AN ABSTRACT OF THE DISSERTATION OF

Julia L. Saligoe-Simmel for the degree of Doctor of Philosophy in Geography presented on October 27, 1997. Title: Analysis of Streamflow Variability in Oregon for Regional Water Quality Monitoring Programs.

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Philip L. Jackson

Streamflow variability can provide valuable information for nonpoint source pollution monitoring program planning. The research papers presented in this thesis examine selected properties of streamflow variability in Oregon to advance its application in regional planning of water quality monitoring programs. The products of this research depict Oregon streams by their relative streamflow variability and evaluate factors that may influence that variability. The three manuscripts examine the application of streamflow variability in the context of regional strategic planning by addressing three related questions: 1.) What is the relationship in Oregon between streamflow variability and watershed size, which is often described as a proxy for streamflow variability?, 2.) What geographic factors in Oregon influence streamflow variability, and are regional-scale factors adequate to efficiently predict streamflow variability on ungaged streams?, and 3.) How is streamflow variability in Oregon affected by seasonal climatic variation? Examination of these questions regarding the behavior of streamflow variability of river systems in Oregon is used to assist in the design of regional and local water quality monitoring programs.

Data are from historical records of established US Geological Survey gaging stations. Simple linear regression depicts the relationship of streamflow variability to basin size on a statewide basis and stratified by ecoregions. The results indicate that basin area is not an appropriate indicator of streamflow variability. Multiple regression is used to develop regional models of streamflow variability. Three models are developed for natural flow streams and streams with upstream diversions. Regional and watershed scale variables are evaluated for their potential contributions to the models. Watershed scale variables do not increase the predictive capacity of the models; therefore, the regional scale is appropriate for efficiently modeling streamflow variability. Seasonal investigation of streamflow variability in Oregon develops its application for seasonal monitoring programs. Spatial and temporal analysis reveal a weak relationship between annual and monthly streamflow variability, indicating potential for refined application of the variability index.

Streamflow variability is an accessible tool for developing water quality monitoring programs. The regional scale distribution of streamflow variability in Oregon demonstrates the ease at which streamflow variability may be estimated on ungaged streams.

ANALYSIS OF STREAMFLOW VARIABILITY IN OREGON FOR REGIONAL WATER QUALITY MONITORING PROGRAMS

by

Julia L. Saligoe-Simmel

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Julia L. Saligoe-Simmel, Author

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DEDICATION

Dedicated to Mark and Evelyn.

ANALYSIS OF STREAMFLOW VARIABILITY IN OREGON FOR REGIONAL WATER QUALITY MONITORING PROGRAMS

CHAPTER 1. INTRODUCTION

Introduction

In the United States, planning of water quality monitoring programs for nonpoint source pollution (NPS) often rely on a hierarchical approach to program design and prioritization. Initial planning occurs at the state or regional level, whereupon individual projects are prioritized and implemented at the local level. A hierarchical strategy provides basic information about the physical and design needs for monitoring projects within regions, and acts as a decision support system for the allocation of funds from national, regional, state and local interests. Although detailed baseline chemical monitoring data are often unavailable to assist in planning NPS monitoring programs, hydrologic and climatic data are readily available with adequate regional-scale coverage to be helpful in NPS program planning. Streamflow variability is an indicator that can provide information to assist such planning.

Streamflow variability may be described as magnitude of deviation from base flow conditions. While all rivers and streams are influenced to some degree by runoff events, a measurement of discharge variation (paired with an understanding of the behavior of water quality variables) can be used as a guide to determine the relative needs for water quality monitoring design. This understanding can provide clues to the sources and behaviors of runoff pollution and the monitoring needs of a project, and is critical in semiarid regions where common hydrologic data may be sparse. The research herein examines selected properties of streamflow variability in Oregon to advance its application in regional planning of water quality monitoring programs.

Justification

The current research addresses the "what, how, where and when" of streamflow variability for water quality monitoring design for Oregon stream systems. In order to address these questions, three components have been broken down and are addressed in separate research manuscripts. The products of this research depict Oregon streams by their relative streamflow variability and evaluate factors that may influence that variability.

While it is recognized that streamflow variability can provide valuable information for NPS monitoring program planning (Richards 1989, 1990), this information has not been applied in the context of regional strategic planning. The three manuscripts examine questions related to the application of streamflow variability for that purpose. The state of Oregon is used as a study area to examine the spatial organization of streamflow variability. Streamflow discharge from historical records provide the data set used to address three primary questions about streamflow variability. They are as follows:

- What is the relationship in Oregon between streamflow variability and watershed size, which is often described as a proxy for streamflow variability?

- What geographic factors in Oregon influence streamflow variability, and are regional-scale factors adequate to efficiently predict streamflow variability on ungaged streams?
- How is streamflow variability in Oregon affected by seasonal climatic variation?

Examining the behavior of streamflow variability of river systems in Oregon may assist in the design of regional and local water quality monitoring programs.

Format

This dissertation is presented in a manuscript format. Chapters 2, 3 and 4 (Papers I, II and III, respectively) are presented as individual manuscripts following journal submission guidelines. Paper I is an examination of the relationship between streamflow variability in Oregon and river basin size. Based on a review of the concept of streamflow variability and how it has been used in hydrology and water quality monitoring applications, streamflow variability in Oregon is quantified and mapped. In the water quality monitoring literature, river basin area has been used as a proxy for streamflow variability. Sampling frequencies for monitoring purposes have been based on the assumption that variability increases as basin area decreases (Figure 1.1). This implies that basin area could determine some of the needs for regional planning of NPS monitoring programs. Paper I tests the validity of the relationship between drainage basin area and streamflow variability. The State of Oregon serves as a study area to account for potential affects of regional diversity. Ecoregions provide a framework for discussing spatial attributes of streamflow variability.

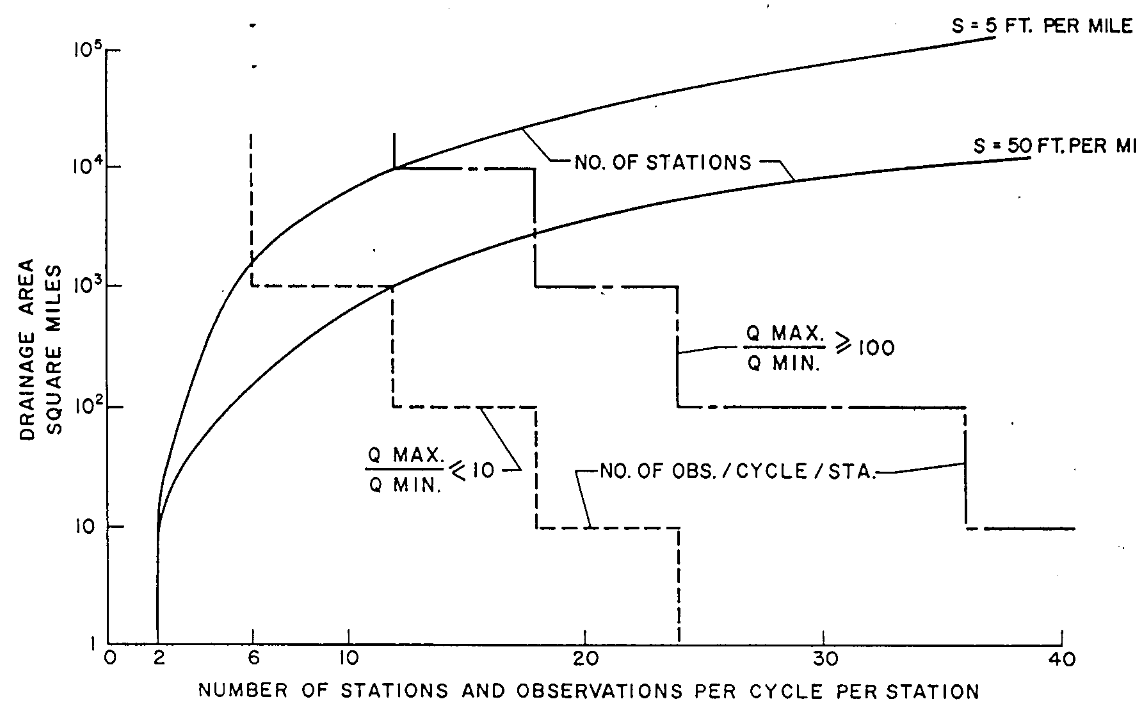

Figure 1.1. Minimum requirements for water quality sampling characterization in streams and rivers (from Pomeroy and Orlob 1967, 73).

The concepts and quantification of streamflow variability developed in Paper I allow for the statistical analysis of geographic parameters affecting streamflow variability in Paper II. The purpose of Paper II is to examine the spatial dimension of streamflow variability in terms of regional and watershed characteristics. This analysis provides a basis to estimate streamflow variability regionally, and at ungaged sites. The information gained from this approach is applied to ungaged stream catchments in Oregon where historic discharge records are unavailable.

Whether even-interval or storm event-based, sampling of NPS pollution is often conducted during monitoring seasons when overland runoff is most likely to occur. Paper III refines the application of the streamflow variability index by examining it on a seasonal basis. Monthly streamflow variability is calculated for the Oregon sites to evaluate seasonal change. The study area is examined for spatial patterns in seasonal variability and the processes that may influence those patterns. Seasonal investigation of streamflow variability provides further insight as to the timing and design needs of NPS water quality monitoring projects.

Literature Review

Streamflow variability is a useful tool for NPS monitoring. Design of water quality monitoring programs for load estimation is often hampered by the lack of existing data from which to determine patterns of flux variance, that help to determine sampling frequencies. For pollutants from nonpoint sources there is often a correlation between streamflow and pollutant flux. Rivers that have highly variable streamflow are likely to have highly variable fluxes, and will require relatively detailed sampling programs for accurate pollutant load estimation. In principle, measures of flow variability may be calibrated with pollutant fluxes for well known watersheds, and then used as a proxy for pollutant flux in streams where data are unavailable to estimate sampling needs (Richards 1989, 262).

The US Environmental Protection Agency (USEPA) defines NPS pollution as "any source of pollution that does not meet the legal definition of 'point source' in section 502(14) of the Clean Water Act" (USEPA 1993). Point sources of pollution discharge through pipes, drainage channels or conduit. They include diffuse sources of pollutants that are collected and channelized, such as urban storm water in sewers. NPS pollution is the diffuse pollution transported by rainfall or snowmelt runoff moving over and through the ground. As the runoff moves, it picks up and carries away natural pollutants and pollutants resulting from human activities, finally depositing them into lakes, rivers, wetlands, coastal and ground waters.

During a storm event that generates surface runoff, one may expect the following:

- Materials that accumulate on the ground are washed off by overland flow, e.g., sediment, nutrients, bacteria and pesticides;
- Materials that accumulate in the stream bed are stirred and transported during an event, e.g., bacteria and sediment;
- Physical properties change due to the nature of events (effects of concentration and dilution), e.g., temperature and turbidity.

Rainfall events often create overland and sub-surface runoff in which soil particles and pollutants mobilize and transport to nearby water bodies. The single hydrologic event can be brief, such as floods lasting hours or days, or it can be relatively lengthy, such as snowmelt runoff lasting weeks or months (Williams 1989, 89). Traditional water quality monitoring programs that employ even-interval sampling procedures may miss significant pollutant loads contributed during runoff events. Monitoring programs that implement low frequency even-interval and periodic-interval sampling have been shown to be insufficient for accurately describing the behavior of suspended sediment in rivers and streams during runoff events (Sanders and Adrian, 1978; Johengen and Beeton, 1992; MacDonald, 1992).

Due to the nature of how NPS pollution is transported to surface waters, water quality monitoring designs must account for the variability of water being discharged through the system. In some respects, the variability of river flow is functionally related to changes in water quality (Sanders et al. 1983). For example, the experiences of the Saline Valley Rural Clean Water Program (RCWP) emphasize the difficulty that projects face in establishing water quality monitoring designs appropriate to the variability of discharge, and pollutant loading, of a river system.

The Saline Valley, Michigan, was one of 21 projects within the U.S. Department of Agriculture's RCWP designed to evaluate methods for controlling agricultural NPS pollution (Johengen and Beeton 1992, 89). Using a fixed, weekly sampling design, water quality trends were monitored from July 1981 to December 1989. The project implemented storm event-based monitoring in June 1988 to quantify temporal and spatial variability in weekly and annual pollutant loading estimates. Researchers used the storm event data to quantify potential errors and evaluate the even-interval, weekly, monitoring data.

Table 1.1. Percentage of weekly loads occurring over seven days following a storm (from Johengen and Beeton, 1992).

# days after storm	DISCHARGE	SUSPENDED SOLIDS	TOTAL PHOSPHORUS	SOLUBLE PHOSPHORUS	NITRATE
1	40	85	71	65	55
2	20	9	15	14	15
3	13	2	5	10	10
4	9	1	3	5	8
5	7	1	3	3	7
6	6	1	2	2	3
7	5	1	1	1	2

Table 1.2. Percentage loading error based on extrapolating a single sampling event over seven days versus sampling for seven days (from Johengen and Beeton, 1992).

	PERCENT ERROR IN WEEKLY LOAD			
# days after storm	SUSPENDED SOLIDS	TOTAL PHOSPHORUS	SOLUBLE PHOSPHORUS	NITRATE
1	505	405	365	295
2	-36	+/-	+/-	+/-
3	-86	-64	-29	-29
4	-93	-79	-64	-43
5	-93	-79	-79	-50
6	-93	-86	-86	-79
7	-93	-93	-93	-86

Results from their analysis indicated that the study area's annual loads are dominated by storm events. Johengen and Beeton (1992) reported that, on the average, 76% of suspended solids, 56% of total phosphorus, 51% soluble phosphorus, and 50% nitrate occurred during 28 days of the year (only 8% of the time). Storm event monitoring revealed that the majority of loading occurred within the first 48 hours of a storm. This reflects a "first-flush" effect, where during the first part of a storm overland flow washes off material that has accumulated on the ground (Table 1.1). Errors in loading estimated from weekly sampling varied as a function of the duration between storm events and weekly sampling efforts. If weekly sampling occurred within 24 hours after a storm, weekly loads were greatly overestimated; conversely, if sampling occurred 5 or more days after a storm, the weekly loads were greatly underestimated (Table 1.2). Adjusted loads indicated that only 19, 34, 47, and 46 percent of the annual loads for suspended solids, total-P, soluble-P, and nitrate, respectively, were estimated by the fixed, weekly sampling design (Table 1.3) (Johengen and Beeton 1992, 92).

Table 1.3. Project's loading estimate from weekly observation (observed) versus adjusted loading estimate based on storm monitoring results (adjusted) (Modified from Johengen and Beeton, 1992).

PERCENT OF WEEKLY LOAD

MEAN ANNUAL LOAD	SUSP. SOLIDS (mton)	TOTAL-P (kg)	SOL-P (kg)	NITRATE (mton)
Observed	240	590	220	24
Adjusted	1,295	1,725	470	52
Percent Observed	19%	34%	47%	46%

The significance of a few individual storms to annual loads appears to be quite characteristic of NPS pollution (Johengen and Beeton 1992, 94; Collins and Dickey 1992, 1; Olive et al. 1995). Understanding the hydrologic properties of a system, including its streamflow variability, can assist in the development of water quality monitoring programs that allow for necessary data collection activities. The experiences of the Saline

Valley RCWP demonstrate the challenges presented to resource managers in defining monitoring designs that enable them to meet their objectives. Clearly, the ability to recognize changes in water quality from nonpoint source pollution is limited by the sensitivity of the monitoring procedures (Bunte and MacDonald 1995, 253).

Geographical Significance

Investigation of geographical properties influencing the streamflow variability of drainage basin systems fits well into the major themes of geographical research. The three research papers emphasize spatial analysis of streamflow variability in Oregon and contribute significant geographical findings to the field of water quality monitoring. They represent a positivist research philosophy, whose ultimate purpose is "the generation of theories to explain and predict the relationship between phenomena" (Mitchell 1989, 19). In 1958, Ackerman called geography the "science of spatial distribution" (Mitchell 1989, 10). McCarty (1963) said geography's focus is "to account for the locations and spatial arrangements of phenomena on the earth's surface" (Mitchell 1989, 10). And in 1971, Abler, Adams and Gould said geography posed questions about location, spatial structure and spatial processes (Mitchell 1989, 10). The manuscripts herein address questions regarding the nature of the relationship between geographical properties and hydrologic processes.

Temporal and spatial scale issues are integral to the analysis and classification of streams in Oregon by their streamflow variability. Levin (1992) described three important steps when planning a study: 1) identify a pattern, 2) look for correlations, and 3) develop a conceptual model and use it to test hypotheses or make predictions. Steps one and two involve statistical techniques and step three involves conceptual models that develop in space. One of the main points Levin makes is that temporal and spatial scales are organizational concepts that link all subdisciplines of geography and ecology, if not all of science. As Charles Hall (1988) points out, ecosystems are very complex systems that are not easily modeled. We use modeling to observe system functions and to make predictions for management. Many scientists have behaved as if pattern and the processes that produce them are insensitive to differences in scale (Wiens, 1989). However, the scale chosen for study often determines the patterns and processes that are observed.

The influence of spatial and temporal scale in water quality monitoring are acknowledged by all three research papers. As such, the implications of using different scales are addressed. Physical processes that determine local and regional streamflow variability are addressed in hierarchies of scale. For the purposes of this research, scale terms common to geographic tradition will be used. Large scale refers spatially to local areas and temporally to short time periods, whereas small scale refers spatially to regional areas and temporally to lengthy time series. As the research papers are intended for a broad audience in geographical as well as water resource disciplines, when practical common scale terms will be used: spatial scale will be referred to by terms such as local or regional, and temporal scale will be specified in terms of hours, days, weeks, etc.

Study Area

The State of Oregon is used as the study area for analyzing streamflow variability. The appropriateness of this study area is two-fold: 1.) the study area expands the geographic coverage of prior research on streamflow variability that originated from the eastern United States, and 2.) several physiographically and climatically disparate regions are present within the boundaries of the State. Ecoregion boundaries provide a geographic framework for exploring the spatial patterns of streamflow variability. Ecoregions play an important role in data stratification, because their development grew out of an effort to classify streams for more effective water quality management (Omernik, 1987). These ecoregions are areas within which there is likely to be less variation than within broader state or major river basin areas (Omernik, 1987). Appendix D provides a brief description of Oregon ecoregions [Figure 2.3]. A description of the methods used to define ecoregion boundaries can be found in J.M. Omernik's *Ecoregions of the Conterminous United States* (1987).

Description of Data

Study Sites

The study sites are comprised of selected stream gage points and their associated watersheds. Surface water discharge data are utilized in this research for the quantification and classification of Oregon river systems. Discharge and watershed area data are taken from the U.S. Geological Survey (USGS) *Water Resources Data - Oregon,* *Water Year 1994* (Hubbard, et al., 1995), and flow-duration statistics are taken from the USGS *Statistical Summaries of Streamflow Data in Oregon: Volume 1* (Moffatt, et al., 1990). Selection of USGS stream-gaging stations is based on a search of stations whose period of record extends over a minimum of ten years. Information as to the upstream impoundments and diversions is also obtained from these sources. Because of their regulating effects, data set selection is based on USGS stream gages with no upstream impoundments (dams and reservoirs). However, to provide adequate geographic coverage of streams and water utilization in Oregon, some gages in the data set do have upstream diversions. To account for possible error due to streamflow diversions, all analyses are examined for the effects of the presence or absence of diversions (information on the presence or absence of diversions can be ascertained from the data tables, Appendix A and B). Some currently dammed stream locations included in Paper I utilize periods of record prior to construction of regulating facilities.

Gage locations and their associated watershed boundaries for the study sites are shown in Figure 1.2. Within each major river basin, the stream networks contain nested watersheds. The result of such nesting is that many gage locations are upstream from each other. Because of the possibility that nested watersheds might unevenly weight the data, the effect of nesting on the validity of the data set was examined using a subset of 100 randomly chosen watersheds. After identifying groups of gages where nesting exists, gages affecting data from nested watersheds were eliminated from the subset based on the following criteria: 1.) if a downstream gage affected the nesting of two or more upstream gages it was eliminated from the subset, if not, then 2.) gages with diversions were selected for elimination first, and 3.) all else being equal, gages with the shortest period of record were eliminated. The two resulting data sets (nested (100 observations), and non-nested (88 observations)) had essentially no differences in the results of a stepwise data analysis in terms of model parameter selection or measures of significance, indicating that, for this data set, watershed nesting is inconsequential.

Streamflow Variability

Although streamflow variability is recognized as an important factor in water quality monitoring design, there is a general lack of discussion of its meaning and application. A clear understanding of its possible meanings will lead to effective communication among projects. Context and scale determine the specific meaning of streamflow variability. The following are examples of different meanings of this term:

- Frequency distribution of *mean daily discharge* over a period of record (Lane and Lei, 1950) (Richards, 1989, 1990);
- Variation in *mean annual discharge* among a series of years (McMahon et al. 1987);
- Change in *mean annual discharge* across space (Leopold et al., 1995).

The meaning of streamflow variability used throughout this text is that first presented by Lane and Lei (1950) and later by Richards (1989, 1990).

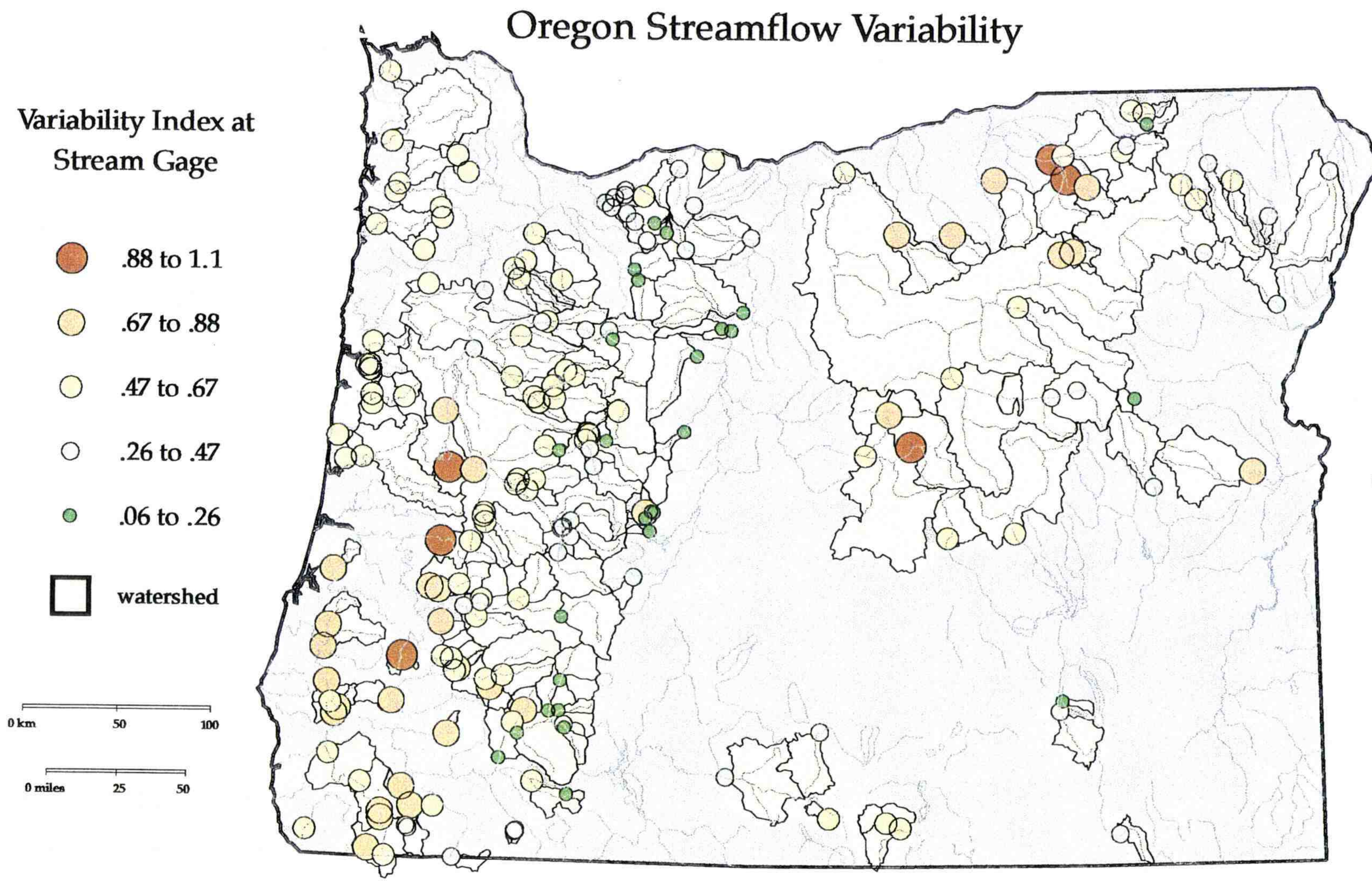

Figure 1.2. Stream gage locations and their associated watersheds.

Streamflow variability is quantified and presented in the following research as the variability index (V_i), expressed as the coefficient of variation of the logs of flows corresponding to the percentiles: {5, 10, 15, 20, ..., 80, 85, 90, 95}(Richards 1989, 261). The index is a function of the slope of the flow duration curve when plotted on logarithmic probability paper (Lane and Lei 1950). This measure of streamflow variability is convenient because it can be readily calculated from flow duration tables provided by the USGS. The variability index is scale independent in log space (Richards 1989, 261), and gives an expression of the relative variability from the mean, expressed as the formula:

$$V_i = \sqrt{\frac{\Sigma(y - \bar{y})^2}{n - 1}} \qquad \text{(Lane and Lei 1950, 1099)}$$

In which: y is the logarithm of the selected discharge at a 5% interval of the duration curve, $\bar{y}$ is the mean of y, and n is the number of selected discharges ($n = 19$ in the given procedure).

Richards (1989) described and evaluated several alternative measures of flow variability for 118 Great Lakes tributaries. Of the measures, the V_i (as described herein) was less strongly affected by the presence of near-zero flows in the tail of the distribution and most successful for estimating flux variances (Richards 1989, 370). Although each of the measures were highly intercorrelated, the V_i was the preferred method for application in water quality monitoring programs. A histogram showing the distribution of flow variability of Oregon streams is presented in Figure 1.3.

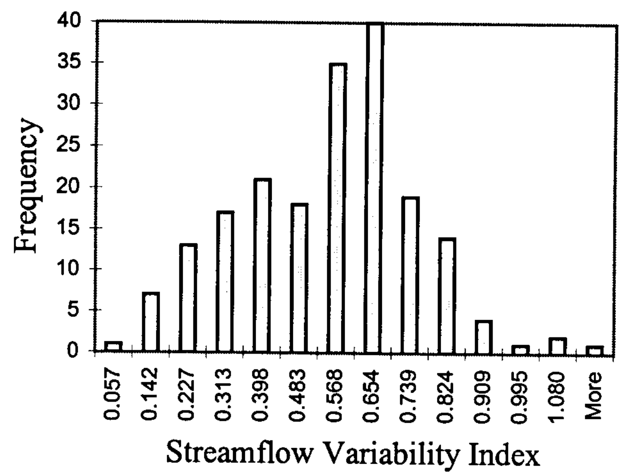

Figure 1.3. Histogram of Oregon streamflow variability index.

Flow duration statistics are calculated by the USGS on gaged streams with at least 10 years of data. The USGS judges this record length as necessary to adequately damp out annual variability effects when calculating flow duration statistics. While the V_i used in the following research is based on a 10 year minimum record, the periods of record do not correspond for each station (periods of record for each station can be ascertained from the begin and end dates in the data tables, Appendix A and B). The effect of the period of record on the V_i was examined by Richards (1989) by comparing earlier publications of flow duration statistics for several rivers with those based on the entire period of record.

When compared to the ranges shown by these indices, the changes in the flow indices were all minor. This suggests that the indices are fairly unresponsive to the length of record used to calculate them, though indices based on shorter periods of record (less than 10 years) are subject to greater uncertainty (Richards 1989, 365).

Paper III uses a monthly stratification of the V_i to examine issues of seasonal water quality sampling strategies. While the method for calculating the variability index is essentially the same, in Paper III it is calculated separately for each month (i.e., flow duration statistics for October during the entire period of record are used to calculate the October V_i). Monthly V_i allow for the examination of streamflow variability between months, and investigation of the effects of gross climatic indicators such as wet and dry seasons.

<u>Watershed and Regional Variables</u>

Paper II evaluates the significance of the relationship between streamflow variability in Oregon and a number of variables that may influence that variability for model development and prediction. Those variables are interpreted in terms of geographic scale as being either regional-scale or watershed-scale. Watershed-scale variables are those whose measurements do not or cannot extend beyond the watershed boundary. For example, watershed size, shape, and slope are all watershed-specific parameters. Alternately, regional-scale variables are those whose measurement is more-or-less continuous across boundaries (e.g., precipitation and temperature). Selection of variables was based on a review of the literature and data availability. Table 3.1 lists the variables included in the analysis and the domain of scale at which the variable is assumed to operate (regional- and watershed-scale data, and a description of those data and their sources is presented in Appendix B).

CHAPTER 2.

RELATIONSHIP OF BASIN SIZE AND STREAMFLOW VARIABILITY IN OREGON

by

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Abstract

Streamflow variability is commonly assumed to increase as river basin size decreases. Water quality monitoring literature often base recommendations for surface water monitoring on this assumption, suggesting that samples be taken more frequently in small basins and less frequently in large basins. In Oregon, data from 193 US Geological Survey gaging stations are used to test the hypothesis that streamflow variability is inversely related to river basin size. Linear regression is used to empirically test this relationship; the relationship is shown not to be significant. Spatial data exploration is used to investigate the geographic distribution of streamflow variability in Oregon, and to assist in evaluating its relationship with basin size. Ecoregions provide the geographic framework for regional analysis of streamflow variability within Oregon's gaged watersheds. The findings of this research suggest that basin area alone is not an adequate predictor of streamflow variability; therefore, water quality sampling frequency recommendations based on basin size may be arbitrary.

(**KEY TERMS**: surface water hydrology; water quality monitoring; nonpoint source pollution; water resources geography.)

Introduction

A primary consideration of surface water quality monitoring programs for nonpoint source (NPS) pollution is the sampling frequency at which trends in water quality can be detected and evaluated. Sampling frequency in turn depends, in part, upon the streamflow variability of water discharge through the system (Sanders et al. 1983). Water quality monitoring programs have traditionally ignored short-term temporal variation in discharge (e.g., flow produced by individual storm events). In recent years, storm-event sampling has been recognized for its importance in monitoring projects: the significance of a few individual storms to annual loads seems to be characteristic of NPS pollution (Johengen and Beeton, 1992). Although much of the literature on monitoring nonpoint pollution considers the importance of the natural variability of stream discharge, this recognition has not necessarily led to adequate monitoring frequency determinations.

