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EVALUATION OF THE TFW STREAM CLASSIFICATION SYSTEM:

STRATIFICATION OF PHYSICAL

HABITAT AREA AND DISTRIBUTION

By

T. J. Beechie and T. H. Sibley

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Prepared by T. J. Beechie and T. H. Sibley

Center for Streamside Studies (AR-10)
and
Fisheries Research Institute (WH-10)
University of Washington
Seattle, WA. 98195

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and
State of Washington
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Olympia, WA. 98504

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EXECUTIVE SUMMARY

This study was conducted to evaluate the effectiveness of the proposed TFW segment types in stratifying the physical habitat characteristics of streams. The segment types evaluated consist of four types that are commonly located in timber lands and have anadromous fish populations (C2, C3, C4, and B2), and one type that occurs in timber lands but generally does not provide habitat for anadromous salmonids (G type). As response variables we used the distribution of channel units in the segment, the percentage of pools, and the percentage of the channel area as coho spawning gravel. Additionally, we evaluated the influence of changes in discharge on the channel unit distribution, the contribution of several independent variables (bankfull discharge, gradient, wood volume, sediment size) in predicting pool percentages, and the influence of bankfull width on the percentage of spawning gravel.

Throughout this study we attempted to evaluate the sources of variability in the distributions of physical habitats in streams, and to identify those sources that provide useful information in addition to the classification system. Three sampling routines were used to address these sources of variability: (1) 16 reference sites, each 100 m in length, were established to observe the changes in channel unit distributions with changes in discharge and to examine the influence of large woody debris in segments, (2) 23 segments in the South Fork of the Stillaguamish River basin were used to examine paired B2 and C3 segments and to evaluate all B2 and C3 segments within a watershed, and (3) 32 segments in several watersheds were surveyed to compare the differences in segment characteristics within a single watershed to those in several watersheds.

We found that the segment types evaluated (B2, C2, C3, C4, and G) stratify the physical habitat characteristics of small streams with moderate success. Large rivers were not included in the analysis; they are expected to have different habitat characteristics.

The reference site data demonstrate that most of the variability in channel unit distributions due to stream discharge occurs between summer low flow and summer base flow. This variability is greatest in the low-gradient B2 segments. Therefore, stream surveys to evaluate the classification system must be conducted at summer low flow to avoid dramatic changes in discharge between sample sites. The sampling of different segment types must be temporally interspersed to avoid bias in the results due to seasonal changes in discharge.

Regression analyses of gradient, wood volume, sediment size, bankfull discharge, and summer low discharge indicate that gradient, bankfull discharge and the interaction between wood volume and gradient are the most important variables in predicting the percentage of pools in a reach of stream. The results suggest that LOD has a greater hydraulic function in low gradient segment types and in smaller streams. Hence, it appears that riparian zone management objectives may eventually be tailored to different segment types. At present, data is insufficient to clarify the necessary management prescriptions.

The non-parametric analyses of paired stream segments in the South Fork of the Stillaguamish River basin show that both the percentages of pools and the percentages of spawning gravels are systematically higher in B2 segments than in C3 segments.

However, the variability between streams is very high. We conclude that differences between B2 and C3 segments are significant within streams, but that differences between streams is often larger than the difference between segments. The discriminant analysis of 8 channel unit groups indicates that, within a watershed, the channel unit distributions in B2 segments are different from those in C3 segments.

Segments distributed across several different watersheds (multiple watershed sites) indicate that the distributions of spawning gravel and pool percentages are stratified to some degree by segment types. In both cases gradient plays a major role in stratifying stream characteristics. Valley bottom width is not clearly correlated with either percentage of pools or percentage of spawning gravel, but bankfull width is a very important factor in predicting spawning gravel percentages. The discriminant analysis also shows that gradient is the dominant factor affecting the distributions of channel unit types. However, valley bottom width appears to be an important factor in low gradient streams. That is, B2 and C4 types have relatively distinct channel unit distributions.

Specific recommendations for the stream classification system include incorporating bankfull width as an additional variable in classification, considering the addition of an additional segment type defined as <0.5% gradient, and further investigation of such factors as LOD volume in individual segments, sub-basin geology, and position of the segment in the drainage network. These issues are to be addresses for each segment type individually. Sampling of segments requires temporal interspersion of different segment types to avoid introducing a bias in the measurement of channel units due to seasonal changes in discharge.

EVALUATION OF THE TFW STREAM CLASSIFICATION SYSTEM: STRATIFICATION OF PHYSICAL HABITAT AREA AND DISTRIBUTION.

1. INTRODUCTION.

Some researchers (e.g. Frissell et al., 1986; Rosgen, 1985; Murphy et al., 1987; Cupp, 1989) have viewed stream classification as a valuable land-use planning tool, whereas others have questioned its validity when population or habitat data are extrapolated from one reach to another even within the same drainage basin (e.g. Hankin, 1984; Reeves and Everest, 1986). Though the specific purposes of stream classification systems may vary, the general intent is to organize streams into meaningful groups to simplify sampling procedures and management strategies. Successful classification implies that the variability of a specific variable or set of variables is reduced within groups and that differences between groups are statistically significant.

Numerous variables may be stratified in forest land streams including:

(1) geomorphic variables (e.g. sediment size, obstruction frequency, stream power);

(2) habitat variables (e.g. pool space, spawning gravels, cover, etc.);

(3) biota (e.g. fish species; fish communities; benthic communities, etc.); and

(4) geologic and hydrologic processes (e.g. sediment transport capacities, debris flow susceptibility, etc.).

In addition, the values of predictor variables fluctuate on a variety of temporal and spatial scales. The temporal scales range from seasonal variability to millennia, while the spatial scales range from centimeters to kilometers. Therefore, we are often unable to put the present day appearance of a stream into a temporal and spatial context. For example, the input of sediment into streams is not constant, and the appearance (i.e. the habitat characteristics) of a reach at a given point in time is dependent on the sediment production history of the watershed (e.g. Hogan, 1989).

It is hoped that classification will eventually determine (with some acceptable range of variability) the "fish potential" of a segment of stream under various land-use practices. It may also provide a means of assessing on-site and cumulative effects of forest practices within watersheds (TFW Ambient Monitoring Program General Work Plan, 1989). This may be accomplished by linking a model predicting fish standing crop from habitat variables to one predicting these same habitat variables from land management practices (Fausch et al, 1988).

1.1 Stream Classification Review.

Numerous researchers have created and employed classification schemes in the past two decades (not including 99 predictive models based on habitat variables which are reviewed by Fausch et al., 1988). In addition, the field application of stream classification systems has become more wide-spread though the systems are rarely tested extensively or discussed in the refereed literature. Recent tests of classification (e.g. Whittier et al., 1988) are beginning to appear in refereed journals as they become more objective and quantitatively based.

A conflict between researchers and managers surfaces in the development and application of stream classification schemes. Managers need simple tools that require a minimum of manpower for application whereas researchers are reluctant to "oversimplify" the system. This has resulted in the wide-spread application of some classification systems without appropriate analyses of their limitations.

Early Classifications.

Horton (1945) and Strahler (1957) are credited with creating the system of numbering streams that is today known as stream order. The system now in use is that of Strahler, which states simply that two streams of order *n* join to form a stream of order *n+1*. Though this system is commonly used to indicate stream size, there is a high degree of variability in stream size and drainage basin area for streams of equivalent order (Beechie and Sibley, 1989, Appendix D). Between large geographic regions the major differences in the size of streams of the same order are primarily attributable to different precipitation regimes and variable water storage capacity. Within regions, the differences are due primarily to different drainage patterns and water storage capacities. Though the system finds nearly universal usage in the United States today, it should be understood that stream order is simply a gross indication of relative stream size and yields virtually no geomorphic information when used independently of other variables.

Leopold and Wolman (1957) defined and discussed the common local stream patterns termed braided, meandering, and straight. These patterns describe visible channel patterns that are associated with geomorphic factors (e.g. sediment supply) that influence the appearance of stream channels. Sediment loading, hydrologic regime, and gradient show definite and characteristic relationships within each of these channel patterns (Richards, 1982). Hence, the simple identification of channel pattern yields important, albeit general, information concerning the hydrologic and sediment regimes of the stream.

Bauer (1972) further developed these relationships by relating the common channel patterns to the entire river drainage basin. He recognized that classification must be based on the inherent capacities of streams rather than the observed condition, and under this premise defined four river zones in his "streamway classification". These zones were defined by geomorphic variables such as gradient, channel pattern, and sediment size, but were given distinctly non-geomorphic titles: Zone I - Estuarine zone, Zone II - Pastoral zone, Zone III - Gravel beach zone, and Zone IV - Boulder-cobble zone. These zones were extremely long in most cases, and provided only a very gross separation of stream types. Because new developments in stream classification have tended towards smaller scales, these zones have fallen into disuse. However, the logic of Bauer's classification of the streamway as something independent of current land use practices and the observed stream condition is continued in several "modern" classification systems.

The early papers discussed above did not have the intent of predicting either geomorphic or biological variables, but were simple methods of grouping sections or types of stream channel based on recognizable physical characteristics. These are primarily from the geomorphic literature, and have not contributed directly to the linkage between the geomorphology of a stream and its biological characteristics.

Recent Stream Classifications.

This section summarizes six papers that illustrate key developments in the area of stream classification, including five structured classification systems or concepts.

Bailey (1978) presented a large scale classification system for use by the Environmental Protection Agency. The units of his classification system (termed ecoregions) delineate large areas of the United States based on climate, physiography, and vegetation. The spatial scale is on the order of hundreds of kilometers, and these regions are temporally constant over hundreds of years. The state of Washington, for example, contains 6 ecoregions: the Okanogan Highland, the Columbia Plateau, the Palouse, the Cascade Range, the Puget Lowland, and the Coast Range. These regions were created with the intent of grouping large numbers of streams for analyzing water quality over the entire nation. This system has now been tested for two areas of the United States, Ohio (Larsen et al., 1986) and Oregon (Whittier et al., 1988), with respect to chemical characteristics of water and fish species distribution. In general, the relationships are predictable and correspond to the boundaries of the ecoregions.

Although Bailey's method of grouping streams is widely accepted for groups of streams at extremely large spatial scales ($>10^4$ km^2), it does not consider differences in channels at the scales of watersheds, whole streams, or individual reaches. Most members of the Timber-Fish-Wildlife Ambient Monitoring Steering Committee (TFW-AMSC) research group seem to agree that this grouping is necessary for statewide management planning, and that different ecoregions exhibit differing land-use problems in addition to differing stream responses. Since streams are not expected to be similar across ecoregions, it is viewed as a necessary component of classification for statewide application.

Warren (1979) presented a hierarchical classification concept in which 11 nested levels fully describe a portion of a stream. The scales of the 11 levels range from regional (on the order of hundreds of kilometers) to microhabitat (on the order of centimeters). Each level is defined in terms of: 1) substrate, 2) climate, 3) water, 4) biota, and 5) culture. Warren described a set of theoretical concepts upon which classification could be based, but did not propose a specific classification system.

Warren attempted to provide an explicit theoretical basis for complex classification, but did not completely depart from previous ideas. He stressed the importance of assessing the "potential" of a stream rather than its current condition. This was consistent with Bauer's suggestion that one must view the capacity of a stream independent of its present condition, but Warren included the value of land-use impacts in his classification under the "culture" variables. Additionally, he recognized that a range of scales is important to classification because the objectives of different studies may require dramatically different levels of resolution.

Vannote et al. (1980) presented a concept that was a true departure from previous attempts to classify streams into discrete units. The River Continuum Concept (RCC) recognized that changes along the length of a stream system are gradational rather than discontinuous. With this recognition there was an implicit denial that stream classification describes "real" units. The theory is derived from geomorphic literature that described a gradient of geomorphic conditions from headwaters to mouth. Thus, the

RCC describes expected systematic changes in stream communities along the length of a river. In this context, disturbance was considered similar to a downstream or upstream shift in the character of a stream. Hence, the analysis of the effect of disturbance on discrete units is abandoned, and the evaluation of disturbance resembles a time series analysis where lineal positions in the stream are substituted for time.

The RCC provides a valuable perspective on streams, but the actual application of the concept in a scientific or management context is lacking. Without the traditional sampling framework for the analysis of treatments on discrete units, the concept is difficult to test with specific hypotheses. Hence, different methods of analysis may be required to facilitate its application.

Lotspeich and Platts (1982) created a hierarchical classification system that was based primarily on the geomorphic controls on streams. It consists of six major levels ranging in scale from Bailey's ecoregion (>10^4 km^2) to the "land type" (~10^2 m^2). This classification disregards the influence of biological and land use components, but maintains the hierarchical structure and the concept of discrete units at a number of spatial scales.

Rosgen (1985) also based his classification on measurable morphological characteristics, but used a single spatial scale (tens to thousands of meters) to define his stream types. The intent of this classification system is to predict the geomorphic responses of stream reaches to various impacts. These units incorporate a number of geomorphic variables, but are characterized primarily by the valley slope, substrate, and channel shape. There is a general agreement with Lotspeich and Platts in that geomorphic controls dominate the stream form. However, Rosgen departs from other recent classification systems by emphasizing only one spatial scale.

Rosgen's stream types (or modifications of them) are probably the most widely used classification system at present, though some tests indicate that it does not function as a reliable predictor of fish populations (e.g. Reeves and Everest, 1986). Predicting fish populations is not its intended purpose, but it is often applied in this fashion. Rosgen's stream types may be most valuable when incorporated into other hierarchical systems that further define the characteristics of a stream and its geomorphic setting.

Frissell and others (1986) created a classification system that stems directly from Warren's conceptual approach. This hierarchical system incorporates six spatial scales, with the entire range of Warren's five variable types. This is the most complex form of stream classification currently being tested in the Northwest. It differs from other systems by recognizing that biotic and cultural variables have a significant effect on the stream character, and incorporates these variables into the classification.

This perhaps represents the extreme of classification in that it may be possible to classify large stream systems and have virtually no repeated units. One may question the value of such a classification system if there are not enough repeatable units in a basin to provide a sufficient data set for analysis. Its advantage however, may be that it provides the variety of levels of resolution that management requires. It is not necessary to use all the possible spatial scales simply because they exist, and the appropriate scale for management will likely provide the repeatable units necessary for evaluation.

1.2 Proposed Classification System.

The TFW-AMSC has proposed the establishment of a stream classification system to stratify streams throughout forested lands of the state of Washington. Among the stated objectives of the TFW-AMSC in establishing this typing system is "the desire to predict the biological and physical response of many streams based on the experience of a few streams" (TFW Ambient Monitoring Program General Work Plan, 1988). Specifically, it is stated that a stream classification system should have "... most if not all of the following capabilities: (1) the classification should reflect processes that determine stream characteristics; (2) stream units should be readily observable in the field or from maps; (3) ecosystem properties should be meaningfully sorted according to a physically-based classification system; (4) stream units should react to environmental changes induced in streams by forest management or natural disturbances in a predictable way; and, (5) large scale mapping of important units should be possible with existing or developing technologies."

The ultimate goal is that the link between an aquatic species or community and land-use practices in the watershed will be established in a manner that is useful to forest land managers. This linkage involves a series of steps which will require extensive evaluation using both statistical and process approaches at several different scales.

The proposed system is a simple hierarchical system that includes four spatial scales: (1) an ecoregion scale, (2) a watershed scale, (3) a segment scale, and (4) a channel unit scale. Among these four levels, the segment scale is considered the most difficult to define (Frissell et al, 1986).

1.3 Objectives.

The objectives of this study are two-fold: (1) to assess whether the chosen response variables are effectively stratified by five of the defined segment types, and (2) to address whether the arbitrarily chosen gradient boundaries (e.g. the 2% boundary between several segment types) correspond to real boundaries in streams.

In this evaluation we address four segment types (B2, C2, C3, C4) that commonly provide spawning and rearing habitat for anadromous salmonids and occur in forested lands of Washington. Three G type segments were also surveyed to contrast with the other segments.

Specific objectives of the study include:

(1) Determine whether channel unit distributions are statistically different in the five segment types (cluster and discriminant analyses).

(2) Determine whether the percentage of pools and percentage of spawning gravels are different in four segment types (ANOVA and non-parametric equivalents).

(3) Evaluate the influence of large organic debris (LOD) on the percentage of pools in stream segments.

(4) Evaluate the influence of stream size on the percentage of pools and percentage of spawning gravels in stream segments.

2. APPROACH.

The proposed TFW classification system is an *a priori* classification system that is patterned after those of Frissell et al (1986) and Cupp (1989). It includes four hierarchical levels and is intended to be used throughout the state of Washington (TFW-AMSC Work Plan 1989). The suggested ecoregion map (refined from Bailey 1978) includes 15 ecoregions within which there are a variable number of watersheds (Figure 2.1). Stream segments are to be classified as one of 19 types (Table 2.1), and channel units (Bisson et al. 1982, Sullivan 1986) will be used to classify morphological features of channels within segments.

The TFW-AMSC Work Plan (1989) states that segments may be the most variable of the four classification levels, and that this variability occurs both spatially and temporally. General indices of sediment regime (low to high inputs), obstructions (low to high frequencies or volumes), and flow regime (changes in peak or mean annual discharges) are suggested as input variables that will dictate the condition of a segment type at a particular point in time.

The evaluation or verification of a classification system of this magnitude requires a conceptual approach that will eventually address the large number of issues in question. This conceptual approach may be viewed as a multi-step process that will address such problems as spatial scales, temporal scales, data collection methods, sampling designs, and methods of analysis. Hence, an understanding of the objectives and logical structure of the classification is critical.

Because a unique set of variables that characterizes a length of stream has not been defined, it is necessary to view the proposed classification scheme in terms of its objectives and to specifically address those objectives in the evaluation. The objectives of the proposed TFW stream classification system (Section 1.2) suggest that ecosystem properties and the physical and biological responses to disturbances should be the focus of an evaluation. In practice, much of the concern is over the potential of streams to produce both sport and commercial salmonid species (genus *Oncorhynchus*). In terms of forest practices impacts, this concern is often reduced to studying the effects of man-induced disturbances on the physical structure of habitats and on primary and secondary production in streams.

2.1. Problems in Variable Definition.

The TFW-AMSC classification system assumes a relationship between the physical structure of a segment and its potential biological productivity, and is intended to predict the physical or biological responses of streams to disturbances (either natural or timber harvest induced). The TFW Ambient Monitoring General Work Plan (1989) follows Fausch et al. (1988) in suggesting that evaluations should focus in two general areas:

(1) How the important physical parameters and processes in segments control the structure of habitats in the segment, and

(2) Quantification of the relationship between physical parameters and potential biological productivity.

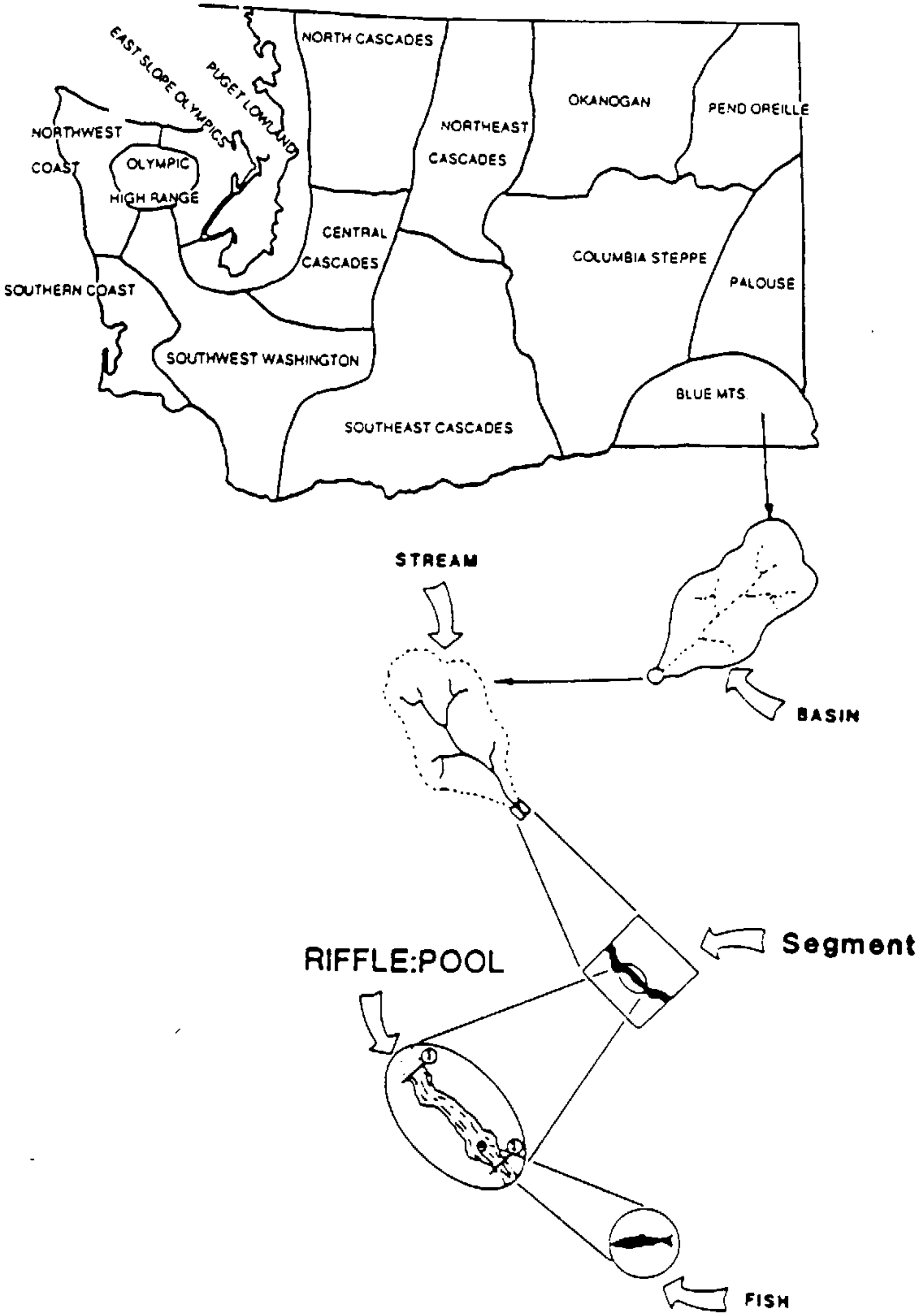


Figure 2.1. Suggested hierarchical classification scheme adapted from the TFW Ambient Monitoring Steering Committee General Work Plan (1989).

Table 2.1. Summary of segment types proposed by TFW-AMSC with revised segment labels for 1990 (Cupp 1990). Asterisks indicate segment types addressed in this study.

