A Hierarchical Framework for Stream Habitat Classification: Viewing Streams in a Watershed Context

CHRISTOPHER A. FRISSELL*
WILLIAM J. LISS
CHARLES E. WARREN
MICHAEL D. HURLEY
Oak Creek Laboratory of Biology
Department of Fisheries and Wildlife
Oregon State University
Corvallis, Oregon 97331, USA

ABSTRACT / Classification of streams and stream habitats is useful for research involving establishment of monitoring stations, determination of local impacts of land-use practices, generalization from site-specific data, and assessment of basin-wide, cumulative impacts of human activities on streams and their biota. This article presents a framework for a hierarchical classification system, entailing an organized view of spatial and temporal variation among and within stream systems. Stream habitat systems, defined and classified on several spatiotemporal scales, are associated with watershed geomorphic features and events. Variables selected for classification define relative long-term capacities of systems, not simply short-term states. Streams and their watershed environments are classified within the context of a regional biogeoclimatic landscape classification. The framework is a perspective that should allow more systematic interpretation and description of watershed–stream relationships.

Managers of streams and their associated resources face problems of understanding and managing nonpoint source pollution, evaluating the complex, cumulative impacts of changing land use on stream habitats and biological communities, and assessing the effectiveness of fish habitat improvement projects and other mitigation procedures. Scientists have developed few generally applicable perspectives or procedures to address such needs. Present approaches to these problems typically involve paired watershed studies, long-term before-and-after monitoring programs, or upstream–downstream comparisons. Yet there exists no integrative, systematic approach for understanding the considerable natural variability within and among stream systems and stream communities (Hall and Knight 1981). How do we select representative or comparable sampling sites in such diverse environments? How can we interpret in a broader context, or how far can we reasonably extrapolate, information gathered at specific sites? How do we assess past and possible future states of a stream?

This article articulates a general approach for classifying stream systems in the context of the watersheds that surround them. The stream classification system is designed to intermesh with a biogeoclimatic land classification system (Warren 1979, Lotspeich and Platts 1982, Warren and Liss 1983), and emphasizes a stream's relationship to its watershed across a wide range of scales in space and time, from the entire channel network to pools, riffles, and microhabitats.

KEY WORDS: Stream habitat; Stream biota; Watersheds; Geomorphology; Classification; Hierarchy; Spatiotemporal scales

Conceptual Framework

We begin with the assumption that structure, operation, and other aspects of the organization and development of stream communities are largely determined by the organization, structure, and dynamics of the physical stream habitat, together with the pool of species available for colonization (Wevers and Warren 1986). Elton (1966) and Southwood (1977) advocated a habitat-centered view of ecological systems, and there is considerable evidence to support the usefulness of such a view for streams (for example, Hynes 1970, Vannote and others 1980, Hawkins 1984, Wevers and Warren 1986). Besides acting directly to determine distributions of organisms, physical conditions within a habitat also mediate levels of food resources available (Rabeni and Minshall 1977) and may constrain the roles of predation or competition (Peckarsky and Dodson 1980). Moreover, we assume that the structure and dynamics of stream habitat is determined by the surrounding watershed. Some have held this view (for example, Hynes 1975) and have called for classification schemes that would couple or integrate aquatic

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*To whom correspondence should be addressed.

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and terrestrial ecosystems (Van Deusen 1954, Slack 1955, Platts 1974 and 1979, Warren 1979, Lotspeich and Platts 1982).

If, as we have assumed, biological patterns in streams are largely adjusted to and controlled by physical patterns, the problem becomes one of understanding these physical patterns across time and space. This requires a broad, integrative framework that places streams, their habitats, and their communities in wider geographic context. Development of a successful soil classification system depended upon principles of soil genesis (to understand variation in soil attributes) and an understanding of how soils are distributed on the landscape (Cline 1949, Soil Survey Staff 1975). We suggest that a stream classification, to be useful for a broad range of objectives, must be based on a conceptual view of how stream systems are organized in space and how they change through time.

In classification the variables selected are intended to simply and meaningfully order streams in the domain of interest. Where the domain is as broad as "all streams," two problems are apparent. First, different variables may be important in different locations. Between geographic regions, and even between streams of dissimilar size or slope within one region, different processes control the form and development of landscapes, watersheds, and streams (Wolman and Gerson 1978, Minshall and others 1983). Thus it is useful to place any classification of streams and stream habitats in a geographic, spatial hierarchy. Bailey's (1983) classification of terrestrial ecoregions is one such hierarchical system. Godfrey's (1977) physiographic classification and Lotspeich and Platts' (1982) system are others. Warren and Liss (1983) describe a classification system that would view a landscape as a nested hierarchy of drainage basins. Watersheds—from the smallest tributary catchments to the largest basins—would be classified according to their biogeoclimatic attributes. With any of these approaches individual sites are kept within a geographic context of large-scale, regional variation in geology, climate, geomorphology, soils, and vegetation.

The second difficulty is that what appear to be the most controlling or constraining variables change with the time frame in which the system is viewed. Seen across a geologic time span (for example, $>10^5$ years) the slope of a stream channel is a changing dependent variable, controlled by climate, geology, initial relief, and time. Yet viewed in a frame of years, channel slope is relatively invariant, and slope may be considered an independent causal variable that controls local channel morphology and sediment transport (Schumm and Lichty 1965, West 1978). The most useful classification of streams and stream habitats must account both for factors that determine long-term behavior of streams and factors that determine behavior of stream habitats (for example, pools and riffles) developing on a smaller spatial and temporal scales.

Smaller-scale systems develop within constraints set by the larger-scale systems of which they are part. For example, the potential pool/riffle morphology of a stream reach is largely determined by the slope of that reach and the input of sediments and water from the contributing drainage basin (Schumm and Lichty 1965). Furthermore, the slope of the reach and the pattern of sediment and water discharge are themselves controlled by large-scale, long-term variables like climate, lithology and structure, basin topography and area, and paleohydrologic history (Schumm and Lichty 1965). Thus a spatially nested, hierarchical model (Allen and Starr 1982), in which the class of any particular system is partly determined by the class of the higher-level system of which it is a part, provides a useful framework for classification.

A hierarchical structure offers these benefits: (a) classification at higher levels narrows the set of variables needed at lower levels, (b) it provides for integration of data from diverse sources and of different levels of resolution, and (c) it allows the scientist or manager to select the level of resolution most appropriate to his or her objectives (Godfrey 1977).

