AN ABSTRACT OF THE THESIS OF

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Stream management and design recommendations related to the Salmon Habitat Recovery Program in the Pacific Northwest require area specific information concerning appropriate methods of stream classification, bankfull discharge recurrence intervals, and hydraulic geometry relationships. New region specific information, based on field measurements, is presented here.

The Rosgen Classification of Natural Rivers (RCNR), commonly used by resource agencies, is field tested in the Pacific Northwest (PNW). RCNR levels I and II were found to contain appropriate ranges of characteristics for the number of active channels, entrenchment, width to depth ratio, channel gradient, and bed material. However, the sinuosity range was found to be too high for many of the stream reaches evaluated. Recommendations for sinuosity range adjustments are included along with proposals for use of the RCNR on modified stream systems, previously outside of the scope of this classification system.

Bankfull discharge recurrence intervals have been variously reported to range from one to two years, with an average of 1.5 years. Analysis of field derived bankfull discharge recurrence intervals for the PNW indicate that regional variation can be

explained by climate and ecoregion classifications. Importantly, while the average bankfull discharge recurrence interval for the PNW is 1.4 years, western Oregon and Washington have intervals of 1.1 to 1.2 years, while Idaho, and eastern Oregon and Washington have intervals of 1.4 to 1.5 years.

Regional hydraulic geometry regression equations were developed from field measurements and include comparisons between drainage area and bankfull width, depth, velocity, and discharge. Bankfull discharge recurrence interval is the basis for regionalization. The development of these regional regression equations allows for extrapolation of data from gaged to ungaged streams within a delineated geographic area.

Stream Classification in the Pacific Northwest:

Methodologies, Regional Analyses, and Applications

by

Janine M. Castro

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STREAM CLASSIFICATION IN THE PACIFIC NORTHWEST: METHODOLOGIES, REGIONAL ANALYSES, AND APPLICATIONS

CHAPTER 1. INTRODUCTION

INTRODUCTION

Stream classification is a useful tool for scientists and managers involved with the research and management of stream systems. Classification can be generally defined as sets of observations or characteristics that are organized into meaningful groups based on measures of similarity or difference (Naiman et al. 1992). One of the most important functions of a stream classification system is communication. Information can be succinctly presented if a classification scheme is appropriate for the area to which it is applied. The nomenclature of a classification system is a type of short-hand which transfers complex sets of characteristics with only a few symbols.

There are numerous stream classification approaches that have been and are currently being applied in the field. Some of the more well-known classifications are those of Davis (1899), Schumm (1963), and Vannote and others (1980), but there have been many other attempts at classifying rivers. No single classification system is comprehensive enough to exclude all others. Rather, classification systems are developed in certain physiographic and climatic areas with specific intended uses. The Davis (1899) classification is based on erosional processes and has three main categories of young, mature, and old; Schumm (1963) classified rivers based on stream aggradation and degradation, while Vannote and others (1980) classified rivers according to their ecologic function (Naiman et al. 1992). All of these classification systems are useful for specific purposes, but all have very definite limitations.

This study focuses on the Pacific Northwest region of the United States (Oregon, Washington, and Idaho) and utilizes the Rosgen Classification of Natural Rivers (RCNR)(Rosgen 1994), a system based on the morphological characteristics of stream channels. The number of active channels, entrenchment, width to depth ratio, sinuosity, channel slope, and bed material are the characteristics used to classify a stream reach with the RCNR. The structure of a classification system can be based on a hierarchical or simple approach while the characteristics are defined in descriptive, taxonomic, genetic, empirical, or functional terms. The Rosgen system has a hierarchical structure with an empirical/descriptive approach to characterization.

LITERATURE REVIEW

Stream classification has evolved considerably over the past one hundred years. During the first half of this century, geomorphic stream classification had mainly a qualitative approach, an excellent example of which is the classification system of Davis (1899). Davis' categories of young, mature, and old include the physical parameters of sinuosity, channel gradient, and valley width, but do not place quantitative restraints on these parameters. Other types of qualitative approaches to geomorphic stream classification (Melton 1936, Popov 1964) were developed in the several decades following the work by Davis (1899). The seminal work of Leopold and Maddock (1953) laid the groundwork for future developments in quantitative geomorphic stream classification.

Leopold and Wolman (1957) presented a quantitative stream classification system based on channel planform including braided, meandering, and straight channels. Along those lines, Kellerhals and others (1976) based their classification on channel pattern along with frequency of islands, bar type, and the relationship of the channel to valley walls, land use, and geology (Montgomery and Buffington 1993).

Rosgen (1985) introduced his version of geomorphic stream classification in the mid-1980's and has since revised this system (Rosgen 1994). The uniqueness of the RCNR (Rosgen 1994) is the alpha-numeric characterization of stream types (Kondolf 1995). The RCNR is based completely on measurable physical criteria and focuses on the reach scale of streams rather than stream units or entire watersheds. However, this system is not process-based and subsequently represents the current state of the classified stream. What could be considered a complimentary classification system for an entire watershed is Montgomery and Buffington's (1993) *Channel Classification, Prediction of Channel Response, and Assessment of Channel Condition.*

Horton (1945) and later Strahler (1957) developed a stream network classification system that is still widely applied (Montgomery and Buffington 1993). However, channel network classifications are complimentary to geomorphic stream classification systems, so they will not be addressed in this paper. A comprehensive review of stream classification systems is presented by Mosley (1987).

PURPOSE

The RCNR is used not only for general stream information, but is presently being applied to resource management objectives such as stream restoration and to hydrologic model calibration. It is in the application to stream restoration, stream modification, and model calibration that the validity and comprehensiveness of the RCNR in the Pacific Northwest (PNW) is critical.

Stream channel design work usually requires specific information about the stream channel of interest; this need is not fulfilled by a stream classification system which is by definition a generalization. However, stream type can indicate channel stability and potentially suitable and unsuitable structures, diversions, or modifications for a particular stream (Rosgen and Fittante 1986). This information should be used as a tool and not as a blueprint for design.

A critical evaluation of the RCNR as it pertains to model calibration and stream channel design work in the PNW provides insight about the typical and unique streams found in this region. An evaluation of the structure and hierarchy of the classification system as it pertains to the PNW indicates the limits of this system. The ranges of such characteristics as channel slope or entrenchment may be different in the PNW as compared to other western mountain states in which case the current Rosgen classification would need to be adapted for use in this region. Potentially, there are specific stream types in the Pacific Northwest that are not well represented by the categories described in the Rosgen classification which could result in inappropriate stream classifications. An analysis of appropriate ranges and limits of the RCNR will provide information for both public and private organizations concerning the potential problems that the system may hold for the PNW or the type of modifications that are necessary for a meaningful application of this classification system.

FORMAT

This dissertation follows a manuscript format and each of the following three chapters is an individual manuscript. The first manuscript is an evaluation of the Rosgen Classification of Natural Rivers in the PNW. It is a descriptive format with descriptive statistics and represents a culmination of this study; it addresses the overall question of interest – "is the Rosgen Classification of Natural Rivers applicable and delineative enough to accurately represent the characteristics of PNW streams for applied studies such as habitat inventories, hydrologic model calibration, and stream channel design work?" The second manuscript focuses on bankfull discharge recurrence intervals in the PNW and regional patterns based on ecoregion, physiography, and climate. By regionalizing bankfull discharge recurrence intervals, the information can be applied to appropriate regions. The third manuscript focuses on regional relationships including comparisons of drainage area, discharge, channel width, channel depth, and flow velocity stratified by stream type to provide general information about ungaged streams. The first manuscript is a general, broad description of the Rosgen classification system, while the second and third manuscripts are related to applications of the RCNR.

JUSTIFICATION

The Rosgen classification was developed for use in western mountain states to fulfill the following needs: prediction of river behavior from physical appearance, prediction of channel response to various environmental stimuli, extrapolation of data from monitored streams to unmonitored streams, and finally for communication among both scientists and natural resource managers (Rosgen and Leopold 1994). There has been an extensive use of the RCNR in the PNW by many groups including federal and state agencies and private consulting firms, including the U.S. Forest Service and the Natural Resources Conservation Service (Kondolf 1995). The academic community has been less inclined to apply this system because there has been little published objective criticism of this system in general and particularly for the PNW region. The adoption of this classification system by the United States Department of Agriculture - Natural Resources Conservation Service (USDA - NRCS) for their watershed projects is the impetus behind this project.

This study provides RCNR stream classification data which will be used to calibrate the Hydrologic Unit Model of the United States (HUMUS) currently underway by USDA - NRCS. If this calibration is successful, then the RCNR could be utilized for sediment transport calculations along with its other applications. A remote classification methodology has been tested for field accuracy; this methodology may potentially be applied to further calibration of the HUMUS model. This study also provides an in-depth analysis of bankfull discharge as it is related to channel morphology and stream type. There has been much controversy and debate over the recurrence interval of the bankfull stage (Williams 1978); the data derived from this study will add empirical evidence to this debate. Field verified regional curves of drainage area versus width, depth, velocity, and discharge have been generated for various PNW regions which allow for the estimation bankfull width, depth, velocity, and discharge for ungaged streams within the respective regions. The determination of the regional boundaries is a part of this study. The criteria for evaluation include an analysis of channel width to depth ratio, channel entrenchment, and sinuosity. The analysis compares actual field measurements of these three criteria to the established ranges given in the RCNR. A critical evaluation of the RCNR and its applicability and limitations for model calibration and stream channel design work in the PNW region is the final product of this study.

The streams that were selected for evaluation are based on watersheds that contain critical habitat for salmonids. The classification of these streams provides information concerning the potential available habitat in these streams and hence the location of potential salmon enhancement projects.

TERMINOLOGY

The area of fluvial geomorphology has, like most other technical specialties, its own unique vocabulary. The following definitions will be used throughout this dissertation.

Bankfull Discharge-- (the geomorphic definition of this term will be used as opposed to the hydraulic definition) the discharge that controls the shape of the stream channel; the discharge which is the most efficient, transporting the most sediment and water with the least amount of energy.

Bankfull Discharge Recurrence Interval – The percent probability that a bankfull discharge will occur in any given year (i.e. 50% probability = 2 year flow event).

Bankfull Width-- The average width measured at the bankfull discharge level.

Width to Depth Ratio-- The ratio between the bankfull width and average bankfull depth.

Floodprone Width-- The width at twice the maximum bankfull depth.

Entrenchment-- A ratio between the floodprone width and bankfull width.

Sinuosity-- A ratio between the stream length versus the valley length.

METHODOLOGIES

Data Collection

A remote classification utilizing the RCNR for selected streams was completed prior to field data collection. Remote classification requires information about channel hydraulics and bed material which is available for streams that have active United States Geological Survey (USGS) gaging stations. The remote classification directly preceded field data collection.

All components for the stream classification were acquired in the field except sinuosity. Sinuosity requires an extensive longitudinal survey of the stream channel which was not feasible, given the number of data sites and the restrictions of private property boundaries; therefore, sinuosity was measured from USGS topographic maps. Channel slope was measured in the field for wadeable streams and was measured from topographic maps for all streams. The field measurements were compared to 20 and 40 foot contour interval topographic map measurements; the field measurements are considered to be more accurate.

Remote Measurements

A remote classification of stream types based on the RCNR requires data for the following variables: number of active channels, entrenchment ratio, width to depth ratio, sinuosity, slope, and bed material type. Most of this information can be derived by analyzing USGS gage records and topographic maps. The gage rating tables, flow frequency data, and cross-sectional remarks provide cross-sectional data, including channel width and depth, and also contain comments about the bed material at the gage cross-section. USGS form 9-275 contains water depth and station position for many different discharges which are used to construct channel cross-sections. The USGS topographic maps were used to estimate sinuosity and channel slope.

Field Measurements

Each gage site was visited during the summer of 1995 and the following data was collected: bankfull width, bankfull depth, floodprone width, channel slope (where possible) and bed material size. The stream reach to be classified was determined by the location of the stream gage and was identified by a short survey of the stream channel. By locating a cross-section in a reach that is different from a reach in which the gage is contained or in a reach different than that used by the USGS for cross-sectional measurements, the comparative analysis of the remote to field classification would be meaningless within the context of this study.

Channel slope was measured in-stream using a transit and stadia rod where possible. Bankfull width was located using field indicators as defined by Dunne and

Leopold (1978). Bankfull depth was determined by averaging the measured depths across the stream channel at the bankfull width level. Cross-section interval distances (the distance between subsequent channel depth measurements) varied depending upon overall channel width. Entrenchment is a ratio of floodprone width to bankfull width and was calculated from the field measurements. Floodprone width has been defined by Rosgen (1994) as the channel width at twice the maximum bankfull depth.

Following field data collection, the remote classification was compared with the field classification. The field classification is considered the more correct of the two approaches and remote classification accuracy was evaluated based on this assumption.

DATA ANALYSIS PROCEDURES

The data was analyzed using two different statistical methods. For the first manuscript, only descriptive statistics were utilized. The descriptive statistics contain mean values, standard deviations, and percent occurrence. The RCNR was established using graphic techniques (Rosgen 1996), therefore comparatively simple descriptive statistics are used for evaluation. For the second two manuscripts, simple linear regression, multiple linear regression, and the Kruskal-Wallis nonparametric test were used as analysis tools.

CHAPTER 2

Evaluation of the Rosgen Stream Classification System in the Pacific Northwest

Janine M. Castro

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ABSTRACT

The validity and comprehensiveness of the Rosgen Classification of Natural Rivers (RCNR) was tested on 82 streams in Oregon, Washington, and Idaho at active United States Geological Survey gaging stations. An objective evaluation of the RCNR provides typical and unique characteristics of streams in the Pacific Northwest region. Because of recent applications of the RCNR, such as channel modification, fish habitat improvement, and hydrologic model calibration, an in-depth review of this classification system to determine if it adequately describes the variety of stream morphological types in the Pacific Northwest was completed. The RCNR contains appropriate ranges of characteristics for entrenchment, width to depth ratio, channel gradient, and bed material, however, the sinuosity range does not fit many of the streams evaluated. This is potentially because of measurement errors, large woody debris loading, or lower sinuosities for streams in the Pacific Northwest compared to streams in the western mountain states where the classification system was developed. Similar findings by researchers in other regions of the United States indicates that the established sinuosity ranges in the RCNR are too high for many of the streams in the United States. The RCNR is, however, a valuable tool for evaluating streams in the PNW with physical, objective criteria.

INTRODUCTION

Stream classification is a useful tool for both scientists and managers involved in the research and management of stream systems. Classification can be generally defined as sets of observations or characteristics that are organized into meaningful groups based on measures of similarity or difference (Naiman et al. 1992). One of the most important functions of a stream classification system is communication.

Information can be succinctly presented if a classification scheme is appropriate for the area to which it is applied. The nomenclature of a classification system can act as a type of short-hand to transfer complex sets of characteristics with only a few symbols.

The classifications of Davis (1899), Leopold and Wolman (1957), and Vannote and others (1980) are some of the more well-known, but there have been many attempts at classifying rivers (Carpenter 1928, Ricker 1934, Horton 1945, Huet 1954, Pennak 1971, Bailey 1978, Warren 1979, Holmes 1983, Paustian et al. 1984, Frissell et al. 1986, Cupp 1989). There is no single classification system that is comprehensive enough to exclude all others; rather, classification systems are developed for certain physiographic and climatic areas with specific intended uses. The Davis (1899) classification is based on erosional processes and has three main categories of young, mature, and old. Leopold and Wolman (1957) classified rivers as straight, meandering, or braided, while Vannote and others (1980) classified rivers according to their ecologic function (Naiman et al. 1992). All of these classification systems are useful for specific purposes, but all have definitive limitations.

This study focuses on the stream classification system developed by Rosgen (1994). The Rosgen Classification of Natural Rivers (Rosgen 1994) is based on the morphological characteristics of stream channels. The number of active channels, entrenchment, width to depth ratio, sinuosity, channel slope, and bed material are the characteristics used to classify a stream reach. The Rosgen system only classifies stream reaches and not entire stream systems. Stream reaches are sets of hydraulic units (pools, riffles, cascades, runs, and glides) and are differentiated by hydraulic unit patterns, changes in discharge, channel geometry, substrate composition, bank composition (Parrott, Marion, and Perkinson 1989), presence or absence of vegetation and vegetation types, and factors in stream stability (channel slope, bank height, and rooting depth) (Reckendorf 1996).

The structure of a classification system can be based on a hierarchical or simple approach while the characteristics are defined in descriptive, taxonomic, genetic, empirical, or functional terms. The Rosgen system has a hierarchical structure with an empirical/descriptive approach to characterization.

OBJECTIVES

The Rosgen classification method was developed over a period of twenty years in the western mountain states to fulfill the following needs: prediction of river behavior from physical appearance, prediction of channel response to various environmental stimuli, extrapolation of data (especially stream geometry) from gaged to ungaged streams and, finally, for communication (Rosgen and Leopold 1994).

The Rosgen Classification of Natural Rivers (RCNR) was developed for use in natural stream systems. However, many streams in the United States and all over the world have been modified either directly or indirectly by human activities. Stream modification includes the obvious disruptions in the natural system such as in-stream structures (bridges, diversions, culverts), floodplain alterations (levees, vegetation removal), streambank alterations (bank revetments, vegetation removal), dam construction, and channelization, but also include more indirect activities such as hydrologic alterations and changes in the sediment load due to land use management (timber harvesting, grazing, agriculture, urbanization, road construction). There are very few streams that are completely unaltered by human activities, so it is important to establish the usefulness of the RCNR on these modified channels.

The RCNR is used not only for general stream information, but is presently being applied to resource management objectives such as stream restoration and hydrologic model calibration in the Pacific Northwest as well as other parts of the United States and England (Rosgen 1994). It is in the application to stream restoration, stream modification, and model calibration that the validity and comprehensiveness of this classification system is critical. The RCNR is being applied by many non-geomorphologists because it is easy to implement and it is relevant to land management problems (Kondolf 1995). The RCNR is being utilized by many governmental agencies in the Pacific Northwest including the U. S. Forest Service (Kondolf 1995) and the Natural Resources Conservation Service (Reckendorf and Steffen 1994).

A fisheries application of the RCNR was developed by Rosgen and Fittante (1986) which rates fish habitat structures based on stream type and was developed to provide fishery resource managers with some approximate guidelines for fish habitat improvement (Rosgen and Fittante 1986). Stream type can also be associated with relative stream stability (Table 2.1). Structural measures to increase stability can be evaluated for potential success or failure based on respective stream type (Rosgen and Leopold 1994). Because of these relationships, the RCNR is gaining widespread acceptance among governmental agencies and private consulting firms (Kondolf 1995). Stream channel design work requires specific information about the stream channel of interest; this need is not fulfilled by a stream classification system which is by definition a generalization. However, stream type can indicate potentially suitable and unsuitable structures, diversions, or modifications for a particular stream (Rosgen and Fittante 1986), but this information should be used as a tool and not as a blueprint for design. For model calibration, a quick and easy remote classification system is more useful than a field intensive classification. Therefore, the feasibility of using the Rosgen system for remote classification has been tested for accuracy and practicality on PNW streams.

Table 2.1 Rosgen Management Interpretations of Various Stream Types

Rosgen Stream Type	Sensitivity to Disturbance	Recovery Potential	Sediment Supply	Streambank Erosion potential	Vegetation Controlling Influence
A1	very low	excellent	very low	very low	negligible
A2	very low	excellent	very low	very low	negligible
A3	very high	very poor	very high	high	negligible
A4	extreme	very poor	very high	very high	negligible
A5	extreme	very poor	very high	very high	negligible
A6	high	poor	high	high	negligible
B1	very low	excellent	very low	very low	negligible
B2	very low	excellent	very low	very low	negligible
B3	low	excellent	low	low	moderate
B4	moderate	excellent	moderate	low	moderate
B5	moderate	excellent	moderate	moderate	moderate
B6	moderate	excellent	moderate	low	moderate
C1	low	very good	very low	low	moderate
C2	low	very good	low	low	moderate
C3	moderate	good	moderate	moderate	very high
C4	very high	good	high	very high	very high
C5	very high	fair	very high	very high	very high
C6	very high	good	high	high	very high
D3	very high	poor	very high	very high	moderate
D4	very high	poor	very high	very high	moderate
D5	very high	poor	very high	very high	moderate
D6	high	poor	high	high	moderate
DA4	moderate	good	very low	low	very high
DA5	moderate	good	low	low	very high
DA6	moderate	good	very low	very low	very high
E3	high	good	low	moderate	very high
E4	very high	good	moderate	high	very high
E5	very high	good	moderate	high	very high
E6	very high	good	low	moderate	very high
F1	low	fair	low	moderate	low
F2	low	fair	moderate	moderate	low
F3	moderate	poor	very high	very high	moderate
F4	extreme	poor	very high	very high	moderate
F5	very high	poor	very high	very high	moderate
F6	very high	fair	high	very high	moderate
G1	low	good	low	low	low
G2	moderate	fair	moderate	moderate	low
G3	very high	poor	very high	very high	high
G4	extreme	very poor	very high	very high	high
G5	extreme	very poor	very high	very high	high
G6	very high	poor	high	high	high

(Rosgen and Fittante 1986)

A critical evaluation of the Rosgen Classification of Natural Rivers as it pertains to model calibration and stream channel design work in the Pacific Northwest provides information about the typical and unique streams found in this area, while an evaluation of the structure and hierarchy of the classification system as it pertains to the Pacific Northwest indicates the limits of this system. The ranges of such characteristics as channel slope or entrenchment are potentially different (i.e. vary within a wider class range) in the Pacific Northwest as compared to the western mountain states, in which case the current RCNR would need to be adapted for use in this region. Potentially, there are specific stream types in the Pacific Northwest that are not well represented by the categories described in the RCNR. This would indicate a need to further study the classification system and to make appropriate modifications that are necessary. An analysis of appropriate ranges and limits of the RCNR provides information for both public and private organizations concerning the potential problems that the system may hold for the Pacific Northwest or the type of modifications that are necessary for a meaningful application of this classification system.