Valley Segment Type Description	Old Symbol	New Symbol
Estuarine Delta	A1	F1
Wide, Alluviated Lowland Plain	B1	F2
* Wide Mainstem Valley	B2 *	F3
Alluvial/Colluvial Fan	B3	F4
Gently Sloping Plateaus and Terraces	C1	F5
* Moderate Slope Bound Valley	C2/C3 *	M1
* Alluviated Moderate Slope Bound Valley	C4 *	M2
U-shaped Valley	F1	U1
Incised, U-shaped, Moderate Gradient	D1	U2
Incised, U-shaped, Steep Gradient	D2	U3
U-shaped, Active Glacial Outwash Valley	F2	U4
V-shaped, Moderate Gradient Bottom	E1	V1
V-shaped, Steep Gradient Bottom	E2	V2
Bedrock Canyon		V3
Alluviated Mountain Valley	E3	V4
* Valley Wall/Headwater, Moderate Gradient Bottom	G1 *	H1
* Valley Wall/Headwater, High Gradient Bottom	G2 *	H2
* VAlley Wall/Headwater, Very High Gradient Bottom	G3 *	H3

The parameters that numerically define like and unlike streams have not been clearly distinguished, though numerous parameters have been chosen to evaluate stream classification in past studies. Fish populations or community structures (Reeves and Everest 1986, Murphy et al. 1987, Whittier et al. 1988) as well as habitat and geomorphic variables (Rosgen 1985; Reeves and Everest, in press; Murphy et al. 1987; Whittier et al. 1988; Cupp 1989) have been chosen by different investigators.

The array of variables measured and analyzed by Whittier et al. (1988) is quite comprehensive though they are not justified by particular objectives (e.g. predicting the impact of landscape disturbances on specific response variables). The variables used include fish species assemblages, macroinvertebrate species, periphyton species, water quality, and physical habitat. It is noteworthy that the ecoregions studied in the Pacific Northwest do not distinctly separate the four mountainous regions with respect to fish, macroinvertebrates, physical habitat, or water quality. Only with respect to periphyton species are some mountainous regions separated into two distinct groups (Whittier et al. 1988).

It is also clear that many of the variables used in previous studies are not independent. For example, Whittier et al. (1988) included 28 variables in their physical habitat analysis, though relatively few stream variables are actually independent (Langbein and Leopold 1966; Richards 1982, pp.149-152; Beschta and Platts 1986). Cupp (1989) used 20 habitat variables to evaluate stream classification in the Gifford Pinchot National Forest in Washington State. The use of correlated variables in statistical analyses may cloud the results of classification studies.

The broad spectrum of variables used by Whittier et al. (1988) and Cupp (1989) to evaluate classification, required extensive field work at each site and limited the length of sampling reaches to approximately 100 meters. Preliminary analyses of individual reaches in this study suggested that 100 meters is too short to characterize the physical habitat of a reach of stream. In addition, observer bias is perhaps unavoidable when short "representative" reaches must be chosen. Hence, it is impractical to use the complete set of physical, chemical, and biological variables to evaluate a stream classification system that must be applied over a wide geographical area. Nevertheless, a thorough statistical analysis of the interactions among these variables would be valuable.

Other studies have used simpler analytical methods on single variables or small sets of variables. Reeves and Everest (in press) look at densities and distributions of fish species and age classes, as well as the distribution of pools, riffles, and glides within the stream types defined by Rosgen (1985). However, they did not employ the sub-types suggested by Rosgen in their study of an Oregon Coast Range river basin. Murphy et al. (1987) evaluated woody debris abundance, pool space, and fish species within and between segment types (patterned after Rosgen 1985) in Southeast Alaska. They suggest that with further refinement the stream classification could be useful.

Though the use of fish densities (usually by species and age class) is common in stream work, juvenile populations of anadromous species are expected to vary with escapement levels and in-stream environmental fluctuations (e.g. low water years, large floods, etc.). Because escapement is controlled by factors outside the stream (both natural mortality and fishing mortality at sea), the use of single population estimates of anadromous species to characterize streams is invalid. Further, natural fluctuations in populations of resident fish species are so large that even these are not reliable when seeking to characterize land-use impacts in streams (Platts and Nelson 1988).

Physical characteristics of streams will vary less than biological characteristics from year to year and therefore provide a more stable response variable to evaluate a classification system. Physical characteristics are necessarily stable over decades or centuries, but are likely to cycle over long time periods (Brown 1972; Dunne and Leopold, 1978 pp.689-690; Richards 1982; Sedell and Dahm 1983; Grette 1985; Hogan 1989). Habitat space also changes with discharge (Sullivan 1986; Hogan and Church 1989) which presents problems when using the spatial relationships of channel units as a response variable.

2.2. The Problem of Spatial Scale.

The problems of spatial scale in stream classification systems are discussed by several researchers (Frissell et al. 1986; Lotspeich and Platts, 1982; Beschta and Platts, 1986). Different spatial scales dictate different levels of resolution that may be used to meet specific information requirements. For example, the evaluation of fish stocks in whole basins may require large scale stratification of habitat information, but the prediction of land use impacts on specific habitats (such as fine sediment in spawning gravels) may require more detailed information. A nested hierarchy facilitates the use of different levels of resolution for different objectives (Frissell et al. 1986).

The proposed valley segments, which correspond to the segment level of Frissel et al. (1986), are the only hierarchical level between watersheds and channel units in the proposed classification system. These valley segments were chosen such that the characteristics describing them (e.g. average gradient and valley bottom width) do not change over a time scale of decades to a few centuries. Though the attributes that define the segment do not change, the condition of a segment (expressed in terms of habitat quantity and quality) may change over years to decades. Hence, this spatial scale has the advantage that the attributes defining a segment are temporally stable on a map. However, this scale requires extensive efforts to describe the habitat characteristics of each segment type at different levels of the input variables (sediment, discharge, LOD).

In contrast, a smaller spatial scale such as that employed by Rosgen is focussed upon channel characteristics (e.g. gradient, sediment size, width/depth ratio). Because these characteristics are sensitive to various impacts (e.g. increased sediment load, landslides, and dam-break floods) the classification of a particular reach may change with time. Thus, a smaller spatial scale is expected to improve the stratification of physical habitat area and distribution, but at the expense of temporal stability. (See Frissell et al. 1986 for examples of different spatial and temporal scales in a hierarchical classification framework.)

2.3. The Problem of Time.

The problems that temporal scales present in stream studies have not been addressed in detail in discussions of classification, though several authors have addressed the problem in the past two decades (e.g. Hickin 1974, Schumm 1975, Grette 1985). Some have suggested that streams may exhibit various types of equilibrium depending on the time scale chosen (Richards 1982). Others maintain that the term "equilibrium" is inappropriate because sediment delivery processes in mountainous basins of the Pacific Northwest are discontinuous and tend to occur as pulses of sediment input followed by relatively long periods of low sediment delivery (Benda 1990). In addition, interactions between tributaries and the main channel of a river may lead to cyclic variations in channel characteristics even if the external conditions remain constant (Richards 1982, pp. 19-20). In addition, the increase in the rate of large organic debris (LOD) loading after man-made or natural disturbances in riparian zones is slow (Grette 1985) and may have a time scale that differs from those of sediment delivery and routing. Hence, the temporal changes in stream segments may be a response to several different and overlapping time scales in a watershed.

Recent human impacts to forested streams such as splash-damming and LOD removal (Sedell and Luchessa 1982) present additional problems for assessing stream classification. Knowledge of the types of man-made and natural events that have occurred in a particular segment is critical to interpreting current stream information. Because the history and "natural" condition of a segment is often unknown, we are limited to speculating on past practices based on regional history and field evidence. However, it is clear that timber harvest and road-building often increase the frequency of natural events such as landslides, thereby altering the time scales that we observe today in streams (Ice 1985). These factors make it difficult to determine the natural variability of segment types and to compare pre- and post-disturbance conditions in individual segment types.

The TFW-AMSC Work Plan (1989) proposes that the temporal scales be addressed by separating controlling variables (water, sediment, LOD) and assessing the level of each variable. This creates a sampling design that can be expressed as a three-dimensional table with three levels for each variable (Fig 2.2). This table describes the possible forms of a single segment type, including interactions of the three variables within a single watershed and ecoregion. A discussion of the sampling effort required to evaluate the classification system state-wide is found in Section 5.3.

The evaluation of changes in the delivery of water and sediment within a segment present difficult practical problems. Changes in the delivery of water to a stream segment will be difficult to detect without historical records of discharge in small streams. Further, natural variations in discharge will require a long time series to distinguish changes in discharge from natural variability. Determination of the condition of a segment with respect to sediment quantity is also difficult because of the discontinuous nature of sediment delivery and the absence of historical information.

LOD (and other in-channel obstructions) may be more easily quantified in stream segments. In this study we address both the frequency and volume of various obstructions in segments. These can be compared to the frequencies and volumes of obstructions in other studies of old-growth streams in the Pacific Northwest to determine whether streams are high or low in LOD. Hence, we are able to address one component of the three-dimensional structure presented in Figure 2.2.

2.4. Addressing Sources of Variability.

General Considerations.

Because of the numerous sources of variability in streams, establishing the relative contributions of different variables is a difficult endeavor. The classification of streams attempts to sort out some of the variation without explicitly understanding each of the landscape and fluvial processes that create habitats in streams. This is a statistical approach that is distinctly different from the physical modelling approach which attempts to describe the various processes that contribute to the formation of physical habitats. The statistical approach may take two general forms: (1) clustering of large amounts of

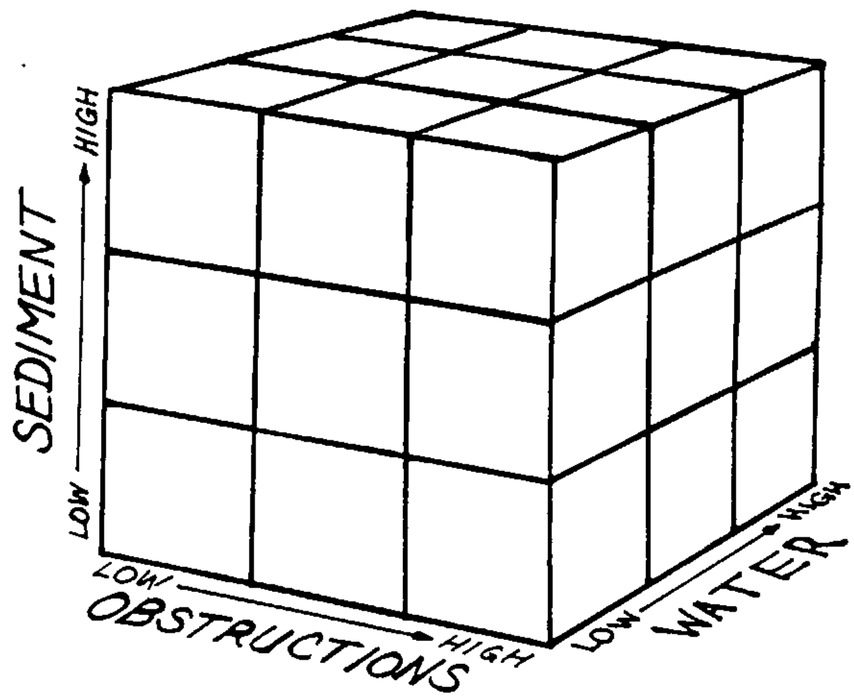


Figure 2.2. Restructuring of the TFW-AMSC Work Plan concept of controlling variables into a three dimensional picture showing all interactions of three variables with three potential states (high, moderate, low).

randomly collected data to create a classification system, or (2) developing an *a priori* classification based on some easily identifiable variables and subsequently testing its effectiveness (Whittier et al. 1988).

Each of the two statistical approaches may be useful under certain conditions. The clustering approach may be the most efficient route to developing or refining a classification system when the importance of particular variables is understood, but the relationships between them are unclear. For example, cluster analysis of the genetic makeup of several different salmonids contributed to the reclassification of some *Salmo* species as *Oncorhynchus* species. Similarly, it will be useful in stream classification for comparing the similarities of channel unit distributions.

The *a priori* approach is more commonly used in stream classification, partially because of the large investment in time and money required to sample streams for the clustering approach (Whittier et al. 1988). Though the *a priori* approach to stream classification allows one to easily develop a sampling structure for verification, it is possible that the incorrect definition of segment types will not be detected. For example, a particular segment type may be defined by an arbitrary range of gradients that does not reflect real differences in habitat distributions. In this case, the sampling structure developed from the *a priori* approach would allow the researcher to determine whether or not the defined classification types are significantly different, but the incorrect definition of classification types would not be discovered if the analyses do not include some form of clustering in verifying classification.

Another consideration in addressing sources of variability for stream classification is determining the relative contributions of known sources of variation, such as gradient, LOD, and sediment size. The above discussion suggests that the assessment of sources of variability should include at least two components:

1) one component should help define the relative importances of known contributing variables in defining variability,

2) and a second should help define thresholds or boundaries within the ranges of individual variables.

<u>Individual Sources of Variability</u>.

It is clear that the distribution of usable habitat area changes as discharge increases or decreases (Sullivan 1986, Hogan and Church 1989). Additionally, changes in discharge probably influence the observer's definition of channel units. The surface area in large pools often changes little with small changes in discharge during summer, but numerous smaller pools tend to disappear as discharge increases. Hence, the distribution of channel units varies with discharge. Though all stream segments were surveyed during summer, small changes in discharge will contribute to the variability within segments.

Because watershed characteristics (e.g. drainage area, sediment supply, landslide hazard, etc.) are numerous and highly variable within and between sub-basins, the use of paired segments will be used to minimize variation between streams. In this study there are sufficient data to conduct paired comparisons of two segment types (B2 and C3) within the watershed of the South Fork of the Stillaguamish River. This allows us to more clearly distinguish the difference between these two segment types and to gain insight into the important variables that create differences between streams (e.g. why C3 segments appear different in separate streams).

The use of two-sample tests over all segments in the South Fork Stillaguamish River basin does not control for variability between streams, but does provide additional information on the effectiveness of stream segments for stratifying streams within a watershed. The results of this comparison juxtaposed against the results of paired segment comparisons will contribute to understanding the sources of variability within a watershed (i.e. between streams).

Several problems may arise with the use of watershed as a level in the hierarchy. Watersheds are defined on the basis of topographic boundaries that may or may not be directly related to the physical factors that control the character of a stream. As an example, a particular geologic formation may occur somewhere within portions of several watersheds, but may not occur throughout any one watershed. Hence, the use of watershed may not provide useful information over and above the use of stream type and ecoregion.

Sources of variability at the scale of watersheds are difficult to address without extensive sampling designs. The most direct approach to assessing variability within and between watersheds is to use a sampling design in which chosen watersheds are considered blocks, with random sampling of individual segment types within each block. However, this requires extensive sampling within each watershed. An indirect approach requires the use of random sampling across several watersheds. The variability observed in this data set can then be compared to the data set from a single watershed. Similar degrees of variability will suggest (but not prove) that watershed is not a significant factor in determining stream character. Conversely, lower variability within the single watershed will suggest that watershed in some way contributes to the character of streams.

2.5. Recent Evaluations and their Implications.

Several recent evaluations of different stream typing systems suggest that the value of classification is perhaps greatest when used to address the stratification of habitat rather than anadromous fish populations (Reeves and Everest, 1986; Murphy et al., 1987). At the scale of ecoregions Whittier and others (1988) suggest that biotic assemblages and physicochemical parameters are also differentiated.

Though the stream types of Rosgen (1985) are discussed as segments in the TFW-AMSC Work Plan, they differ significantly in scale from the adopted model of Cupp (1989). The Rosgen stream types are based on stream channel descriptions, whereas the Cupp segment types are based on local valley forms. However, both are intermediate between watersheds and channel units, and both employ gradient as a primary factor in defining the "type" of a given reach. A comparison of the effectiveness of the two different systems should be instructive in understanding the importance of spatial scale at the segment level.

Classification of in-stream habitats (channel units) has proven useful in stratifying the summer rearing habitats of several species of juvenile salmonids (Bisson et al., 1982; Sullivan, 1986; Bisson et al., 1988). Important features of winter rearing habitats for coho salmon (*Oncorhynchus kisutch*) have also been identified and studied (Peterson and Reid, 1983; Scarlett and Cederholm, 1983). Typical spawning areas for salmonid species are known and the effects of sedimentation have been studied in several instances (e.g. Tagart, 1984). This knowledge of spawning habitats and preferred rearing habitats at two life history stages allows managers to begin addressing the potentials of streams in terms of the distribution of habitats.

2.6. Variables Used in this Study.

Geomorphic and habitat variables are used to assess the proposed classification system. This choice is based on the assumption that the biological potential of a stream is dependent upon its physical characteristics. Additionally, we expect that the habitat character of a stream will be less variable from year to year than will biological data, and therefore will be more appropriate for a single year study.

With respect to salmonid production, this assumption is supported by previous work demonstrating that salmonid species segregate themselves in response to physical characteristics such as velocity and depth (Bisson et al. 1982, Sullivan 1986, Sullivan et al. 1987, Bisson et al. 1988). Conversely, increased primary production is also correlated with increased salmonid production and may override changes in physical habitat (Bisson and Sedell 1984). However, species diversity (or community structure) may be correlated with physical habitat characteristics and may be independent of increased primary production.

We restrict this study to evaluating the effectiveness of the proposed valley types (Cupp 1990) in reducing within segment habitat variability, both within and across watersheds. Nearly all of the segments sampled in this study are located in the North Cascades ecoregion. Stream surveys were suspended during unusually high summer flows to limit variability from changes in discharge.

Three sampling designs were used to evaluate the classification system in three different ways (Table 2.2).

The three designs are as follows:

1) Detailed sampling of 16 reference sites in the South Fork Stillaguamish River basin provided data to evaluate the distribution of habitats within individual reaches of stream at different discharges. Each 100 meter long reference site was surveyed at different discharges ranging from summer low flow to storm flow after Sullivan (1986). These data are used to evaluate the distribution of channel units and the functions of obstructions at different discharges.

2) Surveys of all segments accessible to anadromous salmonids (27 segments) in the South Fork Stillaguamish River basin were used to evaluate the segment types at a

Table 2.2. Table showing the spatial and temporal scales and the scales of sources of variability addressed by three sampling designs used in this study. * = scale not addressed in this study.

	Sampling Region		
	Reference sites	South Fork Stillaguamish	Multiple watersheds
Spatial	100 m	watershed	ecoregion
Temporal	seasonal	*	*
Sources of Variability	discharge, segments	segments, streams	segments, streams, watershed

watershed scale. This sampling design allows the use of paired segment analysis and two-sample hypothesis testing within a watershed. Data used in this level of analysis are restricted to quantities and distributions of channel units. Obstructions were not surveyed in detail for this portion of the analysis.

3) Surveys of 4 segment types (29 individual segments) in 5 different watersheds provide a data base for testing the use of segments within an ecoregion and assessing variability across watersheds. Channel units and obstructions were enumerated during these surveys to evaluate the distributions of channel units and the functions of obstructions in various segment types.

3. METHODS.

During this study the field methods were changed slightly between 1988 and 1989. Channel unit data were completely compatible between years; both geomorphic and obstruction data were collected in a more detailed fashion in 1989.

3.1. Data Collected.

The data collection was designed to include a combination of geomorphic and habitat variables to assess the TFW Stream Classification System. The stream classification system was defined by Cupp (1990) and was modelled after that of Cupp (1989). The major distinguishing features of valley segments are valley bottom gradient, valley bottom width, and valley shape. The data collected in the 1988 surveys include:

UNIT --	General form (P=pool, R=riffle, G=glide) and sequential number of unit.
TYPE --	Specific type (modified from Sullivan, 1986)
LEN. --	Estimated length of unit (paced)
WID. --	Estimated mean width of unit (visual)
DEP. --	Estimated mean depth of unit (visual)
RAW BANKS --	Estimated length of raw banks and bank material in unit (left bank or right bank)
BFW --	Bank full width (visual)
BFD --	Bank full depth (visual)
SEQUENCE --	Main channel, side channel, or off channel.
RIPARIAN --	Comments on riparian vegetation, slumps, slides, landmarks, etc.
LWD --	Large woody debris. (defined below)
MWD --	Medium woody debris. (defined below)
SWD --	Small woody debris. (defined below)
SED --	Sediment code for dominant substrate size.
measL --	Measured length of unit.
measW --	Measured widths of unit.
measD --	Measured depths of unit.

All data except measurements were recorded for each individual channel unit. Measurements were recorded on every fifth glide and every tenth pool and riffle.

Similar data were collected in the 1989 surveys. Three groups of data were collected: (1) channel unit and habitat data, (2) obstruction data, and (3) discharge and hydraulic geometry data.

CHANNEL UNIT AND HABITAT DATA:

UNIT --	General form (P=pool, R=riffle, G=glide) and sequential number of unit.
TYPE --	Specific type (modified from Sullivan, 1986)
LEN. --	Estimated length of unit (paced)
WID. --	Estimated mean width of unit (visual)
DEP. --	Estimated mean depth of unit (visual)
S.G. --	Visual estimate of coho spawning gravel area.

OBSTRUCTION DATA:

UNIT --	Location of obstruction.
OBTYPE --	Obstruction type (e.g. wood, boulder, bedrock)
FUNCTION --	Function of obstruction (e.g. scour, sediment trap, none, etc.).
LENGTH --	Length of obstruction.
DIAMETER --	Diameter or width of obstruction.
ORIENTATION --	Angle of piece from upstream bank.
PERCENT IN --	Estimated percent of obstruction within the bankfull channel.

HYDRAULIC GEOMETRY, DISCHARGE, AND GRADIENT:

BANKFULL WIDTH --	width of channel at a cross section.
BANKFULL DEPTHS --	depth measurements every 0.5 meters across cross-section.
PEBBLE COUNTS --	systematic measurement of 50 - 100 particle diameters.
LOCAL GRADIENT --	gradient at cross section.
ROUGHNESS --	estimate of Manning's n at cross-section.
DISCHARGE --	discharge measurement on day of survey.
AVERAGE GRADIENT --	gradient of at least 100 m of site surveyed with hand level and level rod.

3.2. Code definitions.

The channel units identified in this study were intended to indicate both the obstruction type (wood, boulder) and the hydraulic type (dammed, scour, plunge, etc. -- after Sullivan, 1986) in the case of pools. Beaver ponds are excluded from this analyses because they do not represent the geomorphic processes operating in the stream. They are, however, included in all estimates of available summer rearing habitat.

The codes used on data forms and in computer files are listed below.

Channel Unit Types

Pools	HSP	hydraulic scour pool
	LSP	lateral scour pool
	TP	trench pool
	BOPP	boulder plunge pool
	BOSP	boulder scour pool
	BOEP	boulder eddy pool
	BODP	boulder dammed pool
	WPP	wood plunge pool
	WSP	wood scour pool
	WEP	wood eddy pool
	WDP	wood dammed pool
	BEPP	bedrock plunge pool
	BESP	bedrock scour pool
	BEEP	bedrock eddy pool
	BEDP	bedrock dammed pool
	MWP	wood margin pool
	MOP	other margin pool
	BP	beaver pond

Riffles	RIF	riffle
	RAP	rapids
	CAS	cascade
Glides	G	glide

Woody Debris

LWD	>50 cm diameter and >5 m long
MWD	>20 cm diameter and >3 m long
SWD	>20 cm diameter and >1.5 m long

3.3. Field Procedures.

Each channel unit was assigned a general form and sequence number, and was also classified as a specific channel unit type. The length of each unit was estimated by pacing, and the mean widths and mean depths were visually estimated. One length and several width and depth transects were measured on every fifth glide and on every tenth pool and riffle for calibration of visual estimates. A dominant substrate code was recorded for each channel unit in 1988, and the area of coho spawning gravel (gravels between 16 and 64 mm) was visually estimated (m^2) during both years.