Assumptions about the relationship between basin area and streamflow variability (and consequently sampling frequencies) have been applied to water quality monitoring programs. It is not uncommon in the literature to find sampling frequency recommendations based on the size of the watershed (Pomeroy and Orlob, 1967; Meybeck et al., 1992). These recommendations are based on the assumption that the hydrologic response of smaller river basins to storm events are more variable than larger basins (Lane and Lei, 1950; Searcy, 1959; Pomeroy and Orlob, 1967; Meybeck et al., 1992). This paper challenges the assumption that basin size is an appropriate universal indicator of streamflow variability. As such, this research tests the hypothesis that watershed size is inversely related to streamflow variability.

Although at a conceptual level the prevailing model of hydrologic response may seem reasonable, it does not represent the geographic and hydrologic complexities of many river systems, especially in the western United States. The common assumption that streamflow variability increases as basin size decreases originates primarily in research performed in the eastern US (Lane and Lei, 1950; Mitchell, 1950). For regions where this assumption has not been explicitly tested, information on sampling frequency and water quality monitoring designs may be inaccurate.

This paper examines concepts of streamflow variability, considers different spatial and temporal scales, and quantifies streamflow variability as it relates to these concepts. It traces the origins of the assumption that streamflow variability is inversely related to basin size through the modern literature. Then it identifies and examines spatial characteristics of streamflow variability in Oregon. Finally, it tests the hypothesis that basin size is inversely related to streamflow variability and discusses the implications for water quality monitoring design.

Streamflow Variability

It is necessary to quantify streamflow variability, because making visual or qualitative comparisons among streams is difficult, even when relying on flow duration curves. Streamflow variability may be qualitatively described as the relative number of high and low flows throughout a given year, the range in streamflow, or as a function of the slopes of the ascending and descending limbs of the hydrograph. However, even with a conceptual understanding of streamflow variability, visual comparison among stream hydrographs is not practical. Determining relative annual streamflow variability among streams by examining annual discharge can be a daunting task [Figure 2.1A]. One cannot rely on subjective judgment to make consistent visual interpretations. While it may appear that one stream has high discharge peaks compared to other streams, the descending limb of the hydrograph may taper off slowly. Transforming the vertical axis (discharge) to a logarithmic scale "spreads" out the lower portion of the hydrograph [Figure 2.1B], making visual interpretation easier, yet still subject to inconsistencies. This is especially true when making comparisons among a large number of streams.

This paper analyzes streamflow variability by examining streamflow frequency distributions. Frequency distribution is a term used to describe the distribution of an event over time. Leopold et al. (1995) use frequency distributions in their discussion of the characteristics of climatic events. For example, the statement that the mean annual rainfall of a given region is 76 cm (30 in) provides only a limited amount of information about the characteristics of precipitation. Knowing the frequency distribution of precipitation allows the observer to know whether the total falls bit by bit at a rate of 0.35 cm (0.12 in) per day, whether it is seasonally distributed, or whether half of the annual amount falls regularly in storms of a few hours duration (Leopold et al., 1995).

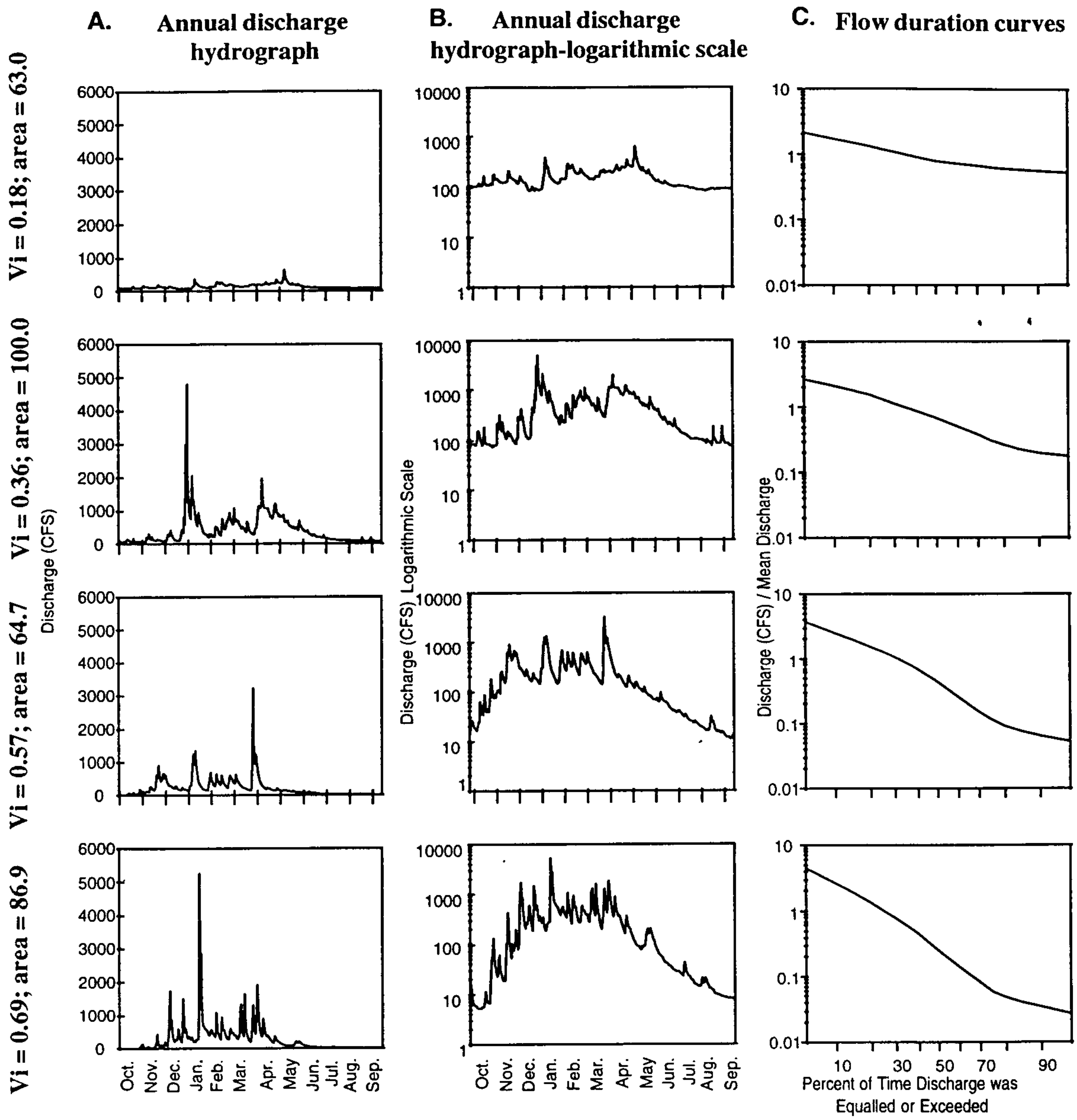

Figure 2.1. Graphs depicting a range of streamflow variability from four streams of comparable basin area: (A.) streamflow hydrographs do not allow for easy distinction of streamflow variability; (B.) "spreading-out" the y-axis to a logarithmic scale makes streamflow variability more distinguishable, yet still subjective; (C.) flow duration curves show the same information in a different way, allowing streamflow variability to be distinguishable for each stream based on the slope of the curve.

Flow duration curves, or frequency distribution curves, of mean daily flow describe the frequency distribution of mean daily flows at a particular location in a stream. A flow duration curve [Figure 2.2] may be thought of as the annual hydrograph with its flows arranged in order of magnitude, where the position of the curve gives the magnitude of flow (Walling, 1971). For example, a discharge of nearly 1.37 m^3/sec (60 cfs) was equaled or exceeded 50 percent of the period of record for the Donner und Blitzen River near Frenchglen, Oregon, while over 11.32 m^3/sec (400 cfs) was discharged in only 5 percent of the time. A wide range of values will be evident in the flow duration statistics on streams with high streamflow variability (Moffatt et al., 1990). Thus, as the position of the duration curve gives the magnitude of the flow, the slope of the curve is a measure of flow variability (Leopold et al., 1995). Flow duration curves that are steep represent flashy streams with high peaks and low minimum flows (Black, 1991).

Although the flow duration curve is a useful means of characterizing the stream flow record, one must exercise caution when interpreting streamflow variability from flow duration curves. When plotted on nonarithmatic graph paper (as is standard in plotting flow duration curves), lines that appear to be parallel may not be parallel (Black, 1991). The only way to compare the slopes of two seemingly parallel lines is to compute the slope between two or more different locations along the curves (Black, 1991). Figure 2.1C demonstrates the flow duration curves of the same four streams of differing streamflow variability but similar mean discharge. Searcy (1959) provides an excellent review of the construction and uses of flow duration curves.

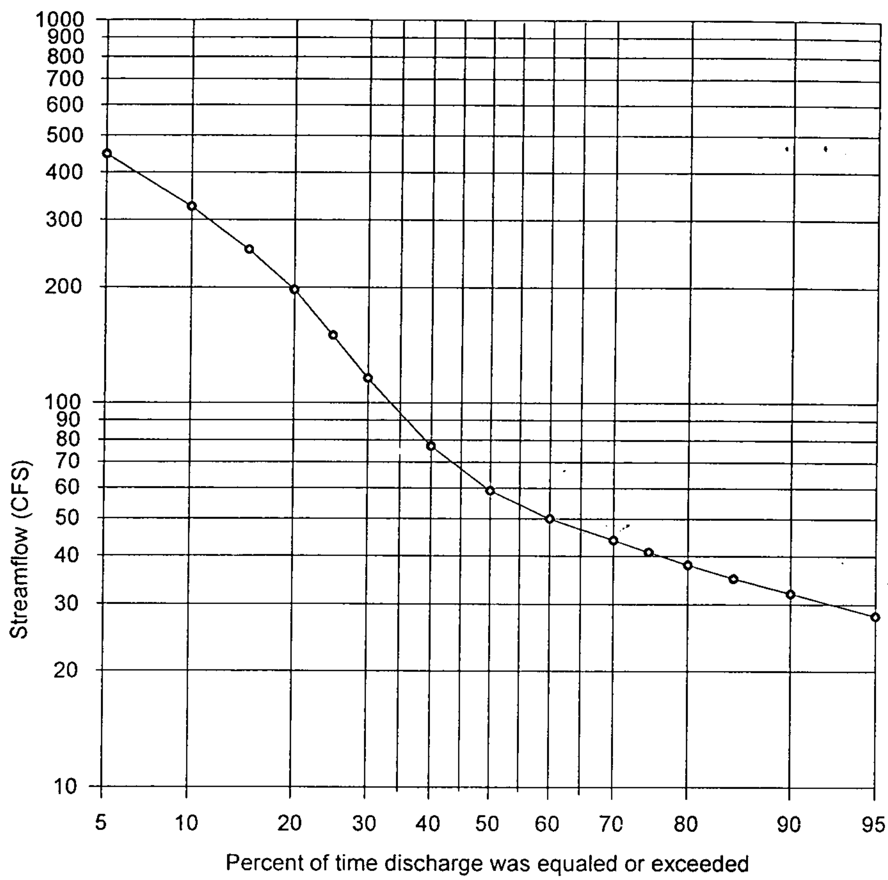

Figure 2.2. Flow duration curve for Donner und Blitzen River, Oregon (data from Moffatt et al., 1990).

By reducing the variability of flow to a discrete value it is possible to compare the values for a large number of streams (Lane and Lei, 1950). Different applications, such as hydropower, irrigation, and flood control, have used several methods to quantify the slope of the flow duration curve as a measure of variability. In 1920, the US Geological Survey adopted a ratio of the flow 50 percent of the time to the flow available 90 percent of the time for hydropower applications (Searcy, 1959). Pomeroy and Orlob (1967) calculate a crude measure of variability, as the ratio of maximum discharge to minimum discharge, for their application to water quality monitoring design in California. Also in 1967, Hall used the ratio of the flow exceeded 30 percent of the time to that exceeded 70 percent of the time for the assessment of water resources in England (Gregory and Walling, 1973).

In an attempt to establish a generally accepted method for indicating the degree of variability in a quantitative way, Lane and Lei (1950) introduced their 'variability index.' Having the objective of comparing streams regarding this characteristic, the standard deviation of the logarithms of stream discharge defines their index. Using flow duration curves developed for stations in the eastern US whose records were of 10 year duration or more, duration curve discharge values were read off at 10 percent intervals from 5 to 95 percent (Lane and Lei, 1950). The variability index was then computed as the standard deviation of the logarithms of these discharges. The advantage of Lane and Lei's variability index over the previously mentioned ratio methods is that it incorporates the full spectrum of duration values rather than the somewhat arbitrary selection of two values.

Streamflow Variability and Basin Size

Recommendations for water quality monitoring design are often based on the assumption in hydrology that streamflow variability increases as basin size decreases.

For example, the State of California established sampling frequency criteria in the late 1960's from river flow and river basin size (Sanders et al., 1983). Pomeroy and Orlob (1967) recommended sampling frequencies based on basin size and the ratio of maximum to minimum stream flow, thus attempting to account for hydrologic variability. Without citing quantitative data, they recommended sampling watersheds greater than 2590 km^2 (1,000 mi^2) at least 12 times per year, whereas small watersheds less than 26 km^2 (10 mi^2) should be sampled twice per week. Streams with a maximum to minimum flow ratio of greater that 100 should be sampled weekly, and well-regulated rivers with a ratio of less than 10 should have minimum surveillance (Pomeroy and Orlob, 1967).

More recently, Meybeck et al. (1992) use basin size to determine the relative need for storm event based sampling. They suggest such sampling is necessary in small rivers whose basin size is less than 1,000 km^2 (386 mi^2), and less frequent sampling (once per month or less) is sufficient for basins greater than 100,000 km^2 (38,610 mi^2). The authors do, however, suggest storm event sampling in large river basins when extreme events are adequately forecasted.

It is instructive to trace the origins of the basin size - streamflow variability assumption through the modern literature. The seminal work on streamflow variability by Lane and Lei (1950) was one of the first to attempt a quantitative study of this relationship. The original conclusion from a study of 224 streams in the eastern United States indicated that "large watersheds will tend to have lower [variability] values than small ones" because of channel storage and desynchronized runoff from rainfall (Lane and Lei, 1950). It appears from a review of the literature that the post-1950 use of this assumption has been in large part based on this work.

However, examination of the detailed technical reviews and concluding response attached to Lane and Lei's 1950 article reveals the questionable reliability of their original conclusion. Some of the reviewers demonstrate the "common sense" origin of this assumption:

- "Both common sense and a study of the tables [Lane and Lei] confirm a definite influence of the size of watersheds on the index... it is apparent that extremely high indexes occur only in small watersheds" (Ospina and Tama in review of Lane and Lei, 1950).
- "The effect of the area of watershed on the uniformity of its drainage is likewise common knowledge" (Wing in review of Lane and Lei, 1950).

Other reviewers, as well as the closing discussion by Lane, raise doubt to the original conclusions:

- In reference to streams from large watersheds having lower indexes than streams from small watersheds, "Surprisingly, a tabulation of the area and variation of 22 streams... reveal that this is not the case" (Lull in review of Lane and Lei, 1950).
- "Review of the data show... the increase [in variability with decreased basin size] was negligible for many cases" (Lane in closing discussion of Lane and Lei, 1950).

Nonetheless, the assumption that streamflow variability increases with decreasing basin size resonates throughout the modern literature. In his work on flow duration curves, Searcy (1959, 31) summarized Lane and Lei's conclusions by stating "they found that large drainage areas tended to have lower values of variability than small ones." The theory of desynchronized runoff with rainfall supports the basin area assumption. The theory states that as a catchment gets larger, rainfall is less likely to be uniform over space or time, thus resulting in more uniform discharges (Knapp, 1979). Water quality monitoring literature has adopted the assumption, indicating that small watersheds usually have low median discharges with extremely large ratios of peak to low discharge (Meybeck et al., 1992).

Study Area

The State of Oregon is the study area for analyzing the streamflow variability - basin size relationship. This area serves as an appropriate western case study because: 1.) prior research discussing this relationship has originated from the eastern United States, and 2.) within its boundaries are several examples of physiographically and climatically disparate regions.

Ecoregion boundaries provide a geographic framework for exploring the spatial patterns of streamflow variability. Ecoregions play an important role in data stratification, because their development grew out of an effort to classify streams for more effective water quality management (Omernik, 1987). These regions are areas within which there is likely to be less variation in ecosystems than within broader state or major river basin areas (Appendix D). A description of the methods used to define their boundaries is provided by Omernik (1987).

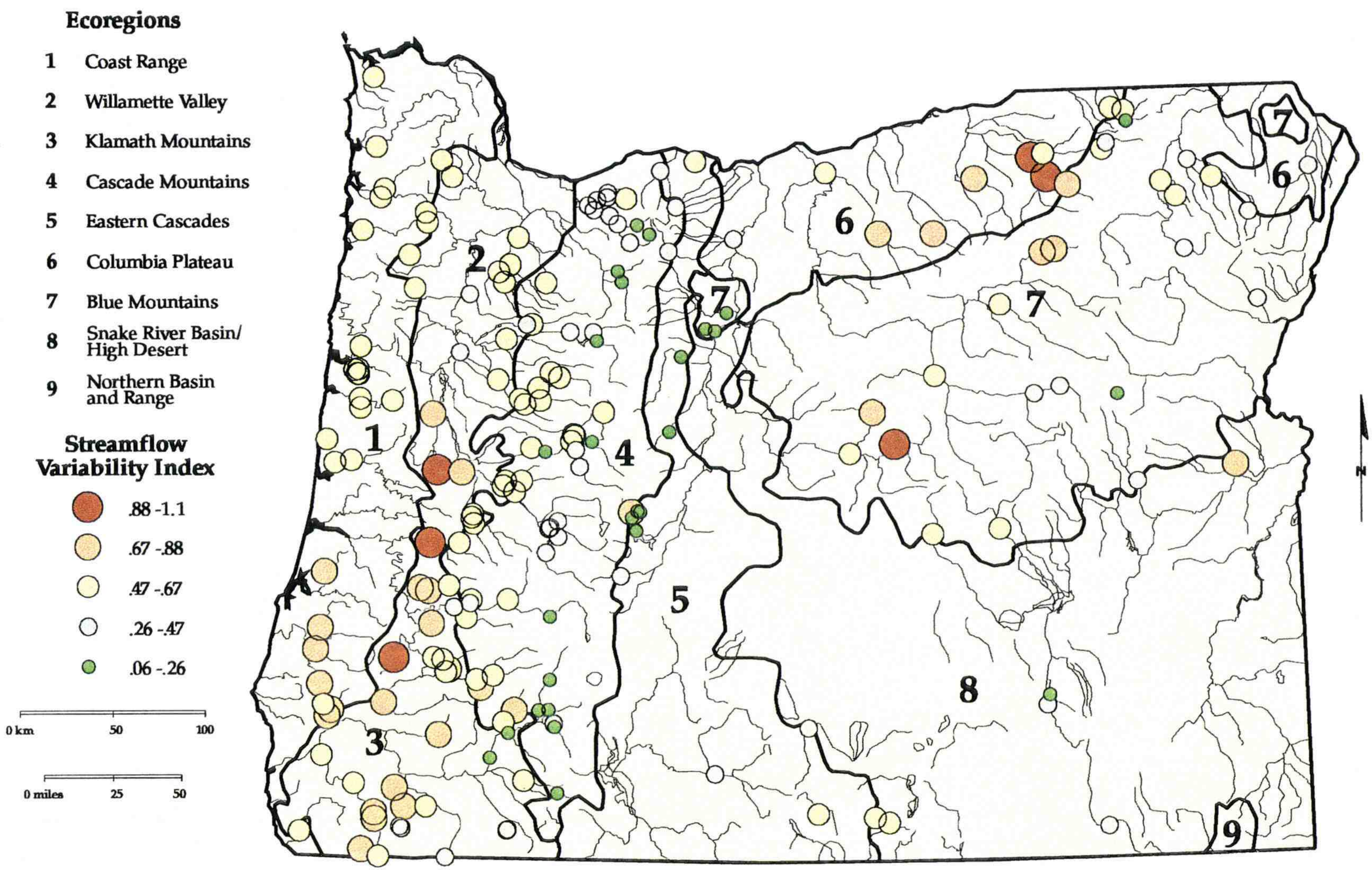

Figure 2.3. Streamflow variability in Oregon, USA. Ecoregion boundaries assist interpretation of spatial patterns of streamflow variability.

Methods

The U.S. Geological Survey *Water Resources Data - Oregon, Water Year 1994* (Hubbard et al., 1995) provides discharge and watershed area data used in the current analysis. The USGS *Statistical Summaries of Streamflow Data in Oregon: Volume 1* (Moffatt et al., 1990) provides flow-duration statistics based on mean daily discharge. Selection criteria include USGS stream-gaging stations whose period of record extends over a minimum of ten years and stream gages with no upstream regulating facilities (dams and reservoirs). It should be noted that the criteria that no upstream regulating facilities are present may introduce bias in the data set towards smaller basin sizes (many larger streams in Oregon possess regulating facilities). Additionally, the data set does include streams that have upstream diversions. This inclusion is necessary to provide good geographic coverage across the state, because most gaged streams in eastern Oregon support diversions. To account for possible error due to streamflow diversions, a subset of the data are examined for the relationship with basin size given an absence of diversions (information on the presence or absence of diversions can be ascertained from the data tables, Appendix A). Included in the data set are some presently dammed streams, where the data are from a period of record prior to construction of regulating facilities. The data set includes 193 stream gages in Oregon. Watershed areas range from 0.77 km^2 (0.3 mi^2) to 19,632 km^2 (7,580 mi^2).

Flow duration statistics are calculated by the USGS on gaged streams with at least 10 years of data. The USGS judges this record length as necessary to adequately damp out annual variability effects when calculating flow duration statistics. While the index of streamflow variability used in the current research is based on a 10 year minimum record, the periods of record do not correspond for each station (periods of record for each station can be ascertained from the data tables, Appendix A). The effect of the period of record on the variability index was examined by Richards (1989) by comparing earlier publications of flow duration statistics for several rivers with those based on the entire period of record. When compared to the ranges shown by these indices, the changes in the flow indices were all minor. This suggests that the indices are fairly unresponsive to the length of record used to calculate them, though indices based on shorter periods of record are subject to greater uncertainty (Richards, 1989).

Streamflow variability is quantified and presented as the variability index (V_i), expressed as the coefficient of variation of the logs of flows corresponding to the percentiles: {5, 10, 15, 20, ..., 80, 85, 90, 95}(Richards 1989, 261). The index is a function of the slope of the flow duration curve when plotted on logarithmic probability paper (Lane and Lei 1950). This measure of streamflow variability is convenient because it can be readily calculated from flow duration tables provided by USGS. The variability index is scale independent in log space (Richards 1989, 261), and gives an expression of the relative variability from the mean, expressed as the formula:

$$V_i = \sqrt{\frac{\Sigma(y - \bar{y})^2}{n - 1}}$$ (Lane and Lei 1950, 1099)

in which y is the logarithm of the selected discharge at a 5% interval of the duration curve; $\bar{y}$ is the mean of y; an n is the number of selected discharges ($n = 19$ in the given procedure).

Richards (1989) described and evaluated several alternative measures (including ratios and spread) of flow variability for 118 Great Lakes tributaries. Of the measures, the V_i (as described herein) was less strongly affected by the presence of near-zero flows in the tail of the distribution and most successful for estimating flux variances (Richards 1989, 370). While based on only 19 flow values, the V_i preserves and reflects the essence of the distribution properties of most of the range of data more than the other measures tested (Richards 1989, 363). Although each of the measures were highly intercorrelated, the V_i was the preferred method for application in water quality monitoring programs.

Within each major river basin, the stream networks contain nested watersheds. The result of such nesting is that many gage locations are upstream from each other. To account for any lack of independence in the data due to nesting, the data set was examined using a subset of 100 randomly chosen watersheds. After identifying groups of gages where nesting exists, gages affecting nested watersheds were eliminated from the subset. The two resulting data sets (nested (100 observations), and non-nested (88 observations)) had essentially no differences in the results of a stepwise data analysis in terms of model parameter selection or measures of significance, indicating that in this data set watershed nesting is inconsequential.

Variability indexes are grouped into classes and mapped to explore spatial patterns in the data. Classes are determined by a constant series method that employs equal division of the data. Five classes were derived from equal step intervals of one standard deviation from the mean. Station locations are identified by the latitude and longitude coordinates provided in the USGS reports. Ecoregion boundaries are incorporated into the map to provide regionalization of such factors as geology, physiography, land use, climate and vegetation (Omernik 1987). Ecoregions assist in the investigation of regional effects in the data and further discussion of geographic factors that may influence streamflow variability in Oregon. Figure 2.3 depicts the location, distribution and range of streamflow variability of the gaging stations used in this analysis.

Basin area is plotted against streamflow variability for all stations in the data set [Figure 2.4] to test the hypothesis that basin size is inversely related to streamflow variability. The arrowed line drawn on the scatterplot represents the assumed direction of the relationship between streamflow variability and basin size. To examine possible regional effects, the data are stratified by ecoregion [Figure 2.5]. Regression lines are fit to each of the data sets. Simple linear regression is used to test the hypothesis that the size of a watershed is an adequate predictor of streamflow variability.

Results

A scatterplot of all data [Figure 2.4] reveals no linear relationship between streamflow variability and basin area. R-squared and p-values are not significant for all data [Table 2.1]. However, stratification by ecoregion reveals patterns in the distribution of the data [Figure 2.5]. Although not statistically significant, the Klamath Mountains and Eastern Cascade Slope ecoregions tend to follow a pattern of slightly decreasing variability with increasing basin area. Conversely, the Blue Mountains, Cascades and Coast Range ecoregions exhibit steady or slightly increasing variability with increasing basin area. Discernible features of the stratified data set include the narrow spread of streamflow variability over a large range of basin areas in the Coast Range ecoregion. Also, the values of streamflow variability in the Eastern Cascade Slope ecoregion are relatively low as compared to the Willamette Valley and Klamath Mountains ecoregions.

A statistically significant relationship is present for the Willamette Valley ecoregion, depicting an inverse relationship with basin area as suggested by the literature. When only streams with no upstream dams or diversions are considered, there is also a significant relationship among V_i and basin area for the Cascades ecoregion ($R^2 = .0865$, p-value = .0382, df = 49). While these ecoregions show significance, the explanatory power of their R^2 is low for both. Examination of non-diverted streams in all other ecoregions showed no significance.

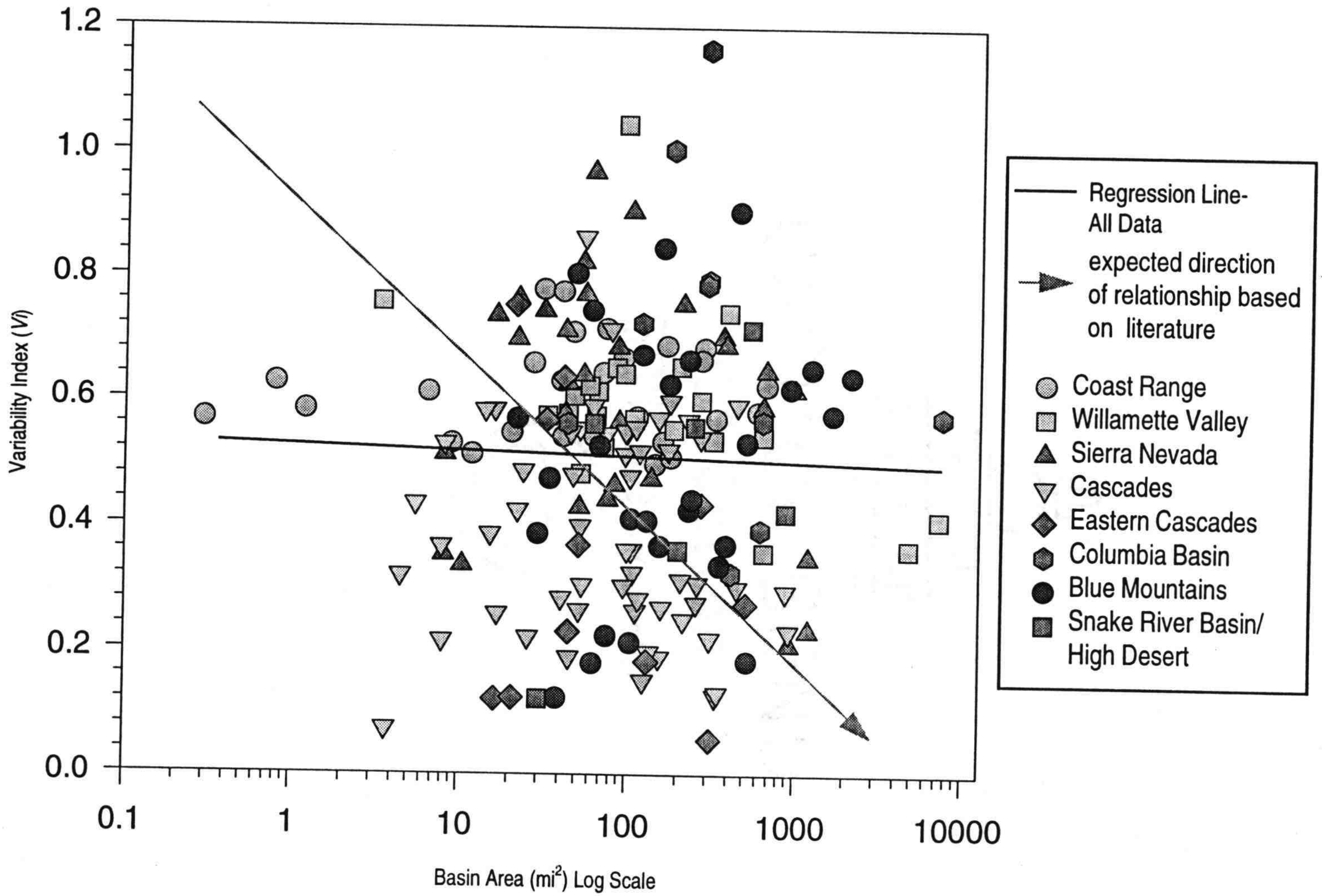

Figure 2.4. Scatterplot of streamflow variability versus basin area in Oregon.

Streamflow variability is highest in the northeastern and southwestern parts of the state. In the northeast, high variability typifies the Columbia Plateau ecoregion. The Columbia Plateau ecoregion is characterized by dry, deep channels cut into the underlying formations. Continental influences dominate the highlands, and considerable elevation differences are responsible for strikingly different mountain and valley climates (Jackson 1993, 56). It is drained by perennial, intermittent and ephemeral streams with basin areas ranging in size from under 1 to over 25,000 square kilometers. Average annual precipitation ranges from 23 to 63.5 cm (9 to 25 in) (Omernik, 1986).