STUDY AREA

The study area is the Pacific Northwest region of the United States and includes selected watersheds in the states of Oregon, Washington, and Idaho (Figure 2.1). United States Geologic Survey (USGS) hydrologic units are the sampling units and the criteria for stream selection is all active stream gages within the selected hydrologic unit. All streams associated with an active gage are evaluated so there is complete selection within each sample unit. The selection of the hydrologic units is not random, but rather unit selection is based on Salmon Initiative streams as defined by the Natural Resources Conservation Service. Salmon Initiative streams are streams

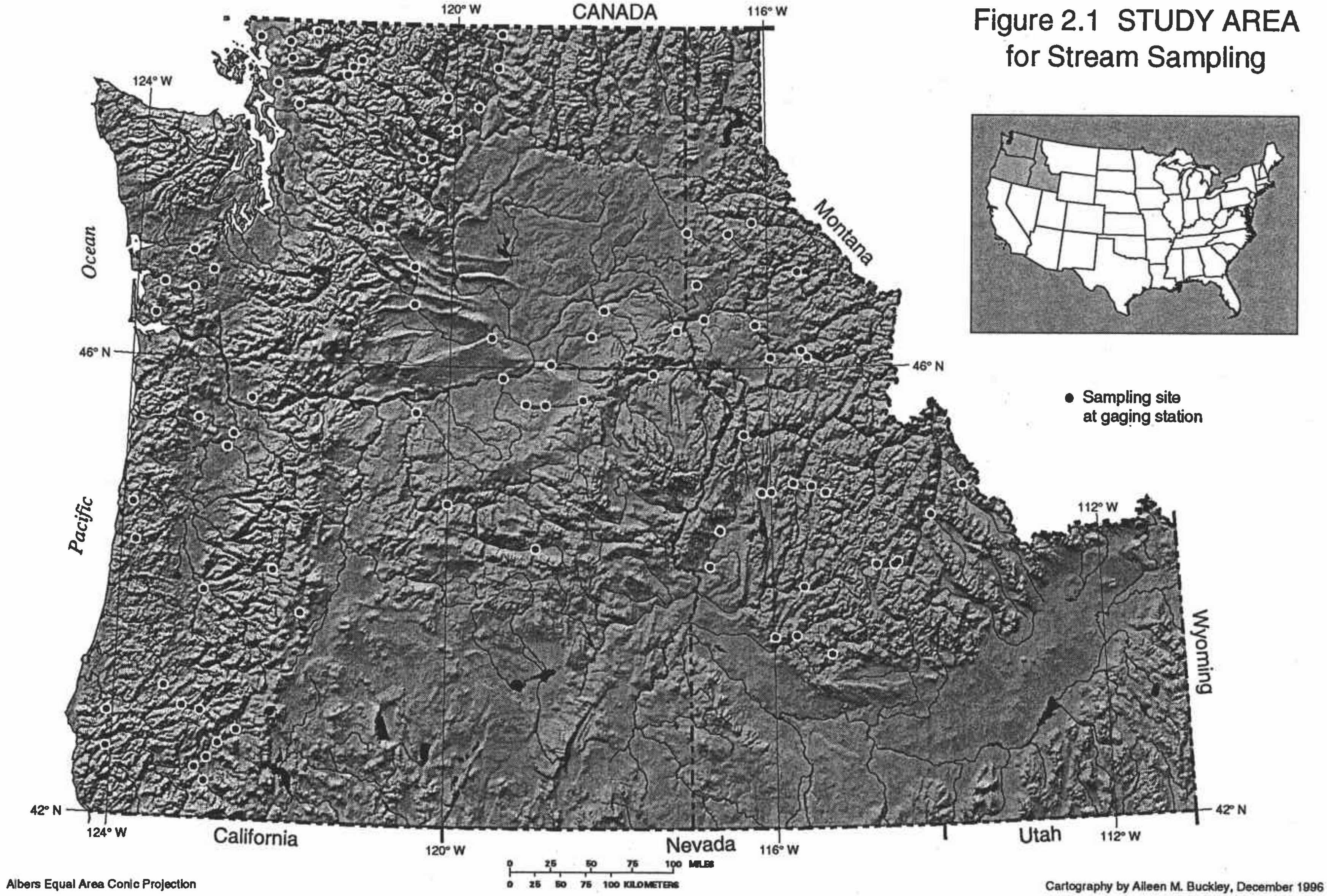


Figure 2.1 STUDY AREA
for Stream Sampling

which have present or historical populations of anadromous salmonids, an expressed public concern and interest in the fishery and the watershed, and a significant portion of the watershed must be in private ownership (USDA-SCS 1994). Streams listed in the Salmon Initiative are classified using the RCNR to provide general geomorphological information which is combined with fisheries data to establish and prioritize fisheries enhancement needs. The sampling procedure is used so that the data derived from this study can be applied to a present resource problem on private lands. The only deviation from this procedure is the sampling method for Idaho, because Idaho does not contain a sufficient number of Salmon Initiative streams to provide a statistically robust analysis. Supplementary hydrologic units were selected by choosing units that are directly adjacent to Salmon Initiative hydrologic units and analyzing all of the actively gaged streams found within this adjacent hydrologic unit.

TERMINOLOGY

The area of fluvial geomorphology has, like most other technical specialties, its own unique vocabulary. The following definitions will be used throughout this paper.

Bankfull Discharge--(the geomorphic definition of this term will be used as opposed to the hydraulic definition) the discharge that controls the shape of the stream channel; the discharge which is the most efficient, transporting the most sediment and water with the least amount of energy. The level of the active floodplain (Leopold 1994).

Bankfull Discharge Recurrence Interval-- The percent probability that a bankfull discharge will occur in any given year (i.e. 50% probability = 2 year flow event).

Bankfull Width-- The average width measured at the bankfull discharge level.

Width to Depth Ratio– The ratio between the bankfull width and average bankfull depth.

Floodprone Width– The width at twice the maximum bankfull depth.

Entrenchment– A ratio between the floodprone width and bankfull width.

Sinuosity– A ratio between the stream length versus the valley length.

Single Thread Channel– A stream with one or two continuous, active channels at bankfull discharge.

Multiple Thread Channel– A stream with three or more continuous, active channels at bankfull discharge.

Slope-- Longitudinal channel slope which is used to approximate the water surface slope at bankfull discharge.

Bed Material Size– The dominant particle size of the bed material (d50) divided into six categories of bedrock, boulder, cobble, gravel, sand, and silt/clay.

METHODOLOGY

Data Collection

A remote classification utilizing the RCNR for selected streams was completed prior to field data collection. Remote classification requires information about channel hydraulics and bed material which is available for streams that have active USGS gaging stations. The remote classification directly preceded field data collection.

All components for the stream classification were acquired in the field except for sinuosity. Sinuosity requires an extensive longitudinal survey of the stream channel which was not feasible given the number of data sites and the restrictions of private property boundaries, therefore, sinuosity was measured from USGS Topographic Quadrangles. Channel slope was measured in the field for wadeable streams and was measured from topographic maps for all streams. The field measurements were compared to the topographic map measurements to determine the level of reliability of slope measurements derived from topographic maps.

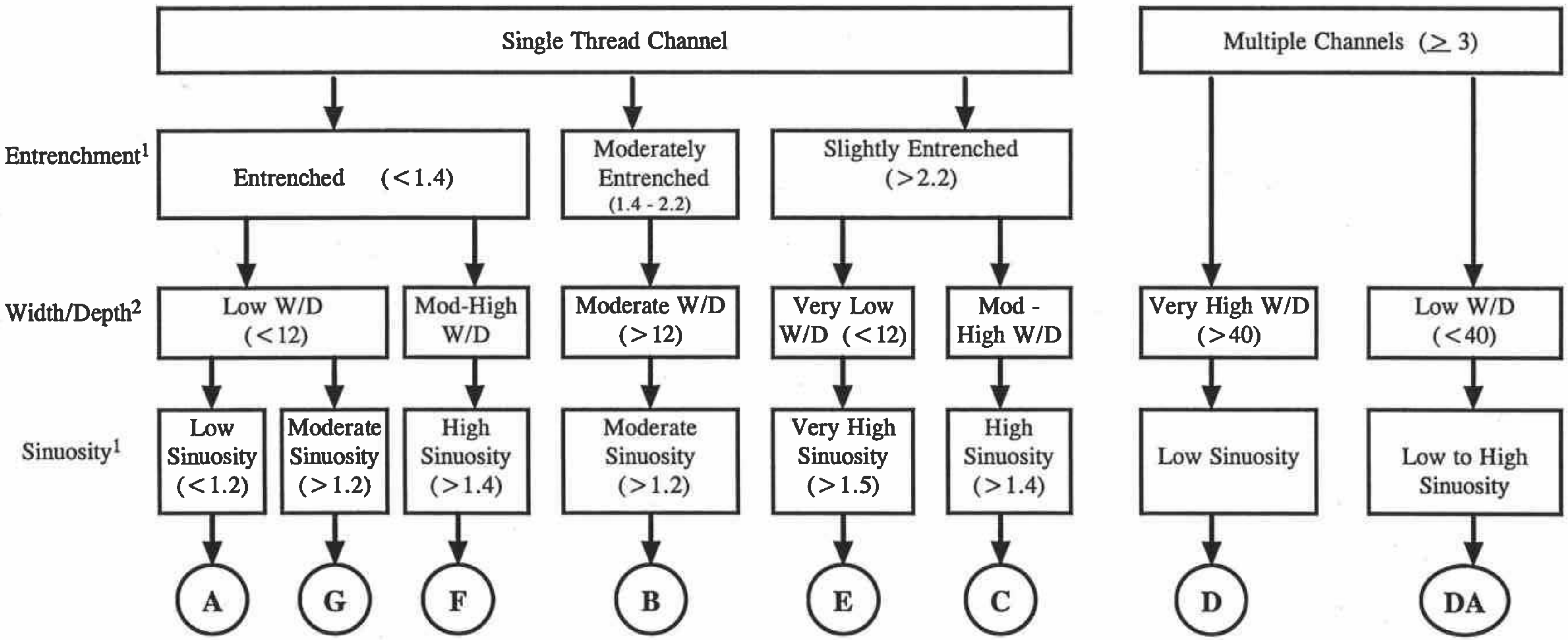
Remote Measurements

A remote classification of stream types based on Rosgen's Classification of Natural Rivers requires data for the following variables: number of active channels, entrenchment ratio, width to depth ratio, sinuosity, slope, and bed material type. Most of this information can be derived by analyzing USGS gage records and topographic maps. The gage rating tables, flow frequency data, and cross-sectional remarks provide cross-sectional data, including channel width and depth, and also contain comments about the bed material at the gage cross-section. USGS form 9-275 contain station position and elevation data which were used to construct channel cross-sections. The USGS topographic maps were used to estimate sinuosity and channel slope, but there are potential errors built into these values because of the inaccuracy of topographic maps to represent stream position and elevation. However, large streams that have limited riparian cover should be accurately represented on USGS topographic maps.

The procedure for determining entrenchment is less direct than determining the other factors necessary for stream classification. If a rating table is extensive enough, the channel width at twice the maximum bankfull depth (defined as floodprone width) can be determined. However, a rating table does not usually cover such a wide range of discharges. Other methods for estimating entrenchment are land use, channel constriction, channel straightening, and gage notes. If the land use within several hundred feet of the stream channel is residential or commercial, the channel is very probably entrenched based on the flood hazard potential associated with nonentrenched stream systems, although, this is problematic for regulated systems. Any channel constriction or channel straightening indicates entrenchment. However, it is not possible to measure channel entrenchment directly. If width measurements are not available for discharges at twice the maximum bankfull depth but depth measurements were taken at the floodprone level, then the channel is assumed to be moderately to severely entrenched. If the channel were not entrenched, it is assumed that the area surrounding the gage would be flooded and a stage height measurement would not have been taken. Using this procedure, the categories of slightly, moderately, and severely entrenched were applied without any corresponding quantitative measure except the ranges defined by Rosgen (1994) (Figure 2.2). The accuracy of high entrenchment ratios associated with streams with floodplains could be improved by reference to Federal Emergency Management Agency (FEMA) flood maps or USGS, United States Army Corps of Engineers, or NRCS floodplain maps (Reckendorf 1996).

Field Measurements

Each gage site was visited during the summer of 1995 and the following data were collected: bankfull width, bankfull depth, floodprone width, channel slope (where possible), bed material size, and the associated gage height. By determining the gage height at the bankfull level, bankfull discharge recurrence interval can be determined from flow frequency curves generated for each of the gaging stations. Once the bankfull discharge recurrence interval is determined, it can be related to geomorphic features of the channel such as the active floodplain.



[1] Values can vary by $\pm$ 0.2 units as a function of the continuum of physical variables within stream reaches
[2] Values can vary by $\pm$ 2.0 units as a function of the continuum of physical variables within stream reaches
Note: Width to depth ratio is calculated using average bankfull depth, while twice maximum bankfull depth is used to determine the floodprone width (used to calculate entrenchment).

Adapted from: Rosgen 1994

Figure 2.2 Key to Classification of Natural Rivers

The stream reach to be classified was determined by the location of the streamflow measurement gage. The reach was identified by a short survey of the stream channel using the reach indicators discussed above. By locating a cross-section in a reach that is different from a reach in which the gage is contained or in a reach different than that used by the USGS for cross-sectional measurements, the comparative analysis of the remote to field classification would be meaningless within the context of this study.

Channel slope was measured in-stream using a transit and stadia rod where possible. Bankfull width was located using field indicators as defined by Dunne and Leopold (1978). Bankfull indicators include: (1) topographic break from vertical bank to flat floodplain, (2) topographic break from steep slope to gentle slope, (3) change in vegetation from bare to grass, moss to grass, grass to sage, grass to trees, or from no trees to trees, (4) textural change of depositional sediment, (5) elevation below which no fine debris (needles, leaves, cones, seeds) occurs, and (6) textural change of matrix material between cobbles or rocks (Dunne and Leopold 1978). Bankfull depth was determined by averaging the measured depths across the stream channel at the bankfull width level. Cross-section interval distances (the distance between subsequent channel depth measurements) varied depending upon overall channel width. Streams zero to 40 feet wide were sampled at two foot intervals. Streams 40 to 150 feet wide were sampled at five foot intervals. Streams greater than 150 feet wide were sampled at ten foot intervals.

The floodprone width (width at twice the maximum bankfull depth) was determined and measured. After the survey data was collected, entrenchment (ratio of floodprone width to bankfull width) and the width to depth ratio were calculated. Average depth is used to calculate the width to depth ratio.

After all of the field data was collected, the remote classification was compared with the field classification. The field classification is considered the most correct of the two approaches and remote classification accuracy was evaluated based on this assumption.

DATA ANALYSES

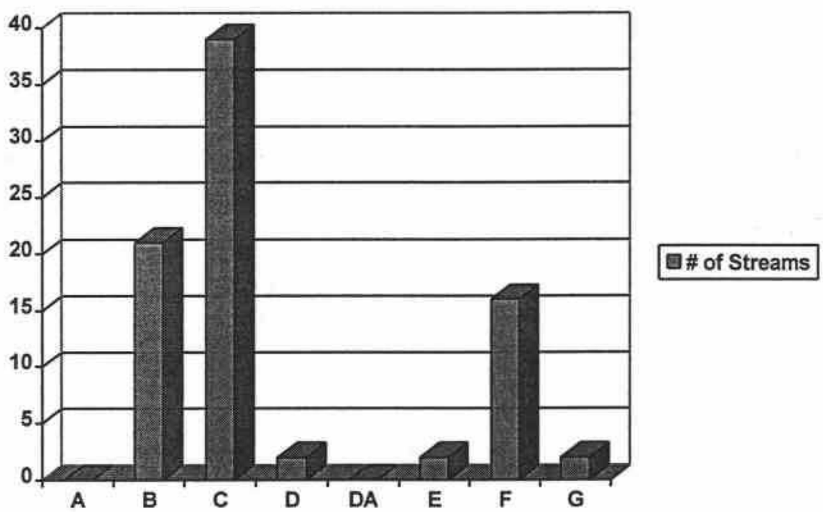
Remote Classification

The remote classification was completed for Oregon streams. Once these streams were field classified, it became evident that the remote classification was impractical because of the entrenchment variable. Since entrenchment is the second delineative variable in the hierarchical classification (after single or multiple thread channel), it is very important for correct classification of streams. More than fifty percent of the entrenchment estimates made from gage data notes and topographic maps were incorrect when compared to the field data. Since there are only three categories of entrenchment, the sites where the remote entrenchment corresponded to the field entrenchment were assumed to be as much because of random probability as correct remote classification. Remote classification was not completed for Washington and Idaho due to this inherent limitation in the remote classification process which carried through the hierarchical classification system and resulted in incorrect stream typing.

Field Classification

The field data collection provided the necessary data to classify 82 streams in the Pacific Northwest. Six of the eight major stream types were identified in the field (Figure 2.3). Of these six, there are three dominate stream types: 'B', 'C', and 'F'. There were no 'A' or 'DA' channels identified in the field. The lack of 'A' channels is probably a product of the sample selection procedure. Type 'A' streams have channel slopes greater than four percent. USGS gaging stations in this sample are typically located on larger streams which, in general, have lower gradients. The lack of 'DA' channels is probably also the result of gage site selection; since 'DA' channels are defined by multiple channels (3 or more active channels at bankfull discharge), they would be more difficult to gage than single thread channels.

Figure 2.3 – Rosgen Stream Types in the Pacific Northwest



Channel types 'D', 'E', and 'G' were each represented by two streams. This low representation can also be attributed to site selection procedures and to regional factors. 'D' channels have very unstable cross-sections (Rosgen and Fittante 1986) with multiple channels, and are therefore likely to be either discontinued by USGS or never initially established in these stream types. Frequently changing cross-sections require modifications to the gage rating table and the end result is unreliable hydrologic data for gages that have unstable cross-sections. 'E' channels frequently flood and are therefore difficult to gage because of access. The two 'E' channels that were identified in this study are located within a flood zone and the gaging stations are located above these flood zones. 'G' channels are very similar to 'A' channels and therefore have the same limitations as 'A' channels. 'G' channels can have slopes lower than two percent but their cross-sections are generally unstable. The two identified 'G' channels are on the upper limit of the width to depth ratio for this stream type (12). Placing these streams into the 'G' category was a judgment call because the streams fell within the stream continuum between 'F' and 'G' channels (width to depth ratios of 13.8 and 13.6).

The three dominant stream types, 'B', 'C', and 'F' channels, represent 92.7 percent of the data, and cover the three levels of entrenchment. Because these stream types represent such a large percentage of the data, specific details about these particular stream types will be addressed in the discussion section including a special discussion of 'D' channels.

RESULTS AND DISCUSSION

The RCNR has appropriate ranges of characteristics for entrenchment, width to depth ratio, channel gradient, and bed material. However, the sinuosity range does not fit the majority of Pacific Northwest streams sampled. The major factor may be the error associated with sinuosity representation on USGS Topographic Quadrangles, however, sinuosity was too low even on large stream channels which are more accurately represented on topographic maps. Other factors such as historic channel straightening or large woody debris loading, also impact the sinuosity range in streams of the Pacific Northwest effectively lowering the sinuosity as channels are straightened or woody debris in the channel increases (Rosgen 1996). The historical straightening that could reduce sinuosity values could be checked by comparing old aerial photographs to more recent photographs if they are available. As the amount of large woody debris in a stream channel increases, the width to depth ratio increases and the sinuosity decreases (Rosgen 1996). Large woody debris is replacing the energy dissipation of stream meanders. A similar study of sinuosity ranges for streams in Wisconsin yielded comparable results: RCNR sinuosity levels were too high (Stevens 1994).

B Channels

'B' channels are single thread, moderately entrenched (1.4 - 2.2) streams with a moderate width to depth ratio (>12) and a moderate sinuosity (>1.2). Once entrenchment is determined to be between 1.4 and 2.2 it becomes a 'B' channel by default; there are no other options in the hierarchical classification. This groups channels of very different character into the same classification. All 21 channels identified as 'B' channels in this study have channel slopes of less than two percent. The classification system attaches a 'c' to 'B' channels with slopes less than two percent.

A review of the data explains why the 'B' channels were not split into separate categories after the entrenchment determination. The data does not support any further separation because there are no identifiable patterns to the data in either width to depth ratio or sinuosity. This does not indicate that these channels are relatively similar; they're not. The median width to depth ratio is 24.0 with a range of 12.7 to 41.0 and the median sinuosity is 1.19 with a range of 1.04 to 1.56. The descriptive statistics of each channel type along with the overall descriptive statistics is found in Table 2.2 located in the Appendix.

The Rogue (Rogue River @ Dodge Bridge) and Umpqua (South Umpqua River @ Tiller) rivers in southern Oregon, parts of the Yakima River (Yakima River @ Umtanum) in central Washington, and the Selway and North Fork Clearwater rivers in Idaho are examples of 'B' channels in the Pacific Northwest.

For modified channels, constriction due to road building or railroad grades often results in what was formerly a 'C' channel that now classifies as a 'B' channel. This is because the stream is constrained to a narrower floodplain due to road grades being built on top of the floodplain at elevations high enough to avoid frequent flooding. Portions of the Yakima River in central Washington is a good example.

C Channels

'C' channels represent the largest single stream type in the study sample composing 39 of the 82 streams. 'C' channels are defined as single thread, slightly entrenched (>2.2) channels with a moderate to high width to depth ratio (>12) and a high sinuosity (>1.4). Sinuosities for the 'C' channels evaluated in this study are lower than the range presented by Rosgen. The median sinuosity value for the 39 'C' channels in this study is 1.28 with a standard deviation of 0.25. Twenty-six of the 39 'C' channels have sinuosities less than 1.4. After applying the stream continuum concept (which allows for +/-0.2 units for sinuosity), 16 of the streams are still outside of the RCNR range. All of the other ranges in the Level I and Level II classification were appropriate for the data gathered on 'C' type streams.

The Umatilla and John Day rivers in eastern Oregon, Okanogan and Nooksack rivers in northern Washington, and Pahsimeroi and Lemhi rivers in Idaho have reaches near the stream gages that are 'C' type channels in the PNW. However, in the case of the Lemhi River, much of the river downstream from the gage has been straightened and incised so that it is an 'F' and 'B' stream type (Reckendorf 1995).

D Channels

The distinction between multiple and single thread channels for the first delineation in the Level I classification is unclear. 'D' channels must have multiple channels at bankfull flow. Multiple channels are defined as three or more channels (Rosgen 1996), however, this is not noted on the classification key. Applying this definition to the two 'D' channels in this study results in a classification error. The two 'D' channels should be classified as a 'C' channel and an 'F' channel, even though their width to depth ratios exceed 60 and there are two active channels present. The Yakima River at Cle Elum, Washington, and the Weiser River in Idaho are the two streams that were originally classified as 'D' channels. After discussing the classification of 'D' channels with Rosgen (1996), these channels should subsequently be classified as a 'C' channel and 'F' channel respectively.