Comments on data forms were recorded to generally characterize the riparian zone and other habitat features such as cover. This information was not intended for rigorous analysis, but to provide map locations, general indications of riparian history, and habitat quality. During the 1988, field season channel stability rating forms were completed for reaches within the surveyed area that had been previously defined in the SFS B.U.M.P. Report (USDA Forest Service, 1978). These data are not presented in this report.

In 1988, the number of pieces of woody debris in each of three size classes was recorded for each channel unit. During the 1989 field season each individual obstruction was enumerated, with woody debris jams of five pieces or more counted as single obstructions. The obstruction type (wood, boulder, bedrock, root-protected bank) and location (channel unit) was noted, and the length and diameter of each obstruction was estimated. Lengths and diameters were measured on obstructions that were functional (plunge, scour, eddy, dam, sediment trap, or debris trap). Orientation, percent of obstruction volume in channel, and percent of channel width blocked were also estimated.

The discharge (Q) was calculated for each stream on the day of the survey using the equation

$$Q = \text{sum}[d_i v_i w_i]$$

where d_i is the water depth at the *i*th location of a velocity measurement, v is the *i*th velocity at 0.6 x depth measured from the surface, and w is the *i*th width of the partial section of the channel width. Velocity and depth were measured with a flow meter at approximately ten equidistant points along a transect. Transects were located in uniform glides when possible to avoid the turbulence of riffles and extreme low velocities in pools.

During 1989, hydraulic geometry data were collected in uniform riffles in each site. Bankfull width was measured to the nearest 0.1 meter and bankfull depths were measured to the nearest centimeter every 0.5 meters along the transect. Particle size diameters were measured on 50 to 100 particles with particles selected systematically along transects from bank to bank. Local gradients were measured with a hand level and level rod and all sightings were doubled (i.e. measured from both the upstream and downstream directions) and averaged. Channel roughness (Manning's *n*) was visually estimated for all low gradient (<2%) sites. In higher gradient sites or sites with large amounts of cobble or boulder, Manning's *n* was calculated from

$$(1 / f^{0.5}) = 2 \log (d/D_{84}) + 1.0 \qquad \text{(Leopold et al., 1964)}$$

and

$$n^2 = (f R^{1/3}) / 8g. \qquad \text{(Richards, 1982).}$$

Where f = Darcy-Weisbach friction factor, d = mean bankfull depth, D_{84} = the particle size of the 84th percentile in the particle size distribution, R = hydraulic radius, and g = acceleration due to gravity (all in SI units). A prediction of the bankfull discharge was calculated by Manning's equation:

$$Q = (A R^{1/3} S^{1/2}) / n$$

where Q = discharge, A = bankfull cross-sectional area, and S = local gradient.

Gradients of segments were surveyed over at least 100 meters of the total segment length with a hand level and level rod. All surveys were completed with closure error less than 5% of the total elevation change. When closure error was greater than 5% of total elevation change the site was resurveyed.

3.4. Visual estimation procedure.

The procedure used in collecting the 1988 habitat data is a modification of those presented by Hankin (1984) and Hankin and Reeves (1988) for estimating fish populations in small streams. These methods employ a two stage sampling design to efficiently estimate the populations of salmonids in small streams. Though the methods were created for the estimation of fish populations, the first stage of the design can be used to estimate habitat areas in streams. These estimation procedures were used only in generating the habitat estimates in Beechie and Sibley (1989). In this case, the second stage component of the variance is not used and the variance equation for each channel unit type is reduced to

$$E(V) = [N^2(N-n)/Nn] * [\mathrm{sum}(Qx_i - m_i) / (n-1)],$$

where N = the total number of estimated units, n = the number of measured units, x = the estimate of unit *i*, m = the measurement of unit *i*, Q = the correction factor for the estimate.

The correction factor is calculated by the equation

$$Q = \mathrm{sum}(m_i)/\mathrm{sum}(x_i).$$

This correction factor is model unbiased if:

1) The relationship between the measured and estimated units is linear and passes through the origin, and

2) The variance increases with increasing primary unit size (Hankin, 1984).

There are no assumptions concerning normal distribution of the data.

3.5 Statistical Analyses.

Paired segment were used for a portion of the data to address the differences between B2 and C3 segment types with a minimum of influence from the variations between streams. The non-parametric Wilcoxon signed rank test (Zar, 1984; p. 153) was employed to test the percentages of pool area and the percentage of channel area in spawning gravel. The two sample Mann-Whitney test (a non-parametric analogue to the paired-sample t-test; Zar, 1984; p. 138) was used for evaluating the percentages of pool area for all B2 and C3 segments in the South Fork Stillaguamish River basin. This test does not minimize the influence of the variability between streams.

Multiple linear regressions and correlation matrices (MINITAB) were used to evaluate the relative importances of several variables in controlling percent pools. We included variables such as gradient, wood volume, stream size (BFQ), and a variety of interaction terms in the analysis.

Cluster analysis (SPSS/PC+ version 2.0) was used to identify groupings of sample segments based on channel unit distributions and controlling variables such as gradient, wood volume, and stream size (bankfull width). Groups were defined on the basis of average between-cluster distances. Discriminant analysis (SPSS/PC+ version 2.0) compares predicted group membership with actual group membership. Actual group membership in this case is the segment type as identified prior to sampling. The predicted group membership is determined by creating linear combinations of predictor variables (discriminant functions) and assigning segments to groups based on these functions. The results of this analysis are a set of discriminant scores which may be plotted graphically to view the groups, and table of predicted group memberships versus actual group memberships with the percentages of segments "correctly classified" (Norusis 1988).

3.6. Study Area.

Study areas used for this project included the 16 reference sites and 26 stream segments were located within the South Fork of the Stillaguamish River basin. An additional 36 segments were sampled in a larger geographic area encompassing the North and South Forks of the Stillaguamish River, the Pilchuck, the Skykomish, and the Snoqualmie River basins (Figure 3.1). These segments were used to evaluate stream segments across watersheds.

Multiple Watershed Sites.

The 36 segments in four major watersheds (hereafter referred to as "multiple watershed sites") are located primarily in the North Cascades ecoregion. The lowland areas in the western part of the study area and the valley bottoms along the major rivers are dominated by glacial-age surficial deposits which include lacustrine clays, outwash sands and gravels, and tills. The eastern part of the study area is located in the Cascade

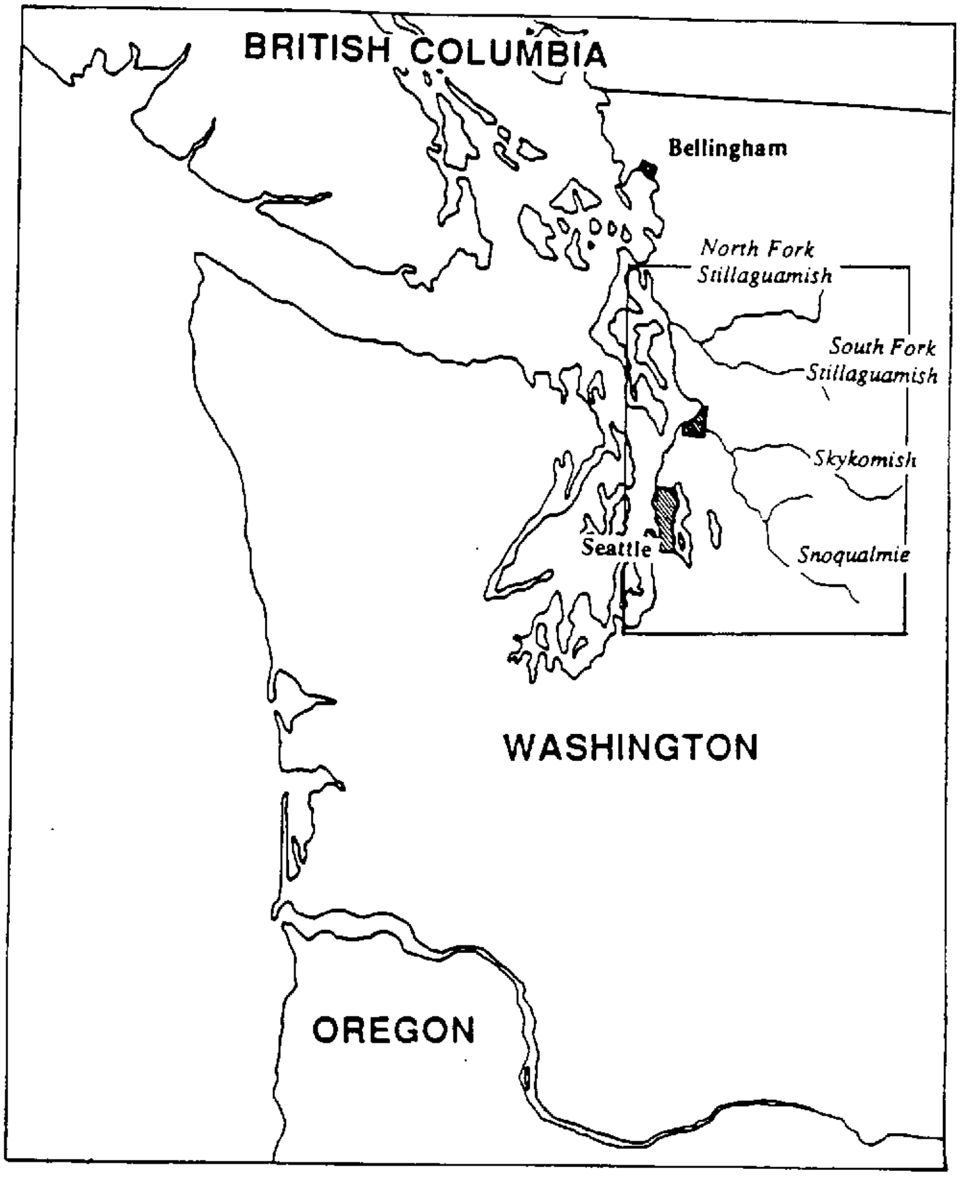


Figure 3.1. Location of the major watersheds in which sample segments are located and of the South Fork Stillaguamish River basin.

Mountains and its foothills. The major rock types in the bedrock portions of the study area include granitic intrusions, andesitic and dacitic volcanics, sandstones, and shales. Major structural features such as the Church Mountain thrust belt, the Weden Creek fault, and numerous fold axes trend NNW-SSE in this part of the Cascades. Foothills areas of the Cascade Mountains also consist of glacial deposits in places (Figure 3.2).

Because we chose to focus on relatively low gradient segment types that provide habitat to anadromous salmonids, few of the sample segments are in bedrock. Many of the segments are located in glacial deposits or alluvial deposits, though the sub-basins in which the segments are located may be dominated by other geologies. The glacial history of the segments varies with location relative to the continental ice sheet that extended through the Puget Lowland approximately 12,000 to 14,000 years ago. Many were buried by the ice sheet whereas others were submerged beneath glacial lakes or located in alpine valleys.

Several vegetation zones occur in the study area, including western hemlock (*Tsuga heterophylla*) in most of the lower elevations and silver fir (*Abies amabilis*) at higher elevations (Figure 3.3). Douglas fir (*Pseudotsuga menziesii*), sitka spruce (*Picea sitchensis*) and western red cedar (*Thuja plicata*) also occur throughout the lower elevations of the study area. Deciduous species found in the study area include red alder (*Alnus rubra*), bigleaf maple (*Acer grandifolium*), vine maple (*Acer circinatum*), cottonwood (*Populus trichocarpa*), and willow (*Salix* spp.).

<u>South Fork Stillaguamish River Basin.</u>

The study basin, located on the western slopes of the Cascade Mountains near Granite Falls, Washington, is approximately 260 km^2 in area. Elevations range from 300 m at Verlot to over 1800 m in the headwaters area. Average annual precipitation is approximately 300 cm at Verlot and 450 cm on the higher peaks.

The bedrock geology of the basin is dominated by pre-Jurassic and Jurassic metamorphic rocks to the west of Silverton, and by Tertiary sedimentary and volcanic rocks to the east of Silverton and Big Four Mountain (Fig 3.4). Several granitic intrusions form peaks at the basin boundaries (Wiebe, 1964; Heath, 1971). Faulting and folding trends in the basin are generally oriented NNW-SSE. The orientation of the upper basin is apparently controlled by the Weden Creek Fault and, to a lesser extent, the synclinal axis in the headwaters area near Del Campo Peak.

The oldest and most heavily metamorphosed rocks are those of the Chilliwack Group (pre-Jurassic), which consists of metamorphosed argillite, ribbon chert, volcanic graywacke, and marble. These rocks, along with the ultramafic rocks of the Church Mountain Thrust imbrication zone (Dungan, 1974), confine the narrowest portion of the South ork Stillaguamish valley between Sawyer Camp and Deer Creek Camp. The Chilliwack Group is bounded by the Church Mountain Thrust contact with the Nooksack Group to the west, and by a fault contact with the Swauk Formation to the east.

The Nooksack Group (Jurassic) consists of slate, slatey conglomerate, and volcanic graywacke. These rocks underlie most of the western part of the study area. The Church Mountain Thrust imbrication zone forms the eastern boundary of the Nooksack Group, where the older rocks of the Chilliwack group have been driven up and over the younger Nooksack rocks. This group defines the lower zone of the main stem SFS from Verlot to Sawyer Camp.

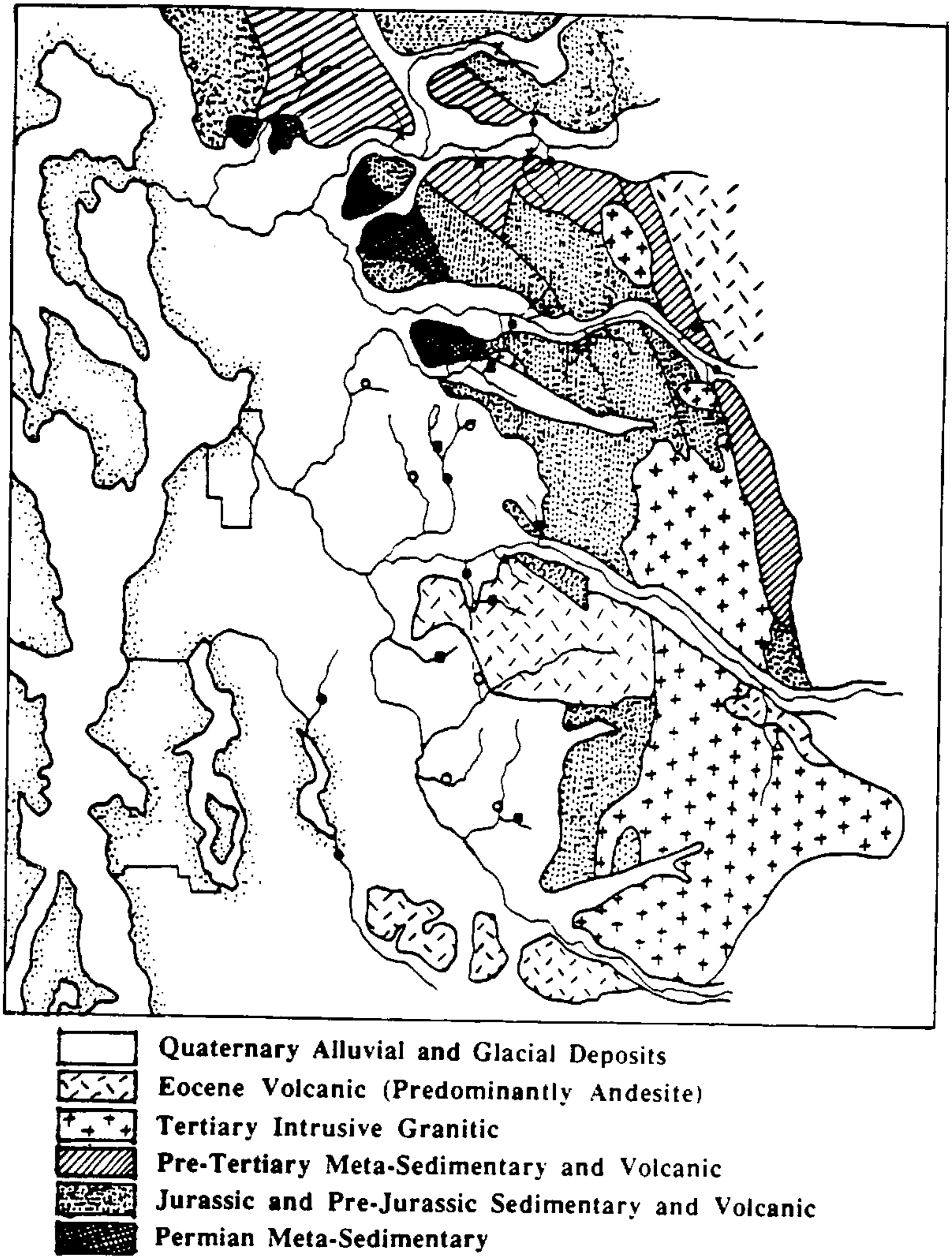


Figure 3.2. Generalized geologic map of the study area in which 36 multiple watershed sites are located.

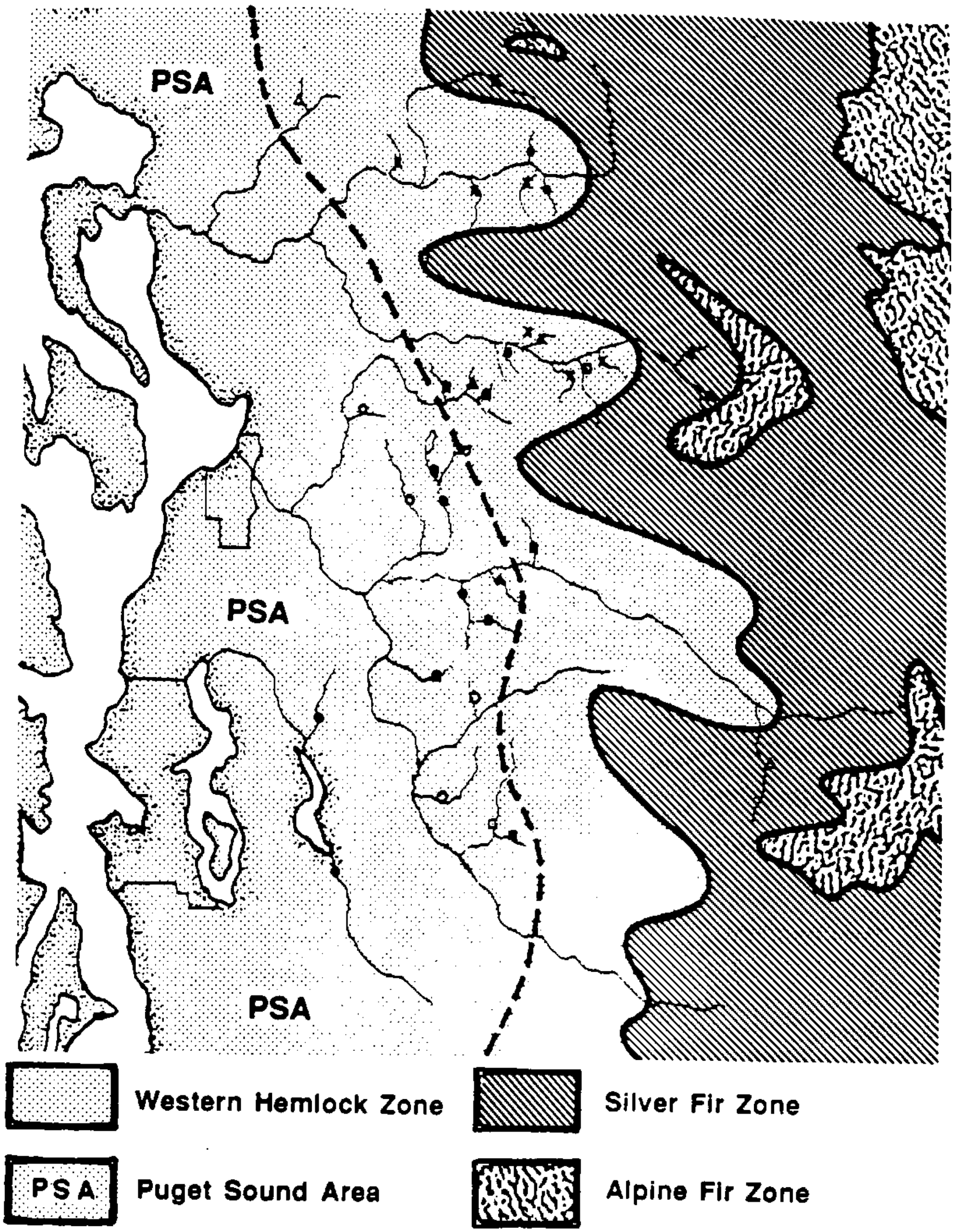


Figure 3.3. Generalized map of vegetation zones for the study area in which 36 multiple watershed sites are located.

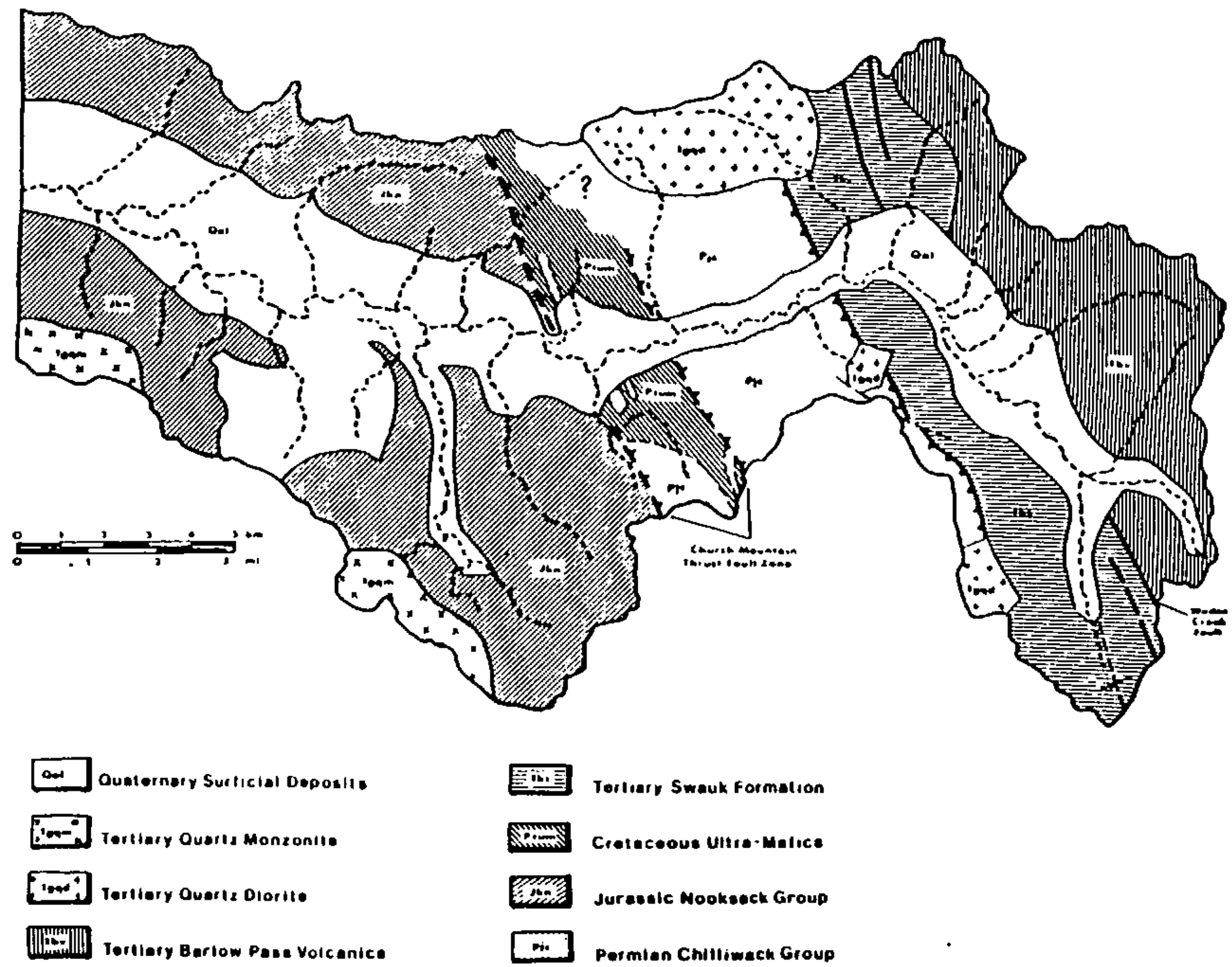


Figure 3.4. Generalized geologic map of the South Fork Stillaguamish River basin. (Adapted from Wiebe 1964, Dungan 1974, and Heath 1971).