In the southwest portion of the state, the Klamath Mountains ecoregion is characterized by steeply sloping, highly dissected mountains, narrow valleys with gently sloping floodplains, and steeply sloping foothills. The area is drained mainly by perennial streams, although intermittent streams occur in headwater reaches and valley floors. Average annual precipitation ranges from as low as 46 cm (18 in) in some valleys to as great as 216 cm (85 in) in some mountain locations (Omernik, 1986).

The streamflow variability indexes in the Coast Range ecoregion are between 0.5 and 0.8. Much of this region is highly dissected by perennial streams, and flow is perennial in watersheds draining areas less than one square mile. The combinations of complex, highly variable local topographic relief and marine influence result in large differences in local precipitation, with average annual precipitation ranging from 140 cm to over 317.5 cm (55 to 125 in) (Omernik, 1986).

Table 2.1. Regression results for streamflow variability versus basin area, stratified by ecoregion.

Ecoregion	R-Squared	p-values	Degrees of Freedom
Coast Range	0.0078	0.6547	27
Willamette Valley	0.1123	0.0173	21
Klamath Mountains	0.0068	0.4458	29
Cascades	0.0057	0.5725	57
Eastern Cascades	0.0678	0.4395	11
Columbia Plateau	0.0594	0.4973	9
Blue Mountains	0.0503	0.2512	27
Snake River Basin/ High Desert	0.317	0.2447	5
All Stations	*0.0008*	*0.7035*	*193*

The Eastern Cascade Slope ecoregion maintain the lowest constant values of streamflow variability. This area is geologically young, with recent volcanic deposits of pumice and ash overlying bedrock. Perennial streams drain watersheds as small as three square miles in the mountains; however, perennial flow is seldom found in watersheds less than ten square miles in the lower flats. Average annual precipitation ranges from 30.5 cm to 63.5 cm (12 to 25 in) (Omernik, 1986).

The spatial patterns revealed in Figure 2.5 support the likelihood that broader, complex regional factors, rather than local (i.e., basin size), influence streamflow variability. The numerical range and distribution of the variability index may differ regionally based on the influence of factors such as climate, geology, vegetation and physiography.

The map of streamflow variability reveals certain aspects of the relationship between variability and basin size. This can be discussed in terms of features that are *not* present on the map. For example, if streamflow variability were inversely related to basin size, the upper stream reaches in a watershed would be more variable than the lower reaches. Hypothetically, the nesting of small watersheds inside larger watersheds would result in a highly complex map. However, the map [Figure 2.3] shows distinct regional patterns in the spatial distribution of streamflow variability, providing qualitative evidence that is not consistent with the basin size - streamflow variability assumption.

Discussion

Assumed relationships between basin size and streamflow variability have been primarily based on research conducted on eastern US streams and rivers. Application of this assumption for water quality monitoring recommendations has ignored regional geographic differences. In Oregon, the relationship between streamflow variability and basin size is not what is expected based upon a review of the literature. That streamflow variability decreases as basin area increases is not an accurate generalization for this study area. Given the geographic complexity of other western US regions, it does not seem unreasonable to extend the implications of this research beyond the borders of Oregon.

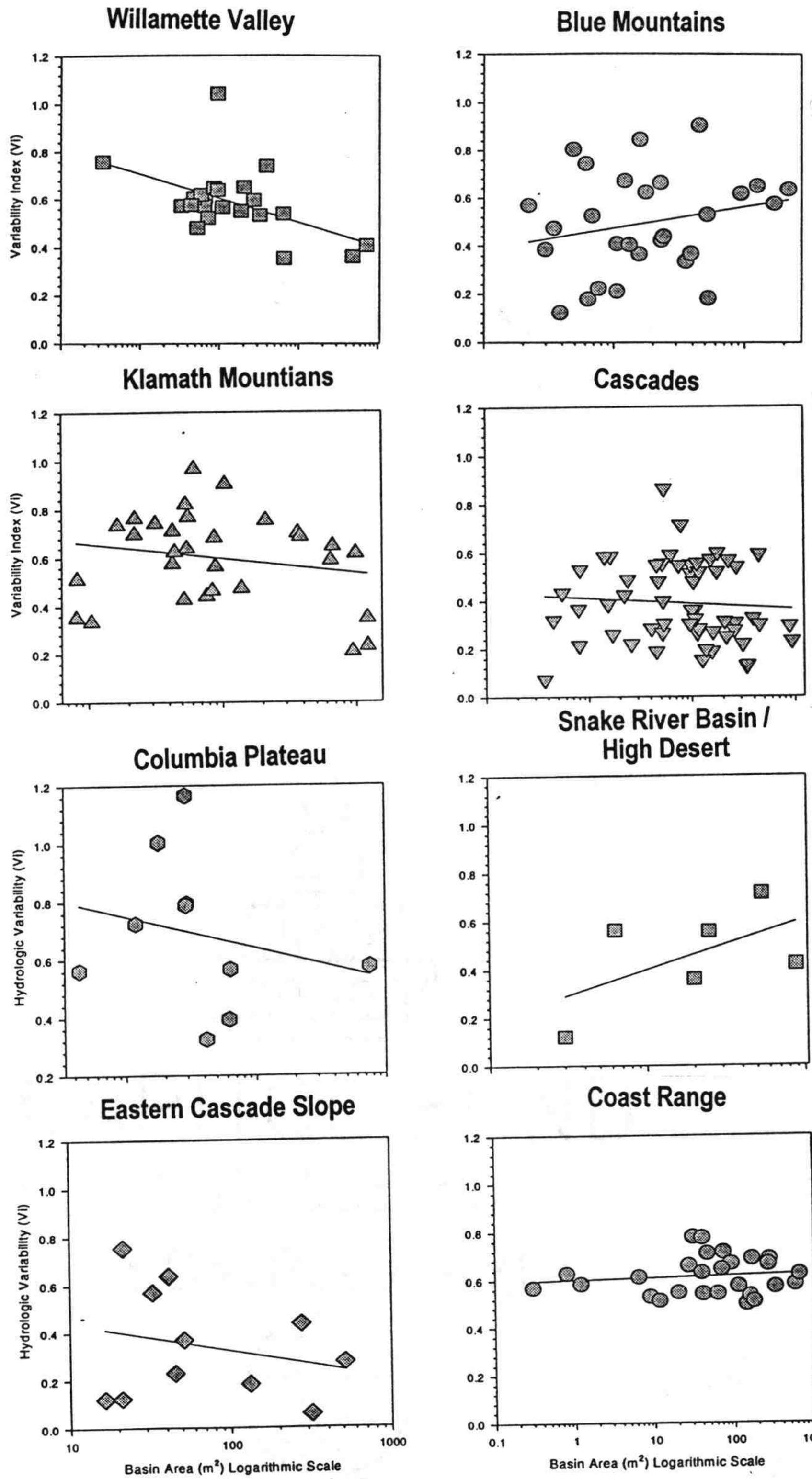

Figure 2.5. Regression scatterplots of streamflow variability versus basin area, stratified by ecoregion.

The results suggest that recommendations for water quality monitoring design based on basin size are incomplete and may be arbitrary. While simplicity in recommendations for water quality monitoring design is often desirable, that simplicity should not be traded for inaccuracies. Based on the findings of this study, sampling frequency recommendations should be developed that specify the degree of streamflow variability rather than relying on basin size as a proxy for that variability. Recommendations based on variability could be readily applied where records of river discharge exist. Given the apparent regional distribution of streamflow variability, methods based on quantitative and qualitative evidence could be developed for predicting streamflow variability where records are absent.

Acknowledgments

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CHAPTER 3.

REGIONAL ANALYSIS OF STREAMFLOW VARIABILITY IN OREGON

by

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Abstract

In the United States, a hierarchical approach is often used for planning water quality monitoring programs and prioritization of projects. Federal and state agencies participate in national and regional decision making, whereby state and local entities often focus on local implementation. Using Oregon as a case study, this research examines scale properties of streamflow variability in regional and watershed analyses, on which a framework for nonpoint source monitoring may be based. Geographic factors are analyzed for their influence on streamflow variability and their application in modeling for prediction. The desired resolution of the analysis is the determining factor for modeling streamflow variability on ungaged streams. The results suggest an approach to modeling streamflow variability that is both practical and efficient, starting at a regional-scale and working down to the watershed-scale.

Introduction

In the United States, planning of water quality monitoring programs for nonpoint source pollution (NPS) often relies on a hierarchical approach to program design and prioritization. Initial planning can occur at the state or regional level, whereupon individual projects are prioritized and implemented at the local level. A hierarchical strategy provides basic information about the physical and design needs for monitoring projects within regions, and acts as a decision support system for the allocation of funds from national, region, state and local interests. Although detailed baseline chemical monitoring data is often unavailable to assist in planning monitoring programs, hydrologic and climatic data are readily available with adequate regional-scale coverage to be helpful in monitoring program planning. Streamflow variability is an indicator that can provide information to assist such planning.

Variability of streamflow can provide useful information in the design of water quality monitoring programs for pollutant load estimation. For pollutants from nonpoint sources there is often a correlation between streamflow and pollutant flux. As flow increases, concentrations from many pollutants also increase, remain approximately constant, or decrease less markedly than flow increases. Flux rates, which are the product of concentration and flow, will tend to increase with increasing flow in those systems (Richards 1989, 261). Thus, streamflow variability can be used as a proxy for flux variability to estimate sampling needs for rivers where chemical observations are lacking. Rivers that have highly variable flows are likely to have highly variable fluxes, and will require a relatively detailed sampling program for accurate pollutant load estimation. (Richards 1989, 261).

It is our position that regional-scale analysis of streamflow variability is the most efficient geographic scale to assist water quality monitoring program planning. The index of streamflow variability (referred to herein as the variability index, V_i) is essentially an average of a river's hydrologic regime over a period of years. While the watershed is an appropriate scale to examine the factors influencing streamflow response to individual runoff events, it does not appear to be a singularly appropriate scale for examining the spatial properties of the variability index. This can be clarified in an analogy: the streamflow variability index is to climate what a runoff event is to weather. As such, we examine streamflow variability at the meso-scale and synoptic-scale as we would examine climate at those scales.

Literature Review

The significance of scale in hydrology has been recognized for some time, though systematic analysis of those effects has only recently been taken up by investigators. Attention has focused on the analysis of hydrologic response at the basin scale but has concentrated mainly on roles of catchment size and structure. The driving climatic forces on hydrologic response are also subject to various scale factors which in turn must influence the catchment response (Hebson and Wood 1986, 133). Hirschboeck (1988, 27) points out in a discussion of hydroclimatology, "flood-producing atmospheric circulation patterns operate within a space-time domain that at times is very different from the domain of hydrologic activity within a drainage basin."

Spatial changes in hydrologic response take place gradually over broad regions (as compared to the watershed-scale). Meybeck et al. (1992, 243) describe climate as the principal factor causing large fluctuations in discharge. They report that the variability and resulting non-uniformity of discharge is moderate in temperate humid climates, but extreme for rivers in savanna areas and in certain subtropical regions. Schroyer and Schuleen (1950, 1128) examine regional-scale influences on streamflow variability by examining monthly indexes of streamflow variability (calculated month-by-month using the same method as described later for the V_i). Since watershed-scale characteristics (e.g., watershed area, slope, length) are constant for a particular river, they conclude that the variations in the monthly indexes must arise from one or more other variables [Figure 3.1].

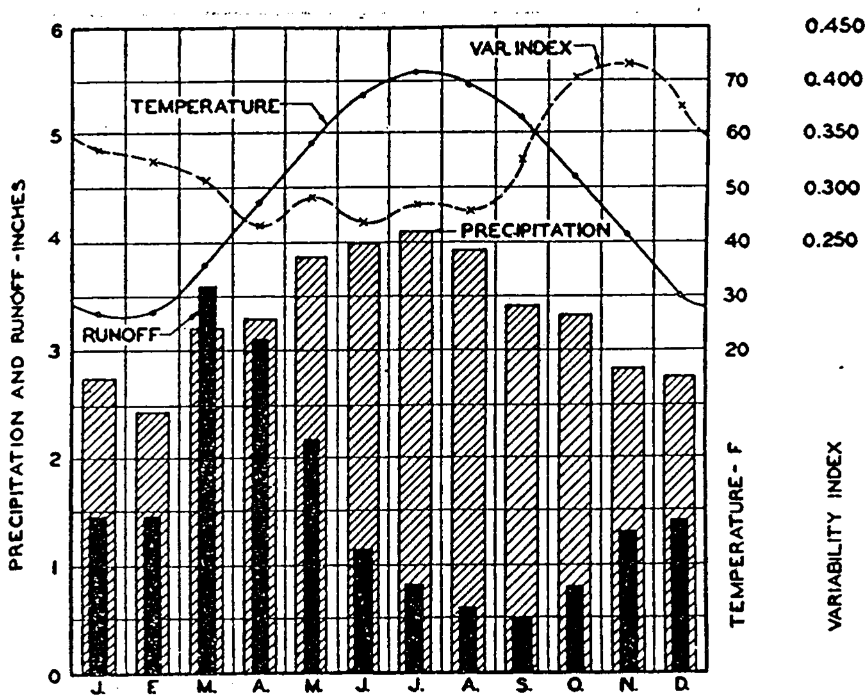

Figure 3.1. Monthly precipitation, runoff, temperature and flow variability index for the Susquehanna River above Holtwood, Pennsylvania (from Schroyer and Schuleen 1950, 1129).

Runoff events of concern in nonpoint source pollution monitoring occur individually at a micro-scale, watershed level. "Traditionally, much effort has been placed on identifying non-climatic sources of streamflow variability that originate within the drainage basin due to such factors as land-use changes, channel modifications, or complex responses" (Hirschboeck 1988, 30).

In recent years, researchers have studied meso, synoptic, and global-scale properties of streamflow variability and the spatial variability of mean annual discharge. For example, Gleick (1987) examined possible hydrologic impacts, including changes in streamflow variability, occurring from changes in climatic conditions and the water resource characteristics of a region. McMahon and others (1987) used streamflow and precipitation records from all continents to investigate streamflow characteristics at the continental-scale. Peterson and others (1987) give a preliminary example linking climate, streamflow variability and riverine chemistry for western North America. These works and others provide evidence that synoptic and global-scale climate patterns influence regional and local hydrology.

The feasibility of a hierarchical strategy that uses streamflow variability to assess NPS monitoring needs depends on how regional and watershed factors influence streamflow variability. Regional streamflow analyses traditionally use a combination of watershed- and regional-scale characteristics for modeling streamflow properties, such as minimum, maximum, and mean annual streamflow, and may be a useful tool in modeling streamflow variability on ungaged streams. While watershed-scale processes undoubtedly influence streamflow-timing, regional-scale factors, such as climate and physiography, may be more effective attributes, in terms of data requirements, for meso-scale modeling of streamflow variability. This paper examines those scale properties for regional analysis of streamflow variability as a major component in regional NPS monitoring strategies.

Objectives

One objective of this study is to determine if broad scale, regional factors significantly influence streamflow variability in Oregon. A second objective is to examine the efficiency of modeling streamflow variability at the regional-scale. This is achieved by answering the questions, "which variables are important in explaining streamflow variability in Oregon?" and "does inclusion of watershed-scale variables increase a model's ability to predict streamflow variability?"

Study Area

As a model for regional-scale analysis of streamflow variability, Oregon offers a variety of different regional settings owing to a mid-latitude location, varied and complex landforms, marine and continental air mass influences, and significant diversity in vegetation and soils. At 249,117 km^2 (96,184 mi^2), the State's area is large enough to identify distinctive geographic regions, and to examine their inherent watershed and streamflow characteristics.

The Columbia River and its tributaries represent the major drainage system for the area, except for Coast Range rivers that discharge directly into the Pacific Ocean. Landform regions form the principal drainage boundaries, and strongly influence climatic patterns. The several geomorphic provinces (Fenneman, 1946) found in the area include parts of the Pacific Border, Cascade Mountains, Columbia Intermontane, and Basin and Range (Figure 3.2). The Pacific Border Province is further subdivided into the Oregon Coast Range, the Willamette Trough, and the Klamath Mountains. The Columbia Intermontane is subdivided into the Columbia Basin, Central Highlands, the High Lava Plains, and the Owyhee Uplands.

The Pacific Border Province extends nearly 402 km (250 mi) from the mouth of the Columbia River on the north, to the mouth of the Rogue River on the south. The Coast Range ranges from 457 to 762 m (1,500 to 2,500 ft) with the high points in the central portion of the range. To the south, geology and topography dramatically change, forming an abrupt transition to the Klamath Mountains section of the Pacific Border Province. Mt. Ashland, at 2,295 m (7,530 ft), represents the highest point in the Klamath Mountains section. River drainages in this province are characteristically long and narrow, reflecting steep stream gradients, and heavy precipitation on the west facing slopes. The climate is classified as Mesothermal; dry-summer subtropical, coastal phase (Koppen, 1930). Marine air masses dominate the coastal zone, resulting in cool annual temperatures, and west slope orographic enhanced rainfall totals 254 to 444 cm (100 to 175 in) per year. Winter rainfall is predominant in this area, with snow accumulation to several feet on the peaks in the northern section to over 152 cm (60 in) in the peaks to the south. Lush Douglas-fir and hemlock forests form the dominant vegetation complex for the area.

The Cascade Mountain Province also extends north to south from the Columbia River Gorge to the California border. The Oregon section is further subdivided into the older western Cascades, and the younger High Cascades to the east. Mountain peak elevations average 2,134 m (7000 ft), but the stratovolcanoes of the High Cascades tower to over 3,048 m (10,000 ft). Rivers on the west slope of the Cascades drain into the Columbia River via the Willamette River system, except for the southern section where the Umpqua, Rogue, and Klamath Rivers flow directly to the Pacific. On the east slope, rivers flow north to the Columbia River. The northern Oregon Cascades produce higher precipitation totals than the southern section, with significantly greater rainfall amounts on west facing slopes. Because of high elevation, the climate of the Cascade Range is classified as Microthermal. The High Cascades accumulate snow depths in winter months that provide the source of runoff for both east and west flowing streams. Summer thunderstorms are not uncommon, but summer streamflow is not greatly affected by these events due to high evaporation, and rapid infiltration of porous volcanic soils. The forest vegetation of the west slope is Douglas-fir and hemlock, and on the east slope, Grand fir and Ponderosa pine.

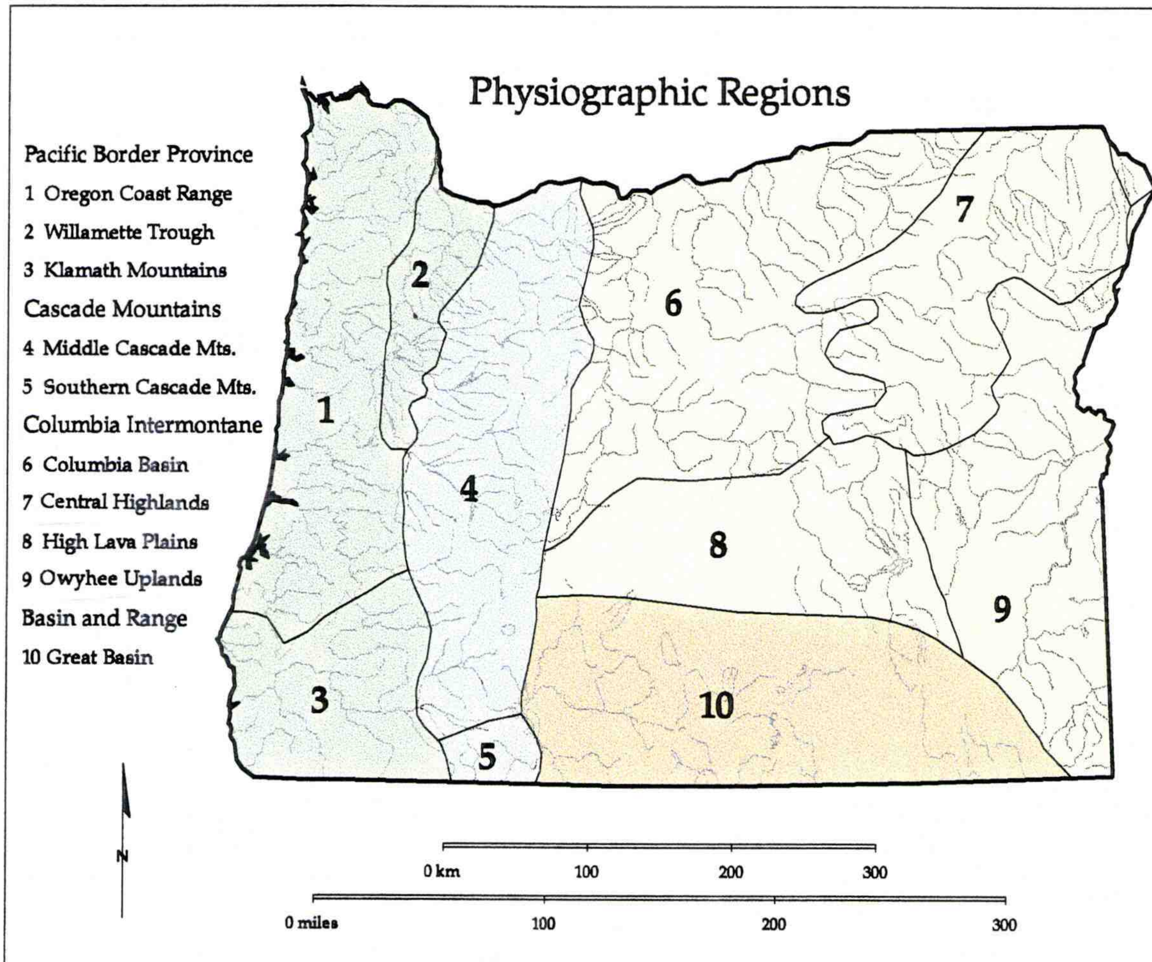

Figure 3.2. Physiographic regions of Oregon (modified from Fenneman, 1946).

The Columbia Intermontane Province in Oregon is topographically diverse and in the rainshadow of the Cascade Mountains. Annual precipitation varies from nearly 127 cm (50 in) in northeast Oregon to less than 25 cm (10 in) on the High Lava Plains. A semi-arid climate characterizes the area, except for the Central Highlands subdivision, where 2,134 to 2,743 m (7,000 to 9,000 ft) peaks produce 64 to 102 cm (25 to 40 in) of orographic precipitation. A large portion of the runoff from the Central Highlands is produced from late spring and early summer snowmelt. Except for the Central Highlands which support forests of Ponderosa pine, Engleman spruce, and lodgepole pine, the area is largely a sagebrush, juniper and bunchgrass savanna.

The Great Basin section of the Basin and Range Province is found in southcentral and southeast Oregon. The basin and range topography is exemplified by Steens Mountain at 2,947 m (9,670 ft) and the Klamath Basin at 1,262 m (4,139 ft). A series of fault block ranges intercepts precipitation during the winter and spring months, and produces intermittent streams that terminate in closed basins forming playa lakes in the wettest years. This section is classified as a mid-latitude steppe and desert. Open pine forests are found in the higher elevations, but bitterbrush, sagebrush and short bunchgrasses predominate in lower elevation zones.

Throughout the study area, a mid-latitude, summer-dry; winter-wet climate regime dominates. This unique Pacific Northwest climate is the result of seasonal latitude shifts in semi-permanent atmospheric pressure cells. The Eastern Pacific High (Hawaiian High) and the Aleutian Low pressure cells migrate latitudinally. By early winter, the Hawaiian High shifts to the tropics, and the Aleutian Low dominates the west coast from 35 to 60 degrees North Latitude. In summer, the Hawaiian High migrates northward, and in effect, deflects cyclonic storms into British Columbia and Southeast Alaska. The clockwise flow of descending air is dry and clear, and resists precipitation formation.

By late Fall, upper level westerly winds associated with the mid-latitude jet stream flow across the area carrying cyclonic storms whose genesis results from the mixing of tropical and polar air masses. In mid-winter, moisture-laden tropical air is entrained in the cyclonic flow and copious rainfall drenches the Oregon Coast Range, and heavy snowfall blankets the Cascade Mountains with lesser amounts accumulating in the Central Highlands of the Columbia Intermontane region. Topography, elevation, and distance from the Pacific Ocean play a large role in regional differences in climate such as temperature averages, and the distribution, amount, and type of precipitation that falls across Oregon.

Methodology

Long-term (minimum 10 consecutive years) streamflow discharge records for Oregon are used to examine the spatial distribution of streamflow variability. Because of the regulating effects of dams, the data set is comprised of 189 gages located on rivers with no upstream dams (Figure 3.3). Of these gages, 96 are on rivers that have upstream diversions. Due to the lack of undiverted streams in eastern Oregon, their inclusion helps provide adequate geographic coverage across the state. Fully 75% of gages east of -121° longitude have upstream diversions. To account for the effects of including diverted streams, the model selection is conducted on a split data set of all observations where no known diversions exist, and a data set comprised exclusively of observations with upstream diversions.

The gages and their associated watersheds are comprised of several mainstem rivers and their tributaries, many of which, by their very nature, are nested watersheds. The result of such nesting is that several gage locations are upstream from each other. The effect of nesting on the validity of the data set was examined using a sample data set of 100 randomly chosen gages. After identifying groups of watersheds where nesting exists, gage locations affecting nested watersheds were eliminated from the subset based on the following criteria: 1.) if a downstream gage affected the nesting of two or more upstream gages it was eliminated from the subset, if not, then 2.) gages with diversions were selected for elimination first, and 3.) all else being equal, gages with the shortest period of record were eliminated. The two resulting data sets (nested - 100 observations, and non-nested - 88 observations) had essentially no differences in the results of a stepwise regression analysis in terms of model parameter selection or measures of significance and predictive capacity, indicating that watershed nesting is inconsequential in this data set.

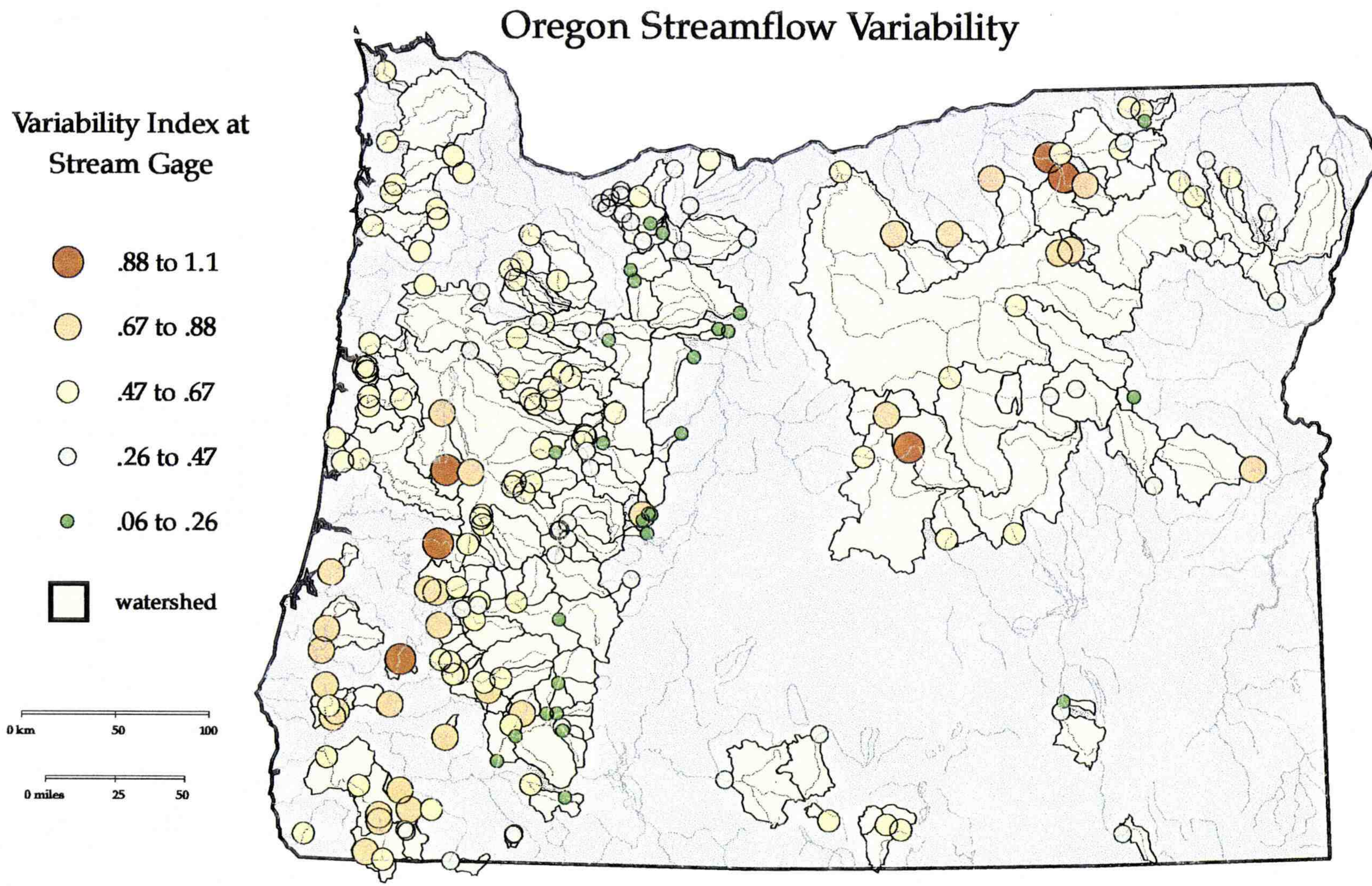

Figure 3.3. Stream gage location and streamflow variability.

Variability Index

Quantification of streamflow variability uses flow duration statistics from historical streamflow records (Lane and Lei, 1950). Flow duration statistics are calculated by the USGS on gaged streams with at least 10 years of data. The USGS judges this record length as necessary to adequately damp out annual variability effects when calculating flow duration statistics. While the index of streamflow variability (V_i) in the current research is based on a 10 year minimum record, the periods of record do not correspond for each station (periods of record for each station can be ascertained from the begin and end dates in the data tables, Appendix B). The effect of the period of record on the V_i was examined by Richards (1989) by comparing earlier publications of flow duration statistics for several rivers with those based on the entire period of record. When compared to the ranges shown by these indices, the changes in the flow indices were all minor. This suggests that the indices are fairly unresponsive to the length of record used to calculate them, though indices based on shorter periods of record are subject to greater uncertainty (Richards 1989, 365).

Flow duration curves that are steep represent flashy streams with high peaks and low minimum flows (Black, 1991). A wide range of values will be evident in the flow duration statistics on streams with high streamflow variability (Moffatt et al., 1990). Thus, as the position of the duration curve gives the magnitude of the flow, the slope of the curve is a measure of streamflow variability (Leopold et al., 1995). The steeper the flow duration curve, the higher the flow variability and the larger the variability index.