F Channels

Sixteen streams are classified as 'F' channels and are defined as single thread, severely entrenched (< 1.4) streams, with a moderate to high width to depth ratio (> 12) and a high sinuosity (> 1.4). The streams that classified as 'F' channels fit the classification well, except for sinuosity. Eleven of the 16 stream types had sinuosities below the range set by Rosgen (1994). Even after implementing the stream continuum concept, seven streams still remained below the range set by the RCNR.

Many of the streams that are classified as 'F' channels are entrenched because they have incised through their own floodplain and are now actively widening (the typical 'F' genesis). However, several streams in Idaho (5) are classified as 'F' channels but do not share this genesis. The Clearwater, Lochsa, Selway, and Salmon rivers which classified as 'F' channels are entrenched not because of recent accelerated incision, but because of very steep valley walls and confinement due to road construction. These channels are severely entrenched and have very high width to depth ratios, but have low sinuosities. It may be that small lateral floodplains have been eroded because of increased flows or other hydrologic changes due to land management activities. Constriction of the stream channel due to road building may increase entrenchment (indicated by a lower entrenchment ratio). The Siletz River in western Oregon and the Naselle River in southwestern Washington are examples of 'F' channels which developed because of channel incision down through the active floodplain.

Entrenchment

For modified channels, entrenchment determinations are a problem. This is especially true for channels that have been dredged. Entrenchment is based on the width at twice the maximum bankfull depth. If a channel is dredged, it has an unnaturally deep maximum depth. This forces the floodprone level up higher and may actually increase the entrenchment ratio effectively moving entrenchment from severely to moderately to slightly entrenched. For modified channels it seems appropriate to use an alternative method for entrenchment measurements. Using a multiple of 3.0 times the average channel depth rather than twice the maximum bankfull depth may eliminate some of the distortion in entrenchment caused by dredging or structure induced scouring. The range of entrenchment at twice maximum bankfull depth is 5.2 - 50.6 with an average value of 17.0, while the range is 3.3 - 48.9 with an average of 17.2 at 3.0 times the average depth (Figure 2.4). This 3.0 multiple was determined by utilizing a graphic technique comparing the twice maximum bankfull depth measurement and the corresponding 3.0 multiplied by average bankfull depth. An analysis of variance indicates that there is no statistical difference between these two data sets (p-value = 0.8765).

Width to Depth Ratio

The width to depth ratio at the bankfull discharge level is a very consistent parameter in this classification system. It is critical to calculate the width to depth ratio using average bankfull depth and not maximum bankfull depth. This parameter is a good indication if a 'C', 'B', or 'F' channel is becoming unstable, because the width to depth ratio is generally high in many unstable alluvial channels. Further delineations based on the width to depth ratio are possible within the context of this classification system. The lack of an upper limit on the width to depth ratios is a disadvantage to the system. An example is a 'C' channel with a width to depth ratio of 15 versus another 'C' channel with a width to depth ratio of 70. The streams are very different, however, they are classified as the same stream type.

Sinuosity

Sinuosity is the most problematic of the variables in the RCNR Level I and Level II classifications. Sinuosity is too low for 62.5 percent of the Pacific Northwest channels sampled. After applying the stream continuum concept, 30.5 percent of the streams are still outside of the range given for their stream type. This indicates that (1) the measurement of sinuosity from topographic maps is inaccurate, (2) streams in the Pacific Northwest have lower sinuosities than streams used to develop the RCNR, (3) larger stream systems have lower sinuosities, or (4) the range defined by the RCNR are too high for most stream systems in general. Since this sinuosity discrepancy has

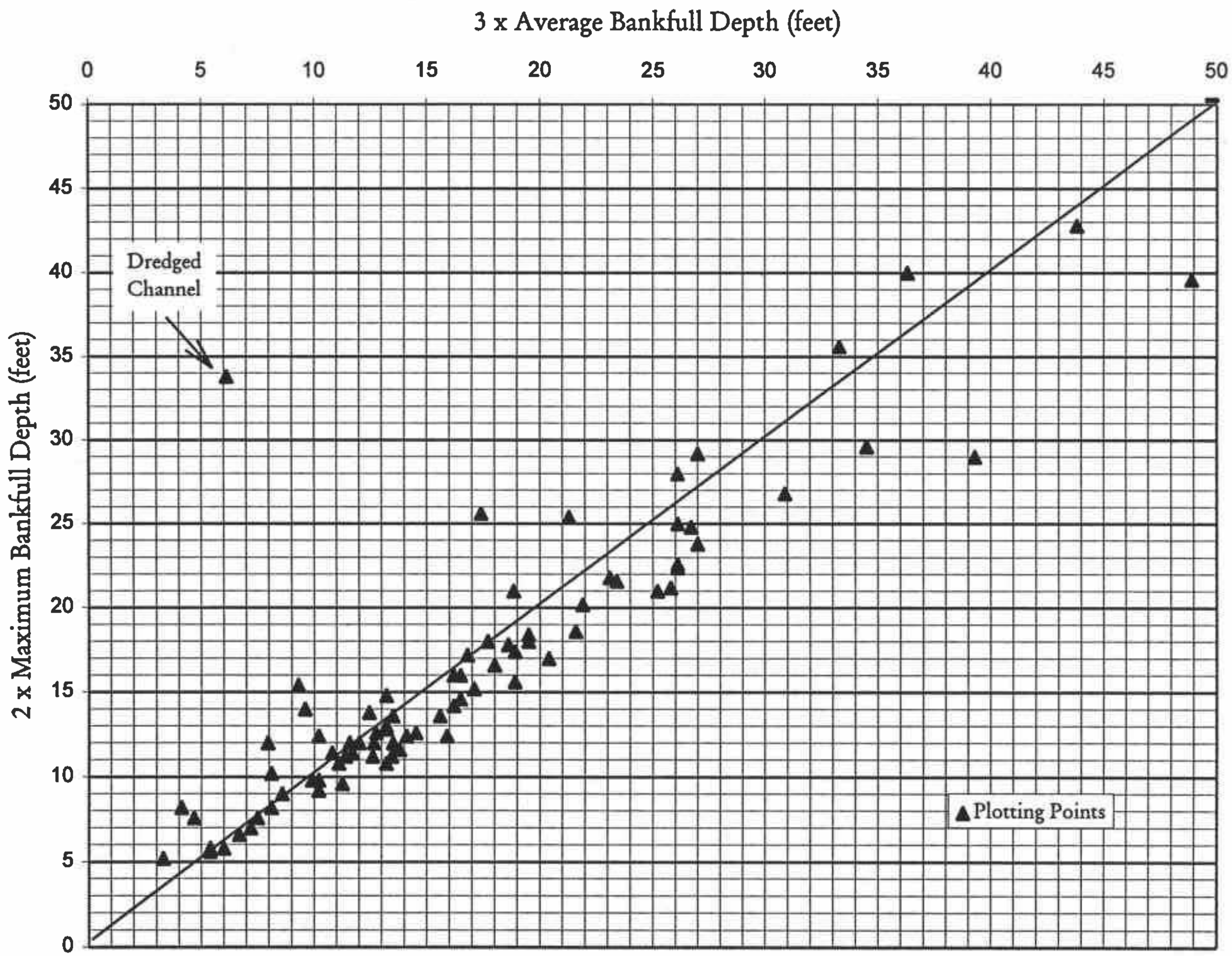


Figure 2.4 Floodprone Depth Calculation Comparison

been identified and noted by Stevens (1994) for streams in Wisconsin, there is supporting evidence that the RCNR sinuosity range is too high and should be lowered. However, it is possible that since many of the streams in this data set are not truly natural streams but are modified channels, that this modification results in a lower sinuosity. The abundance of large woody debris in streams of western Oregon and western Washington could also explain why these particular streams have low sinuosities, however, this does not apply for east side streams in Oregon and Washington and all of Idaho.

Channel Slope

Channel slope did not represent a problem in classification, but some interesting patterns did appear concerning stream gradient. Every 'B' channel identified had a slope of less than two percent. This may indicate that the B2c classification, for instance, is more common than the B2 classification in the PNW. In the RCNR, extensions such as 'b' or 'c' indicate a stream type that is within the scope of the classification type but outside of the "normal" range of that particular group (Rosgen 1994). However, the lower slopes may be a product of the site selection criteria because of the large average channel size (median width = 128 feet).

Bed Material

Because the entire spectrum of bed material is included in the RCNR, bed material is descriptive rather than delineative. One limitation is found with bi-modal distributions, such as sand and cobble. A stream that has a bedload composed of sand and cobble may have a median particle size of gravel. Classifying a stream as gravel bedded when there is essentially no gravel in the system is misleading. It is recommended that a combination of the two represented categories, such as C3/5 rather than C4, be applied to provide a more correct classification for some stream channels. Rosgen (1996) recommends that a channel be considered bedrock controlled if out of 100 samples in a Wolman pebble count, 50 or more are bedrock "hits." The same system as above could be used to indicate the average sediment size in the bedrock channel if applicable (i.e. C1(4) to indicate a bedrock channel with some gravel) (Rosgen 1996).

CONCLUSIONS

The Rosgen Classification of Natural Rivers provides a valuable system for geomorphic classification of streams in the Pacific Northwest, although a few changes in the system, such as alternative floodprone calculations, width to depth ratio upper limits, and modified sinuosity ranges, would result in a more appropriate classification for modified streams and larger stream channels in this region.

For Pacific Northwest streams, lower sinuosity categories may need to be applied. From the data available, it is not clear if the lower sinuosities are a result of measurement errors, channel modifications, or is an inherent characteristic of Pacific Northwest streams. Further field analysis of this parameter is required to make this distinction. Using the descriptive statistics as a guide, modified sinuosities for certain channel types could be adopted for PNW streams (Table 2.3).

Table 2.3 Proposed Sinuosity

Channel Type	Sinuosity	Stream Continuum
B	> 1.15	+/- 0.10
C	> 1.25	+/- 0.15
F	> 1.20	+/- 0.10

Characterization of 'D' channels based entirely on multiple channels minimizes the functional importance of the width to depth ratio. High sediment loads, shallow, wide channels, and frequently shifting active channels present similar management problems to braided stream regardless of the number of channels at any single moment in time. This issue could be addressed in the delineative criteria for 'C' channels. An upper limit to the width to depth ratio for 'C' stream types, such as 60, would separate the very wide, shallow streams from the more stable channel type. This would provide a functional category for streams that are wide and unstable similar to 'D' channels but have only a single active channel at the bankfull discharge.

The 'B' type channels are a "catch-all" category with a variety of morphologic and hydrologic attributes. It would be more useful if the 'B' channels could be split into more delineative categories, however, the data do not support any further refinement of this channel type because of a distinct lack of patterns. There is high diversity in this category but any further division would be arbitrary and would result in pseudo-categories which would not convey any additional information.

Two additions to the classification key will eliminate some common errors made while classifying streams using the RCNR. For multiple channels, noting that multiple refers to three or more active channels at bankfull will reduce the errors associated with classifying a stream with two active channels. It should be noted that average depth be used when calculating the width to depth ratio, and maximum depth be used when determining the floodprone width.

Entrenchment, width to depth ratio, channel slope, and bed material ranges within the Rosgen Classification of Natural Rivers, with very few exceptions, accurately represent the stream channels of the Pacific Northwest region. The Rosgen Classification of Natural Rivers is easily adaptable to the Pacific Northwest Region; minor modifications will provide more precise classification of river types and will assist both managers and scientists who are dealing with large numbers of streams or stream types. Modifications will vary depending upon the specific intended use of the classification data. Maintaining the primary components of the classification system (entrenchment, width to depth ratio, and sinuosity) will allow for general communication between managers, researchers, and others involved in stream studies, however, any modifications to this system should be adequately documented so that others using the system are aware of the regional adjustments.

The database developed for this study will provide further information for fluvial geomorphology research. All stream data collected for this study is contained in Table 2.4 located in the Appendix; an accompanying map (Figure 2.5, Appendix) provides the location of specific gaging station sample sites. As more data is collected and analyzed, the relationships discussed in this paper can be further evaluated and tested with greater resolution.

REFERENCES

Bailey, R.G. 1978. Description of ecoregions of the United States. Intermountain Region, United States Forest Service, Ogden, Utah.

Carpenter, K.E. 1928. *Life in Inland Waters*. Macmillan: New York.

Cupp, C.E. 1989. Stream corridor classification for forested lands of Washington. Washington Forest Protection Association, Olympia, Washington.

Davis, W. M. 1899. The geographical cycle. *Geographical Journal*. 14: 481-504.

Dunne, T. and L.B. Leopold. 1978. *Water in Environmental Planning*. W.H. Freeman and Company: San Francisco, California.

Frissell, C.A., W.J. Liss, C.E. Warren, and M.D. Hurley. 1986. A hierarchical framework for stream classification: viewing streams in a watershed context. *Environmental Management*, 10:199-214.

Holmes, N.T.H. 1983. British rivers: a working classification. *British Wildlife*, 1:20-36.

Horton, R.E. 1945. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. *Geological Society of America Bulletin*, 56:275-370.

Huet, M. 1954. Biologie, profils en long et en travers des eaux courantes. Bulletin Francais de Pisciculture, 175:41-53.

Kondolf, G.M. 1995. Geomorphological stream channel classification in aquatic habitat restoration: uses and limitations. *Aquatic Conservation*, 5:127-141.

Leopold, L.B. and Wolman, M.G. 1957. *River channel patterns: braided, meandering, and straight*. Professional Paper 282-B, United States Geological Survey: Washington, D.C.

Naiman, R.J., D.G. Lonzarich, T.J. Beechie, and S.C. Ralph. 1992. General principles of classification and the assessment of conservation potential in rivers. In: P.J. Boon, P. Calow, and G.E. Petts (eds), *River Conservation and Management. New York: John Wiley and Sons*.

Parrott, H., D.A. Marion, and R.D. Perkinson. 1989. A four-level hierarchy for organizing wildland stream resource information. *In Headwaters Hydrology:*

Proceedings of the Symposium. eds. Woessner, W.W. and D.F. Potts. American Water Resources Association: Missoula, Montana.

Paustian, S.J., D.A. Marion, and D.F. Kelliher. 1984. Stream channel classification using large scale aerial photography for southeast Alaska watershed management. RNRF Symposium on the Application of Remote Sensing to Resources Management, May 22-27, 1983: Seattle, Washington.

Pennak, R.W. 1971. Towards a classification of lotic habitat. *Hydrobiologia*, 38:321-334.

Reckendorf, F.F. 1996. Personal Communication, October 1, 1996.

Reckendorf, F.F. 1995. Lemhi River Fish Stream Improvement Study, Lemhi County, Idaho. Reckendorf and Associates, Salem, Oregon.

Reckendorf, F. and L. Steffen. 1994. Fluvial Geomorphology Workshop. USDA -- Soil Conservation Service. June 13 -- 17: Reno, Nevada.

Ricker, W.E. 1934. An ecological classification of certain Ontario streams. *Publications of the Academy of Natural Sciences of Philadelphia*, 101:277-341.

Rosgen, D.L. 1994. A classification of natural rivers. *Catena* 22: 169-199.

Rosgen, D.L. 1996. Personal Communication, December 2, 1996.

Rosgen, D.L. and B. Fittante. 1986. Fish Habitat Structures -- a selection guide using stream classification. 5th Trout Stream Habitat Improvement Workshop. Lock Haven University, Lock Haven, Pennsylvania. Pennsylvania Fish Commission Publics, Hamsburg, PA. pp. 13-29.

Rosgen, D.L. and L.B. Leopold. 1994. Short course on applied fluvial geomorphology. Course Materials by Wildland Hydrology Consultants, 1 Stevens Lake Rd., Pagosa Springs, CO 81147.

Stevens, T.A. 1994. Evaluation of the Rosgen Stream Classification System on the Chequamegon National Forest, Wisconsin. University of Idaho Masters Thesis.

USDA-SCS. 1994. Salmon Recovery Initiative Draft. United States Department of Agriculture, Soil Conservation Service, West National Technical Center, Portland, Oregon.

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E.C. Cushing. 1980. The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences*. 37: 130-137.

Warren, C.E. 1979. Toward classification and rationale for watershed management and stream protection. Report No. EPA-600/3-79-059. United States Environmental Protection Agency, Corvallis, Oregon.

APPENDIX

Table 2.2 Descriptive Statistics

Pacific Northwest Streams:

	BFW (ft)	*BFD (ft)*	*W:D*	*maxD (ft)*	*FPW (ft)*	*Entrench*	*Sinuosity*	*Slope (%)*
max	600.00	16.60	65.00	25.30	3260.00	32.50	2.07	4.30
min	13.00	1.10	4.80	2.60	42.00	1.10	1.03	0.02
median	127.50	5.02	25.70	7.10	303.50	2.34	1.25	0.38
stddev	111.82	3.26	11.82	4.52	652.78	4.03	0.25	0.64
skew	1.52	1.33	1.04	1.45	2.47	5.00	1.28	3.22

B Channels:

	BFW (ft)	*BFD (ft)*	*W:D*	*maxD (ft)*	*FPW (ft)*	*Entrench*	*Sinuosity*	*Slope (%)*
max	360.00	13.10	41.00	14.80	680.00	2.10	1.56	1.60
min	45.00	2.00	12.70	2.90	70.00	1.35	1.04	0.10
median	125.00	5.50	24.00	8.00	238.00	1.70	1.19	0.40
stddev	89.92	2.83	7.55	3.31	159.16	0.22	0.13	0.38
skew	0.76	0.90	0.47	0.27	0.87	0.05	0.79	1.80

C Channels:

	BFW (ft)	*BFD (ft)*	*W:D*	*maxD (ft)*	*FPW (ft)*	*Entrench*	*Sinuosity*	*Slope (%)*
max	590.00	16.60	65.00	25.30	3260.00	32.50	2.07	4.30
min	28.00	1.10	12.60	2.60	78.00	2.22	1.03	0.04
median	155.00	4.40	27.90	6.30	560.00	3.40	1.28	0.32
stddev	116.04	3.57	11.54	5.36	798.66	5.13	0.25	0.83
skew	1.34	1.37	1.06	1.55	1.70	4.18	1.10	2.80

D Channels:

	BFW (ft)	*BFD (ft)*	*W:D*	*maxD (ft)*	*FPW (ft)*	*Entrench*	*Sinuosity*	*Slope (%)*
max	270.00	4.40	64.70	6.40	2270.00	8.40	1.32	0.29
min	220.00	3.40	61.40	4.60	633.00	2.90	1.17	0.25
median	245.00	3.90	63.05	5.50	1451.50	5.65	1.25	0.27
stddev	35.36	0.71	2.33	1.27	1157.53	3.89	0.11	0.03

E Channels:

	BFW (ft)	*BFD (ft)*	*W:D*	*maxD (ft)*	*FPW (ft)*	*Entrench*	*Sinuosity*	*Slope (%)*
max	105.00	8.60	12.20	10.60	580.00	5.50	1.81	0.56
min	13.00	2.70	4.80	4.10	42.00	3.20	1.13	0.08
median	59.00	5.65	8.50	7.35	311.00	4.35	1.47	0.32
stddev	65.05	4.17	5.23	4.60	380.42	1.63	0.48	0.34

Table 2.2 Continued

F Channels:

	BFW (ft)	*BFD (ft)*	*W:D*	*maxD (ft)*	*FPW (ft)*	*Entrench*	*Sinuosity*	*Slope (%)*
max	600.00	16.30	44.40	19.80	750.00	1.37	1.96	1.25
min	53.00	2.04	16.10	4.80	63.00	1.10	1.04	0.02
median	140.00	5.05	25.65	7.80	160.00	1.20	1.21	0.47
stddev	134.93	3.37	9.43	4.27	166.16	0.08	0.29	0.39
skew	2.32	2.01	0.23	1.49	2.52	0.54	0.97	0.54

G Channels:

	BFW (ft)	*BFD (ft)*	*W:D*	*maxD (ft)*	*FPW (ft)*	*Entrench*	*Sinuosity*	*Slope (%)*
max	90.00	6.50	13.80	9.00	125.00	1.39	2.06	0.95
min	34.00	2.50	13.60	3.80	47.00	1.38	1.05	0.06
median	62.00	4.50	13.70	6.40	86.00	1.39	1.56	0.51
stddev	39.60	2.83	0.14	3.68	55.15	0.00	0.71	0.63

NOTE: The skew value for stream types D, E, and G are not included because of the low population in each group.

