AN ABSTRACT OF THE THESIS OF

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Title: A Hierarchical Stream Habitat Classification System: Development and Demonstration

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William J. Liss

Classification of streams and stream habitats is useful for research involving establishment of monitoring stations, determining 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 thesis presents a framework for a hierarchical classification system, entailing an organized view of spatial and temporal variation between and within stream systems. Stream habitat systems, defined and classified on several spatio-temporal 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 classification. The framework is a perspective that should allow more systematic interpretation and description of watershed/stream relationships.

The classification system was used to assess changes in stream habitat caused by logging and debris removal in a fourth-order stream in the High Cascades of Oregon. Habitat organization, trout density, and habitat use were compared in logged (clear-cut, 1962) and forested stream sections in the same stream segment. The hierarchical classification system allowed pool/riffle habitats to be related to the geomorphic history of different stream reaches. Due to the presence of large debris dams and abundant woody debris, forested reaches varied in morphology and encompassed a wide array of pool/riffle habitats, including debris-created pools and side channels. Clear-cut reaches were relatively homogeneous, and were dominated by boulder-formed habitats. Although trout density was highly reach-specific, total density of the forested section was 40% greater than that of the clear-cut section. The smallest size class was absent and large (>14 cm) individuals were uncommon in clear-cut reaches. A regression model showed that most of the variation among reaches in trout density was related to the relative area comprised of six key pool/riffle types. The habitat classification system proved useful in demonstrating that the forested stream section, because of its diversity of pool/riffle types, may best provide the range of habitats required by all size classes through changing streamflow conditions.

A Hierarchical Stream Habitat Classification System: Development and Demonstration

by

Christopher A. Frissell

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Assistant Professor of Fisheries in charge of major

Redacted for Privacy

Head of Department of Fisheries and Wildlife

Redacted for Privacy

Dean of Graduate School

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Typed by the author and Trudy White for Christopher A. Frissell

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CONTRIBUTIONS OF COAUTHORS

Because this thesis consists of two manuscripts submitted to journals for publication, coauthors are listed on the chapter title pages. This work draws upon a larger body of closely-related, past and ongoing research at Oak Creek Laboratory of Biology. The particular contributions of coauthors to each paper are summarized below.

W. J. Liss--Collaborated in development of the conceptual approach to classification, and theoretical models; helped in field data collection; advised in organization and presentation of results; reviewed and edited manuscripts.

C. E. Warren--Played the major role in intial theoretical development of the conceptual basis and form of the classification system; reviewed manuscript.

C. A. Corrarino--Helped in field work, development of field methods; advised in presentation of results; reviewed manuscript.

M. D. Hurley--Collaborated in development of methods to apply classification concepts in the field, and in early map and field work; reviewed manuscript.

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INTRODUCTION

Streams are complex ecological systems. Characteristics of streams vary spatially, both at broader levels of resolution, as between regions with different climate, geology, and biota, and at finer scales of resolution, as between microhabitats in an individual riffle. Temporal variation is equally significant. Whereas a large flood or major landslide may change characteristics of a stream system over a long period of time, runoff from a small storm event may change conditions over a very short interval. Any perspective that intends to provide an integrated, general view of stream ecosystems must put individual events and observations into the context of larger- and smaller-scale patterns.

While the river continuum concept of Vannote et al. (1980), for example, provides some general view of operational, structural, and functional aspects of stream ecosystems, others have shown that these generalizations may not strictly apply in some geographic regions (e.g., Winterbourne et al. 1981, Culp and Davies 1982). And many studies demonstrate that community patterns at finer scales of resolution are much more complex and discontinuous than predicted (e.g., Resh 1983, Bruns et al. 1984). Perhaps longitudinal continuum spects of stream organization are best viewed within the context of a broader framework, one that would account for spatial and temporal variation among and within different stream systems.

Warren (1979) and Warren and Liss (1983) describe a watershed/stream classification system that accounts for geographical differences among stream systems, including their biota. Wevers and Warren (in preparation) argue that stream communities may be viewed as biological systems organized within a template provided by physical habitat. The present thesis presents a hierarchical system of stream habitat classification, by which smaller-scale stream habitat patterns may be related to larger-scale geomorphic and biogeoclimatic patterns within stream systems, watersheds, and regions.

The goal of this research is to develop a framework for more systematic interpretation and description of watershed /stream relationships. The first paper in this thesis discusses the conceptual basis, theoretical development, and possible applications of the habitat classification system. The second manuscript, describing a portion of the field studies completed during development of the classification framework, discusses how we applied the system to assess changes in stream habitat and cutthroat trout populations in a Cascade Range stream. Together, these papers illustrate how the stream habitat classification system might be useful both for studies with very broad objectives, and those with more specific aims.

A HIERARCHICAL FRAMEWORK FOR STREAM HABITAT CLASSIFICATION: VIEWING STREAMS IN A WATERSHED CONTEXT

Christopher A. Frissell[1]

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

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 paper presents a framework for a hierarchical classification system, entailing an organized view of spatial and temporal variation between and within stream systems. Stream habitat systems, defined and classified on several spatio-temporal 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.

Introduction

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 paper 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.

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

If biological patterns in streams, as we have assumed, 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 communities in a 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) physiograpic 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 a 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.

Benefits of a hierarchical structure include: 1) classification at higher levels narrows the set of variables needed at lower levels; 2) it provides for integration of data from diverse sources and of different levels of resolution; 3) it allows the scientist or manager to select the level of resolution most appropriate to his or her objectives (H.G. Brown III and A.E. Godfrey, unpublished manuscript, USDA Forest Service, Intermountain Region, Ogden, Utah).

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 (Fig. 1). While the system develops, or changes in state and organization through time, it develops only within a set of constraints imposed by 1) its potential capacity and 2) conditions in its environment. This set of constraints determines all possible performances or behaviors of the system.

System potential capacity is a theoretical concept: 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 (Fig. 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.

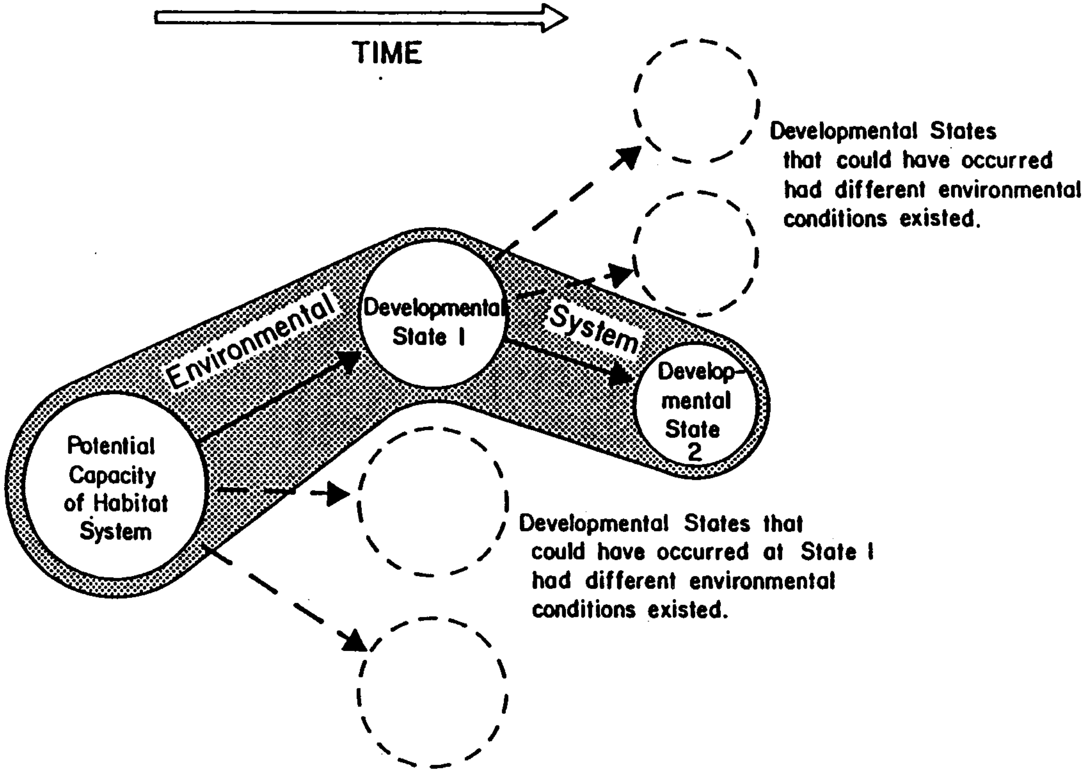


Figure 1. Diagrammatic view of a habitat system showing that from some origin a system passes through a particular sequence of developmental states, jointly determined by its potential capacity and the development of its environmental system. After Warren and others (1979).

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 (Fig. 2). At each level in the hierarchy, systems can be seen to develop and persist predominantly at a specified spatio-temporal 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 (Fig. 3). 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

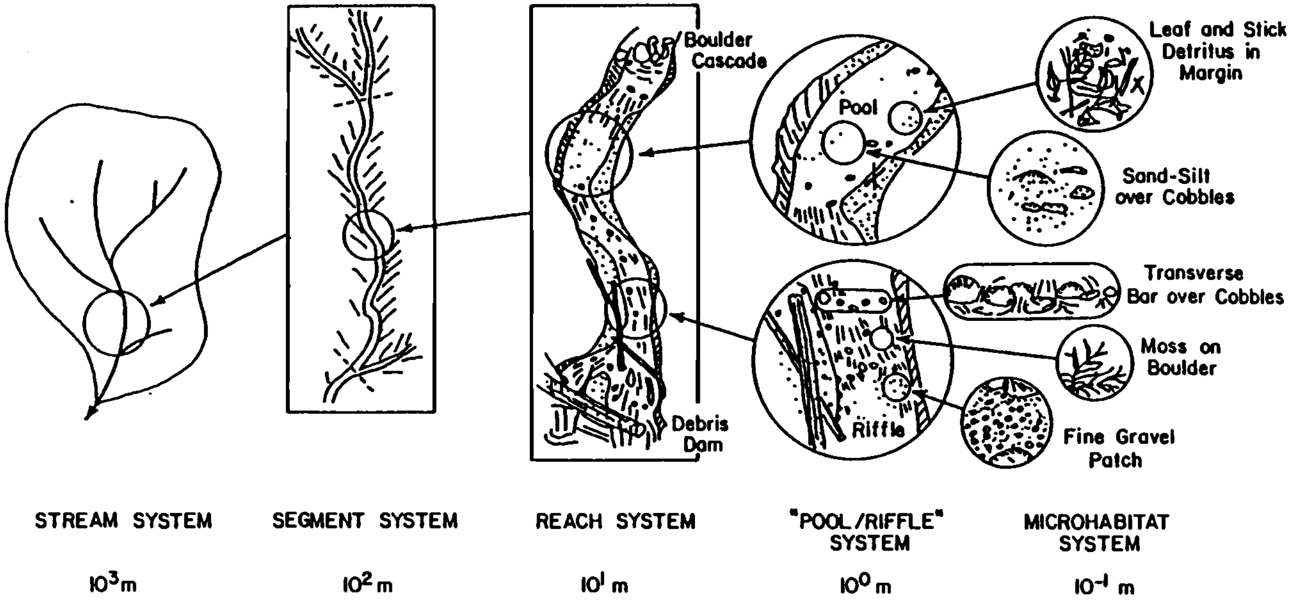


Figure 2. Hierarchical organization of a stream system and its habitat subsystems. Approximate linear spatial scale, appropriate to second- or third-order mountain stream, is indicated.

Table 1. Some events or processes controlling stream habitat on different spatio-temporal scales. Evolutionary events change potential capacity, i.e., extrinsic forces that create and destroy systems at that scale. Developmental processes are intrinsic, progressive changes following a system's genesis in an evolutionary event. Space and time scales indicated are appropriate for a second- or third-order mountain stream.

System Level	Linear Spatial Scale	Evolutionary Events	Developmental Processes	Time Scale Of Continuous Potential Persistence
Stream System	10^3m	tectonic uplift, subsidence; catastrophic volcanism; sea level changes; glaciation, climatic shifts	planation; denudation; drainage network development	$10^6 - 10^5$ y
Segment System	10^2m	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 1st-order channels	$10^4 - 10^3$ y
Reach System	10^1m	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	$10^2 - 10^1$ y
Pool/riffle System	10^0m	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 y $- 10^0$ y
Microhabitat System	10^{-1}m	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	$10^0 - 10^{-1}$ y

Table 2. Habitat spatial boundaries, conformant with the temporal scales of Table 1. Vertical dimension refers to upper and lower surfaces, longitudinal dimension to upstream-downstream extent, and "lateral" dimension to cross channel or equivalent horizontal extent. Scaled to second- or third-order mountain stream.

System Level	Capacity Time Scale	Vertical Boundaries	Longitudinal Boundaries	Lateral Boundaries	Linear Spatial Scale
Stream System	$10^6 - 10^5$y	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	10^3 m
Segment System	$10^4 - 10^3$y	bedrock elevation; tributary junction or falls elevation	tributary junctions; major falls, bedrock lithologic or structural discontinuities	valley side slopes or bedrock outcrops controlling lateral migration	10^2 m
Reach System	$10^2 - 10^1$y	bedrock surface; relief of major sediment-storing structures	slope breaks; structures capable of withstanding <50y flood	local sideslopes or erosion-resistant banks; 50y floodplain margins	10^1 m
Pool/riffle System	$10^1 - 10^0$y	depth of bedload subject to transport in <10y flood; top of water surface	water surface and bed profile slope breaks; location of genetic structures	mean annual flood channel; mid-channel bars; other flow-splitting obstructions	10^0 m
Micro-habitat System	$10^0 - 10^{-1}$y	depth to particles immoveable in mean annual flood; water surface	zones of differing substrate type, size, arrangement; water depth, velocity	same as longitudinal	10^{-1}

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 (Fig. 3). In the example above, two reach classes could have been defined: 1) alluvial soils/gravelly banks, and 2) 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, in the field, show some degree of interpenetration and complexity that no model can completely represent.