The variability index expressed as the coefficient of variation of the logs of flows corresponding to the percentiles: {5, 10, 15, 20, ..., 80, 85, 90, 95}(Richards 1989, 261). This measure of streamflow variability is convenient because it can be readily calculated from flow duration tables provided by the U.S. Geological Survey (USGS). The variability index is scale independent in log space, and gives an expression of the relative variability from the mean, expressed as the formula:

$$V_i = \sqrt{\frac{\Sigma(y - \bar{y})^2}{n - 1}}$$ (Lane and Lei 1950, 1099)

In which y is the logarithm of the selected discharge at a 5% interval of the duration curve, $\bar{y}$ is the mean of y, and n is the number of selected discharges (n = 19 in the given procedure).

Richards (1989) described and evaluated several alternative measures of flow variability for 118 Great Lakes tributaries. Of the measures, the V_i (as described herein) was less strongly affected by the presence of near-zero flows in the tail of the distribution and most successful for estimating flux variances (Richards 1989, 370). Although each of the measures were highly intercorrelated, the V_i was the preferred method for application in water quality monitoring programs.

Watershed- and Regional-Scale Data

This paper examines independent variables from a selection of geographic characteristics in Oregon for their predictive capacity in models of streamflow variability. Those variables are interpreted in terms of geographic scale as being either regional-scale or watershed-scale. Watershed-scale variables are those whose measurements do not or cannot extend beyond the watershed boundary. For example, watershed size, shape, and slope are all watershed-specific parameters. Alternately, regional-scale variables are those whose measurement is more-or-less continuous across

Table 3.1. Explanatory variables and their domain of scale.

All explanatory variables (and data sources)	Watershed-scale	Regional-scale
watershed area (Moffatt et al. 1990)	x	
gage elevation (Moffatt et al. 1990)	x	
watershed slope (Lystrom 1970, Harris 1979, and USGS topographic maps)	x	
watershed length (Lystrom 1970, Harris 1979, and USGS topographic maps)	x	
watershed shape (calculated area / length)	x	
storage (Lystrom 1970, Harris 1979, and USGS topographic maps)	x	
diversions (Moffatt et al. 1990)	x	
stream order (USGS Oregon 1996)	x	
mean discharge (Moffatt et al. 1990)	x	
soil infiltration (USDA 1994)		x
temperature warmest month (Loy et al. 1976)		x
temperature coldest month (Loy et al. 1976)		x
precipitation (Daly et al. 1996)		x
precipitation frequency (NOAA ...)		x
isoerodent index (Soil & Water Cons. Soc. 1993)		x
latitude (Moffatt et al. 1990)		x
longitude (Moffatt et al. 1990)		x

boundaries (e.g., precipitation and temperature). Selection of variables was based on a review of the literature and data availability. Table 3.1 lists the variables available for analysis and the domain of scale at which the variable is assumed to operate.

Analytical Techniques

Cross validation is used for model selection and determination of model performance. The data are partitioned into two samples: a model fitting sample (100 observations), and a validation sample (89 observations). The general strategy for model selection is regional-scale models are built first, then watershed-scale variables are added. Regional-scale models are considered to be sufficient when adding watershed-scale variables does not greatly improve the fit of the model.

Initial data exploration and spatial data analysis indicate that due to the relatively large number of diversions in the eastern part of the state, it may be inappropriate to combine these data with those of western Oregon. The relationship between longitude and the V_i supports this conclusion (Figure 3.4). To account for east-west differences, the analysis is also performed on a split data set between eastern and western Oregon at -121° longitude.

Stepwise regression (forward and backward selection) is used for model selection. This procedure is a technique to evaluate which of the available variables are statistically significant for modeling streamflow variability in Oregon. Spearman's correlation

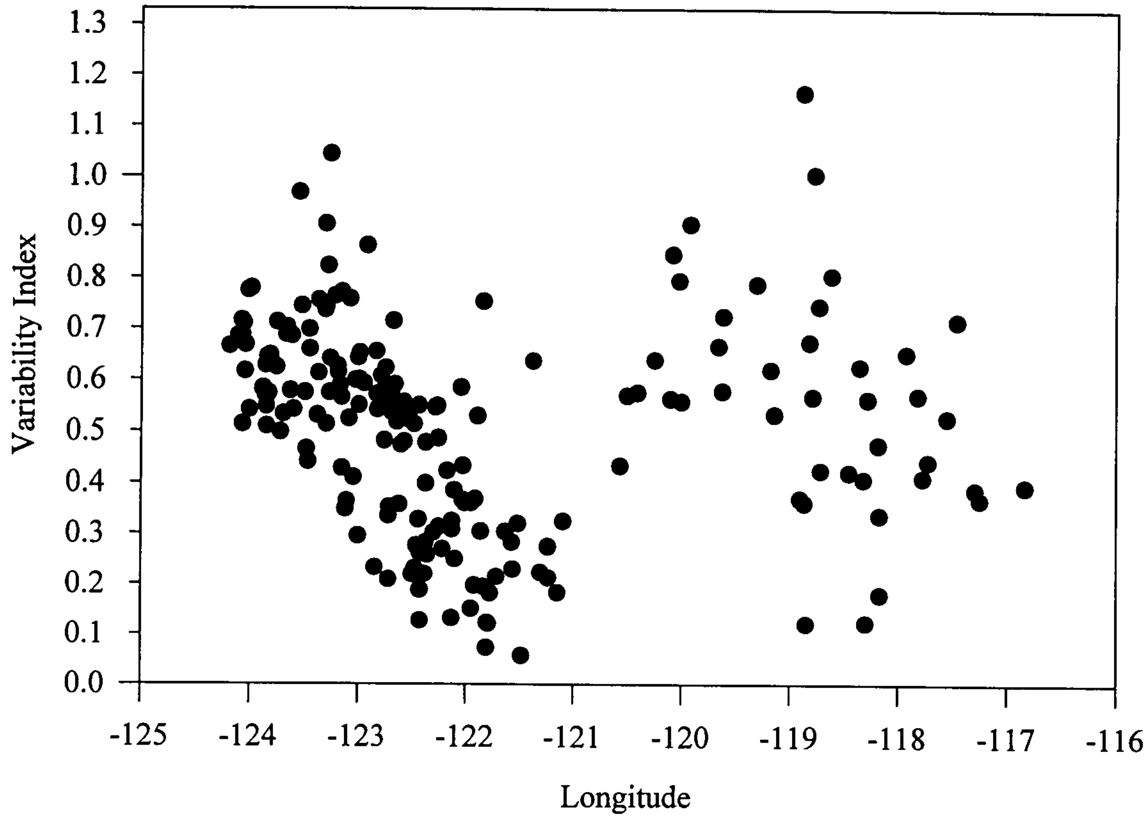

Figure 3.4. Scatterplot of longitudinal location of stream gages and streamflow variability indexes.

coefficients are used for diagnosing multicolliniarity in the data set. Redundant variables are removed as candidates for model selection. The formal influential diagnostic, R-student statistic, is used to check for extremely influential observations in all models (Myers 1990, 353). Outlying residual observations are removed. The limits for the stepwise regression selection procedure is set to five variables and the significance level for variable inclusion/exclusion is set at 0.05.

The following criteria are used to evaluate the results for model selection: 1.) models with the largest R^2 statistic are preferred; 2.) models with the fewest number of variables are preferred; 3.) models with the smallest C(p) statistic (estimate of $TMSE/\sigma^2$) are preferred; and 4.) smaller values of the PRESS statistic (predicted residual sum of squares) suggest models of greater predictive ability. The explanatory variables in the preferred models are used to qualitatively examine those variables and their domains of scale. Model performance is determined by applying the fitted models (n=100) to estimate the response in the validation sample (n=89). The lowest values of the residual sum of squares (RSS) from the validation sample are used as criteria to determine the best of the candidate models. Note that the final estimation of parameters is derived from applying the preferred model(s) from the fitting sample to the appropriate observations in the entire data set (n=189).

Results

Initial Model Selection

The results of model selection parameters among the entire state and those based on an east-west division indicate that an east-west division in the data produces superior models in terms of the criteria presented in the above section. As such, the results presented herein will be a comparison of models for eastern and western Oregon, using -121° as the boundary line. Tables 3.2 and 3.3 summarize the results of model selection for the fitted sample, and the residual sum of squares for the estimated response in the validation sample. Model selection was performed in western Oregon on a data set including both diverted and non-diverted streams, a set including only non-diverted streams, and a set including only streams with diversions. Eastern Oregon lacked enough data points in the fitting sample to examine diverted and non-diverted streams separately, and as such the model selection was run only on the data set including both diverted and non-diverted streams.

The results of model selection on the fitted sample for western Oregon indicate that the model for “regional-scale variables with no diversions” is the most preferred based on the model selection criteria. Adding the watershed-scale variables, basin shape and stream order, increases the explanatory power of this model by about 8%, but at the cost of a much increased C(p) statistic and an addition of two variables. There is essentially no change among the RSS’s when these models are applied to the validation sample.

The models selected for the regional scale variables with “all observations” and “diversions only” are fairly comparable in terms of a balance among selection criteria. While “all observations” has a higher R^2 and lower C(p) statistic, “diversions only” has a lower PRESS statistic suggesting greater predictive ability, lower RSS when applied to the validation sample, and fewer variables in the model. The “all observations” model R^2 increases by about 6% when watershed-scale variables are added, and may be seen as a compromise between the models “no diversions” and “diversions only”. In model

Table 3.2. Summary of model selection results on the fitted sample for western Oregon observations.

data set	selected regional-scale variables	added watershed-scale variables	R^2	C(p)	PRESS	df	[1]RSS
All Observations	-cold temperatures -latitude		0.7439	2.4957	0.9559	76	1.8395
		-basin shape -stream order	0.8016	3.3629	0.7836	76	1.7721
No Diversions	-cold temperatures		0.7586	2.4957	0.3591	42	1.0313
		-basin shape	0.8374	4.5580	0.2497	42	1.0320
Diversions Only	-cold temperatures		0.7104	3.2375	0.6253	33	0.8702
		-none added	0.7104	4.6227	0.6253	33	0.8702

[1]RSS - Residual sum of squares using the fitted model estimate of the response in the validation sample.

Table 3.3. Summary of model selection results on the fitted sample for eastern Oregon observations.

data set	selected regional-scale variables	added watershed-scale variables	R^2	C(p)	PRESS	df	[1]RSS
All Observations	-precipitation frequency -latitude		0.5165	1.6023	0.3633	19	0.8066
		-none added	0.5165	1.6023	0.3633	19	0.8066

[1]RSS - Residual sum of squares using the fitted model estimate of the response in the validation sample.

application, it is justifiable to use the "no diversions" and "diversions only" models to predict streamflow variability on ungaged streams in western Oregon.

In eastern Oregon, the explanatory power of the selected model is much less than that for all western Oregon selected models. Nonetheless, the low PRESS statistic suggests a high predictive ability. Given the relative lack of data on ungaged streams in eastern Oregon, model application still may provide insightful information on streamflow variability for initial planning of water quality monitoring programs.

Model Application

As stated in the analytical techniques section, the final estimation of model parameters comes from applying the preferred models to the entire data set. The three preferred models selected for application are as follows:

- V_i west_no diversions = 0.3820 + 0.0556 (cold_temp)
- V_i west_diversions only = 0.4509 + 0.0614 (cold_temp)
- V_i east_with and without diversions = -2.9580 + 0.0980 (latitude) - 0.0533 (prec_frq)

The explanatory power of the models is reduced by about 10 to 15% when applied to the entire data set. Table 3.4 provides a summary of model parameter statistics. Application of the models to the entire data set saw little or no improvement in the models explanatory power when watershed-scale variables were added.

Table 3.4. Final estimation of parameters for model application to eastern and western Oregon.

regional-scale variables		**add watershed-scale variables**	
observations with no diversions (west)	R^2 =0.6556 df =81	observations with no diversions (west)	R^2 =0.6732 df =81
only observations with diversions (west)	R^2 =0.5405 df =64	only observations with diversions (west)	R^2 =.05405 df =64
all observations (east)	R^2 =0.4078 df =40	all observations (east)	R^2 =0.4078 df =40

The selection of preferred models with regional-scale only variables allows for regional-scale application of the models to the study area. With the assistance of a geographic information system (GIS), the models can be run on mapped data of the model variables and the predicted streamflow variability indexes can be mapped for the entire state (Figures 3.5, 3.6 and 3.7). The advantage of regional-scale modeling of the V_i is evident in the efficiency at which the index may be estimated at a broad geographic scale. For example, the inclusion of watershed-scale data in the models would entirely preclude regional-scale application and mapping due to inefficiency. It would neither be reasonable or practical (or even possible given technical limitations) to access watershed-scale data for all watersheds in the state in order to apply the models on a region-wide basis.

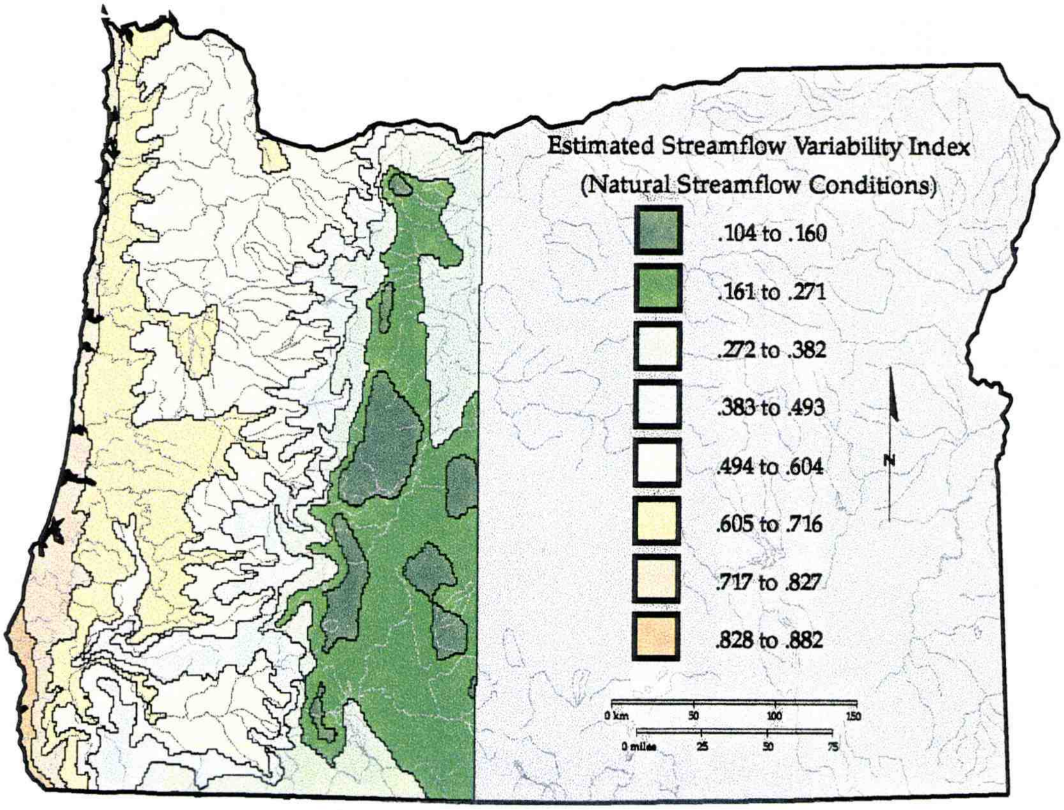

Figure 3.5. Estimated streamflow variability for western Oregon streams with no upstream diversions ($R^2 = 0.66$).

Application of the models reveals that the range of the estimated V_i under presumed natural streamflow conditions (no diversions) is lower overall than that on streams with diversions (Figures 3.5 and 3.6). The highest estimated variability is along the Oregon Coast Range (especially to the south) where river drainages are characteristically long and narrow, reflecting steep gradients and heavy precipitation on west facing slopes. Lowest streamflow variability is found in the Cascade Mountain

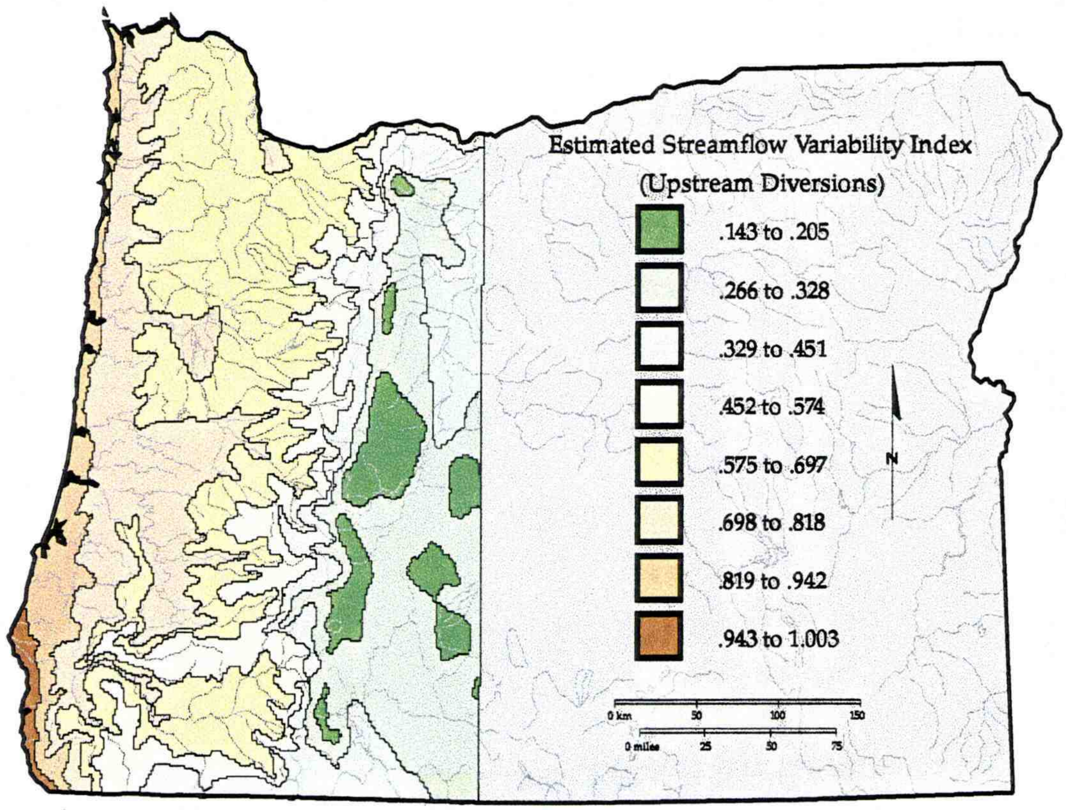

Figure 3.6. Estimated streamflow variability for western Oregon streams with upstream diversions ($R^2 = 0.54$).

Province High Cascades. It is here where high evaporation and rapid infiltration of porous volcanic soils greatly reduce the effects from runoff from summer thunderstorms and rapid snowmelt.

The increased complexity of the map of eastern Oregon (Figure 3.7) is a combined result of the topographic diversity of the region and the level of detail of the source map of precipitation frequency. The slight horizontal striping is a relic of latitude

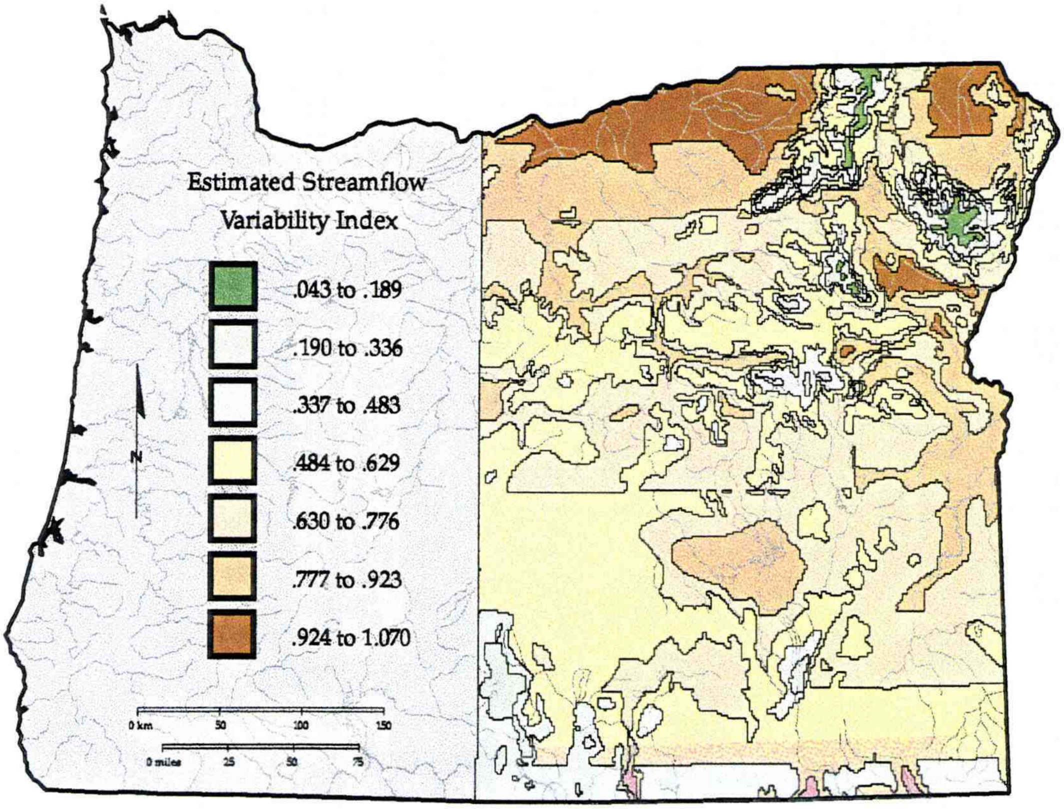

Figure 3.7. Estimated streamflow variability for eastern Oregon streams with and without upstream diversions ($R^2 = 0.41$).

being one of the input variables. Notable features on the map include a broad range in the estimated V_i, as well as the large area of high variability in the northeast. While relatively moderate to low streamflow variability is estimated in the Great Basin section of the Basin and Range Province, the lowest levels of streamflow variability are to be found in northeastern Oregon.

The variables selected in the preferred models are instructive when examining streamflow variability. Regional differences in cold temperature averages and precipitation frequency are related to landform characteristics, elevation, and distance from the Pacific Ocean. While other differences in climate are also related to these factors and were available for selection in the models, often they were highly correlated and eliminated due to redundancy or lack of significance. East of the Cascade Mountain Province, distance from the Pacific Ocean is less important to streamflow variability. The selection of latitude as a model variable may be explained by the seasonal latitude shift in atmospheric pressure cells.

Discussion

It would appear that streamflow variability is linked to region specific characteristics, especially seasonal temperature and precipitation attributes. Estimation of streamflow variability on ungaged streams in Oregon is shown to be feasible using only regional-scale variables for model selection. Regional-scale variables selected for this study are available from easily accessible data sets.

Considering the nature of the index of streamflow variability, it is appropriate that streamflow variability should be analyzed on the regional-scale. Temporally, streamflow variability represents a broad time scale. It depicts the annual discharge variability based on long-tern records of daily discharge. In essence, the resolution of regional-scale factors and the index of streamflow variability are synchronous with each other. At a different level, the analysis of watershed-scale factors and a measure a watershed's response to a single storm-event may be synchronous.

The results of this research suggest that, given a hierarchical approach to planning water quality monitoring programs, regional modeling of streamflow variability is both practical and efficient. This mapped information can be used in state and regional decision making to help determine relative sampling needs based on streamflow characteristics. Going down the hierarchical ladder, the addition of watershed-scale variables can increase the explanatory power of the models on a watershed-by-watershed basis. It would be suggested that further investigation of streamflow properties then continue on specific streams where monitoring is to take place.

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CHAPTER 4.

SEASONALITY OF STREAMFLOW VARIABILITY IN OREGON

by

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Abstract

A primary consideration of surface water quality monitoring programs for nonpoint source (NPS) pollution is the sampling frequency at which trends in water quality can be detected and evaluated. Sampling frequency in turn depends, in part, upon the streamflow variability of water discharge through the system. Whether even-interval or storm event-based, sampling of NPS pollution is often conducted during monitoring seasons when overland runoff is most likely to occur. This investigation refines the application of streamflow variability to monitoring programs by examining it on a monthly and seasonal basis. Monthly streamflow variability is calculated for 86 Oregon study sites and seasonal change is evaluated. The study area is examined for spatial and temporal patterns in streamflow variability and the processes that may influence those patterns. The results show that monthly indexes of streamflow variability are spatially and temporally dynamic when compared to annual indexes of streamflow variability. Seasonal assessment of streamflow variability may provide further insight as to the timing and design needs of NPS water quality monitoring projects.

(**KEY WORDS**: nonpoint source pollution, water quality monitoring, seasonal change)

Introduction: Streamflow Variability and Water Quality Monitoring

Streamflow variability can be a useful tool for planning nonpoint source (NPS) monitoring projects. Design of water quality monitoring programs for load estimation is often hampered by the lack of existing data from which to determine patterns of flux variance, that help to determine sampling frequencies. For pollutants from nonpoint sources there is often a correlation between streamflow and pollutant flux. Rivers that have highly variable streamflow are likely to have highly variable fluxes, and will require relatively detailed sampling programs for accurate pollutant load estimation. In principle, measures of flow variability may be calibrated with pollutant fluxes for well known watersheds, and then used as a proxy for pollutant flux in streams where data are unavailable to estimate sampling needs (Richards 1989, 262).

Although detailed baseline chemical monitoring data is often unavailable to assist in planning NPS monitoring programs, hydrologic and climatic data are readily available with adequate regional-scale coverage to be helpful in NPS program planning. Streamflow variability is an indicator that can provide information to assist such planning. Nonpoint pollution sampling is often conducted during monitoring seasons when overland runoff is most likely to occur. Seasonal assessment of streamflow variability may provide further insight as to the timing and design needs of NPS water quality monitoring projects.

Streamflow variability may be described as magnitude of deviation from base flow conditions. While all rivers and streams are influenced to some degree by runoff events, a measurement of discharge variation (paired with an understanding of the behavior of water quality variables) can be used as a guide to determine the relative needs for water quality monitoring design. This understanding can provide clues to the sources and behaviors of runoff pollution and the monitoring needs of a project, and is critical in semiarid regions where common hydrologic data may be sparse. The research herein examines monthly streamflow variability in Oregon to examine its potential for application in planning water quality monitoring programs.

Streamflow Variability Index

Streamflow variability is quantified and presented as the variability index (V_i), expressed as the coefficient of variation of the logs of flows corresponding to the percentiles: {5, 10, 15, 20, ..., 80, 85, 90, 95}(Richards 1989, 261). The index is a function of the slope of the flow duration curve when plotted on logarithmic probability paper (Lane and Lei 1950). This measure of streamflow variability is convenient because it can be readily calculated from flow duration tables provided by the U.S. Geological Survey (USGS). The variability index is scale independent in log space (Richards 1989, 261), and gives an expression of the relative variability from the mean, expressed as the formula:

$$V_i = \sqrt{\frac{\Sigma(y - \bar{y})^2}{n - 1}}$$ (Lane and Lei 1950, 1099)

In which y is the logarithm of the selected discharge at a 5% interval of the duration curve, $\bar{y}$ is the mean of y, and n is the number of selected discharges (n = 19 in the given procedure).

Richards (1989) described and evaluated several alternative measures of annual streamflow variability for 118 Great Lakes tributaries. Of the measures, the V_i (as described herein) was less strongly affected by the presence of near-zero flows in the tail of the distribution and most successful for estimating flux variances (Richards 1989, 370). Although each of the measures were highly intercorrelated, the V_i was the preferred method for application in water quality monitoring programs.

Monthly and annual flow duration statistics are calculated by the USGS on gaged streams with at least 10 years of data. The USGS judges this record length as necessary to adequately damp out annual variability effects when calculating flow duration statistics. While the V_i used in the current research is based on a 10 year minimum record, the periods of record do not correspond for each station (periods of record for each station can be ascertained from the begin and end dates in the data tables, Appendix A and B). The effect of the period of record on the V_i was examined by Richards (1989) by comparing earlier publications of flow duration statistics for several rivers with those based on the entire period of record. When compared to the ranges shown by these indices, the changes in the flow indices were all minor. This suggests that the indices are fairly unresponsive to the length of record used to calculate them, though indices based on shorter periods of record (less than 10 years) are subject to greater uncertainty (Richards 1989, 365).

Monthly stratification of the V_i is used to examine issues of seasonal water quality sampling strategies. Using the above formula, the variability index is calculated separately for each month (i.e., flow duration statistics for October during the entire period of record are used to calculate the October V_i). Monthly flow duration statistics are also readily available from USGS flow duration tables. Monthly V_i allow for the examination of streamflow variability between months, and investigation of the effects of gross climatic indicators such as wet and dry seasons. To the author's knowledge, this is the first such investigation of monthly streamflow variability.

Study Sites

As a model for regional-scale analysis of streamflow variability, Oregon offers a variety of different regional settings owing to a true mid-latitude location, varied and complex landforms, marine and continental air mass influences, and significant diversity in vegetation and soils. At 249,117 km^2 (96,184 mi^2), the State's area is large enough to identify distinctive geographic regions, and to examine their inherent streamflow characteristics. Monthly streamflow variability is calculated for the Oregon study sites and seasonal change is evaluated. The study area is examined for spatial patterns in seasonal variability and the processes that may influence those patterns.

The study sites are comprised of selected USGS stream gages. Discharge data are from the U.S. Geological Survey (USGS) *Water Resources Data - Oregon, Water Year 1994* (Hubbard, et al., 1995), and flow-duration statistics are from the USGS *Statistical Summaries of Streamflow Data in Oregon: Volume 1* (Moffatt, et al., 1990). Selection of stream-gaging stations is based on a search of stations whose period of record extends over a minimum of ten years. Information as to the upstream impoundments and diversions is also obtained from these sources. Because of their regulating effects, data set selection is based on USGS stream gages with no upstream impoundments (dams and reservoirs) or diversions. Some currently dammed stream locations utilize periods of record prior to construction of regulating facilities.

For comparison, the data are presented as annual and monthly maps of streamflow variability. To aid in data visualization and pattern detection, data points are represented as Thiessen polygons, in which the centerpoint of each polygon is the stream gage location. Due to the distribution and utilization of water resources in Oregon, there is a highly uneven distribution of natural-flow gaged streams in western and eastern Oregon. The maps are not intended to suggest that the study sites are representative of all natural streamflow conditions in Oregon, or that the areas covered by each polygon represent all streams within their boundary. Annual streamflow variability for the study sites are shown in Figure 4.1.