The Swauk Formation (Tertiary) and the Barlow Pass Volcanics (Tertiary) characterize the eastern part of the basin upstream of Deer Creek Camp. The Swauk Formation consists of massive conglomerate, arkosic sandstone, and dark siltstone. It is bounded by fault contacts to the east and west. The Barlow Pass Volcanics consist of rhyolite, andesite, and basalt, with interbedded sandstones and breccias. The fault contact with the Swauk Formation is mapped at the northern and southern ends of the upper basin, and is inferred to continue beneath the surficial deposits.

The quaternary surficial deposits are dominated by lacustrine clays deposited during the most recent continental glaciation of the North Cascades (approximately 15,000 years B.P.). Outwash sands are less extensive but control the morphology of some streams in the SFS basin. The major deposit of outwash sands is found between Benson and Wiley Creeks. Smaller areas of talus and alluvial debris fans are also found within the valley. A more complete assessment of the surficial geology can be found in Benda and Johnson (1989).

Two vegetation zones dominate the valley. The western Hemlock zone covers most of the lower elevations. This zone consists mostly of western hemlock (*Tsuga heterophylla*) with Douglas fir (*Pseudotsuga menzeisii*), sitka spruce (*Picea sitchensis*), and western red cedar (*Thuga plicata*). Red alder (*Alnus rubra*) is found in most of the riparian zones and on unstable glacial deposits. The higher elevations comprise the silver fir zone. This zone consists largely of silver fir (*Abies amabilis*) with some sitka spruce (*Picea sitchensis*) and grand fir (*Abies grandis*).

During the late 1800's and early 1900's, logging and mining were the principal activities in the basin. Mining operations were centered around Silverton, and logging operations appear to have been limited to elevations under 550 meters (1800 feet) throughout the basin. A railroad ran the length of the valley to the mining town of Monte Cristo via Barlow Pass. Logging operations since the 1950's have been distributed throughout the basin at all elevations.

Historically, the upper 56 km of the SFS river were inaccessible to anadromous stocks due to the natural barrier at Granite Falls. Access was permitted by the construction of a fish ladder in 1954. Since then, coho salmon (*Oncorhynchus kisutch*), chinook salmon (*O. tshawytscha*), pink salmon (*O. gorbuscha*), and steelhead trout (*O. mykiss*) have been introduced by hatchery releases above the falls. As of the late 1970's, coho and steelhead are the only well-established anadromous salmonids above the falls (South Fork Stillaguamish B.U.M.P., 1978). Since 1988, chinook fry have been released near Silverton in an effort to increase the chinook salmon runs above the falls. Resident species include cutthroat (*O.clarkii*) and rainbow trout (*O. mykiss*).

From 1973 to 1976, an emergency trapping and hauling project found chinook escapement above Granite Falls to be less than 100 fish per year, though spawning gravels have been estimated to be available for nearly 10,000 pairs of spring and fall chinook (South Fork Stillaguamish B.U.M.P., 1978). Coho escapement above Granite Falls in 1975 was 2,578 spawners, but escapements in the entire Stillaguamish system were low in 1975. It has been estimated that over 3,500 coho may be expected in a good escapement year. Less than 100 pink salmon were counted above the falls during the trapping and hauling project in 1975. The potential escapement for pink salmon has been estimated at 2,000 spawners (SFS B.U.M.P., 1978). Only two chum salmon (*O. keta*) were handled in each of the trapping and hauling projects of 1974 and 1975. Steelhead smolts were planted annually at levels ranging from 2,900 winter-run smolts in 1960 to

22,000 winter-run and 12,000 summer-run smolts in 1977.

Sample Segment Locations.

Locations of individual sample segments and reference sites in the South Fork of the Stillaguamish River basin are shown in Figure 3.5. Sample segments in the larger geographic area (multiple watershed sites) are shown in figure 3.6.

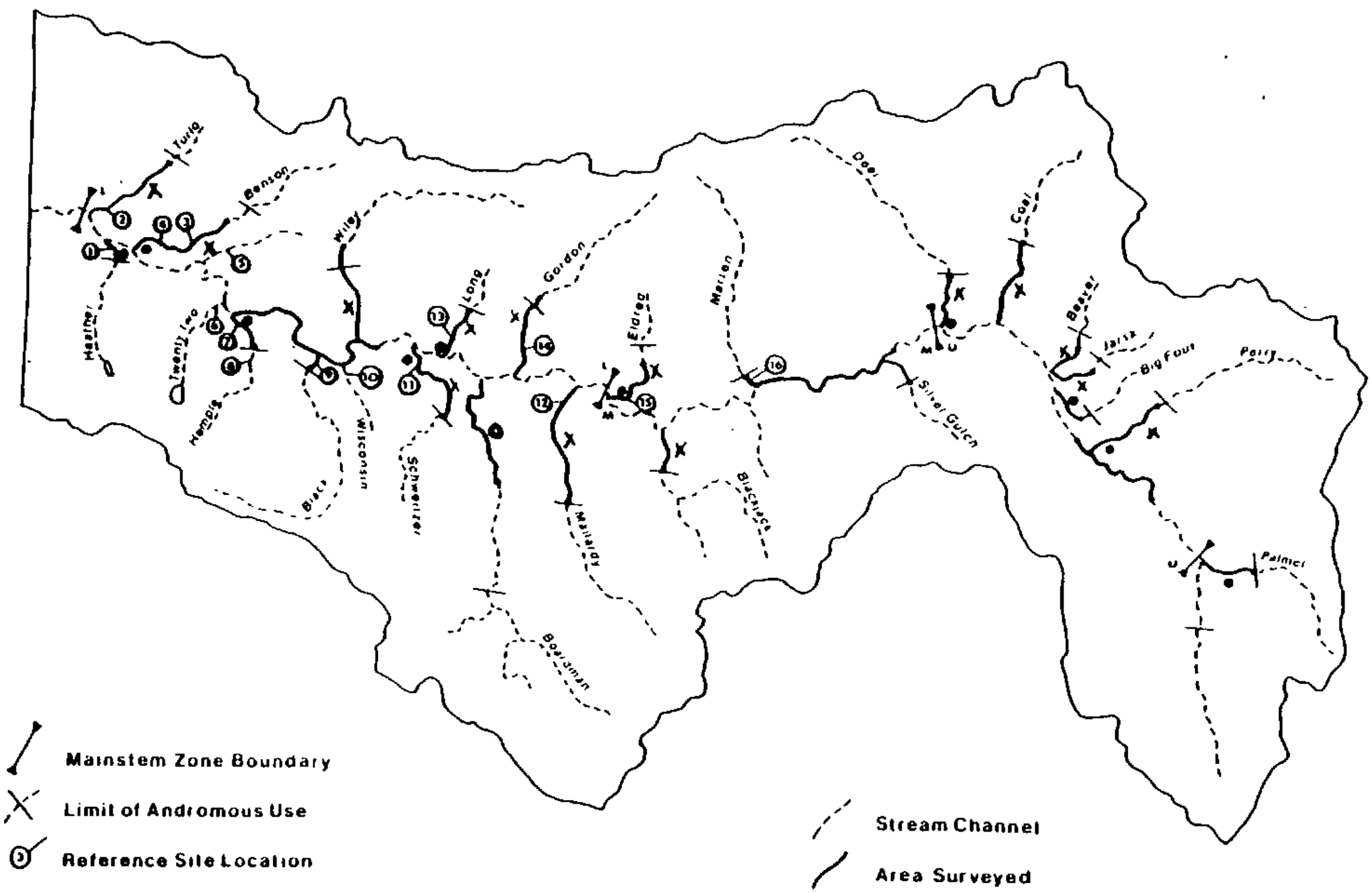


Figure 3.5. Locations of sample segments and reference sites in the South Fork Stillaguamish River basin. ● = B2, x = C3, o = C4.

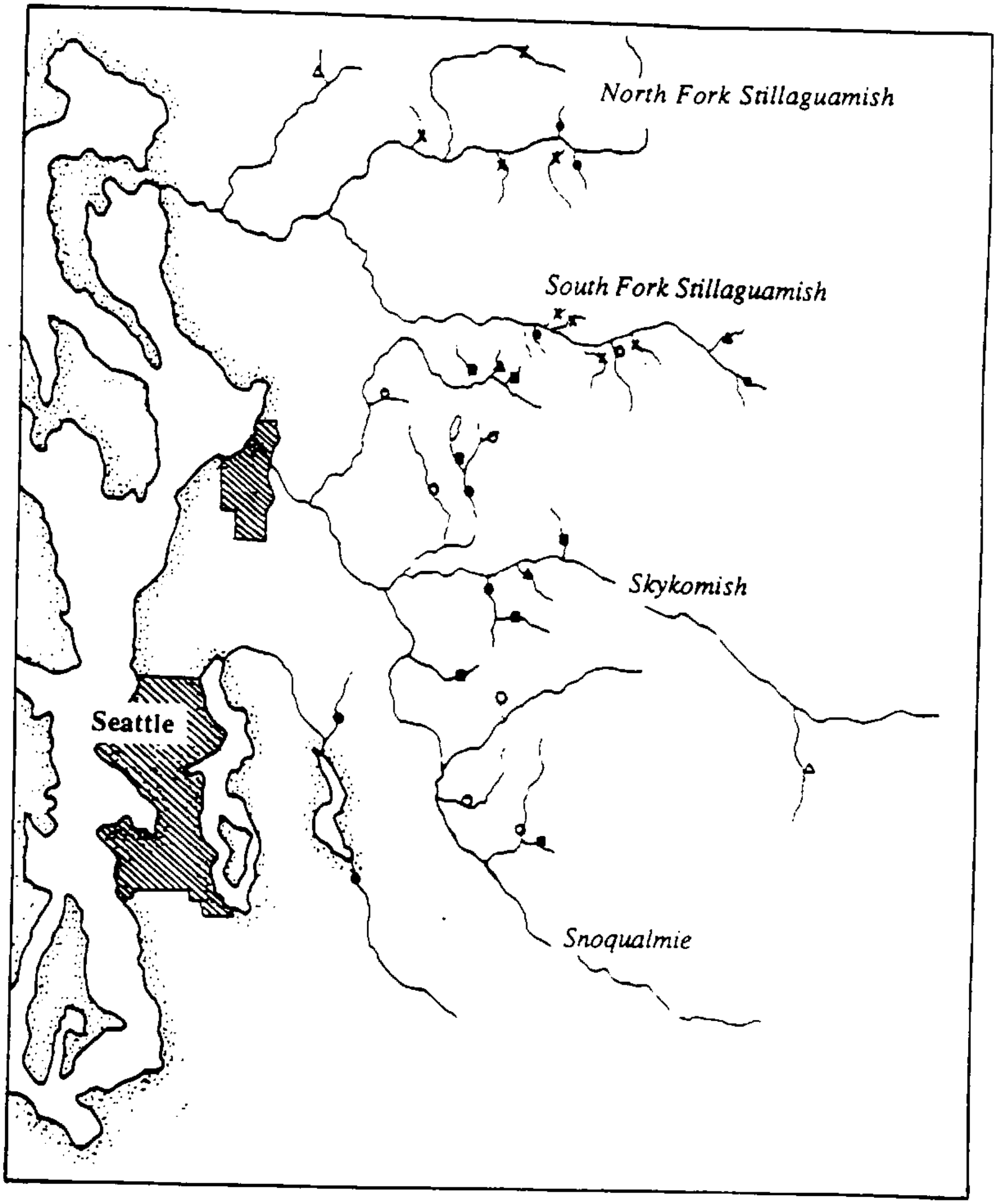


Figure 3.6. Locations of multiple watershed sites. ● = B2, ■ = C2, X = C3, O = C4, ▲ = G, Δ = E.

4. RESULTS AND DISCUSSION.

The following sections present the results of each of the three sampling routines. Because each of the data sets is intended to address specific elements of the variability in streams, the data sets are analyzed individually.

4.1. Reference Sites.

The reference sites were established prior to the choice of a classification scheme by the TFW-AMSC. Therefore, sites were chosen to represent a range of gradients and quantities of organic debris. Sites were later classified according to the proposed guidelines.

The reference site sampling was intended to address the variability of habitat surface areas within sites as a function of discharge. However, these data are also used to address sources of variability in habitat surface areas between sites as a function of geomorphic variables (obstruction volume, gradient, sediment size, bankfull discharge, etc.). Because these sites are not randomly chosen within the segment types B2, C3, and G, these data are not used to statistically evaluate the differences between segment types.

Obstruction data from the reference sites indicate that enumerating and classifying obstructions is most accurately accomplished at low discharges. At higher discharges most small pieces are either missed or classified as non-functional when in fact they may trap sediment or cause scouring of the bed. The following analyses use obstruction counts from summer low discharges only.

Summary of site characteristics.

Geomorphic data for the reference sites are summarized in Table 4.1. Obstruction volumes for each site are summarized by type and association in Table 4.2. Data for individual sites are listed in Appendix A.

Table 4.1. Summary of geomorphic characteristics of reference sites in the South Fork Stillaguamish River basin. BFW = bankfull width, D_{50} = median particle size of armor layer, Q = discharge.

Site	Length	Drainage Area	Gradient	BFW	D_{50}	Predicted Bankfull Discharge
	(meters)	(km^2)	(%)	(m)	(mm)	(m^3/s^{-1})
B2 Sites						
1	92.0	3.6	0.9	6.4	30	3.65
4	107.3	4.9	1.4	7.3	29	3.13
7	105.3	4.0	1.7	6.2	57	1.32
11	93.4	4.8	0.9	6.6	22	3.56
15	110.7	3.9	1.5	5.7	23	1.34
mean			1.3	6.4	32	
C3 Sites						
2	107.3	6.9	3.2	5.5	16	1.50
3	111.4	4.6	2.2	7.4	49	5.48
12	106.7	9.9	2.8	16.2	118	5.64
13	101.9	0.9	3.3	4.6	43	1.26
14	108.7	7.8	3.2	10.4	103	6.45
mean			3.0	8.8	66	
G Sites						
5	103.4	3.2	8.8	7.2	21	4.17
6	83.4	4.1	16.0	8.8	260	12.59
8	110.7	3.7	8.5	7.8	130	5.36
9	103.0	13.1	5.3	19.9	300	17.54
10	102.4	1.2	23.0	7.7	73	2.85
16	99.5	8.6	8.5	13.0	150	23.07
mean			11.7	10.7	156	

Table 4.2 Summary of obstruction volumes for individual reference sites. Volume indices are expressed in m^3 of obstruction per m^2 of channel area. Banks refers to resistant banks (bedrock, large cobble, root protected, etc.) and is expressed as a percentage of the total length of channel edge. The total length of channel edge in a site is assumed to be twice the total length of the site.

	Volume Index ($m^3m^{-2} \times 10^3$)					Length (%)
	Organic Debris				Boulders	Banks
Site	Single	Clump	Jam	Total		
B2 Sites						
1	12.9	9.8	0.0	22.8	0.0	9.0
4	0.1	2.2	56.1	58.4	0.0	9.6
7	3.2	2.1	0.0	5.4	0.0	7.1
11	11.2	8.6	12.7	32.5	0.0	2.9
15	5.4	1.1	59.7	66.2	0.0	14.2
mean				37.1	0.0	8.6
C3 Sites						
2	7.5	4.1	124.4	135.9	0.3	1.9
3	2.9	0.8	0.6	4.4	0.1	0.0
12	1.0	1.4	71.1	73.6	3.4	0.9
13	2.8	10.0	0.0	12.8	0.0	2.5
14	1.6	0.1	33.2	24.9	0.4	7.6
mean				50.3	0.8	2.6
G Sites						
5	16.1	19.6	344.0	379.7	5.4	0.0
6	2.5	2.9	127.8	133.1	40.9	3.0
8	1.4	5.8	75.2	82.4	12.6	2.0
9	0.5	0.3	5.2	6.0	1.0	3.4
10	15.7	6.1	111.5	133.4	21.6	2.0
16	4.9	2.4	71.8	79.1	39.8	3.0
mean				162.7	20.2	2.2

Variation in channel unit areas with changes in discharge.

In all reference sites, the percentage of the total water surface area identified as pools generally decreases with increasing discharge (Figures 4.1-4.3). Exceptions occur in three sites (3, 4, and 7). In sites 3 and 7, obstructions near the edges of the bankfull channel do not affect the flow of water until the discharge rises to approximately 20% of the predicted bankfull discharge. In site 4, no units were identified at summer low flow because the flow was sub-surface (i.e intra-gravel) throughout the site. However, site 3, which is located approximately 700 meters upstream of site 4, maintained surface flow throughout the summer.

The true surface area (m^2) of pools also decreases with increasing discharge (Figures 4.4-4.6). Exceptions to this trend occur at different flow levels in sites 3, 4, 7, 11, and 12. Though the average area of pools in B2 segments is 3 to 4 times higher than the average area of pools in C3 segments, there are no clear differences in the patterns of change in pool area with changes in discharge. That is, the largest incremental changes in pool area occur at low discharges in both B2 and C3 types.

Changes in the discharge also influence the position of pools in the channel. Of the total pool area in each reference site, the percentage of pools located along the edges of channels increases with increasing discharge. In the 11 sites surveyed at high discharge, 36 of the 39 (92%) pools located near the edges of channels were created by in-channel obstructions (LOD or boulders).

Examination of the data for individual sites (Appendix A) indicates that most units identified as pools at low discharges are identified as glides at higher discharges. The unusually large increases in glide surface areas in sites 1 and 11 are a result of the low gradients (<1%) of these sites. Riffle units in these sites are very small at summer low flow. Short, low-relief riffles in these sites are absorbed into adjacent glides and hydraulic scour pools as discharges increase.

Hydraulic scour pools disappear most rapidly with relatively small increases in discharge. The velocities in hydraulic scour pools appear to increase rapidly with increases in discharge because the pools are shallow and are not associated with obstructions that hinder the flow of water through the unit. At higher discharges, hydraulic scour pools were always identified as glides.

The changes in the relative proportions of channel unit areas with changes in discharge agree with the changes in usable habitat area noted by Sullivan (1986). The decrease in total pool area as discharge increased was partially compensated by the increase in total water surface area in the reference sites. Nevertheless, the pool area decreased with increasing discharge in all cases.

These results suggest that the timing of stream surveys will affect the observed distribution of channel units. This seasonal and within-season variability will alter the interpretation of evaluation data when care is not taken to minimize the effects of changes in discharge on sampling results. Therefore, it is important that individual segment types not be sampled in temporal blocks (e.g. all C3 types first, all B2 types next, etc.), which may result biased measures of channel unit distributions. Sampling methods that may be used to control this variability include restricting stream surveys to standard flow periods (e.g. summer base flow or summer low flow), and randomizing or sequencing the sampling of various segment types.

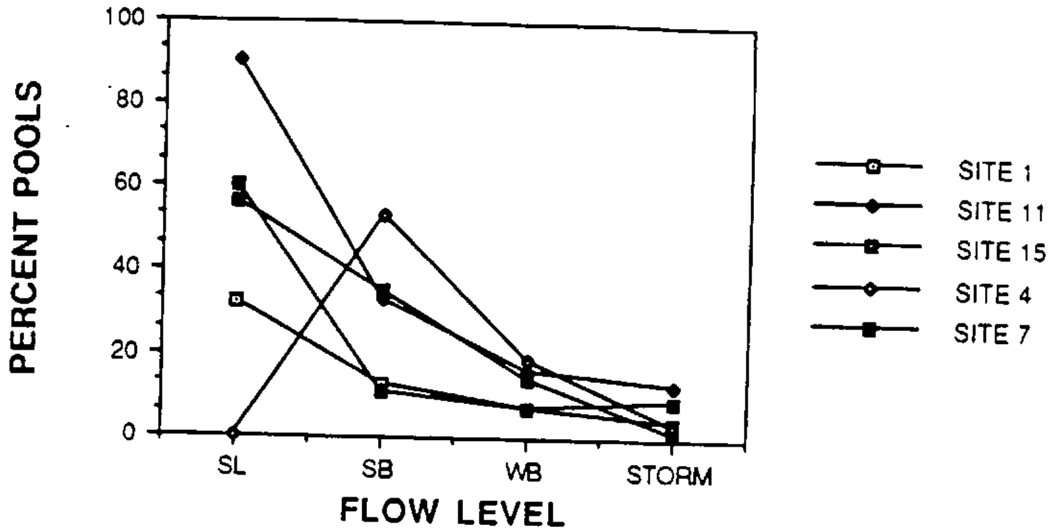


Figure 4.1. Percentages of pool area at different flow levels in low-gradient (B2) reference sites in the South Fork Stillaguamish River basin. SL = Summer Low Flow, SB = Summer Base Flow, WB = Winter Base Flow, STORM = Storm Flow, after Sullivan (1986).