Many performances or behaviors of streams are highly variable in space and time. If stream classification were based on more transient stream performances (for example, Pennak 1971), then the stream would change class with every change in performance and very little would be gained by classification. And yet a useful classification ought to account for not only the present state and performances of a stream, but also its potential states and performances over a range of conditions (Warren 1979, Warren and Liss 1983).

Warren and others (1979) define *potential capacity*, in general systems theory terms, as all possible developmental states and all possible performances that a system may exhibit while still maintaining its integrity as a coherent entity (Figure 1). While the system develops, or changes in state and organization through time, it develops only within a set of constraints imposed by (a) its potential capacity and (b) conditions in its environment. This set of constraints determines all possible performances or behaviors of the system.

System potential capacity is a theoretical concept:

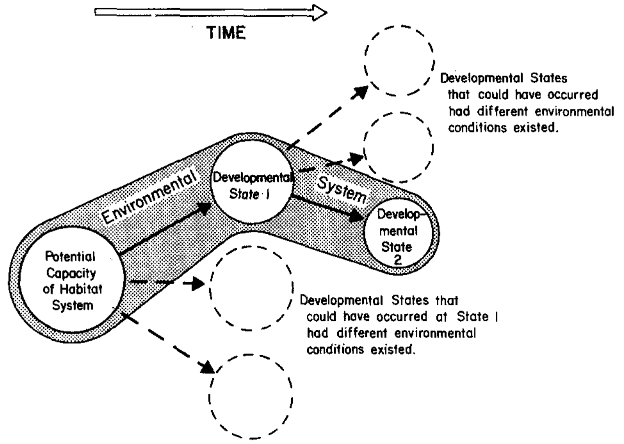


Figure 1. Diagrammatic view of a habitat system showing that from some origin a system passes through a particular sequence of developmental states, jointly determined by its potential capacity and the development of its environmental system. After Warren and others (1979).

it can never be fully and directly explained empirically (Warren and others 1979). The concept, however, provides direction or a perspective for selection of appropriate variables for classification. It suggests that for a system defined within a given frame of time and space, variables selected for classification should be those that are most general, invariant, and causal or determining of the behavior of the system (Warren and Liss 1983). Variables selected according to these criteria can be thought of as proxies or indices of system potential capacity.

A stream habitat of a given class and (theoretically) having a particular potential capacity can be understood to develop or change in state and organization through time (Figure 1), these changes occurring ultimately in conformity with changes in the watershed environment. System evolution we define theoretically as change in system potential capacity. In a habitat system it is manifest as a change in the distinguishing form or structure of the system. Thus, a pool whose bed aggrades and surface slope steepens in a severe flood is no longer a pool; it has evolved into a riffle or glide. When a log step forming a plunge pool decays and collapses, the plunge pool no longer persists as that particular class of habitat. Processes associated with both developmental and evolutionary changes in stream habitats will be considered in later sections.

A Hierarchical Model of Stream Systems

Stream systems can be defined as hierarchically organized systems incorporating, on successively lower levels, *stream segment, reach, pool/riffle,* and *microhabitat* subsystems (Figure 2). At each level in the hierarchy, systems can be seen to develop and persist predominantly at a specified spatiotemporal scale (Table 1). Geologic events of low frequency and high magnitude (Wolman and Miller 1960) cause fundamental evolutionary changes in stream and segment systems, while relatively high-frequency, low-magnitude geomorphic events can change the potential capacities of reaches, pool/riffle systems, and microhabitats, and cause evolution at these smaller scales.

The hierarchy is spatially nested, that is, a system at one level forms the environment of its subsystems at lower levels. Habitats at all levels reside within the watershed environment, yet each segment, reach, or pool/riffle system plays a particular structural and functional role (physically and biologically) in the stream system and exists in a particular location in the watershed.

After one defines hierarchical levels, classification of systems within any level involves two further steps. The first is delineating the boundaries between systems. Table 2 describes some spatial criteria that are useful in identifying stream habitat subsystems. Geomorphic features that constrain potential physical changes in the stream, relative to the level-specific space-time frame, can be considered observable indicators of the potential capacity of the associated habitat systems. For example, a stream reach dissecting a terrace with banks composed of gravelly alluvium has a different capacity (for example, for bank erosion, channel morphology changes, or fish production) than an adjacent reach cutting through clayey, cohesive soils of a landslide deposit. The boundary of the two reaches would correspond to the location where gravelly bank materials grade into clayey banks.

The last step in classification is to describe how the systems that have been delineated are similar or dissimilar, assigning them to some group within the total population. In the example above, two reach classes could have been defined: (a) alluvial soils/gravelly banks, and (b) colluvial soils/clayey banks. Reaches in both classes exist within a common space–time frame, yet within this frame they differ predictably in their origin, development, and potential response to environmental changes, including human activities.

Finally it is important to note that while this model is a useful tool for interpreting the natural variability in streams, it is not intended to completely mirror their organization. The systems described here will,

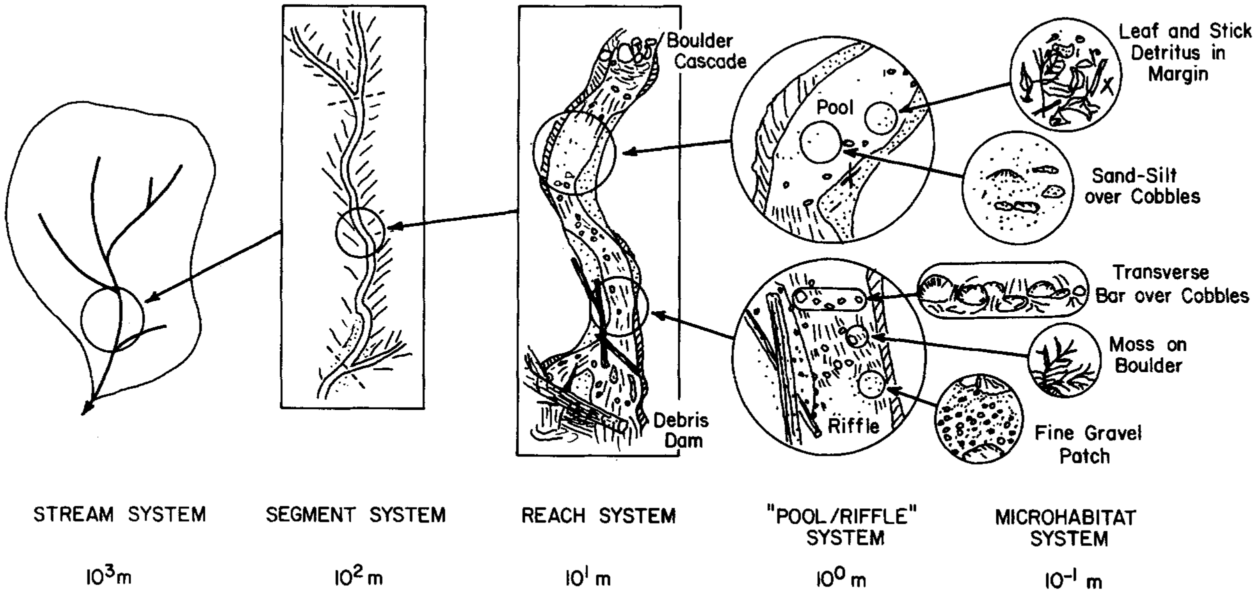


Figure 2. Hierarchical organization of a stream system and its habitat subsystems. Approximate linear spatial scale, appropriate to second- or third-order mountain stream, is indicated.