Table 2.4 Pacific Northwest Stream Data

Gage #	Stream Name	State	Type	BFW	BFD	W:D	maxD	FPW	Ent	Sin	Slope	Latitude	Longitude
14159000	McKenzie River	OR	B2c	125	5.2	24	6.8	238	1.90	1.16	0.82	44.1792	122.1292
14306500	Alsea River	OR	B4c	140	5.4	25.9	8	255	1.82	1.32	0.22	44.3861	123.8306
14308000	S. Umpqua River	OR	B1c	90	7.1	12.7	12.7	130	1.44	1.11	0.33	42.9306	122.9472
14308600	S. Umpqua River	OR	B1c	147	4.5	32.7	6.8	258	1.76	1.56	0.36	42.9681	123.1667
14339000	Rogue River	OR	B3c	240	6.28	38.2	10.5	335	1.40	1.31	0.25	42.5250	122.8417
14359000	Rogue River	OR	B1c	260	11.5	22.6	14.8	350	1.35	1.23	0.14		
14372300	Rogue River	OR	B4c	360	13.1	27.5	14.5	680	1.90	1.17	0.10	42.5806	124.0583
12020000	Chehalis River	WA	B4c	110	5.4	20.4	7.1	180	1.64	1.18	0.25	46.6175	123.2764
12179000	Skagit River	WA	B4c	240	10.3	23.3	13.4	440	1.80	1.19	0.40	48.6075	121.3606
12209000	S.F. Nooksack River	WA	B3c	125	6	20.8	8.3	202	1.60	1.04	0.19	48.6644	122.1656
12449950	Methow River	WA	B3c	110	5.5	20	8	225	2.10	1.41	0.51	48.0775	119.9839
12452800	Entiat River	WA	B4c	80	4.4	18.2	6.5	110	1.40	1.36	0.21	47.8186	120.4219
12484500	Yakima River	WA	B4c	220	7.3	30.1	10.1	427	1.94	1.16	0.18	46.8628	120.4789
13344500	Tucannon River	WA	B4c	45	2.4	18.7	3.5	70	1.56	1.16	0.51	46.5047	118.0653
14017000	Touchet River	WA	B4c	65	2	32.5	2.9	120	1.85	1.36	0.43	46.2744	118.2203
14222500	E.F. Lewis River	WA	B4c	120	5.9	20.3	9	223	1.86	1.07	0.77	45.6703	122.4650
13185000	Boise River	ID	B4c	180	4.4	41	7.4	374	2.10	1.19	0.70	43.6592	115.7261
13240000	Lake Fork Payette R.	ID	B3c	95	3.9	24.4	5.7	145	1.50	1.32	1.60	44.9136	115.9964
13316500	Little Salmon River	ID	B3c	84	4	21	6	140	1.70	1.07	1.33	45.4131	116.3247
13336500	Selway River	ID	B3c	310	8.4	36.9	10.5	504	1.60	1.25	0.40	46.0867	115.5128
13340600	N.F. Clearwater River	ID	B4c	300	8.7	34.5	11.3	500	1.70	1.07	0.44	46.8406	115.6197
13333000	Grande Ronde River	OR	C4	200	5.8	34.5	12.8	1485	7.40	1.44	0.33	45.9464	117.4483
14020000	Umatilla River	OR	C4	55	4.25	12.9	6.3	200	3.60	1.18	0.91	45.7197	118.3222
14021000	Umatilla River	OR	C1	120	3.86	31.1	6	290	2.40	1.16	0.21	45.6722	118.7917
14026000	Umatilla River	OR	C4	125	4.22	29.6	6	285	2.28	1.43	0.26	45.6772	119.0358
14038530	John Day River	OR	C4	82	1.8	45.6	2.9	600	7.30	1.09	0.57	44.4186	118.9053
14046500	John Day River	OR	C3	225	7.7	29.2	10.9	700	3.11	1.48	0.32	44.7939	120.0006
14048000	John Day River	OR	C4	285	4.4	65	5.4	800	2.80	1.25	0.73	45.5878	120.4083
14050000	Deschutes River	OR	C4	60	1.56	38.5	3.8	560	9.30	1.30	0.31	43.8142	121.7758
14157500	C. F. Willamette River	OR	C4	162	4.48	36	5.6	360	2.22	1.64	0.16	43.9806	122.9653

Table 2.4 Continued

Gage #	Stream Name	State	Type	BFW	BFD	W:D	maxD	FPW	Ent	Sin	Slope	Latitude	Longitude
14328000	Rogue River	OR	C3	160	4.15	38.6	6.9	420	2.63	1.17	1.07	42.7750	122.4986
14357500	Bear Creek	OR	C4	62	3.3	18.8	4.9	157	2.53	1.11	0.82	42.3244	122.8653
12027500	Chehalis River	WA	C5c-	300	14.6	20.5	21.4	2800	9.30	1.36	0.10	46.7761	123.0344
12031000	Chehalis River	WA	C4c-	280	16.6	16.9	25.3	2375	8.50	1.76	0.07	46.9381	123.3003
12167000	N.F. Stillaguamish R.	WA	C4	260	8.9	29.2	12.4	2310	8.90	1.86	0.16	48.2617	122.0464
12178000	Skagit River	WA	C4b	210	8.7	24.1	14	710	3.40	1.03	2.50	48.6719	121.2467
12181000	Skagit River	WA	C4	350	6.5	53.8	9.2	2350	6.70	1.32	0.17	48.5339	121.4286
12210500	Nooksack River	WA	C4	250	8.7	28.7	12.5	750	3.00	1.37	0.13	48.8106	122.2003
12213100	Nooksack River	WA	C5c-	220	12.1	18.2	20	1200	5.50	1.29	0.04	48.8450	122.5881
12439500	Okanogan River	WA	C4	590	5.7	42.1	7.6	590	2.46	1.47	0.24	48.9308	119.4192
12445000	Okanogan River	WA	C3c-	195	9	21.7	14.6	545	2.80	1.27	0.08	48.6325	119.4606
12447200	Okanogan River	WA	C5c-	245	11.1	22.1	17.8	898	3.70	1.11	0.10	48.2814	119.7033
12449500	Methow River	WA	C3	200	6.3	31.8	7.8	1240	6.20	1.41	0.30		
12500450	Yakima River	WA	C4	230	7.2	31.9	9.3	640	2.78	1.28	0.24	46.5344	120.4661
12510500	Yakima River	WA	C4c-	250	5.5	45.5	7.3	850	3.40	1.40	0.08	46.2536	119.4769
13334700	Asotin Creek	WA	C4	28	2.23	12.6	3.3	174	6.20	1.14	1.40		
14018500	Walla Walla River	WA	C3c-	92	4.84	19	6.3	317	3.45	1.79	0.10	46.0278	118.7286
12414500	St. Joe River River	ID	C3	260	6.2	42	8.9	3260	12.5	1.17	0.14	47.2747	116.1881
12414900	St. Maries River	ID	C3	95	3.4	27.9	6.2	445	4.70	1.63	0.32	47.1764	116.4917
12422950	Hangman Creek	ID	C6	40	2.7	15	5.1	1300	32.5	1.03	0.15	47.1900	117.0169
13186000	S.F. Boise River	ID	C3	125	3.8	32.9	5.6	565	4.50	1.15	0.43	43.4944	115.3056
13200000	Mores Creek	ID	C3	75	2.86	26.2	4.5	202	2.70	1.11	0.58	43.6481	115.9889
13235000	S.F. Payette River	ID	C3	155	5.3	29.2	6.2	490	3.20	1.38	0.61	44.0853	115.6211
13239000	N.F. Payette River	ID	C4	60	3.4	17.6	4.9	390	6.50	1.70	0.59	44.9075	116.1178
13258500	Weiser River	ID	C3	70	3.6	19.4	5.7	205	2.90	1.28	0.49	44.5797	116.6389
13297330	Thompson Creek	ID	C4	28	1.1	25.5	2.6	78	2.80	1.05	1.82	44.2669	114.5133
13297355	Squaw Creek	ID	C4	36	1.37	26.3	4.1	101	2.80	1.08	1.48	44.2906	114.4706
13302005	Pahsimeroi River	ID	C4	45	3.1	14.5	7.7	125	2.80	2.07	0.67	44.6919	114.0475
13305000	Lemhi River	ID	C4	60	2.65	22.6	6	260	4.30	1.11	1.90	44.9400	113.6378
13311000	E.F. of S.F. Salmon R.	ID	C3b	36	1.8	20	2.8	86	2.40	1.17	4.30	44.9058	115.3283

Table 2.4 Continued

Gage #	Stream Name	State	Type	BFW	BFD	W:D	maxD	FPW	Ent	Sin	Slope	Latitude	Longitude
12479500	Yakima River	WA	D4	270	4.4	61.4	6.4	2270	8.40	1.32	0.29		
13266000	Weiser River	ID	D3	220	3.4	64.7	4.6	633	2.90	1.17	0.25	44.2675	116.7711
14202000	Pudding River	OR	E5	105	8.6	12.2	10.6	580	5.50	1.81	0.08	45.2333	122.7489
13346800	Paradise Creek	ID	E6	13	2.7	4.8	4.1	42	3.20	1.13	0.56	46.7319	118.0233
14033500	Umatilla River	OR	F1	130	3.2	40.6	7	150	1.15	1.04	1.00	45.9031	119.3258
14203500	Tualatin River	OR	F5	53	2.04	25.9	16.9	63	1.19	1.69	0.05	45.4750	123.1231
14207500	Tualatin River	OR	F5	165	4.7	35.1	6.2	207	1.25	1.16	0.52	45.3508	122.6750
14305500	Siletz River	OR	F1	160	6.3	25.4	8.7	182	1.14	1.36	0.28	44.7153	123.8861
14312000	S. Umpqua River	OR	F4	340	9	37.8	11.9	394	1.16	1.96	0.13	43.1333	123.3972
14325000	S.F. Coquille River	OR	F4	150	3.75	40	4.8	170	1.13	1.66	0.39	42.8917	124.0694
14337600	Rogue River	OR	F4	180	8.7	20.7	11.2	225	1.25	1.38	0.48	42.6556	122.7139
12010000	Naselle River	WA	F4	95	4.6	20.7	5.8	130	1.37	1.43	0.47	46.3742	123.7422
12200500	Skagit River	WA	F5	600	16.3	36.8	19.8	750	1.25	1.83	0.02	48.4450	122.3342
12205000	N.F. Nooksack River	WA	F4	90	5.6	16.1	8.6	100	1.11	1.15	1.05	48.9061	121.8431
13296500	Salmon River	ID	F3	120	6.8	17.6	8.5	140	1.20	1.26	0.83	44.2683	114.7319
13310700	S.F. Salmon River	ID	F4	115	5.4	21.3	7.1	145	1.30	1.12	0.39	44.9872	115.7242
13313000	Johnson Creek	ID	F3	100	4.2	23.8	5.6	135	1.35	1.13	1.18	44.9622	115.4994
13337000	Lochsa River	ID	F3	280	7.8	35.9	10.8	330	1.18	1.14	0.30	46.1506	115.5864
13338500	S.F. Clearwater River	ID	F3	200	4.5	44.4	6	220	1.10	1.08	0.47	46.0867	115.9756
13339500	Lolo Creek	ID	F3	75	3.7	20.3	5.4	94	1.25	1.07	1.25	46.3722	116.1611
12013500	Willapa River	WA	G6c	90	6.5	13.8	9	125	1.39	2.06	0.06		
13342450	Lapwai Creek	ID	G4c	34	2.5	13.6	3.8	47	1.38	1.05	0.95	46.4275	116.8042

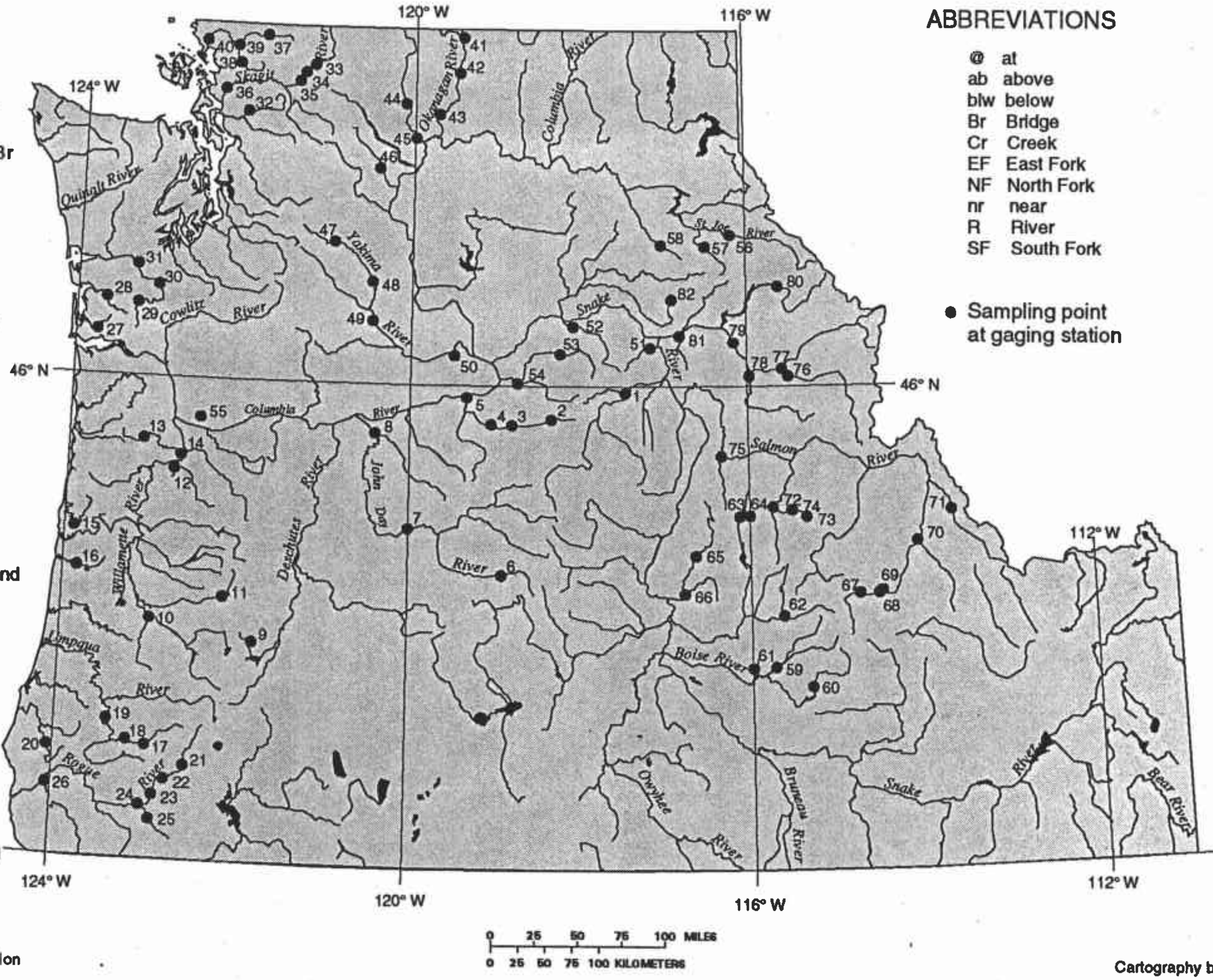
Key:

Gage #	=	USGS gaging station number
Stream Name	=	Stream name plus locational infomation
State	=	State in which the gage is located
Type	=	RCNR stream type
BFW	=	Bankfull width
BFD	=	Bankfull depth
W:D	=	Width to depth ratio
maxD	=	Maximum depth at bankfull
FPW	=	Floodprone width
Ent	=	Entrenchment
Sin	=	Sinuosity
Slope	=	Channel slope
Latitude	=	Latitude
Longitude	=	Longitude

Figure 2.5 STREAM SAMPLING POINTS

<u>OREGON</u>
1 Grande Ronde @ Troy
2 Umatilla ab Meacham
3 Umatilla @ Pendleton
4 Umatilla @ Yoakum
5 Umatilla nr Umatilla
6 John Day nr John Day
7 John Day @ Service Cr
8 John Day @ McDonald Ferry
9 Deschutes blw Snow Cr
10 Coast Fork Willamette
11 McKenzie @ McKenzie Br
12 Pudding @ Aurora
13 Tualatin nr Dilley
14 Tualatin @ West Linn
15 Siletz nr Siletz
16 Alsea @ Tidewater
17 S. Umpqua @ Tiller
18 S. Umpqua @ Days Cr
19 S. Umpqua @ Brockway
20 SF Coquille
21 Rogue ab Prospect
22 Rogue nr Mcleod
23 Rogue @ Dodge Br
24 Bear Cr @ Medford
25 Rogue @ Raygold
26 Rogue nr Agness

<u>WASHINGTON</u>
27 Naselle nr Naselle
28 Willapa nr Willapa
29 Chehalis nr Doty
30 Chehalis nr Grande Mound
31 Chehalis @ Porter
32 NF Stillaguamish nr Arlington
33 Skagit @ Newhalem
34 Skagit ab Alma Cr
35 Skagit @ Marblemount
36 Skagit nr Mt. Vernon
37 NF Noosack blw Cascade Cr
38 SF Nooksack nr Wickersham
39 Nooksack @ Deming
40 Nooksack @ Ferndale
41 Okanogan @ Oroville



Albers Equal Area Conic Projection

42 Okanogan nr Tonasket
43 Okanogan @ Malott
44 Methow @ Twisp
45 Methow nr Pateros
46 Entiat nr Ardenvoir
47 Yakima @ Cle Elum
48 Yakima @ Umtanum
49 Yakima ab Ahtanum
50 Yakima @ Kiona
51 Asotin blw Kearney Gulch
52 Tucannon nr Starbuck
53 Touchet @ Bolles
54 Walla Walla nr Touchet
55 EF Lewis nr Heisson

<u>IDAHO</u>
56 St. Joe
57 St. Maries
58 Hangman Creek
59 Boise R nr Twin Sp
60 SF Boise
61 Mores Cr
62 SF Payette
63 NF Payette
64 Lake Fork Payette
65 Weiser nr Cambridge
66 Weiser @ Presley Switch
67 Salmon R blw Yankee Fork
68 Thompson Cr
69 Squaw Cr
70 Pahsimerol @ Ellis
71 Lemhi
72 SF Salmon
73 EF of SF Salmon
74 Johnson Cr
75 Little Salmon nr Riggins
76 Selway
77 Lochsa
78 SF Clearwater
79 Lolo Cr
80 NF Clearwater
81 Lapwai Cr nr Lapwai
82 Paradise Cr @ Moscow

Cartography by Aileen M. Buckley, December 1996

CHAPTER 3

Bankfull Flow Recurrence Intervals:
Patterns in the Pacific Northwest

Janine M. Castro and Dr. Philip L. Jackson

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ABSTRACT

Bankfull discharge recurrence interval in streams has been reported to be approximated at a 1.5 year flow event. This study tests the linkage between regional factors (climate, physiography, and ecoregion) in the Pacific Northwest (PNW) and the frequency of bankfull discharge events. It is our position that stream management strategies, especially those designed to assist stream restoration work, should be geographically relevant and operate within an understanding of regional relationships between channel types and variability in bankfull discharge recurrence intervals. The mean value for bankfull discharge recurrence interval in the PNW is 1.4 years; however, when the data is stratified by ecoregion, the more humid areas of western Oregon and western Washington have a mean value of 1.2 years, substantially below the 1.5 year average used by other authors. Climate is a statistically significant factor for bankfull discharge recurrence interval while physiography is not. When more data becomes available, other regional or subregional factors, such as hydrologic regime, could be tested to determine if they are controlling factors for bankfull discharge recurrence intervals.

INTRODUCTION

"Bankfull stage" is defined as the stream level which "corresponds to the discharge at which channel maintenance is most effective, that is, the discharge at which moving sediment, forming or reforming bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channels" (Dunne and Leopold 1978, p. 608). Bankfull stage has applied importance for the design of fish habitat structures, streambank restoration designs, and other instream and riparian work. By providing approximations of the bankfull discharge recurrence interval, scientists and managers can more accurately estimate both physical and biological responses to stream corridor manipulations and estimate project costs.

Research on bankfull discharge recurrence intervals for North American streams has resulted in general agreement that bankfull recurrence intervals are approximately equal to a 1.5 year event (annual maximum), (Dury et al. 1963; Leopold, Wolman, and Miller 1964; Hickin 1968; Dunne and Leopold 1978; Leopold 1994). Williams (1978) however, found that while the mode value of bankfull discharge recurrence for 36 active floodplain stations he observed was approximately a 1.5 year event, the large variability in his data set (1 to 32 years) caused this 1.5 year interval to be of little value for the stations evaluated. Nolan and others (1987) suggested that there is a link between stream channel type and bankfull discharge recurrence interval, and that this relationship may explain some of the variability found in the recurrence intervals. This paper tests such a linkage in the context of regional factors potentially related to stream channel morphology. It is our position that stream management strategies, especially those designed to assist stream restoration work, should be geographically relevant and operate within an understanding of regional relationships between channel types and variability in bankfull discharge recurrence intervals. To investigate this potential relationship, an extensive field survey of 82 gaged streams in the Pacific Northwest (PNW) was completed during the summer of 1995.

The field survey utilized the Rosgen Classification of Natural Rivers (RCNR), (Rosgen 1994), to evaluate the delineative attributes of this system and its usefulness for describing the streams found in this diverse geographic region. Since the RCNR is based on the morphologic characteristics of stream channels at bankfull stage, the stream surveys were conducted at active United States Geological Survey (USGS) gaging sites so that discharge at the field identified bankfull level could be determined. There are many definitions of bankfull discharge, however for this paper, it is defined as the elevation of the active floodplain which is the level surface formed by the stream during the present climate (Leopold 1994).

OBJECTIVES

One objective of this study is to test the validity of the 1.5 year bankfull discharge recurrence interval. The data were stratified by stream type to determine if a relationship exists between bankfull discharge recurrence interval and stream morphology. A second objective is to determine if there are any broad scale regional patterns to the bankfull discharge recurrence interval. Regionalization was based on criteria related to climatic, physiographic, and ecoregion characteristics. The shape of a stream channel is generally agreed to be controlled by the discharge, characteristics of the bedload, character and composition of the channel bed and bank material, and local vegetation (Leopold, Wolman, and Miller 1964). Climatic patterns affect stream discharge and vegetation to a large extent, while physiography influences the characteristics of the bedload, channel banks, and channel bed. Ecoregions combine vegetation and physiography, thereby regionalizing many of the factors that are thought to control the shape of the stream channel.

STUDY AREA

The study area includes selected watersheds in the states of Oregon, Washington, and Idaho. USGS hydrologic units are the sampling units and all streams associated with an active gage are evaluated so there is complete selection within the sample unit (Figure 3.1). The selection of the hydrologic units is not random, but rather unit selection is based on Salmon Initiative (SI) streams as defined by the Natural Resources Conservation Service. Salmon Initiative streams are those which have present or historical populations of anadromous salmonids and/or threatened or endangered species. The watersheds must contain privately owned lands and there must be an expression of strong public concern and interest in the fishery and the watershed (USDA-SCS 1994). Eighty-two streams in Oregon, Washington, and Idaho were evaluated. In Idaho, where relatively few SI streams have been designated, streams directly adjacent to SI hydrologic units were sampled to provide a statistically viable analysis.

Geographic position and landform character combine to produce the unique climatic patterns of the Pacific Northwest that result in distinctive regional differences in annual runoff amounts, seasonal stream flow cycles, and the type and density of vegetation. Mid-latitude, west coast position dictates a wet-winter, dry-summer precipitation regime over much of the region, while strong oceanic and continental contrasts result from coastal and interior mountain chains. Pacific border ranges, the Olympics to the north, the central Coast Range, and the Siskiyou-Klamath mountains to the south, draw huge amounts of precipitation from winter storms sweeping in from the Pacific. Farther inland, the orography of the High Cascade crest effectively completes the regional east-west moisture divide. The result of this east-west divide is a distinctive difference in vegetative communities, described broadly by Franklin and Dyrness (1973) as the western evergreen forest zone, the eastern evergreen forest zone, and the shrub-steppe-juniper zone.

