

AN ABSTRACT OF THE THESIS OF

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Abstract approved:

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Problem areas identified are: The needs a) to develop curve fitting procedures to estimate flood flow distributions; b) to incorporate precipitation data into frequency analysis procedures; and c) to better define flood potentials for ungauged streams.

Closely related to the above, it is noted that variables commonly used to estimate flood magnitudes usually do not serve as optimum predictors. Hydrophysical variables are shown to increase the ability to estimate flood magnitudes of all frequencies within the Willamette River basin of western Oregon.

The major hypotheses tested show that the traditional "regionalization" procedure is not hydrologically sound. The objective herein is to regionalize flood distributions by basin parameters. These parameters include climatic variables that are hydrologically meaningful and easy to measure or estimate.

Regression equations are developed to estimate the descriptive statistics of each stream's flood distribution. The mean of the logarithms of the annual peak flows describes numerically the position of a flood frequency curve. The standard deviation of

the logarithms of the peak flows describes numerically the slope of the flood frequency curve assuming a log-normal or log Pearson type III distribution.

Watershed relief is the strongest estimator of flood distributions for all but the low elevation streams ( $R^2 = 56\%$ ). Relief influences within-basin climatic variability. Large flood climatology differences yield desynchronized runoff from the various source areas. Only rarely do the different elevation areas synchronize and then they yield exceptionally large peak flows.

Antecedent conditions are shown to be related to flood distributions. Those basins with large year-to-year differences in antecedent conditions have steeper flood frequency curves ( $R^2 = 76\%$ ). Precipitation zones, soil permeability, and forest cover all influence antecedent conditions. Drier basins with permeable soils and forest cover have steeper flood frequency curves.

Lakes and ponds act as sinks on all peak flows, and streams which flow through them have less steep flood frequency curves. In combination with watershed relief and mean annual precipitation, these three variables explain 86% of the stream-to-stream differences in the slopes of flood frequency curves in the Willamette River basin.

Drainage area, terrain roughness, forest cover, and precipitation explain over 95% of the stream-to-stream differences in average flood magnitudes. Steeper slopes yield larger flood peaks as does lesser forest cover. As elevation increases, average flood magnitudes decrease, but extreme peak flows are

larger.

Collectively these estimation equations reduce standard errors of 50-year floods from over 40% to less than 14%. They also reduce standard errors of ten-year and 25-year floods from 46% to 15%.

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on Flood Frequency Distributions  
in the Willamette River Basin

by

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## Watershed and Climate Influences on Flood Frequency

### Distributions in the Willamette River Basin

#### CHAPTER ONE PROBLEM AND OBJECTIVES

##### I. RESEARCH TOPIC

An accurate estimate of the flood potential at any site is a key element to an effective flood damage abatement program. To-date, flood estimates have been imprecisely defined despite much effort to that end. Furthermore, frequencies of occurrence have been crudely estimated, even though frequencies are important in any risk evaluation.

To the above end, the Water Resources Council (Hydrology Committee, 1976:25) identified additional needed flood flow frequency studies. Included in this summary are:

1. Selection of distribution of peak flows.
2. Fitting procedures to estimate the distributions.
3. Procedures to incorporate precipitation into frequency analysis.
4. Define flood potentials for ungauged streams.

The Hydrology Committee, "had expected to find that the proper distribution for a watershed would vary depending upon watershed and hydrometeorological conditions. Time did not permit exploration of this idea."

The major thrust of this research was to explore the above idea. Fitting procedures were developed to estimate the distributions of peak flows from ungauged streams in the Willamette River basin; particularly those streams in the forested, mountainous regions. The results allow better definition of flood potentials for ungauged streams in the Willamette basin than existed previously.

The techniques developed herein incorporate precipitation magnitude, intensity, and form and also incorporate terrain roughness, soil permeability, and percent forest cover. Also, frequency (distribution) regions, based on physical parameters in contrast to median ratios, are identified and predicted by the regression techniques presented here.