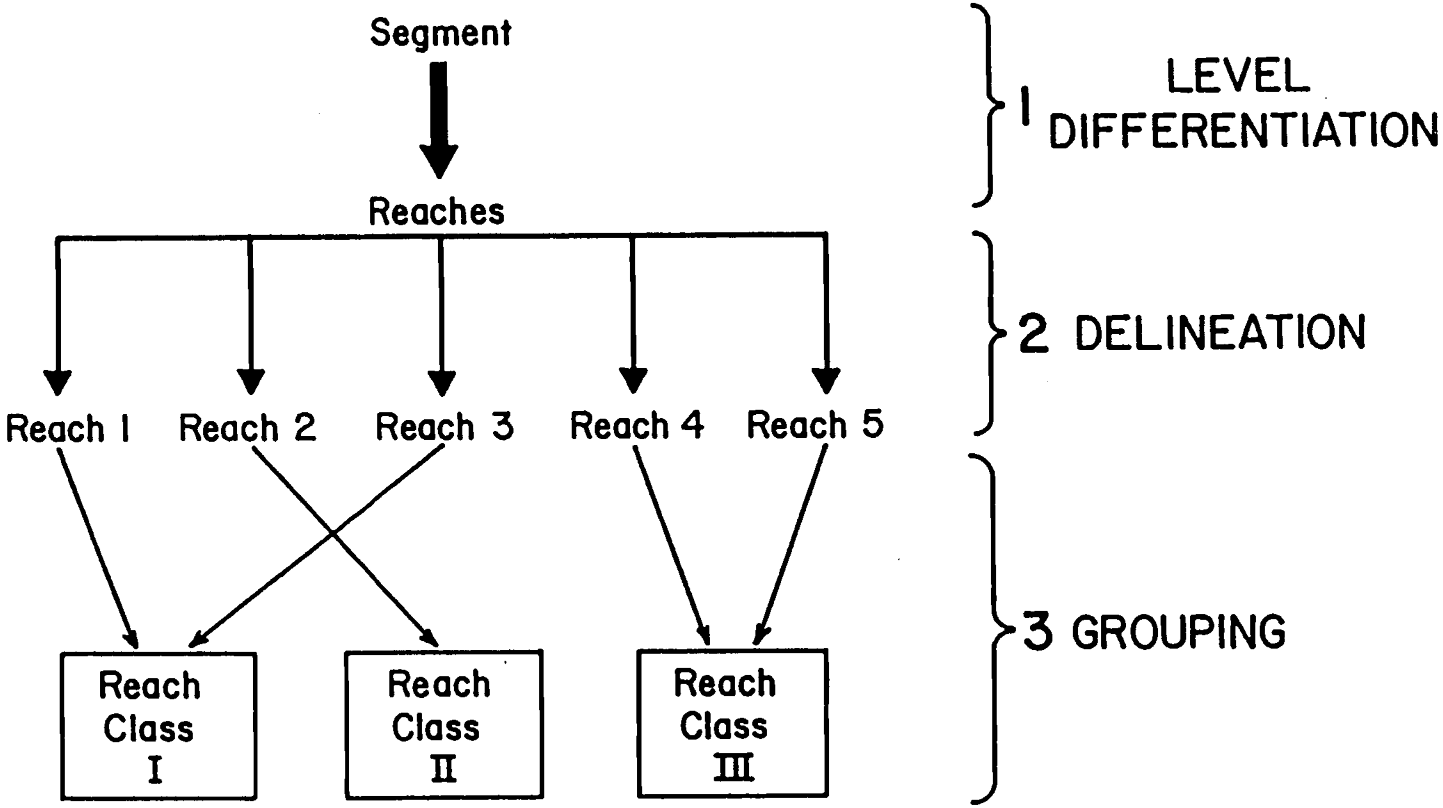


Figure 3. The three steps in habitat classification: differentiation of levels, delineation (spatial decomposition of the higher-level system), and grouping according to similarity.

Stream Habitat Classification

Based on 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 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 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). Phenomema 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).

Table 3. General variables for classifying habitats by potential capacity. Not all variables are necessary to distinguish classes in all circumstances. Best specific metrics or indices may vary regionally or with study objectives.

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 side slopes	local sideslopes floodplain	substrates immoveable in <10y flood	overhanging cover
biota		potential climax vegetation	bank composition	bank configuration	
culture		soil associations	riparian vegetation state		

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 based on 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 1983) 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 lays 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 of a segment is determined by the 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 (Strahler (1952) order or Shreve (1967) link number), 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 based on 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 persist as geomorphic features across a similar scale of space and time, and may play major roles in the physical and biological organization of streams. The segment unit in most cases can be classified using existing topographic, geologic, and vegetation and soils maps. Aerial photo interpretation is also useful.

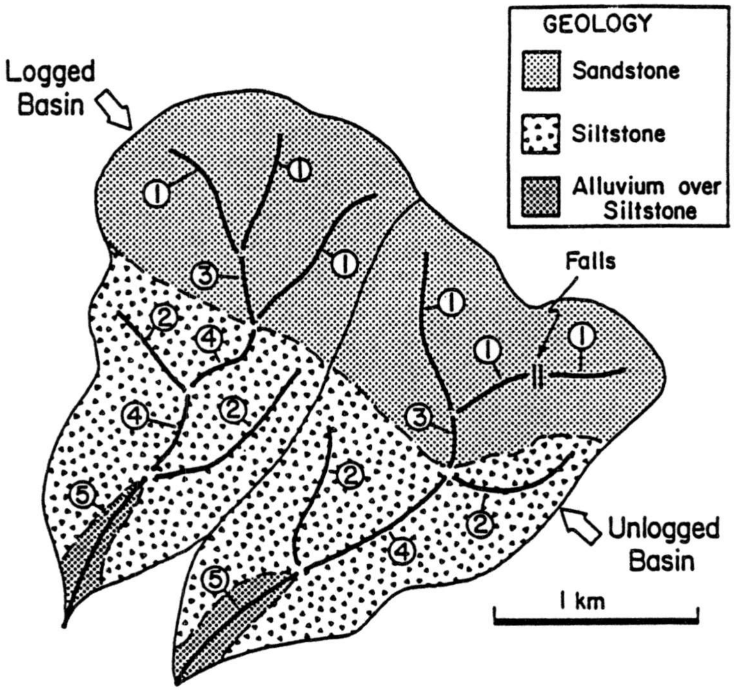
The potential capacity of a stream segment could be changed by any major change in watershed capacity including such geologic events as local volcanism or glaciation, faulting, or very large landslides (Table 1). A segment system develops by slow upstream migration of nickpoints and downwearing, widening,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

Drainage area, 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 determines 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 4 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 similar 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



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 4. Classification of segment systems in two hypothetical watersheds.

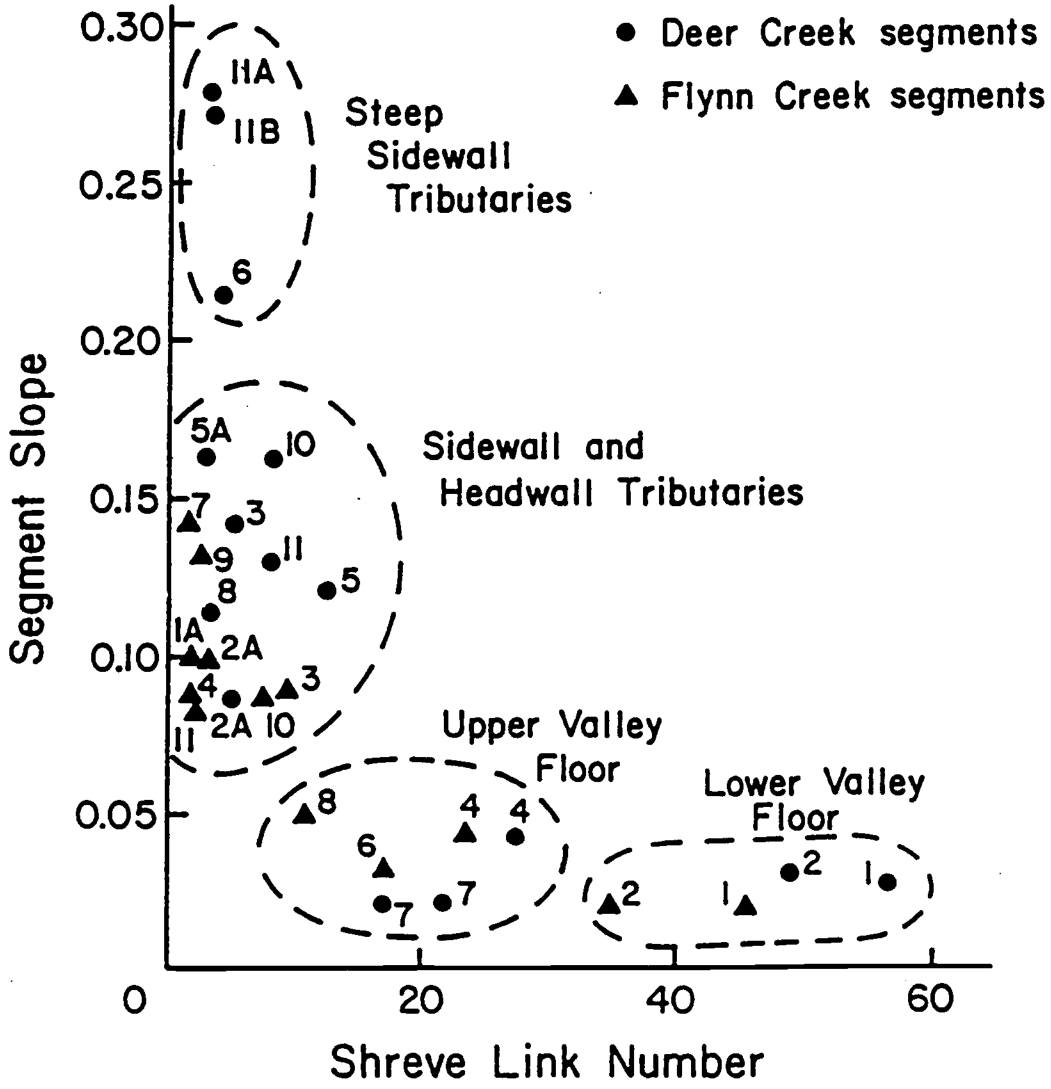
basin of a segment constrain the kinds of smaller-scale habitat systems that can evolve there.

Figure 5 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. 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) should also be considered. 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 5. Simple ordination of stream segments of two Oregon Coast Range watersheds, based on data derived from US Geological Survey 1:62,500-scale topographic quadrangle. Points are individual stream segments, identified by number or number-and-letter code as designated on a stream system map inscribed over the topographic base map (not shown). Ordination axes reflect fundamental channel slope and position in the drainage network. 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 accounts for geographic variation among segments at different points along the longitudinal gradient.


● Deer Creek segments
▲ Flynn Creek segments
Steep Sidewall Tributaries
Sidewall and Headwall Tributaries
Upper Valley Floor
Lower Valley Floor
11A
11B
6
5A
10
7
3
9
11
5
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1A
2A
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20
40
60
Segment Slope
Shreve Link Number

Figure 5.

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 side slopes, 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 (Fig. 6) 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 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).

Figure 6. Variation in slope and channel width in forested (a) and logged (b) sections of Minto Creek, a fourth-order stream in the Oregon Cascades (Frissell and others, in preparation). 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 a result of logging, debris removal, and subsequent bed and bank degradation. This section also has a different array of pool/riffle subsystem types and microhabitats. Note 8X exaggeration in elevation in longitudinal profiles.

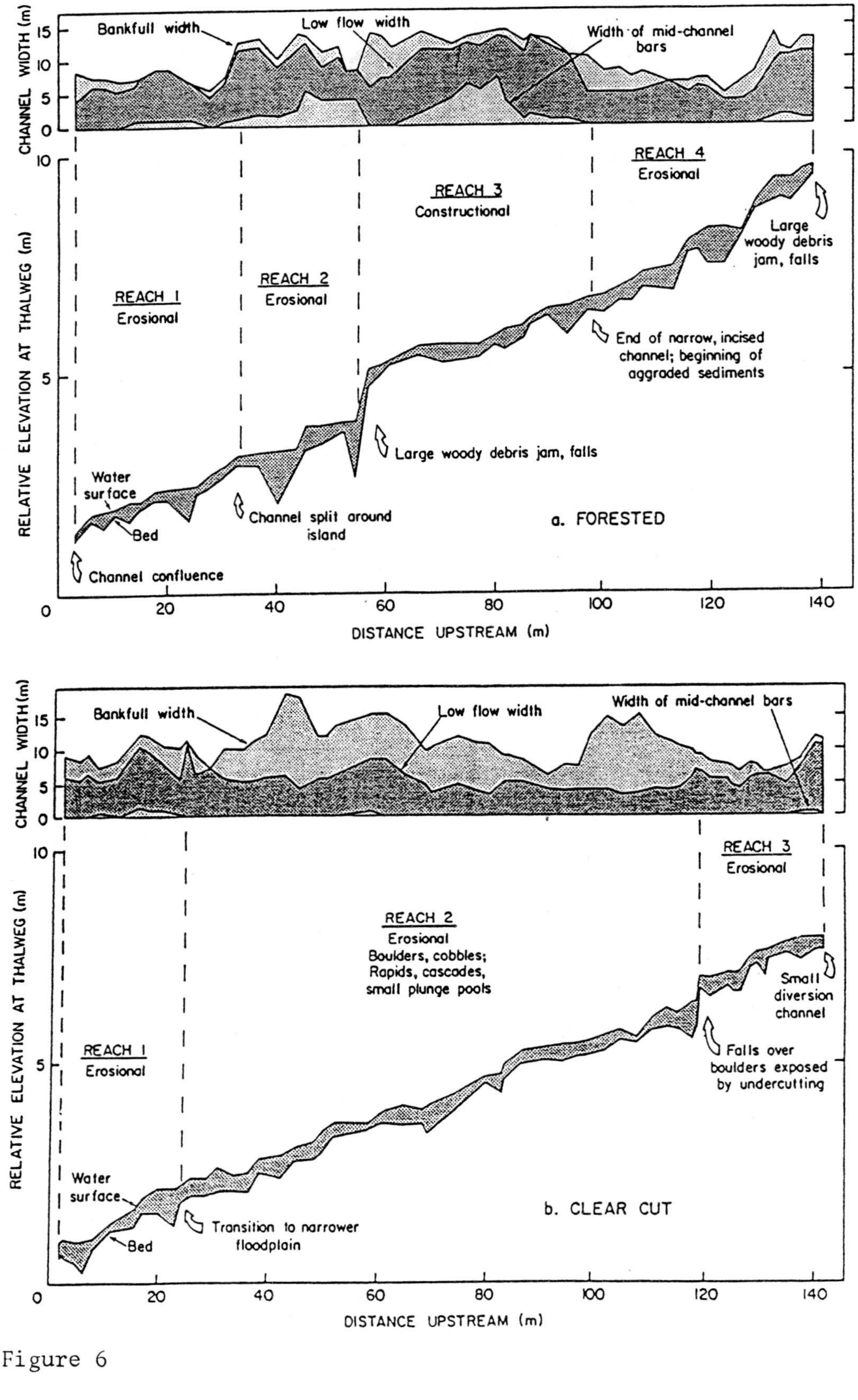
CHANNEL WIDTH (m)
15
10
5
0
Bankfull width
Low flow width
Width of mid-channel bars
RELATIVE ELEVATION AT THALWEG (m)
10
5
0
REACH 1
Erosional
REACH 2
Erosional
REACH 3
Constructional
REACH 4
Erosional
Large woody debris jam, falls
End of narrow, incised channel; beginning of aggraded sediments
Large woody debris jam, falls
Water surface
Bed
Channel split around island
a. FORESTED
Channel confluence
20
40
60
80
100
120
140
DISTANCE UPSTREAM (m)
CHANNEL WIDTH (m)
15
10
5
0
Bankfull width
Low flow width
Width of mid-channel bars
RELATIVE ELEVATION AT THALWEG (m)
10
5
0
REACH 3
Erosional
REACH 2
Erosional
Boulders, cobbles;
Rapids, cascades,
small plunge pools
Small diversion channel
REACH 1
Erosional
Falls over boulders exposed by undercutting
Water surface
Bed
Transition to narrower floodplain
b. CLEAR CUT
20
40
60
80
100
120
140
DISTANCE UPSTREAM (m)

Figure 6

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 1982), 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, the variables in Table 3 have been chosen for classifying reaches.