In the region's interior, the northern Rocky Mountains of Idaho, and the Blue and Wallowa ranges of northeast Oregon are climatically different from the surrounding more arid Columbia Basin, Snake River Plain, and High Lava Plateau. While the vast interior area takes on the continental character of greater seasonal

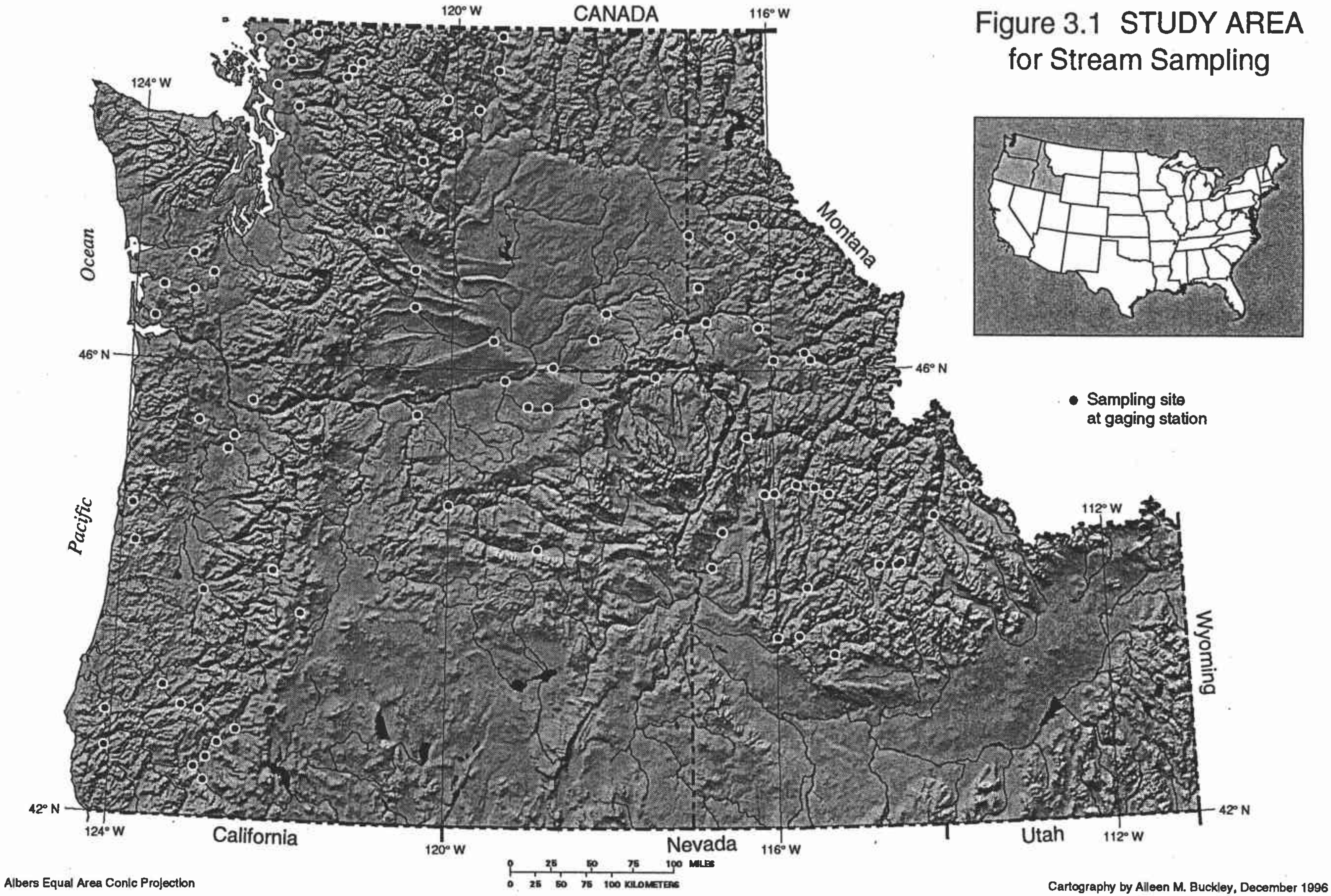


Figure 3.1 STUDY AREA for Stream Sampling

temperature ranges, the mountains have much higher annual precipitation totals, primarily in the form of winter snow and spring rain.

In terms of average equivalent depth of water, the region's highest yearly runoff, as much as 150", is found along the western flanks of the Coast Range and Olympic Mountains. The Cascades produce a runoff of nearly 120", and at the crest of the Blue Mountains, runoff amounts to about 20", while the northern Rocky Mountains of Idaho produce between 20" and 40" annually. Resulting stream flow cycles alternate naturally between high winter flows and low autumn flows west of the Cascades, with bankfull conditions occurring during the cool season. To the east of the Cascades, high flow periods occur in late spring and early summer, with low flows in late autumn and winter. The Columbia River, and its Canadian tributaries, reach natural high flows in mid-summer (Highsmith 1968).

METHODOLOGY

Gage Data

Compilation of stream gage data for the purpose of flow frequency curve generation was completed during the winter and spring of 1995. Annual flow frequency curves were created using USGS gage data and the 1.5 year stream discharge was determined. The annual maximum flow frequency curves were generated using up to fifty systematic events representing 50 years of data. For gages with more than fifty years of record, the fifty most recent events were utilized.

Field Measurements

Bankfull indicators were visually observed in the field using guidelines set out by Dunne and Leopold (1978). Bankfull indicators include: (1) topographic break from vertical bank to flat floodplain, (2) topographic break from steep slope to gentle slope, (3) change in vegetation from bare to grass, moss to grass, grass to sage, grass to trees, or from no trees to trees, (4) textural change of depositional sediment, (5) elevation below which no fine debris (needles, leaves, cones, seeds) occurs, and (6) textural change of matrix material between cobbles or rocks. Once the bankfull width was determined, the stage height was surveyed at the bankfull level. For streams which had no outside gage available, all measurements were taken and a note was made of the height of the bankfull level above the observed water surface at the gaging station. The USGS was then contacted to determine the gage height at the date and time that the survey was conducted. Using the most recent rating table (obtained from the USGS database) the gage height was related to discharge which was then taken as the field measured bankfull discharge. This discharge was then found on the annual maximum flow frequency curve to determine the field derived bankfull discharge recurrence interval. Several streams have bankfull discharge values below a 1.0 year event; these were recorded as 1.0 year events or events that have nearly a 100 percent chance of occurring in any single year.

Analytical Techniques

Bankfull discharge recurrence intervals were evaluated using an analysis of variance (ANOVA) to determine regional patterns and the associated summary statistics. The data was transformed using a reciprocal transformation to adjust for the non-normal distribution; a reciprocal transformation is appropriate for recurrence interval data (Ramsey and Schafer 1993). The bankfull discharge recurrence intervals were stratified by RCNR stream type and analyzed using an ANOVA to determine if there is a difference between group (stream type) means. The data was then stratified by regions which include climate, physiography, and ecoregion. Again, these data were analyzed using an ANOVA to evaluate differences between group means and establish regional patterns. These groups were also analyzed using the Kruskal-Wallis non-parametric method. Since mean values are of critical importance, and reciprocal transformation data cannot be back-transformed, once groups were defined as being statistically unique, descriptive statistics for the selected region were calculated from the non-transformed data.

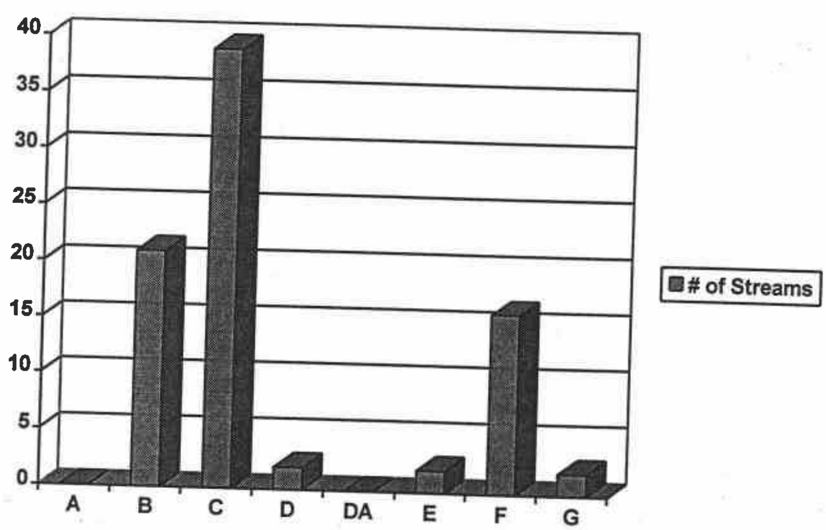
Stream Type

Six of the eight major Rosgen (1994) stream types were identified in the PNW. Of these six, three stream types dominate: 'C', 'B', and 'F' (Figure 3.2). There were no 'A' or 'DA' channels identified in the field. The lack of 'A' channels is probably a product of the sample selection procedure. Type 'A' streams have channel gradients greater than four percent and are usually smaller tributary channels in mountainous areas. USGS gaging stations in this sample are typically located on larger streams which, in general, have lower gradients. The lack of 'DA' channels is probably a result of site selection by the USGS; the presence of multiple channels results in excessive gage station monitoring and calibration to insure reliable data, therefore stream reaches with multiple channels are rarely used as USGS gage sites.

Channel types 'D', 'E', and 'G' were each represented by two streams. This low representation can also be attributed to site selection procedures and to regional factors. Stream gages are often discontinued by USGS for channels that have very unstable cross-sections such as a 'D' stream type (Rosgen and Fittante 1986).

Frequently changing cross-sections require modifications to the gage rating table with the end result being unreliable hydrologic data for gages that have unstable cross-sections. Stream channels that frequently flood, such as 'E' stream types, are difficult to gage because of access problems. The two 'E' channels that were identified are located within a flood zone and the gaging stations are located above these flood zones. Similar entrenchment and width to depth ratios cause 'G' channels to be very similar to 'A' channels and therefore have the same limitations as 'A' channels for USGS gaging stations. 'G' channels can have slopes lower than two percent but their cross-sections are generally unstable (Rosgen and Leopold 1994).

Figure 3.2 – Rosgen Stream Types in the Pacific Northwest



The three dominant stream types in the PNW study sample are 'B', 'C', and 'F' channels. Even though only three channel types represent 92.7 percent of the data, they do cover the three levels of entrenchment as set out by Rosgen (1994).

Distinguished by their classic pool/riffle morphology, 'C' channels are often found in wide alluvial valleys and have low to moderate gradients. These streams are not entrenched, have width to depth ratios greater than 12, and have high sinuosity (>1.4). 'B' channels are moderately entrenched with moderate width to depth ratios (>12), and are often found in mountainous areas with U-shaped valley bottoms. 'F' channels are entrenched systems that are generally confined by valley walls or abandoned floodplains and have a high width to depth ratio (>12) and high sinuosity (>1.4) (Rosgen 1994).

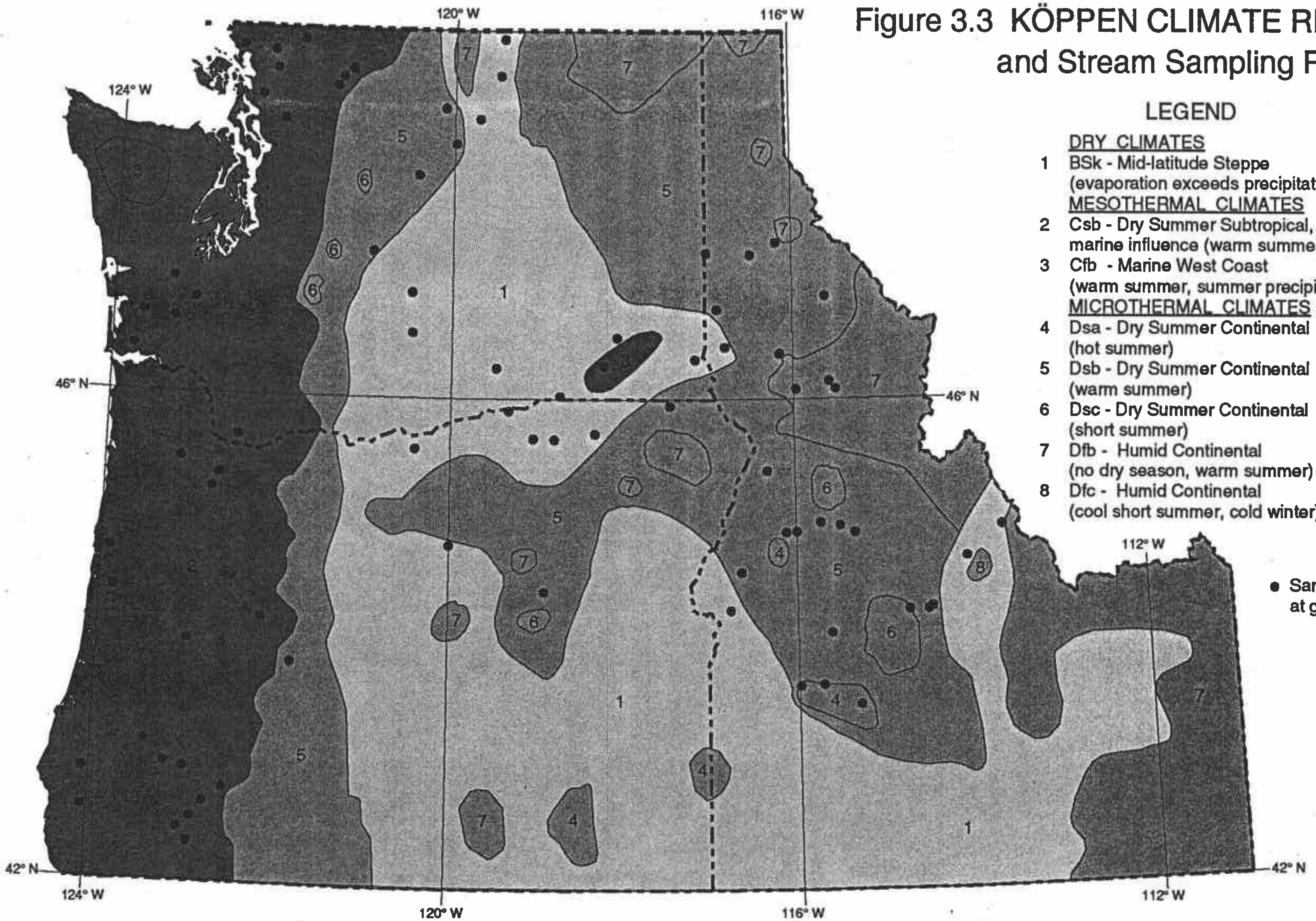
Climate

The climatic patterns of the Pacific Northwest were regionalized according to the Köppen-Geiger classification system. Köppen's classifications system, while truly a global scale empiric view of climatic features, offers a suitable procedure for classifying broad regional patterns within the PNW. This climatic classification takes into account the amount and type of precipitation, temperature, seasonality, and vegetative associations. The Köppen system was chosen because of its widespread use and general acceptance by the academic community and because of the ease of application to the Pacific Northwest (Trewartha and Horn 1980).

The Pacific Northwest can be classified into three broad Köppen climate regions (Figure 3.3). These regions, and two associated sub-regions, have been delineated and mapped according to nearest-neighbor analysis, from the classification of 72 geographically representative weather stations (Lucas and Jackson 1995).

The mid-latitude steppe (BSk) summarizes the character of the interior dry climate area. Mesothermal climates, predominately subtropical dry-summer (Csb) and west coast (Cfb), are found in much of the region west of the Cascade Range; the

Figure 3.3 KÖPPEN CLIMATE REGIONS and Stream Sampling Points



LEGEND

DRY CLIMATES

1 BSk - Mid-latitude Steppe (evaporation exceeds precipitation)

MESOTHERMAL CLIMATES

2 Csb - Dry Summer Subtropical, marine influence (warm summer)

3 Cfb - Marine West Coast (warm summer, summer precipitation)

MICROTHERMAL CLIMATES

4 Dsa - Dry Summer Continental (hot summer)

5 Dsb - Dry Summer Continental (warm summer)

6 Dsc - Dry Summer Continental (short summer)

7 Dfb - Humid Continental (no dry season, warm summer)

8 Dfc - Humid Continental (cool short summer, cold winter)

● Sampling site at gaging station

Lucas, B. and P.L. Jackson. 1995. Köppen Climate Classification of the Pacific Northwest, Unpublished map (scale 1:4,000,000).

0 25 50 75 100 MILES
0 25 50 75 100 KILOMETERS

Albers Equal Area Conic Projection
Cartography by Aileen M. Buckley, December 1996

mountainous areas including the Cascades and interior ranges to the east are classified as microthermal, or summer-dry continental, and humid continental climates (Ds, Df) (Jackson 1992).

The mid-latitude steppe region (BSk) is typified where potential evaporation exceeds precipitation. This is a vast area encompassing the Columbia Intermontane physiographic province which extends from the Columbia Basin in the north, through the Harney High Lava Plateau, and eastward into the Snake River Plain. Here, the factors of rainshadow, interior location, high elevation, semi-permanent high pressure, and cold, dry, polar air influence in winter combine to produce aridity and large seasonal temperature ranges. Annual precipitation averages 7-14" with over 80 percent occurring as winter snow and spring rain. Peak runoff in locally fed streams occurs in late spring as convective rainstorms melt foothill and mountain snowpacks. Except for the Columbia Basin and the Snake River Plain, much of the runoff results in intermittent stream flow and interior drainage.

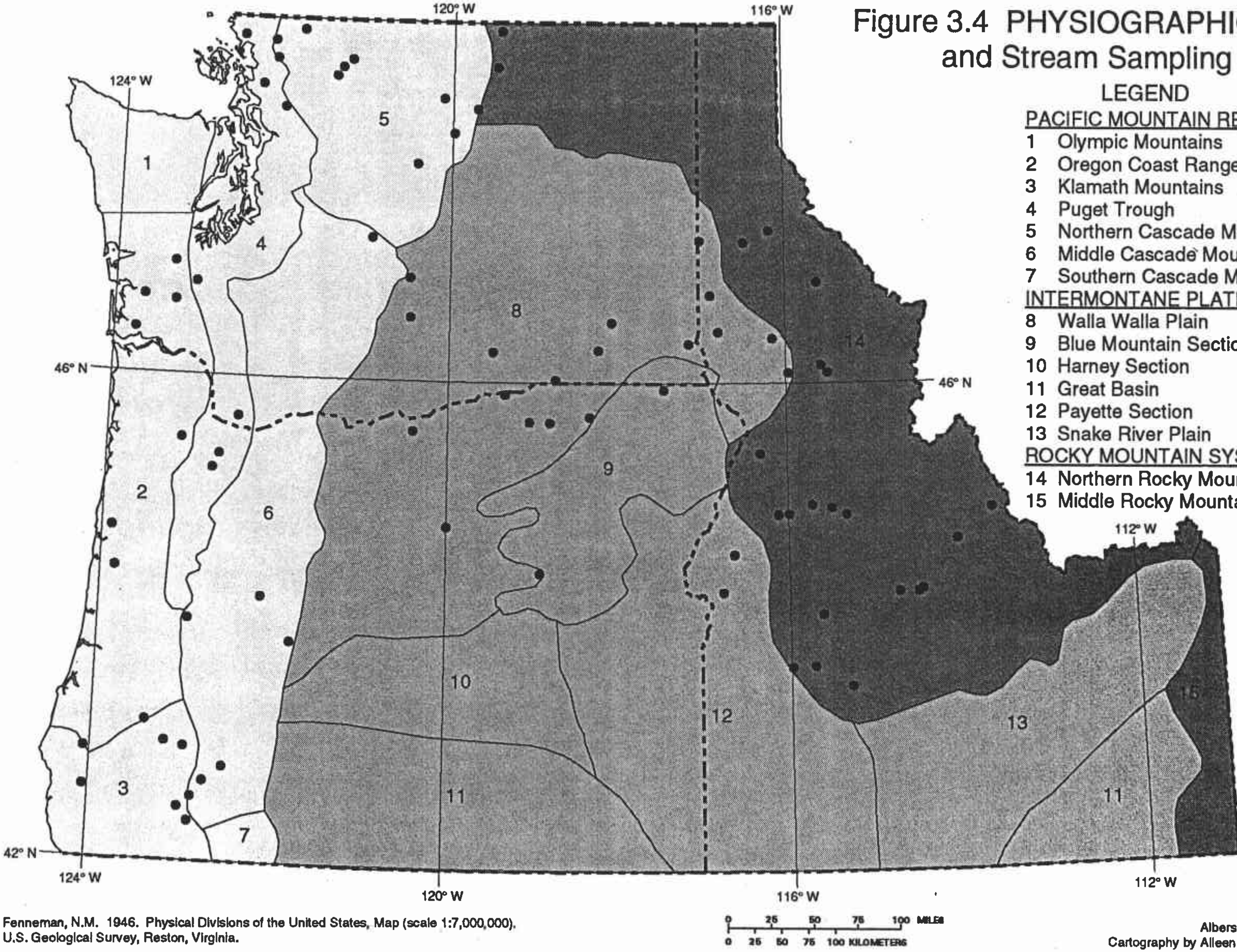
The mesothermal climates (C) are characterized by a modest seasonal temperature range and annual precipitation exceeding evaporation. The Csb climate, known as dry-summer subtropical, is found to the west of the Cascade Range in the Rogue, Willamette, and Puget lowlands, and west to the Pacific Ocean. The marine west coast climate (Cfb), featuring year-round precipitation, is limited geographically to the Olympic Peninsula; however, much of the coastal zone is humid, even in summer, due to heavy night and morning fog formation. Winter months are dominated by zonal jet stream flows and fronts that produce copious amounts of precipitation. Coastal rivers respond rapidly to these storm events, with highest stream flow levels occurring intermittently from December through March. Peak runoff events occur under antecedent conditions of surface saturation, with heavy rains falling on melting mountain snowpacks.

The microthermal climates (D) occur throughout the major mountain areas where cold, snowy winters and warm, short summers are the rule. The Dsb climate, a dry-summer continental classification, is somewhat unique, mapped by Köppen and Geiger (1930) as occurring only in the PNW and in the Pantid Mountains extending through northern Turkey and Iraq. Annual snowfall in the western Cascades, 300-500" on average, greatly exceeds the 35-75" totals in the Blue and Rocky Mountains to the east. Runoff is chiefly from snowmelt, peaking in the late spring and early summer.