Several concepts must be introduced in order to identify the problem and the objectives of this study. A statistical population (or sample representative of a population) may follow one of several types of frequency distributions. The most important, and one for which probabilities are computed and reported, is the normal or Gaussian distribution. It has the characteristics of its mean value ( $\bar{x}$ ) being equal to its median value and 36 percent of the population being one standard deviation ( $s$ , i.e. square root of the variance) from the mean as shown in Figure 1.

Knowledge of the probability of values being equalled or exceeded allow a different frequency curve to be constructed.

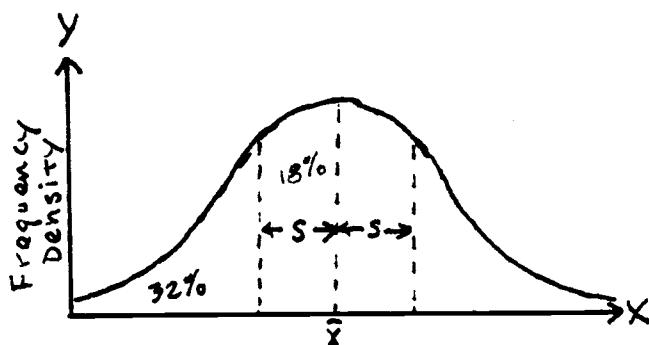


Figure 1: Probability curve for normal distribution.  
 $\bar{x}$  is the mean value and  $s$  is the standard deviation.

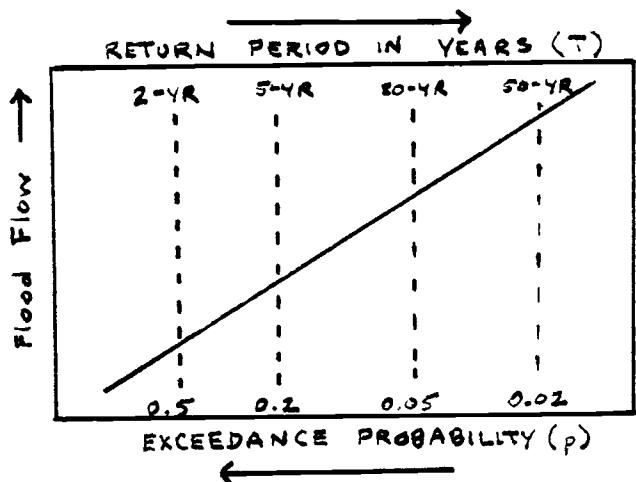


Figure 2: Flood frequency curve.

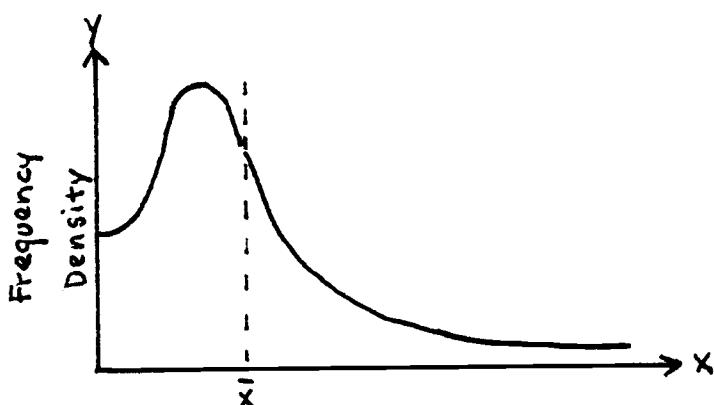


Figure 3: Frequency distribution of flood sample.

This curve plots the magnitude of the x-value against the probability of occurrence (p). In flood hydrology the use of annual flood peaks to define a flood population led to the development of the concept of return interval (T). This is the average number of years between events of a given magnitude or larger. It is computed by finding the inverse of 'p';  $T = \frac{1}{p}$ . This is illustrated in Figure 2.