Table 1. Some events or processes controlling stream habitat on different spatiotemporal scales.

System level	Linear spatial scale[a] (m)	Evolutionary events[b]	Developmental processes[c]	Time scale of continuous potential persistence[a] (years)
Stream system	10^3	Tectonic uplift, subsidence; catastrophic volcanism; sea level changes; glaciation, climatic shifts	Planation; denudation; drainage network development	10^6–10^5
Segment system	10^2	Minor glaciation, volcanism; earthquakes; very large landslides; alluvial or colluvial valley infilling	Migration of tributary junctions and bedrock nickpoints; channel floor downwearing; development of new first-order channels	10^4–10^3
Reach system	10^1	Debris torrents; landslides; log input or washout; channel shifts, cutoffs; channelization, diversion, or damming by man	Aggradation/degradation associated with large sediment-storing structures; bank erosion; riparian vegetation succession	10^2–10^1
Pool/riffle system	10^0	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 system	10^{-1}	Annual sediment, organic matter transport; scour of stationary substrates; seasonal macrophyte growth and cropping	Seasonal depth, velocity changes; accumulation of fines; microbial breakdown of organics; periphyton growth	10^0–10^{-1}

[a] Space and time scales indicated are appropriate for a second- or third-order mountain stream.

[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.

in the field, show some degree of interpenetration and complexity that no model can completely represent.

On the basis of the geomorphic processes and forms most important in each space–time frame, we have developed a small set of general variables—proxies or indices of potential capacity—useful for classifying habitats at each level in the stream hierarchy (Table 3). The objectives of the following section are to describe these variables, illustrate how habitat units are defined, and suggest what kinds of classes might be developed at each scale. While the

Table 2. Habitat spatial boundaries, conformant with the temporal scales of Table 1.

System level	Capacity time scale[a] (years)	Vertical boundaries[b]	Longitudinal boundaries[c]	Lateral boundaries[d]	Linear spatial scale[a] (m)
Stream system	10^6–10^5	Total initial basin relief; sea level or other base level	Drainage divides and seacoast, or chosen catchment area	Drainage divides; bedrock faults, joints controlling ridge valley development	10^3
Segment system	10^4–10^3	Bedrock elevation; tributary junction or falls elevation	Tributary junctions; major falls, bedrock lithologic or structural discontinuities	Valley sideslopes or bedrock outcrops controlling lateral migration	10^2
Reach system	10^2–10^1	Bedrock surface; relief of major sediment-storing structures	Slope breaks; structures capable of withstanding <50-year flood	Local sideslopes or erosion-resistant banks; 50-year floodplain margins	10^1
Pool/riffle system	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	Mean annual flood channel; midchannel bars; other flow-splitting obstructions	10^0
Microhabitat system	10^0–10^{-1}	Depth to particles immovable in mean annual flood; water surface	Zones of differing substrate type, size, arrangement; water depth, velocity	Same as longitudinal	10^{-1}

[a] Scaled to second- or third-order mountain stream.

[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.

proposed variables are general in nature, this discussion is oriented toward small mountain streams in forested environments.

Stream Systems

A stream system includes all surface waters in a watershed. That the development and physical characteristics of a stream system are dependent upon the geologic history and climate of its drainage basin is widely recognized (for example, Hack 1957, Schumm and Lichty 1965, Douglas 1977). Phenomena such as tectonic uplift, subsidence, folding, faulting, volcanism, glaciation, and climatic or sea level changes set major physical constraints within which stream systems develop (Table 1). Stream system and drainage basin development involves headward and lateral extension of the channel network, and lowering of basin relief by surface erosion (Horton 1945) or groundwater-mediated processes (Higgins 1984).

Within a given physiographic region, stream systems with similar geologic structure and geomorphic histories should have similar network structure and longitudinal profiles (Hack 1957). Thus, stream systems might be classified on the basis of the biogeoclimatic region in which they reside (Warren 1979, Bailey 1983), the slope and shape of their longitudinal profiles (Hack 1957), and some index of drainage network structure (Strahler 1964), as shown in Table 3. Stream systems of a class would have watersheds with similar land types (Lotspeich and Platts 1982) and similar arrays of segment subsystems.

Thinking at the spatial scale of the stream system is required to assess basin-wide, cumulative effects of management activities, or to integrate observations from scattered sites within watersheds. Understanding the long-term developmental and spatial relationships between stream systems lay the foundation for classifying smaller-scale landscape and stream units, and might help in interpretation of biogeographic and evolutionary patterns of stream organisms and communities.

Segment Systems

A segment is a portion of a stream system flowing through a single bedrock type and bounded by tributary junctions or major waterfalls (Table 2). A segment appears relatively uniform in slope on a map-derived longitudinal profile (map scale 1:20,000 to 1:80,000). The class segment is determined by the

Table 3. General variables for classifying habitats by potential capacity.[a]

Watershed	Stream system	Segment	Reach	Pool/riffle	Microhabitat
Biogeoclimatic region	Watershed class	Stream class	Segment class	Reach class	Pool/riffle class
Geology	Long profile slope, shape	Channel floor lithology	Bedrock relief, slope	Bed topography	Underlying substrate
Topography	Network structure	Channel floor slope	Morphogenetic structure or process	Water surface slope	Overlying substrate
Soils		Position in drainage network	Channel pattern	Morphogenetic structure or process	Water depth, velocity
Climate		Valley sideslopes	Local sideslopes, floodplain	Substrates immovable in <10-year flood	Overhanging cover
Biota		Potential climax vegetation	Bank composition	Bank configuration	
Culture		Soil associations	Riparian vegetation state		

[a] Not all variables are necessary to distinguish classes in all circumstances; best specific metrics or indices may vary regionally or with study objectives.