Physiography

The physiographic regions are based on the Physical Divisions of the United States by Fenneman (1946). The Major Divisions of Fenneman's (1946) physiography are represented in the Pacific Northwest by the Rocky Mountain System, the Intermontane Plateaus, and the Pacific Mountain System (Figure 3.4). The Rocky Mountain System within the PNW study area encompasses only the northern Rocky Mountains. The Intermontane Plateaus include the Columbia Plateau, Colorado Plateau, and the Basin and Range Province, however, the PNW gage sites are represented only by the Columbia Plateau which includes the Walla Walla Plain, Blue Mountains, Harney Section, Payette Section, and Snake River Plain. The Pacific Mountain System division includes the Sierra-Cascade Mountains and the Pacific Border Province in the PNW. The Pacific Mountain System is composed of the following seven provinces in the study area: Olympic Mountains, Oregon Coast Range, Klamath Mountains, Puget Trough, and the Northern, Middle, and Southern Cascade Mountains.

Figure 3.4 PHYSIOGRAPHIC REGIONS and Stream Sampling Points



LEGEND

PACIFIC MOUNTAIN REGION
1 Olympic Mountains
2 Oregon Coast Range
3 Klamath Mountains
4 Puget Trough
5 Northern Cascade Mountains
6 Middle Cascade Mountains
7 Southern Cascade Mountains

INTERMONTANE PLATEAUS
8 Walla Walla Plain
9 Blue Mountain Section
10 Harney Section
11 Great Basin
12 Payette Section
13 Snake River Plain

ROCKY MOUNTAIN SYSTEM
14 Northern Rocky Mountains
15 Middle Rocky Mountains

● Sampling site at gaging station

Fenneman, N.M. 1946. Physical Divisions of the United States, Map (scale 1:7,000,000). U.S. Geological Survey, Reston, Virginia.

Albers Equal Area Conic Projection
Cartography by Aileen M. Buckley, December 1996

The Rocky Mountain System is the area north and west of Yellowstone National Park within the boundaries of the United States. The area is typified by homogeneous mountain peak elevations and the lack of distinct directional trends or mountain ranges. The mountainous areas are divided by valleys or canyons. Igneous and metamorphic rocks dominate the mountains while Tertiary lake bed deposits are more typical of the valleys (Fenneman 1931).

The Columbia Plateau encompasses approximately 100,000 square miles of Washington, Oregon, and Idaho. The boundaries are the Cascade Range to the west, the Rocky Mountain Province to the north and east, and the Great Basin to the south. The transition from the Columbia Plateau to the Great Basin is gradual so the position of this physiographic boundary is somewhat arbitrary. This area is composed primarily of horizontal layers of lava which have a surface expression of level plateaus or rolling hills (Fenneman 1946). The Columbia Plateau is distinctive because of the dissected volcanic plateaus, complex mountains, and young incised valleys (Rosenfeld 1985).

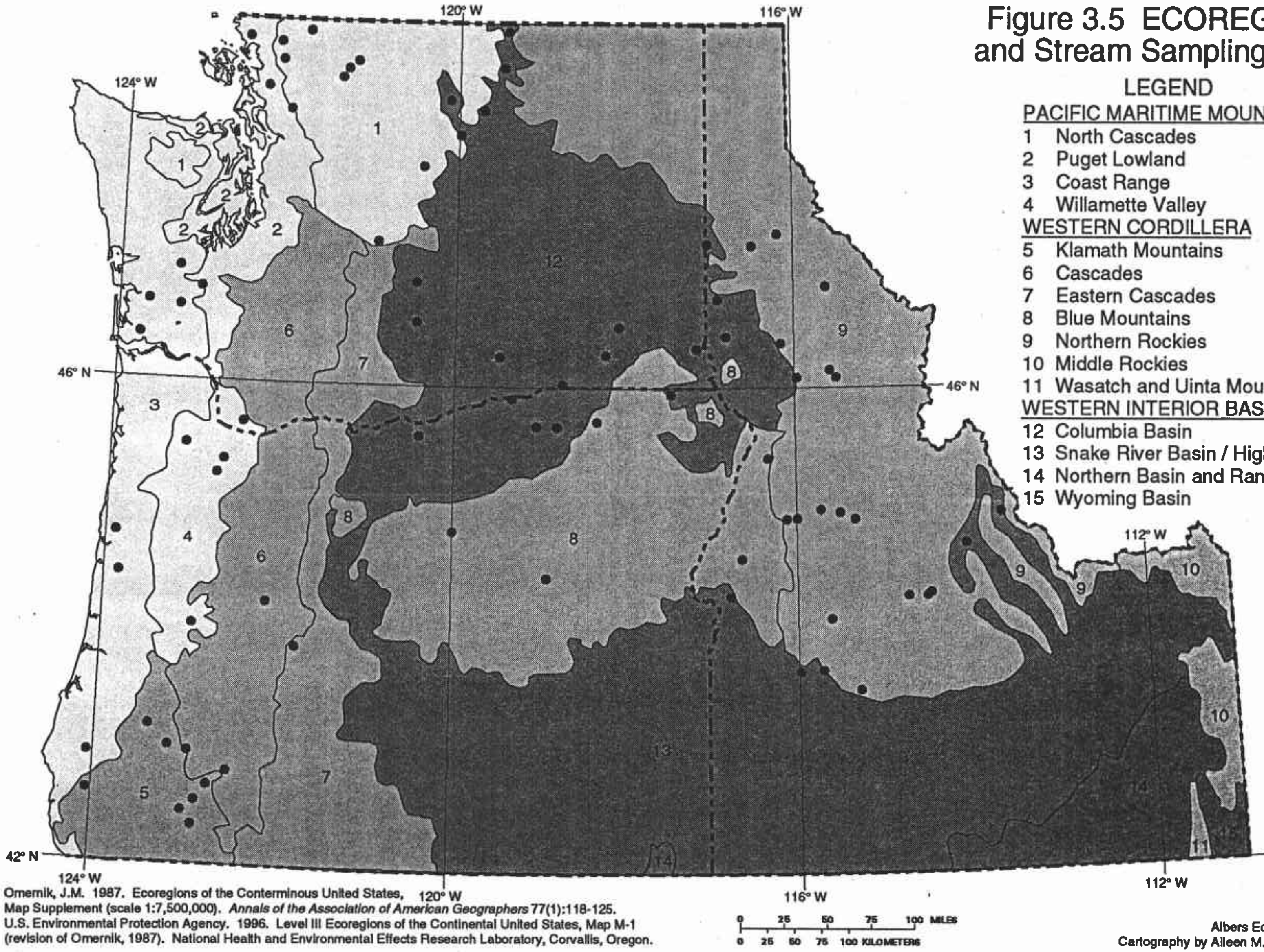
The Pacific Mountain System is defined by north-south trending mountain ranges and a line of great valleys. The northern, middle, and southern Cascade Mountains, representing the Cascade-Sierra Mountains, have sharp alpine summits of accordant height and predominant volcanic cones. The Pacific Border Province and Cascade-Sierra Mountains express this north-south pattern in the PNW. The Willamette, Cowlitz, Upper Chehalis, and Puget Sound Valleys are the result of crustal deformation along a north-south axis. The Puget Trough, which includes the above valleys, is approximately 350 miles long in its United States extent and up to 50 miles in width. The Olympic Section is very similar to the Cascades with accordant crests and local alpine peaks. The Oregon Coast Range extends from the Olympic Mountains in Washington south to the Klamath Mountains in southern Oregon. The Coast Range is composed of weak rocks that have been severely eroded resulting in deeply dissected mountains. The Klamath Mountains are located west of the Cascades between the Coast Ranges of Oregon and California and are composed of older, more resistant rock than the Oregon Coast Range (Fenneman 1946).

Ecoregions

Ecoregions as defined and mapped by Omernik (1987) were used to divide the Pacific Northwest into meaningful regional units that include not only the physical and biologic components but also address cultural changes to the landscape. Four component maps are used to generate the PNW ecoregion map; these include Major Land Uses (Anderson 1970), Classes of Land-Surface Form (Hammond 1970), Potential Natural Vegetation (Kuchler 1970), and soils maps from the Natural Resources Conservation Service and other sources. Other maps were consulted to verify Omernik's conceptualized regions. These supplementary maps included Surficial Geology (Hunt 1979), Physical Divisions (Fenneman 1946), Land Resource Regions and Major Land Resource Areas of the United States (USDA-SCS 1981), Climates of the United States (Baldwin 1973), and the Census of Agriculture (US Bureau of the Census 1969, 1974, 1978). Climate was not considered as a component map but rather as a supplementary source.

The PNW is composed of 16 ecoregions, however, the PNW gaging stations were represented by the eleven ecoregions that are organized under three major ecoregion divisions: Pacific Maritime Mountains (Coast Range, Puget Lowlands, Willamette Valley, and North Cascades), Western Cordillera (Cascades, Klamath Mountains, Eastern Cascades, Blue Mountains, and Northern Rockies), and the West Interior Basin and Ranges (Snake River Basin and Columbia Plateau) (Figure 3.5).

Figure 3.5 ECOREGIONS and Stream Sampling Points



LEGEND

PACIFIC MARITIME MOUNTAINS
1 North Cascades
2 Puget Lowland
3 Coast Range
4 Willamette Valley

WESTERN CORDILLERA
5 Klamath Mountains
6 Cascades
7 Eastern Cascades
8 Blue Mountains
9 Northern Rockies
10 Middle Rockies
11 Wasatch and Uinta Mountains

WESTERN INTERIOR BASIN AND RANGES
12 Columbia Basin
13 Snake River Basin / High Desert
14 Northern Basin and Range
15 Wyoming Basin

● Sampling site at gaging station

Omernik, J.M. 1987. Ecoregions of the Conterminous United States, Map Supplement (scale 1:7,500,000). *Annals of the Association of American Geographers* 77(1):118-125.
U.S. Environmental Protection Agency. 1996. Level III Ecoregions of the Continental United States, Map M-1 (revision of Omernik, 1987). National Health and Environmental Effects Research Laboratory, Corvallis, Oregon.

Albers Equal Area Conic Projection
Cartography by Aileen M. Buckley, December 1996

The Pacific Maritime Mountains support dense forests composed of Redwood, Sitka Spruce, Cedar, Hemlock, Douglas Fir, and Silver Fir. The Western Cordillera is more arid than most of the Pacific Maritime Mountains and is characterized by Douglas Fir forests and Cedar-Hemlock-Douglas-Fir forests. The West Interior Basin and Ranges is distinctively drier than the other two major ecoregions and this is reflected in the vegetation composition of a dominant grassland/shrubland community composed of sagebrush, wheatgrass, rabbit brush, and juniper (Frenkel 1985).

RESEARCH RESULTS

The mean value for bankfull recurrence in the Pacific Northwest is 1.4 years. The data is negatively skewed with a mode value of 1.0. A reciprocal transformation was used to correct for the non-normal distribution of this data. After reviewing the partial residuals during the statistical analysis, the reciprocal transformation adequately adjusted the data.

Five stream sample sites in the stream data set were removed before the data were analyzed. The McKenzie River site at the McKenzie Bridge in Oregon was discarded because of high flows during the time of field data collection which masked the bankfull indicators. Lapwai Creek near Lapwai, Idaho has a calculated recurrence interval of 18 years. This outlier is a result of gage data that did not correlate with the field measurements; there was no outside gage to verify the stage height during the time of data collection and the discharge recorded by USGS did not correlate to the field measured discharge. The Umatilla River site near Umatilla, Oregon was removed because of the lack of bankfull indicators at the time of data collection. This stretch of the Umatilla River is bedrock with vertical banks with no depositional forms in the channel. The Okanogan River site at Oroville, Washington is immediately downstream (500 feet) from a dam and there was no access to survey a sufficient length of the stream channel. The gage on the Pahsimeroi River at Ellis, Idaho has recently been relocated downstream from the old gage site. The flow frequency curve for this station was generated using the old data which does not apply to the new gage location. The remaining 77 data points have bankfull discharge recurrence intervals which range from a low of a 1.0 year flow event to a high of a 3.11 year flow event.

Stream Type

The data was stratified into three groups based on stream type. Of the six stream types (B, C, D, E, F, and G) that are represented in the study sample, only three stream types (B, C, and F) were used in the analysis; there was not enough data to include the remaining three stream types. The bankfull recurrence intervals were stratified into B, C, and F stream types and were analyzed. There is no evidence that these three stream types have separate mean values (Table 3.1).

Table 3.1 Stream Type Summary Statistics

Group	Sample Size	Reciprocal Average	Kruskal - Wallis Avg. Rank
B	20	.7822	38.20
C	40	.7499	40.36
F	16	.8004	34.22
p-value		0.6804	0.6401

Climate

The bankfull discharge recurrence interval data was stratified by broad climatic zones. Three major climate regions (C, B, and D) were represented in the PNW. These three groups were compared and there is conclusive evidence to support a difference in mean values (two-sided p-value = 0.0448) (Table 3.2). By reviewing the mean values of each group, climates B and D appear to have close mean values while C climates are substantially different. Based on this information and a statistical comparison of means of the B and D zones (two-sided p-value = 0.7432), these climatic types regionalized together as BD. The rationale for larger regionalization was based on the origin of the streams in these areas; the streams located in B climate zones do not truly represent B climates because the streams originate in D climates and reflect the hydrology of these more humid areas. The streams located in the B climate zones are essentially exotic. The BD and C climates, when compared to one another, illustrated significant statistical differences (two-sided p-value = 0.0140). Ultimately, two broad climate regions emerge as hydrologically important for the Pacific Northwest, one represented by the Csb and Cfb climates and the other represented by the combination of BSk, Dsa, Dsb, and Dsc climates.

Table 3.2 Climatic Region Summary Statistics

Group	Sample Size	Reciprocal Average	Kruskal - Wallis Avg. Rank
BD	44	.7173	44.41
C	31	.8354	28.90
p-value		0.0140	0.0024

Physiography

The stream data was further stratified by three broad physiographic regions; these regions are the Rocky Mountain System (RMS), Intermontane Plateaus (IP), and the Pacific Mountain System (PMS). There evidence indicates that these three groups share the same mean (two-sided p-value = 0.2167) indicating that regionalization by physiographic province is not meaningful in the context of bankfull discharge recurrence interval (Table 3.3).

Table 3.3 Physiographic Region Summary Statistics

Group	Sample Size	Reciprocal Average	Kruskal - Wallis Avg. Rank
RMS	21	.7189	45.93
IP	18	.7672	39.94
PMS	36	.8141	32.40
p-value		0.2167	0.0702

Ecoregion

There is conclusive evidence (two-sided p-value = 0.0005) that the Pacific Maritime Mountains (PMM), Western Cordillera (WC), and West Interior Basin and Ranges (WIBR) ecoregion divisions do not share the same mean value (Table 3.4). The Western Cordillera and the West Interior Basin and Ranges have very similar values; again, this may be a result of the WIBR streams reflecting the hydrology of the contributing WC areas.

Table 3.4 Ecosystem Region Summary Statistics

Group	Sample Size	Reciprocal Average	Kruskal - Wallis Avg. Rank
PMM	17	.9318	16.44
WC	37	.7126	46.38
WIBR	21	.7624	40.69
p-value		0.0005	0.00001

CONCLUSIONS

Average bankfull discharge recurrence interval for the Pacific Northwest is 1.4 years. This is lower than the 1.5 year average discussed by other authors (Dury et al. 1963; Leopold, Wolman, and Miller 1964; Hickin 1968; Dunne and Leopold 1978; Leopold 1994) but within the general range of 1 to 2 years. It has been shown that by using a regionalization scheme, bankfull discharge recurrence interval can be further refined for specific areas within the Pacific Northwest.

The broadly held assumption that the bankfull discharge recurrence interval is approximately a 1.5 year event is probably appropriate for streams in Idaho, eastern Washington, and eastern Oregon. However, this assumption does not hold for more humid areas such as western Oregon and western Washington which have an average recurrence interval of 1.2 years (Table 3.5). By recognizing the regional physical variations in the geography of the PNW, more specific generalizations regarding bankfull discharge recurrence interval can be derived.

Table 3.5 Descriptive Statistics for Major Ecoregion Divisions

	ALL	PMM	WC	WIBR
Average	1.4 (1.411)	1.2 (1.153)	1.5 (1.516)	1.4 (1.434)
Median	1.2 (1.25)	1.0 (1.00)	1.4 (1.36)	1.3 (1.26)
Mode	1.0 (1.00)	1.0 (1.00)	1.2 (1.16	1.1 (1.09)
Standard Deviation	0.5 (0.509)	0.5 (0.476)	0.5 (0.475)	0.5 (0.544)

**Numbers in parentheses represent the values before rounding.

Stream type (B, C, and F channels) is not a significant controlling factor of flow frequency at bankfull discharge (two-sided p-value = 0.6804). This has not been thoroughly tested for many of the other RCNR stream types such as 'E' channels because this stream type is not well represented in this data set. Since stream type is not a significant parameter in regional bankfull discharge recurrence intervals, bankfull discharge frequency can be determined at a gaging station and applied upstream or downstream of the gage (reaches which may be more representative of the stream) regardless of stream type.

Of the three regionalization schemes tested, ecoregion provides the most statistically significant factor related to bankfull discharge recurrence interval (two-sided p-value = 0.0005), however climate also has a significant relationship to bankfull discharge recurrence interval (two-sided p-value = 0.0140). Physiography is not a statistically significant factor for bankfull discharge recurrence interval at this regional scale (two-sided p-value = 0.2167).

The regionalization scheme is scale dependent. While climate is a major controlling factor at the PNW regional scale, other factors probably control the variability of bankfull discharge recurrence interval within a homogeneous climatic zone. It is not clear what other controlling factors influence bankfull discharge recurrence interval because ecoregions are a compilation of a variety of attributes. It is clear, however, that at this regional scale, climate is a controlling factor, while physiography is not. A more refined analysis is required to identify the controlling factors of bankfull discharge at a higher resolution scale.

Further analyses of bankfull discharge recurrence interval will provide additional data to refine the relationship between physical environmental factors, here represented by ecoregion, climate, and physiography, and bankfull discharge recurrence interval. A similar methodology could be employed in any other part of the United States to derive appropriate bankfull discharge recurrence intervals for those regions. When using approximations or averages of physical characteristics, geographically delineating the limits of these averages is critically important to reduce misapplication of the tool. With the diversity of climatic regions, geomorphic provinces, and vegetative zones in the United States, a generalized bankfull recurrence interval (such as 1.5 years) has only limited application. By refining these generalizations to geographic regions, we can begin to understand and quantify the diversity of stream systems.

When designing streambank restoration projects or fish habitat structures, design criteria often refers to the bankfull level. This is particularly true for the placement of toe rock for bank protection. When analyzing stream hydrology using USGS gage data, the bankfull discharge recurrence interval in the Pacific Northwest can now be defined by regional patterns rather than relying on the 1.5 year event average. This should provide a more accurate level for bankfull discharge and reduce the cost of structures designed for full effectiveness at the bankfull level.

REFERENCES

Anderson, J.R. 1970. Major land uses. Map (scale 1:7,500,000). In *The National Atlas of the United States of America*, pp. 158-159. Revised from a map by F.J. Marschner. Washington, D.C.: U.S. Geological Survey.

Baldwin, J.L. 1973. Climates of the United States. U.S. Department of Commerce. NOAA. Washington, D.C.: U.S. Government Printing Office.

Dunne, T. and L.B. Leopold. 1978. *Water in Environmental Planning*. San Francisco: W.H. Freeman and Co.

Dury, G.H., J.R. Hails, and H.B. Robbie. 1963. Bankfull discharge and the magnitude frequency series. *Australian Journal of Science*. 26:123-124.

Fenneman, N.M. 1946. Physical Divisions of the United States. Map (scale 1:7,000,000). Reston, VA: U.S. Geological Survey.

Fenneman, N.M. 1931. *Physiography of Western United States*. New York: McGraw-Hill Book Co. Inc.

Franklin, J.F. and C.T. Dyrness. 1973. Natural Vegetation of Oregon and Washington. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station. Rep. PNW-8. Printed by Oregon State University Press, Corvallis, OR. 1988.

Frenkel, R. 1985. Vegetation of the Pacific Northwest. In *Atlas of the Pacific Northwest, 7th edition*. eds. A.J. Kimerling and P.L. Jackson. Oregon State University Press: Corvallis, Oregon.

Hammond, E.H. 1970. Classes of land-surface form. Map (scale 1:7,500,000). In *The National Atlas of the United States of America*, pp. 62-63. Washington, D.C.: U.S. Geological Survey.

Hickin, E.J. 1968. Channel morphology, bankfull stage and bankfull discharge of streams near Sydney. *Australian Journal of Science*. 30: 274-275.

Highsmith, R.M. Jr. 1968. Surface Waters. In *Atlas of the Pacific Northwest, 4th Edition*. eds. R.M. Highsmith and J. Leverance. Oregon State University Press: Corvallis, Oregon.

Hunt, C.B. 1979. Surficial geology. Color proof of unpublished map (scale 1:7,500,000). U.S. Geological Survey, Washington, D.C.

Jackson, P.L. 1992. Climate of the Pacific Northwest. In *Atlas of the Pacific Northwest, 8th edition*. eds. A.J. Kimerling and P.L. Jackson. Oregon State University Press: Corvallis, Oregon.

Köppen, W. and R. Geiger. 1930. Climate of the Earth. World Map of Climate Classification. (scale 1:16,000,000). Justus Perthes Map Publishers: Darmstadt, Germany.

Kuchler, A.W. 1970. Potential natural vegetation. Map (scale 1:7,500,000). In *The National Atlas of the United States of America*, pp. 89-91. Washington, D.C.: U.S. Geological Survey.

Leopold, L.B. 1994. *A View of the River*. Cambridge, Mass.: Harvard University Press.

Leopold, L.B., M.G. Wolman, and J.P. Miller. 1964. *Fluvial Processes in Geomorphology*. San Francisco:W.H. Freeman and Co.

Lucas, B. and P.L Jackson 1995. Koppen Climate Classification of the Pacific Northwest (1960 to 1990 temperature and precipitation data). Unpublished map (scale 1:4,000,000).

Nolan, M., T. Lisle, and H. Kelsey. 1987. Magnitude and frequency of sediment transport and channel geometry in northwestern California. In *Proceedings of the International Symposium on Erosion and Sedimentation in the Pacific Rim*, eds. Beschta and others. Corvallis, OR, August 1987, p. 439-449.

Omernik, J.M. 1987. Ecoregions of the conterminous United States: map supplement. *Annals of the Assoc. of Am. Geographers*. 77(1):118-125.