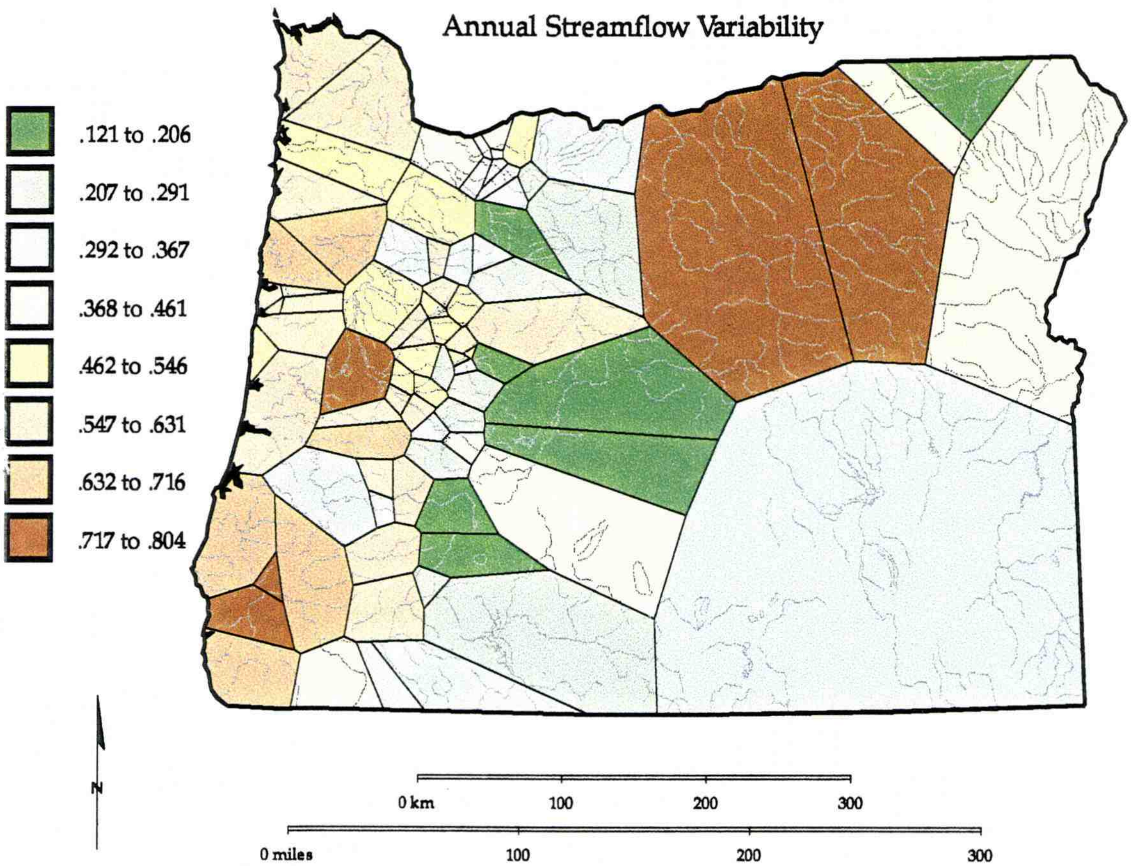

Figure 4.1. Annual streamflow variability in Oregon under natural flow conditions.

Monthly Streamflow Variability

Monthly streamflow variability indexes represent the variation in streamflow discharge for each month over a series of years. As with annual streamflow variability, the monthly indexes bear little relation to total stream discharge. Monthly indexes also seemingly bear little relation to the annual variability index. This is demonstrated with an example from the South Fork Coquille River in southwestern Oregon. Annual streamflow variability for this river is quite high, with a V_i of 0.775 (annual and monthly V_i for all gage sites are presented in Appendix C). Monthly duration curves for the South Fork Coquille River near Illahe, Oregon are presented in Figure 4.2. The slope of each curve depicts the monthly streamflow variability, with little regard for amount of discharge. For example, the relatively steep slopes for October and November equate to similar variability indexes, even though their range in discharge differs by an order of magnitude. Similarly, the relatively low, even slope and low variability of June can be contrasted with a low-to-moderate slope for September, even though discharge is greater in June.

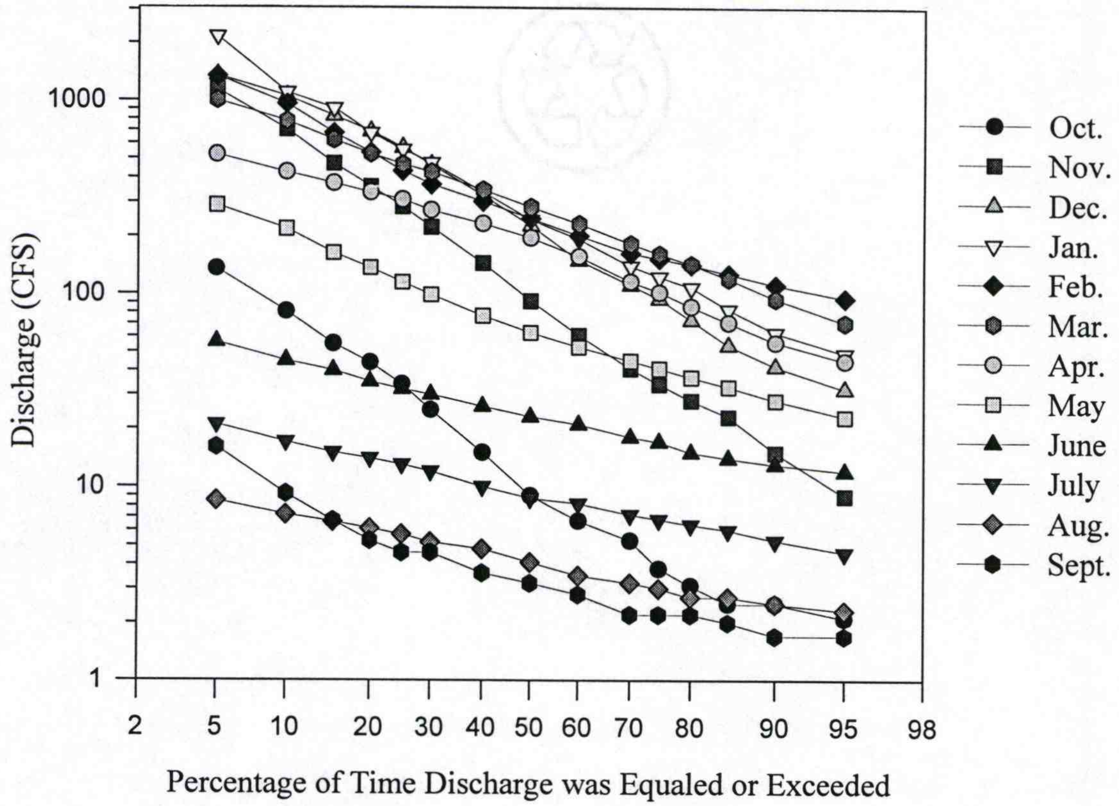

Figure 4.2. Monthly flow duration curves for the South Fork Coquille River near Illahe, Oregon, for the period 1957 - 1974.

Examination of monthly mean discharge and monthly variability also reveals the behavior of streamflow variability in relation to discharge (Figure 4.3). In October and November, when mean discharge is low but increasing, streamflow variability is quite high. As maximum mean discharges are reached in the Winter months of December through February, streamflow variability steadily decreases. This indicates that while streamflow is highest during these months, it is relatively steady as compared to October and November. Low Summer streamflow variability and discharge is accounted for primarily by low Summer precipitation. The September rise in the variability index shows the start of the rainy season with precipitation runoff adding to streamflow variability, though not an increase in mean discharge. With this understanding of monthly streamflow variability, it is mapped for each month to examine temporal and spatial changes in Oregon (Figure 4.4).

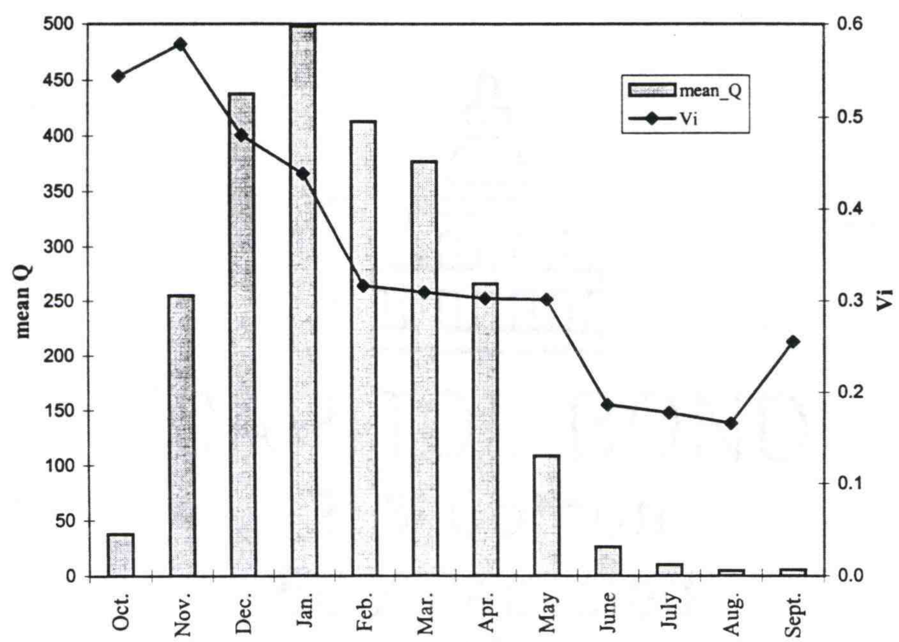

Figure 4.3. Streamflow variability and mean discharge for the South Fork Coquille River near Illahe, Oregon, for the period 1957 - 1974.

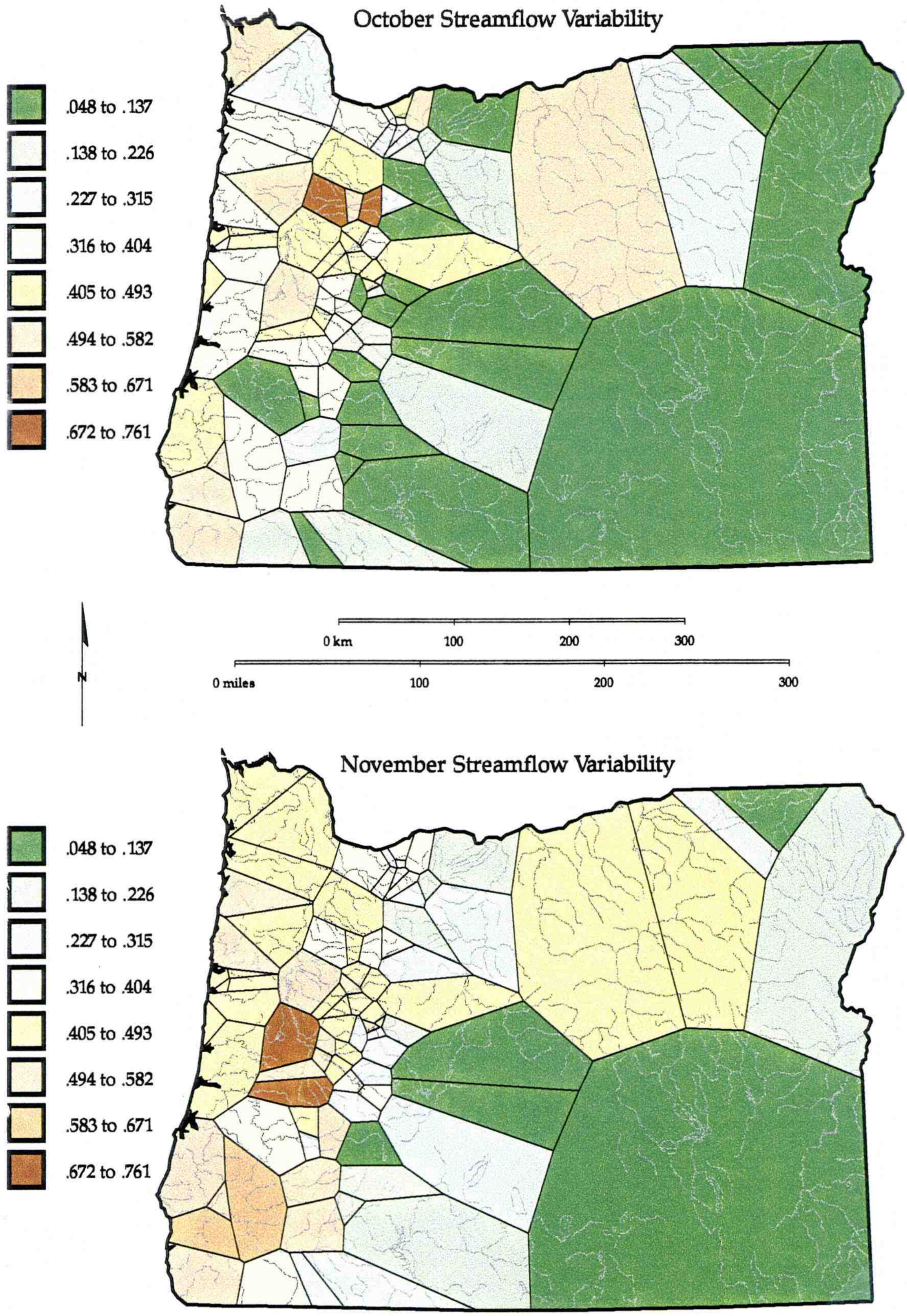

Figure 4.4. Monthly streamflow variability in Oregon under natural flow conditions.

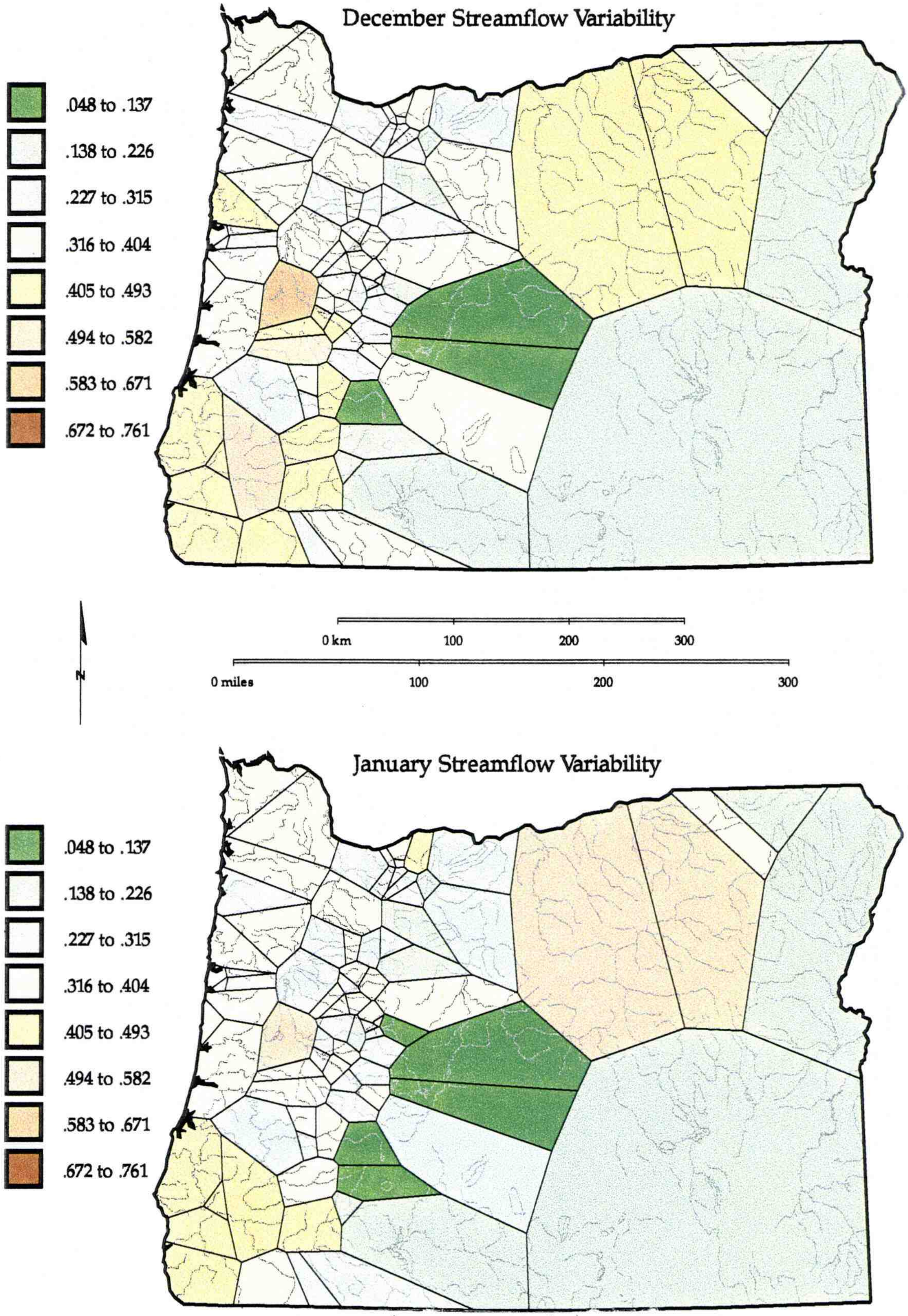

Figure 4.4., Continued.

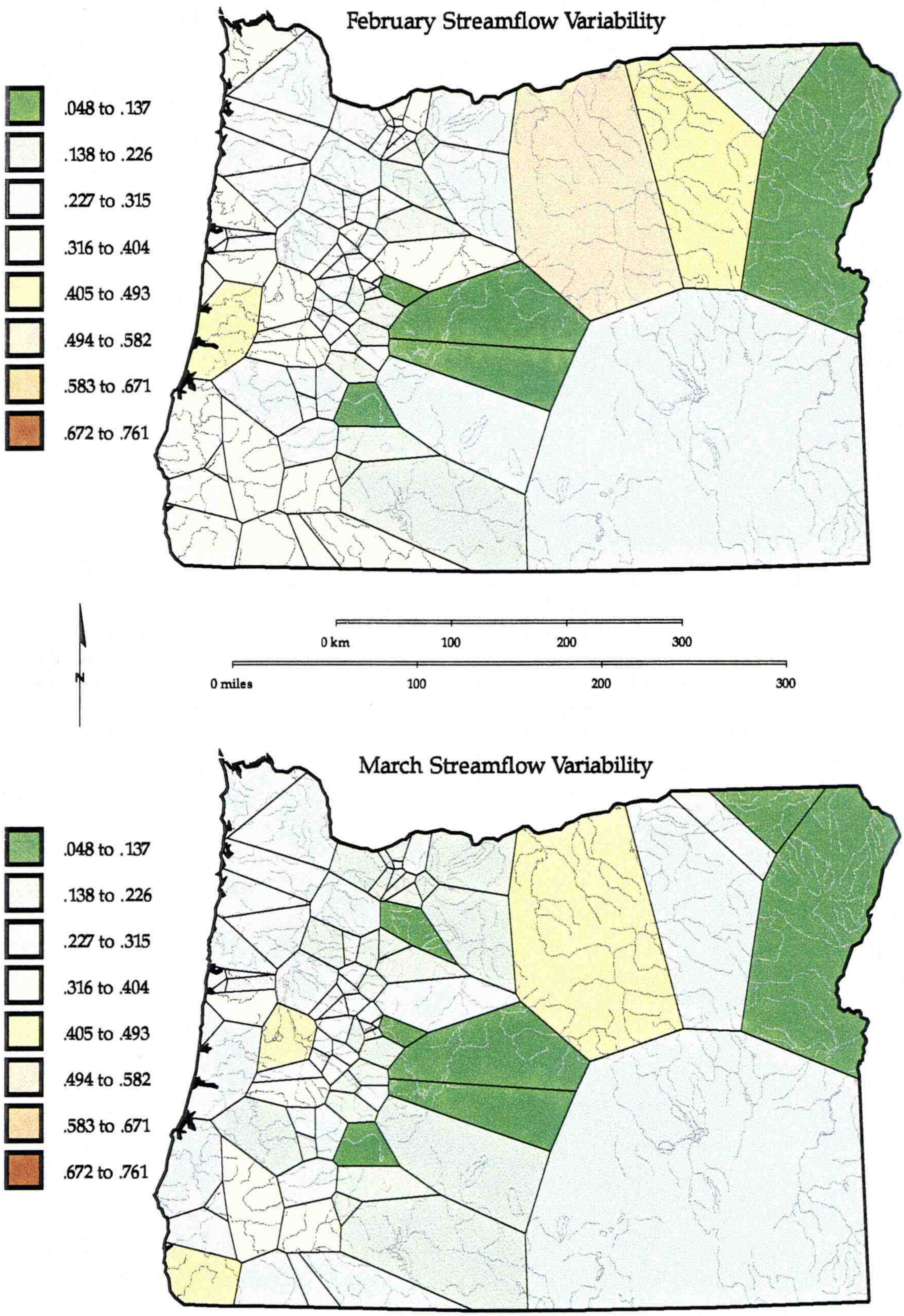

Figure 4.4., Continued.

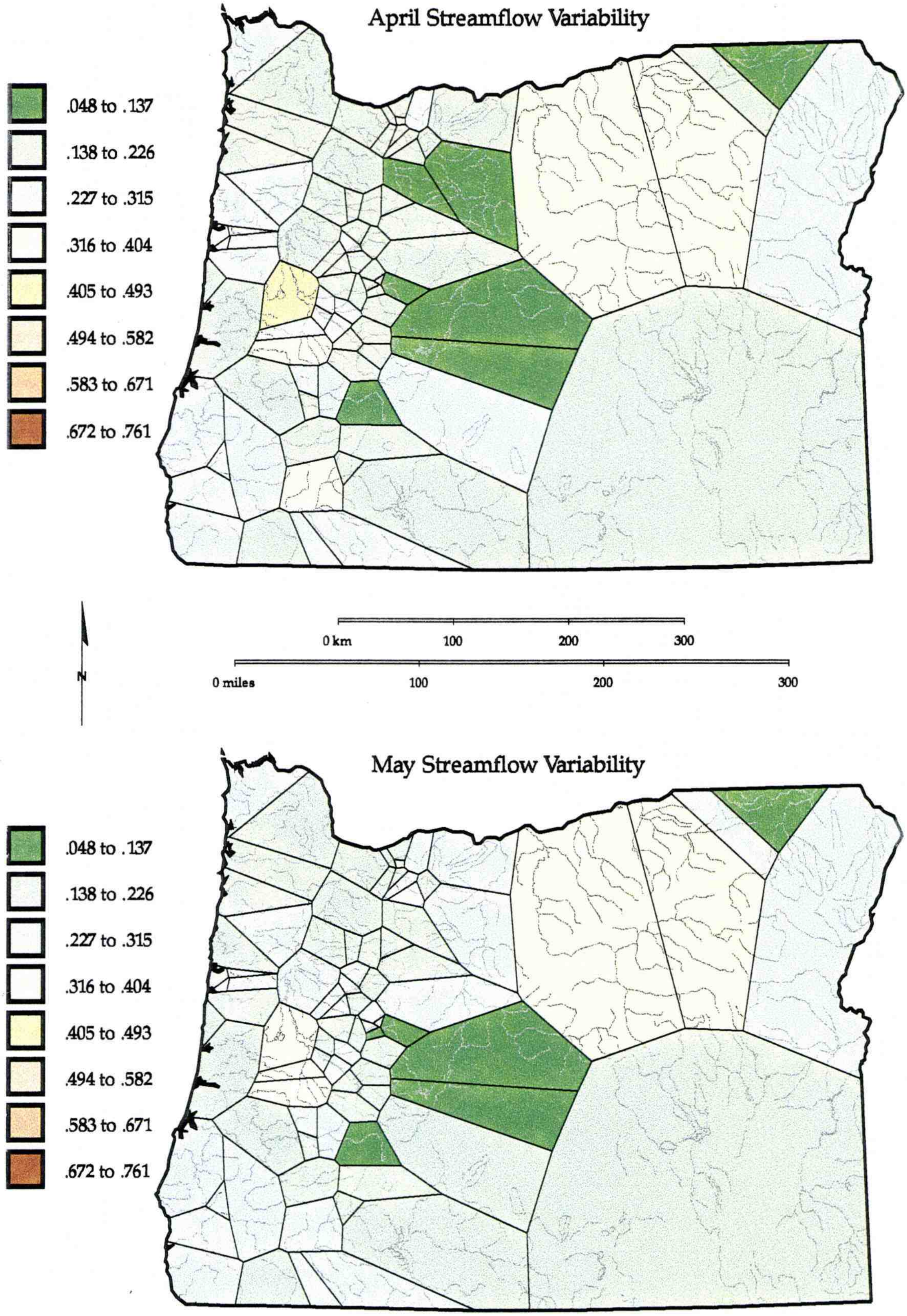

Figure 4.4., Continued.

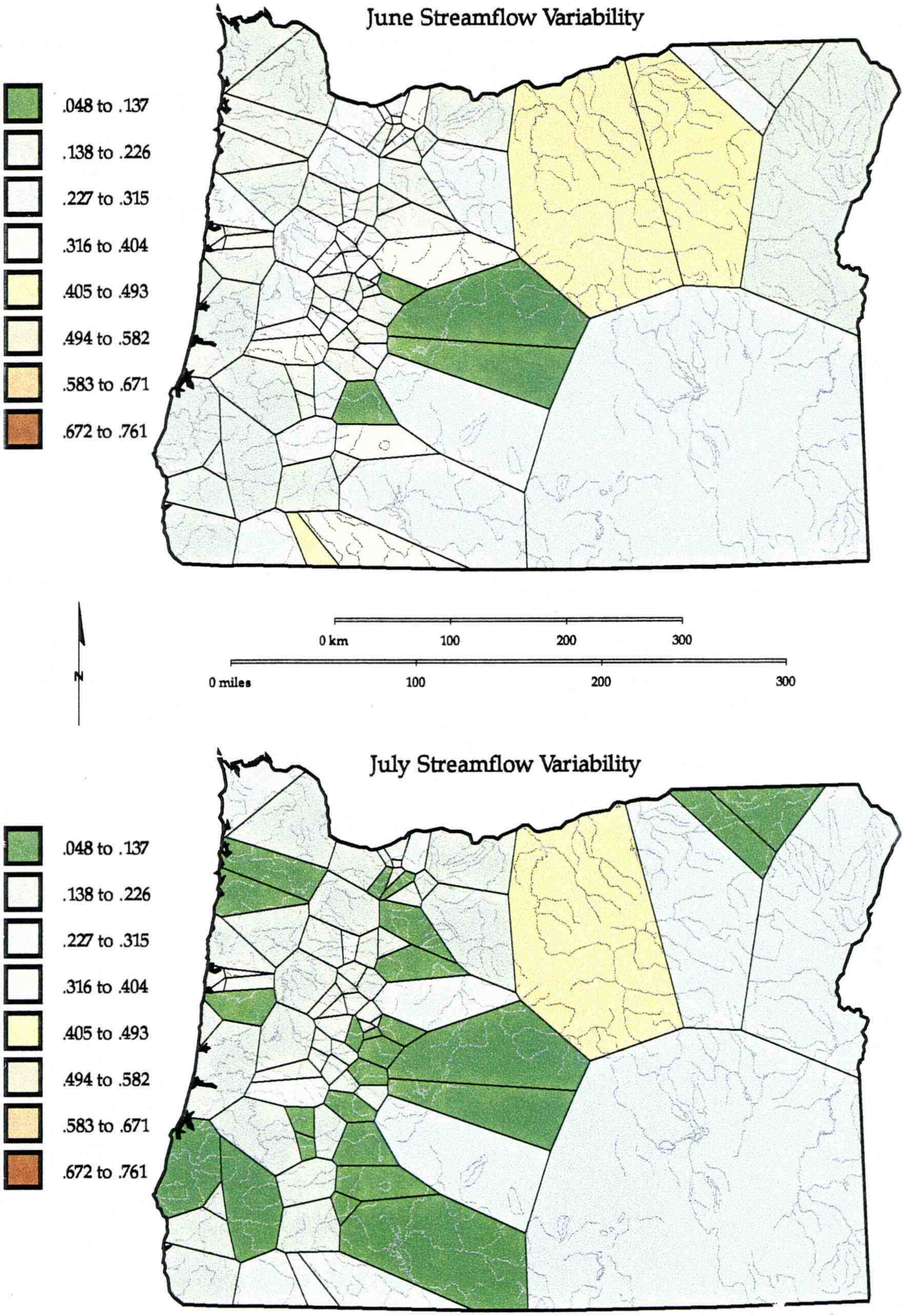

Figure 4.4., Continued.

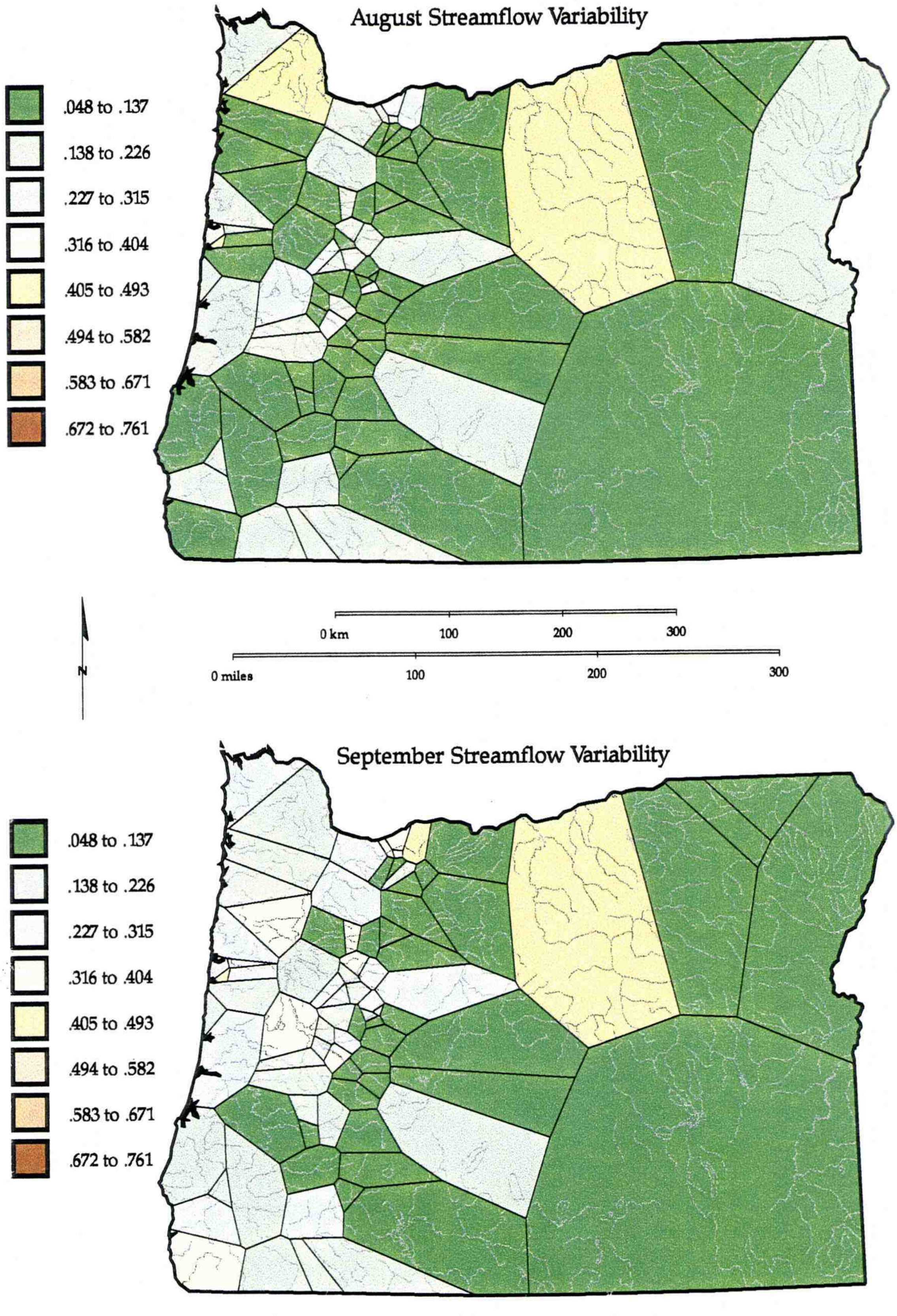

Figure 4.4., Continued.