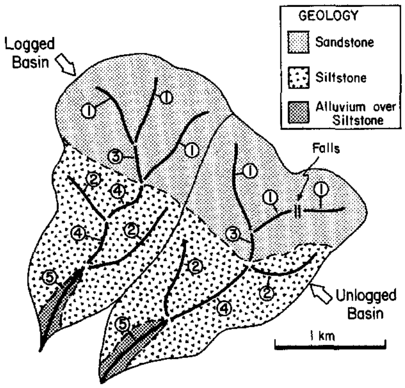
class of the stream system in which it resides, the lithology and structure of underlying and adjacent bedrock [or glacial drift or alluvial deposits in some landscapes (Ruhe 1975, Strayer 1983)], slope, position in the drainage network—by order (Strahler 1952) or by link number (Shreve 1967)—and valley side slopes (Table 3). In some cases where streams cross major biogeoclimatic discontinuities, or ecotones (for example, from deciduous forest to grassland vegetation type), segments can be further discriminated on the basis of soil associations, land types (Lotspeich and Platts 1982), or potential natural vegetation (Daubenmire 1968). Lakes should be considered segment-level units of a stream system, as they may persist as geomorphic features across a similar scale of space and time, and play major roles in the physical and biological organization of streams. The segment unit in most cases can be classified by using existing topographic, geologic, and vegetation and soil maps. Aerial photointerpretation is also useful.

The potential capacity of a stream segment could be changed by any major change in watershed capacity including such geologic events as local volcanism or glaciation, faulting, or very large landslides (Table 1). A segment system develops by slow upstream migration of nickpoints and downwearing, widening, or extensive infilling of the valley floor (West 1975), development of new channel heads (Douglas 1977), and other processes measurable on a time scale of many centuries.

Drainage areas, and thus hydrologic characteristics, abruptly change at tributary junctions. Knighton (1982), Miller (1958), and Hack (1957) describe changes in bed material size, shape, and lithology where tributaries join, or at major bedrock outcrops and lithologic contacts. Hack (1957) and Keller and Tally (1979) showed that lithology and geologic structure determine the slopes of stream segments and valley walls. In the Pacific Northwest, channel scour and deposition by massive debris torrents is often controlled by tributary junctions (Swanson and Lienkaemper 1978; L. Benda, Forest Sciences Laboratory, Oregon State University, personal communication). Teti's (1984) work demonstrates how water chemistry patterns can vary where tributaries converge. Bruns and others (1984) describe discrete changes in stream macroinvertebrate communities below tributary junctions—in effect, natural discontinuities in the river continuum (Vannote and others 1980).

Large dams, diversions, channelization projects, levees, mining, and activities causing groundwater depletion, soil salinization, or desertification can change potential capacities of stream systems and segments.

Figure 3 illustrates how segments might be classified in two hypothetical watersheds. Since the streams are similar in capacity, habitats within segments of the same class might be compared to evaluate the effects of management activities that have occurred in one watershed but not in the other. Segments of the same class should potentially have sim-



STREAM SEGMENT CLASSIFICATION

Segment Class	Order	Slope	Sideslopes	Geology	Description
1	1	15-25%	Steep, no flood plain	Sandstone	Steep headwall tributaries
2	1	10-12%	Moderate, no flood plain	Siltstone	Lateral low gradient tributaries
3	2	12-15%	Steep, no flood plain	Sandstone	Upper valley mainstems
4	2	5-7%	Moderate, narrow flood plain	Siltstone	Mid-valley mainstems
5	2	3-4%	Gentle, wide flood plain	Alluvium over siltstone	Lower valley mainstems

Figure 3. Classification of segment systems in two hypothetical watersheds.

ilar kinds of reaches, pools and riffles, and microhabitats, if their watersheds are in similar states. The slope, valley walls, bedrock floor topography, and contributing drainage basin of a segment constrain the kinds of smaller-scale habitat systems that can evolve there.

Figure 4 shows one useful way to begin segment classification. Segments of two adjacent stream systems in the Oregon Coast Range were delineated from a topographic map. Both streams have similar kinds of segments, except for certain steep sidewall tributaries in Deer Creek. In a paired basin study, one should compare segments that lie nearest each other in this diagram. One should also consider potential differences in basin-wide response to management activities that could be caused by the steep tributaries peculiar to Deer Creek (for example, greater probability of upslope mass failures entering the main channel as debris torrents). If two stream systems have few kinds of segments in common, that is, little overlap in the ordination plot, they must be considered unsuitable for a paired-basin study.

Reach Systems

The reach system is sometimes the least physically discrete unit in the hierarchy. Nevertheless, this is an exceedingly useful scale for describing medium- and long-term effects of human activities in streams. Fishery biologists and aquatic ecologists frequently determine population parameters and distributional patterns or describe community composition on the spatial scale of the stream reach. The reach, variously defined, is also a common unit of field description among fluvial geomorphologists.

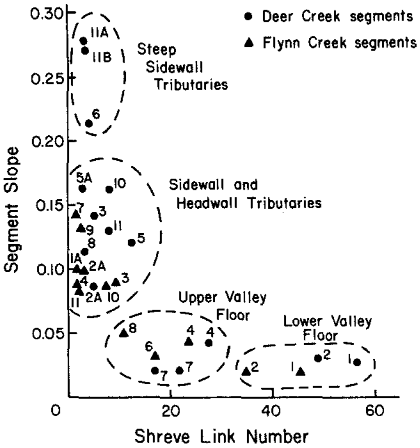


Figure 4. Simple ordination of stream segments of two Oregon Coast Range watersheds, based on data derived from US Geological Survey 1:62,500-scale quadrangle. *Axes* reflect channel slope and position in the drainage network. *Points,* coded by numbers, represent individual segments. *Clusters,* delineated subjectively, correspond to common geomorphic regions in the two basins. The *x*-axis summarizes longitudinal continuum aspects (Vannote and others 1980) of the stream systems, while the *y*-axis summarizes geographic variation between segments along the longitudinal gradient.

We view reaches as integrated geomorphic units. Some understanding of their genesis as well as form is necessary for adequate classification. A reach system is defined as a length of a stream segment lying between breaks in channel slope, local sideslopes, valley floor width, riparian vegetation, and bank material (Table 2). The reach typically possesses a characteristic range of channel bed materials. Its length can be measured in meters to tens of meters in small, steep streams, or perhaps hundreds of meters or more in fifth-order and larger streams. Reach-associated features are visible in the field and sometimes on low-level aerial photographs, but only rarely on topographic maps.