Ramsey, F. and D. Schafer. 1993. The Statistical Sleuth. Oregon State University Bookstores Inc.: Corvallis, Oregon.

Rosenfeld, C. 1985. Landforms and geology of the Pacific Northwest. In *Atlas of the Pacific Northwest, 7th edition*. eds. A.J. Kimerling and P.L. Jackson. Oregon State University Press: Corvallis, Oregon.

Rosgen, D.L. 1994. A classification of natural rivers. *Catena* 22: 169-199.

Rosgen, D.L. and B. Fittante. 1986. Fish Habitat Structures – a selection guide using stream classification. 5th Trout Stream Habitat Improvement Workshop. Lock Haven University, Lock Haven, Pennsylvania. Pennsylvania Fish Commission Publics, Hamsburg, PA. pp. 13-29.

Rosgen, D.L. and L.B. Leopold. 1994. Short course on applied fluvial geomorphology. Course Materials by Wildland Hydrology Consultants, 1 Stevens Lake Rd., Pagosa Springs, CO 81147.

Trewartha, G.T., and L.H. Horn. 1980. *Introduction to Climate*. New York : McGraw-Hill Book Co.

U.S. Bureau of the Census. 1969. Census of Agriculture. Vol. 5, Special Reports. Part 15. Graphic Summary. Washington, D.C.: U.S. Government Printing Office.

U.S. Bureau of the Census. 1974. Census of Agriculture. Vol. 4, Special Reports. Part 1. Graphic Summary. Washington, D.C.: U.S. Government Printing Office.

U.S. Bureau of the Census. 1978. Census of Agriculture. Vol. 5, Special Reports. Part 1. Graphic Summary. Washington, D.C.: U.S. Government Printing Office.

USDA-SCS. 1981. Land resource regions and major land resource areas of the United States. United States Department of Agriculture, Soil Conservation Service. Agricultural handbook 296. Washington DC: US Government Printing Office.

USDA-SCS. 1994. Salmon Recovery Initiative Draft. USDA, Soil Conservation Service, West National Technical Center, Portland, Oregon.

Williams, G.P. 1978. Bank-full discharge of rivers. *Water Resources Research*, 14(6):1141-1153.

CHAPTER 4

Hydraulic Geometry Relationships in Streams of the Pacific Northwest

Janine M. Castro

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ABSTRACT

Regional curves have been developed in various parts of the United States to relate hydraulic geometry variables, such as bankfull width, depth, and velocity, to bankfull discharge and drainage area. This study derives geographic/spatial relationships for stream discharge and channel hydraulics for the Pacific Northwest region of the United States. These regression equations allow individuals to estimate bankfull width, depth, velocity, and discharge for ungaged streams within ecoregions of the Pacific Northwest. The data was stratified by stream types based on the Rosgen Classification of Natural Rivers, however, stream type was not statistically significant (D-value = 0.40), indicating that hydraulic geometry variables are not influenced by stream type. The development of regional regression equations provides geographically relevant information and will result in more accurate estimates of hydraulic geometry variables in the Pacific Northwest.

INTRODUCTION

The hydraulic geometry of stream channels represent a symbolic and functional change from the qualitative geomorphology practiced in the early part of this century to the quantitative geomorphology more characteristic of the field during the past 50 years. A seminal work by Leopold and Maddock (1953) introduced quantitative geomorphology by the way of the hydraulic geometry of stream channels. This work encouraged further quantification of stream analyses and directed much of the research in fluvial geomorphology. There has been extensive research in the area of hydraulic geometry relationships since the concept received widespread acknowledgment in the nineteen-fifties (Leopold and Maddock 1953). The spatial variation of hydraulic geometry studies has been quite wide. Hogan and Church (1989) evaluated the hydraulic geometry of two small streams on the west coast of the Queen Charlotte Islands in British Columbia, Canada, while Park (1977) had a world-wide perspective of the variability of hydraulic geometry exponents.

Even though there has been extensive research in hydraulic geometry, there is surprisingly little data concerning regional relationships. Leopold (1994) has been the foremost proponent of using regional curves to estimate expected levels of bankfull discharge. Rosgen (1994) has also proposed that stream widths that are significantly different from the predicted regional value may be unstable or in a state of transition.

The Rosgen Classification of Natural Rivers (Rosgen 1994) is based on the morphological characteristics of stream channels which represent much of the hydraulic geometry discussed by Leopold and Maddock (1953). The number of active channels, entrenchment, width to depth ratio, sinuosity, channel slope, and bed material are the important characteristics used to classify a stream reach using the Rosgen Classification of Natural Rivers (RCNR). Hydraulic geometry parameters include channel width and depth, velocity, water surface slope, and channel roughness (Leopold 1994). Channel width, channel depth, and water surface slope are utilized in the RCNR and are also important hydraulic geometry parameters. When classifying streams using the RCNR it is valuable to compile the data for later analysis of hydraulic geometry of a stream system, a larger watershed, or an entire region.

Over 80 streams in the Pacific Northwest (PNW) region (Oregon, Washington, and Idaho) were field visited and classified using the RCNR during the summer of 1995. The stream survey data was compiled for analysis of the hydraulic geometry and based on this data, field verified regional regression equations, using bankfull discharge, bankfull width, bankfull depth, and drainage area as variables, were generated for various regions within the Pacific Northwest which allow for the estimation of bankfull width, depth, velocity, and discharge for ungaged streams within the respective regions. Regional boundaries were generated in an earlier phase of this study based on relationships between bankfull discharge and climatic and physiographic zone, and ecoregion. These three regionalization schemes were used because they represent the factors that control the shape of the stream channel (discharge, characteristics of the bed load, character and composition of the channel bed and bank material, and vegetation) (Leopold, Wolman, and Miller 1964). Ecoregions were determined to be the most statistically significant units based on bankfull discharge recurrence intervals and are therefore utilized for the analysis of the hydraulic geometry of these PNW streams.

The streams that were selected for evaluation are based on watersheds that contain critical habitat for salmonids, public interest in the fishery, and a percentage of private land in the respective watershed. The development of regional regression equations for these streams will provide important information which can be applied to ungaged streams on both public and private lands in the Pacific Northwest region.

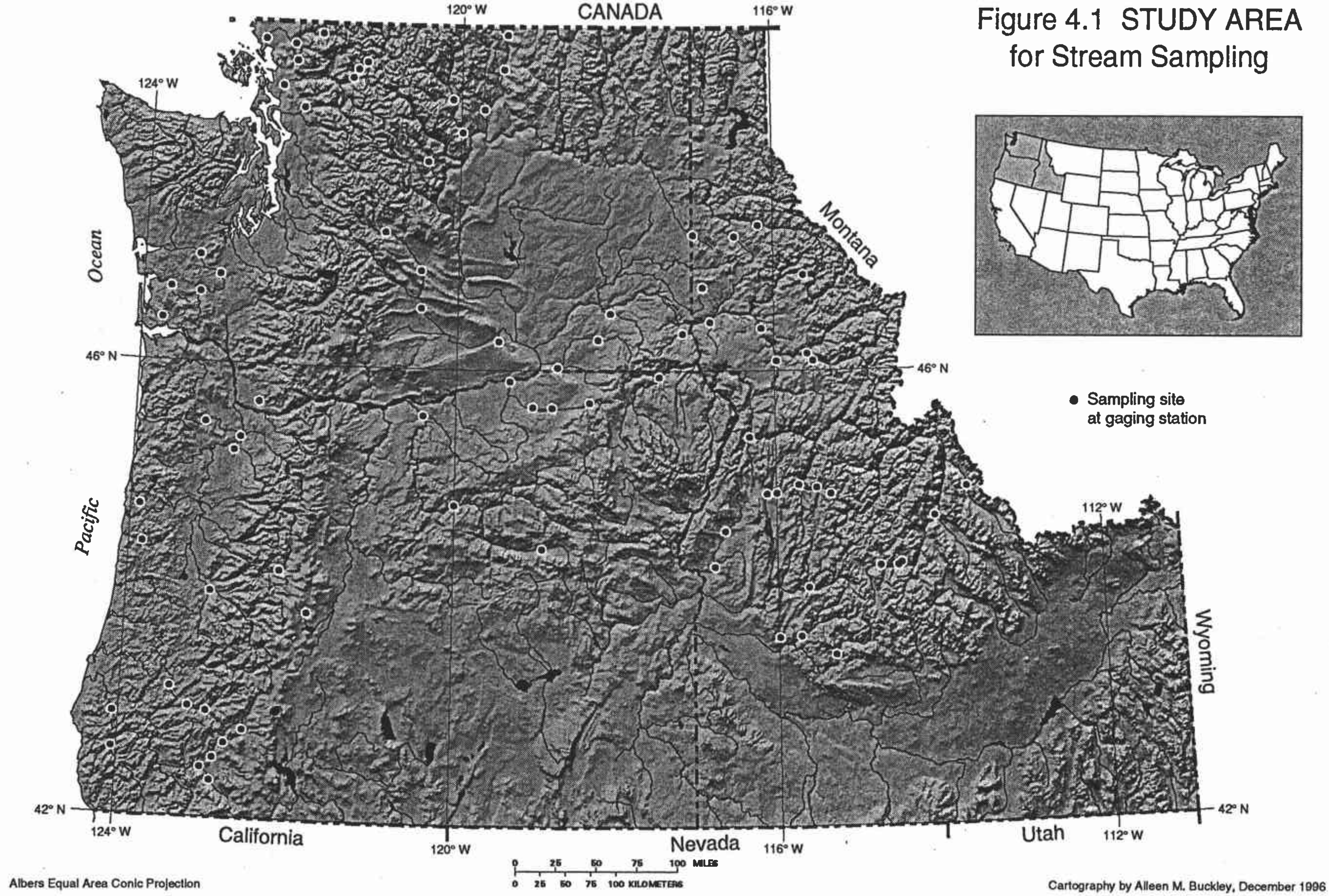
OBJECTIVES

The objective of this study is the generation of geographic/spatial relationships for stream discharge and channel hydraulics stratified by Pacific Northwest ecoregions. Regional regression equations comparing bankfull width, depth, velocity, discharge, and drainage area were developed for ecoregions which will allow individuals to estimate bankfull width, depth, velocity, and discharge for ungaged streams within the regions utilizing these equations. Similar regression curves have been generated by Leopold (1994) and have proved to be applicable and useful in the field; however, the curves generated by Leopold (1994) are watershed specific and have no set geographic limits. The ecoregion regression equations generated for this study will provide information about channel hydraulics of Pacific Northwest streams along with geographic boundaries to provide users with an area of applicability of these relationships.

STUDY AREA

The study area includes selected watersheds in the states of Oregon, Washington, and Idaho (Figure 4.1). United States Geologic Survey (USGS) hydrologic units are the sampling units and the criteria for stream selection is all active stream gages within a selected hydrologic unit. All streams associated with an active gage are evaluated so there is complete selection within the sample unit. The selection of the hydrologic units is not random, but rather unit selection is based on Salmon Initiative streams as defined by the Natural Resources Conservation Service. Salmon Initiative streams are streams which have present or historical populations of anadromous salmonids, public concern and interest in the fishery, and the watersheds must have a portion of the land in private ownership (USDA-SCS 1994). Streams listed in the Salmon Initiative were classified using the RCNR to provide general geomorphological information about the streams and this data along with fisheries data, is used to establish and prioritize fisheries enhancement needs. This selection procedure was used so that the data derived from this study can be applied to a present resource problem on private lands. The only deviation from this procedure is the sampling method for Idaho which does not contain a sufficient number of Salmon Initiative streams with active USGS gaging stations to provide a statistically robust analysis. Supplementary hydrologic units were selected by choosing units that are directly adjacent to Salmon Initiative hydrologic units.

Figure 4.1 STUDY AREA for Stream Sampling



METHODOLOGY

Data Collection

The field classification included visiting each gage site and collecting the following data: channel slope, bed material size, bankfull width, bankfull depth, and floodprone width. Bed slope was substituted for water-surface slope and was measured in-stream using a transit and stadia rod. The bankfull discharge level was located using field indicators, such as the break in slope on point bars and other indicators defined by Dunne and Leopold (1978). Bankfull width was measured at the bankfull level and bankfull depth was then determined as an average of the measured depths across the stream at the bankfull width level. Cross-section interval distances vary depending upon overall channel width. Streams that are up to 40 feet wide were sampled at two foot intervals, streams 40 to 150 feet wide were sampled at five foot intervals, and streams that are greater than 150 feet wide were sampled at ten foot intervals. Entrenchment is a ratio of floodprone width to bankfull width. Floodprone width has been defined by Rosgen (1994) as the width at twice the maximum bankfull depth.

Regional regression equations were generated from data that had already been compiled from the earlier phases of this study. These regional equations include drainage area, bankfull discharge, width, and depth. The regions were determined by analyzing data using an analysis of variance and the Kruskal-Wallis non-parametric test; included as explanatory variables were the Köppen climate zones, physiographic provinces, and ecoregions (as defined by the US Environmental Protection Agency). These regional criteria were selected based on the controlling factors of stream morphology which include discharge, channel slope, sediment load, and roughness factors such as vegetation (Leopold 1994). These factors are represented at a regional scale by climate, physiographic province, and ecoregion. The regional regression equations can then be compared to regional equations from other areas of the United States to determine if they are statistically different.

Data Analyses

The data were initially analyzed as one large sample to develop very general relationships for the entire Pacific Northwest (PNW) region using simple regression techniques. After the initial analysis, the data was stratified into ecoregions and regression equations were generated for the three ecoregions which include the Pacific Maritime Mountains (PMM), the Western Cordillera (WC), and the West Interior Basin and Ranges (WIBR) (Figure 4.2). The regression equations were not tested to determine uniqueness between the three ecoregions because these regions were established using bankfull discharge recurrence interval data; therefore, some regression equations may appear to be quite similar between groups. The data was further stratified by RCNR stream type to determine if the regression equations could be refined for specific channel morphology.

Six regression equations were developed for all of the streams sampled in the Pacific Northwest study area as a group and the same variables were used to generate six regression equations for each of the three major ecoregions. The dependent variables include width, depth, and bankfull discharge, while the independent variables include drainage area and bankfull discharge. Having the two equations relating width to discharge and depth to discharge, it is possible to derive a third equation representing the relationship between velocity and discharge based on the equation $Q = AV$ (where Q=discharge, A=area, and V=velocity).

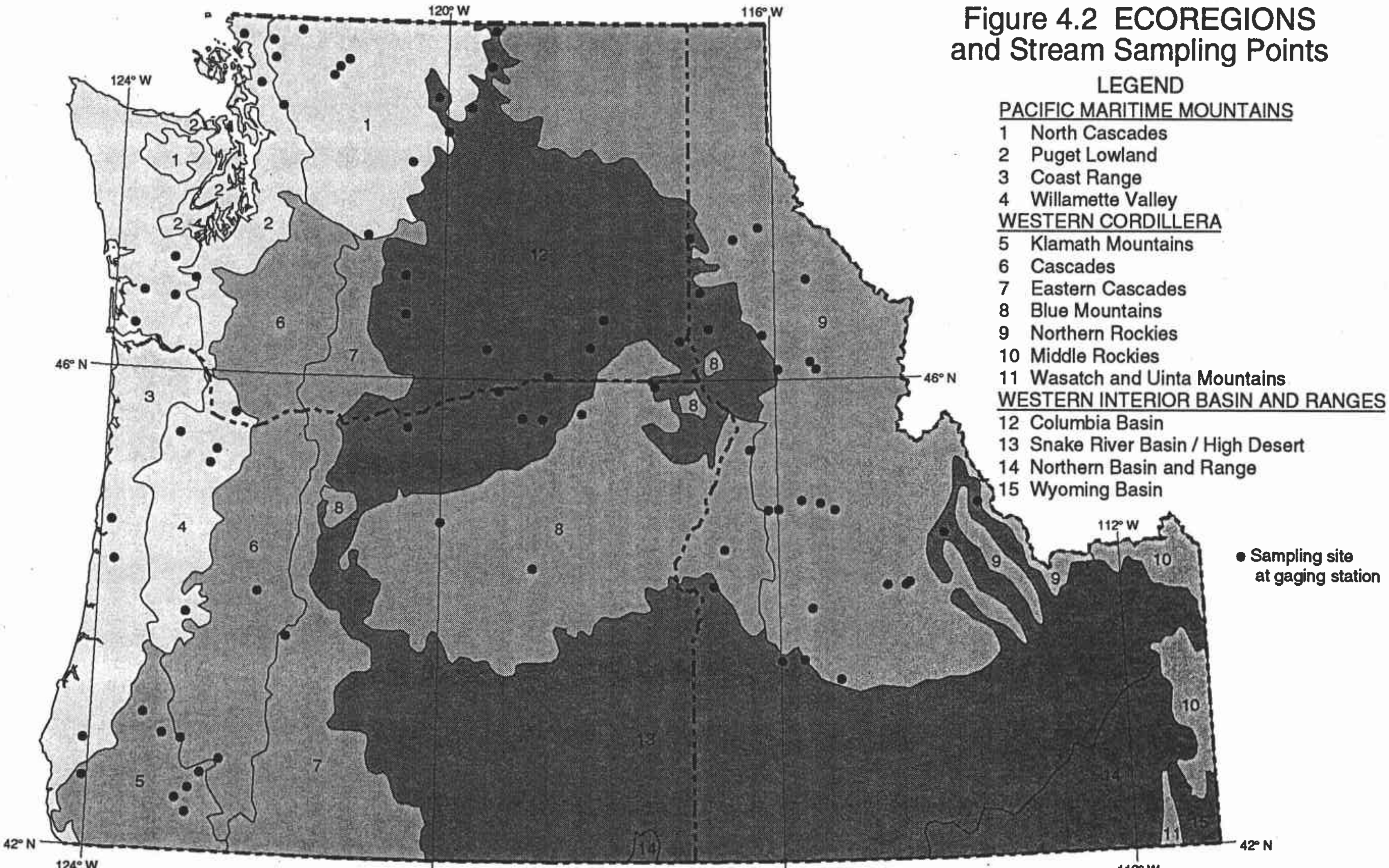


Figure 4.2 ECOREGIONS and Stream Sampling Points

Omernik, J.M. 1987. Ecoregions of the Conterminous United States, Map Supplement (scale 1:7,500,000). *Annals of the Association of American Geographers* 77(1):118-125.
U.S. Environmental Protection Agency. 1996. Level III Ecoregions of the Continental United States, Map M-1 (revision of Omernik, 1987). National Health and Environmental Effects Research Laboratory, Corvallis, Oregon.

Combining the following equations:

$$w = aQ^b \qquad d = cQ^f \qquad v = kQ^m$$

where w = width, d = depth, v = velocity, Q = discharge, and a, b, c, and f are constants,

it follows that:

$$wdv = (aQ^b)(cQ^f)(kQ^m)$$

$$Q = (ack)Q^{(b+f+m)}$$

therefore:

$$ack = 1, \text{ and}$$

$$b + f + m = 1$$

After deriving the a, b, c, and f variables, the k and m variables are simple to calculate.

The data was transformed with a natural logarithm to adjust for non-constant variability in the data set and also to adjust for skew. When logarithmic data is back-transformed to its original scale, the data represents median values rather than mean values. Since all of the data in this study was transformed, all values generated using the regression equations will represent median values.

RESEARCH RESULTS

When the ecoregion regression equations were stratified by RCNR stream type, the R-squared value did not significantly increase indicating that stream type is not an important explanatory variable. Based on this evidence, regression equations including the stream type variable were not included in the final analysis.

The following equations were derived from actual field data except for the equation including velocity which was derived mathematically. The equations derived from field data have an associated R-squared value which indicates how well the derived equation fits the data.

Q = bankfull discharge in cubic feet per second

A = drainage area in square miles

w = bankfull width in feet

d = bankfull mean depth in feet

v = bankfull mean velocity in feet per second

a = coefficient representing width

c = coefficient representing depth

k = coefficient representing velocity

b = exponent in the width to discharge/drainage area relationship

f = exponent in the depth to discharge/drainage area relationship

m = exponent in the velocity to discharge/drainage area relationship

Table 4.1 Regression Equations for Pacific Northwest Streams

Regression Equation	Coefficient	Exponent	R-Squared
$w = aQ^b$	2.34	0.49	81.0%
$w = aA^b$	11.80	0.38	48.9%
$d = cQ^f$	0.22	0.38	75.9%
$d = cA^f$	1.13	0.24	29.0%
$v = kQ^m$	1.95	0.13	
$Q = dA^t$	50.93	0.67	44.3%

Table 4.2 Regression Equations for Pacific Maritime Mountain Streams

Regression Equation	Coefficient	Exponent	R-Squared
$w = aQ^b$	2.37	0.50	76.0%
$w = aA^b$	12.39	0.43	58.7%
$d = cQ^f$	0.15	0.45	61.9%
$d = cA^f$	0.66	0.39	48.7%
$v = kQ^m$	2.81	0.05	
$Q = dA^t$	91.05	0.67	45.7%

Table 4.3 Regression Equations for West Interior Basin and Range Streams

Regression Equation	Coefficient	Exponent	R-Squared
$w = aQ^b$	0.96	0.60	86.8%
$w = aA^b$	3.27	0.51	82.9%
$d = cQ^f$	0.36	0.31	72.0%
$d = cA^f$	0.79	0.24	58.4%
$v = kQ^m$	2.89	0.09	
$Q = dA^t$	13.05	0.77	79.4%

Table 4.4 Regression Equations for Western Cordillera Streams

Regression Equation	Coefficient	Exponent	R-Squared
$w = aQ^b$	3.50	0.44	84.4%
$w = aA^b$	9.40	0.42	53.6%
$d = cQ^f$	0.20	0.39	87.4%
$d = cA^f$	0.61	0.33	44.2%
$v = kQ^m$	1.43	0.17	
$Q = dA^t$	17.28	0.86	51.3%

The R-squared values for the equations relating bankfull width to bankfull discharge are very similar between all three major ecoregions and the Pacific Northwest. Two of the three ecoregions have slightly higher R-squared values than the Pacific Northwest. There is more variability among the R-squared values for the bankfull depth versus bankfull discharge equations. One ecoregion (WIBR) has a similar R-squared value as the PNW, while the WC ecoregion has a much higher R-squared value and the PMM ecoregion has a much lower R-squared value than the PNW equation.

The Pacific Maritime Mountain ecoregion rated the poorest among the three ecoregions based on the fit of the regression models to the data. The regression equations representing all of the PNW are almost as strong as the regression equations developed specifically for the Pacific Maritime Mountain ecoregion. This indicates significant variability in the data.