Flood data, however, are usually not normally distributed. The data must be 'normalized'. Figure 3 demonstrates the frequency distribution of a representative stream's flood sample (20 years of flood record is still only a sample of the total population of floods from that stream). Note that the shape of this curve is different than a 'normal' curve. This restricts the use of probability theory of 'normal' populations in creating a flood frequency curve (Figure 2). Experience demonstrates that the logarithms of the peak flows are approximately normally distributed. The frequency distribution of the logarithms of the peak flows can be used, with probability theory, to create Figure 2, a flood frequency curve. The values are usually plotted in arithmetic form on log-log graph paper.

Due to the computations involved, S, the standard deviation of the logarithms, is numerically equivalent to the slope of the flood frequency curve. The mean of the logarithms, M, positions the curve on the graph. A direct comparison can be made to the standard regression equation,  $Y = a + bX$ , where b

is the slope of the curve and  $a$  is the Y intercept. In flood frequency curves, however, the curve never can intercept Y because  $X$  is never zero (in humid climates).  $M$  is used to position the curve, such that the computation for floods is:

$$Q = \text{antilog} (M + SK)$$

where;  $K$  is the frequency factor which accounts for the exceedance probability or return interval (the X-axis).

## II. PROBLEM IDENTIFICATION

### A. Introduction

Four related problem areas were identified: Distributions of peak flows and their relation to the climate and watershed characteristics of their respective drainage basins; frequencies of annual peak flows; consideration of the variables used in flood estimations; and flood magnitude estimation. Synopses of these problem areas lead to and introduce the statements of specific research objectives based on formulated hypotheses.

### B. Regionalization Technique

The primary problem of this thesis concerns the "regionalization" procedure universally used in estimation of peak flow distributions and magnitudes. An understanding of the regionalization technique is fundamental to understanding the problems identified herein because flood distributions relate to flood frequencies and because extreme peaks are estimated based on so-called "regionalized" peak flow curves.

The basic assumption made in regional frequency analysis is that all streams in the peak flow region have similar distributions of their annual peaks such that approximation of each stream's peak flow distribution is made best by aggregation of flow records into one regional distribution. This contrasts with determining the flood distribution of each stream based on that stream's record.

The obvious advantage of the aggregation technique is that one can maximize the use of very limited hydrologic data. Areas with

only a few streams possessing long periods of record and a number of streams with short peak flow records may be regionalized by record extension, using correlation techniques. This advantage is lost if the area in question has many streams with sufficiently long records to analyze.

The major problem with this traditional technique is that experience shows that not all streams in a region have similar peak flow distributions. Secondly, experience suggests that the same characteristics of a stream's basin which control the average magnitude peaks do not necessarily control the magnitude of the extreme events. Furthermore, the variables which control the distributions of peak flows may be different than those found in either of the first two sets. These problems are elaborated upon in the summary of the regionalization procedure.

#### 1. Procedure

First, a dimensionless base or regional frequency curve (or curves) is developed, expressed in terms of ratios of floods at specified frequencies (or probabilities) to the mean annual flood. Second, relations between the mean annual flood and basin characteristics are determined. Typically, these characteristics are topographical variables such as area, basin elevation, and stream length and gradient. More recently, climate variables such as mean annual precipitation sometimes are examined also. Many studies, however, limit the variables to drainage area. An estimated mean annual flood (M.A.F.) can then be determined for

any stream within the frequency region and, from the regional frequency relations, the discharges for any desired return interval can be estimated. From this, a frequency curve for that stream can be developed.

The procedure consists of several steps, summarized by Langbein and Hardison (1955):

1. Compile in tabular form the annual peaks and select the base period accordingly; generally the longest period of record of the stream records.
2. Extend the short term records to the base period by correlation with nearby long-period stations. Consistency is tested by use of a double mass curve.
3. Using a graphical or numerical distribution technique (such as Gumbel's or the log Pearson type III) develop a frequency curve.
4. Determine whether or not all the streams are in a homogeneous region with regard to flood producing characteristics (the test is described by Dalrymple (1960) and others).
5. The ratios of floods at selected return periods to the mean annual flood are tabulated and the median of the ratios of each return period is calculated.
6. The median ratios (of all the stations) are used to plot a regional frequency curve.

