.

Habitat classification also provides a means to minimize effort and maximize the statistical reliability of population estimates, especially if estimates are required for large spatial scales. We have often based population estimates on samples taken from single, arbitrarily selected sections of stream and have assumed that these estimates are representative of the entire stream within a drainage basin. Although such sampling can sometimes yield valuable information regarding the factors potentially limiting populations (e.g., Hawkins et al. 1983), it is not valid to use a single sample estimate to extrapolate population abundances beyond the boundaries of the area sampled (e.g., abundances within an entire basin).

If habitats can be classified and enumerated, statistically sound estimates of population abundance at several spatial scales can be made by censusing the amount of different habitat types within a stream and then sampling a subset of each habitat type for biota. This approach yields habitat-specific estimates of abundance that can be combined to generate an estimate of population abundance in the stream segment as a whole (e.g., Hankin 1986; Hankin and Reeves 1988). However, accurate, whole-stream estimates require that habitat types be

consistently classified. If field personnel do not consistently identify different habitat types, habitat-specific estimates of abundance will be in error and among-basin comparisons will be compromised.

This type of watershed-level survey can also be used as a method of monitoring at different scales. In the Willamette River basin, Sedell and Luchessa (1982) have reconstructed the historic habitat descriptions and fish distributions to compare conditions in the basin from the 1930s to current conditions. If basin-level habitat surveys are repeatable and accurate, they can be used as a long-term monitoring tool to compare current conditions with changes in management over time. By resurveying streams, changes in habitat frequency can be compared with desired objectives.

Restoration of degraded stream ecosystems may sometimes require that we restore habitat features that are damaged or lost by channel alteration. If sampling reveals that certain channel elements may be limiting recovery of a population or community, stream managers may want to manipulate the abundance of specific types of channel units toward a more desired set of conditions. Fisheries managers have frequently attempted to increase the production of fish by this type of channel manipulation (see Everest and Sedell 1983; Wesche 1985), although evaluations of the effectiveness of such practices are sorely lacking. We believe a consistent method of channel unit classification would facilitate our abilities to set realistic restoration objectives and to develop efficient ways of evaluating the effectiveness of specific restoration practices.

Recommendations

We believe a hierarchical classification of channel units may alleviate problems that some users have with Bisson's (Bisson et al. 1982) original classification scheme. Hierarchical systems allow choice of the level of habitat resolution that is required for specific objectives (Frissell et. al. 1986; O'Neill et al. 1986) and provide a consistent means for either collapsing or splitting data sets if comparisons across studies are desired. Such a system is valuable if data on community-wide and ecosystem-wide, as well as species-specific, responses are needed.

Figure 1 illustrates our perception of the hierarchical relationships among different types of channel units. In constructing this hierarchy, we first identified which physical characteristics were needed to describe specific channel units. We then ranked the importance of these factors as descriptive features useful in defining and discriminating among different types of channel units. Rankings used in this scheme were based on consensus derived from our combined experience classifying stream habitats. Although too few empirical studies exist at this time on which to base an objective

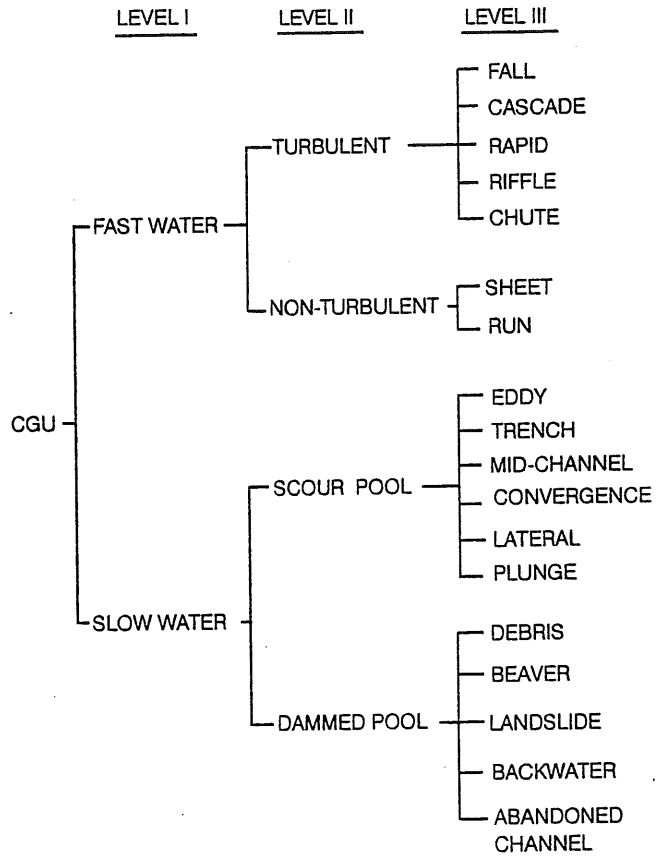

Figure 1. Similarity dendrogram illustrating how channel geomorphic units (CGU) can be classified with increasing levels of resolution. Three levels of classification are shown that can be used to distinguish classes.

analysis, a few studies provide data supporting the idea that these habitat classes differ significantly in the manner we suggest (Sullivan 1986; Bisson et al. 1988).