Table 4 summarizes how these variables have been applied in field studies (Frissell and others in preparation, Frissell and Liss in preparation). Different classification schemes may prove useful for different applications. Our classification emphasizes (1) the relationship of a reach system to watershed events, and (2) the potential persistence and developmental trend of the reach, and thus (3) 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 (Figs. 5, 6, and 7, Table 3, also see Keller 1972 for a general model).

Table 4. Reach classes in small Oregon streams (Frissell and Liss in preparation). Morphogenetic classes are further subdivided by segment class, whether banks are clayey colluvium or gravelly alluvium, whether side slopes allow lateral migration, and riparian vegetation state. Persistence scale: long-term = >100y; moderate = 20-100y; short term = <20y. Slope scale: Moderate = same as segment slope; low = less than segment slope; steep = greater than segment slope.

Gross typology	Morphogenetic class	Morphogenetic process	Relative length	Mean slope	Dominant substrates	Developmental trend	Potential persistence
EROSIONAL (Zones of exposure of bedrock floor or trend toward degradation of bed) Channel pattern: straight	BEDROCK OUTCROP	irregular bedrock resistance to weathering	moderate to short	variable; moderate to steep	bedrock	stable; all sediments transported	long-term
	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)
	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 (Zones of aggradation of alluvium) Channel pattern: straight often verging on braided	BEDROCK OUTCROP	sediment storage behind resistant bedrock features	variable	low	gravels, fines, bedrock	stable; inputs balance outputs	long-term
	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)
	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

Figure 7. Upper panel: 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. Lower panel: Development of the same reach in terms of the importance of different hypothetical classes of pools and riffles.

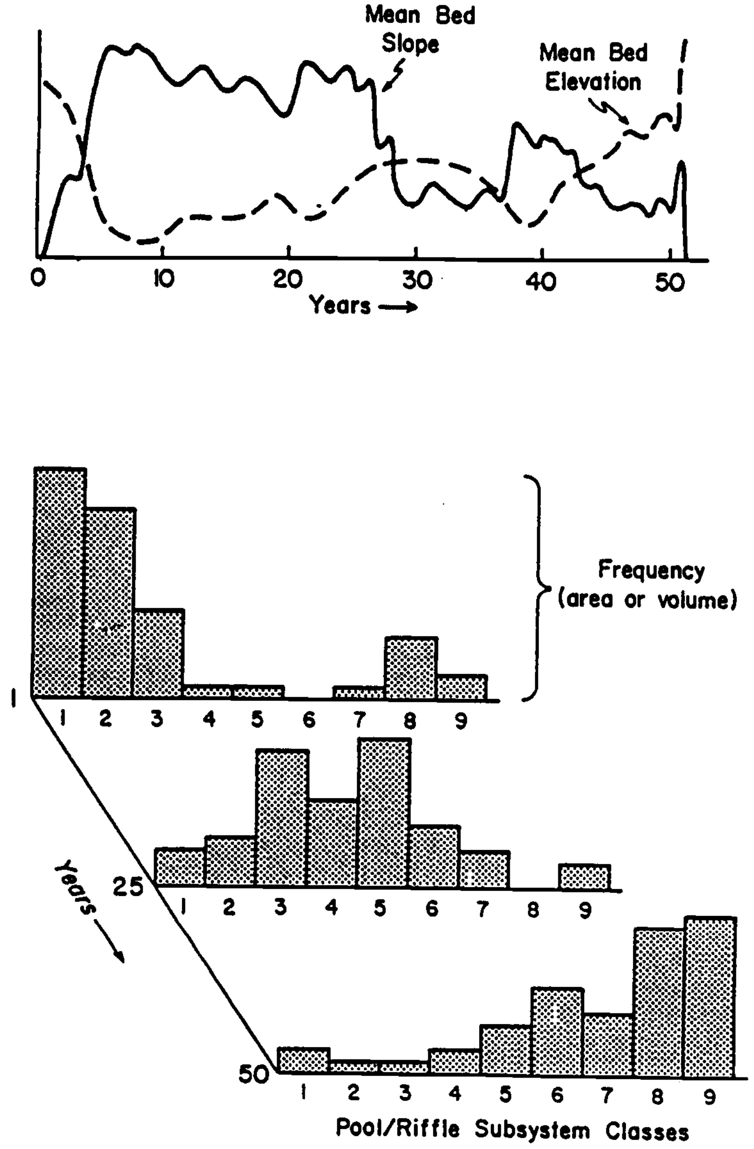
Mean Bed Slope
Mean Bed Elevation
0
10
20
30
40
50
Years →
Frequency (area or volume)
1
1 2 3 4 5 6 7 8 9
25
1 2 3 4 5 6 7 8 9
50
1 2 3 4 5 6 7 8 9
Years
Pool/Riffle Subsystem Classes

Figure 7.

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 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" (Fig. 8) based predominantly on Bisson and others (1982). These forms reflect (1) bed topography and low water surface slope, (2) 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 (3) 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 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 (Fig. 9). 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 1978, Gorman and Karr 1975, Bryant 1980, Triska and others 1982). Our observations (Frissell and Liss in

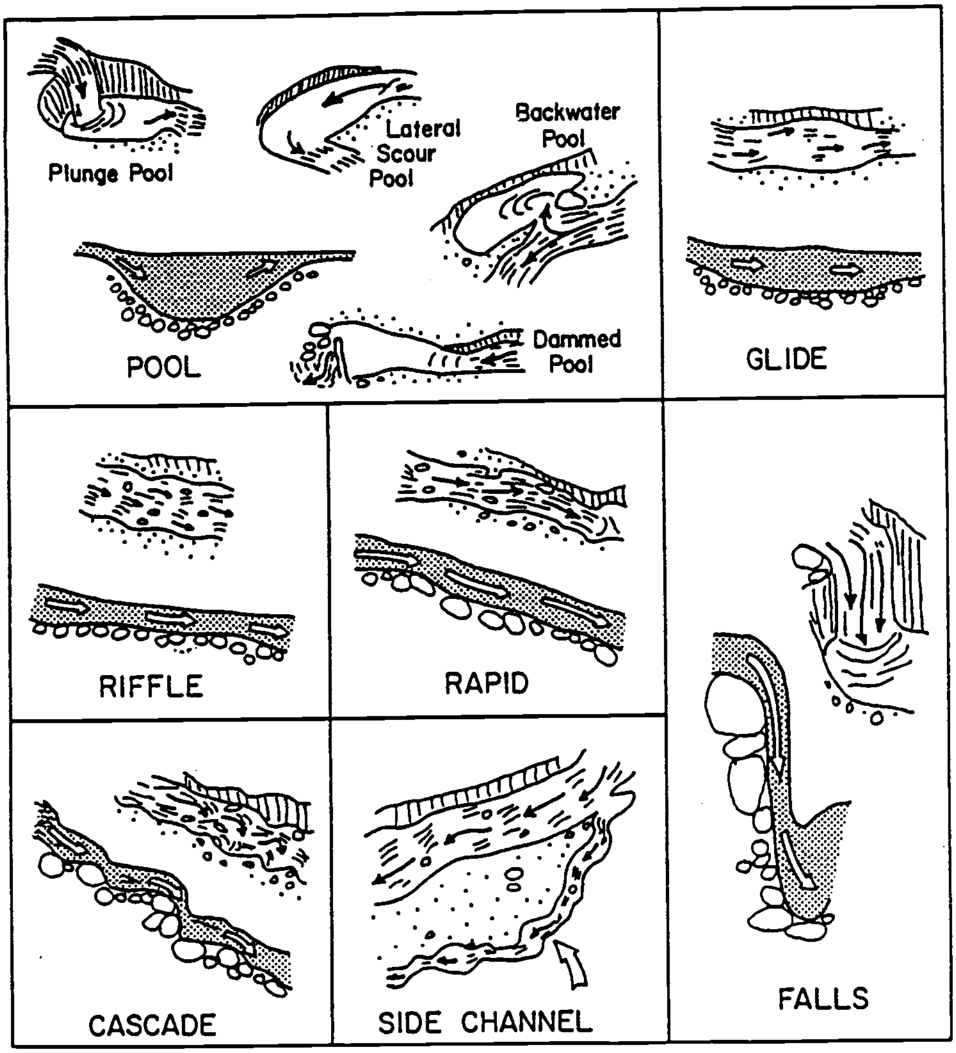

Figure 8. Fundamental pool/riffle forms, reflecting bed topography, low water surface slope, hydrodynamic pattern, and position in relation to the main channel. Longitudinal profile (shaded) and oblique views are shown. Modified from Bisson and others (1982).

Figure 9. 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 (Frissell and Liss, in preparation).

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 9.

preparation) 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 in preparation). 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 (in press) suggests most stream invertebrates may be microhabitat specialists and that understanding "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 (1977), 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 1977). Bed particle size, shape, and transport dynamics are dependent on the geology, climate, vegetation, and land use of the drainage basin (Hack 1957, Miller 1958, Knighton 1982, Douglas 1977).

Except in spring-fed streams with constant flows, individual microhabitats are disturbed at least annually, and thus they develop and evolve over time scales of days, weeks, or months. Jackson and Beschta (1982) provide a useful descriptive model of bedload transport in which bed material is partitioned according to size. Our observations (Frissell and Liss in preparation) support their generalization that, in Oregon Coast Range streams, fine gravel, sand, and smaller particles are transported frequently during the wet season in even small storm events, while large gravel- and cobble-sized materials are transported only in larger events approaching mean annual flood. Thus, smaller substrates provide more-frequentlydisrupted habitats than do larger substrates. These fine and coarser sediment fractions are usually spatially segregated on the stream bed (Dudgeon 1982, Jackson and Beschta 1982), and occur in different amounts and in different locations within different kinds of pool/riffle systems. Lenat and others (1981), evaluating benthos in North Carolina streams, found distinctive communities developing on fine sand substrates, compared to adjacent rocky habitats. Such sand-associated communities developed only during the low-flow season, when sand substrates remained stable.

Processes other than direct transport also act to disturb microhabitats. These include scour of stationary particles or bedrock by high-velocity flows and particles in transport, burial by deposited bedload, and, where aquatic macrophytes occur, seasonal senescence or cropping of vegetation. Inputs of leaf litter and other organic debris create new habitats 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

Table 5. Specific variables used in field classification of microhabitats of small streams in the Oregon Coast Range. Substrates listed in descending order of stability. If underlying substrate has no overlying layer, overlying class is coded same as underlying class.

Environment	Dominant Underlying Substrate	Dominant Overlying Substrate	Water Depth	Water Velocity	Overhead Cover
Stream system Segment class Reach class Pool/riffle class	Bedrock Boulders Cobbles Wood Large gravels Fine gravels, sand Silt-clay	Bedrock Boulders Cobbles Wood Large gravels Fine gravels, sand Moss Silt-clay Fine particulate organic matter Fresh soil peds	Graded scale, 0-50 cm	Graded scale, 0-100 $cm \cdot sec^{-1}$	Tree roots Soil bank Woody debris Foliage

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 spatio-temporal differences in their habitats. 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. The frequency and 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.

Discussion

The habitat classification system has been oriented primarily toward third-order and smaller streams. Yet the relative spatio-temporal 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 stream-side 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.

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 in press). Viewing stream communites as systems organized and developing around spatially-defined habitats (Wevers and Warren in preparation) 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 spatio-temporal array of habitat types dependent upon the watershed, and differences between segments are evident as differences in this pattern. Habitats within segments are not homogenous, 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 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 allowed.