Findings

Examination of the annual V_i and the V_i among months reveals distinct seasonal distributions in streamflow variability (Table 4.1). Among the 86 study sites, the maximum annual V_i is 0.804. The maximum V_i for a single month is 0.761, with eight months having a maximum of 0.5 or less. In all months, the minimum V_i is less than the minimum annual V_i. The range for monthly V_i covers a high of 0.712 to a low of 0.288. The annual V_i range is 0.683. The month of May has the lowest maximum monthly V_i, 0.393 for all study sites. October has the highest maximum monthly V_i, 0.761 for all study sites. The maps of monthly streamflow variability (Figure 4.4) depict August as the month in which most study sites have the lowest monthly V_i. August also has the lowest mean monthly V_i for all study sites. Overall, July, August, and September have the lowest mean monthly V_i for all study sites.

Graphic presentation of monthly streamflow variability (Figure 4.4) makes it possible to evaluate spatial and temporal patterns among stream gages. In western Oregon, April through September are months of low streamflow variability. High V_i are seen from October through January, with dramatic increases in September and October. February and March show a slow decline in the V_i with a reduction in mean discharges for the region. The highest values of streamflow variability for this region are found in the southwest, in which some of the highest annual V_i are also found. The southwestern portion of the state is part of the Coastal Province (Fenneman, 1946) in which watersheds are characteristically long and narrow, reflecting steep stream gradients, and precipitation is heavy on west facing slopes. The area is drained primarily by perennial streams,

	Annual Vi	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*
Minimum	0.121	0.049	0.089	0.106	0.096	0.085	0.079	0.085	0.105	0.117	0.069	0.045	0.049
Maximum	0.804	0.761	0.688	0.591	0.529	0.500	0.435	0.441	0.393	0.431	0.478	0.491	0.473
Mean	0.455	0.316	0.382	0.335	0.310	0.277	0.235	0.212	0.218	0.228	0.173	0.142	0.188
Range	0.683	0.712	0.599	0.485	0.433	0.415	0.355	0.356	0.288	0.313	0.409	0.446	0.424

Table 4.1. Descriptive statistics for annual and monthly streamflow variability in Oregon.

although intermittent streams occur in headwater reaches and valley floors (Omernik, 1986).

Southeastern Oregon is characterized by limited study sites. Streamflow variability is relatively low all months of the year, with slight increases in December through March and again in June and July. This region shows the lowest statewide V_i from August to November. Southeastern Oregon is classified as mid-latitude steppe and desert (Fenneman, 1946).

The greatest spatial and temporal variability in monthly V_i is found in northeastern Oregon. In some areas, such as the northcentral portion, monthly V_i are consistently moderate to high throughout the year. This portion of the state also has some of the highest annual V_i among the study sites. Topographic diversity typifies this region, characterized by dry deep channels cut into the underlying formations. Continental influences dominate the highlands, and considerable elevation differences are responsible for strikingly different mountain and valley climates (Jackson 1993, 56). The region is drained by perennial, intermittent and ephemeral streams (Omernik, 1986).

When compared to annual streamflow variability, monthly V_i show inconsistent spatial and temporal patterns. While the map of annual V_i shows southwestern and northeast/northcentral Oregon as having very high streamflow variability, these areas differ considerably in their distribution of monthly V_i. The northeast/northcentral region shows relatively consistent V_i when compared to all other regional of the state, remaining moderate to high throughout the year. Conversely, the southwestern portion of the state shows the greatest range in monthly streamflow variability, with the highest V_i in November and the lowest in August. Central Oregon tends to have the lowest monthly V_i, and is consistent with what is seen in the annual V_i. These patterns reveal that the relationship of monthly to annual streamflow variability changes across space.

Summary and Conclusions

This research has examined 1.) temporal patterns of monthly streamflow variability, 2.) spatial patterns of monthly streamflow variability, and 3.) the relationship of monthly and annual streamflow variability. The results of this investigation indicate the following:

1. There is a limited relationship between the annual streamflow variability index and monthly streamflow variability indexes. A possible explanation is that annual flow duration statistics, used to calculate the annual V_i, are not directly associated with monthly flow duration statistics.

2. There appears to be a definite seasonal trend to the distribution of monthly streamflow variability. Monthly streamflow variability appears to follow seasonal climatic cycles.

3. The relationship of annual and monthly streamflow variability changes spatially. High annual indexes do not directly relate to the range in monthly streamflow variability experienced by a region.

If water quality monitoring for NPS pollution is to occur during a short period or a monitoring season, it may be possible to utilize monthly streamflow variability in program planning. In this regard, monthly indexes of streamflow variability may provide information to assist in the timing of intensive sampling for variable-interval water quality monitoring.

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CHAPTER 5.

SUMMARY

Summary Statement

The research papers presented in this thesis examine selected properties of streamflow variability in Oregon to advance its application in regional planning of water quality monitoring programs. The papers address the "what, how, where and when" of streamflow variability for water quality monitoring design for Oregon stream systems. The products of this research depict Oregon streams by their relative streamflow variability and evaluate factors that may influence that variability. It is recognized that streamflow variability can provide valuable information for NPS monitoring program planning (Richards 1989, 1990). The three manuscripts presented in this thesis examine questions related to the application of streamflow variability in the context of regional strategic planning.

Three primary questions about streamflow variability are addressed by this research. They are as follows:

- What is the relationship in Oregon between streamflow variability and watershed size, which is often described as a proxy for streamflow variability?
- What geographic factors in Oregon influence streamflow variability, and are regional-scale factors adequate to efficiently predict streamflow variability on ungaged streams?
- How is streamflow variability in Oregon affected by seasonal climatic variation?

Examining these questions regarding the behavior of streamflow variability of river systems in Oregon may assist in the design of regional and local water quality monitoring programs.

Paper I (Chapter 2) is an examination of the relationship between streamflow variability in Oregon and river basin size. River basin size if often used as a proxy for streamflow variability, and Paper I tests the validity of that relationship. The concepts and quantification of streamflow variability developed in Paper I allow for the statistical analysis of factors affecting streamflow variability using geographic parameters in Paper II.

Paper II (Chapter 3) serves to further the understanding of regional planning of NPS monitoring by examining the spatial dimension of streamflow variability in terms of regional and watershed characteristics. The purpose of Paper II is to examine the scale of the characteristics influencing streamflow variability to provide information for estimating streamflow variability regionally, and at ungaged sites. The examination of regional-scale influences is applicable to regional-level monitoring needs assessment and design. The information gained from this approach is applied to ungaged stream catchments in Oregon where historic discharge records are unavailable.

Whether even-interval or storm event-based, sampling of NPS pollution is often conducted during monitoring seasons when overland runoff is most likely to occur. Paper III (Chapter 4) refines the application of the streamflow variability index by examining it on a seasonal basis. Monthly streamflow variability is calculated for the Oregon study sites and seasonal change is evaluated. The study area is examined for spatial patterns in seasonal variability and the processes that may influence those patterns. Seasonal investigation of streamflow variability provides further insight as to the timing and design needs of NPS water quality monitoring projects.

Considering the nature of the index of streamflow variability, it is appropriate that streamflow variability is analyzed on the regional-scale. Temporally, streamflow variability represents a broad time scale. It depicts the annual discharge variability based on long-term records of daily discharge. In essence, the resolution of regional-scale factors and the index of streamflow variability are synchronous with each other. At another level, the analysis of watershed-scale factors and a measure a watershed's response to a single storm-event may be synchronous.

Streamflow Variability and Basin Size

Assumed relationships between basin size and streamflow variability have been primarily based on research conducted on eastern US streams and rivers. Application of this assumption for water quality monitoring recommendations has ignored regional geographic differences. In Oregon, the relationship between streamflow variability and basin size is not what is expected based upon a review of the literature. That streamflow variability decreases as basin area increases is not an accurate generalization for this study area. Analysis of the state-wide data set showed no significant relationship between basin area and streamflow variability. When the data are stratified by ecoregions, a significant relationship between basin area and streamflow variability is present in only one of nine ecoregions. The distribution of streamflow variability in Oregon suggests spatial complexity, and the likelihood that other factors are responsible for this streamflow characteristic. Given the geographic complexity of other western US regions, it does not seem unreasonable to extend the implications of this research beyond the borders of Oregon.

The results suggest that recommendations for water quality monitoring design based on basin size are incomplete and may be arbitrary. While simplicity in recommendations for water quality monitoring design is often desirable, that simplicity should not be traded for inaccuracies. Based on the findings of this study, sampling frequency recommendations should be developed that specify the degree of streamflow variability rather than relying on basin size as a proxy for that variability. Recommendations based on variability could be readily applied where records of river discharge exist. Given the apparent regional distribution of streamflow variability, methods based on quantitative and qualitative evidence could be developed for predicting streamflow variability where records are absent.

Regional Analysis of Streamflow Variability

Paper II develops three models to estimate streamflow variability on ungaged streams in Oregon. The models are built exclusively from regional-scale variables and applied to the entire study area. Streamflow variability for western Oregon streams with no upstream dams or diversions is estimated with an $R^2 = 0.66$. For western Oregon streams with upstream diversions, streamflow variability is estimated with an $R^2 = 0.54$. And for eastern Oregon streams with and with out upstream diversions, streamflow variability is estimated with an $R^2 = 0.41$. It appears that streamflow variability is linked to region specific characteristics, especially seasonal temperature and precipitation attributes. Estimation of streamflow variability on ungaged streams in Oregon is shown to be feasible using regional-scale variables alone for model selection. Regional-scale variables selected for this study are available from easily accessible data sets.

The results of this research suggest that given a hierarchical approach to planning water quality monitoring programs, regional modeling of streamflow variability is both practical and efficient. This mapped information can be used in state and regional decision making to help determine relative sampling needs based on streamflow characteristics. Going down the hierarchical ladder, the addition of watershed-scale variables can increase the explanatory power of the models on a watershed-by-watershed basis. It would be suggested that further investigation of streamflow properties then continue on specific streams where monitoring is to take place.

Seasonality of Streamflow Variability

This research has examined 1.) temporal patterns of monthly streamflow variability, 2.) spatial patterns of monthly streamflow variability, and 3.) the relationship of monthly and annual streamflow variability. The results of this investigation indicate the following:

1. There is a limited relationship between the annual streamflow variability index and monthly streamflow variability indexes. A possible explanation is that annual flow duration statistics, used to calculate the annual V_i, are not directly associated with monthly flow duration statistics.

2. There appears to be a definite seasonal trend to the distribution of monthly streamflow variability. Monthly streamflow variability appears to follow seasonal climatic cycles.

3. The relationship of annual and monthly streamflow variability changes spatially. High annual indexes do not directly relate to the range in monthly streamflow variability experienced by a region.

If water quality monitoring for NPS pollution is to occur during a short period or a monitoring season, it may be possible to utilize monthly streamflow variability in program planning. In this regard, monthly indexes of streamflow variability may provide information to assist in the timing of intensive sampling for variable-interval water quality monitoring.

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APPENDICES

APPENDIX A.

DATA - CHAPTER 2, PAPER I

Station	*Vi*	diversions	area (mi*2)	area (km*2)
10370000	0.562	1	63.00	163.17
10371500	0.557	1	249.00	644.91
10384000	0.433	1	275.00	712.25
10393500	0.619	1	934.00	2419.06
10396000	0.360	0	200.00	518.00
10397000	0.121	0	30.00	77.70
10403000	0.665	1	228.00	590.52
10406500	0.420	1	882.40	2285.42
11340500	0.568	1	32.90	85.21
11497500	0.274	1	513.00	1328.67
13216500	0.336	1	355.00	919.45
13226500	0.715	1	539.00	1396.01
13270800	0.123	0	38.50	99.72
13288200	0.367	1	156.00	404.04
13292000	0.393	1	622.00	1610.98
13320000	0.410	1	105.00	271.95
13323500	0.651	1	1250.00	3237.50
13323600	0.569	0	22.00	56.98
13329500	0.386	0	29.60	76.66
13330500	0.526	1	68.00	176.12
13331500	0.441	1	240.00	621.60
14010000	0.179	0	63.00	163.17
14010800	0.474	1	34.40	89.10
14011000	0.562	1	43.80	113.44
14020000	0.407	0	131.00	339.29
14020300	0.625	0	176.00	455.84
14021000	0.566	1	637.00	1649.83
14022200	0.804	0	48.60	125.87
14022500	1.004	1	180.00	466.20
14025000	1.165	1	291.00	753.69
14032000	0.787	1	291.00	753.69
14034800	0.724	1	120.00	310.80
14038500	0.424	1	231.00	598.29
14038530	0.369	1	386.00	999.74
14040500	0.577	1	1680.00	4351.20
14042000	0.744	1	60.70	157.21
14042500	0.673	1	121.00	313.39
14044000	0.532	1	515.00	1333.85
14047390	0.794	0	297.00	769.23
14048000	0.574	1	7580.00	19632.20
14050000	0.182	1	132.00	341.88
14050500	0.121	0	16.50	42.74
14052000	0.753	0	21.50	55.69

Station	Vi	diversions	area (mi*2)	area (km*2)
14054500	0.123	0	21.00	54.39
14061000	0.368	0	51.50	133.39
14075000	0.229	1	45.20	117.07
14078000	0.905	1	450.00	1165.50
14078500	0.846	1	159.00	411.81
14079500	0.638	1	2160.00	5594.40
14091500	0.057	1	316.00	818.44
14092885	0.223	1	75.80	196.32
14093000	0.212	1	105.00	271.95
14097100	0.183	1	526.00	1362.34
14097200	0.283	0	40.70	105.41
14101500	0.324	1	417.00	1080.03
14113200	0.636	1	41.50	107.49
14113400	0.319	0	4.50	11.66
14118500	0.303	1	95.60	247.60
14131000	0.073	0	3.70	9.58
14134000	0.214	0	8.00	20.72
14134500	0.304	0	54.00	139.86
14135000	0.360	0	100.00	259.00
14135500	0.360	0	106.00	274.54
14137000	0.308	0	262.00	678.58
14138800	0.529	0	8.20	21.24
14138870	0.433	0	5.50	14.25
14139700	0.366	0	7.90	20.46
14139800	0.385	0	15.40	39.89
14141500	0.423	0	22.30	57.76
14144800	0.276	0	258.00	668.22
14144900	0.398	0	52.70	136.49
14145500	0.327	0	392.00	1015.28
14146000	0.263	1	113.00	292.67
14146500	0.282	0	117.00	303.03
14150300	0.518	0	118.00	305.62
14150800	0.577	0	43.90	113.70
14151000	0.553	0	186.00	481.74
14151500	0.482	0	52.50	135.98
14152500	0.524	1	72.10	186.74
14155500	0.599	0	270.00	699.30
14156000	0.652	0	85.00	220.15
14156500	0.642	1	95.30	246.83
14158790	0.584	0	16.20	41.96
14159000	0.132	0	348.00	901.32
14159200	0.269	0	160.00	414.40
14159500	0.313	0	208.00	538.72

Station	*Vi*	diversions	area (mi*2)	area (km*2)
14161100	0.548	0	45.80	118.62
14161500	0.486	0	24.10	62.42
14162000	0.546	0	75.00	194.25
14162500	0.231	0	930.00	2408.70
14163000	0.480	0	47.60	123.28
14167000	1.044	1	95.10	246.31
14169300	0.758	0	3.40	8.81
14170000	0.742	1	391.00	1012.69
14174000	0.363	1	4840.00	12535.60
14178000	0.249	0	216.00	559.44
14179000	0.324	0	108.00	279.72
14181500	0.301	0	453.00	1173.27
14182500	0.556	0	112.00	290.08
14183000	0.357	0	655.00	1696.45
14185000	0.520	0	174.00	450.66
14185800	0.478	0	104.00	269.36
14185900	0.549	0	99.20	256.93
14186000	0.540	0	271.00	701.89
14187000	0.554	0	51.80	134.16
14187100	0.590	0	62.30	161.36
14187500	0.542	0	640.00	1657.60
14188800	0.569	1	109.00	282.31
14191000	0.410	1	7280.00	18855.20
14193000	0.574	0	64.70	167.57
14193300	0.659	0	27.40	70.97
14194300	0.530	0	9.00	23.31
14195000	0.612	1	6.50	16.84
14198500	0.513	0	97.00	251.23
14200000	0.536	1	323.00	836.57
14200300	0.606	1	47.90	124.06
14201000	0.654	1	204.00	528.36
14201500	0.622	1	58.70	152.03
14204000	0.574	0	33.20	85.99
14204500	0.613	1	66.10	171.20
14208000	0.197	0	136.00	352.24
14209000	0.151	1	126.00	326.34
14251500	0.630	0	40.10	103.86
14251500	0.630	1	40.10	103.86
14301000	0.623	1	667.00	1727.53
14301500	0.533	1	161.00	416.99
14302500	0.498	1	145.00	375.55
14303600	0.509	1	180.00	466.20
14306030	0.644	0	71.00	183.89

Station	*Vi*	diversions	area (mi*2)	area (km*2)
14306100	0.542	1	63.00	163.17
14306400	0.573	0	114.00	295.26
14306500	0.570	1	334.00	865.06
14306600	0.547	0	20.50	53.10
14306700	0.568	0	0.30	0.78
14306800	0.627	0	0.80	2.07
14306810	0.583	0	1.20	3.11
14306900	0.513	0	11.90	30.82
14307620	0.581	0	588.00	1522.92
14307645	0.541	1	41.20	106.71
14307700	0.571	0	152.00	393.68
14308000	0.592	1	449.00	1162.91
14308500	0.863	1	54.40	140.90
14308600	0.588	1	641.00	1660.19
14308700	0.771	1	55.30	143.23
14309500	0.685	0	86.90	225.07
14310700	0.626	1	43.90	113.70
14311000	0.640	1	54.20	140.38
14311200	0.968	1	61.30	158.77
14312200	0.823	1	53.20	137.79
14315500	0.127	0	339.00	878.01
14316700	0.568	0	227.00	587.93
14317500	0.295	0	886.00	2294.74
14317600	0.550	0	97.40	252.27
14318000	0.598	1	177.00	458.43
14318500	0.348	0	1210.00	3133.90
14319200	0.736	1	16.40	42.48
14319900	0.565	1	88.60	229.47
14320700	0.755	1	210.00	543.90
14322000	0.905	1	104.00	269.36
14324500	0.710	1	46.90	121.47
14324600	0.779	0	31.20	80.81
14324700	0.775	0	40.60	105.15
14324900	0.668	0	93.20	241.39
14325000	0.688	1	169.00	437.71
14326800	0.715	1	73.90	191.40
14327000	0.685	1	282.00	730.38
14327500	0.189	0	156.00	404.04
14328000	0.219	0	312.00	808.08
14330500	0.264	0	52.00	134.68
14331000	0.220	0	26.00	67.34
14333500	0.188	1	45.50	117.85
14337600	0.209	1	938.00	2429.42

Station	Vi	diversions	area (mi*2)	area (km*2)
14337800	0.714	1	78.80	204.09
14337870	0.583	0	14.20	36.78
14339000	0.232	1	1215.00	3146.85
14339500	0.258	0	17.00	44.03
14341500	0.474	1	138.00	357.42
14353000	0.335	0	10.50	27.20
14353500	0.352	0	8.10	20.98
14361600	0.428	0	51.80	134.16
14368500	0.513	0	8.20	21.24
14370000	0.744	1	31.40	81.33
14371500	0.764	1	22.10	57.24
14372500	0.577	1	42.30	109.56
14375000	0.441	1	76.20	197.36
14375100	0.465	1	83.90	217.30
14375500	0.712	1	42.40	109.82
14377000	0.702	1	364.00	942.76
14377100	0.688	1	380.00	984.20
14377500	0.698	1	22.00	56.98
14378000	0.647	1	665.00	1722.35
14378200	0.616	1	988.00	2558.92
14400000	0.665	0	271.00	701.89

Station	meanQ (cfs)	meanQ (m*3/sec)	period of rec
10370000	46.0	1.30	1913-1973
10371500	138.0	3.91	1923-1987
10384000	149.0	4.22	1925-1987
10393500	179.0	5.07	1903-1987
10396000	128.0	3.62	1911-1987
10397000	13.0	0.37	1911-1970
10403000	42.0	1.19	1952-1980
10406500	17.0	0.48	1932-1987
11340500	27.0	0.76	1909-1919
11497500	323.0	9.14	1954-1987
13216500	138.0	3.91	1914-1987
13226500	54.0	1.53	1964-1985
13270800	27.0	0.76	1963-1981
13288200	324.0	9.17	1958-1987
13292000	519.0	14.69	1929-1956
13320000	119.0	3.37	1911-1987
13323500	668.0	18.90	1956-1981
13323600	41.0	1.16	1938-1950
13329500	74.0	2.09	1915-1978
13330500	114.0	3.23	1915-1985
13331500	470.0	13.30	1912-1987
14010000	177.0	5.01	1903-1987
14010800	52.0	1.47	1970-1987
14011000	47.0	1.33	1930-1987
14020000	227.0	6.42	1933-1987
14020300	205.0	5.80	1975-1987
14021000	5.5	0.16	1904-1987
14022200	44.0	1.25	1973-1987
14022500	1.3	0.04	1921-1987
14025000	48.0	1.36	1921-1976
14032000	28.0	0.79	1928-1987
14034800	23.0	0.65	1961-1987
14038500	89.0	2.52	1926-1951
14038530	220.0	6.23	1969-1987
14040500	503.0	14.23	1927-1987
14042000	43.0	1.22	1951-1970
14042500	96.0	2.72	1914-1987
14044000	256.0	7.24	1930-1987
14047390	63.0	1.78	1975-1987
14048000	2100.0	59.43	1905-1987
14050000	151.0	4.27	1938-1987
14050500	63.0	1.78	1923-1987
14052000	7.5	0.21	1924-1987

Station	meanQ (cfs)	meanQ (m*3/sec)	period of rec
14054500	38.0	1.08	1923-1987
14061000	72.0	2.04	1912-1958
14075000	105.0	2.97	1906-1987
14078000	89.0	2.52	1943-1975
14078500	96.0	2.72	1944-1954
14079500	331.0	9.37	1941-1973
14091500	1500.0	42.45	1912-1987
14092885	98.0	2.77	1975-1987
14093000	111.0	3.14	1912-1974
14097100	114.0	3.23	1973-1987
14097200	165.0	4.67	1969-1981
14101500	427.0	12.08	1918-1987
14113200	28.0	0.79	1963-1981
14113400	7.2	0.20	1961-1971
14118500	554.0	15.68	1933-1987
14131000	25.0	0.71	1926-1936
14134000	44.0	1.25	1910-1987
14134500	205.0	5.80	1928-1950
14135000	438.0	12.40	1914-1936
14135500	452.0	12.79	1936-1952
14137000	1360.0	38.49	1911-1987
14138800	58.0	1.64	1964-1987
14138870	34.0	0.96	1976-1987
14139700	67.0	1.90	1964-1987
14139800	108.0	3.06	1975-1987
14141500	145.0	4.10	1911-1987
14144800	816.0	23.09	1959-1987
14144900	150.0	4.25	1959-1982
14145500	1140.0	32.26	1914-1960
14146000	293.0	8.29	1913-1951
14146500	427.0	12.08	1913-1987
14150300	413.0	11.69	1963-1987
14150800	118.0	3.34	1963-1982
14151000	588.0	16.64	1936-1968
14151500	179.0	5.07	1936-1948
14152500	200.0	5.66	1936-1987
14155500	688.0	19.47	1940-1949
14156000	191.0	5.41	1936-1946
14156500	241.0	6.82	1946-1981
14158790	91.0	2.58	1961-1987
14159000	1660.0	46.98	1911-1962
14159200	637.0	18.03	1959-1987
14159500	927.0	26.23	1948-1962

Station	meanQ (cfs)	meanQ (m*3/sec)	period of rec
14161100	259.0	7.33	1964-1987
14161500	125.0	3.54	1950-1987
14162000	393.0	11.12	1936-1964
14162500	4000.0	113.20	1925-1962
14163000	212.0	6.00	1952-1987
14167000	176.0	4.98	1940-1987
14169300	5.2	0.15	1963-1975
14170000	703.0	19.89	1922-1940
14174000	13500.0	382.05	1894-1941
14178000	1010.0	28.58	1907-1987
14179000	576.0	16.30	1932-1987
14181500	2260.0	63.96	1912-1952
14182500	765.0	21.65	1932-1987
14183000	3250.0	91.98	1906-1952
14185000	821.0	23.23	1936-1987
14185800	630.0	17.83	1963-1987
14185900	674.0	19.07	1963-1987
14186000	1450.0	41.04	1932-1947
14187000	224.0	6.34	1948-1972
14187100	233.0	6.59	1974-1987
14187500	2910.0	82.35	1906-1965
14188800	496.0	14.04	1963-1987
14191000	21300.0	602.79	1910-1941
14193000	260.0	7.36	1934-1987
14193300	140.0	3.96	1959-1973
14194300	47.0	1.33	1959-1987
14195000	25.0	0.71	1929-1951
14198500	540.0	15.28	1936-1987
14200000	1160.0	32.83	1928-1979
14200300	208.0	5.89	1964-1980
14201000	711.0	20.12	1940-1966
14201500	221.0	6.25	1936-1985
14204000	115.0	3.25	1936-1970
14204500	225.0	6.37	1941-1987
14208000	477.0	13.50	1920-1970
14209000	495.0	14.01	1910-1955
14251500	167.0	4.73	1928-1941
14251500	167.0	4.73	1928-1941
14301000	2700.0	76.41	1940-1987
14301500	1190.0	33.68	1915-1987
14302500	966.0	27.34	1931-1972
14303600	1070.0	30.28	1965-1987
14306030	255.0	7.22	1973-1987

Station	meanQ (cfs)	meanQ (m*3/sec)	period of rec
14306100	279.0	7.90	1958-1987
14306400	552.0	15.62	1961-1987
14306500	1510.0	42.73	1940-1987
14306600	120.0	3.40	1959-1970
14306700	1.6	0.05	1959-1973
14306800	4.4	0.12	1959-1973
14306810	6.5	0.18	1959-1973
14306900	92.0	2.60	1973-1987
14307620	2140.0	60.56	1968-1987
14307645	297.0	8.41	1968-1985
14307700	319.0	9.03	1956-1986
14308000	1040.0	29.43	1911-1987
14308500	83.0	2.35	1955-1987
14308600	1180.0	33.39	1975-1987
14308700	44.0	1.25	1956-1972
14309500	273.0	7.73	1956-1987
14310700	65.0	1.84	1956-1972
14311000	73.0	2.07	1956-1986
14311200	102.0	2.89	1957-1973
14312200	77.0	2.18	1956-1973
14315500	875.0	24.76	1926-1948
14316700	743.0	21.03	1957-1987
14317500	2260.0	63.96	1924-1945
14317600	373.0	10.56	1958-1973
14318000	472.0	13.36	1955-1987
14318500	3110.0	88.01	1916-1938
14319200	25.0	0.71	1956-1967
14319900	205.0	5.80	1976-1987
14320700	495.0	14.01	1956-1973
14322000	218.0	6.17	1956-1973
14324500	249.0	7.05	1955-1981
14324600	144.0	4.08	1957-1970
14324700	199.0	5.63	1957-1974
14324900	514.0	14.55	1957-1970
14325000	794.0	22.47	1917-1987
14326800	281.0	7.95	1964-1981
14327000	945.0	26.74	1929-1968
14327500	498.0	14.09	1930-1952
14328000	830.0	23.49	1908-1987
14330500	127.0	3.59	1932-1949
14331000	43.0	1.22	1934-1949
14333500	118.0	3.34	1925-1981
14337600	2290.0	64.81	1966-1976

Station	**meanQ (cfs)**	**meanQ (m*3/sec)**	**period of rec**
14337800	151.0	4.27	1974-1987
14337870	22.0	0.62	1974-1987
14339000	2680.0	75.84	1939-1976
14339500	17.0	0.48	1927-1950
14341500	108.0	3.06	1922-1957
14353000	8.9	0.25	1925-1987
14353500	9.4	0.27	1925-1983
14361600	108.0	3.06	1978-1987
14368500	16.0	0.45	1947-1958
14370000	81.0	2.29	1944-1957
14371500	59.0	1.67	1946-1987
14372500	179.0	5.07	1942-1987
14375000	212.0	6.00	1942-1965
14375100	24.0	0.68	1966-1987
14375500	219.0	6.20	1955-1986
14377000	1210.0	34.24	1926-1961
14377100	1330.0	37.64	1962-1987
14377500	74.0	2.09	1942-1956
14378000	2340.0	66.22	1957-1968
14378200	4090.0	115.75	1961-1981
14400000	2360.0	66.79	1970-1987

APPENDIX B.