Stream segments in forested, mountainous watersheds frequently have complex, highly variable longitudinal profiles (Figure 5), owing to the influences of large woody debris (Heede 1972, Keller and Tally 1979, Keller and Swanson 1979), landslides and bank failures (Pearce and Watson 1983), and channel shifting associated with these features. Minor outcrops due to irregularities in the bedrock of the

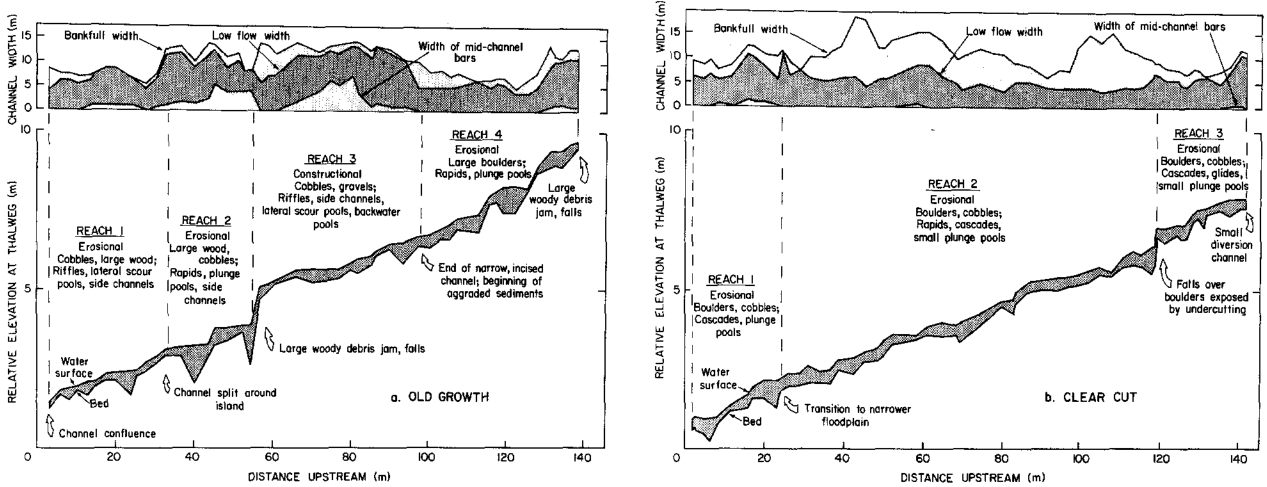


Figure 5. Variation in slope and channel width in **(a)** old-growth and **(b)** logged sections of Minto Creek, a fourth-order stream in the Oregon Cascades (Frissell 1986). One possible classification of reaches is indicated, and features associated with reach morphogenesis are noted at *bottom*. Both study sections lie within the same stream segment. The lesser complexity of reach-scale organization in the clear-cut section **(b)** is apparently a result of logging, channel debris removal, and subsequent bed and bank degradation. This section also has a different array of pool/riffle subsystem types and microhabitats. Note ×8 vertical exaggeration in slope profiles.

channel floor also contribute (Douglas 1977). Variations in channel slope correspond with variations in channel cross section (Keller and Swanson 1979, Mosely 1981), bed materials (Keller and Tally 1979, Beschta 1979), and sediment transport (Mosley 1981, Bilby 1981, Beschta 1979). These variations are often so great within a stream segment that conventional means of predicting channel form from drainage area, discharge, or map-derived slope estimates may prove of little value in the field (Phillips and Harlin 1984).

Geomorphic evidence suggests that a stable piece of large wood may influence a channel for anywhere from tens to hundreds of years (Megahan 1982, Keller and Swanson 1979, Keller and Tally 1979, Bryant 1980), and the impacts of a mass movement event may last for decades, and probably much longer (Pearce and Watson 1983, Swanson and Dyrness 1975). Local variations in sideslopes or floodplain form (Keller and Swanson 1979), riparian vegetation (Triska and others 1982, Murgatroyd and Ternan 1983), and composition of the bank material (Schumm 1960) also constrain channel form and dynamics in the temporal and spatial frame of the stream reach. Considering these observations, we have chosen the variables in Table 3 for classifying reaches.

Table 4 summarizes how these variables have been applied in field studies (Frissell 1986, Frissell and Liss 1986). Different classification schemes may prove useful for different applications. Our classification emphasizes (a) the relationship of a reach system to watershed events, and (b) the potential persistence and developmental trend of the reach, and thus (c) its long-term role as a unit of stream habitat. A reach of certain class should have a characteristic potential developmental history and predictable spatial association of pool/riffle subsystem classes (Figures 4–6 and Table 3; also see Keller 1972 for a general model).

Pool/Riffle Systems

A pool/riffle system is a subsystem of a reach having characteristic bed topography, water surface slope, depth, and velocity patterns. Geomorphologists often refer to these units as *bedforms.* Keller and Melhorn (1973), discussing the origin and development of pools and riffles, point out that they are produced at relatively high flows. Riffle and pool form at low flow reflects the structure inherited from previous flood events. At high flows, pools are zones of convergent flow and bed scour, while riffles are zones of divergent flow and deposition of bedload (Keller and Melhorn 1973, Jackson and Beschta 1982). This is the converse of how many aquatic ecologists, viewing streams at low flow (when only fine sediments and organic materials are transported), conceive of these habitats; Moon (1939) classified pools as "depositional" habitats and riffles as "erosional" zones.

In many streams, habitats at this level are complex, and include not simply pools and riffles, but

Table 4. Reach classes in small Oregon streams (Frissell and Liss 1986).

Gross typology	Morphogenetic class[a]	Morphogenetic process	Relative length	Mean slope[b]	Dominant substrates	Developmental trend	Potential persistence[c]
Erosional	Bedrock outcrop	Irregular bedrock resistance to weathering	Moderate to short	Variable; moderate to steep	Bedrock	Stable; all sediments transported	Long-term
(Zones of exposure of bedrock floor or trend toward degradation of bed)	Colluvium (nickpoint)	Downcutting through landslide or torrent debris	Moderate to short	Steep, later becoming moderate	Boulders, cobbles, clay soil	Active degradation (unless reloaded)	Generally moderate; depends on deposit size
	Torrent scour	Channel scour by debris torrent or flood	Moderate to long	Moderate to steep	Bedrock, some boulders	Transport of most sediments; local aggradation	Moderate (due to likely recruitment of constructional features)
Channel pattern: straight	Alluvium	Downcutting through alluvium of old constructional reach	Moderate	Moderate	Cobbles, gravels	Slow degradation	Moderate to short-term
	Root blockage (nickpoint)	Channel shift after colluvium or debris jam blockage; tree roots delay downcutting	Short to moderate	Moderate to low	Tree roots, gravels, cobbles, clay soil	Stable period followed by degradation	Short-term; very short if small roots
Constructional	Bedrock outcrop	Sediment storage behind resistant bedrock features	Variable	Low	Gravels, fines, bedrock	Stable; inputs balance outputs	Long-term
(Zones of aggradation of alluvium)	Colluvium	Sediment storage behind landslide or debris torrent deposits	Variable	Low	Gravels, cobbles, fines	Degradation, shortening (unless reloaded)	Long-term to moderate (depends on deposit size)
Channel pattern: straight often verging on braided	Large woody debris	Sediment storage behind large logs or debris jams	Moderate	Low	Gravels, fines wood	Net aggradation until decay or washout	Moderate, sometimes long-term
	Small woody debris	Sediment storage behind jam of small debris	Short	Low to moderate	Gravels, cobbles, fines, wood	Aggradation, then quick washout	Short-term