A three-level hierarchy should provide the level of resolution needed for most research and management purposes (Fig. 1). At the coarsest level of resolution, fluvial geomorphologists recognize riffles and pools as two primary channel unit types (Yang 1971; Keller and Melhorn 1978; O'Neill and Abrahams 1987). Riffles are topographic high points in the bed profile and are composed of coarser sediments, whereas pools are low points with finer substrates (Richards 1982). At base flows, riffles have rapid, shallow flow with steep water-surface gradient, whereas pools are generally deep, slow-flowing and have a gentle surface slope (Richards 1978). Although riffles and pools do not always have sharp boundaries, they appear to represent distinctly different ecological habitats. The biota inhabiting them are markedly different in both taxonomic composition and the morphological, physiological, and behavioral traits they possess.

For many biota, however, important differences in habitat use occur at finer levels of resolution than recognized by geomorphologists (e.g., Minshall 1984; Bisson et al. 1988). Stream ecologists

recognize subcategories of riffle and pool that further refine the physical and biological functions of these units. Both Bisson et al. (1982) and Helm (1985) refer to specific types of riffles and pools, which may cause some confusion in terminology. To avoid further confusion, we refer to the broad categories of riffle and pool as fast-water and slow-water channel units, respectively.

Both fast-water units and slow-water units can be divided into two subclasses. Fast-water units can be divided into either high-turbulent or low-turbulent classes based on differences in gradient, bed roughness and step development (Table 1). We use the term "step development" in reference to the distinct breaks in bed slope that may occur within a channel unit. Two types of pools can be distinguished based on whether they are formed by scour or damming (Table 2). Both subdivisions appear to be ecologically relevant. The types and abundances of riffle-dwelling benthos are strongly affected by the amount of turbulence (Statzner et al. 1988). Dammed pools tend to accumulate and retain sediment and organic debris to a greater extent than scour pools. The retentiveness of stream habitats in terms of nutrients, sediment or organic debris is an important factor affecting stream ecosystem energetics (Benke et al. 1988; Meyer et al. 1988). The presence and abundance of cover, and hence fish (Devore and White 1978; Shirvell 1990), also appear to be associated with type of pool. Dammed pools often have greater amounts of cover than scour pools, because they are usually formed behind wood, debris or large substrates.

The fast- and slow-water classes can be further divided based on other criteria. Most of these subclasses correspond to the names and definitions of stream habitat types provided by the Habitat Inventory Committee of the Western Division, American Fisheries Society (Helm 1985). For this reason, we have attempted to preserve the nomenclature used by Bisson et al. (1982) and Helm (1985). In some cases, we have either collapsed or added categories based on how well original definitions fit within our hierarchical framework. For example, we used ranked differences in gradient, percent super critical flow, bed roughness, mean velocity and step development to identify subclasses of both turbulent (falls, cascades, rapids, riffles, chutes) and non-turbulent (sheets and runs) units. The subclass of sheet was not identified by either Bisson et al. (1982) or Helm (1985). This subclass refers to units with shallow water flowing over smooth bedrock, a common habitat type in some geographic regions. Individual pool types within scour and dammed groups differ in terms of their location within the flood or active channel (i.e., main channel or off channel), longitudinal and cross-sectional depth profiles, characteristics of surficial substrates, and the constraining feature that helps form them. This is the finest level of resolution that we believe can be visually distinguished.

We have not included some habitat types identified in Bisson et al. (1982) and Helm (1985); e.g., pocket water, alcove, slackwater pool, underscour pool. In general, these habitats were collapsed within broader categories. For example, we considered alcoves to be a form of eddy, and pocket water pools were small-scale habitat features that exist within fast-water channel units.

We had trouble placing some commonly cited "habitats" within this framework. Whereas, we agreed on the names for and characteristics of most habitat types, glides were more difficult to define. Some of us, in fact, had markedly different ideas of

Table 1. Classes of fast-water channel units and variables used to distinguish them. Differences among classes are ranked for each variable. In all rankings, 1 indicates highest magnitude. Supercritical (SC) flow is a measure of turbulence and is ranked by amount of broken surface water within the channel unit. Step development is ranked by the number and size of energy dissipation features within a habitat unit.

Class	Gradient	SC flow	Bed roughness	Mean velocity	Step development
Turbulent:					
Fall	1	NA	NA	1	1
Cascade	2	1	1	2	2
Chute	3	2	4	3	5
Rapid	4	3	2	4	3
Riffle	5	4	3	5	4
Nonturbulent:					
Sheet	Var	6	6	6	5
Run	6	5	5	7	5

NA = Not Applicable
Var = Variable

Table 2. Classes of slow-water channel units. Channel location refers to whether the unit occurs in the main flow of the stream or near a bank. Shape of the units are indexed by location of the deepest point along both longitudinal and cross-sectional (L and X) depth profiles. Substrate character refers to the degree of sorting, erosional resistance and/or size of particles. The forming constraint describes the feature causing water to pool.