DATA - CHAPTER 3, PAPER II

Station	Vi	start_d	end_d	Diversions	area_mi	elev_ft
10370000	0.562	1913	1973	1	63.0	5472.41
10371500	0.557	1923	1987	1	249.0	4980.34
10384000	0.433	1925	1987	1	275.0	4430.00
10393500	0.619	1903	1987	1	934.0	4195.00
10396000	0.360	1911	1987	0	200.0	4254.00
10397000	0.121	1911	1970	0	30.0	4184.93
10403000	0.665	1952	1980	1	228.0	4449.70
10406500	0.420	1932	1987	1	882.4	4351.52
11340500	0.568	1909	1919	1	32.9	4949.37
11497500	0.274	1954	1987	1	513.0	4305.35
13216500	0.336	1914	1987	1	355.0	3320.00
13226500	0.715	1964	1985	1	539.0	2527.21
13270800	0.123	1963	1981	0	38.5	4341.75
13288200	0.367	1958	1987	1	156.0	2800.00
13292000	0.393	1929	1956	1	622.0	1941.14
13320000	0.410	1911	1987	1	105.0	3081.76
13323500	0.651	1956	1981	1	1250.0	2660.31
13323600	0.569	1938	1950	0	22.0	3800.00
13329500	0.386	1915	1978	0	29.6	4500.00
13330500	0.526	1915	1985	1	68.0	3250.00
13331500	0.441	1912	1987	1	240.0	2540.48
14010000	0.179	1903	1987	0	63.0	2050.00
14010800	0.474	1970	1987	1	34.4	1940.00
14011000	0.562	1930	1987	1	43.8	1467.00
14020000	0.407	1933	1987	0	131.0	1854.81
14020300	0.625	1975	1987	0	176.0	1803.05
14021000	0.566	1904	1987	1	637.0	1054.30
14022200	0.804	1973	1987	0	48.6	1870.00
14022500	1.004	1921	1987	1	180.0	1343.60
14025000	1.165	1921	1976	1	291.0	951.04
14032000	0.787	1928	1987	1	291.0	1400.00
14034800	0.724	1961	1987	1	120.0	2320.00
14038530	0.369	1969	1987	1	386.0	3130.56
14040500	0.577	1927	1987	1	1680.0	2229.84
14042000	0.744	1951	1970	1	60.7	3969.53
14042500	0.673	1914	1987	1	121.0	3588.61
14044000	0.532	1930	1987	1	515.0	2544.56
14047390	0.794	1975	1987	0	297.0	1714.50
14048000	0.574	1905	1987	1	7580.0	392.27
14050000	0.182	1938	1987	1	132.0	4445.00
14050500	0.121	1923	1987	0	16.5	4450.00
14052000	0.753	1924	1987	0	21.5	4520.00
14054500	0.123	1923	1987	0	21.0	4370.00

Station	Vi	start_d	end_d	Diversions	area_mi	elev_ft
14061000	0.368	1912	1958	0	51.5	4630.00
14075000	0.229	1906	1987	1	45.2	3490.00
14078000	0.905	1943	1975	1	450.0	3690.00
14078500	0.846	1944	1954	1	159.0	4356.00
14079500	0.638	1941	1973	1	2160.0	3476.25
14091500	0.057	1912	1987	1	316.0	1974.36
14092885	0.223	1975	1987	1	75.8	1600.00
14093000	0.212	1912	1974	1	105.0	1380.00
14097100	0.183	1973	1987	1	526.0	1400.00
14097200	0.283	1969	1981	0	40.7	2740.00
14101500	0.324	1918	1987	1	417.0	870.15
14113200	0.636	1963	1981	1	41.5	425.00
14113400	0.319	1961	1971	0	4.5	4347.00
14118500	0.303	1933	1987	1	95.6	802.10
14131000	0.073	1926	1936	0	3.7	2905.16
14134000	0.214	1910	1987	0	8.0	3445.53
14134500	0.304	1928	1950	0	54.0	2500.00
14135000	0.360	1914	1936	0	100.0	1350.00
14135500	0.360	1936	1952	0	106.0	1089.20
14137000	0.308	1911	1987	0	262.0	730.00
14138800	0.529	1964	1987	0	8.2	2540.00
14138870	0.433	1976	1987	0	5.5	1440.00
14139700	0.366	1964	1987	0	7.9	1960.00
14139800	0.385	1975	1987	0	15.4	990.00
14141500	0.423	1911	1987	0	22.3	720.00
14144800	0.276	1959	1987	0	258.0	1556.83
14144900	0.398	1959	1982	0	52.7	1630.80
14145500	0.327	1914	1960	0	392.0	1208.10
14146000	0.263	1913	1951	1	113.0	1245.67
14146500	0.282	1913	1987	0	117.0	1462.36
14150300	0.518	1963	1987	0	118.0	844.42
14150800	0.577	1963	1982	0	43.9	863.70
14151000	0.553	1936	1968	0	186.0	637.81
14152500	0.524	1936	1987	1	72.1	852.58
14155500	0.599	1940	1949	0	270.0	685.24
14156000	0.652	1936	1946	0	85.0	750.00
14156500	0.642	1946	1981	1	95.3	676.62
14158790	0.584	1961	1987	0	16.2	2610.00
14159000	0.132	1911	1962	0	348.0	1419.04
14159200	0.269	1959	1987	0	160.0	1709.51
14159500	0.313	1948	1962	0	208.0	1236.42
14161100	0.548	1964	1987	0	45.8	1386.90
14161500	0.486	1950	1987	0	24.1	1377.76

Station	Vi	start_d	end_d	Diversions	area_mi	elev_ft
14162000	0.546	1936	1964	0	75.0	1231.62
14162500	0.231	1925	1962	0	930.0	855.57
14163000	0.480	1952	1987	0	47.6	764.56
14167000	1.044	1940	1987	1	95.1	374.00
14169300	0.758	1963	1975	0	3.4	442.33
14170000	0.742	1922	1940	1	391.0	270.57
14174000	0.363	1894	1941	1	4840.0	167.18
14178000	0.249	1907	1987	0	216.0	1590.07
14179000	0.324	1932	1987	0	108.0	1573.95
14181500	0.301	1912	1952	0	453.0	1093.78
14182500	0.556	1932	1987	0	112.0	655.41
14183000	0.357	1906	1952	0	655.0	602.49
14185000	0.520	1936	1987	0	174.0	759.88
14185800	0.478	1963	1987	0	104.0	1040.00
14185900	0.549	1963	1987	0	99.2	1050.00
14186000	0.540	1932	1947	0	271.0	733.44
14187000	0.554	1948	1972	0	51.8	716.08
14187100	0.590	1974	1987	0	62.3	590.00
14187500	0.542	1906	1965	0	640.0	370.39
14188800	0.569	1963	1987	1	109.0	380.84
14191000	0.410	1910	1941	1	7280.0	114.14
14193000	0.574	1934	1987	0	64.7	315.00
14193300	0.659	1959	1973	0	27.4	562.02
14194300	0.530	1959	1987	0	9.0	560.00
14195000	0.612	1929	1951	1	6.5	815.00
14198500	0.513	1936	1987	0	97.0	791.35
14200000	0.536	1928	1979	1	323.0	104.00
14200300	0.606	1964	1980	1	47.9	218.50
14201000	0.654	1940	1966	1	204.0	119.76
14201500	0.622	1936	1985	1	58.7	155.00
14204000	0.574	1936	1970	0	33.2	449.31
14204500	0.613	1941	1987	1	66.1	208.81
14208000	0.197	1920	1970	0	136.0	2040.00
14209000	0.151	1910	1955	1	126.0	2052.31
14251500	0.630	1928	1941	0	40.1	63.27
14301000	0.623	1940	1987	1	667.0	32.60
14301500	0.533	1915	1987	1	161.0	71.89
14302500	0.498	1931	1972	1	145.0	58.00
14303600	0.509	1965	1987	1	180.0	43.00
14306030	0.644	1973	1987	0	71.0	28.43
14306100	0.542	1958	1987	1	63.0	272.31
14306400	0.573	1961	1987	0	114.0	130.00
14306500	0.570	1940	1987	1	334.0	48.16

Station	Vi	start_d	end_d	Diversions	area_mi	elev_ft
14306600	0.547	1959	1970	0	20.5	460.00
14306700	0.568	1959	1973	0	0.3	440.00
14306800	0.627	1959	1973	0	0.8	685.00
14306810	0.583	1959	1973	0	1.2	600.00
14306900	0.513	1973	1987	0	11.9	141.00
14307620	0.581	1968	1987	0	588.0	41.00
14307645	0.541	1968	1985	1	41.2	40.00
14307700	0.571	1956	1986	0	152.0	1240.25
14308000	0.592	1911	1987	1	449.0	991.80
14308500	0.863	1955	1987	1	54.4	1279.25
14308600	0.588	1975	1987	1	641.0	738.55
14308700	0.771	1956	1972	1	55.3	810.00
14309500	0.685	1956	1987	0	86.9	1018.48
14310700	0.626	1956	1972	1	43.9	775.25
14311000	0.640	1956	1986	1	54.2	642.81
14311200	0.968	1957	1973	1	61.3	749.53
14312200	0.823	1956	1973	1	53.2	498.95
14315500	0.127	1926	1948	0	339.0	2373.00
14316700	0.568	1957	1987	0	227.0	1128.55
14317500	0.295	1924	1945	0	886.0	770.00
14317600	0.550	1958	1973	0	97.4	940.00
14318000	0.598	1955	1987	1	177.0	828.33
14318500	0.348	1916	1938	0	1210.0	645.00
14319200	0.736	1956	1967	1	16.4	511.46
14319900	0.565	1976	1987	1	88.6	699.22
14320700	0.755	1956	1973	1	210.0	371.26
14322000	0.905	1956	1973	1	104.0	305.96
14324500	0.710	1955	1981	1	46.9	76.95
14324600	0.779	1957	1970	0	31.2	2117.30
14324700	0.775	1957	1974	0	40.6	1871.04
14324900	0.668	1957	1970	0	93.2	585.32
14325000	0.688	1917	1987	1	169.0	197.42
14326800	0.715	1964	1981	1	73.9	79.72
14327000	0.685	1929	1968	1	282.0	2.79
14327500	0.189	1930	1952	0	156.0	3465.00
14328000	0.219	1908	1987	0	312.0	2620.00
14330500	0.264	1932	1949	0	52.0	3390.00
14331000	0.220	1934	1949	0	26.0	3400.00
14333500	0.188	1925	1981	1	45.5	2780.00
14337600	0.209	1966	1976	1	938.0	1489.08
14337800	0.714	1974	1987	1	78.8	1813.83
14337870	0.583	1974	1987	0	14.2	1773.24
14339000	0.232	1939	1976	1	1215.0	1272.39

Station	Vi	start_d	end_d	Diversions	area_mi	elev_ft
14339500	0.258	1927	1950	0	17.0	4660.00
14341500	0.474	1922	1957	1	138.0	1729.97
14353000	0.335	1925	1987	0	10.5	2962.75
14353500	0.352	1925	1983	0	8.1	2903.70
14361600	0.428	1978	1987	0	51.8	2023.56
14368500	0.513	1947	1958	0	8.2	1680.00
14370000	0.744	1944	1957	1	31.4	1034.85
14371500	0.764	1946	1987	1	22.1	2354.20
14372500	0.577	1942	1987	1	42.3	1780.00
14375000	0.441	1942	1965	1	76.2	1777.22
14375100	0.465	1966	1987	1	83.9	1713.92
14375500	0.712	1955	1986	1	42.4	1516.14
14377000	0.702	1926	1961	1	364.0	1232.00
14377100	0.688	1962	1987	1	380.0	1198.80
14377500	0.698	1942	1956	1	22.0	1650.10
14378000	0.647	1957	1968	1	665.0	829.18
14378200	0.616	1961	1981	1	988.0	125.86

Station	slope	length	shape	storage	meanQ	s_order
10370000	111.0	12.0	0.11	1.00	46	5
10371500	96.9	22.0	0.21	2.72	138	8
10384000	33.3	32.0	0.20	1.09	149	7
10393500	12.3	65.0	0.30	1.01	179	5
10396000	97.8	22.5	0.18	1.10	128	5
10397000	197.0	12.2	0.07	1.20	13	5
10403000	41.7	25.6	0.21	1.05	42	4
10406500	152.0	22.0	0.11	1.00	17	6
11340500	246.0	6.5	0.07	1.27	27	8
11497500	51.0	37.2	0.26	1.60	323	6
13216500	67.4	34.4	0.23	1.00	138	8
13226500	43.0	43.7	0.31	1.00	54	11
13270800	370.0	7.5	0.10	1.00	27	9
13288200	143.0	26.4	0.16	1.16	324	15
13292000	72.6	56.0	0.31	1.04	519	6
13320000	114.0	26.4	0.13	1.00	119	5
13323500	35.3	68.0	0.32	1.05	668	9
13323600	231.0	11.6	0.06	1.00	41	1
13329500	296.0	10.8	0.08	1.20	74	2
13330500	178.0	18.4	0.11	1.00	114	2
13331500	69.0	45.5	0.15	1.70	470	4
14010000	189.0	17.8	0.09	1.00	177	1
14010800	207.0	13.3	0.08	1.00	52	1
14011000	167.0	16.4	0.08	1.00	47	2
14020000	138.0	17.8	0.15	1.00	227	3
14020300	90.3	19.3	0.15	1.00	205	2
14021000	47.1	45.3	0.28	1.01	5.5	6
14022200	186.7	10.0	0.10	1.00	44	1
14022500	115.0	26.5	0.16	1.00	1.3	3
14025000	64.2	35.3	0.21	1.00	48	7
14032000	78.5	37.2	0.23	1.00	28	3
14034800	106.0	17.0	0.15	1.00	23	2
14038530	75.0	32.2	0.28	1.00	220	4
14040500	27.3	78.1	0.34	1.01	503	7
14042000	66.6	10.4	0.09	1.00	43	1
14042500	60.7	16.9	0.14	1.00	96	2
14044000	26.8	65.7	0.24	1.00	256	5
14047390	87.0	29.0	0.20	1.00	63	8
14048000	12.0	279.0	0.82	1.01	2100	11
14050000	328.0	22.4	0.15	2.40	151	6
14050500	120.0	11.3	0.06	1.96	63	6
14052000	188.0	6.4	0.05	3.79	7.5	7
14054500	127.0	9.8	0.06	1.15	38	8

Station	slope	length	shape	storage	meanQ	s_order
14061000	27.3	13.0	0.09	1.15	72	8
14075000	236.0	16.7	0.08	1.23	105	22
14078000	57.9	33.6	0.25	1.42	89	15
14078500	41.7	19.2	0.17	1.00	96	15
14079500	34.2	56.2	0.47	1.34	331	18
14091500	48.6	38.4	0.24	1.75	1500	26
14092885	110.5	24.6	0.09	1.00	98	28
14093000	106.0	29.6	0.10	1.19	111	29
14097100	69.2	33.6	0.30	1.01	114	30
14097200	203.0	15.7	0.08	1.00	165	30
14101500	81.7	44.4	0.26	1.23	427	32
14113200	261.8	13.8	0.10	1.30	28	2
14113400	418.3	5.1	0.03	1.00	7.2	1
14118500	138.0	18.4	0.12	1.62	554	3
14131000	1020.0	6.4	0.02	1.00	25	1
14134000	590.0	5.2	0.03	1.00	44	1
14134500	131.0	15.6	0.08	1.11	205	2
14135000	129.0	24.8	0.10	1.18	438	4
14135500	165.4	30.0	0.10	1.18	452	5
14137000	92.2	37.6	0.24	1.08	1360	7
14138800	370.0	3.6	0.04	1.24	58	6
14138870	472.7	3.7	0.03	1.00	34	6
14139700	375.0	5.0	0.04	1.00	67	5
14139800	214.3	8.3	0.05	1.00	108	6
14141500	196.0	13.6	0.05	1.67	145	6
14144800	107.0	32.7	0.21	1.18	816	2
14144900	259.0	14.5	0.10	1.06	150	1
14145500	75.0	42.1	0.28	1.34	1140	3
14146000	135.0	33.0	0.12	2.15	293	3
14146500	89.7	24.7	0.16	1.51	427	3
14150300	72.0	18.7	0.16	1.00	413	3
14150800	200.0	11.5	0.09	1.00	118	4
14151000	43.7	27.0	0.19	1.00	588	5
14152500	58.0	16.4	0.12	1.00	200	4
14155500	82.3	31.7	0.23	1.04	688	4
14156000	49.4	21.3	0.12	1.02	191	3
14156500	42.8	24.0	0.12	1.02	241	4
14158790	285.7	4.4	0.06	1.00	91	5
14159000	44.6	30.8	0.26	1.45	1660	6
14159200	137.0	26.2	0.16	2.00	637	4
14159500	123.0	32.5	0.18	1.77	927	5
14161100	342.9	9.0	0.10	1.00	259	4
14161500	258.0	9.5	0.07	1.00	125	4

Station	slope	length	shape	storage	meanQ	s_order
14162000	145.0	14.7	0.12	1.00	393	5
14162500	58.3	54.6	0.40	1.27	4000	7
14163000	101.0	12.0	0.10	1.00	212	7
14167000	10.9	23.3	0.14	1.00	176	8
14169300	57.1	2.5	0.03	1.00	5.2	8
14170000	6.0	48.9	0.27	1.65	703	9
14174000	18.8	154.0	0.75	1.03	13500	10
14178000	93.3	35.7	0.20	1.60	1010	4
14179000	180.0	21.8	0.13	1.19	576	4
14181500	66.3	49.1	0.29	1.33	2260	5
14182500	77.4	29.5	0.13	1.36	765	6
14183000	53.3	68.5	0.30	1.24	3250	7
14185000	102.0	23.5	0.19	1.03	821	6
14185800	100.0	22.0	0.12	1.30	630	4
14185900	107.0	21.2	0.13	1.00	674	4
14186000	71.6	32.4	0.20	1.02	1450	5
14187000	129.0	13.6	0.11	1.00	224	4
14187100	154.6	13.3	0.11	1.00	233	5
14187500	35.7	49.4	0.32	1.02	2910	7
14188800	88.0	27.0	0.13	1.03	496	6
14191000	11.2	189.0	1.00	1.02	21300	11
14193000	124.0	15.1	0.10	1.00	260	6
14193300	120.0	9.7	0.08	1.00	140	6
14194300	680.0	3.5	0.05	1.00	47	6
14195000	335.0	5.1	0.04	1.00	25	5
14198500	83.1	17.8	0.14	1.02	540	7
14200000	40.5	44.0	0.24	1.03	1160	11
14200300	141.4	17.8	0.07	1.00	208	7
14201000	72.3	35.4	0.21	1.04	711	9
14201500	103.0	28.6	0.07	1.01	221	8
14204000	127.0	10.5	0.08	1.03	115	6
14204500	71.2	19.3	0.11	1.03	225	8
14208000	136.0	19.3	0.17	1.22	477	8
14209000	87.5	19.2	0.17	1.08	495	7
14251500	55.4	14.2	0.07	1.00	167	1
14301000	6.4	104.0	0.33	1.01	2700	8
14301500	50.4	32.3	0.16	1.00	1190	4
14302500	62.0	29.7	0.15	1.01	966	5
14303600	45.0	39.7	0.15	1.12	1070	7
14306030	42.9	16.5	0.09	1.00	255	2
14306100	44.2	16.6	0.11	1.02	279	3
14306400	25.0	19.5	0.13	1.03	552	3
14306500	21.9	45.0	0.22	1.03	1510	5

Station	slope	length	shape	storage	meanQ	s_order
14306600	12.5	5.5	0.07	1.00	120	4
14306700	580.0	1.1	0.01	1.00	1.6	4
14306800	174.0	1.3	0.02	1.00	4.4	4
14306810	458.0	1.6	0.02	1.00	6.5	4
14306900	262.5	5.5	0.05	1.00	92	1
14307620	100.0	41.5	0.22	1.03	2140	6
14307645	17.6	10.0	0.09	1.00	297	4
14307700	27.5	21.8	0.17	1.00	319	4
14308000	87.1	39.8	0.32	1.09	1040	6
14308500	133.0	10.0	0.11	1.60	83	5
14308600	61.8	39.3	0.35	1.01	1180	7
14308700	480.0	13.5	0.07	1.00	44	6
14309500	52.5	20.3	0.13	1.00	273	6
14310700	128.0	15.0	0.10	1.01	65	5
14311000	42.3	20.5	0.10	1.02	73	6
14311200	146.0	10.2	0.10	1.00	102	4
14312200	115.0	14.2	0.11	1.03	77	8
14315500	69.0	40.0	0.25	3.42	875	3
14316700	60.7	24.2	0.19	1.02	743	5
14317500	69.6	79.0	0.33	1.96	2260	7
14317600	163.0	17.2	0.14	1.02	373	6
14318000	139.0	23.9	0.19	1.10	472	7
14318500	58.2	79.5	0.40	1.44	3110	9
14319200	55.9	7.4	0.06	1.04	25	9
14319900	152.2	13.7	0.13	1.00	205	6
14320700	54.6	28.8	0.17	1.00	495	9
14322000	27.0	19.5	0.14	1.04	218	9
14324500	35.5	28.2	0.08	1.02	249	3
14324600	96.3	12.6	0.07	1.00	144	1
14324700	79.2	16.0	0.08	1.04	199	2
14324900	103.0	25.0	0.10	1.04	514	4
14325000	82.0	36.6	0.18	1.06	794	5
14326800	28.0	31.5	0.10	1.00	281	3
14327000	18.1	44.1	0.21	1.02	945	6
14327500	76.6	28.2	0.20	1.16	498	3
14328000	59.1	44.7	0.22	1.08	830	4
14330500	138.0	17.4	0.10	1.84	127	2
14331000	311.0	9.0	0.07	1.17	43	1
14333500	220.0	15.1	0.09	1.00	118	2
14337600	91.7	40.5	0.41	1.00	2290	8
14337800	373.3	10.0	0.13	1.00	151	7
14337870	375.0	5.0	0.06	1.00	22	6
14339000	34.2	79.5	0.47	1.11	2680	9

Station	slope	length	shape	storage	meanQ	s_order
14339500	108.0	7.5	0.06	1.05	17	4
14341500	182.0	22.3	0.14	1.01	108	7
14353000	617.0	5.8	0.05	1.00	8.9	8
14353500	535.0	6.2	0.04	1.00	9.4	8
14361600	285.7	14.2	0.10	1.00	108	8
14368500	475.0	5.0	0.05	1.00	16	9
14370000	180.0	10.4	0.09	1.00	81	11
14371500	132.0	10.3	0.07	1.00	59	10
14372500	308.0	9.7	0.10	1.04	179	7
14375000	170.0	15.1	0.13	1.05	212	6
14375100	210.0	12.8	0.12	1.00	24	7
14375500	128.0	9.7	0.09	1.02	219	6
14377000	112.0	26.9	0.24	1.04	1210	10
14377100	180.0	24.3	0.24	1.00	1330	11
14377500	333.0	6.8	0.07	1.04	74	10
14378000	38.1	48.3	0.32	1.02	2340	13
14378200	109.5	50.3	0.35	1.01	4090	15

Station	soilperm	warmtemp	coldtemp	precip	prec_frq	isoerod
10370000	52	16.0	-4.4	27.06	15.00	5.0
10371500	57	15.8	-4.6	29.18	14.40	5.0
10384000	45	15.2	-4.9	24.05	15.50	7.7
10393500	63	16.1	-5.0	21.14	13.00	5.0
10396000	75	16.4	-4.5	28.55	13.80	5.0
10397000	74	17.3	-2.9	25.78	13.10	5.0
10403000	66	17.2	-4.0	21.19	14.10	5.0
10406500	68	17.9	-3.6	15.43	12.50	5.0
11340500	45	15.0	-4.7	28.23	15.40	5.0
11497500	50	15.9	-3.5	22.67	15.40	11.8
13216500	65	16.7	-5.6	24.67	15.40	5.0
13226500	71	20.7	-3.2	12.82	13.30	5.0
13270800	51	14.9	-6.7	30.45	17.60	5.0
13288200	63	15.7	-5.7	57.95	20.90	13.8
13292000	61	15.1	-5.6	32.33	15.90	15.0
13320000	55	17.3	-3.6	47.27	17.30	14.5
13323500	58	17.5	-2.9	28.47	16.10	20.1
13323600	52	17.5	-1.4	40.44	18.00	15.0
13329500	68	14.1	-6.7	58.53	21.50	15.0
13330500	55	14.2	-5.9	47.89	17.60	15.0
13331500	57	14.9	-5.6	55.43	18.30	15.0
14010000	54	17.3	-3.2	55.19	22.50	32.7
14010800	56	18.8	-3.0	51.96	21.70	30.1
14011000	60	19.1	-2.5	48.38	21.20	28.9
14020000	54	18.0	-2.2	41.83	19.70	32.8
14020300	55	17.2	-2.7	35.66	19.30	30.0
14021000	51	19.8	-1.0	28.87	15.60	21.8
14022200	55	18.9	-1.1	28.30	15.70	24.6
14022500	60	18.4	-1.4	27.39	15.40	25.8
14025000	66	19.4	-0.8	22.34	12.40	15.7
14032000	70	19.7	-0.6	22.06	12.00	6.2
14034800	68	18.5	-1.3	23.49	13.40	5.0
14038530	62	17.5	-3.4	24.54	15.20	5.0
14040500	64	17.5	-3.3	19.97	14.20	5.0
14042000	53	16.8	-4.9	28.50	15.00	30.0
14042500	54	16.7	-4.9	29.06	15.60	29.2
14044000	61	16.6	-4.0	22.51	15.50	9.4
14047390	70	18.3	-1.2	19.65	13.50	5.0
14048000	65	18.3	-2.4	18.94	13.80	7.4
14050000	48	14.1	-5.0	88.22	35.30	25.1
14050500	43	15.0	-5.0	68.06	30.00	29.9
14052000	38	15.0	-5.0	66.24	27.70	30.0
14054500	38	15.0	-5.0	56.31	25.30	22.1

Station	soilperm	warmtemp	coldtemp	precip	prec_frq	isoerod
14061000	36	14.9	-4.6	51.05	27.90	15.0
14075000	50	14.4	-4.8	97.49	36.00	22.3
14078000	67	17.9	-3.6	19.41	13.60	5.0
14078500	65	16.2	-4.4	24.90	15.20	5.0
14079500	68	18.0	-3.4	16.54	13.70	5.0
14091500	34	15.7	-3.3	45.81	33.30	30.1
14092885	43	16.5	-2.7	45.46	27.30	20.0
14093000	48	17.1	-2.2	36.07	23.60	16.2
14097100	40	16.4	-2.5	34.10	25.10	19.6
14097200	38	14.6	-3.1	48.49	44.30	38.6
14101500	46	16.4	-2.4	24.08	27.50	20.0
14113200	34	17.5	-0.9	36.30	19.60	15.0
14113400	33	16.2	-3.0	73.25	40.40	30.0
14118500	39	16.5	-0.8	107.27	44.10	62.1
14131000	56	14.0	-2.5	100.54	45.50	62.6
14134000	49	13.9	-3.1	78.23	46.70	50.0
14134500	50	15.5	-0.4	64.30	41.10	50.0
14135000	48	16.2	0.4	68.86	40.00	63.1
14135500	48	16.4	0.5	69.77	39.70	64.9
14137000	48	16.6	0.7	82.94	39.90	71.8
14138800	54	17.0	1.0	94.60	48.40	85.3
14138870	50	18.8	2.9	107.36	44.70	90.0
14139700	52	18.5	2.2	103.96	46.00	90.0
14139800	49	18.7	2.6	100.50	42.50	90.0
14141500	44	18.8	2.7	90.37	39.80	88.0
14144800	48	16.0	-0.9	59.65	35.00	30.0
14144900	48	16.8	-0.5	55.23	33.30	30.0
14145500	47	16.4	-0.4	58.53	34.40	30.0
14146000	47	15.9	-1.0	59.89	35.20	29.4
14146500	48	16.2	0.0	62.10	35.60	30.0
14150300	47	17.6	2.7	65.06	41.40	51.1
14150800	49	18.9	2.9	59.76	39.60	40.5
14151000	48	18.3	2.9	61.58	40.50	48.5
14152500	48	17.2	3.0	61.78	37.50	50.5
14155500	48	17.3	2.8	63.85	35.00	41.9
14156000	50	17.4	2.5	60.40	34.20	50.0
14156500	51	17.6	2.6	59.10	34.10	50.0
14158790	53	17.7	-0.9	85.28	48.60	61.3
14159000	48	17.0	-1.4	87.07	42.50	45.2
14159200	50	16.4	-1.2	75.87	39.40	42.7
14159500	49	16.6	-0.8	75.05	39.50	49.5
14161100	49	17.0	1.0	82.44	51.20	85.8
14161500	48	17.4	0.5	78.31	47.30	76.6

Station	soilperm	warmtemp	coldtemp	precip	prec_frq	isoerod
14162000	48	17.1	0.8	79.62	49.50	83.2
14162500	49	16.9	-0.8	80.32	42.00	53.8
14163000	48	17.9	1.7	65.09	44.90	76.4
14167000	68	19.0	5.0	45.68	32.60	100.0
14169300	70	19.0	5.0	42.50	32.50	96.3
14170000	67	18.7	3.8	49.37	33.40	94.3
14174000	54	17.8	2.0	60.38	36.00	53.9
14178000	43	17.1	-0.9	92.31	39.70	48.1
14179000	49	16.5	-0.6	99.41	38.20	50.5
14181500	45	17.0	-0.2	93.18	40.20	55.3
14182500	50	17.1	1.5	93.44	43.80	85.4
14183000	47	17.2	0.5	91.75	40.30	64.6
14185000	50	17.4	2.4	87.45	45.30	86.5
14185800	50	17.0	2.2	90.47	49.20	76.4
14185900	48	17.0	2.3	93.47	48.40	85.6
14186000	47	17.3	2.4	88.68	47.60	80.3
14187000	48	18.0	2.8	83.59	34.00	71.9
14187100	49	18.2	2.9	80.35	33.60	68.1
14187500	49	17.8	2.6	81.92	42.50	75.5
14188800	54	18.2	2.8	84.47	35.70	70.7
14191000	54	17.9	2.1	65.40	36.70	58.5
14193000	45	17.0	3.0	98.21	53.60	83.0
14193300	46	17.0	3.0	105.99	52.10	74.5
14194300	46	17.0	3.0	110.95	55.30	103.8
14195000	45	17.0	3.0	101.93	53.00	92.0
14198500	46	17.2	2.4	96.80	39.90	89.9
14200000	49	18.1	2.8	75.84	32.60	71.7
14200300	50	17.2	3.0	71.10	36.80	74.2
14201000	56	18.0	2.9	63.08	31.30	66.9
14201500	47	17.8	2.8	72.49	35.00	75.6
14204000	43	17.0	3.0	81.09	42.40	69.9
14204500	42	17.0	3.0	73.08	37.90	63.1
14208000	42	16.1	-0.7	80.70	38.10	42.9
14209000	45	15.7	-0.4	58.69	37.60	56.0
14251500	40	17.0	4.3	125.84	49.10	100.0
14301000	44	17.0	3.2	90.28	39.10	78.8
14301500	45	17.8	3.5	145.43	56.60	130.8
14302500	45	17.0	3.4	131.56	55.90	158.2
14303600	45	16.9	3.9	119.34	54.50	160.4
14306030	53	17.0	4.8	78.86	41.50	140.8
14306100	46	17.1	3.4	91.92	52.20	79.7
14306400	54	17.9	4.9	93.76	51.60	100.9
14306500	50	17.6	4.3	90.65	50.60	92.4