[a] Morphogenetic classes are further subdivided by segment class, whether banks are clayey colluvium or gravelly alluvium, whether sideslopes allow lateral migration, and riparian vegetation state.

[b] Slope scale: moderate = same as segment slope, low = less than segment slope, and steep = greater than segment slope.

[c] Persistence scale: long-term = >100 years, moderate = 20–100 years, and short-term = <20 years.

rapids, runs or glides, falls, side channels, and other forms. Bisson and others (1982) provide a useful system of naming such habitats and also demonstrate that different salmonid species in Pacific Northwest streams prefer different habitat types. Gorman and Karr (1978) suggest that fish community structure in small streams depends on habitat complexity and temporal stability. Clearly, a useful classification of pool/riffle systems should account for their origin, structure or form, and temporal development and persistence.

Our classification begins with definition of pool/riffle "forms" (Figure 7) based predominantly on Bisson and others (1982). These forms reflect (a) bed topography and low water surface slope, (b) gross aspects of hydrodynamics (for example, plunge pool formed by scour below a vertical fall, or lateral scour pool formed by horizontally directed flow), and (c) position relative to the main channel (for example, backwater pools, side channels). Through an annual cycle of development, each habitat type may have a characteristic pattern of flow velocities, depths, and sediment dynamics, which should be of prime importance in determining its suitability as habitat for different organisms.

Pool/riffle systems are often associated with large structures causing local scour and aggradation, such as woody debris (Keller and Swanson 1979, Swanson

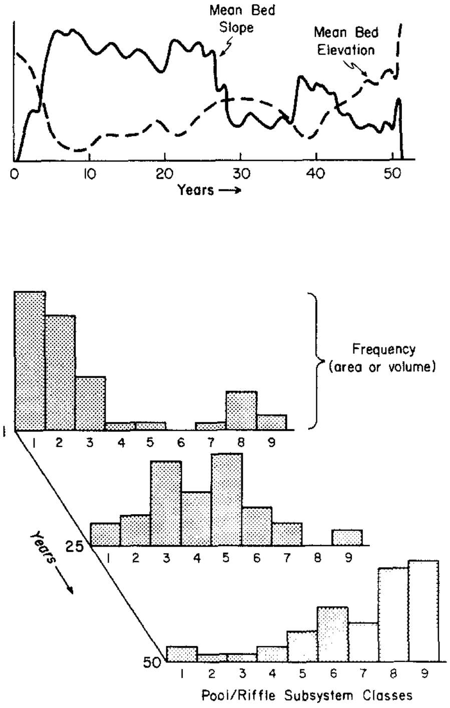


Figure 6. (Top) Changes in mean bed elevation and slope of a hypothetical reach system during its history. Following initial aggradation behind a debris jam formed at a newly fallen tree, bed elevation fluctuates somewhat with changes in jam structure, bedload storage and transport, and bank erosion. After 50 years, the reach system is obliterated by decay and washout of the debris jam. **(Bottom)** Development of the same reach in terms of the importance of different hypothetical classes of pools and riffles.

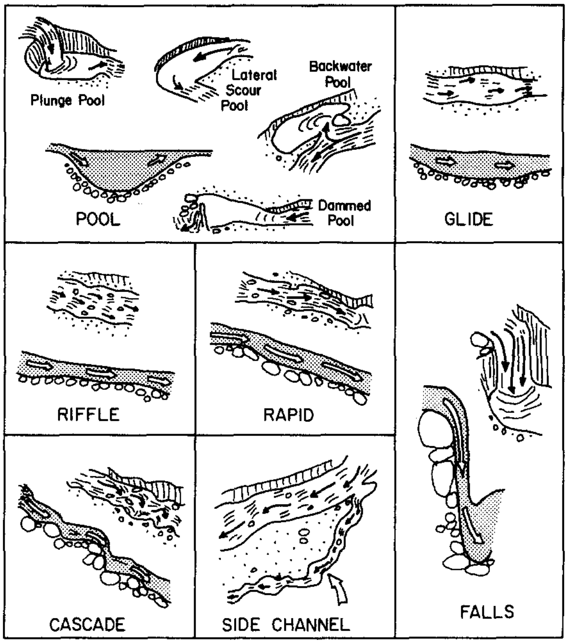


Figure 7. Fundamental pool/riffle forms, reflecting bed topography, low water surface slope, hydrodynamic pattern, and position in relation to the main channel. Longitudinal profile (*shaded*) and oblique views are shown. Modified from Bisson and others (1982).

and Lienkaemper 1978), mass-movement- or flood-deposited boulders, and bedrock outcrops (Bryant 1980). This is the second major aspect in pool/riffle system classification (Figure 8). The potential persistence of a particular pool or riffle is dependent upon the stability of the associated morphogenetic feature, whether this is an extremely long-lived bedrock outcrop, moderately long-lived large wood, or a transient gravel bar. This genetic variable also serves to link stream habitat at this scale to watershed or riparian processes. Land management activities can profoundly change the types and temporal stabilities of pool/riffle systems in a stream reach (Swanson and Dyrness 1975, Gorman and Karr 1978, Bryant 1980, Triska and others 1982). Our observations (Frissell and Liss 1986) suggest pools and riffles associated with less stable morphogenetic features are less resilient and less resistant to disturbance by flows approaching or exceeding mean annual flood.

Sometimes local anomalies such as variations in bank configuration (for example, overhanging soil bank, overhanging roots or wood cover, or no overhanging cover) or large boulders inherited from past floods may distinguish otherwise similar pool/riffle systems. These, together with the other variables listed in Table 3, can be used to define pool/riffle classes, with each class having a characteristic sequence of spatially associated microhabitat subsystems.