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 which causes changes 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 spatio-temporal 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 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 re-colonization over a period of years or decades may be preserved if other streams in the region have not been subjected to the same disturbance at the same time (Warren and Liss 1983). Such a view suggests that conservation of habitat diversity and of community kinds should be an important consideration in watershed and stream management across the spectrum of spatio-temporal scales, from microhabitats to entire biogeoclimatic provinces (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 between 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 the 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 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 spatio-temporal 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 comunities 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 spatio-temporal 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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STREAM HABITAT, TIMBER HARVEST, AND CUTTHROAT TROUT IN AN OREGON CASCADES STREAM: APPLICATION OF A GEOMORPHIC HABITAT CLASSIFICATION SYSTEM

Christopher A. Frissell
Charles A. Corrarino
William J. Liss

Oak Creek Laboratory of Biology
Department of Fisheries and Wildlife
Oregon State University
Corvallis, Oregon 97331

Abstract

To assess changes in stream habitat caused by logging and debris removal in a fourth-order stream in the High Cascades of Oregon, we compared habitat organization, trout densities, and habitat use in logged (clear-cut, 1962) and forested stream sections. A hierarchical habitat classification system, based on geomorphic variables, allowed pool/riffle habitats to be related to the geomorphic setting of different stream reaches. Due to the presence of large debris dams and abundant woody debris, forested reaches varied in morphology and encompassed a wide array of pool/riffle habitats, including debris-created pools and side channels. Clear-cut reaches were relatively homogenous, and were dominated by boulder-formed habitats. Although trout densities were highly reach-specific, total density (number $\cdot$ m^{-2}) of the forested section was 40% greater than that of the clear-cut section. The smallest size class was absent and large (>14 cm) individuals were uncommon in clear-cut reaches. A regression model showed that most of the variation among reaches in trout density was related to the relative area of six key pool/riffle types. The habitat classification system was useful in demonstrating that the forested stream section, because of its diversity of reach and pool/riffle types, may best provide the range of habitats required by all size classes through changing streamflow conditions.

Introduction

Relationships among watershed geomorphology, stream habitat, and aquatic biota are complex and highly variable in space and time. Yet understanding these relationships is critical to assessing the effects of land use activities on fish populations, especially in the steep, forested terrain of the Pacific Northwest. Road construction and timber harvest can cause profound changes in the morphology and dynamics of stream channel features that provide habitat for aquatic biota (Swanson et al. 1976; Swanston and Swanson 1976; Swanson and Lienkaemper 1978; Triska et al. 1982; Swanson et al. 1982; Lyons and Beschta 1983).

The geology, geomorphology, climate, soils, vegetation, and land use of a watershed determine the kinds of habitat present in its stream system (Warren 1979; Lotspeich and Platts 1982). Natural events such as landslides, debris torrents, floods, and forest fires change stream morphology across many scales in time and space. The effects of human activities on stream habitat can only be assessed in the context of this inherent spatial and temporal variation (Swanston 1980; Hall and Knight 1981). The effects of disturbance may vary, depending on the biogeoclimatic characteristics of the watershed, as well as the slope, valley form, soils, and other constraints within particular stream reaches (Elser 1960; Frissell et al. 1985).

Spatial and temporal variation are likewise serious complications in biological data. Hall and Knight's (1981) review documents year-to-year variation in salmonid population densities of up to several orders of magnitude. Spatial variation between reaches of a single stream may be equally significant (e.g., Shetter and Hazzard 1938; Elser 1968; Gard and Flittner 1974). Such variability severely limits our ability to draw statistical inferences from most field data. Costs or limited population size may prohibit taking sample sizes large enough to detect statistically significant patterns (Eberhardt 1978). Generalizing across longer time spans from biological data gathered at a particular time is often difficult to justify from a statistical point of view.

Eberhardt (1978) suggests that systematic (stratified) sampling is generally preferable to standard randomized sampling if "costs of full randomization may be excessive," if "sampling one unit is likely to affect nearby units," or if "the spatial pattern of the phenomenon being studied is of primary importance." Each of these considerations is frequently important in studies of fish population in streams. Habitat classification is a useful tool for stratifying or "systematizing" stream population surveys (Eberhardt 1978; Hankin 1984).

Classifications, whether explicit or implicit, play crucial theoretical roles in explanation, prediction, generalization, and hypothesis generation in research (Warren 1979, Warren and Liss 1983). Geographical classification systems are essential for land use planning and management (Platts 1980). We believe a stream and stream habitat classification system can serve as a framework for organization, analysis, and integration of data within a single study, or for relating information from diverse sources (Frissell et al. 1985).

In this paper we discuss the application of a hierarchical, geomorphic habitat classification system to assess the effects of logging on resident cutthroat trout (_Salmo clarki clarki_ Richardson) in an Oregon stream. We suggest that such a classification system might often provide an informative, economical complement or alternative to more traditional approaches to environmental assessment and habitat management.

Approach

The framework for stream habitat classification of Frissell et al. (1985) views streams as hierarchically organized systems. This classification system provides a general conceptual structure allowing small-scale, site-specific observations of stream systems to be interpreted within the context of large-scale variation within and among stream systems. Biogeoclimatic characteristics of watersheds (Warren 1979) are tied to geomorphic landforms of streams; these in turn are related to fluvial features that provide habitat for aquatic communities, including fishes.

In the classification, the entire stream system of a watershed is divided into an array of stream segments, segments are subdivided into a series of reaches, reaches into pool/riffle systems, and pools and riffles into microhabitats (Fig. 10). Systems at each hierarchical level of classification have a characteristic spatial

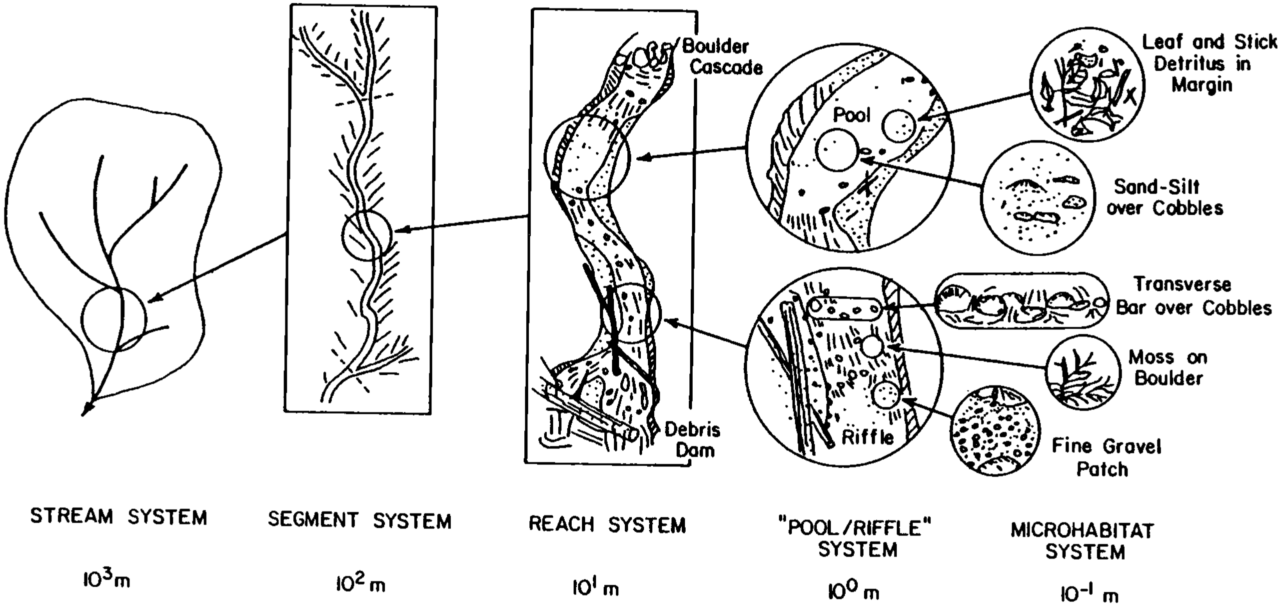

Figure 10. Schematic view of the hierarchical nature of the stream habitat classification system applied to Minto Creek. Spatial scales are order-of-magnitude approximations appropriate to a stream the size and slope of Minto Creek. Reproduced from Frissell et al. (1985).

Table 6.—Time scales, spatial scales, geomorphic context, and classification variables for each level in the stream habitat hierarchy. After Frissell et al. (1985).

System Level	Time Scale (Persistence)	Spatial Scale	Geomorphic events causing major changes	Classification variables
Stream System	$10^6 - 10^5$y	10^3m	Tetonic uplift, subsidence; catastrophic volcanism; sea level changes; glaciation, climatic shifts, drainage capture	Watershed biogeoclimatic attributes; long profile slope, shape; drainage network structure
Segment System	$10^4 - 10^3$y	10^2m	Minor glaciation, volcanism; earthquakes; very large landslides; alluvial or colluvial valley infilling	Stream system class; channel floor lithology, slope; position in drainage network; valley side slopes; potential climax vegetation; soils
Reach System	$10^2 - 10^1$y	10^1m	Debris torrents; landslides; log input or washout; channel shifts, cutoffs; channelization diversion, or damming by man	Segment class; bedrock relief, slope; morphogenetic structure or process; channel pattern; local side slopes or floodplain form; bank composition; riparian vegetation state
Pool/riffle system	$10^1 - 10^0$y	10^0m	Input or washout of wood, boulders, etc., small bank failures; flood scour or deposition; thalweg shifts; numerous human activities	Reach class; bed topography; water surface slope; morphogenetic structure or process; substrates immovable in 10 y flood; bank configuration
Microhabitat System	$10^0 - 10^{-1}$y	10^{-1}m	Annual sediment, organic matter transport; scour of stationary substrates; macrophyte growth and senescence	Pool/riffle class; substrate type; water depth, velocity; overhanging cover

scale and develop within a particular temporal frame (Table 6). Segments, for example, are long, relatively persistent units whose characteristics are determined by the drainage network structure, bedrock type, and major topographic and edaphic features of the watershed. Reaches are smaller, less-persistent units which may be significantly changed by such phenomena as major floods, changes in riparian vegetation, or human intervention. Pool/riffle systems and microhabitats are progressively smaller-scale systems, susceptible to change during events of lower magnitude and greater frequency.

Because of this divergence in spatiotemporal scale, systems at any level can be classified with a relatively small set of geomorphic variables (Table 6). These variables account for factors that most determine the form and potential of systems at the scale of interest. Because potential of any system depends upon its environment (Warren 1979), the class of a system at any level depends on the class of the higher-level system in which it resides. (The suitability of a particular pool for fish, for example, may depend upon its being located in a reach having adequate food-producing riffles.) Together these variables are useful in defining the geomorphic origin, structure, and temporal dynamics of habitats at any of the hierarchical levels. The conceptual basis, rationale, and potential applications of the classification are further detailed in Frissell et al. (1985).

Study Area

Minto Creek is a fourth-order stream in the High Cascades physiographic province (Fenneman 1928; Legard and Meyer 1973) of western Oregon, U.S.A. The stream, located in the Willamette National Forest, flows westward to the North Santiam River (Fig. 11). The climate is characterized by cool, wet winters and warm, dry summers. Annual precipitation exceeds 300 cm, with much of this falling as snow. Maximum streamflow occurs during rain-on-snow events in the winter months (Harr 1976), with later peaks during spring snowmelt. The stream segment studied has a channel gradient of about five percent, averages 5 m to 10 m wide at low flow, and lies at an elevation of about 800 m.

The watershed is about 19 km^2 and lies on basalt, andesite, and pyroclastic flows of Pliocene to Pleistocene age, with local Holocene basalt flows (Wells and Peck 1961). The upper one-half of the basin was extensively glaciated, and the lower portion, including the study area, is an incised valley deeply filled with bouldery alluvial deposits of Quaternary age (Legard and Meyer 1973). Valley sideslopes are steep, grading to a gently rolling valley floor about 100 m wide. Old channels and terraces with various degrees of soil and vegetation development suggest the stream historically shifted across the valley at frequent intervals. Bedrock is nearly absent in the channel.

Two 140 m stream sections were selected for study. The upstream section lies in a mature stand of western red cedar (_Thuja plicata_),

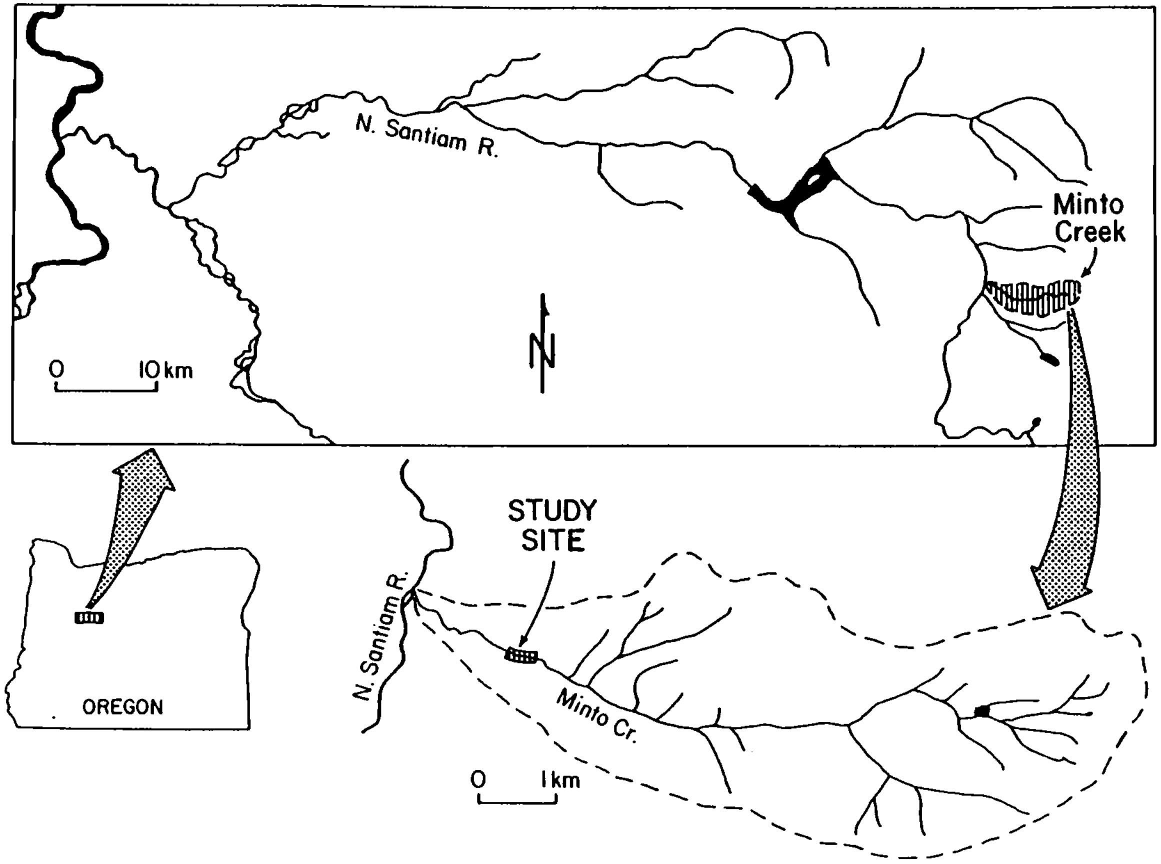

Figure 11. Location of the study site in the Oregon Cascade Range. Dark areas are lakes and reservoirs.

western hemlock (Tsuga heterophylla), old-growth Douglas-fir (Pseudotsuga menziesii), and other conifers. The understory is sparse, and the stream is well-shaded. Several cut stumps indicate a few large trees were selectively harvested in the distant past, and it appears that some debris removal has occurred in the stream. Nevertheless, many large, stable debris dams remain intact, often incorporating several fallen conifers interlocked with debris floated from upstream. This study section is representative of a larger forested zone extending several hundred meters upstream. Two or three clearcuts and roads lie in the basin above.