The use of this curve is best demonstrated by example.

Suppose the magnitude of the so-called fifty-year (two-percent chance of occurrence in any one year) flood is required for an ungauged site where the drainage area is 100 square miles and the mean annual flood has been related to the drainage area by equation or nomograph. This is, in fact, the Oregon State Engineer's procedure. By use of the equation or nomograph the mean annual flood is estimated. From the frequency curve the ratio of the fifty-year peak to the mean annual peak is determined. Multiplication of the mean annual peak by this ratio yields an estimate of the fifty-year peak for the ungauged stream.

The State Engineer developed separate curves for the Cascades, the Coast Range and the low elevation streams. This should, but does not, indicate three frequency regions within the Willamette River basin. The last point is explained in section 3.

## 2. Weaknesses

The regional technique has several inherent weaknesses. First, extension of short term records by correlation with long term records both assumes and creates similar distributions for the streams involved and this is not necessarily the case. The "analytical" test of homogeniety does not account for this inherent building of similar distributions because the test follows the correlation procedure.

Second, use of a median ratio further assumes and creates a regional frequency. This is in contrast to analyzing the data to

determine if a central value is justified.

Third, because the ratios are applied regionally, extreme events are merely multiples of mean floods. This arithmetic procedure prohibits a true analysis of the significant factors which account for extreme events because the same variables which account for the mean flood necessarily account for the extreme floods. A key example is Lystrom's work (1970) of western Oregon in which he reports the same variables in peak flow equations for each of several different return intervals.

Fourth, although the mean annual flood is correlated to basin characteristics in each of the existing flood studies, correlations to flood distributions have not been attempted. An exception is Thomas, Broom, and Cummins' (1963) Snake River study. That study identified an increase in the ratio of the ten-year peak to the mean annual peak with a corresponding increase in average basin elevation. The authors did not identify a cause of this correlation.

Fifth, some studies identify sub-regions within a given flood frequency region. These sub-regions are incorrectly identified as flood frequency regions. Section 2.3 elaborates upon this point.

### 3. Regions

Frequency regions have been defined by the homogeneity test but these regions are not necessarily true frequency regions. This occurs because the short-term records are extended by correlation to "nearby" stations that have long-term records.

Heavy emphasis is thereby put upon the longer stream records, creating areas of stations with nearly identical flood distributions (albeit, synthesized distributions). This negates the opportunity to correctly apply the homogeneity test.

The Oregon State Engineer (1971) determined three flood frequency curves for the Willamette River basin, thereby implying the existence of three flood frequency sub-regions. The results are of questionable worth because of the use of the "regionalization" technique. Furthermore, the three regions, the Cascades, Coast Range, and low elevations, have parallel frequency curves (same slope) which indicates that the regions have the same distributions but have different magnitudes per unit area at each given frequency. Thus, the State Engineer's report defines flood magnitude, not flood frequency, regions.

The curves further suggest that extreme peaks in the Coast Range are by the same proportion larger than the mean annual floods as are the Cascade's streams' proportions. One can accept different mean annual floods due to the differences in lithology, soil, topography, and climate of the two regions and one can accept different magnitudes between the regions for extreme peaks, but it was difficult for this investigator to accept that the ratios of extreme floods to mean floods would be maintained.

In summary, often what are called "flood frequency" regions are, in fact, flood magnitude regions and the uniformity of flood distributions from stream-to-stream and from region-to-region

(as demonstrated by parallel flood frequency curves) could be attributed to the regionalization technique rather than true consistency. If a region had a sufficiently large number of stations with long periods of record, tests of homogeneity would be more meaningful and true frequency regions could be defined. In addition, distributions might be related to watershed and climate variables in predictive manners and this idea could be tested. Flood frequency could then be regionalized by watershed and climate variables in contrast to "regionalizing" by aggregating correlation results. The third benefit could be superior estimation of extreme flood events in terms of frequency of occurrence.