Microhabitat Subsystems

Microhabitat subsystems are defined as patches within pool/riffle systems that have relatively homogenous substrate type, water depth, and velocity. Many studies have demonstrated the usefulness of work at this scale in understanding the distributions and trophic and life history adaptations of stream organisms (for example, Linduska 1942, Cummins and Lauff 1969, Rabeni and Minshall 1977, Hynes 1970) and the structure and dynamics of stream communities (Reice 1974, Dudgeon 1982, McAuliffe 1983, Wevers and Warren 1986). Habitat patches at this scale are useful units for investigation of the behavioral ecology of fishes (Smith and Li 1983) and aquatic invertebrates (Hart 1981). Hawkins (1985)

POOL/RIFFLE FORMS

MORPHOGENETIC FEATURES ↓ DECREASING STABILITY	Plunge pool	Lateral scour pool	Dammed pool	Glide	Riffle	Rapid	Cascade	Falls	Backwater pool	Side channel
Bedrock Outcrop	.050	.005	-	.005	.030	.035	.015	.010	-	-
Boulders	.035	.005	-	.015	.015	.015	.030	.005	-	-
Large Wood	.025	.060	.010	.010	.005	-	.020	.005	-	.020
Roots	.030	.015	.005	.005	.005	-	.005	.020	-	.015
Soil Knickpoint	.010	.010	-	-	-	.015	.005	-	-	-
Small Wood	.035	.045	.005	.025	-	-	.020	.005	.005	-
Gravel Bar	-	.020	.015	.040	.196	.015	.005	-	-	.010

Figure 8. Pool/riffle forms and associated morphogenetic features observed in second-order streams of the Coast Range of Oregon. *Numbers* are frequencies of occurrence out of 199 total observations. Data compiled from surveys of about 18 total reaches (378 m total length) in three streams.

suggests most stream invertebrates may be microhabitat specialists and states that "pattern at small scales should provide insights to pattern at larger scales." Physical features that control microhabitat distribution can be seen to control invertebrate distributions as well.

In our view, classification of microhabitats should account for their origins and development, as well as their characteristics at any single time. Laronne and Carson (1976), Carling and Reader (1982), and Dudgeon (1982) show that the structure and arrangement of bed particles reflect the processes and temporal patterns of their deposition, as well as their potential for future transport. The relationship of a patch of bed material to its larger-scale (pool/riffle or reach) environment is also important in understanding its dynamics (Laronne and Carson 1976, Jackson and Beschta 1982). Bed particle size, shape, and transport dynamics are dependent on the geology, climate, vegetation, and land use of the drainage basin, as well as on the general drainage network position and slope of the stream segment under consideration (Hack 1957, Miller 1958, Knighton 1982, Douglas 1977).

Except in certain spring-fed streams with relatively constant flows and physicochemical conditions, individual microhabitats are disturbed at least annually, and thus they develop over time scales of days, weeks, or months. Particle size of bed material is a major determinant of the frequency of one major evolutionary process, particle transport. For example, in Oregon Coast Range streams a particle size threshold exists, in which fine gravel, sand, and smaller particles are transported with even minor increases in stream flow, while coarse gravels and cobbles are transported only in larger storm events approaching mean annual flood (Jackson and Beschta 1982, Frissell and Liss 1986). Because of such patterns in transport response, bed materials are sorted by size, and relative discrete substrate patches are usually discernible (Laronne and Carson 1976, Jackson and Beschta 1982). These patches develop distinctive benthic communities, depending upon their physical characteristics and temporal stability (Hynes 1970, Lenat and others 1981, Hawkins 1985).

Processes other than direct transport also act to disturb microhabitats. The duration of time a substrate patch is within the wetted perimeter of the channel is perhaps the most important determinant of its capacity as a stream habitat. Other important processes include scour of stationary particles of bedrock by high-velocity flows and particles in transport, burial by deposited sediments, and, where aquatic macrophytes occur, growth, seasonal senescence, and cropping of vegatation. Inputs of leaf litter and other organic debris creates new microhabitats seasonally. Within these seasonal evolutionary constraints, microhabitats develop by accumulation of fine sediments and organic matter, breakdown of organic particulates, growth of periphyton, and other processes (Table 1).

In microhabitat classification, several specific variables are employed (Tables 3 and 5). When placed in the context of the encompassing pool/riffle and higher-level systems, microhabitat patterns in space and time appear greatly simplified. Dominant underlying substrate (for example, 2–8 cm below substrate surface in small streams) may reflect annual or longer-term transport dynamics, while dominant overlying substrate reflects short-term or seasonal dynamics of the habitat. Substrate, velocity, and depth are usually somewhat correlated. This strategy for microhabitat classification was developed to describe the organization of benthic macroinvertebrate communities sampled at low flow, and to interpret differences between communities in relation to spatiotemporal differences in their habitats. Specific definitions of microhabitat classes could be varied to suit different study objectives. A year-long sampling program would require identification of microhabitats that exist only at high flows.

Discussion

The habitat classification system has been oriented

Table 5. Specific variables used in field classification of microhabitats of small streams in the Oregon Coast Range (Frissell and Liss 1986).

Environment	Dominant underlying substrate[a]	Dominant overlying substrate[a,b]	Water depth	Water velocity	Overhead cover
Stream system	Bedrock	Bedrock	Graded scale, 0–50 cm	Graded scale, 0–100 cm · s^{-1}	Tree roots
Segment class	Boulders	Boulders			Soil bank
Reach class	Cobbles	Cobbles			Woody debris
Pool/riffle class	Wood	Wood			Foliage
	Large gravels	Large gravels			
	Fine gravels, sand	Fine gravels, sand			
	Silt–clay	Moss			
		Silt–clay			
		Fine particulate organic matter			
		Fresh soil peds			

[a] Substrates listed in descending order of stability.

[b] If underlying substrate has no overlying layer, overlying class is coded same as underlying class.

primarily toward third-order and smaller streams, yet the relative spatiotemporal relationships between levels in the hierarchy may remain intact even in the largest rivers. Even the kinds of genetic processes may remain similar; only the absolute scale of frequencies and magnitudes of events, and of system capacities, increases with increasing stream size. While a simple bank slump may create a rapid in a second-order stream, and this habitat may persist for years, a rapid in a sixth-order river may originate from a massive landslide whose influence lasts for centuries (Leopold 1969). Woody debris plays functionally different, perhaps less dramatic roles in larger rivers than in small streams (Keller and Swanson 1979). Habitat in many large rivers may depend more on upstream influences and less on streamside phenomena. Still, discrete segments, reaches, pools, riffles, and microhabitats are identifiable, each habitat retaining a spatial and temporal dependency on the higher-level system of which it is a part. Future effort should be directed toward scaling concepts of habitat potential capacity to watershed and stream size. Rates at which habitat systems at any given level develop and evolve, as well as controlling variables, may also vary systematically between biogeoclimatic regions for any given stream size. This presents interesting possibilities for comparing general aspects of habitat and community dynamics between streams in different parts of the world.