The second study section, about 150 m downstream, was clear cut by tractor logging in about 1962 on one bank. No buffer strip was left, and virtually all large wood was removed from the channel. A small diversion ditch for domestic water use lies at the head of this study section, and its construction probably contributed to disturbance of the channel. The riparian vegetation is dominated by red alder (Alnus rubra) and Douglas-fir 10-20 y old. Vine maple (Acer circinatum) and willow (Salix sp.) occur in the understory. The canopy remains open over the stream. A boulder-rich bed and steep, raw banks up to 2 m high indicate active channel erosion, including bank erosion and probably vertical incision, since logging. Large woody debris is rare and scattered compared to the upstream section. Nearly complete removal of instream woody debris was commonly required in Willamette National Forest timber sale contracts at the time this site was logged. Many kilometers of streams in the area today retain only minimal amounts of large wood, in contrast to natural debris loadings that may exceed 25 kg/m^2 (Swanson et al. 1982). A major flood occurred in Minto Creek in 1964, apparently washing debris from upstream and lodging small debris accumulations at two locations along the margins of the clear-cut study section. The 1964 flood, which had an estimated recurrence interval of 100 y in another Oregon Cascades basin (Lyons and Beschta 1983), caused extensive erosion and deposition in Minto Creek, as it did in other Pacific Northwest streams (Stewart and LaMarche 1976; Lyons and Beschta 1983). The clear-cut study section is part of a debris-poor, clear-cut and "cleaned" zone extending far downstream in Minto Creek.

Cutthroat trout and shorthead sculpins (*Cottus confusus* Bailey and Bond) were the only fishes found in the stream.

Methods

Habitat Assessment

To confirm that the two study sections did not vary at the segment scale, we surveyed valley cross sections and measured channel slope with a hand level and rod. Topographic maps, landtype maps (Legard and Meyer 1973), and a geologic map (Wells and Peck 1961) were consulted to assure no discontinuities in valley configuration, soils, or bedrock occurred between the study sections.

Within each study section, we identified several reaches based on variation in channel and valley morphology occurring over tens of meters. We surveyed longitudinal profiles and measured mid-channel bar, bankfull, and low flow channel widths at 2-5 m intervals. Apparent geomorphic history and general reach descriptions (slope, channel pattern, woody debris, degree of incision, eroding banks) were noted on sketch maps. Reaches were classified as erosional or depositional, depending on their geomorphic origin. Means and variation (standard deviation) in width and depth measurements were compared between reaches and between study sections.

Within each reach, pool/riffle systems were classified by a two-step procedure. Systems were first classified according to a system modified from Bisson et al. (1982) (See Frissell et al. 1985). This procedure defines pools, riffles, and other features by morphological characteristics — bed topography and water surface slope (e.g., pool, glide, riffle) -- and hydrodynamic pattern (e.g., lateral scour pool, vertical plunge pool (Fig. 12).

The second step involved identification of the dominant geomorphic feature apparently causing the pool/riffle system to develop. These morphogenetic features included large woody debris (>10 cm diameter), very large boulders (>100 cm median diameter), boulders (25.6-100 cm), submerged cobble (6.4-25.5 cm) bars, and submerged gravel (<6.4 cm) bars. Very large boulders, and large wood when incorporated in jams or anchored in banks (Swanson et al. 1976), are stable, persistent structures. Gravel and cobble bars are inherently less stable, and may be turned over or shifted by

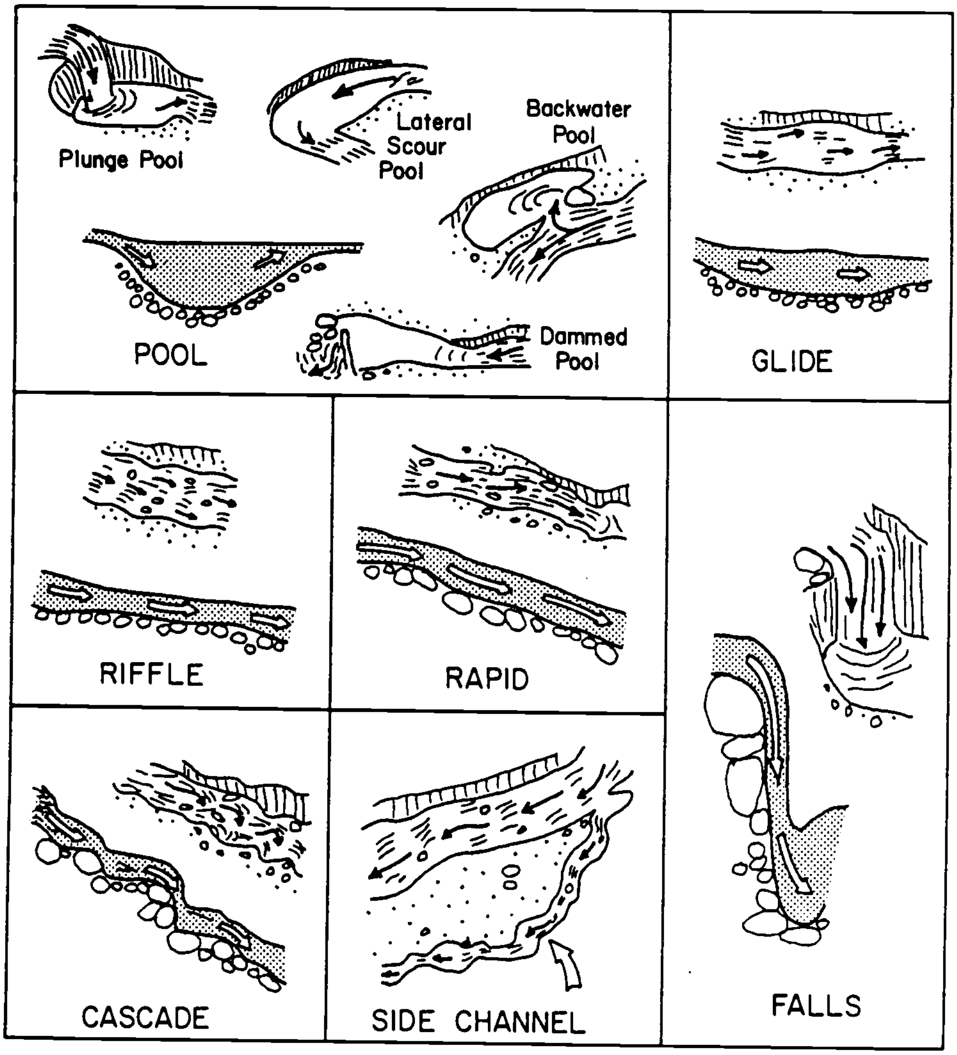

Figure 12. Morphological-hydrodynamic classes of pool/riffle systems, adapted from Bisson et al. (1982). Longitudinal profile (shaded) and oblique views are shown. Morphogenetic features (not shown, see text) were also incorporated in pool/riffle classification. Reproduced from Frissell et al. (1985).

annual floods. Hydraulic calculations (following Baker and Ritter 1975; Dackombe and Gardiner 1983) revealed that a stream with slope and channel cross section like that of Minto Creek may generally be capable of transporting boulders of over 60 cm median diameter during a mean annual flood (Frissell, unpublished data). Pools and riffles formed by boulders may thus be subject to disturbance more frequently than would perhaps be expected. We measured length, width, and maximum depth of each habitat in the field. Relationships between morphogenetic features, morphology, and surface area or volume of individual habitats were statistically analyzed by regression and pairwise t-tests. Distribution of surface area among pool/riffle classes was compared between reaches and between study sections, and significance evaluated with Kolmogorov-Smirnov goodness of fit tests (Sokal and Rohlf 1981)

Trout Distribution

We sampled fish populations in individual pool/riffle systems with a portable backpack electroshocker on 27 August 1984. The low densities of trout and small size and relative isolation of suitable habitats made it feasible to make several passes through each habitat until no more fish were seen, without the use of blocking nets. We felt that, given the configuration of habitats, placement of blocking nets would have disturbed and caused redistribution of fish far more than careful electroshocking alone. We measured total length of captured fish, and estimated length of the few individuals seen but not caught. The lowermost reach (30 m) of the old growth section was not electrofished due to lack of field time.

We calculated relative density (numbers per m^2 of habitat surface area) of trout for each pool/riffle system, reach, andstream section. We feel these population data are reliable estimates of relative densities for assessing distribution of fish in this study. Dense overhanging cover may have reduced capture efficiency, possibly causing relative underestimation of fish numbers in certain wood-created habitats, especially in the forested section.

While length frequency distributions were comparable to those of Wyatt (1959) and Aho (1977) for other Cascades populations, scale aging of coastal cutthroat trout is difficult due to extensive scale regeneration (Moring et al. 1981). Therefore we compared size class structure of the population between reaches and between sections.

To assess the importance of different pool/riffle types, we calculated use coefficients for each pool/riffle class and trout size class with the linear selection index of Strauss (1979). While Strauss advocated this index for analysis of food selection, we applied it to assess habitat selection as follows:

$$\underline{L} = \underline{r}_{\underline{i}} - \underline{p}_{\underline{i}},$$

where $\underline{r}_{\underline{i}}$ is the relative proportion of the total population found in habitat $\underline{i}$ and $\underline{p}_{\underline{i}}$ is the relative proportion of habitat $\underline{i}$ in the stream. The index ranges from a minimum of near -1.00, indicating a habitat extremely abundant but completely avoided by fish, to a maximum of near +1.00 for a habitat that is extremely rare but used exclusively by fish. A value of 0 indicates the habitat is used in proportion to its abundance in the stream.

Results

Habitat Assessment

No major differences between study sections were apparent at the segment scale. Topography, soils, and bedrock all appeared uniform. Examination of stumps in the clear cut confirmed that this stand was very similar to the upstream forested stand before logging. Valley floor width and topography did not vary substantially (Fig. 13).

Due to the role of large woody debris dams, several geomorphically discrete reach systems comprised the forested section (Fig. 14a). Reach 1 (F1) was formed by the channel splitting around a small island protected by woody debris (only one branch of this split channel was studied). Reach 2 (F2) was a short stretch between this channel split and a large debris dam upstream. Reach 3 (F3) was a wide, low-gradient constructional system--that is, developed in sediment deeply aggraded behind the debris dam. Reach 4 (F4) was a narrow, steep system formed by channel incision below a second large debris dam at the head the forested study section.

In contrast, reaches in the clear-cut section were rather uniform and less easily distinguished (Fig. 14b). Woody debris had little influence on the longitudinal profile, and the channel was

Figure 13. Representative valley and stream channel cross sections for Minto Creek study sections. Fig. 13a traverses valley in middle of forested reach 3, 13b traverses valley near downstream end of clear-cut reach 2. Arrows indicate abandoned and flood overflow channels. Note 2X vertical exaggeration of elevation in valley cross sections.

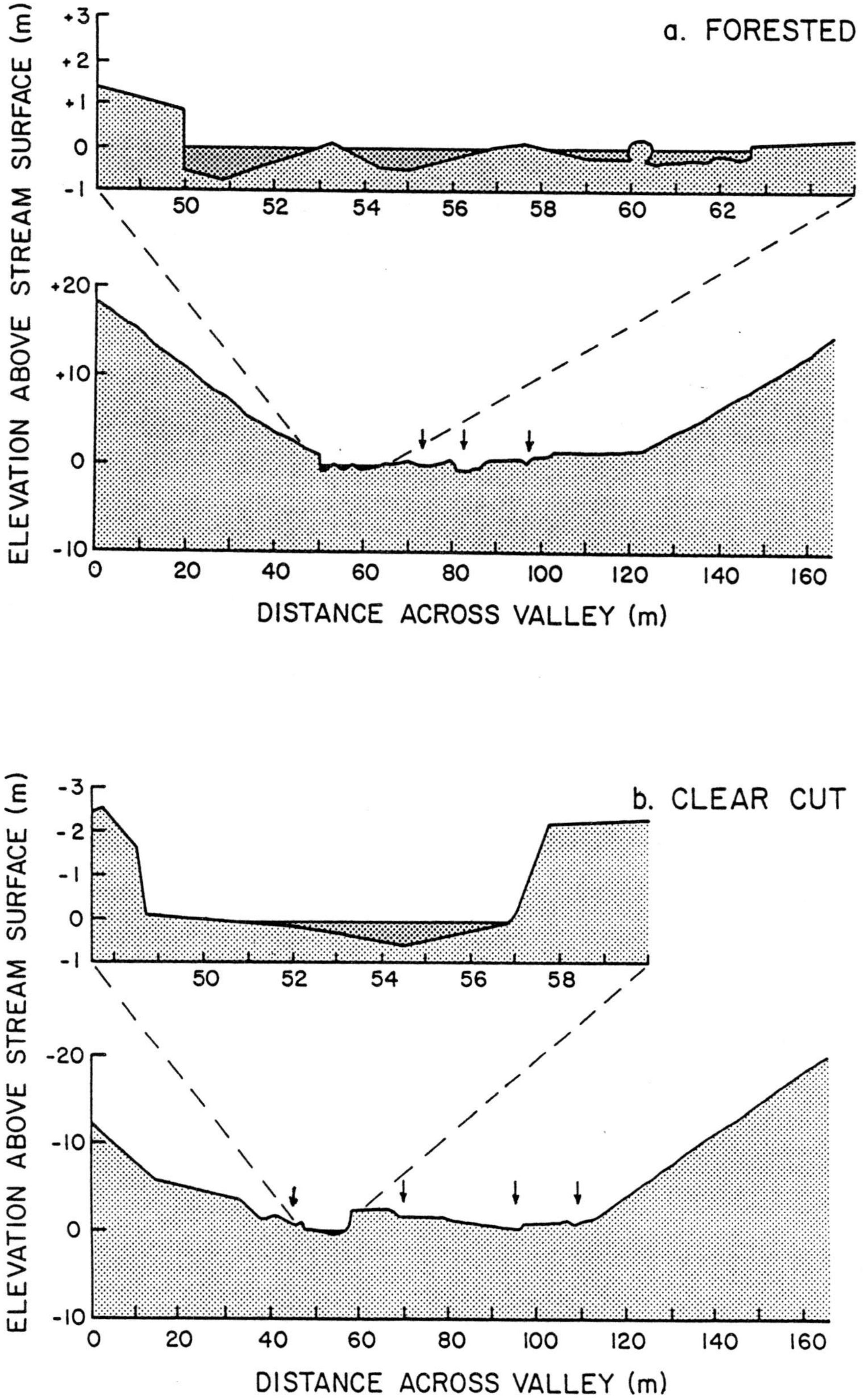
a. FORESTED
ELEVATION ABOVE STREAM SURFACE (m)
+3
+2
+1
0
-1
50
52
54
56
58
60
62
+20
+10
0
-10
0
20
40
60
80
100
120
140
160
DISTANCE ACROSS VALLEY (m)
b. CLEAR CUT
ELEVATION ABOVE STREAM SURFACE (m)
-3
-2
-1
0
-1
50
52
54
56
58
-20
-10
0
-10
0
20
40
60
80
100
120
140
160
DISTANCE ACROSS VALLEY (m)

Figure 13.