The Western Interior Basin and Range regression equations overall have very high R-squared values. This indicates lower variability in the data resulting in a tighter fitting model. This could be the result of the WIBR ecoregion which is relatively uniform in the study area as compared to the PMM ecoregion which has extensive spatial variability.

The Western Cordillera ecoregion has two very strong regression equations, bankfull width and bankfull depth versus bankfull discharge. The regression equations relating stream data to drainage area are not as strong. This indicates high variability in physical attributes of the watershed, such as slopes or snowpack, but also indicates that the channel morphology in these areas are strongly controlled by bankfull discharge events.

In all four groups, the equations with discharge (*Q*) as the independent variable, have higher R-squared values than the equations with drainage area (*A*) as the independent variable. This indicates the strong relationship between bankfull discharge and channel geometry compared to the weaker relationship between drainage area and channel geometry.

CONCLUSIONS

By developing six regression equations for each of the three ecoregions representing the Pacific Northwest, it is possible to evaluate some of the controlling factors of channel hydraulics at the PNW regional level. When working in the West Interior Basin and Range ecoregion, using any of the six regression equations would be appropriate. However, when working in the Western Cordillera ecoregion, it would be more valuable to rely on the regression equations that contain bankfull discharge as the independent variable because the R-squared value is considerably higher than in the other regression equations, however, this will be difficult for ungaged streams. Manning's or other flow continuity equations can be used to estimate a discharge for the bankfull channel cross-section identified in the field. These discharge estimates could then be compared to regional equations to determine if the bankfull discharge is within the appropriate range for recurrence intervals for that region.

The Pacific Maritime Mountain ecoregion regression equations are overall only a slight improvement over the Pacific Northwest regression equations. When more data becomes available in the PMM ecoregion, it may be possible to further stratify the data and develop regression equations for smaller regions within the PMM which may eliminate some of the large scale physical variability, such as hydrologic regime (rain dominated versus snow dominated systems), of the PMM ecoregion and result in stronger regression equations just as this study has done for the PNW region.

The development of regional regression equations is important for people working on ungaged streams. The more refined the regression equations are for their respective regions, the more appropriate the estimates of hydraulic geometry parameters will become. This study attempted to develop a set of relationships that could be used on Pacific Northwest streams and this process needs to occur in other regions as well. Only with this expanded data will we be able to accurately and objectively compare the hydraulic geometry of streams throughout the United States and throughout the world.

REFERENCES

Dunne, T. and L.B. Leopold. 1978. *Water in Environmental Planning*. W.H. Freeman and Company: San Francisco, California.

Hogan, P.L. and M. Church. 1989. Hydraulic geometry in small, coastal streams: progress towards quantification of salmonid habitat. *Canadian Journal of Fisheries and Aquatic Sciences* 46:844-852.

Leopold, L.B. 1994. *A View of the River*. Cambridge Mass.: Harvard University Press.

Leopold, L.B., M.G. Wolman, and J.P. Miller. 1964. *Fluvial Processes in Geomorphology*. San Francisco:W.H. Freeman and Co.

Leopold, L.B. and T. Maddock Jr. 1953. The hydraulic geometry of stream channels and some physiographic implications. United States Geological Survey Professional Paper 252. U.S. Government Printing Office: Washington D.C.

Park, C.C. 1977. World-wide variations in hydraulic geometry exponents of stream channels: an analysis and some observations. *Journal of Hydrology* 33:133-146.

Rosgen, D.L. 1994. A classification of natural rivers. *Catena* 22: 169-199.

USDA - SCS (United States Department of Agriculture - Soil Conservation Service). 1994. Draft Salmon Recovery Initiative. Portland, Oregon.

CHAPTER 5. SUMMARY

SUMMARY STATEMENT

Currently available regional information concerning stream channel geometry and hydraulics in the Pacific Northwest is limited not withstanding the significant amount of stream research that takes place within this region. The present research provides a large geographic framework within which focused and detailed studies can be put into a regional context. Specific products of this study include data to support calibration of the HUMUS model, regional stream data to evaluate Salmon Initiative priorities, construction of regional relationships which are applicable to ungaged Pacific Northwest streams, and bankfull discharge recurrence intervals which will aid in channel design work.

EVALUATION OF THE ROSGEN CLASSIFICATION OF NATURAL RIVERS

The Rosgen Classification of Natural Rivers provides a valuable system for geomorphic classification of streams in the Pacific Northwest, although a few changes in the system would result in a more appropriate classification for modified streams and larger stream channels in this region.

For Pacific Northwest streams, lower sinuosity categories may need to be defined. From the data available, it is not clear if the lower sinuosities are a result of measurement errors, channel modifications, or is an inherent characteristic of Pacific Northwest streams. Further field analysis of this parameter is required to make this distinction. Using the descriptive statistics as a guide, sinuosities for specific channel types could be adopted for PNW streams (Table 5.1).

Table 5.1 Proposed Sinuosity

Channel Type	Sinuosity	Stream Continuum
B	> 1.15	+/- 0.10
C	> 1.25	+/- 0.15
F	> 1.20	+/- 0.10

Characterization of 'D' channels based entirely on multiple channels minimizes the functional importance of the width to depth ratio. High sediment loads, shallow, wide channels, and frequently shifting active channels present similar management problems to braided stream regardless of the number of channels at any single moment in time. This issue could be addressed in the delineative criteria for 'C' channels. An upper limit to the width to depth ratio for 'C' stream types, such as 60, would separate the very wide, shallow streams from the more stable channel type. This would provide a functional category for streams that are wide and unstable similar to 'D' channels but have only a single active channel at the bankfull discharge.

The 'B' type channels are a "catch-all" category with a variety of morphologic and hydrologic attributes. It would be more useful if the 'B' channels could be split into more delineative categories; however, the data do not support any further refinement of this channel type because of a distinct lack of patterns. There is high diversity in this category but any further division would be arbitrary and would result in pseudo-categories which would not convey any additional information.

Entrenchment, width to depth ratio, channel slope, and bed material ranges within the Rosgen Classification of Natural Rivers, with very few exceptions, accurately represent the stream channels of the Pacific Northwest region. The Rosgen

Classification of Natural Rivers is easily adaptable to the Pacific Northwest Region; minor modifications will provide more precise classification of river types and will assist both managers and scientists who are dealing with large numbers of streams or stream types. Modifications will vary depending upon the specific intended use of the classification data. Maintaining the primary components of the classification system (entrenchment, width to depth ratio, and sinuosity) will allow for general communication between managers, researchers, and others involved in stream studies. However, any modifications to this system should be adequately documented so that others using the system are aware of the regional adjustments.

BANKFULL DISCHARGE RECURRENCE INTERVALS

Overall average bankfull discharge recurrence interval for the Pacific Northwest is 1.4 years. This is lower than the 1.5 year average discussed by other authors (Dury et al. 1963; Leopold, Wolman, and Miller 1964; Hickin 1968; Dunne and Leopold 1978; Leopold 1994) but within the general range of 1 to 2 years. It has been shown that by using a regionalization scheme, bankfull discharge recurrence interval can be further refined for specific areas within the Pacific Northwest.

The broadly held assumption that the bankfull discharge recurrence interval is approximately a 1.5 year event is probably appropriate for streams in Idaho, eastern Washington, and eastern Oregon. However, this assumption does not hold for more humid areas such as western Oregon and western Washington which have an average recurrence interval of 1.2 years (Table 5.2). By recognizing the regional physical variations in the geography of the PNW, more specific generalizations regarding bankfull discharge recurrence interval can be derived.

Table 5.2 Descriptive Statistics for Major Ecoregion Divisions

	ALL	PMM	WC	WIBR
Average	1.4 (1.411)	1.2 (1.153)	1.5 (1.516)	1.4 (1.434)
Median	1.2 (1.25)	1.0 (1.00)	1.4 (1.36)	1.3 (1.26)
Mode	1.0 (1.00)	1.0 (1.00)	1.2 (1.16	1.1 (1.09)
Standard Deviation	0.5 (0.509)	0.5 (0.476)	0.5 (0.475)	0.5 (0.544)

**Numbers in parentheses represent the values before rounding.

Stream type (B, C, and F channels) is not a significant controlling factor of flow frequency at bankfull discharge (two-sided p-value = 0.6804). This has not been thoroughly tested for many of the other RCNR stream types such as 'E' channels because this stream type is not well represented in this data set. Since stream type is not a significant parameter in regional bankfull discharge recurrence intervals, bankfull discharge frequency can be determined at a gaging station and applied upstream or downstream of the gage (reaches which may be more representative of the stream) regardless of stream type.

Of the three regionalization schemes tested, ecoregion provides the most statistically significant factor related to bankfull discharge recurrence interval (two-sided p-value = 0.0005), however climate also has a significant relationship to bankfull discharge recurrence interval (two-sided p-value = 0.0140). Physiography is not a statistically significant factor for bankfull discharge recurrence interval at this regional scale (two-sided p-value = 0.2167).

The regionalization scheme is scale dependent. While climate is a major controlling factor at the PNW regional scale, other factors probably control the variability of bankfull discharge recurrence interval within a homogeneous climatic zone. It is not clear what other controlling factors influence bankfull discharge recurrence interval because ecoregions are a compilation of a variety of attributes. It is clear, however, that at this regional scale, climate is a controlling factor, while physiography is not. A more refined analysis is required to identify the controlling factors of bankfull discharge at a higher resolution scale.

Further analyses of bankfull discharge recurrence interval will provide additional data to refine the relationship between physical environmental factors, here represented by ecoregion, climate, and physiography, and bankfull discharge recurrence interval. A similar methodology could be employed in any other part of the United States to derive appropriate bankfull discharge recurrence intervals for those regions. When using approximations or averages of physical characteristics, geographically delineating the limits of these averages is critically important to reduce misapplication of the tool. With the diversity of climatic regions, geomorphic provinces, and vegetative zones in the United States, a generalized bankfull recurrence interval (such as 1.5 years) has only limited application. By refining these generalizations to geographic regions, we can begin to understand and quantify the diversity of stream systems.

When designing streambank restoration projects or fish habitat structures, design criteria often refers to the bankfull level. This is particularly true for the placement of toe rock for bank protection. When analyzing stream hydrology using USGS gage data, the bankfull discharge recurrence interval in the Pacific Northwest can now be defined by regional patterns rather than relying on the 1.5 year event average. This should provide a more accurate level for bankfull discharge and reduce the cost of structures designed for full effectiveness at the bankfull level.

REGIONAL HYDRAULIC GEOMETRY RELATIONSHIPS

By developing six regression equations for each of the three ecoregions representing the Pacific Northwest, it is possible to evaluate some of the controlling factors of channel hydraulics at the PNW regional level. When working in the West Interior Basin and Range ecoregion, using any of the six regression equations would be appropriate. However, when working in the Western Cordillera ecoregion, it would be more valuable to rely on the regression equations that contain bankfull discharge as the independent variable because the R-squared value is considerably higher than in the other regression equations, however, this will be difficult for ungaged streams. Manning's or other flow continuity equations can be used to estimate a discharge for the bankfull channel cross-section identified in the field. These discharge estimates could then be compared to regional equations to determine if the bankfull discharge is within the appropriate range for recurrence intervals for that region.

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BIBLIOGRAPHY

Anderson, J.R. 1970. Major land uses. Map (scale 1:7,500,000). In *The National Atlas of the United States of America*, pp. 158-159. Revised from a map by F.J. Marschner. Washington, D.C.: U.S. Geological Survey.

Bailey, R.G. 1978. Description of ecoregions of the United States. Intermountain Region, United States Forest Service, Ogden, Utah.

Baldwin, J.L. 1973. *Climates of the United States.* U.S. Department of Commerce. NOAA. Washington, D.C.: U.S. Government Printing Office.

Carpenter, K.E. 1928. *Life in Inland Waters*. Macmillan: New York.

Cupp, C.E. 1989. Stream corridor classification for forested lands of Washington. Washington Forest Protection Association, Olympia, Washington.

Davis, W. M. 1899. The geographical cycle. *Geographical Journal*. 14: 481-504.

Dunne, T. and L.B. Leopold. 1978. *Water in Environmental Planning*. W.H. Freeman and Company: San Francisco, California.

Dury, G.H., J.R. Hails, and H.B. Robbie. 1963. Bankfull discharge and the magnitude frequency series. *Australian Journal of Science*. 26:123-124.

Fenneman, N.M. 1946. Physical Divisions of the United States. Map (scale 1:7,000,000). Reston, VA: U.S. Geological Survey.

Fenneman, N.M. 1931. *Physiography of Western United States*. New York: McGraw-Hill Book Co. Inc.

Franklin, J.F. and C.T. Dyrness. 1973. *Natural Vegetation of Oregon and Washington*. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station. Rep. PNW-8. Printed by Oregon State University Press, Corvallis, OR. 1988.

Frenkel, R. 1985. Vegetation of the Pacific Northwest. In *Atlas of the Pacific Northwest, 7th edition*. eds. A.J. Kimerling and P.L. Jackson. Oregon State University Press: Corvallis, Oregon.

Frissell, C.A., W.J. Liss, C.E. Warren, and M.D. Hurley. 1986. A hierarchical framework for stream classification: viewing streams in a watershed context. *Environmental Management*, 10:199-214.

Hammond, E.H. 1970. Classes of land-surface form. Map (scale 1:7,500,000). *In The National Atlas of the United States of America*, pp. 62-63. Washington, D.C.: U.S. Geological Survey.

Hickin, E.J. 1968. Channel morphology, bankfull stage and bankfull discharge of streams near Sydney. *Australian Journal of Science*. 30: 274-275.

Highsmith, R.M. Jr. 1968. Surface Waters. *In Atlas of the Pacific Northwest, 4th Edition*. eds. R.M. Highsmith and J. Leverance. Oregon State University Press: Corvallis, Oregon.

Hogan, P.L. and M. Church. 1989. Hydraulic geometry in small, coastal streams: progress towards quantification of salmonid habitat. *Canadian Journal of Fisheries and Aquatic Sciences* 46:844-852.

Holmes, N.T.H. 1983. British rivers: a working classification. *British Wildlife*, 1:20-36.

Horton, R.E. 1945. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. *Geological Society of America Bulletin*, 56:275-370.

Huet, M. 1954. Biologie, profils en long et en travers des eaux courantes. *Bulletin Francais de Pisciculture*, 175:41-53.

Hunt, C.B. 1979. Surficial geology. Color proof of unpublished map (scale 1:7,500,000). U.S. Geological Survey, Washington, D.C.

Jackson, P.L. 1992. Climate of the Pacific Northwest. In *Atlas of the Pacific Northwest, 8th edition*. eds. A.J. Kimerling and P.L. Jackson. Oregon State University Press: Corvallis, Oregon.

Kellerhals, R., M. Church, and D.I. Bray. 1976. Classification and analysis of river processes. *Journal of the Hydraulics Division, ASCE*. HY7:813-829.

Kondolf, G.M. 1995. Geomorphological stream channel classification in aquatic habitat restoration: uses and limitations. *Aquatic Conservation*, 5:127-141.

Köppen, W. and R. Geiger. 1930. Climate of the Earth. World Map of Climate Classification. (scale 1:16,000,000). Justus Perthes Map Publishers: Darmstadt, Germany.

Kuchler, A.W. 1970. Potential natural vegetation. Map (scale 1:7,500,000). In *The National Atlas of the United States of America*, pp. 89-91. Washington, D.C.: U.S. Geological Survey.

Leopold, L.B. 1994. *A View of the River*. Cambridge Mass.: Harvard University Press.

Leopold, L.B. and T. Maddock Jr. 1953. The hydraulic geometry of stream channels and some physiographic implications. United States Geological Survey Professional Paper 252. U.S. Government Printing Office: Washington D.C.

Leopold, L.B. and Wolman, M.G. 1957. River channel patterns: braided, meandering, and straight. Professional Paper 282-B, United States Geological Survey: Washington, D.C.

Leopold, L.B., M.G. Wolman, and J.P. Miller. 1964. *Fluvial Processes in Geomorphology*. San Francisco:W.H. Freeman and Co.

Lucas, B. and P.L Jackson 1995. Koppen Climate Classification of the Pacific Northwest (1960 to 1990 temperature and precipitation data). Unpublished map (scale 1:4,000,000).

Melton, F.A. 1936. An empirical classification of flood-plain streams. *Geographical Review*. 26:593-609.

Montgomery, D.R. and J.M Buffington. 1993. Channel classification, prediction of channel response, and assessment of channel condition. Report TFW-SH10-93-002 prepared for the SHAMW committee of the Washington State Timber/Fish/Wildlife Agreement. Department of Geological Sciences and Quaternary Research Center, University of Washington, Seattle, WA 98195.

Mosely, M.P. 1987. The classification and characterization of rivers. In *River Channels: Environment and Process*, K. Richards (ed). Basil Blackwell.

Naiman, R.J., D.G. Lonzarich, T.J. Beechie, and S.C. Ralph. 1992. General principles of classification and the assessment of conservation potential in rivers. In: P.J. Boon, P. Calow, and G.E. Petts (eds), *River Conservation and Management*. New York: John Wiley and Sons.

Nolan, M., T. Lisle, and H. Kelsey. 1987. Magnitude and frequency of sediment transport and channel geometry in northwestern California. In *Proceedings of the International Symposium on Erosion and Sedimentation in the Pacific Rim*, eds. Beschta and others. Corvallis, OR, August 1987, p. 439-449.

Omernik, J.M. 1987. Ecoregions of the conterminous United States: map supplement. *Annals of the Assoc. of Am. Geographers*. 77(1):118-125.

Park, C.C. 1977. World-wide variations in hydraulic geometry exponents of stream channels: an analysis and some observations. *Journal of Hydrology* 33:133-146.

Parrott, H., D.A. Marion, and R.D. Perkinson. 1989. A four-level hierarchy for organizing wildland stream resource information. *In Headwaters Hydrology: Proceedings of the Symposium*. eds. Woessner, W.W. and D.F. Potts. American Water Resources Association: Missoula, Montana.

Paustian, S.J., D.A. Marion, and D.F. Kelliher. 1984. Stream channel classification using large scale aerial photography for southeast Alaska watershed management. RNRF Symposium on the Application of Remote Sensing to Resources Management, May 22-27, 1983: Seattle, Washington.

Pennak, R.W. 1971. Towards a classification of lotic habitat. *Hydrobiologia*, 38:321-334.

Popov, I.V. 1964. Hydromorphological principles of the theory of channel processes and their use in hydrotechnical planning. *Soviet Hydrology*. 2:188-195.

Ramsey, F. and D. Schafer. 1993. The Statistical Sleuth. Oregon State University Bookstores Inc.: Corvallis, Oregon.

Reckendorf, F.F. 1996. Personal Communication, October 1, 1996.

Reckendorf, F.F. 1995. Lemhi River Fish Stream Improvement Study, Lemhi County, Idaho. Reckendorf and Associates, Salem, Oregon.

Reckendorf, F. and L. Steffen. 1994. Fluvial Geomorphology Workshop. USDA – Soil Conservation Service. June 13 – 17: Reno, Nevada.

Ricker, W.E. 1934. An ecological classification of certain Ontario streams. *Publications of the Academy of Natural Sciences of Philadelphia*, 101:277-341.

Rosenfeld, C. 1985. Landforms and geology of the Pacific Northwest. In *Atlas of the Pacific Northwest, 7th edition*. eds. A.J. Kimerling and P.L. Jackson. Oregon State University Press: Corvallis, Oregon.

Rosgen, D.L. 1996. Personal Communication, December 2, 1996.

Rosgen, D.L. 1994. A classification of natural rivers. *Catena* 22: 169-199.

Rosgen, D.L. 1985. A stream classification system. In Johnson, R.R., C.D. Zeibell, D.R. Patton, P.F. Pfolliott, and R.H. Hamre (eds.). Riparian Ecosystems and Their Management: Reconciling Conflicting Uses. pp. 91-95, United States Forest Service, General Technical Report M-120, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Rosgen, D.L. and B. Fittante. 1986. Fish Habitat Structures – a selection guide using stream classification. 5th Trout Stream Habitat Improvement Workshop. Lock Haven University, Lock Haven, Pennsylvania. Pennsylvania Fish Commission Publics, Hamsburg, PA. pp. 13-29.

Rosgen, D.L. and L.B. Leopold. 1994. Short course on applied fluvial geomorphology. Course Materials by Wildland Hydrology Consultants, 1 Stevens Lake Rd., Pagosa Springs, CO 81147.

Schumm, S. A. 1963. A Tentative Classification of Alluvial River Channels. US Geological Survey Circular 477. Government Printing Office: Washington D.C.

Stevens, T.A. 1994. Evaluation of the Rosgen Stream Classification System on the Chequamegon National Forest, Wisconsin. University of Idaho Masters Thesis.

Strahler, A.N. 1957. Quantitative analysis of watershed geomorphology. *American Geophysical Union Transactions*, 38:913-920.

Streif, B. 1995. Personal Communication. Fisheries Biologist, USDA, Natural Resources Conservation Service, Salmon Recovery Team, Portland, OR.

Trewartha, G.T., and L.H. Horn. 1980. *Introduction to Climate*. New York : McGraw-Hill Book Co.

U.S. Bureau of the Census. 1969. Census of agriculture. Vol. 5, Special Reports. Part 15. Graphic Summary. Washington, D.C.: U.S. Government Printing Office.

U.S. Bureau of the Census. 1974. Census of agriculture. Vol. 4, Special Reports. Part 1. Graphic Summary. Washington, D.C.: U.S. Government Printing Office.

U.S. Bureau of the Census. 1978. Census of agriculture. Vol. 5, Special Reports. Part 1. Graphic Summary. Washington, D.C.: U.S. Government Printing Office.

USDA-SCS. 1981. Land resource regions and major land resource areas of the United States. United States Department of Agriculture, Soil Conservation Service. Agricultural handbook 296. Washington DC: US Government Printing Office.

USDA-SCS. 1994. Salmon Recovery Initiative Draft. USDA, Soil Conservation Service, West National Technical Center, Portland, Oregon.

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E.C. Cushing. 1980. The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences*. 37: 130-137.

Warren, C.E. 1979. Toward classification and rationale for watershed management and stream protection. Report No. EPA-600/3-79-059. United States Environmental Protection Agency, Corvallis, Oregon.

Williams, G.P. 1978. Bank-full discharge of rivers. *Water Resources Research*, 14(6):1141-1153.