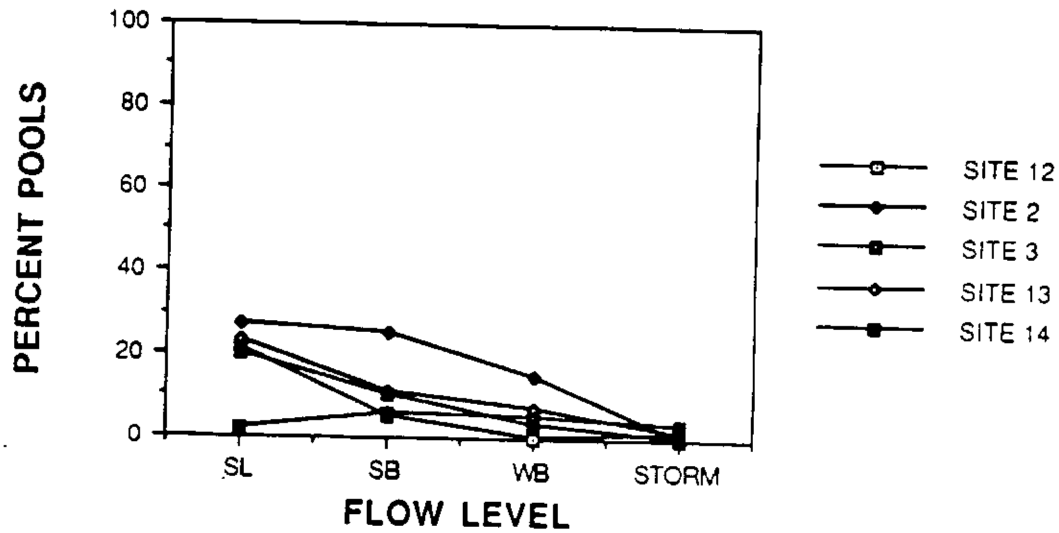


Figure 4.2. Percentages of pool area at different flow levels in moderate-gradient (C3) reference sites in the South Fork Stillaguamish River basin. SL = Summer Low Flow, SB = Summer Base Flow, WB = Winter Base Flow, STORM = Storm Flow, after Sullivan (1986).

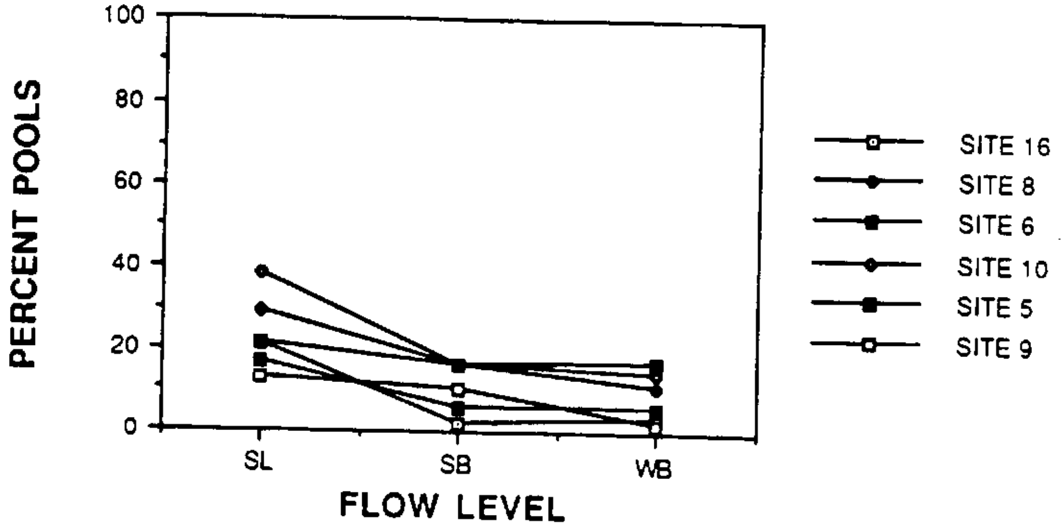


Figure 4.3. Percentages of pool area at different flow levels in high-gradient (G) reference sites in the South Fork Stillaguamish River basin. SL = Summer Low Flow, SB = Summer Base Flow, WB = Winter Base Flow, STORM = Storm Flow, after Sullivan (1986).

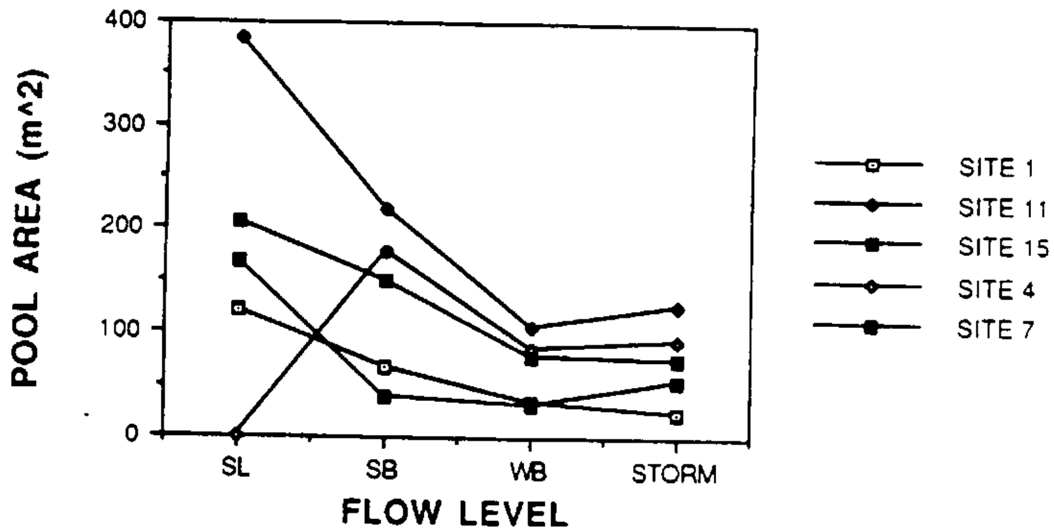


Figure 4.4. Total surface areas of pools at different flow levels in low-gradient (B2) reference sites in the South Fork Stillaguamish River basin. SL = Summer Low Flow, SB = Summer Base Flow, WB = Winter Base Flow, STORM = Storm Flow, after Sullivan (1986).

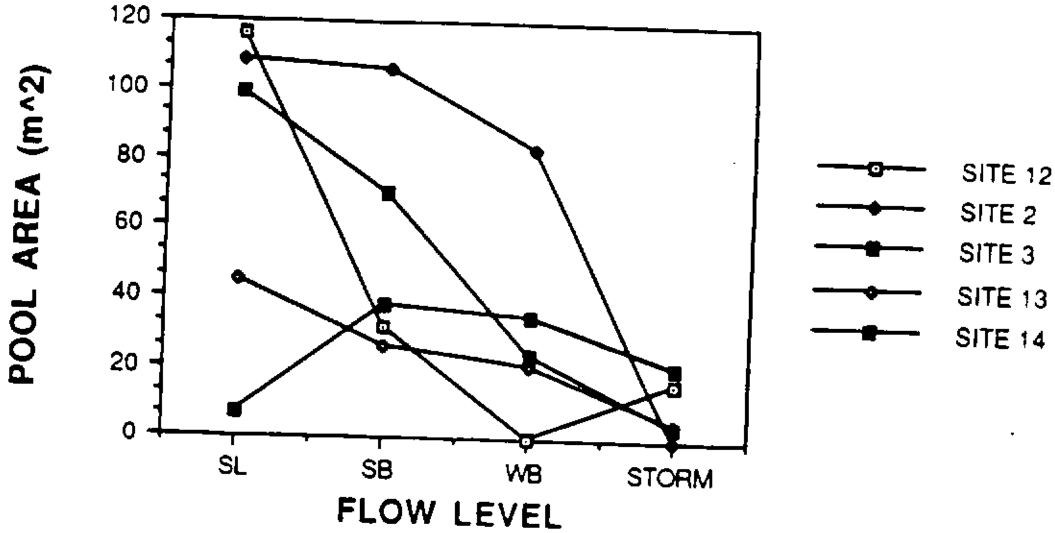


Figure 4.5. Total surface areas of pools at different flow levels in moderate-gradient (C3) reference sites in the South Fork Stillaguamish River basin. SL = Summer Low Flow, SB = Summer Base Flow, WB = Winter Base Flow, STORM = Storm Flow, after Sullivan (1986).

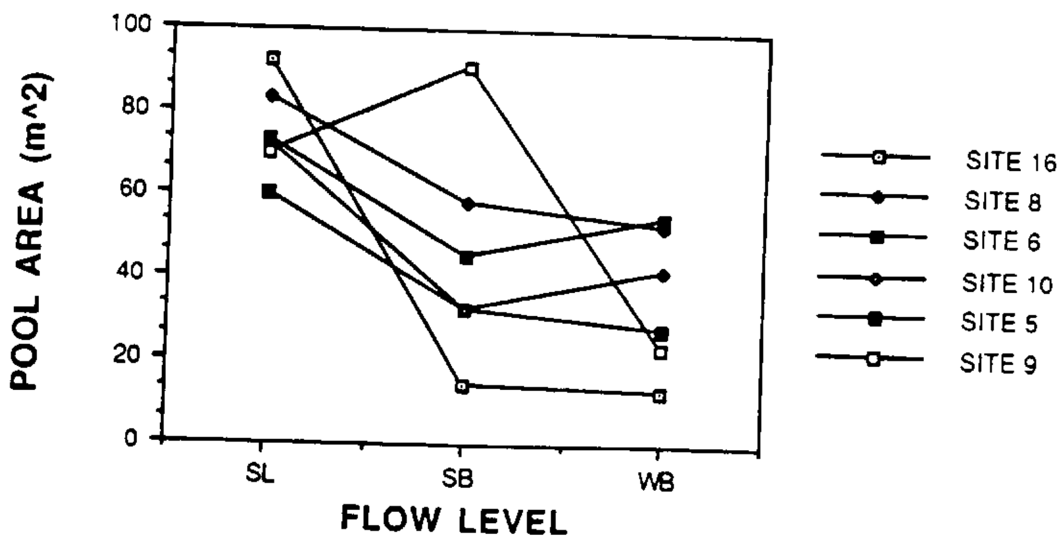


Figure 4.6. Total surface areas of pools at different flow levels in high-gradient (G) reference sites in the South Fork Stillaguamish River basin. SL = Summer Low Flow, SB = Summer Base Flow, WB = Winter Base Flow, STORM = Storm Flow, after Sullivan (1986).

Notable exceptions to these trends are attributable to recent disturbances in some streams. In particular, the subsurface flow in lower Benson Creek (Site 4) is likely a result of an increased sediment load from several recent landslides and at least one dam-break flood in the watershed. In others such as upper Benson Creek (Site 3), the lack of woody debris in the main channel from the dam-break flood may account for the lack of scouring and the low areas of pools in the main channel. The woody debris that remains in Site 3 is at the channel edges and in a side channel, resulting in an increase in pool area as the discharge increases. A similar effect is found in lower Hemple Creek (Site 7) where several paired deflectors are located at the edges of a straight section of the channel.

Relative importance of several physical factors in predicting the percentage of summer pools.

Multiple linear regression analysis was used to evaluate the relative importance of different sources of variability in pool areas between sites. Sites with gradients higher than 4% were not included in this analysis because the physical relationships among these variables may not be consistent at higher gradients. That is, at higher gradients much of the transport of particles in the stream may be due to gravity rather than the basal shear stress created by flowing water. The dependent variable is the percentage of pools, which is expressed as

$$\text{Percentage pools} = (AREA_{pools}) / (AREA_{total}) * 100$$

where $AREA_{pools}$ is the surface area of all pools in the site, and $AREA_{total}$ is the total water surface area of the site. Independent variables were gradient (GRAD), bankfull discharge (BFQ, m^3s^{-1}), summer low discharge (SLQ, m^3s^{-1}), index of wood volume per unit area (WOOD, expressed here as $kg{\cdot}m^{-2}$, where the density of wood is assumed to be 0.5 $g{\cdot}cm^{-3}$, USDA Forest Service 1974), and median sediment size (D_{50}, mm). We expected an interaction effect between gradient and wood volume, which would result in a decreased influence of wood on the area of pools as gradient increased. This interaction was expressed as

"GR/WD" = GRAD / WOOD.

Because the "independent" variables were chosen based on expected physical relationships between the formation of pools and geomorphic controlling variables, the initial regression employed all six variables. Though this regression explained 70% of the variability in pool area between sites (adjusted $r^2 = 0.703$, $P = 0.121$), three variables (WOOD, D_{50}, and BFQ) contributed little to the sums of squares. Omission of these three variables resulted in the following regression equation (adjusted $r^2 = 0.830$, $P = 0.003$):

$$\text{POOLS} = 104 - 1540(\text{GRAD}) - 7.6(\text{GR/WD}) - 457(\text{SLQ}).$$

A stepwise regression resulted in the same equation.

A correlation matrix (Table 4.3) shows that BFQ, D_{50}, and WOOD are highly correlated with other variables. The variable D_{50} is highly correlated with BFQ as expected from relationships between discharge and the sediment transport capacity of streams. Similarly, SLQ is highly correlated with BFQ because both are a function of the drainage basin area. The correlation between WOOD and GRAD appears to be at least

Table 4.3 Correlation matrix of "independent" variables that influence the percentage pools at summer low flow.

	POOLS	GRAD	GR/WD	SLQ	BFQ	D50	WOOD
POOLS	1.000						
GRAD	-0.676	1.000					
GR/WD	-0.414	**0.094**[a]	1.000				
SLQ	-0.482	**0.030**[a]	**-0.300**[a]	1.000			
BFQ	-0.421	0.255	0.069	**0.568**[b]	1.000		
D50	-0.438	0.385	0.111	0.336	**0.773**[b]	1.000	
WOOD	-0.018	**0.600**[b]	-0.481	0.216	-0.190	0.010	1.000

a. Low correlation coefficients between GRAD and GR/WD, GRAD and SLQ, and GR/WD and SLQ, which are the variables in the best-fit equation for the reference sites.

b. High correlation coefficients between SLQ and BFQ, GRAD and WOOD, and D50 and BFQ, which are the untransformed variables entered into the step-wise regression of the data for the Multiple Watershed Sites.

partially an artifact of the recent management history in the reference sites. Because of the correlation between these pairs of variables, only one from each pair should be used in a regression analysis.

The above regression results suggest that gradient, the interaction between wood and gradient, and summer low discharge are the dominant controls on the percentage pools in channels. However, the three variables that produce this good correlation (GRAD, GR/WD, and SLQ) may be an artifact of the small sample size (n = 10) or may be surrogates for more physically important parameters. Though these three variables are expected to influence the percentage of pool space in a reach, it is surprising that they produce such a high r^2 (83%), are *linearly* correlated, and preclude the expected importance of BFQ. These results should not be extrapolated to other streams.

Alternatively, the short length of the sample sites may reduce the spatial variability in the independent variables that would be found along longer reaches of the channel, resulting in a better understanding of the relationships between the independent variables and the proportion of pool space. Values of independent factors such as gradient, wood volume, and substrate size are relatively consistent over the 100 meter sample sites. Hence, the regression analysis may more clearly represent the relationships between the independent variables.

Similar regressions are evaluated in Section 4.3 (Results and Discussion: Multiple Watershed Sites) using a larger sample of longer segments of streams. Those regressions suggests that $(GRAD)^{0.5}$, $(WD/GR)^{0.5}$, and BFQ determine the percentage of pools in a channel. Applying this regression model to the 10 reference sites analyzed above yields the equation (adjusted $r^2 = 0.425$, $P = 0.104$):

$$POOLS = 103 - 437(GRAD)^{0.5} + 7.7(WD/GR)^{0.5} - 4.10(BFQ).$$

The variables in the above equation show the expected non-linear relationships between pools, gradient and wood, and the expected positive and negative relationships with pools. Because this equation more closely expresses the anticipated relationships between the independent variables and percentage of pool space, it appears that the high correlation observed in the first regression is an artifact of the small sample size.

Discharge-area relationships.

The discharge-area relationships for the reference sites suggest that the hydrology of individual segments (especially B2 types in this case) is influenced by the upstream structure of the basin, the geology underlying the reach, and the past history of distrurbance in the reach. Though these results are not conclusive when considered separately, the findings are supported by similar results shown in Sections 4.2 and 4.3.

Figure 4.7 considers the relationships between discharge and the drainage area of the watershed. It suggests that the drainage basins upstream of sites 1 and 6 are distinctly different from the others. Site 1 (B2 type) and Site 6 (G2 type) have summer low discharges 5 and 9 times higher, respectively, than three other tributaries with similar drainage areas. Both of these tributaries originate in cirque lakes at an elevation of approximately 740 meters on the north side of Mount Pilchuck. Later snow-melt on the north side of the mountain and runoff storage in the headwater lakes probably account for the differences in discharge when the streams were sampled in mid-summer.

In contrast, the discharges in Site 4 and Site 6 (both B2 types) are unusually low in mid-August. The discharge of Site 6 was less than half that of sites with smaller drainage areas, and the discharge of the Site 4 site was zero. Both of these sites are in sandy outwash deposits (Benda et al,. In press), whereas most of the other sites are underlain by relatively impermeable lacustrine clay deposits or bedrock. Additionally, the Site 4 appears to have aggraded as a result of several landslides that have occurred in the headwaters since 1980. Prior to 1980 this reach maintained surface flow throughout the summer (D. Somers, Tulalip Fisheries, personal communication).

Figure 4.8 shows the discharge area relationship for the five B2 reference sites. It is clear that summer low discharge in these segments is only partially controlled by drainage area. The resultant effects on the distribution of summer rearing habitats may be significant because the largest changes in the distribution of summer rearing habitats occur near the low end of the discharge range (Figures 4.1-4.3).

These data also suggest that some B2 segments may be susceptible to aggradation because of their location downstream of steeper headwater channels. Severe aggradation may result in a loss of rearing space if the stream flows sub-surface at low discharge (e.g. Site 4). The potential of any particular B2 segment to to become aggraded will depend on upstream sources of sediment (e.g. landslides) and the processes necessary to transport sediment to the B2 segment (e.g. large runoff floods or dam-break floods). Hence, the position of the B2 segment in a watershed will influence its habitat potential and the degree to which upstream management will affect the segment.

Large organic debris as obstructions.

The previous discussion of factors controlling pool space in segments suggested

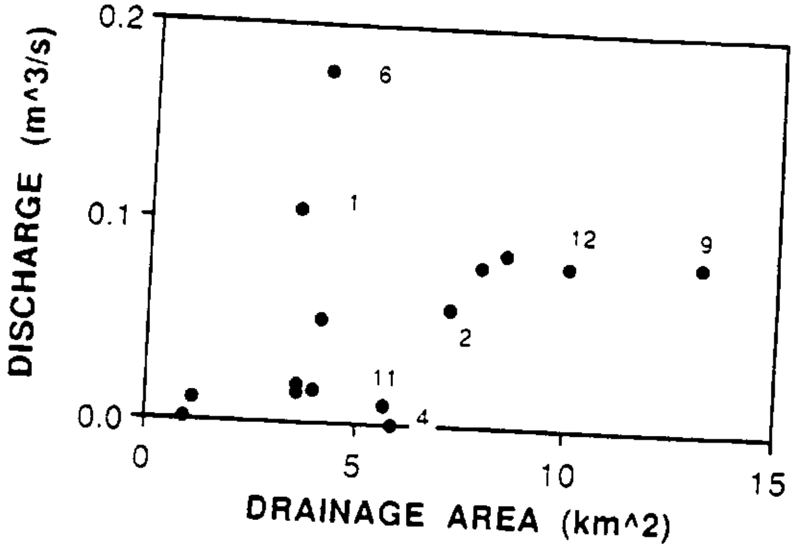


Figure 4.7. Discharge-area relationship for South Fork Stillaguamish reference sites at summer low flow. Labels = Reference Site numbers.

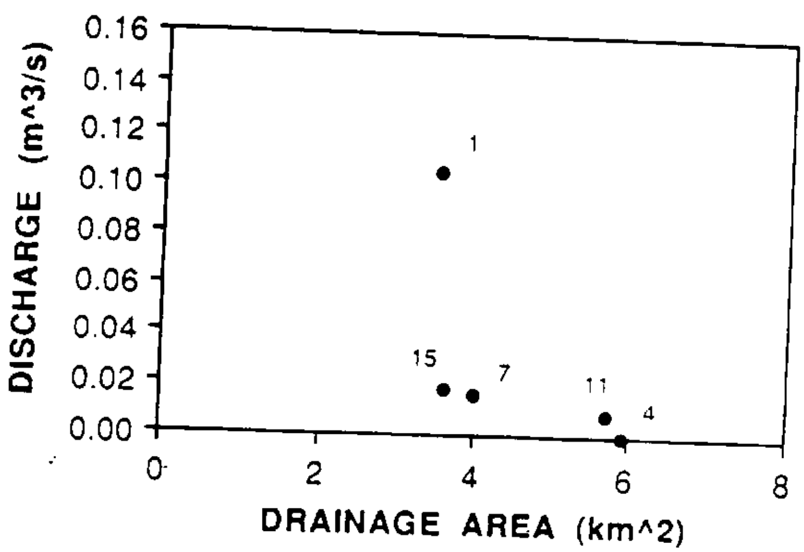


Figure 4.8. Discharge-area relationship at summer low flow for B2 segment reference sites in the South Fork Stillaguamish River basin. Labels = Reference Site numbers.

that the volume of wood obstructions in the channel contributes significantly to pool formation in streams (see also Bisson et al. 1987). Because of the interaction with gradient, a similar volume of wood obstructions in a higher gradient segment type (e.g. C3, 2%-4% gradient) is expected to have less influence on pool space than in a lower gradient segment (e.g. B2, 0%-2% gradient).

Obstruction volumes for all 16 reference sites indicate that wood constitutes the highest proportion of the possible in-channel obstruction types (boulder, wood, bedrock) (Table 4.4). In B2 and C3 sites, wood obstructions constitute over 95% of the total volume of obstructions in each site (range = 95.6% to 100%) regardless of the magnitude of the wood volume. In G sites, wood constitutes a lesser proportion of the total volume (range = 67% to 99%), but remains the major component of obstruction volume in the sites.

In low gradient sites the mean diameter of functional woody debris was not clearly related to either stream size or stream power. However, the range of bankfull widths of the B2 reference sites was small (5.7 to 7.3 m). In some sites (e.g. Heather Creek, Figure 4.9) the median diameter of debris pieces that were functional was clearly different from the median diameter of all pieces in the site. In the five low gradient sites combined, less than 30% of the pieces of woody debris that are smaller than 40 cm in diameter are functional, whereas more than 50% of the pieces of woody debris greater than 40 cm in diameter are functional (Figure 4.10).

4.2. South Fork Stillaguamish River Basin Sites.

The upper portion of the South Fork Stillaguamish River Basin is a small basin (260 km^2) relative to other major watersheds in the Western Cascades. This portion of the Stillaguamish River watershed, though geologically complex, is relatively simple in its large scale geomorphic structure. The valley is generally narrow with little flood plain for low gradient tributary development and can be broadly stratified into three zones (Beechie and Sibley 1989, Benda et al. 1990). Because of the small size and simple structure, the total number of different segment types in the basin is small. The types that are used by anadromous salmonids are dominantly B2 and C3 types with a few B3 and C4 segments also present.

Table 4.4. Percentages of total in-channel obstruction volume due to wood. Other components of total volume are boulder and bedrock.