#### 4. Frequency and Distribution

Frequencies of peak flows have been largely ignored also by researchers, especially in terms of correspondence with watershed characteristics. By analyzing flow distributions one can also determine frequencies. Steep flood frequency curves indicate several stream flow characteristics, one of them being lower flood frequencies than are associated with those streams having gentler flood frequency curves. Thus, by studying differences in the distributions of peak flows one examines simultaneously the differences in the frequencies of peak flows. Secondly, by developing numerical relationships between distributions and watershed characteristics, extreme peaks can be better estimated. The following section more completely explains this.

### C. Watershed and Climate Variables

#### 1. Introduction

Four problems occur which are associated with causative estimation efforts. First, flood formulas typically are not of high predictive value. For example, Lystrom's (1970) models have standard errors of 46% and Johnson and Omang's (1976) are over 90%. Second, modeling efforts involve input variables which are difficult to measure accurately; often more difficult to estimate than the desired output variable. Third, precipitation has not been adequately incorporated into flood magnitude studies, and when it has been included in the equation it has been forced in and no, or little, attempt is made to interpret its meaning. Fourth, flood distributions have not been examined in conjunction with watershed characteristics. These problems are briefly discussed below.

With the exception of mean basin elevation, tests have not been made concerning the relations between selected watershed or climate variables with the distribution of peak flows or with the frequency of peak flows. Instead, researchers have attempted to develop estimation equations for extreme peaks of assigned frequencies. Reich (1970) found, "no usable relation between the extreme statistics of rainfall and floods although there is probably a causal linkage." Potter (1953) and Benson (1962b) found terrain variables to be of more significance to the explanation of extreme peak flows than climatic or vegetation variables.

As indicated previously, an emphasis of this research was to attempt incorporation of precipitation into flood estimation procedures. Prior to this study precipitation had been poorly incorporated into flood distribution methods.

Lystrom (1970) and others have incorporated precipitation into flood magnitude equations but precipitation variables are usually not as important as basin geometry in explaining stream-to-stream differences. For example, the U.S. Geological Survey typically uses terrain variables such as drainage area, basin relief, mean elevation, percent area in lakes and ponds, and channel slope and length (see Bodhaine and Thomas, 1964).

True modeling, such as Leaf's subalpine model for the U.S. Forest Service; BURP, also a Forest Service model; and the Stanford model, includes precipitation and many other variables. These efforts have not addressed flood distributions. They often demand greater error in estimating inputs (e.g., groundwater storage and routing) than the errors associated with flood flow formulas. Also, the greater accuracy of flood equations probably occurs partially because the terrain variables within given physiographic regions are more significant to explaining stream-to-stream differences than are any other variables. Each physiographic region has a distinctive combination of geology, topography, climate, vegetation, and soils.

## 2. Climate Variables

The most obvious variables to examine in a study of peak

flow distributions are climatic variables, particularly in conjunction with their distributions. However, mean annual peak storm sizes are arbitrarily delineated and determination of the distributions of these annual peak storms, particularly on a basin-by-basin basis, is beyond practicality. Mean annual precipitation intensities of selected time periods (e.g., six-hour or 24-hour maximums) are commonly substituted for mean maximum storms.

Precipitation intensity is estimated by regionalization and is regionally determined using isohyetal lines drawn from station data. Isohyetals are drawn on the basis of elevation and exposure, in contrast to direct measurement. Due to the dearth of stations, frequency curves of precipitation intensity on a basin-by-basin basis are rough estimates and all but mean values are assumed to be of little assistance in an analytical study.