Class	Channel location	L-section profile	X-section profile	Substrate character	Forming constraint
Scour					
Eddy	bank	mid	mid	surface fines	lateral obstruction
Trench	main	uniform	uniform	uniform, resistant	bilateral resistance
Mid-channel	main	mid	mid	uniform, resistant	constriction at head
Convergence	main	mid	mid	sorted, fine at head	convergence of streams
Lateral	main	up or mid	side	sorted, resistant	deflector at head
Plunge	main	up	variable	sorted	obstruction at head
Dammed					
Debris	main	tail	variable	sorted, fine	debris
Beaver	main	tail	variable	uniform, fine	beaver dam
Landslide	main	irreg	irreg	variable	colluvium
Backwater	bank	tail	variable	uniform, fine	obstruction
Abandoned channel	bank	tail	mid	uniform, fine	headward deposits by active channel

what makes up a glide. One reason for the lack of consensus may be that glides are often the low-flow remnants of high-flow scour pools (c.f. Keller 1971; Lisle 1979) and are thus extended transitional areas between fast- and slow-water habitats. For these reasons, we deleted glides from our classification.

We recognize that not all types of channel units may exist in any one stream at any specific time. For example, during higher (floods) or lower (drought) flows, some units may change in physical character (e.g., a run may change to a riffle). Although most ecological and management studies are conducted during base flow conditions, we doubt if any fundamentally different types of units would be needed to characterize habitats available to and used by stream biota under other flow regimes.

Discussion

The classification system we describe here is meant to be a foundation for describing stream habitats at the scale of channel geomorphic units. In principle, this approach should be easily integrated into the spatial hierarchical classification systems proposed by Platts (1980), Frissell et al. (1986) and Gregory et al. (1991). Doing so should ultimately provide a more sound understanding of the structural and functional properties of stream ecosystems that occur at different scales.

Determining how well the proposed classification approach works will depend, in part, on eventually quantifying the amount of variance in physical attributes that exists both within and between channel unit classes. The proposed approach to classifying channel units will certainly require refinement and validation. Perhaps the most important immediate task is to objectively verify that these or similar classes actually comprise a useful set of different habitat types. The most straightforward way of doing this is to collect a sufficiently large set of habitat data in several streams and use cluster or ordination techniques to reveal if our groupings have an objective basis. Special attention may have to be paid to how different habitat variables are weighted. For those habitat classes that have an objective physical basis, it will then be necessary to

determine to what extent the different channel units are biologically different and for what taxa.

A particularly vexing problem with this scheme is that it is not clear to what extent the nature of channel units is dependent on stream size. For example, as streams get larger, the size of channel units increases, and the boundaries between them may become less distinct. It is likely that channel units in large streams comprise several smaller scale habitat patches that are physically and biologically equivalent to entire stream channel units in small streams. Additional research is clearly needed to explore how well classifications designed for small streams can be used to describe river habitats.

One of the most important advantages of this type of classification system is that individual habitats can be rapidly assigned to classes based on visual appearances. However, valid comparisons either across streams or through time assume that all observers will assign habitats to the correct classes. No studies have been published that quantify the magnitude of subjective bias that exists among observers, although results from unpublished data show that bias can be a problem if field crews are inadequately trained and supervised (unpublished independent data sets of L. M. Decker, C. P. Hawkins, J. L. Kershner, C. K. Overton and G. H. Reeves). It is important that the accuracy of visual assignments be evaluated before the adequacy of such approaches are taken for granted. One way of doing this would be to measure the relevant physical variables for a subset of habitat units after they have been visually assigned to classes. Comparing visually with empirically determined assignments would serve two purposes. First, it would generate statistics regarding precision and accuracy of visual estimates. Second, such checks would serve to identify and limit bias among individual observers.

We expect that with testing and use, this system will be modified and improved to increasingly reflect the physical and biological reality of stream habitats. With improvement, the main advantages of this approach should become increasingly evident, i.e., the flexibility that hierarchical classifications provide in addressing different objectives, the ability to rapidly classify habitats through visual observations, and the ability to conduct statistically sound, large-scale surveys at a reasonable cost.

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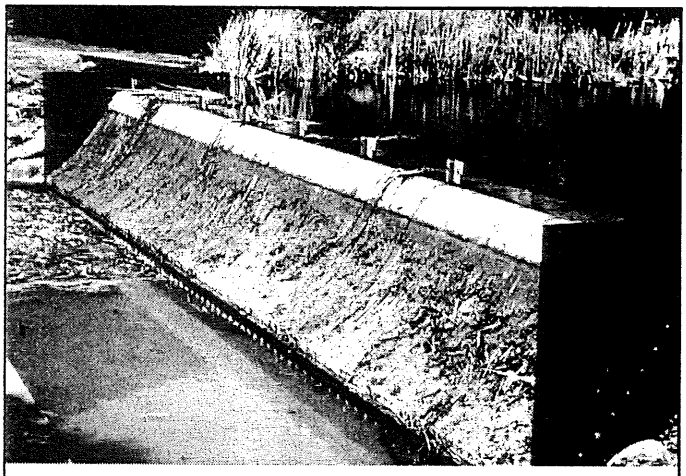

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