Segment Type	Mean Percent of Total Volume	St. Dev.	Range	Sample Size
B2	100.0%	0.0%	100% - 100%	5
C3	98.3%	1.8%	95.6% - 100%	5
G	83.3%	10.8%	66.5% - 98.5%	6

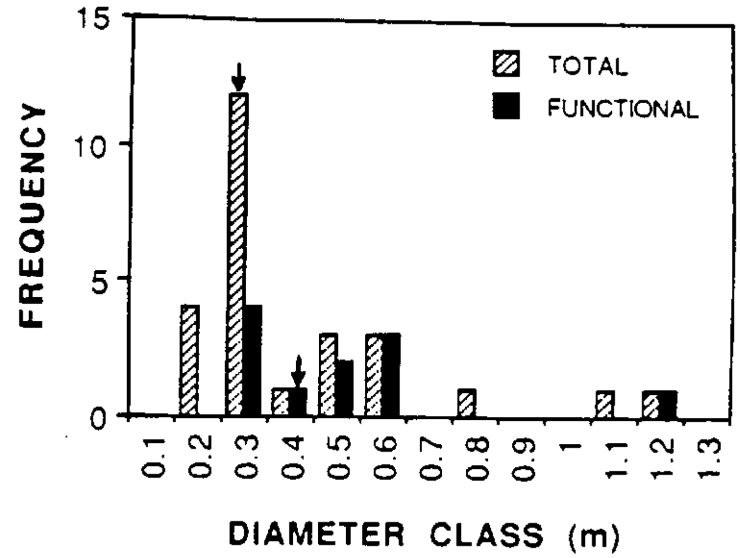


Figure 4.9. Frequency distributions of diameters of pieces of woody debris in Reference Site 1 (Heather Creek). Arrows indicate diameter class in which the median of each group is located. Total = all pieces of woody debris in the site; Functional = pieces of woody debris that cause scour, create eddies, or trap sediment or debris.

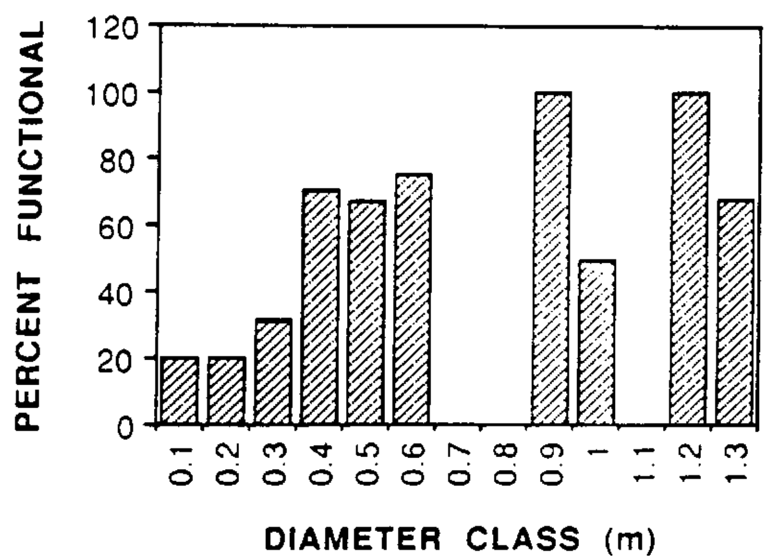


Figure 4.10. Percentages of the total number of pieces of woody debris in each of 13 size classes that are functional in all five low gradient reference sites. Diameter class labels indicate the lower boundary of the size class in meters.

Percentages of Summer Pool Surface Area in Paired Segments.

In general, a paired segment analysis addresses the variability between two segment types and reduces the influence of variability between streams. Five streams were suitable for comparison of B2 and C3 segment types with respect to summer pool percentages: Benson, Schweitzer, Eldred, Long, and Deer Creeks (Figure 4.11). In each case the percentage of stream surface area in pools is lower in C3 segments, though the magnitude of the difference varies dramatically. For example, the B2 and C3 segments in Schweitzer Creek (SH) exhibit little difference in percentages of pool space (73% and 69%, respectively). Several geomorphic factors appear to contribute to this condition (Benda et al. 1990):

1) Boulder lag deposits in the stream result in approximately one third of the C3 segment length being low gradient (1-2.5%),

2) The sediment supply to Schweitzer Creek is dominated by gravel-size and smaller particles (i.e. very little coarse sediment) which allows easier scour of the bed,

3) The Schweitzer Creek watershed does not contain areas of landslide hazard that have infleunced the stream in the recent past or that put the stream at risk to debris flows or dam-break floods.

In contrast, Benson Creek exhibits a very large difference between the percentages of pools in the B2 and C3 segments (52% and 16%, respectively). Several landslides and at least one dam-break flood have altered the habitat characteristics of this stream since 1980. The C3 segment is characterized by long riffles and few pools, whereas the B2 segment contains a relatively high proportion of pools (expressed as a percentage of the total water surface area). However, this proportion does not express the loss of approximately 800 meters of channel that now dry up in summer. (Recall that this segment did not flow sub-surface prior to 1980. See Part 1, Reference Sites.)

Because this simplest stratification of rearing habitat character is based on percentages, the appropriate statistical test is the non-parametric Wilcoxon paired-sample test (Wilcoxon, 1945). The null and alternative hypotheses are as follows:

H_0: the percentage of summer pool space in B2 segments is less than or equal to the percentage of summer pool space in C3 segments.

H_A: the percentage of summer pool space in B2 segments is greater than the percentage of summer pool space in C3 segments.

The null hypothesis is rejected at an alpha level of 0.05. Hence, we conclude that B2 segments have higher percentages of summer pool space than C3 segments.

For all B2 and C3 segments that were sampled in the basin, the one-tailed Mann-Whitney Test (Zar, 1984, p. 139) is the appropriate analog to the two sample T-test (i.e. not paired). Because we expect that lower gradient streams will have greater percentages of pool space than higher gradient streams, the null and alternative hypotheses are as follows:

H_0: The percentage of pool space in B2 segments is less than or equal to the percentage of pool space in C3 segments.

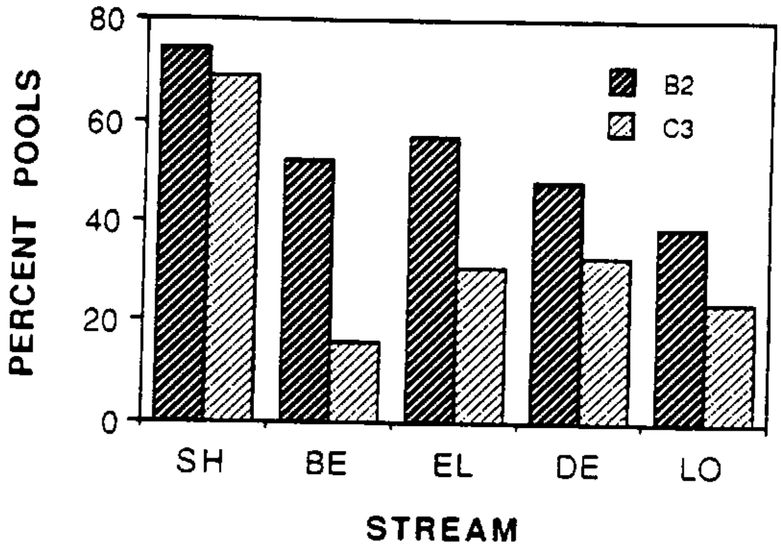


Figure 4.11. Percentages of summer pool areas in 5 pairs of B2 and C3 segments in the the South Fork Stillaguamish River basin. SH = Schweitzer Creek, BE = Benson Creek, EL = Eldred Creek, DE = Deer Creek, and LO = Long Creek.

H_A: The percentage of pool space in B2 segments is greater than the percentage of pool space in C3 segments.

The null hypothesis is rejected (P = 0.001), suggesting that B2 segments generally have a higher percentage of summer pool space than do C3 segments.

Though each of these tests indicates that B2 segments have higher percentages of summer pool space than do C3 segments, it is important to recognize that

1) all of these segments are located in a single basin (the South Fork Stillaguamish River basin),

2) all of these segments are in basins where logging has occurred, and

3) many of these streams may have been impacted by previous harvest practices (e.g. splash dams) or LOD removal.

Hence, we cannot conclude that streams in "natural" settings or streams in other basins will show the same distinct relationships. Streams in old-growth forests (here defined as >400 years old) may exhibit less distinct differences because of the effects of LOD in the streams. Specifically, summer pool percentages in C3 segments are expected to be higher in unharvested basins due to the presence of LOD obstructions. The regression analyses in Parts 1 and 3 of these results support this hypothesis. In these anlyses the interaction term between wood volume and gradient is a significant variable. The data in this report are not appropriate for testing this hypothesis directly, although a sampling strategy can be formulated to address the question.

Conversely, streams in other forested watersheds of the North Cascades ecoregion should show similar relationships where timber harvest has taken place. Though the sample of streams in the South Fork Stillaguamish River basin does not include the complete range of possible geologic settings and timber harvest impacts, the range of conditions is fairly represented (see section 4.3).

Comparison of Spawning Gravel Percentages.

The relative areas of coho spawning gravels can be compared using the non-parametric paired and unpaired methods described above for pool area percentages. Spawning gravel areas are expressed in m^2 of spawning gravel per 100 m^2 of channel area (percent area).

The paired segment data (Figure 4.12) show that in all cases the spawning gravel percentages are higher in B2 segments than in C3 segments, but the percentages and the magnitudes of differences vary dramatically between streams. The Wilcoxon paired sample test indicates that spawning gravel percentages in B2 segments are not significantly greater than those of C3 segments ($0.05 < P < 0.10$).

In Benson Creek (BE) the spawning gravel percentage is slightly higher in the C3 segment than in the B2 segment. Recall that Benson Creek has recently been impacted by several landslides which may account for the high percentage of spawning gravel in the C3 segment. Landslides appear to contribute to increases in the quantity of spawning gravels in sediment poor streams in Oregon (L. Benda, personal communication). However, we also note that the number of spawners in Benson Creek declined

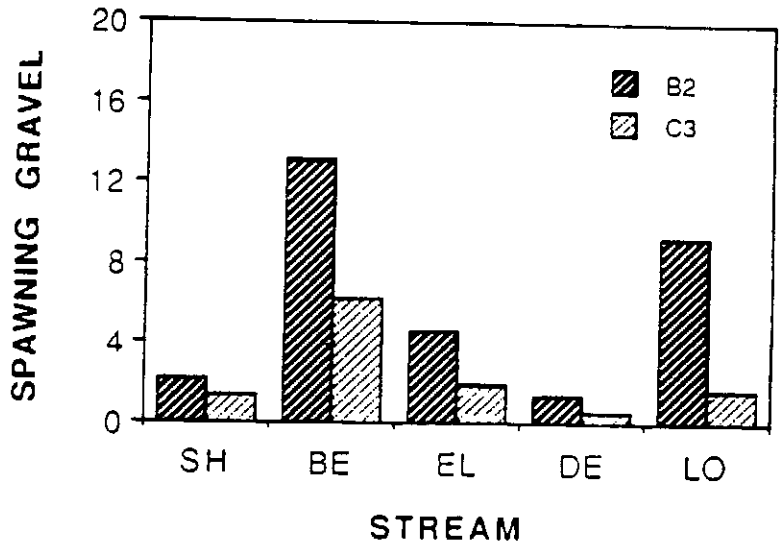


Figure 4.12. Bar graph showing differences in spawning gravel percentages between paired B2 and C3 segments in the South Fork Stillaguamish River basin.

dramatically in 1980 and has not recovered to date (WDF, unpublished data), suggesting that suitable gravels alone are not sufficient to allow recovery of the spawning stock.

These data are expressed as a percentage of the bankfull channel area, and do not account for differences in stream size. It has been shown that stream power (which incorporates gradient and discharge) strongly influences the quantity of spawning gravel in the stream (Benda et al. 1990). This suggests that some indicator of stream size (e.g. bankfull width or estimated bankfull discharge) should be incorporated into the classification scheme.

Distributions of Channel Unit Types.

Comparing the distributions of channel units between segment types requires several different analyses to address the "success" of the classification system. In this study we employ the following:

1) three dimensional contigency tables are used to compare segment types and streams as sources of variability. This table will help to illustrate whether differences in the distribution of channel units are due primarily to differences between streams or differences between segment types;

2) cluster and discriminant analysis help determine whether anticipated differences between segment types are expressed in the distributions of channel units;

The paired segments can be used to compare the sources of variability (i.e. streams and segment types) affecting the channel unit distributions. This three dimensional contingency table (Table 4.5) with channel unit areas, stream, and segment type cannot be evaluated with the Chi-square test because several cells contain zero values. With zero values in cells the test tends to reject the null hypothesis with a probability greater than alpha (Zar, 1984; p.49).

Examination of Table 4.5 shows that B2 segments tend to be low in cascades and plunge pools. By definition cascades have gradients higher than 4%; hence, it is unlikely that they will be found in B2 segments (average gradients between 0% and 2%). Though plunge pools do occur in B2 segments, the low frequency may also be attributable to the low gradient of B2 segments. The C3 segments in the five streams are characterized by much higher percentages of riffles and cascades (Figures 4.13a and 4.13b). Lateral scour pools are also much less common in the C3 segments. The higher gradients of C3 segments (2% to 4%) probably account for most of these differences. Though figures 4.13a and 4.13b show substantial variation between streams,it is clear that segment type accounts for some of the variability between segments.

Cluster Analysis.

Cluster analyses of channel unit distributions were used to assess the apparent natural groupings of B2 and C3 segments in the South Fork Stillaguamish River basin. The channel unit groups were assessed separately from the geomorphic variables to view the natural groupings of 23 segments in the basin. Clusters were formed using the average, within-group linkage (Norusis 1988).

Table 4.5. Three dimensional contingency table for paired B2 and C3 segments in the South Fork Stillaguamish River basin. Channel unit frequencies are the percentages of total area of that channel unit type in each stream segment. RIF = riffles and rapids, CAS = cascades, GL = glides, BWP = dammed pools and eddy pools, PP = plunge pools, HSP = hydraulic scour pools, LSP = lateral scour pools and trench pools, OSP = obstruction (wood and boulder) scour pools.

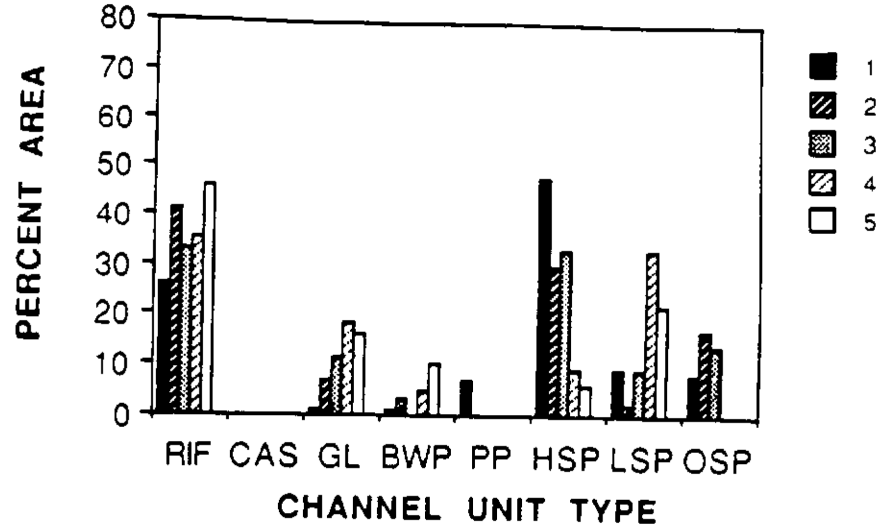
B2 SEGMENTS

	CHANNEL UNIT TYPE							
Stream	RIF	CAS	GL	BWP	PP	HSP	LSP	OSP
Schweitzer	26	0	1	1	7	48	9	8
Benson	41	0	7	3	0	30	2	17
Eldred	33	0	11	0	0	33	9	14
Deer	35	0	18	5	0	9	33	0
Long	46	0	16	10	0	6	22	0

C3 SEGMENTS

	CHANNEL UNIT TYPE							
Stream	RIF	CAS	GL	BWP	PP	HSP	LSP	OSP
Schweitzer	30	2	0	15	12	13	11	17
Benson	74	1	10	2	0	5	0	8
Eldred	60	2	17	5	8	2	1	5
Deer	50	4	12	2	1	22	0	9
Long	57	10	9	1	2	14	0	7

A.



B.

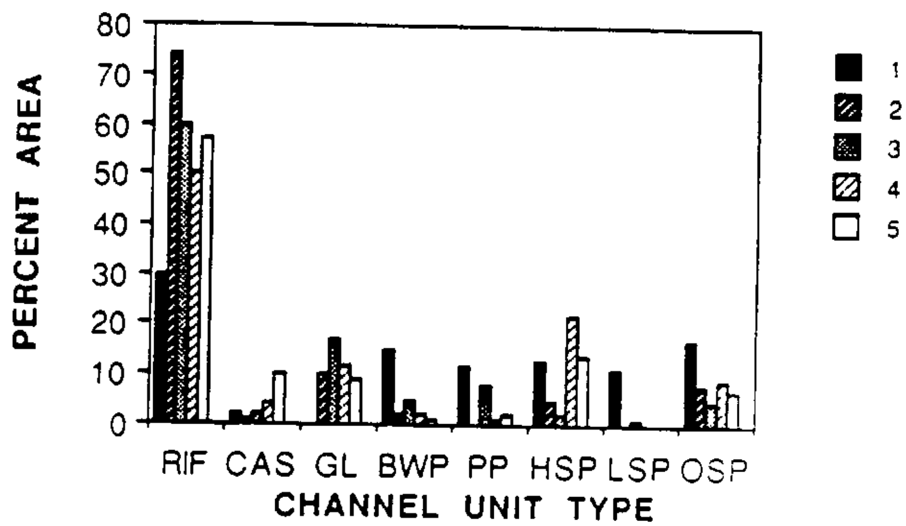


Figure 4.13. Percentages of total water surface area occurring in eight channel unit groups in B2 segements (A) and C3 segments (B). RIF = riffles and rapids, CAS = cascades, GL = glides, BWP = dammed and eddy pools, PP = plunge pools, HSP = hydraulic scour pools, LSP = lateral scour and trench pools, OSP obstruction (boulder and wood) scour pools. Legend: 1 = Schweitzer Creek, 2 = Benson Creek, 3 = Eldred Creek, 4 = Deer Creek, 5 = Long Creek.

Table 4.6. Classification results from discriminant analysis of 23 B2 and C3 segments in the South Fork Stillaguamish River basin.

Actual Group	No. Cases	Predicted Group B2	Predicted Group C3
B2	12	11 (92%)	1 (8%)
C3	11	0 (0%)	11 (100%)

Percent of cases correctly classified: 95.6%

The independent variables in the habitat analysis include only the percentages of the total surface area in each of the eight channel unit groups discussed in the previous section. Actual surface areas of channel unit groups were not used because the total area of each sample segment influenced the resultant clusters.

Clusters identified by the program bore strong resemblance to the B2 and C3 segment types, with only 4 of 23 segments (17%) occuring outside of the expected cluster at 80% similarity. The preceeding paired segment analyses suggested the B2 and C3 segments of Schweitzer Creek were very similar. Examination of clusters revealed no distinct pattern to the deviations from the expected groupings of streams.

Discriminant Analysis.

Discriminant analysis of the channel unit data for segments in the South Fork Stillaguamish River basin indicate that the differences in channel unit distributions between B2 segments (0%-2%, unconstrained) and C3 segments (2%-4%, constrained) are quite clear.

The all-groups histogram for the 23 segments indicates a distinct separation between B2 and C3 segments, based on channel unit distributions (Figure 4.14). The only incorrectly classified segment is the B2 portion of Heather Creek, which has an unusually high percentage of riffles and cascades relative to other B2 segments. The classification results (Table 4.6) show that over 95% of the segments were correctly classified.

The variables that were most highly correlated with the discriminant function were the percentage of riffles ($r = -0.44$), percentage of cascades ($r = -0.44$), percentage of hydraulic scour pools ($r = 0.28$), and percentage of lateral scour pools ($r = 0.24$). Percentages of riffles and cascades were expected to be dominant discriminating variables in this analysis because of the gradient difference between the two segment types. Hydraulic and lateral scour pools are more likely to occur in low gradient streams.

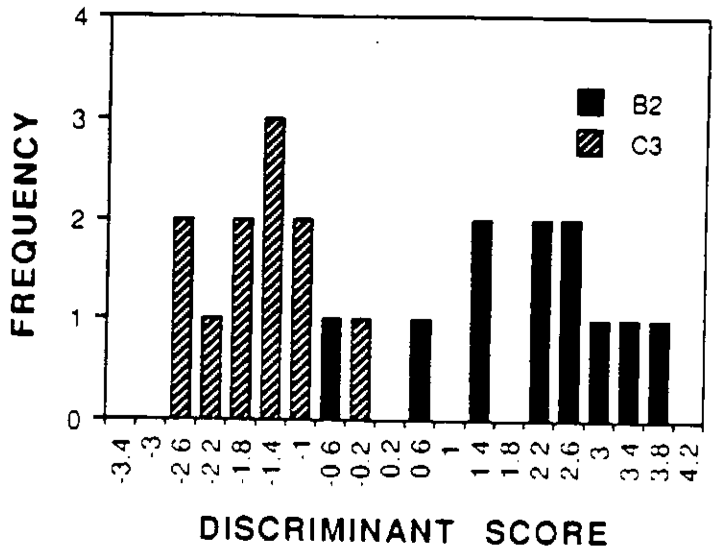


Figure 4.14. All-groups histogram for discriminant analysis of B2 and C3 segments in the South Fork Stillaguamish River basin.

4.3. MULTIPLE WATERSHED SITES.

Of the 36 segments surveyed in several watersheds of the North Cascades, 29 segments distributed among B2, C2, C3, and C4 types were used for most of the following analyses. The G segments were omitted from all but the discriminant analysis due to insufficient sample size (n = 3). The G segments were used in the discriminant analysis because the gradients of these segments were much higher than in any of the other segment types. The remaining E segments (n = 4) were ommitted from all analyses.

Spawning Gravel Distribution.

The distribution of spawning gravels in the four segment types were assessed by two methods: (1) one-way analysis of variance between segment types and (2) graphical analysis of spawning gravel area as a function of gradient and mean bankfull width. These two methods are used to address two specific aspects of the segment types. The ANOVA adresses only the significance of the differences between group means where groups are defined as the segment types. The graphical analysis allows one to view the data in the absence of classification, and to thereby locate apparent thresholds in gradient and/or stream size with respect to the quantity of spawning gravels. In this fashion we attempted to confirm that the gradient boundaries that define segments correspond to other physical features of the stream.

An ANOVA was used to test the differences in means of bankfull widths between segment types to verify that there were no systematic differences in stream sizes between segment types. The means of bankfull widths (Figure 4.15) were not significantly different between segment types (P = 0.84). Hence, we conclude that the bankfull widths are not a factor in determining the differences in spawning gravel percentages between segment types.

A Kruskal-Wallis test (a non-parametric quivalent to the ANOVA) showed that the means of the spawning gravel percentages ($m^2/100m^2$, Figure 4.16) were significantly different between segment types (P < 0.001). Tukey-type multiple comparisons indicated that the mean percentages of spawning gravels were significantly different between all segment types except C2 and C3 types. This indicates that there is a systematic difference in the percentages of spawning gravels between segment types, but there is a high degree of overlap between segment types. More than 2/3 of the spawning gravel percentages in all four types are less than 5%. Hence, it seems clear that B2 and C4 segments tend to have higher percentages of coho spawning gravel than C2 or C3 types, but any given B2 or C4 segment may also have a low percentage.