As mentioned previously, the classification variables presented in Table 3 are general in that they are meant to account for variation across a broad range of possible stream types and geographic environments. The specific variables employed in a classification project are likely to be fewer, because (a) within any given geographic region or stream system, the range of variation may be relatively narrow, and some of the variables from Table 3 will not be relevant, and (b) the particular objectives of the project may dictate that certain variables assume overwhelming importance. The lack of information about some factors may be a further practical constraint. Nevertheless, we emphasize that consideration of the full range of possible sources of variation in stream habitat characteristics can be a useful and revealing exercise; unanticipated patterns may emerge and very fine distinctions in physical features may sometimes be of critical biological importance.

Southwood (1977) developed a framework in which life history strategies of organisms are viewed in terms of the spatial and temporal availability, predictability, and favorableness of habitats. The classification system we discuss is useful to account for these habitat dimensions. Understanding the temporal persistence and spatial relationships of habitat types should help explain the ecological organization of their associated communities (Dudgeon 1982, Hawkins 1985). Viewing stream communities as systems organized and developing around spatially defined habitats (Wevers and Warren 1986) should provide increased understanding of stream community structure and evolution, and the evolution of life history types among aquatic plants, invertebrates, and fishes.

Lotspeich and Platts (1982), in discussion of their land-and-stream classification system, state that "stream habitats at the level of land type" (roughly equivalent to our segment level) "become quite homogenous. . . ." Many interpretations of the river continuum concept (for example, Minshall and others 1983) assume homogeneity within a stream section of given order. In our experience and that of others (Resh 1983, Phillips and Harlin 1984), however, stream habitats and their communities often are variable and spatially diverse within stream segments. In the view presented here, a stream segment is understood to have a predictable spatiotemporal array of habitat types dependent upon the watershed, and differences between segments are evident as differences in this pattern. Habitats within segments are not homogeneous, but there is order in their heterogeneity. This perspective on stream habitat organization, when coupled with a biogeoclimatic classification like that of Lotspeich and Platts (1982) or Warren and Liss (1983), may provide for a richer understanding of ecological patterns in streams, and a stronger framework for stream ecosystem management than previous models alone allow.

Because of the disparate time scales among levels in the habitat hierarchy, events that change habitat potential at small scales may not affect the potential capacity of systems at larger scales. Yet any event that causes shifts in a large-scale system will change the capacity of all the lower-level systems it encompasses. For example, streams are most sensitive to man-caused or natural disturbances at the microhabitat spatiotemporal scale. While pool/riffle systems of a stream may remain intact if riparian zones are protected, potential capacities of microhabitats basin-wide may shift with slight changes in the hydrologic or sediment transport regimes of a watershed. Such changes (for example, silting-in of gravels) can have drastic effects on biota within the short-term time frame of most sampling programs for evaluation of environmental impacts. Yet, if reach and pool/riffle structure remain intact, the capacity of the biological community to recover via recolonization over a period of years or decades may be preserved.

Of course, reestablishment of biological communities similar to predisturbance communities can occur only if the pool of species available for colonization remains largely unaltered (Gore 1982). Because both habitat organization and colonization play major roles in stream community development (Sheldon 1984, Wevers and Warren 1986), conservation of habitat diversity and of community kinds should be important considerations in watershed and stream management across the spectrum of spatiotemporal scales, from microhabitats to entire biogeoclimatic regions (Warren and Liss 1983, Jenkins and others 1984).

Scientists developing tools for understanding long-term stream habitat changes due to cumulative impacts of land-use activities could benefit from this approach in that it not only provides a means of defining habitat classes, but also ties each of these classes to particular kinds of watershed processes and events. Different morphogenetic events create stream habitats having different forms and different capacities to persist in the face of habitat-disrupting events (for example, floods, sedimentation, landslides). Land-use changes and vegetative succession in a watershed change not only the kinds of events impinging on a stream, but also the frequencies at which such events occur. Thus both spatial structure and temporal stability and predictability of habitats change. These patterns vary among different kinds of reaches, stream segments, watersheds, and biogeoclimatic regions. Models that ignore classification at these higher levels may prove neither predictive nor useful.

Understanding a stream system as a hierarchy of habitat subsystems may be useful in evaluating the potential or realized impacts of nonpoint source pollution. Only low-gradient segments, for example, may be susceptible to deposition of fine sediments, and within these areas, certain gently sloping reaches or particular habitats like side channels and backwater pools may be most severely affected. The landtypes in a watershed can be seen to determine potential sediment sources as well as the underlying pattern of stream habitat and its potential for degradation.

Careful assessment of a site-specific phenomenon, for example a habitat improvement structure or a locally eroding streambank, requires identification of comparable control sites. According to specific objectives, pools and riffles, reaches, or segments should be compared in this way only if they are similar in class. This framework provides a way to identify sites having similar potential.

Monitoring programs and sampling efforts require selection of representative sites. Only after arriving at a broad understanding of the range of habitat kinds in a stream system or region, and of how these habitats vary in space and time, can one select an array of sites to meaningfully and efficiently represent that domain. Conversely, habitat classification could be used to evaluate the reliability or bias of an existing monitoring network or data set.

Conclusions

This framework for stream habitat classification provides a systematic view of spatial and temporal variation among stream systems. By viewing streams as hierarchically organized systems, the approach focuses on a small set of variables at each level that most determine system behaviors and capacities within the relevant spatiotemporal frame. Microscale patterns are constrained by macroscale geomorphic patterns. Each unit of the stream remains in the context of the watershed as a whole. Such a classification defines the structure, development and persistence, and environment of each habitat, features which determine its suitability for different organisms. Thus, stream communities can be viewed as systems organized within this hierarchical habitat template.

Our approach is related to recent trends in oceanography and limnology, in that it emphasizes the role of physical processes in ordering biological systems and the role of spatiotemporal scales in understanding these phenomena (Legendre and Demers 1984). This framework is presented as a tool that can guide researchers and managers in conceiving and executing studies, perhaps affording new ways of dealing with old problems. We believe the perspective allows a more integrated and holistic view of streams and their watersheds than is presently available.

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