Figure 14. Channel width and slope variation in forested (a) and clear-cut (b) study sections. Reaches are identified, and geomorphic features associated with reach development are indicated.

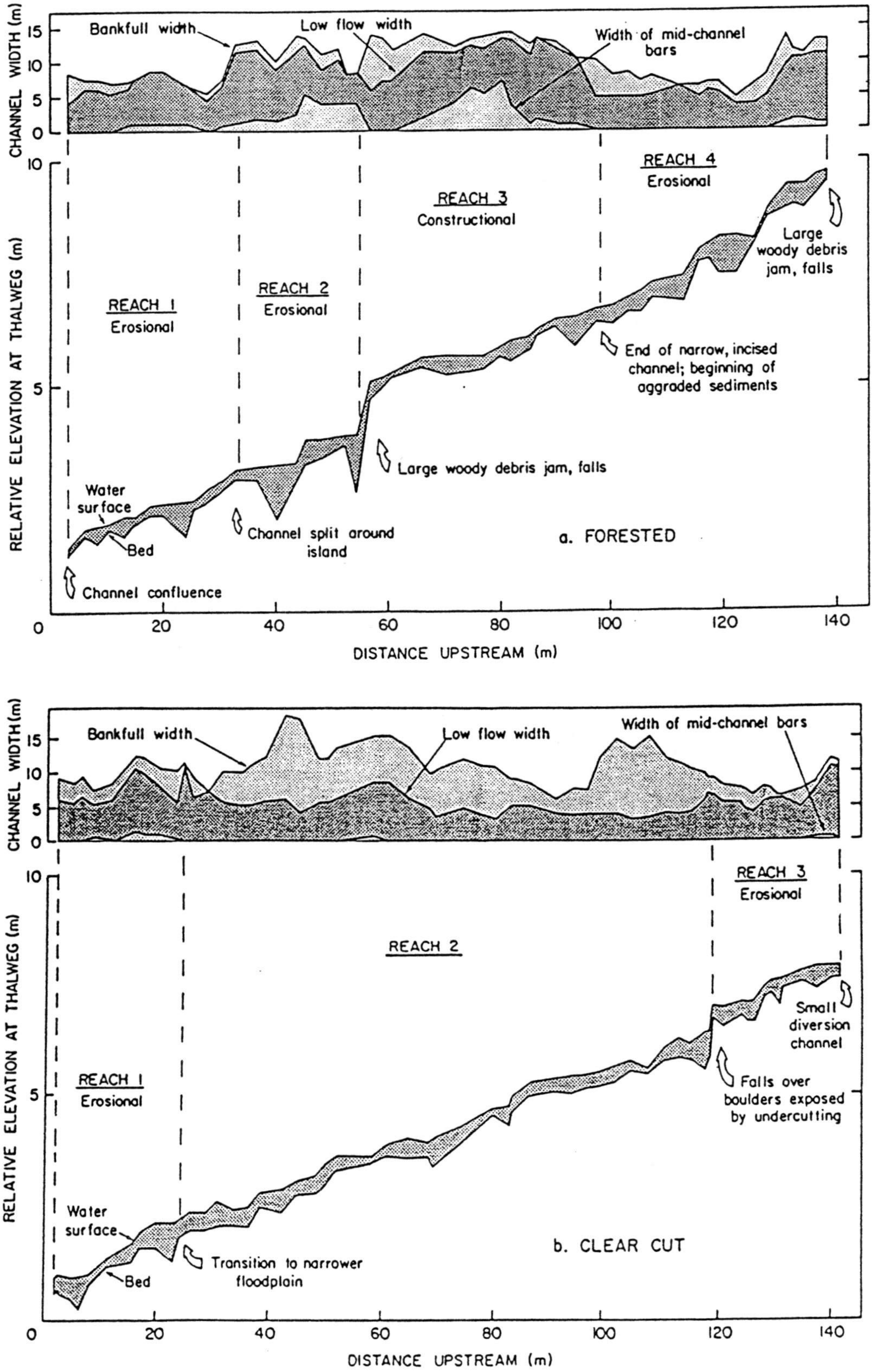
CHANNEL WIDTH (m)
15
10
5
0
Bankfull width
Low flow width
Width of mid-channel bars
RELATIVE ELEVATION AT THALWEG (m)
10
5
REACH 1
Erosional
REACH 2
Erosional
REACH 3
Constructional
REACH 4
Erosional
Large woody debris jam, falls
End of narrow, incised channel; beginning of aggraded sediments
Large woody debris jam, falls
Water surface
Bed
Channel split around island
a. FORESTED
Channel confluence
0
20
40
60
80
100
120
140
DISTANCE UPSTREAM (m)
CHANNEL WIDTH (m)
15
10
5
0
Bankfull width
Low flow width
Width of mid-channel bars
RELATIVE ELEVATION AT THALWEG (m)
10
5
REACH 3
Erosional
REACH 2
Small diversion channel
REACH 1
Erosional
Falls over boulders exposed by undercutting
Water surface
Bed
Transition to narrower floodplain
b. CLEAR CUT
0
20
40
60
80
100
120
140
DISTANCE UPSTREAM (m)

Figure 14.

continuously steep in slope. Reach 1 (CC1) began where the channel made a tight turn and the valley floor narrowed somewhat, constraining the floodplain. Reach 1 continued below the lowermost boundary of the study section. Reach 2 (CC2) was separated from Reach 3 (CC3) by a small falls over a transverse wedge of boulders. The upper end of CC3 began at the intake of the small, man-made diversion ditch. All three clear-cut reaches were boulder-dominated, erosional systems, formed by downcutting through the coarse valley floor materials. Only slight variations in geomorphic setting distinguished them.

Reach morphometry reflected the differences in reach-level organization of the two study sections. The clear-cut low flow channel was less complex and structurally more uniform. While reach widths were similar between study sections, mean low flow width was significantly greater in the forested (8.94 m) than in the clear-cut (6.00 m) section (t-test, $\underline{P}<0.01$). The standard deviation in low flow width of the forested section (SD = 2.99) was nearly twice that of the clear-cut section (SD = 1.85). This variation was associated with an order of magnitude difference in mean width of exposed mid-channel bars (forested = 1.47 m; clear-cut = 0.11 m, $\underline{P}<0.001$). Mid-channel bars were rare in the clear-cut reaches, but well-developed in the forested section, where lower local gradients and flow deflection by woody debris allowed sediment to aggrade. Bars in the clear-cut reaches occurred primarily along the channel margins. While mean depth at the thalweg was about the same in each study section (forested = 0.35 m; clear cut = 0.37 m), variation in depth at the thalweg was about 50% greater in the forested section (SD = 0.22; clear-cut, SD = 0.15). This reflected the presence of deeper pools in forested reaches.

The two sections differed tremendously in the relative area occupied by each pool/riffle class (Fig. 15). The clear-cut section was dominated by boulder-formed habitats (82% of the 39 habitats classified), with a few (15%) developed around scattered woody debris and a single pool (3%) scoured below a very large boulder. Cobble and gravel bars played no important role. In contrast, pool/riffle systems in the forested section were created by a greater diversity of morphogenetic features, including large wood (44% of the 43 habitats classified) followed by boulders (30%), cobble bars (19%), very large boulders (5%), and gravel bars (2%).

Diversity of morphogenetic features was related to the general pattern of substrate diversity of habitats in Minto Creek. In the forested section, cobbles predominated in riffles and rapids, and gravel patches were extensive in the low-gradient constructional reach and within other debris-protected alcoves. Cobbles and especially gravels were uncommon in the clear-cut section, occurring only in isolated, small lenses behind boulders and the few logs present. The clear-cut section had a relatively homogeneous bed, continuously armored or paved (sensu Parker and Klingeman 1982) with boulders. Minto Creek is swift enough that, except where

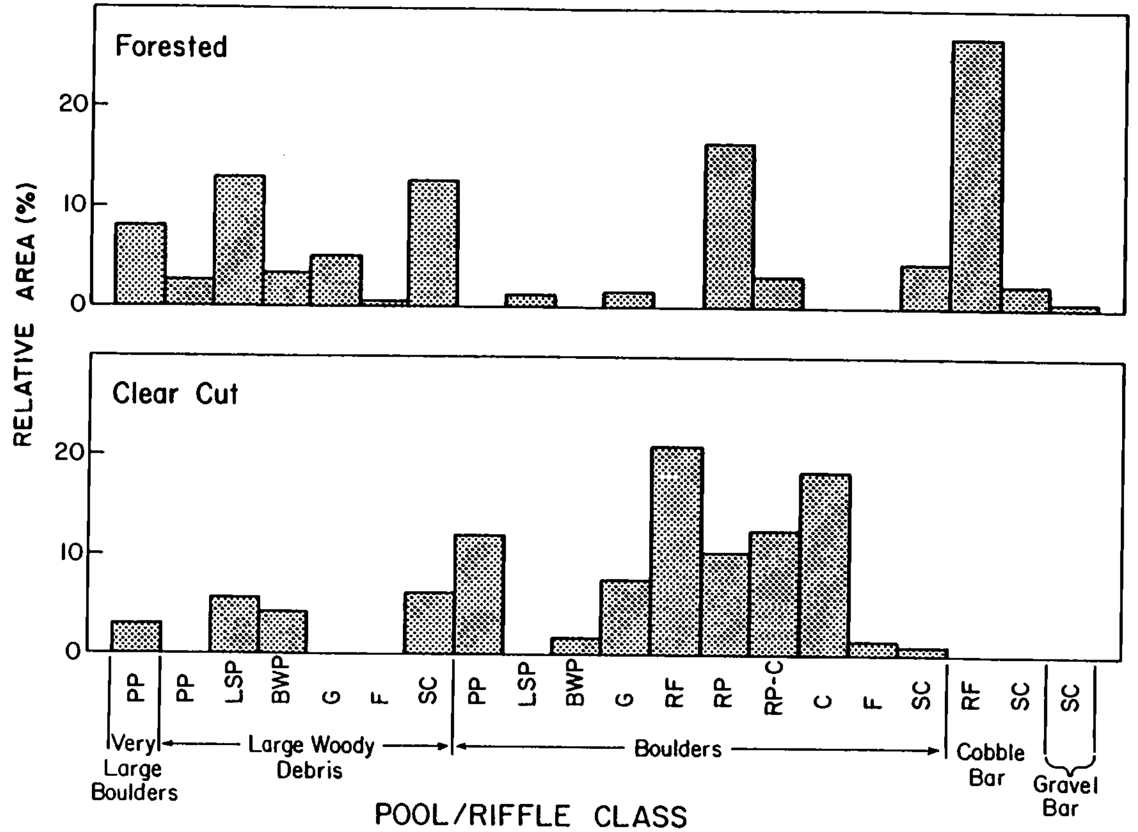

Figure 15. Relative surface area occuped by each pool/riffle class in Minto Creek study sections. Distributions are significantly different between sections ($\underline{P} < 0.01$, Kolmogorov-Smirnov test for goodness of fit). PP = plunge pools, LSP = lateral scour pools, BWP = backwater pools, G = glides, RF = riffles, RP = rapids, RP-C = rapid-cascade complexes, C = cascades, F = falls, and SC = side channels. Morphogenetic feature classes also indicated.

obstructions to flow exist, gravel-size particles are easily transported, even at low flow.

Certain pool/riffle types differed drastically in abundance between study sections. While the clear-cut section consisted of about 18% boulder cascades (by surface area), cascades were absent in the forested section (Table 7). Riffles in clear-cut reaches were formed by boulders, while those in the forested section were formed by cobbles. The forested section had about four times the area of lateral scour pools and almost ten times the area of side channels relative to the clear-cut section.

The relative area of pools was greater in the forested section than in the clear-cut section, chiefly due to the greater mean size of pools formed by very large boulders (31.4 m^2) and large woody debris (15.1 m^2), compared to those created by boulders (11.4 m^2). Pools formed by large woody debris were extremely variable in size, including both the largest (48.8 m^2) and smallest (a 1.1 m^2 backwater) pools recorded.

Pool/riffle organization varied widely between reaches (Table 7). Overall, variation in pool/riffle composition was greater among forested reaches than among clear-cut reaches. The slope of a stream reach reflected its geomorphic origin, and was closely related to the array of pool/riffle habitats present. Boulders were the dominant habitat-forming feature in the steeper erosional reaches (F4, CC reaches), but in moderately-sloping erosional reaches (F1, F2) and in the constructional reach (F3), cobble bars

Table 7. Percent surface area (m^2) of habitat in each pool/riffle class in Minto Creek by reach and study section.