A contour plot of spawning gravel percentage as a function of gradient and bankfull width (Figure 4.17) illustrates the importance of the interaction between gradient and stream size in controlling the distribution of spawning gravels in streams. Natural boundaries in gradient and bankfull width are suggested by the plot, though boundaries are not distinct. These data represent a relatively small sample (N = 30) for creating a contour plot. Furthermore, boundaries suggested by this plot may at best be interpreted as suggestive because of the continuous nature of all the variables involved. The *a priori* 2% boundary between segment types appears to correspond reasonably well to the distribution of coho spawning gravels, but there also appears to be a second gradient boundary near 0.5%. Boundaries in stream widths appear to occur near 7 meters, 10 meters, and 17 meters.

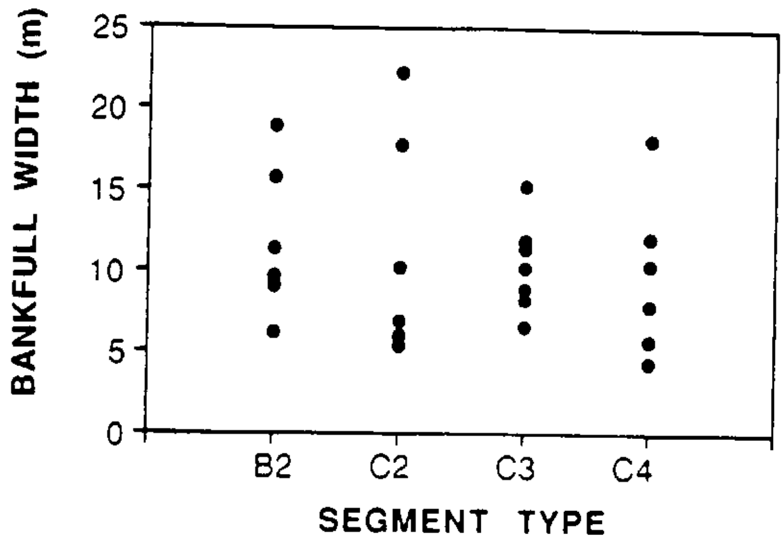


Figure 4.15. Distributions of mean bankfull widths for individual segments by segment type.

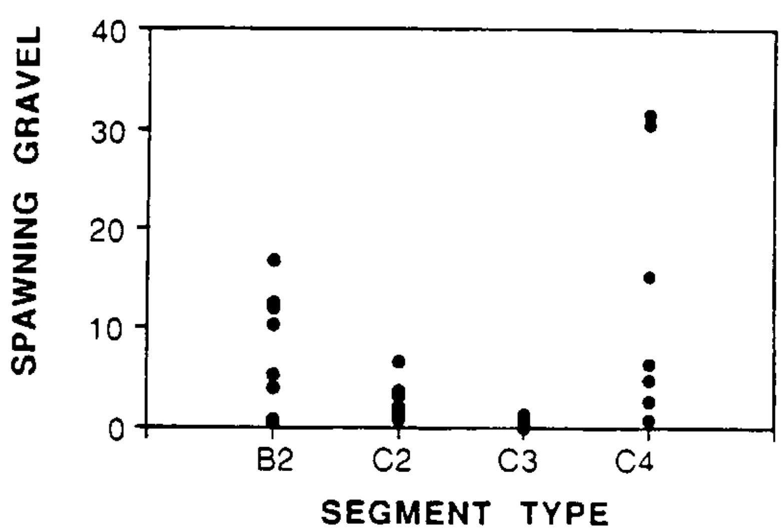


Figure 4.16. Distributions of spawning gravel percentages for individual segments by segment type.

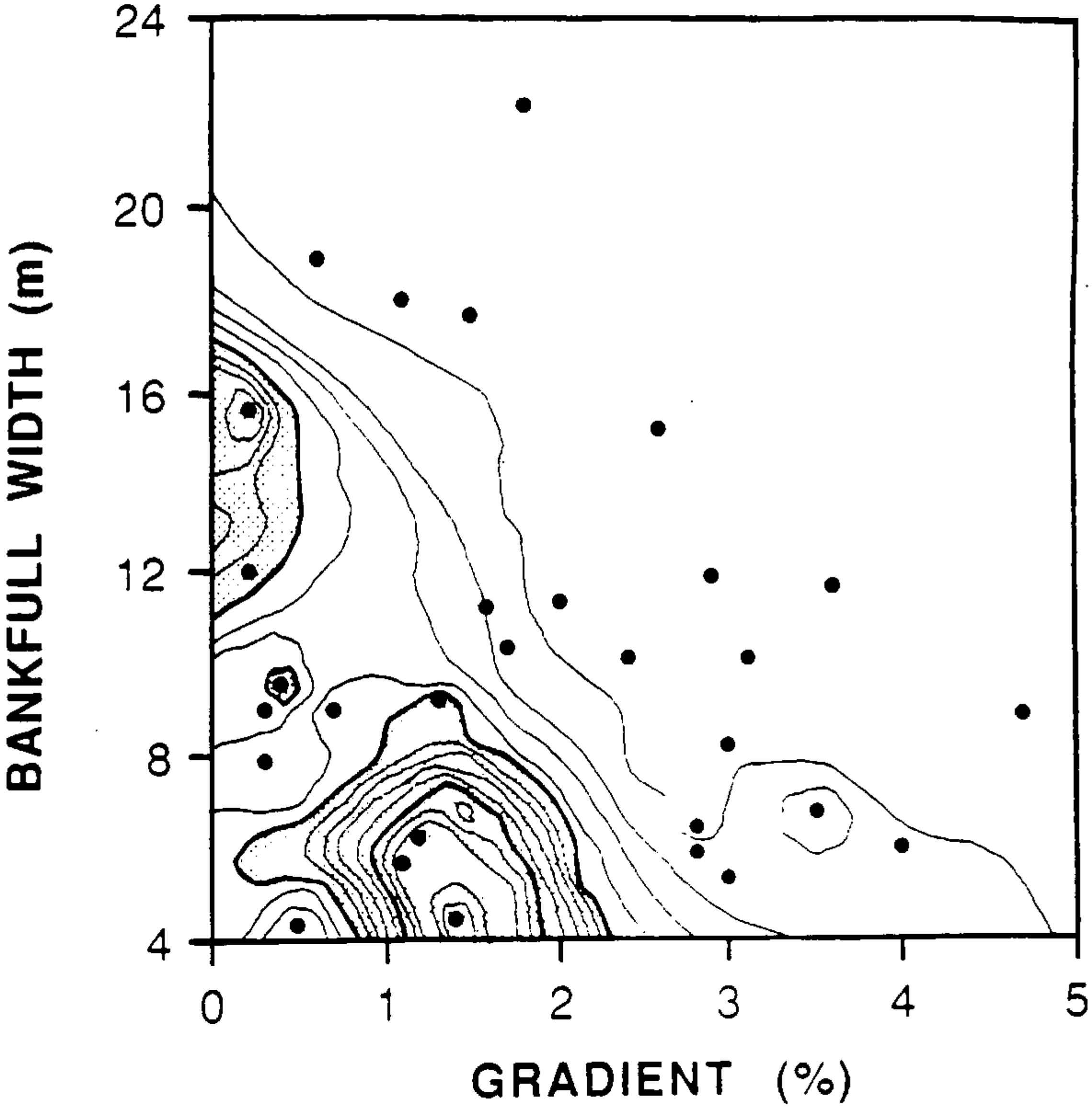


Figure 4.17. Contour plot of percent of channel area as coho spawning gravel ($m^2/100m^2$) as a function of gradient (%) and bankfull width (meters). Contour interval is 2%. Shaded areas are greater than 10% of channel area in spawning gravel.

Discriminant Analysis.

Channel unit distributions among segments in multiple watersheds were analyzed using discriminant analysis to evaluate whether the distributions of channel units in segments correspond to segment types. The independent variables in this analysis were the surface area percentages of each of the eight channel unit groups. Absolute values were not used because unequal sample sizes influenced the results of the analysis.

Of the 32 segments in the analysis, 25 (78%) were correctly classified on the basis of channel unit distributions (Table 4.7). The G type segments are most different from the other 4 types (Figure 4.18), primarily because of their higher gradients which ranged from 7.8% to 8.9%. The highest correlation between the discriminating variables (channel unit percentages) and the first canonical discriminant function indicates that the first function is most highly correlated with cascades ($r^2 = 0.68$). The second canonical discriminant function is most highly correlated with lateral scour pools ($r^2 = 0.64$). These results are expected because of the range of gradients of stream segments in the analysis. The frequency (or total area) of cascades is closely related to stream gradient because it is the only distinct high gradient channel unit group (>4%) used in this analysis. The frequency of lateral scour pools is less directly tied to the gradient, but is related through sinuosity. Lateral scour pools are common in low-gradient meandering streams, but are less frequent in higher gradient channels that tend to have a straight channel pattern.

C2 segments were the least distinct group (43% classified as other types on the basis of channel units). Of the segments that were reclassified as other segment types, one was classified as a C3 segment and one was classified as a C4 segment. A review of the the particular segments that were misclassified does not indicate any systematic pattern in controlling variables such as stream size or woody debris index.

The C2 segment type (analyzed in the multiple watershed sites) appeared to be the least distinct group based on the discriminant results in Table 4.7, but Figure 4.18 shows that C2 and C4 segments overlap. More subjective analysis of Figure 4.18 indicates that gradient is the major factor influencing the channel unit distribution (represented by cascades in Function #1 on the x-axis), and that channel constraint may be important in the B2 and C4 types which have lower gradients (the difference represented by lateral scour pools in Function #2 on the y-axis). Additional B2 and C4 segments should be evaluated to determine whether this effect is significant.

Additionally, C2 and C3 segments have similar gradients and similar valley bottom widths, but they are clearly separated in Figure 4.18. It is unclear whether this difference is due to the different positions in the drainage network (C3 tends to be below steep headwall streams with relatively high landslide potential whereas C2 does not) or due to the differences in typical watershed geology (C2 tends to occur in extensive areas of quaternary glacial outwash deposits whereas C3 is more varied in local geologic setting.

Percentages of Pool Area.

The percentages of pool area in the multiple watershed sites (Figure 4.19) were evaluated with a Kruskall-Wallis test. The percentages of pool area in the four segment types (B2, C2, C3, and C4) are significantly different ($P < 0.001$). The Tukey-type Table 4.7. Predicted group memberships resulting from discriminant analysis of channel unit distributions for 32 sample segments.

Actual Group	No. of Cases	Predicted Group Membership				
		C3	C2	C4	B2	G
C3	8	6 (75%)	1 (12%)	0 (0%)	0 (0%)	1 (13%)
C2	6	1 (17%)	4 (66%)	1 (17%)	0 (0%)	0 (0%)
C4	7	0 (0%)	1 (14%)	5 (71%)	1 (14%)	0 (0%)
B2	8	0 (0%)	0 (0%)	1 (13%)	7 (87%)	0 (0%)
G	3	0 (0%)	0 (0%)	0 (0%)	0 (0%)	3 (100%)

Percentage of cases correctly classified: 78.1%.

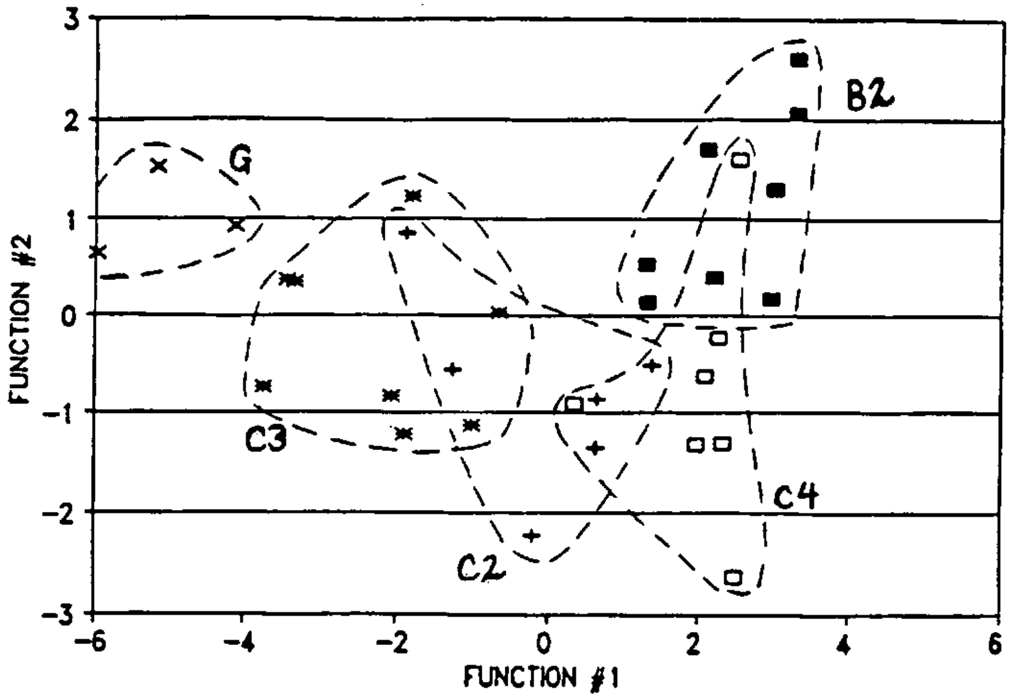


Figure 4.18. All-groups scatterplot of the first two discriminant functions for discriminant analysis of 32 sample segments based on channel unit distributions.

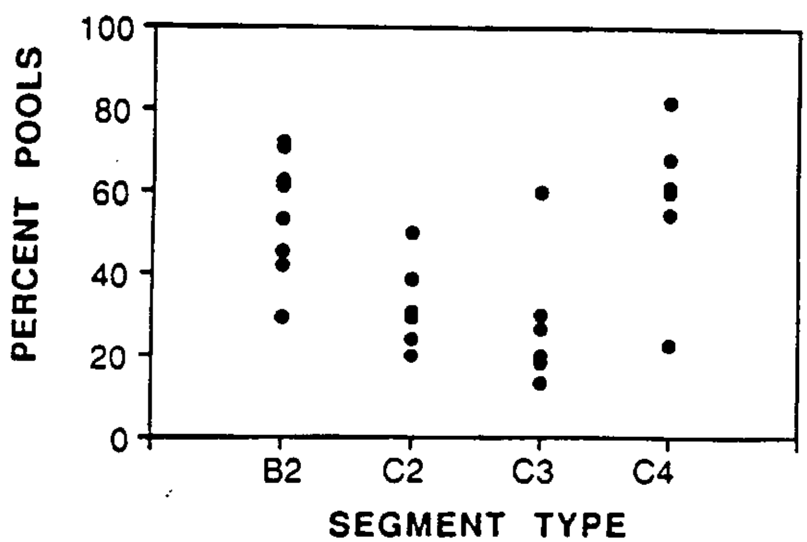


Figure 4.19. Percentages of pool area in individual segments of 4 types.

multiple comparisons show that the pool percentages are significantly different (alpha = 0.05) between all possible pairings of segment types except the B2-C4 and C2-C3 pairs. That is, pool percentages are significantly different between types with different gradients, but not between types with similar gradients (B2 and C4 segments range from 0% to 2%, and C2 and C3 segments range from 2% to 4%).

Again we must recognize that a statistically significant difference only indicates that *on average* the percentages of pools will differ between the segment types noted above. There is a large amount of overlap in the values of all segment types shown in Figure 4.19, demonstrating that pool percentages of 25% to 55% may occur in any of these segment types. Therefore, the precision and predictive capability of the segment types are questionable when the percentage of pools is the response variable.

Physical Factors Affecting Pool Area.

Regression analysis of several variables that are expected to control the area of pools in channels were used to evaluate the influence of each variable on the percentage of the water surface area in pools in each of the multiple watershed sites. A correlation matrix is also used to review the correlations between individual variables.

A correlation matrix (Table 4.8) shows the correlation coefficients between several of the variables entered into a stepwise regression analysis. Note that the correlations between percent pools and the independent variables involving gradient are relatively high, whereas the correlation with bankfull discharge (BFQ) is low. A stepwise regression did not include bankfull discharge as a significant variable. Only $GRAD^{0.5}$ and an interaction term (lnWD/GR) were included in the final regression model resulting from the stepwise analysis. The bankfull discharge variable was added based on the expected relationship between stream size and the percentage of pool space. The variable $(WD/GR)^{0.5}$ was chosen over ln(WD/GR), based on the residual plots from individual linear regressions between the percentage of pools and each of the two variables.

The final regression model resulted in the equation

$$POOLS = 52.4 - 206(GRAD)^{0.5} + 6.58(WD/GR)^{0.5} - 0.60(BFQ)$$

which explains approximately 60% of the variability in percent pools (adjusted r^2 = 0.594, Figure 4.20). This equation expresses the variables with the expected transformations and with the correct signs on coefficients. That is, the woody debris and gradient variables are expected to be non-linearly related to the percentage of pools, and the percentage of pools (1) decreases with increasing gradient, (2) increases with increasing wood volume, and (3) decreases with increasing discharge. However, the magnitudes of coefficients may not be correct. Because the sample size is small (n=29), the magnitudes of the coefficients may change significantly with an increased amount of information. Furthermore, the range of each variable is small, and the equation can only be expected to apply to streams with gradients between 0% and 4% and bankfull discharges between 3 m^3s^{-1} and 30 m^3s^{-1}.

Table 4.8. Correlation matrix of six predictor variables and the percentage of pools in 29 sites ranging from 0.2% to 4% gradient.

	POOLS	WOOD	GRAD	BFQ	WD/GR	$GRAD^{0.5}$	$(WD/GR)^{0.5}$
POOLS	1.000						
GRAD	-0.583	1.000					
WOOD	0.026	0.291	1.000				
BFQ	**-0.180**[a]	-0.126	-0.156	1.000			
WD/GR	0.286	-0.009	0.528	-0.152	1.000		
$GRAD^{0.5}$	**-0.563**[a]	0.889	0.227	**-0.124**[b]	-0.288	1.000	
$(WD/GR)^{0.5}$	**0.418**[a]	-0.111	0.641	**-0.155**[b]	0.946	**-0.377**[b]	1.000

a. Correlations between pools and independent variables used in final model.
b. Correlations between independent variables used in final model.

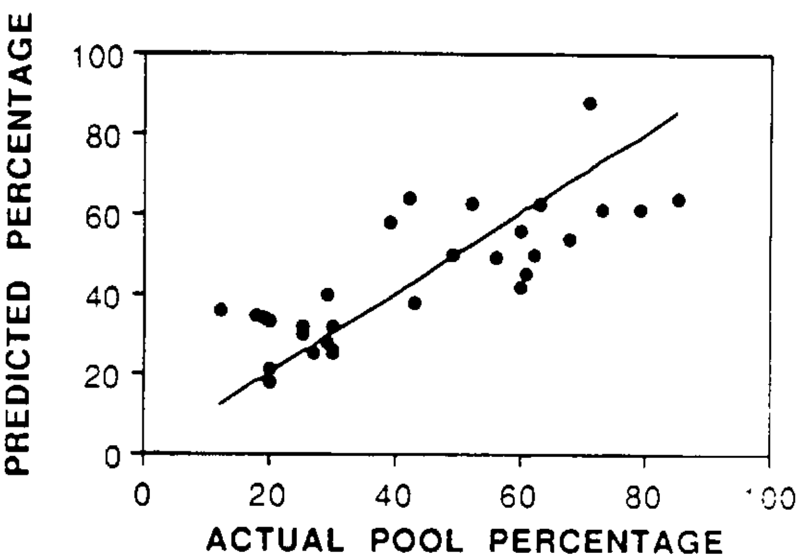


Figure 4.20. Predicted pool percentages plotted against actual pool percentages over 32 sample segments. Predictions are generated from the equation:

$$POOLS = 52.4 - 206(GRAD)^{0.5} + 6.58(WD/GR)^{0.5} - 0.60(BFQ)$$

Applying this model to the reference site data further supports the above conclusion (see Section 4.1). The resulting equation for the reference sites was

$$POOLS = 103 - 437(GRAD)^{0.5} + 7.7(WD/GR)^{0.5} - 4.10(BFQ).$$

The coefficient for each variable bears the same sign and is within an order of magnitude of that calculated in the regression of the data from multiple watersheds. The regression of the reference site data explains only about 43% of the variability in the percentage of pools, but the sample size is very small (n = 10).

5. CONCLUSIONS.

5.1. Success of Segment Types in Stratifying Physical Habitat.

The results of all three sampling strategies show that in the absence of other variables or other hierarchical classification levels, the segment types sampled stratify physical habitat with moderate success. That is, univariate analyses show that segment types had significantly different average values, but that all four types overlap to some degree. The overlap is most distinct with simple response variables such as percentages of spawning gravel or percentages of pool area. Discriminant analysis using the distributions of channel unit groups identifies segments more clearly.

The South Fork Stillaguamish River basin sites show that B2 types are significantly different from C3 sites, though considerable overlap in percentages of pools and in spawning gravel percentages remains. Gradient appears to account for most of the variation. The C4 segment type (analyzed in the multiple watershed sites) appeared to be the least distinct group based on the discriminant results in Table 4.7, but Figure 4.18 shows that C2 and C4 segments overlap. More subjective analysis of Figure 4.18 indicates that gradient is the major factor influencing the channel unit distribution (represented by cascades in Function #1 on the x-axis), and channel constraint may be important in the B2 and C4 types which have lower gradients (the difference represented by lateral scour pools in Function #2 on the y-axis).

Additionally, C2 and C3 segments have similar gradients and similar valley bottom widths, but they are clearly separated in Figure 4.18. It is unclear whether this difference is due to the different positions in the drainage network (C3 tends to be below steep headwall streams with relatively high landslide potential whereas C2 does not) or due to the differences in typical watershed geology (C2 tends to occur in extensive areas of quaternary glacial outwash deposits whereas C3 is more varied in local geologic setting).

5.2. Controlling Variables.

The results of this study show that segment type alone does not effectively stratify the distribution of physical habitat in streams. Hence, other controlling variables should be considered. The TFW-AMSC Work Plan outlines ecoregion, watershed, segment, and channel unit as the hierarchical classification scheme with sediment, discharge, and obstruction characteristics as input variables that control the appearance of a segment at a given point in time.

The preceding analyses indicate that variables such as stream size (represented by the bankfull width or bankfull discharge estimate) and obstruction volume (primarily LOD) influence the quantity and distribution of physical habitat in streams (percentage of pools and percentage of spawning gravel) in addition to segment type. These variables were not tested within segment types in this study due to insufficient sample sizes.

Stream size is the easiest of these variables to address in subsequent hypothesis testing because it is easily measured in the field and it is visible enough on aerial photos to provide efficient sample site selection. Two approaches to this problem seem reasonable:

(1) The subtypes used by Rosgen (1985) include channel width categories.

These may be used as *a priori* width categories to be tested using specified response variables such as D_{50}, percentage of spawning gravel, or percentage of pools.

(2) In the absence of *a priori* categories, graphic and clustering approaches may be used to define the boundaries of width categories.

Because width is a continuous variable, threshold levels may not be obvious. Hence, the *a priori* approach may provide the most efficient sampling framework.

Obstruction volumes clearly influence the distributions of channel units in segments. This is evident from the importance of the interaction term in a multiple linear regression. However, our data does not provide a sufficient number of samples in streams with high obstruction volumes for testing the effect of wood volume categories (e.g. low, moderate, or high wood volumes) on individual segment types. Additional segments in old-growth or perhaps old-second-growth segments are required to effectively test wood volume categories.