Station	soilperm	warmtemp	coldtemp	precip	prec_frq	isoerod
14306600	53	17.0	5.0	90.13	52.10	139.1
14306700	54	17.0	5.0	87.50	52.50	140.0
14306800	54	17.0	5.0	83.18	45.20	140.0
14306810	54	17.0	5.0	82.50	44.00	140.0
14306900	46	16.8	5.4	97.70	56.80	105.9
14307620	53	17.8	4.6	74.90	44.50	97.6
14307645	48	17.0	5.0	90.27	51.20	100.0
14307700	44	16.4	1.2	49.47	30.60	30.0
14308000	43	16.8	1.6	52.96	31.40	30.0
14308500	38	17.0	1.5	42.34	33.50	30.0
14308600	43	17.1	1.9	49.57	30.80	30.0
14308700	55	18.5	3.5	43.52	26.00	30.0
14309500	47	15.4	1.9	73.02	44.70	50.0
14310700	55	17.9	3.4	45.95	27.90	31.5
14311000	61	18.9	3.6	39.63	29.00	47.2
14311200	50	17.3	4.0	44.34	31.50	50.2
14312200	58	18.7	4.4	37.15	27.10	50.0
14315500	47	15.6	-1.7	58.11	34.20	28.0
14316700	44	17.5	1.1	54.77	35.10	30.0
14317500	46	17.1	0.2	55.64	34.70	32.0
14317600	43	17.4	2.2	63.00	41.20	50.0
14318000	44	17.2	2.4	63.76	34.60	41.6
14318500	46	17.2	0.9	56.98	35.00	35.6
14319200	54	19.0	4.6	39.29	28.00	63.3
14319900	54	17.3	3.1	60.77	37.30	50.0
14320700	58	18.1	4.0	50.31	33.10	59.4
14322000	56	18.4	4.0	47.32	32.60	69.0
14324500	54	17.0	5.5	97.40	51.60	180.0
14324600	54	15.3	2.9	111.96	51.30	53.6
14324700	54	15.5	3.1	111.17	51.50	57.5
14324900	51	16.3	4.0	103.90	52.80	71.6
14325000	52	16.5	4.7	95.41	49.40	70.3
14326800	50	17.0	5.6	67.85	46.00	142.5
14327000	51	17.0	5.5	73.19	45.70	110.7
14327500	43	15.4	-2.3	54.26	34.50	20.9
14328000	44	15.7	-1.7	53.41	34.30	20.8
14330500	52	15.5	-1.6	56.65	36.00	29.5
14331000	53	16.4	-0.6	54.58	37.10	19.7
14333500	49	15.5	-0.9	57.20	36.60	15.0
14337600	50	16.6	-0.1	48.50	33.20	24.2
14337800	54	17.2	1.3	46.01	34.40	30.0
14337870	49	17.0	1.0	38.14	33.90	30.0
14339000	53	17.0	0.3	46.06	32.60	25.6

Station	soilperm	warmtemp	coldtemp	precip	prec_frq	isoerod
14339500	54	15.2	-2.1	49.66	27.50	30.0
14341500	63	17.5	0.4	40.38	25.80	30.0
14353000	56	17.1	0.6	52.18	29.60	30.0
14353500	57	17.2	0.0	47.60	27.90	26.6
14361600	13	4.7	-0.3	17.26	8.50	8.3
14368500	67	19.2	1.9	43.95	34.60	43.6
14370000	67	18.7	1.5	46.75	37.40	64.9
14371500	49	17.0	1.2	55.34	34.50	30.0
14372500	4	1.3	0.1	8.55	3.80	12.2
14375000	62	17.4	-0.7	65.65	41.40	65.6
14375100	62	17.5	-0.5	64.52	41.00	66.0
14375500	32	11.3	0.7	64.40	37.10	114.1
14377000	51	15.6	0.5	64.20	39.20	97.2
14377100	51	15.9	0.5	63.52	39.40	96.2
14377500	64	19.0	1.0	51.43	34.40	51.6
14378000	57	16.9	0.9	71.82	42.20	88.3
14378200	59	17.2	1.7	87.34	47.30	87.9

Station	Latitude_DD	Longitude_DD
10370000	42.2164	-120.101
10371500	42.1892	-120.001
10384000	42.6847	-120.569
10393500	43.7153	-119.176
10396000	42.7911	-118.867
10397000	42.8439	-118.849
10403000	43.6917	-119.658
10406500	42.1556	-118.454
11340500	42.2372	-120.504
11497500	42.4472	-121.238
13216500	43.9483	-118.173
13226500	44.0194	-117.460
13270800	44.4069	-118.300
13288200	44.8806	-117.253
13292000	45.5625	-116.833
13320000	45.1556	-117.774
13323500	45.5125	-117.926
13323600	45.4333	-117.822
13329500	45.3375	-117.292
13330500	45.5269	-117.551
13331500	45.62	-117.726
14010000	45.83	-118.169
14010800	45.885	-118.185
14011000	45.9022	-118.282
14020000	45.7197	-118.322
14020300	45.6889	-118.356
14021000	45.6722	-118.792
14022200	45.5067	-118.616
14022500	45.5492	-118.773
14025000	45.6528	-118.879
14032000	45.5467	-119.304
14034800	45.2628	-119.614
14038530	44.4186	-118.905
14040500	44.5208	-119.625
14042000	45.1711	-118.731
14042500	45.1569	-118.819
14044000	44.8889	-119.140
14047390	45.2647	-120.021
14048000	45.5878	-120.408
14050000	43.8142	-121.776
14050500	43.8183	-121.794
14052000	43.8133	-121.838
14054500	43.7158	-121.803

Station	Latitude_DD	Longitude_DD
14061000	43.4778	-121.914
14075000	44.2339	-121.566
14078000	44.1639	-119.922
14078500	44.3319	-120.082
14079500	44.1167	-120.250
14091500	44.6258	-121.482
14092885	44.7722	-121.304
14093000	44.7614	-121.233
14097100	44.8567	-121.149
14097200	45.1778	-121.575
14101500	45.2417	-121.094
14113200	45.6486	-121.376
14113400	45.4083	-121.519
14118500	45.5986	-121.635
14131000	45.3139	-121.808
14134000	45.2653	-121.717
14134500	45.2222	-121.861
14135000	45.3194	-121.953
14135500	45.3611	-122.011
14137000	45.3917	-122.128
14138800	45.4528	-121.890
14138870	45.4822	-122.027
14139700	45.4583	-122.031
14139800	45.4439	-122.106
14141500	45.4153	-122.172
14144800	43.5972	-122.456
14144900	43.6806	-122.369
14145500	43.7222	-122.438
14146000	43.7292	-122.426
14146500	43.7625	-122.372
14150300	43.9708	-122.638
14150800	43.9139	-122.688
14151000	43.9444	-122.774
14152500	43.6417	-123.085
14155500	43.7931	-122.990
14156000	43.7444	-122.983
14156500	43.7764	-122.999
14158790	44.3347	-122.046
14159000	44.1792	-122.129
14159200	44.0472	-122.217
14159500	44.1361	-122.247
14161100	44.2181	-122.264
14161500	44.2097	-122.256

Station	Latitude_DD	Longitude_DD
14162000	44.1819	-122.279
14162500	44.125	-122.469
14163000	44.1458	-122.571
14167000	44.0219	-123.255
14169300	44.0125	-123.076
14170000	44.3139	-123.296
14174000	44.6389	-123.106
14178000	44.7069	-122.100
14179000	44.7528	-122.128
14181500	44.7528	-122.297
14182500	44.7917	-122.578
14183000	44.7889	-122.617
14185000	44.3931	-122.510
14185800	44.5153	-122.371
14185900	44.5403	-122.435
14186000	44.4597	-122.524
14187000	44.3722	-122.622
14187100	44.3986	-122.660
14187500	44.4986	-122.822
14188800	44.7117	-122.765
14191000	44.9444	-123.042
14193000	45.1431	-123.493
14193300	44.9708	-123.449
14194300	45.3653	-123.378
14195000	45.3139	-123.365
14198500	45.0097	-122.479
14200000	45.2444	-122.686
14200300	45.0094	-122.788
14201000	45.0631	-122.829
14201500	45.1017	-122.745
14204000	45.6417	-123.265
14204500	45.5556	-123.186
14208000	45.0167	-121.919
14209000	45.0722	-121.950
14251500	46.0672	-123.789
14301000	45.7042	-123.754
14301500	45.4847	-123.689
14302500	45.4403	-123.717
14303600	45.2667	-123.846
14306030	44.6581	-123.838
14306100	44.3792	-123.594
14306400	44.3375	-123.826
14306500	44.3861	-123.831

Station	Latitude_DD	Longitude_DD
14306600	44.5139	-123.847
14306700	44.5153	-123.856
14306800	44.5389	-123.851
14306810	44.5347	-123.876
14306900	44.1681	-124.065
14307620	44.0625	-123.882
14307645	44.0472	-124.003
14307700	42.9542	-122.828
14308000	42.9306	-122.947
14308500	42.8903	-122.917
14308600	42.9681	-123.167
14308700	42.9819	-123.149
14309500	42.8042	-123.610
14310700	43.0319	-123.192
14311000	43.0417	-123.258
14311200	43.0389	-123.543
14312200	43.2194	-123.276
14315500	43.2639	-122.422
14316700	43.35	-122.728
14317500	43.3278	-123.000
14317600	43.3458	-122.992
14318000	43.2528	-123.025
14318500	43.3056	-123.117
14319200	43.3889	-123.303
14319900	43.4178	-123.154
14320700	43.4028	-123.363
14322000	43.6417	-123.297
14324500	43.4764	-124.056
14324600	42.7583	-123.986
14324700	42.725	-124.011
14324900	42.7847	-124.040
14325000	42.8917	-124.069
14326800	43.1842	-124.076
14327000	43.0708	-124.106
14327500	42.9347	-122.421
14328000	42.775	-122.499
14330500	42.7069	-122.389
14331000	42.6889	-122.383
14333500	42.7778	-122.426
14337600	42.6556	-122.714
14337800	42.7736	-122.671
14337870	42.7111	-122.749
14339000	42.525	-122.842

Station	Latitude_DD	Longitude_DD
14339500	42.3444	-122.358
14341500	42.4083	-122.600
14353000	42.1486	-122.715
14353500	42.1528	-122.708
14361600	42.0044	-123.150
14368500	42.2667	-123.294
14370000	42.3611	-123.519
14371500	42.6417	-123.211
14372500	42.0028	-123.625
14375000	42.15	-123.464
14375100	42.1597	-123.478
14375500	42.0389	-123.747
14377000	42.1972	-123.658
14377100	42.2319	-123.663
14377500	42.2639	-123.450
14378000	42.3792	-123.811
14378200	42.5208	-124.043

Watershed Characteristics

The watershed characteristics computed for each gaging station and used as independent variables in this analysis are described below:

1. Drainage area (area_mi), in square miles, the total contributing area upstream from the gaging station (from Moffatt et.al. 1990).
2. Catchment shape (shape), calculation of basin area / basin length.
3. Main channel length (length), in miles, from the gaging station to the basin divide, as measured in accordance with guidelines given by the Water Resource Council (1968) or taken in part from the various River Mile Index publications prepared by the Hydrology and Hydraulics of the Pacific Northwest River Basins Commission (1963-1968) and . (data from Lystrom, 1970; Harris et.al., 1979; Harris et.al., 1983; and resulting GIS analyses).
4. Main channel slope (slope), in feet per mile, determined from elevations at points 10 and 85% of the distance along the channel from the gaging station to the divide (data from Lystrom, 1970; Harris et.al., 1979; Harris et.al., 1983; and resulting GIS analyses). This index was described and used by Benson (1962, 1964).
5. Annual mean discharge (meanQ), CFS, for period of record (data from Moffatt et.al. 1990).
6. Gage elevation (elev_ft), in feet above sea level (from Moffatt et.al. 1990). A few stations with records prior to dam construction have gage elevation recordings for the present-day gage, which may be up- or down-stream from location during period of record. Correct datum for period of record is used when available.
7. Area of lakes and ponds (storage), expressed as a percentage of the drainage area, determined from the most recent quadrangle maps available.
8. Start and end dates (start_d/end_d), period of data record of the gaging stations (data from Moffatt et.al. 1990)
9. Status of diversions (Diversions), expresses as: 0 = no dams or diversions upstream from gaging station; 1 = diversion(s) present upstream from station (from Moffatt et.al. 1990).

Regional Characteristics

The regional characteristics used in this analysis are described below:

1. Soil permeability (soilperm), calculated from the State Soil Geographic (STATSGO) Data Base, hydrology codes for the state of Oregon. Hydrology groups were recoded and the data presented herein is based on an area weighted average for the stream gage's associated watershed. The scale of the data is relative, ranking 1-25 for high infiltration rates, deep soils, well drained to excessively drained sands and gravels; 25-50 for moderate infiltration rates, deep and moderately deep, moderately well and well drained soils with moderately coarse textures; 50-75 for slow infiltration rates, soils with layers impeding downward movement of water, or soils with moderately fine or fine textures; and, 75-100 for very slow infiltration rates, clayey soils, soils with a high water table, or shallow soils to an impervious layer (data from USDA, 1994).

2. Mean temperatures of the warmest month (warmtemp), data represent the average temperatures of the warmest month from 1931-1960, given the area weighted average for each gage's associate watershed (data from Loy et al., 1976).

3. Mean temperatures of the coldest month (coldtemp), data represent the average temperatures of the coldest month from 1931-1960, given the area weighted average for each gage's associate watershed (data from Loy et al., 1976).

4. Mean annual precipitation (precip), data represent mean annual precipitation, 1961-1990, given the area weighted average for each gage's associate watershed (data from Daly et al., 1994).

5. Precipitation frequency (prec_frq), data represent the area weighted average of each gage's watershed of 2-year 24-hour precipitation in tenths of an inch (data from NOAA).

6. Isoerodant index (isoerod), based on mapped values for the Revised Universal Soil Loss Equation (RUSLE). The index represents a 22 year average for an area's storm energy and 30 minute intensity for qualifying storms. The data presented herein are based on area weighted averages for each gage's associate watershed (data from Soil and Water Conservation Society, 1993).

7. Latitude and longitude (Latitude_DD/Longitude_DD), in decimal degrees, geographic location of the gaging stations (data from Moffatt et al. 1990).

APPENDIX C.

DATA - CHAPTER 4, PAPER III

Station	River	Annual *Vi*	Oct.	Nov.	Dec.	Jan.
14022200	'NF McKay Cr.'	0.804	0.241	0.482	0.470	0.499
14047390	'Rock Cr.'	0.794	0.503	0.477	0.442	0.494
14324600	'SF Coquille R.'	0.779	0.570	0.547	0.466	0.439
14324700	'SF Coquille R.'	0.775	0.544	0.597	0.481	0.439
14169300	'Amazon Cr.'	0.758	0.510	0.688	0.591	0.529
14309500	'WF Cows Cr.'	0.685	0.386	0.589	0.519	0.465
14324900	'SF Coquille R.'	0.668	0.483	0.519	0.464	0.433
14400000	'Chetco R.'	0.665	0.536	0.579	0.472	0.412
14193300	'Mill Cr.'	0.659	0.500	0.453	0.386	0.403
14156000	'Mosby Cr.'	0.652	0.363	0.677	0.561	0.376
14306030	'Yaquina R.'	0.644	0.367	0.562	0.460	0.397
14251500	'Youngs R.'	0.63	0.575	0.433	0.332	0.347
14306800	'Flynn Cr.'	0.627	0.458	0.485	0.349	0.340
14155500	'Row R.'	0.599	0.423	0.570	0.457	0.328
14187100	'Wiley Cr.'	0.59	0.448	0.445	0.384	0.347
14158790	'Smith R.'	0.584	0.453	0.456	0.358	0.358
14306810	'Deer Cr.'	0.583	0.444	0.436	0.335	0.341
14337870	'W Branch Elk Cr.'	0.583	0.317	0.517	0.463	0.428
14307620	'Siuslaw R.'	0.581	0.375	0.457	0.367	0.325
14150800	'Winberry Cr.'	0.577	0.397	0.477	0.413	0.379
14193000	'Willamine Cr.'	0.574	0.369	0.494	0.347	0.311
14204000	'Gales Cr.'	0.574	0.283	0.480	0.394	0.322
14306400	'Five R.'	0.573	0.394	0.488	0.385	0.347
14307700	'Jackson Cr.'	0.571	0.290	0.520	0.476	0.386
14306700	'Needle Branch'	0.568	0.365	0.429	0.371	0.380
14316700	'Steamboat Cr.'	0.568	0.369	0.515	0.448	0.394
14182500	'Little N Santiam R.'	0.556	0.539	0.437	0.346	0.341
14187000	'Wiley Cr.'	0.554	0.459	0.448	0.327	0.348
14151000	'Fall Cr.'	0.553	0.421	0.550	0.419	0.349
14317600	'Rock Cr.'	0.55	0.355	0.466	0.385	0.355
14185900	'Quartzville Cr.'	0.549	0.487	0.443	0.385	0.368
14161100	'Blue R.'	0.548	0.429	0.455	0.388	0.358
14306600	'Drift Cr.'	0.547	0.446	0.404	0.306	0.338
14162000	'Blue R.'	0.546	0.454	0.531	0.377	0.353
14187500	'S Santiam	0.542	0.484	0.540	0.335	0.304
14186000	'M Santiam R.'	0.54	0.421	0.510	0.375	0.297
14194300	'N Yamhill R.'	0.53	0.360	0.416	0.307	0.317
14138800	'Blazed Alder Cr.'	0.529	0.503	0.371	0.379	0.404
14185000	'S Santiam R.'	0.52	0.436	0.465	0.366	0.344
14150300	'Fall Cr.'	0.518	0.374	0.453	0.384	0.364
14198500	'Molalla R.'	0.513	0.446	0.447	0.350	0.351
14306900	'Big Cr.'	0.513	0.416	0.430	0.384	0.336
14161500	'Lookout Cr.'	0.486	0.353	0.450	0.351	0.323

Station	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
14022200	0.431	0.239	0.319	0.393	0.417	0.253	0.124	0.131
14047390	0.500	0.429	0.363	0.369	0.416	0.478	0.428	0.473
14324600	0.326	0.306	0.307	0.315	0.188	0.188	0.180	0.226
14324700	0.317	0.310	0.303	0.302	0.186	0.177	0.166	0.255
14169300	0.378	0.416	0.441	0.382	0.269	0.224	0.246	0.403
14309500	0.364	0.327	0.296	0.249	0.138	0.130	0.120	0.190
14324900	0.331	0.314	0.285	0.290	0.160	0.124	0.113	0.190
14400000	0.398	0.435	0.292	0.260	0.178	0.137	0.113	0.339
14193300	0.304	0.308	0.263	0.233	0.148	0.140	0.109	0.325
14156000	0.323	0.355	0.343	0.320	0.343	0.231	0.189	0.211
14306030	0.362	0.282	0.246	0.213	0.264	0.220	0.188	0.254
14251500	0.324	0.287	0.262	0.230	0.213	0.237	0.185	0.267
14306800	0.288	0.284	0.249	0.227	0.190	0.173	0.156	0.266
14155500	0.344	0.293	0.278	0.326	0.313	0.220	0.176	0.210
14187100	0.382	0.246	0.224	0.274	0.289	0.218	0.233	0.290
14158790	0.331	0.263	0.222	0.257	0.359	0.291	0.165	0.237
14306810	0.291	0.298	0.252	0.221	0.184	0.169	0.158	0.280
14337870	0.391	0.331	0.364	0.289	0.213	0.182	0.225	0.243
14307620	0.425	0.255	0.223	0.176	0.163	0.148	0.147	0.232
14150800	0.300	0.264	0.227	0.252	0.311	0.212	0.262	0.346
14193000	0.270	0.244	0.210	0.181	0.151	0.135	0.119	0.177
14204000	0.257	0.263	0.202	0.154	0.150	0.152	0.491	0.213
14306400	0.320	0.380	0.230	0.178	0.154	0.128	0.106	0.190
14307700	0.282	0.245	0.202	0.209	0.267	0.176	0.116	0.135
14306700	0.329	0.302	0.271	0.250	0.227	0.325	0.458	0.448
14316700	0.314	0.276	0.236	0.229	0.232	0.147	0.109	0.173
14182500	0.312	0.252	0.203	0.220	0.294	0.252	0.180	0.354
14187000	0.276	0.240	0.208	0.247	0.232	0.198	0.162	0.243
14151000	0.292	0.275	0.257	0.271	0.252	0.181	0.122	0.170
14317600	0.247	0.262	0.227	0.231	0.179	0.132	0.102	0.152
14185900	0.339	0.256	0.217	0.247	0.292	0.211	0.190	0.328
14161100	0.322	0.243	0.221	0.260	0.278	0.181	0.135	0.259
14306600	0.273	0.263	0.229	0.242	0.163	0.139	0.127	0.263
14162000	0.311	0.246	0.208	0.244	0.250	0.175	0.126	0.174
14187500	0.291	0.238	0.217	0.234	0.274	0.206	0.136	0.224
14186000	0.264	0.265	0.233	0.256	0.278	0.203	0.126	0.221
14194300	0.250	0.226	0.197	0.168	0.162	0.132	0.110	0.183
14138800	0.352	0.261	0.230	0.234	0.332	0.272	0.233	0.446
14185000	0.299	0.232	0.194	0.219	0.262	0.213	0.137	0.225
14150300	0.301	0.251	0.233	0.227	0.244	0.164	0.155	0.246
14198500	0.311	0.248	0.201	0.219	0.244	0.198	0.148	0.275
14306900	0.330	0.256	0.211	0.192	0.204	0.194	0.154	0.222
14161500	0.291	0.228	0.206	0.224	0.261	0.165	0.118	0.176

Station	River	Annual *Vi*	Oct.	Nov.	Dec.	Jan.
14151500	'Little Fall Cr.'	0.482	0.348	0.512	0.388	0.312
14163000	'Gate Cr.'	0.48	0.352	0.431	0.353	0.303
14185800	'M Santiam R.'	0.478	0.377	0.409	0.366	0.335
14138870	'Fir Cr.'	0.433	0.408	0.338	0.342	0.334
14361600	'Elliott Cr.'	0.428	0.163	0.380	0.422	0.318
14141500	'Little Sandy R.'	0.423	0.383	0.386	0.307	0.308
14020000	'Umatilla R.'	0.407	0.103	0.266	0.329	0.317
14144900	'Hills Cr.'	0.398	0.212	0.390	0.372	0.349
13329500	'Hurricane Cr.'	0.386	0.132	0.149	0.150	0.139
14139800	'SF Bull Run R.'	0.385	0.354	0.307	0.315	0.336
14061000	'Big Marsh Cr.'	0.368	0.187	0.258	0.328	0.298
14139700	'Cedar Cr.'	0.366	0.337	0.329	0.331	0.359
10396000	'Donner und Blitzen R.'	0.36	0.101	0.116	0.160	0.210
14135000	'Salmon R.'	0.36	0.300	0.364	0.311	0.261
14135500	'Salmon R.'	0.36	0.301	0.393	0.277	0.259
14183000	'N Santiam R.'	0.357	0.761	0.396	0.265	0.263
14353500	'EF Ashland Cr.'	0.352	0.140	0.251	0.316	0.275
14318500	'N Umpqua R.'	0.348	0.116	0.343	0.303	0.281
14353000	'WF Ashland Cr.'	0.335	0.125	0.242	0.286	0.276
14145500	'MF Willamette R.'	0.327	0.154	0.330	0.343	0.301
14179000	'Breitenbush R.'	0.324	0.237	0.344	0.297	0.290
14113400	'Dog R.'	0.319	0.063	0.165	0.237	0.270
14159500	'SF McKenzie R.'	0.313	0.186	0.307	0.283	0.267
14137000	'Sandy R.'	0.308	0.243	0.333	0.282	0.267
14134500	'Salmon R.'	0.304	0.183	0.299	0.269	0.230
14181500	'N. Santiam R.'	0.301	0.716	0.318	0.256	0.240
14317500	'N Umpqua R.'	0.295	0.088	0.308	0.288	0.252
14097200	'White R.'	0.283	0.139	0.230	0.318	0.300
14146500	'Salmon Cr.'	0.282	0.138	0.289	0.293	0.247
14144800	'MF Willamette R.'	0.276	0.126	0.285	0.284	0.254
14159200	'SF McKenzie R.'	0.269	0.122	0.252	0.263	0.234
14330500	'SF Rogue R.'	0.264	0.088	0.166	0.217	0.217
14178000	'N. Santiam R.'	0.249	0.125	0.240	0.240	0.210
14162500	'McKenzie R.'	0.231	0.130	0.256	0.237	0.209
14328000	'Rogue R.'	0.219	0.102	0.192	0.217	0.190
14134000	'Salmon R.'	0.214	0.137	0.209	0.207	0.184
14208000	'Clackamas R.'	0.197	0.096	0.200	0.196	0.199
14327500	'Rogue R.'	0.189	0.088	0.150	0.166	0.133
14010000	'SF Walla Walla R.'	0.179	0.062	0.103	0.140	0.142
14159000	'McKenzie R.'	0.132	0.076	0.144	0.149	0.134
14315500	'N Umpqua R.'	0.127	0.049	0.089	0.110	0.100
14054500	'Brown Cr.'	0.123	0.124	0.122	0.117	0.108
14050500	'Cultus R.'	0.121	0.118	0.114	0.106	0.096

Station	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
14151500	0.261	0.268	0.263	0.220	0.203	0.162	0.134	0.164
14163000	0.280	0.229	0.201	0.211	0.191	0.142	0.121	0.185
14185800	0.272	0.222	0.198	0.219	0.259	0.177	0.143	0.245
14138870	0.344	0.214	0.201	0.192	0.292	0.211	0.227	0.381
14361600	0.325	0.228	0.160	0.187	0.293	0.232	0.173	0.172
14141500	0.274	0.215	0.176	0.217	0.258	0.189	0.143	0.294
14020000	0.286	0.235	0.195	0.232	0.260	0.119	0.054	0.055
14144900	0.239	0.231	0.182	0.177	0.245	0.170	0.113	0.135
13329500	0.133	0.132	0.260	0.252	0.170	0.233	0.163	0.110
14139800	0.307	0.207	0.199	0.209	0.263	0.168	0.194	0.320
14061000	0.287	0.225	0.252	0.216	0.269	0.240	0.197	0.171
14139700	0.313	0.229	0.190	0.211	0.236	0.144	0.153	0.269
10396000	0.254	0.301	0.226	0.209	0.238	0.230	0.132	0.106
14135000	0.259	0.197	0.183	0.230	0.226	0.136	0.092	0.157
14135500	0.259	0.197	0.166	0.201	0.193	0.148	0.091	0.096
14183000	0.264	0.192	0.172	0.193	0.219	0.153	0.093	0.137
14353500	0.325	0.258	0.235	0.261	0.332	0.301	0.203	0.151
14318500	0.252	0.216	0.210	0.212	0.225	0.146	0.081	0.070
14353000	0.318	0.256	0.237	0.274	0.431	0.266	0.192	0.152
14145500	0.249	0.196	0.165	0.157	0.191	0.140	0.075	0.069
14179000	0.259	0.192	0.182	0.174	0.187	0.166	0.103	0.098
14113400	0.287	0.221	0.202	0.237	0.187	0.186	0.103	0.085
14159500	0.253	0.179	0.152	0.132	0.199	0.105	0.045	0.050
14137000	0.240	0.176	0.154	0.168	0.182	0.121	0.085	0.115
14134500	0.194	0.177	0.190	0.226	0.212	0.143	0.094	0.071
14181500	0.227	0.185	0.163	0.182	0.205	0.174	0.102	0.110
14317500	0.240	0.200	0.205	0.191	0.189	0.099	0.060	0.053
14097200	0.241	0.219	0.127	0.238	0.251	0.157	0.121	0.113
14146500	0.207	0.169	0.160	0.163	0.187	0.131	0.083	0.074
14144800	0.213	0.181	0.147	0.148	0.189	0.126	0.074	0.074
14159200	0.208	0.162	0.148	0.153	0.204	0.096	0.055	0.055
14330500	0.191	0.165	0.188	0.195	0.229	0.134	0.109	0.094
14178000	0.185	0.148	0.140	0.151	0.175	0.113	0.072	0.066
14162500	0.200	0.148	0.138	0.144	0.156	0.096	0.070	0.061
14328000	0.183	0.149	0.146	0.171	0.194	0.121	0.093	0.089
14134000	0.175	0.143	0.141	0.145	0.185	0.160	0.113	0.087
14208000	0.178	0.126	0.135	0.156	0.176	0.080	0.053	0.049
14327500	0.152	0.137	0.141	0.177	0.340	0.109	0.077	0.072
14010000	0.145	0.132	0.122	0.134	0.152	0.069	0.052	0.051
14159000	0.130	0.092	0.094	0.105	0.117	0.083	0.066	0.060
14315500	0.107	0.092	0.108	0.124	0.133	0.077	0.056	0.049
14054500	0.104	0.102	0.112	0.121	0.123	0.118	0.128	0.128
14050500	0.085	0.079	0.085	0.135	0.123	0.107	0.119	0.112

APPENDIX D.

PREDOMINANT CHARACTERISTICS OF ECOREGIONS IN OREGON (MODIFIED FROM OMERNIK, 1986)

Ecoregion	Land Surface Form	Potential Natural Vegetation	Land Use	Soils
Coast Range	Low to high mountains	Spruce/ cedar/ hemlock/ Douglas-fir, redwood	Forest and woodland mostly ungrazed	Udic soils of high rainfall areas
Willamette Valley	Plains with hills, or open hills	Cedar/ hemlock/ Douglas-fir, mosiac of Oregon oakwoods and cedar/ hemlock/ Douglas-fir	Emphasis on cropland - with some pasture, woodland, forest	Xeric Mollisols, Vertisols and Alfisols of interior valleys
Cascades	High mountains	Silver fir/ Douglas-fir, fir/ hemlock, western spuce/ fir, Doug-fir, cedar/ hemlock/ Doug-fir, spruce/ cedar/ hemlock	Forest and woodland mostly ungrazed	Udic soils of high rainfall mountains
Klamath Mountains	High mountains	Mixed conifer forest, red fir, lodgepole pine/ subalpine forest (hemlock)	Forest and woodland grazed	Ultisols (Xerults)
Eastern Cascades Slopes and Foot Hills	Varied: tablelands - moderate to high relief, plains with low mountains, open low mnts., high mountains	Western ponderosa pine	Forest and woodland grazed	Xeric soils of moderate rainfall areas
Columbia Plateau	Varied: irregular plains, tablelands with moderate to high relief, open hills	Wheatgrass/ bluegrass, fescue/ wheatgrass, sagebrush steppe	Mostly cropland, cropland with grazing land	Xerolls, channeled scablands
Blue Mountains	Low to high open mountains	Grand fir/ Douglas-fir, western ponderosa pine, western spuce fir/ fir, Douglas-fir	Forest and woodland grazed	Soils of eastern interior mnts., Mollisols, Inceptisols
Snake River Basin / High Desert	Tablelands with moderate to high relief, plains with hills or low mnts.	Sagebrush steppe, saltbush/ greasewood	Desert shrubland grazed, some irrigated agriculture	Aridisols, aridic Mollisols
Northern Basin and Range	Plains with low to high mountains, open high mnts.	Great Basin sagebrush, saltbush/ greasewood	Desert shrubland grazed	Aridisols