	Clear-cut				Forested				
Pool/riffle class	CC1	CC2	CC3	Total	F1	F2	F3	F4	Total
Very large boulders									
Plunge pool	0.0	5.0	0.0	3.0	0.0	0.0	0.0	31.4	8.2
Large woody debris									
Plunge pool	0.0	0.0	0.0	0.0	6.6	7.8	0.0	0.0	2.5
Lateral scour pool	0.0	0.0	29.1	5.7	12.1	33.9	13.3	0.0	13.1
Backwater pool	8.6	0.9	9.7	4.2	0.0	2.8	5.1	3.5	3.3
Glide	0.0	0.0	0.0	0.0	0.0	0.0	12.7	0.0	4.9
Falls	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.3
Side channel	3.6	0.0	0.0	0.7	12.8	7.9	20.6	3.1	12.4
Boulders									
Plunge pool	25.3	6.5	14.8	12.1	0.0	0.0	0.0	0.0	0.0
Lateral scour pool	0.0	0.0	0.0	0.0	7.1	0.0	0.0	0.0	1.2
Backwater pool	0.8	2.7	0.0	1.8	0.0	0.0	0.0	0.0	0.0
Glide	0.0	9.7	9.3	7.6	0.0	0.0	2.3	2.4	1.5
Riffle	12.1	17.0	12.9	21.1	0.0	0.0	0.0	0.0	0.0
Rapid	24.9	5.8	8.2	10.2	15.7	15.0	4.8	34.9	16.4
Rapid-Cascade complex	0.0	21.2	0.0	12.6	0.0	0.0	0.0	11.5	3.0
Cascade	24.8	19.3	9.0	18.4	0.0	0.0	0.0	0.0	0.0
Falls	0.0	0.0	7.0	1.4	0.0	0.0	0.0	0.0	0.0
Pool/riffle class									
Side channel	0.0	1.8	0.0	1.1	0.0	4.7	0.0	13.3	4.3
Cobble bar									
Riffle	0.0	0.0	0.0	0.0	45.9	21.0	40.2	0.0	27.2
Side channel	0.0	0.0	0.0	0.0	0.0	6.9	0.0	0.0	1.2
Gravel bar									
Side channel	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.3

and woody debris were more important. Side channels, like the mid-channel bars associated with them, were best-developed in F3, moderately abundant in F1 and F2, and rare in steeper reaches, including all clear-cut reaches. The distribution of very large boulder plunge pools was largely a function of the scattered distribution of very large boulders in the valley floor sediment. These boulders, relicts of past glacial deposition or mass movement events, created major rapid-plunge pool sequences wherever they were exposed in erosional reaches.

Trout Distribution

Total trout density of the forested section was about 40% greater than that of the clear-cut section (Fig. 16). Densities appeared very low overall compared to data from other Cascades streams (Aho 1977, Hawkins et al. 1983). While fish of 10-14 cm were most abundant in the clear-cut section, all other size classes were more abundant in the forested section. The largest trout (>14 cm) were about twice as abundant in the forested section, an important observation because the minimum legal size for trout is 15 cm for this area. Fish in the smallest size class, which appeared to be young-of-the-year, were surprisingly few in the forested section, but entirely absent in the clear-cut section.

Between-reach variation in density was large (Table 8), so that if we compared total densities by reach, the mean for forested reaches was not significantly different from the mean for clear-cut

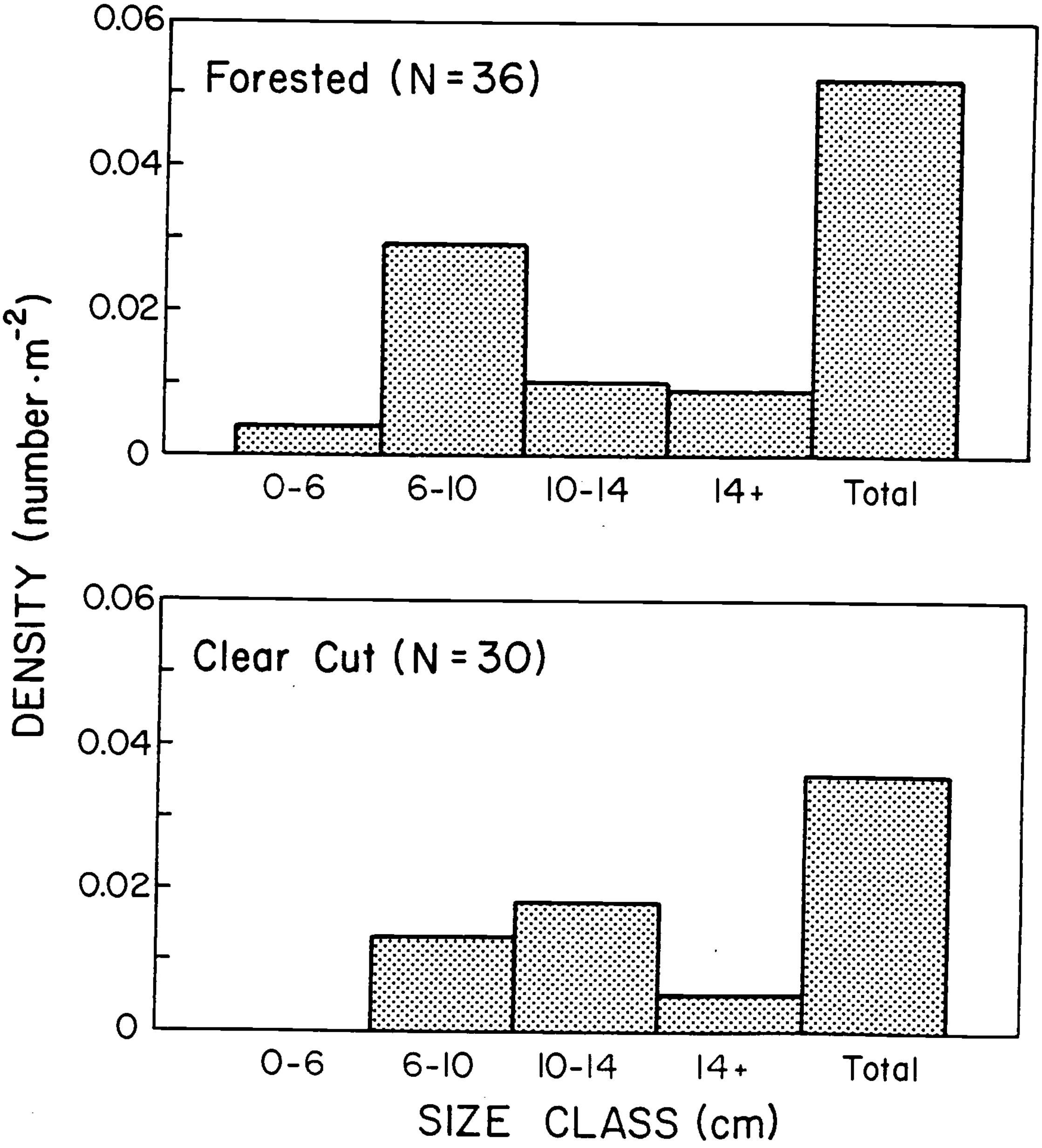

Figure 16. Total and size-class specific densities of trout in forested and clear-cut sections of Minto Creek.

Table 8. -- Density (number · m^{-2}) of trout in forested (F) and clear cut (CC) reaches of Minto Creek.

Reach	Size Class				Total
	0-6	6-10	10-14	14 +	
F2	0.007	0.007	0.007	0.014	0.035
F3	0.006	0.025	0.006	0.003	0.040
F4	0.000	0.050	0.018	0.014	0.082
CC1	0.000	0.029	0.012	0.006	0.052
CC2	0.000	0.006	0.016	0.006	0.028
CC3	0.000	0.018	0.024	0.000	0.043

*F1 not sampled

reaches (t-test, $\underline{P}<0.26$). Reach F4 had by far the highest total densities, and those of CC2 were lowest.

Habitat use analyses showed that trout clearly selected certain pool/riffle types (Table 9). For the population as a whole, large woody debris backwater pools were most preferred, followed by very large boulder plunge pools, large woody debris plunge pools, boulder backwater pools, large woody debris side channels, boulder rapids, boulder plunge pools, and large woody debris plunge pools (Table 8). The remaining habitats were occupied at very low densities or not used at all. These results are generally similar to those reported by Bisson et al. (1982) for cutthroat trout in Washington streams, except that trout in Minto Creek had little affinity for lateral scour pools, and fish in their study were absent from side channels. Cutthroat are generally strongly attracted to woody debris cover (Bustard and Narver 1975a, Bisson et al. 1982, Bisson and Nielsen 1983).

Different size classes used somewhat different ranges of pool/riffle types (Table 8). Only trout in the smallest two size classes used large woody debris side channels. Large woody debris backwater pools and very large boulder plunge pools were dominated by fish of the two intermidiate size classes, and boulder backwater pools and large woody debris plunge pools were dominated by trout of the two largest size classes. Boulder rapids were used by fish of all sizes, but were most strongly selected by the smallest and largest size classes.

Table 9. — Habitat selection index (L) values for pool/riffle classes, by trout size class (see text).

Pool/riffle class	Size Class 0-6	 6-10	 10-14	 14 +	Total
Very large boulders					
Plunge pool	-0.620	+0.099	+0.165	+0.038	+0.105
Large woody debris					
Plunge pool	-0.007	-0.007	-0.007	+0.093	+0.008
Lateral scour pool	-0.092	-0.027	-0.001	+0.008	-0.016
Backwater pool	-0.041	+0.120	+0.140	+0.059	+0.110
Glide	-0.027	-0.027	+0.019	-0.027	-0.012
Falls	-0.002	-0.002	-0.002	-0.002	-0.002
Side channel	+0.607	+0.101	-0.060	-0.060	+0.046
Boulders*					
Plunge pool	-0.066	+0.031	+0.025	+0.034	+0.025
Backwater pool	-0.007	+0.025	+0.174	+0.093	+0.083
Glide	-0.050	-0.017	+0.041	-0.050	-0.004
Riffle	-0.115	-0.083	-0.070	-0.015	-0.070
Rapid	+0.202	+0.030	-0.040	+0.169	+0.036
Rapid-Cascade complex	-0.084	-0.051	-0.084	-0.084	-0.069
Cascade	-0.100	-0.100	-0.055	-0.100	-0.085
Falls	-0.007	-0.007	-0.007	-0.007	-0.007
Side channel	-0.030	+0.003	-0.030	-0.030	-0.015
Cobble bar					
Riffle	-0.105	-0.105	-0.105	-0.105	-0.105
Side channel	-0.007	-0.007	-0.007	-0.007	-0.007
Gravel bar					
Side channel	-0.003	-0.003	-0.003	-0.003	-0.003

*Boulder lateral scour pool not present in reaches sampled for trout

Differences in trout densities between the study sections could not be explained simply in terms of total area or volume of pools present. The trout density in a reach was not related to the total volume ($\underline{r} = -0.057$) or surface area ($\underline{r} = 0.189$) of pools in the reach. Small pools often held as many trout as large pools. When all pools and glides were lumped as "pools", and all other habitats combined as "riffles", mean trout density in "pools" did not differ significantly between clear-cut and forested reaches (t-test, $\underline{P} > 0.30$) (Fig. 17). Trout density in "riffles" of forested reaches, however, was about four times that in "riffles" of clear-cut reaches (t-test, $\underline{P} < 0.01$). As is clear from the habitat use analysis (Table 4), trout apparently selected certain specific types of pools and riffles and apparently avoided others.

To better explain differences between trout populations of the two study sections, we used the data in Table 9 to determine which habitats were most strongly selected by each size class. By compiling the three most-used habitats for each size class (two habitats only for trout <6 cm), we arrived at a list of six habitats: very large boulder plunge pools, large woody debris plunge pools, large woody debris backwater pools, large woody debris side channels, boulder backwater pools, and boulder rapids. Regression of the relative area within each reach comprising these key pool/riffle types versus total trout density of the reaches showed that this simple model summarized well most of the density variation among reaches, and between study sections overall (Fig 18).

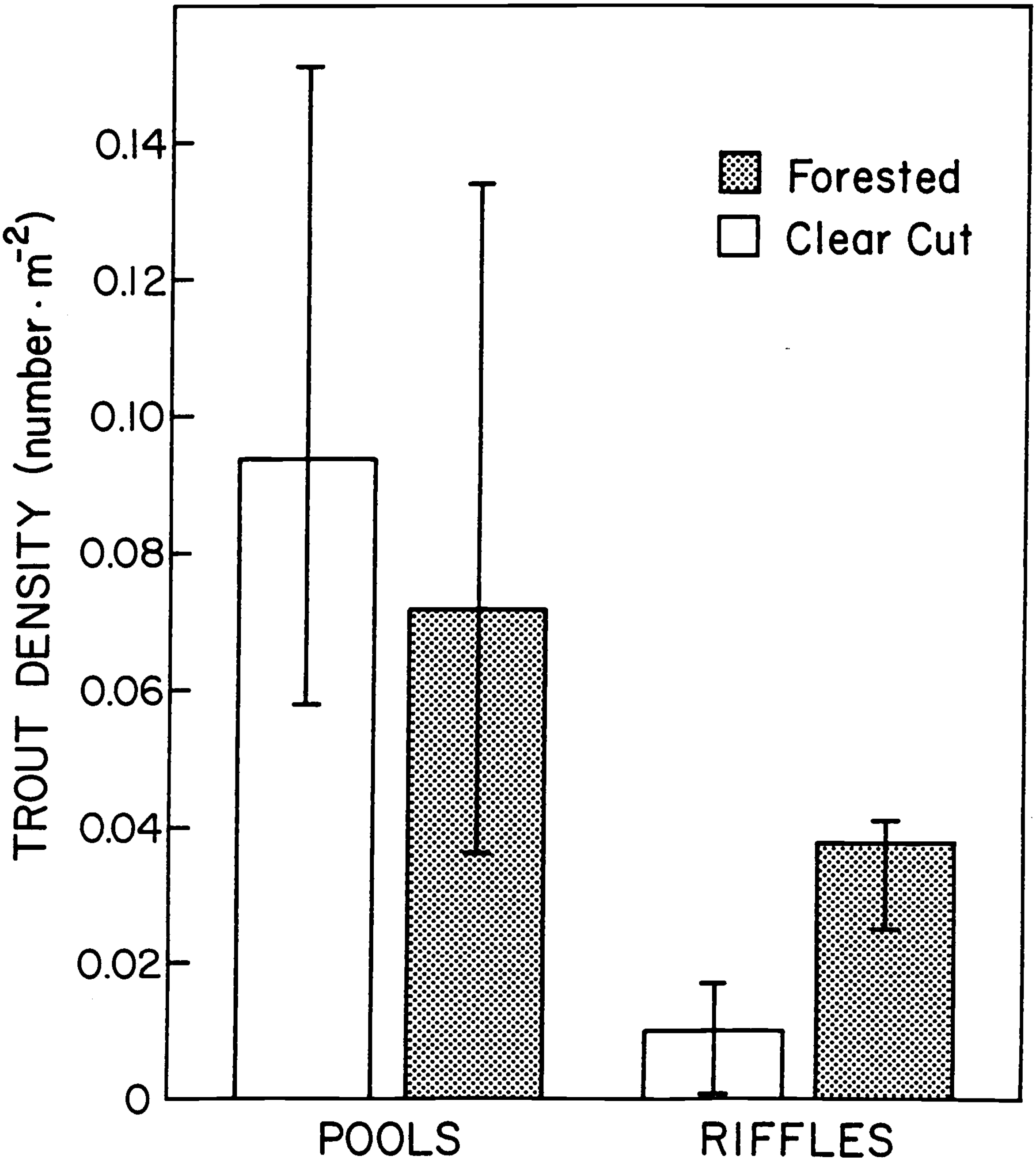

Figure 17. Total trout densities in combined "pools" and combined "riffles" in clear-cut and forested reaches of Minto Creek. Bars indicate means, brackets are ranges for three reaches in each study section.