Additional characteristics that we may consider relate to sediment delivery processes and channel stability. The geology of the upper watershed will heavily influence both the type and size of sediment supplied to a segment and the mode of delivery (e.g. by stochastic processes such as landslides). Specific rock types may be grouped by relative permeability and hardness. This may preclude the use of watershed as a hierarchical level because the geology is highly variable within watersheds.

Bank material (especially in mixed glacial-age surficial deposits) will influence the channel pattern, migration rates of the channel, and the types of channel units present in a segment. Other stream classification systems use a variety of additional input variables to further stratify reaches of streams. For example, Rosgen (1985) includes riparian vegetation types as one of six "sub-type" variables because of its influence on the stability of the channel banks. These may also be considered eventually.

5.3. Sampling Approach.

Though the hierarchy proposed by TFW-AMSC is relatively simple (ecoregion, watershed, segment, channel unit), a complete statistical evaluation of a single response variable in segments within an ecoregion may include 8 segment types (a conservative estimate) and 6 major watersheds. With only 3 samples per segment type (which is certainly insufficient), this would require 144 samples for a complete two-way ANOVA which addresses only the variability within segments and watersheds. Assuming that at least 8 samples are required to begin to address the variability within a watershed, 384 samples are required. Bearing in mind that this does not include any factor other than segment type (i.e. simple factors such as geology and harvest history not considered), it seems clear that a strictly statistical approach to hierarchical classification is not feasible.

Streamlining of the sampling design and field methods based on *specific* hypotheses (i.e. selected response variables with expected relationships) are required to efficiently assess conceptual and practical problems with classification. Examples of specific testable hypotheses are:

(1) H_0: Distinct geologies do not influence the distributions of channel units in a segment type. (A specific test may be: the distributions of channel units are similar between C2 segments in andesite and C2 segments in glacial till.)

(2) H_O: Spawning gravel percentages in B2 segments are independent of stream size.

When testing any of these hypotheses it is important to select sample sites carefully so that other factors do not influence the results. For example, the first null hypothesis may require that stream size be randomized, whereas the second null hypothesis may require that the geologic type be held constant.

5.4. Effect of Discharge Changes During Sampling Period.

Because discharge changes will influence the distributions of channel units and the percentage of pools in streams, care must be taken to restrict field surveys to a relatively constant period of discharge (e.g. summer low flow -- July and August) and to temporally intersperse measurement of different segment types during this period. Various methods of interspersion (e.g. random, randomized block, systematic; see Hurlbert, 1984) may be used depending on the hypothesis and number of segment types involved.

5.5. Discharge-Area Relationships.

The discharge-area relationships shown for the reference sites indicate that discharge patterns may be highly variable even in close geographic proximity. It may be very difficult to include some of these features in the classification system itself. It should be noted that many of the watershed characteristics must be included in a process of interpreting segments on-site. That is, a large number of factors such as the elevation range of the watershed (which influences the snow-level and the transitional rain-on-snow zone) and the presence or absence of various water and sediment storage features (e.g. lakes or bogs) must be considered when attempting to assess the potential of a segment within the context of historical patterns of disturbance.

5.6. A Comment on Map Accuracy.

At best, topographic maps provide an estimate of the gradient of stream channels. Several map scales are available from U.S.G.S., but only 1:24,000 (7.5') maps seemed to provide useful information. Larger scales such as 1:62,500 (15') were sufficient only when geologic maps and field experience in the region were used to aid in the classification of stream segments. Unfortunately, 1:24,000 scale maps are still unavailable for some portions of the state.

Within segments, distinct and systematic changes in channel gradient and form are common. However, these changes are often undetectable on the 1:24,000 maps or on 1:12,000 scale aerial photos. Field verification of segment typing is preferred, though it may be possible to increase confidence in the classification with the use of detailed geologic maps and local area field experience in different segment types and geologies.

5.7. Basin-wide Estimate of Habitat Space and Effects of Dam-break Floods.

The basin-wide estimate of habitat space in the South Fork of the Stillaguamish River basin was included in the 1989 Annual Report (Beechie and Sibley 1989). Though insufficient data were available on channels impacted by dam-break floods, it is clear that woody debris is less prevalent and that pool space is reduced in after these events. It appears that only low gradient (<2%), unconstrained (valley bottom width >4 X channel width) channels are not susceptible to dam-break floods.

6. RECOMMENDATIONS.

6.1. General Recommendations.

During the course of this study, several issues pertaining to expectations placed upon both stream classification and the Level I survey methods have become apparent. First, the immediate utility of this stream classification seems to be overestimated. It may be useful to clarify long-range goals for the stream classification system, and to present them to the various cooperators involved in its evaluation. Specific goals to be addressed include:

(1) Clarification of the anticipated uses of stream classification system (e.g. application of RMZ prescriptions of segment types or evaluation of sites for habitat enhancement works),

(2) General time frame for the anticipated use of the system for management purposes (i.e. how long will it be before this system is expected to have practical benefits?), and

(3) Clarification of the specific steps required (i.e. questions to be answered) before the system is useful in a management context (See section 6.2).

Second, there is a widespread misconception about the capacity of the Level I survey methods to detect changes in stream channels. The data collected in the Level I survey should be viewed as largely descriptive in nature. These methods are used to provide a sufficiently detailed characterization of the riparian zone, stream channel, and channel units to evaluate the stream classification system from a variety of perspectives. However, they are not designed to detect small changes in the geomorphology and habitat characteristics of streams from year to year. These methods should easily detect major changes (e.g. from "sluice-outs"), but will not detect normal amounts of channel migration or shifts in the location of individual habitat units.

To detect and quantify the sensitivity of segment types to changes in sediment or wood loading, Level II surveys must be implemented. The Level II survey sites (permanent channel cross-sections, scour chains, etc.) must be established in several segment types to begin evaluating the relationships between changes in the channel morphology and the habitat characteristics of the stream. These data are required to assess whether particular changes in channels such as aggradation of the bed or channel shifting result in changes in the overall habitat characteristics of segments. Furthermore, because streams are dynamic, it is important to begin quantifying "normal" variations on an annual basis to provide some baseline with which to compare disturbances.

6.2. Specific Recommendations.

We have alluded to a number of specific recommendations for stream classification in this report. They are summarized here.

(1) Although segment type accounts for some of the variability in the habitat characteristics of streams, the average bankfull width of the channel provides very useful additional information for determining spawning gravel suitability and the influence of LOD on the channel. Bankfull width should be included as an additional descriptor (perhaps similar to stream sub-types, Rosgen 1985).

(2) Analyses of percentage of channel area as coho spawning gravel indicates that a segment type defined as gradient <0.5% may be appropriate in addition to the gradient break at 2.0%. Other classification systems have included this breakdown (e.g. Rosgen 1985).

(3) If C2 and C3 segments are now considered to be a single segment type (M1), the position of the segment within the drainage network is important. The positions of other low gradient segments should also be considered when viewing potential timber harvest impacts. This issue may be approached first with air photo analysis to determine which segments are susceptible to particular disturbances. For example, a B2 segment below a G2 segment may have a high potential for aggradation due to landslides whereas a B2 segment below a C4 may not.

(4) The volume of LOD affects the channel unit characteristics of the stream in some segments. To evaluate whether this is significant in a given segment type, an arbitrary choice of high and low wood frequencies may be used to test whether the amount of LOD influences the distribution of channel units is a segment type.

(5) Further analysis of sub-basin geology may help to predict downstream impacts in individual segment types. Geology may affect seasonal discharge patterns, sediment production, and channel characteristics.

(6) Changes in discharge influence the identification of channel units in the stream. Therefore, segments types must be temporally interspersed during the summer. This will avoid a systematic bias in channel unit distributions between segment types.

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APPENDIX A. Summary channel unit data for reference sites at different discharges. Q = discharge (m^3s^{-1}); Rif = riffles, rapids, and cascades; G = glides; MainP = main channel pools; MarP = pools at channel margins; WP = pools formed by wood obstructions; HSP = hydraulic scour pools; LSP = lateral scour pools; BOP = pools formed by boulder obstructions; Ptotal = total pool area. All areas in m^3.

Low Gradient (B2) Sites.

Heather (Site 1)

Q	Rif	G	MainP	MarP	WP	HSP	LSP	BOP	Ptotal
0.11	202	48.8	6.9	113.6	108.8	13.7	0	0	122.5
0.59	405.3	34	0	67.1	54.1	13	0	0	67.1
0.79	410.9	71	0	34.1	32.8	11.3	0	0	44.1
2.37	246.8	349.3	0	24.1	24.1	0	0	0	24.1

3.65 = estimated bankfull discharge

Schweitzer (Site 11)

Q	Rif	G	MainP	MarP	WP	HSP	LSP	BOP	Ptotal
0.01	44.8	0	354.5	30	317.7	34.3	32.5	0	384.5
0.24	405.3	34	98.2	121.2	219.4	0	0	0	219.4
0.65	299.8	280.3	58.6	48	106.6	0	0	0	106.6
0.92	167.2	405.3	0	127.1	127.1	0	0	0	127.1
1.27	199.1	412.1	0	87.9	87.9	0	0	0	87.9

3 = estimated bankfull discharge

Eldred (Site 15)

Q	Rif	G	MainP	MarP	WP	HSP	LSP	BOP	Ptotal
0.02	91.6	72.8	195.9	9.9	78.3	30.9	96.6	0	205.8
0.04	187.8	86.2	131.2	18.9	65.8	18	61.6	0	145.4
0.3	318.4	176.9	16.4	61.9	61.9	0	34.3	0	96.2
0.55	453.6	80.5	34.3	40.9	40.9	0	16.4	0	57.3
1.78	667.4	55.8	0	4.8	4.8	0	0	0	4.8

1.34 = estimated bankfull discharge

Lower Benson (Site 4)

Q	Rif	G	MainP	MarP	WP	HSP	LSP	BOP	Ptotal
0	0	0	0	0	0	0	0	0	0
0.07	108.6	45.1	158.4	20.6	80.8	30.45	67.7	0	178.95
0.35	321.3	51.7	40.1	46.1	51	0	35.2	0	86.2
0.45	311.4	54.7	36.8	57.3	79.1	0	15	0	94.1
1.91	201.5	444.6	0	23.3	23.3	0	0	0	23.3

3.13 = estimated bankfull discharge

Lower Hemple (Site 7)

Q	Rif	G	MainP	MarP	WP	HSP	LSP	BOP	Ptotal
0.02	97.5	15.1	169.2	0	97.8	63.8	0	7.6	169.2
0.09	146.2	158	20	18.9	36.8	12.1	0	0	48.9
0.48	436.6	0	0	32.8	21.6	0	0	0	21.6
0.71	500.6	14.4	0	54.3	32	0	0	0	32

1.32 = estimated bankfull discharge

APPENDIX A (cont.). Summary channel unit data for reference sites at different discharges. Q = discharge (m^3s^{-1}); Rif = riffles, rapids, and cascades; G = glides; MainP = main channel pools; MarP = pools at channel margins; WP = pools formed by wood obstructions; HSP = hydraulic scour pools; LSP = lateral scour pools; BOP = pools formed by boulder obstructions; Ptotal = total pool area. All areas in m^3.

Moderate Gradient (C3) Sites.

Mallardy (Site 12)

Q	Rif	G	MainP	MarP	WP	HSP	LSP	BOP	Ptotal
0.08	274.9	160.2	102.4	13.7	82.5	0	0	28.1	110.6
0.26	501.8	134.8	20.1	11.6	26.3	0	0	5.3	31.6
0.96	695.8	130.3	0	0	0	0	0	0	0
6.46	1204.4	0	0	16	16	0	0	0	16

5.64 = estimated bankfull discharge

Turlo (Site 2)

Q	Rif	G	MainP	MarP	WP	HSP	LSP	BOP	Ptotal
0.06	237.2	48.8	95.2	13.1	53.1	55.2	0	0	108.3
0.08	300	14.6	83.4	22.3	43.5	0	0	0	43.5
0.58	462.2	0	63.8	19	82.8	0	0	0	82.8

1.5 = estimated bankfull discharge

Upper Benson (Site 3)

Q	Rif	G	MainP	MarP	WP	HSP	LSP	BOP	Ptotal
0.05	374.5	40.6	0	7	7	0	0	0	7
0.38	610.3	0	0	37.7	13.2	24.5			37.7
0.47	630.1	0	0	34.5	11.5	23			34.5
2.15	780.6	22.04	4	17.4	12	5.3	0	3.1	20.4

5.48 = estimated bankfull discharge

Long (Site 13)

Q	Rif	G	MainP	MarP	WP	HSP	LSP	BOP	Ptotal
0.01	117.6	35.2	44.8	0	36.1	0	8.7	0	44.8
0.03	160.3	44.3	24.5	1.7	24.5	0	1.7	0	26.2
0.18	242.9	17.8	20.9	0	20.9	0	0	0	20.9
0.93	369.9	0	0	5.4	5.4	0	0	0	5.4

1.26 = estimated bankfull discharge

Gordon (Site 14)

Q	Rif	G	MainP	MarP	WP	HSP	LSP	BOP	Ptotal
0.08	307.8	75	92.5	6.1	23.8	55	0	19.8	98.6
0.37	568.6	50.4	49.7	20.7	20.5	49.7	0	3.3	73.5
0.7	598.6	73.9	0	23.8	15.5	0	0	8.3	23.8
5.07	1005.5	0	0	4	4	0	0	0	4

7.32 = estimated bankfull discharge

APPENDIX A (cont.). Summary channel unit data for reference sites at different discharges. Q = discharge (m^3s^{-1}); Rif = riffles, rapids, and cascades; G = glides; MainP = main channel pools; MarP = pools at channel margins; WP = pools formed by wood obstructions; HSP = hydraulic scour pools; LSP = lateral scour pools; BOP = pools formed by boulder obstructions; Ptotal = total pool area. All areas in m^3.

High Gradient (G) Sites.

Marten (Site 16)

Q	Rif	G	MainP	MarP	WP	HSP	LSP	BOP	Ptotal
0.09	228.5	89.7	74.4	17.1	0	0	0	55.9	55.9
0.418	503.5	67.7	0	14.2	0	0	0	28.9	28.9
1.04	469.5	57.4	0	13.6	0	0	0	16.2	16.2

Upper Heeple (Site 8)

Q	Rif	G	MainP	MarP	WP	HSP	LSP	BOP	Ptotal
0.015	211.2	0	72.9	9.9	26.9	0	0	55.9	82.8
0.022	507.6	12.8	30.6	27.7	29.4	0	0	28.9	58.3
0.87	614.7	0	39.7	13.2	36.7	0	0	16.2	52.9

Twenty-two (Site 6)

Q	Rif	G	MainP	MarP	WP	HSP	LSP	BOP	Ptotal
0.177	295.5	22.2	13.3	46.3	23.5	0	0	36.1	59.6
0.422	517	0	0	32	19.4	0	0	12.6	32
*	469.3	0	0	27.8	16.3	0	0	11.5	27.8

Wisconsin (Site 10)

Q	Rif	G	MainP	MarP	WP	HSP	LSP	BOP	Ptotal
0.0058	126.2	0	28.7	46.3	23.5	0	0	36.1	59.6
0.104	264.3	9.2	0	32	19.4	0	0	12.6	32
0.32	417.3	0	14	27.8	16.3	0	0	11.5	27.8

Black (Site 9)

Q	Rif	G	MainP	MarP	WP	HSP	LSP	BOP	Ptotal
0.083	498.3	34.6	46.8	23.3	0	0	0	70.1	70.1
0.715	1063.5	0	0	91.2	7.3	0	0	83.9	91.2
2.3	1293.6	0	0	23	8.4	0	0	14.6	23

Maiden (Site 5)

Q	Rif	G	MainP	MarP	WP	HSP	LSP	BOP	Ptotal
0.024	219.8	32.3	48.9	23.7	72.6	0	0	0	72.6
0.075	361.4	0	24.9	19.8	34.7	0	0	0	34.7
0.36	426.9	0	38.9	16.2	55.1	0	0	0	55.1

APPENDIX B. List of segment types and diagnostic characteristics (Cupp 1990). Segment types evaluated in this study are B2 (now F3), C2 and C3 (now M1), C4 (now M2), and G types (now H types). Valley bottom gradient is measured from topographic maps in lengths of 1000 feet or more. Sideslope gradient characterizes the hillslopes within 1000 horizontal and 300 vertical feet of the from the active channel. Valley bottom width is the ratio of the valley bottom width to the active channel width. Stream order is defined by Strahler (1957).

Valley bottom and sideslope geomorphic characteristics used to identify 18 valley segment types in forested lands of Washington. **Valley bottom gradient** is measured in lengths oF 1000 ft. or more. **Sideslope gradient** characterizes the hillslopes within 1000 horizontal and 300 vertical ft. distance from the active channel. **Valley bottom width** is a ratio of the valley bottom width to active channel width. **Stream order** as defined by Strahler (1957). Valley segment type name include alphanumeric mapping codes in boldface.

Valley Segment Type	Valley Bottom Gradient	Side-Slope Gradient	Valley Bottom Width	Channel Pattern	Stream Order	Landform and Geomorphic Features
F1 - Estuarine Delta	≤ .5%	< 5%	> 5X	unconstrained; highly sinuous; often braided	any	occur at mouth of streams on estuarine flats in and just above zone of tidal influence
F2 - Alluviated Lowlands	≤ 1%	> 5%	> 5X	unconstrained; highly sinous	any	wide floodplains typically formed by present or historic large rivers within flat to gently rolling lowland landforms; sloughs, oxbows, and abandoned channels commonly associated with mainstem rivers
F3 - Wide Mainstem Valley	≤ 2%	< 5%	> 5X	unconstrained moderate to high sinuosity; braids common	any	wide valley floors bounded by mountain slopes; generally associated with mainstem rivers and the tributary streams flowing through the valley floor; sloughs and abandoned channels common
F4 - Alluvial/ Colluvial Fan	1%-3%	≤ 10%	> 3X	variable; generally unconstrained	1-4	generally occur where tributary streams enter low gradient valley floors; ancient or active alluvial / colluvial fan deposition overlying floodplains of larger, low gradient stream segments; stream may actively downcut through deep alluvial fan deposition

Valley bottom and sideslope geomorphic characteristics of 18 valley segment types.

Valley Segment Type	Valley Bottom Gradient	Side-Slope Gradient	Valley Bottom Width	Channel Pattern	Stream Order	Landform and Geomorphic Features
FS - Gently Sloping Plateaus and Terraces	≤ 2%	< 10%	1-2X	moderately constrained; low to moderate sinuosity	1-3	drainage ways shallowly incised into flat to gently sloping landscape; narrow active floodplains; typically associated with small streams in lowlands, cryic uplands or volcanic flanks
M1 - Moderate Slope Bound	2%-5%	10%-30%	< 2X	constrained; infrequent meanders	1-4	constrained, narrow floodplains bounded by moderate gradient sideslopes; typically found in lowlands and foothills, but may occur on broken mountain slopes and volcano flanks
M2 - Alluviated, Moderate Slope Bound	≤ 2	< 5%, gradually increase to 30%	2-4X	unconstrained; moderate to high sinuosity	1-4	active floodplains and alluvial terraces bounded by moderate gradient hillslopes; typically found in lowlands and foothills, but may occur on broken mountain slopes and volcano flanks
V1 - V-Shaped, Moderate Gradient Bottom	2%-6%	30%-70%	< 2X	constrained	≥2	deeply incised drainage ways with steep competent sideslopes; very common in uplifted mountainous topography; less commonly associated with marine or glacial outwash terraces in lowlands and foothills
V2 - V-Shaped, High Gradient Bottom	6%-11%	30%-70%	< 2X	constrained	≥ 2	same as above, but valley bottom longitudinal profile steep with pronounced stairstep characteristics

Valley bottom and sideslope geomorphic characteristics of 18 valley segment types.

Valley Segment Type	Valley Bottom Gradient	Side-Slope Gradient	Valley Bottom Width	Channel Pattern	Stream Order	Landform and Geomorphic Features
V3 - Bedrock Canyon	3%-11%	70%+	< 2X	highly constrained	≥ 2	canyon-like stream corridors with frequent bedrock outcrops; frequently stairstepped profile; generally associated with folded, faulted or volcanic landforms
V4 - Alluviated Mountain Valley	1%-4%	channel adjacent slopes < 10%; increase to 30%+	2-4X	unconstrained; high sinuosity with braids and side-channels common	2-5	deeply incised drainage ways with relatively wide floodplains; distinguished as "alluviated flats" in otherwise steeply dissected mountainous terrain
U1 - U-Shaped Trough	< 3%	< 5%; gradually increases to 30%+	> 4X	unconstrained; moderate to high sinuosity; side channels and braids common	1-4	drainage ways in mid to upper watersheds with history of glaciation, resulting in U-shaped profile; valley bottom typically composed of glacial drift deposits overlain with more recent alluvial material adjacent to channel
U2 - Incised U-Shaped Valley, Moderate Gradient Bottom	2%-5%	steep channel adjacent slopes, decreases to < 30%, then increases to > 30%	< 2X	moderately constrained by unconsolidated material; infrequent short flats with braids and meanders	2-5	channel downcuts through deep valley bottom glacial till, colluvium or coarse glacio-fluvial deposits; cross sectional profile variable, but generally weakly U-shaped with active channel vertically incised into valley fill deposits; immediate sideslopes composed of unconsolidated and often unsorted coarse grained deposits

Valley bottom and sideslope geomorphic characteristics of 18 valley segment types.

Valley Segment Type	Valley Bottom Gradient	Side-Slope Gradient	Valley Bottom Width	Channel Pattern	Stream Order	Landform and Geomorphic Features
U3 - Incised U-Shaped Valley, High Gradient Bottom	6%-11%	steep channel adjacent slopes, decreases to < 30%, then increases to > 30%	< 2X	moderately constrained by unconsolidated material; infrequent short flats with braids and meanders	2-5	channel downcuts through deep valley bottom glacial till, colluvium or coarse glacio fluvial deposits; cross sectional profile variable, but generally weakly U-shaped with active channel vertically incised into valley fill deposits; immediate sideslopes composed of unconsolidated and often unsorted coarse grained deposits
U4 - Active Glacial Outwash Valley	1%-7%	initially < 5%, increasing to > 60%	< 4X	unconstrained; highly sinuous and braided	1-3	stream corridors directly below active alpine glaciers; channel braiding and shifting common; active channel nearly as wide as valley bottom
H1 - Moderate Gradient Valley Wall / Headwater	3%-6%	> 30%	< 2X	constrained	1-2	small drainage ways with channels slightly to moderately entrenched into mountain toeslopes or headwater basins.
H2 - High Gradient Valley Wall / Headwater	6%-11%	> 30%	< 2X	constrained; stairstepped	1-2	small drainageways with channels moderately entrenched into high gradient mountainslopes or headwater basins; bedrock exposures and outcrops common; localized alluvial/colluvial terrace deposition
H3 - Very High Gradient, Valley Wall / Headwater	11%+	> 60%	< 2X	constrained; stairstepped	1-2	small drainage ways with channels moderately entrenched into very steep mountainslopes or headwater basins; bedrock exposures and outcrops frequent