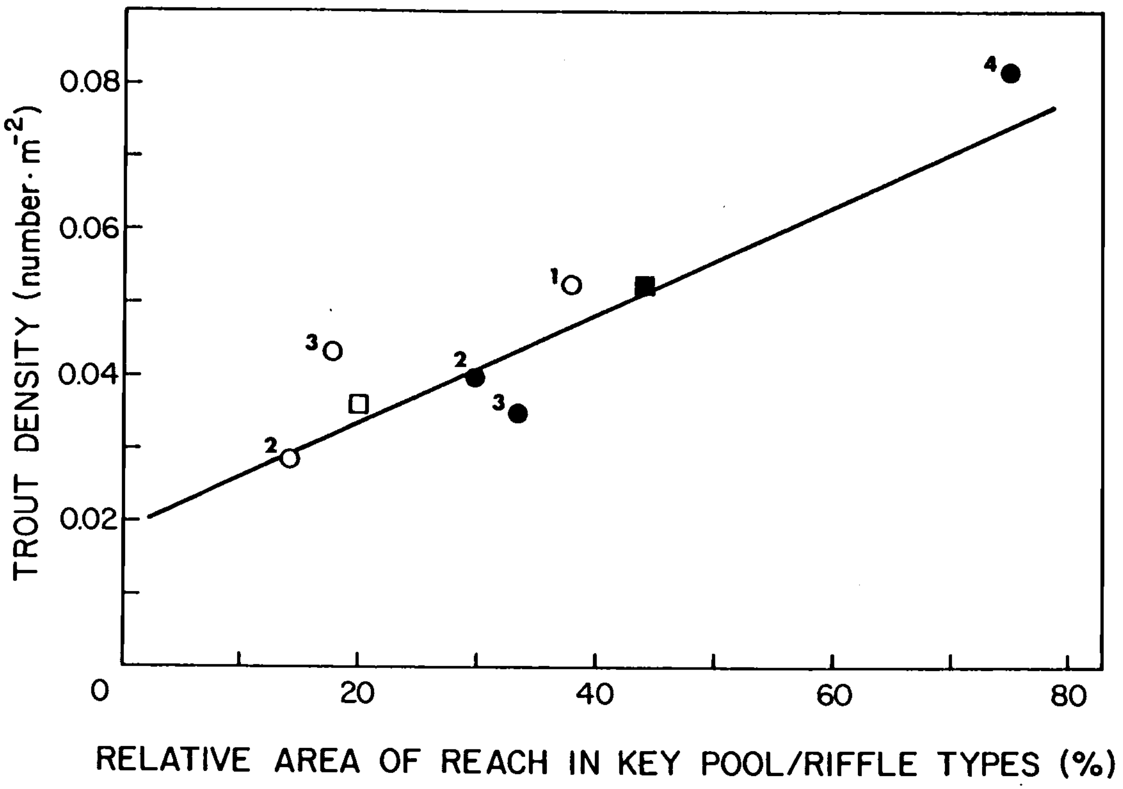

Figure 18. Regression of total trout densities in forested (shaded circles) and clear-cut (open circles) reaches of Minto Creek, against total relative surface area of each reach comprising the six key pool/riffle types listed in text. Fitted equation is $y = (8.15 \cdot 10^{-4})x + 0.018$; $r = 0.93$, $P < 0.01$. Square symbols represent overall values for forested (shaded) and clear-cut (open) study sections.

Discussion

The forested and clear-cut study sections of Minto Creek clearly differed in habitat organization and size and structure of fish populations present. Nevertheless, statistical analysis of most standard measures of habitat and population structure would not have reflected differences between study sections, owing to small sample sizes and wide reach-to-reach variation. Habitat classification not only allowed us to analyze and interpret this variation but also provided a framework for synthesis of small-scale (e.g., pool/riffle) patterns with larger-scale (e.g., reach, section) patterns.

In the study area, a rather simple model of pool/riffle composition explained much of the variation in trout densities (Fig. 18), because most of the population was distributed within a small number of pool/riffle types. We caution against extrapolation of this model to other sites without further analysis. Habitat selection varies with food resources and population density (Chapman 1966), the range of habitats available (Johnson 1980), season, and other factors. Nevertheless, this kind of model could, with further development, prove useful for identification of stream reaches most in need of protection of enhancement, and might suggest what specific kinds of geomorphic processes or riparian features best provide the array of habitats required by trout of all sizes.

Previous studies in the Oregon Cascades have found increases in cutthroat trout abundance in clear-cuts compared to adjacent forested sites (Aho 1977; Murphy and Hall 1981; Murphy et al. 1981; Hawkins et al. 1983). Studies elsewhere in western Oregon and Washington have reported both significant decreases (Moring and Lantz 1974, 1975) and increases (Hawkins et al. 1983; Bisson and Sedell in press) in cutthroat trout populations of clear-cut sites. Clearly, responses of fish populations to logging vary not only by region, but also beween sites with different geomorphic characteristics within a region. Minto Creek is not only larger than the streams in previous studies from the Cascades, it also lies in the High Cascades physiographic province. Previous study sites were located in the Western Cascades province, which differs somewhat in elevation, bedrock lithology topography, soils, and hydrologic regime (Meyer and Legard 1973; Franklin and Dyrness 1973; Harris et al. 1979). Consequent differences in stream characteristics like slope, sediment size, sediment transport, and streamflow may cause stream habitats and biota to respond differently to similar perturbations. A general system of watershed/stream classification should allow better design and interpretation of research and more effective application of results (Warren 1979; Hall and Knight 1981, Frissell et al. 1985).

The paucity of cutthroat in the smallest size class suggests recruitment may vary substantially between years. Cutthroat spawn in May through June in the Oregon Cascades, and emerge in July (Wyatt 1959). Because cutthroat spawn in gravel-sized substrates (Reiser and Bjornn 1979), eggs and embryos may be susceptible to destruction by snowmelt freshets in May or June. Flooding is known to cause mortality of incubating salmonid eggs (Reiser and Bjornn 1979). Seegrist and Gard (1972), for example, reported that spring floods sometimes destroyed rainbow trout redds in a Sierra Nevada stream, depressing certain year classes. Flooding in Minto Creek may affect clear-cut reaches more severely than forested reaches, because the small lenses of gravel found behind boulders and in channel margins are easily transported when stream flow increases (Jackson and Beschta 1981; Carling and Reader 1982). The abundant gravel in the side channels of the constructional reach in the forested section may remain relatively undisturbed, due to flow deflection by woody debris, and to the lower slope, greater width, and thus limited stream power in this reach. While many trout spawn in small tributaries of Western Cascades streams (Wyatt 1959), tributaries of Minto Creek are few, exceedingly steep, and largely inaccessible. Debris dams in the mainstem could play a critical role in providing spawning and rearing habitat.

Hydrologic records are consistent with the possibility that flooding caused mortality in the 1984 year class in Minto Creek. Peak discharge in June 1984 for the Breitenbush River, a High Cascades stream just north of Minto Creek, was 27%-37% higher than that of the previous two years. June floods of such magnitude are not rare, however, having occurred about every 3 to 5 years since 1960 (US Geological Survey, Water Resources Data for Oregon, 1960-1984). Spring snowmelt floods may be less frequent or less severe in Western Cascades streams than in the High Cascades (see Harris et al. 1979), because snowpack recedes earlier at lower elevations.

More predictable spawning habitat could be just one of many benefits to trout provided by the geomorphic complexity of the forested portion of Minto Creek. The diversity of habitats available may also provide for the needs of juvenile and adult trout over a wide range of seasonal and annual variations in streamflow. It may be of selective advantage for trout to occupy a small home range, within which food, cover, spawning areas, overwintering habitat, and other resources are predictably accessible. This could explain why site tenacity, the tendency for individuals to remain in specific habitat patches for the major portion of their lives (Morse 1980), has frequently been reported for cutthroat trout. Miller (1954,1957) suggested that cutthroat in a Rocky Mountain stream spend their entire lives within a stream section less than 20 m long. Aho (1977) found that the majority of trout marked in one year in a Cascades stream were recaptured within 25 m of their original location the following year. Wyatt's (1959) results were similar. It is possible that trout in clear-cut reaches of Minto Creek may suffer higher mortality associated with displacement during floods or frequent migration between suitable habitats. If so, densities in the clear-cut section might have been still lower except for consistent recruitment from nearby forested reaches. Further study of these possibilities is necessary, but we suggest that protection of reach-scale habitat diversity, including concern for the spatial juxtaposition of different habitat types, should be considerations in stream habitat management.

Changes in the Minto Creek at the reach level have caused changes in pool/riffle habitats and microhabitats. Debris dams are common features in the forested parts of the stream. Within the forested zone (about 500 m) which includes the upper study section, five major debris dams span the channel, creating constructional reaches. Debris dams and constructional reaches are absent in clear-cut portions of Minto Creek and many other streams nearby. Besides the effect of direct removal of stream debris, past clear-cutting has eliminated the large streamside conifers that are the source of debris for the channel, and, when standing, act as anchors or retention devices to stabilize dams (Swanson et al. 1976; Swanson et al. 1982). Additionally, decaying stumps and young trees in the clear-cut section of Minto Creek apparently do not provide bank protection that allows development of undercut banks (Keller and Swanson 1979), as roots of large, living trees do in the forested reaches.

Large woody debris dams play a major ecological role in streams of forested landscapes. The physical effects of debris dams include the storage of stream sediments (Beschta 1979; Keller and Swanson 1979; Bilby 1981; Mosely 1981), creation of upstream braided reaches and midchannel bars (Keller and Swanson 1979), facilitation of channel shifts and meander cutoffs (Keller and Swanson 1979), establishment of pools and riffles (Keller and Tally 1979; Mosely 1982; Bryant 1983), and development of stepped channel profiles, which creates variable channel morphology and flow conditions, and causes dissipation of stream energy at falls (Heede 1972; Keller and Swanson 1979). By retaining fine organic matter, debris dams increase food resources for aquatic invertebrates (Bilby 1981; Swanson et al. 1982; Triska et al. 1982). Debris dams also directly provide cover and habitat for fish (Hall and Baker 1982; Sedell et al. 1982; Triska et al. 1982; Bryant 1983).

Debris dams in the forested section of Minto Creek play many of these roles. Storage of sediments in Reach F3 created a diverse complement of pool/riffle habitats. On a larger scale, the mosaic of reach types in the forested section was the result of a complex process of debris dam development, sediment aggradation, channel shifting, and incision of new channels. Reach F4, with the highest density of cutthroat, apparently formed when a large debris dam upstream collected sediment and diverted flow from an older channel. That channel, now colonized by alders 10-15 y old, exists as a long secondary channel, dry at low flow except for a few isolated pools, parallel to but about 20 m north of the present stream. Incision of the new channel caused about six large trees to fall across what is now reach F4, providing dense overhead cover and creating backwaters. Root wads of standing trees support deeply undercut banks along the margins of pools and rapids.

Inactive secondary channels of various ages are distributed widely on the valley floor of Minto Creek. Many of these channels carry water at high winter flows, and provide passage around debris dams, as well as off-channel overwintering habitat during large floods (Hall and Baker 1982; Bisson and Nielsen 1983). Secondary channels and other portions of the riparian zone are known to provide critical winter habitat in Pacific Northwest streams (Bustard and Narver 1975a, 1975b; Sedell et al. 1980; Bisson and Nielsen 1983). Certain spring-fed secondary channels harbor high densities of trout throughout the summer (C. Frissell, personal observation).

The fact that diverse high-quality habitat is associated with debris dams and periodically-shifting channels might mean that even present stream protection measures may be inadequate for Minto Creek and similar systems. Current practices generally call for a narrow buffer strip along stream margins, and minimal disturbance of in-stream debris, successfully avoiding most of the short-term negative impacts of logging and debris removal. Such a treatment on Minto Creek, however, would probably set the stage, over the long term, for channel shifts that might only serve to funnel the stream onto logged, debris-free areas of the valley floor.

For streams like Minto Creek, where debris dams are ecologically important and abandoned channels indicate channel shifts are historically frequent, we suggest that it would be appropriate to designate the entire valley floor as a stream protection management unit. Selective harvest, small patch cuts, or no cutting would be allowable silvicultural treatments. These management strategies would be consistent with the objective of constraining the stream, regardless of possible channel shifts, to pass through at least some stands of mature forest. Large clear-cuts would be discouraged. These management objectives could benefit wildlife, water quality, and recreational resources as well. Implementation of such a policy might be difficult, however, because alluvial bottomlands are among the most productive lands in the Cascades for Douglas-fir, western red cedar, and other commercially important trees (Legard and Meyer 1973).

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