An important relationship to understanding the interpretations made in this study is the inverse relationship between mean precipitation and percent variability. This inverse relationship holds true, in general, for annual totals and for intensity values. In addition, stream flow volumes, being smaller than but directly related to precipitation totals, usually show this inverse relationship at an intensified scale. The inverse relationship is due to hydrophysical process as well as due to the arithmetic involved. High intensity, short duration storms are typically associated with drier climates and low intensity but long duration storms are associated with more humid climates. Similarly, flash-floods are associated with drier

climates and more broadly crested flood peaks are associated with humid climates.

The Willamette basin picture is more complicated still. Water is commonly stored in the form of snow prior to its annual peak and snow water equivalents increase with elevation. Whereas Lystrom (1970) reported a direct relationship between elevation and peak flows for all frequencies, the situation was expected to be more complex. An inverse relationship for average peaks and elevation and a direct relationship for extreme peaks was expected, thus yielding a positive correlation between elevation and peak flow frequency distribution. At the same time, an inverse relationship was expected between precipitation variables and peak flow distributions and yet precipitation and elevation are directly correlated. The above hypotheses were further complicated by findings of Reich (1970), Potter (1949), and Benson (1962b) listed earlier.

In summary, precipitation totals on a storm-by-storm basis, for any given basin without a nearby weather station are difficult to measure; distributions of storm sizes (in frequency of occurrence sense) are nearly impossible to estimate on a basin-by-basin basis; annual precipitation means are related to flow magnitudes and distributions; and precipitation form and magnitude have been related to elevation and exposure but precipitation form has important significance on flood magnitude and, presumably, on flood distributions. Although Lystrom (1970) correctly demonstrated the

joint influences between the above variables with multiplicative equations for the mean event, there were reasons to believe that the equations for longer return interval peaks are misleading. Few have examined peak flow distributions as they may relate to climate indices.

### 3. Basin Morphometry

As indicated in the introduction to this section, basin and stream geometry has been the most successful set of variables in peak flow estimation equations but this success is only moderate. Only the Snake River study correlated an element of geometry, mean basin elevation, with flood distributions. Furthermore, due to the regionalization techniques, results have shown that the same geometry variables which account for the mean event also account for the extreme events, and this isn't necessarily true.

Regionalization by watershed characteristics could demonstrate this last point and allow recognition of the most critical variables for extreme events. Also, variables which control distributions may be different than those variables which correlate with peaks of selected frequencies. All this was untested prior to this thesis.

Geometry variables not commonly used in flood estimation but which may be important are land slope, local relief, total basin relief, basin hypsometry, exposure, headwater elevation, and watershed shape. Land slope was shown by Hudziekewicz (1968) to be significantly correlated with the mean annual peak for twenty-three

streams in the Willamette basin. Two weaknesses to that study were evident, thus necessitating further study herein; high elevation streams were not studied and only five years of data were used.

Tolle (1976) found land slope is the most highly correlated variable to peak flows per square mile for twelve northwestern Montana streams and this influence of slope increases with return interval. The latter suggests an influence on the distributions of peak flows that have been unexplored.

The usual slope variable used is channel gradient. Illogical results are often reported, however. For instance, Johnson and Omang (1976) reported an inverse relation between channel gradient and peak flows. Although this can be explained in terms of bigger drainages having more gentle main channel gradients, the equations are of erroneous implications. Lystrom also included main channel slope as a variable but reported it as being insignificant.

Local relief, closely related to land slope, but a distinctly different geometry attribute, had not been used in flood estimations. Not only could it be an easily measured, useful variable for flood estimations but it could have shown differences in flood distributions because local relief could interact with average peaks in a manner which is different than with extreme peaks.

Basin hypsometry had not been examined as a flood controlling attribute by anyone, to the best of this investigator's knowledge. Hypsometry is the relation between percent elevation to percent area.

It should relate to percent snow cover figures and for that reason was studied here.

Watershed shape has been demonstrated to relate to mean annual floods of the Umpqua drainage in western Oregon by Tolle (1974) and Morisawa (1959a) and Wong (1963) elsewhere. Askew (1970) demonstrated that shape relates directly to concentration time of flow. This variable had not been examined as an influence on the distribution of peaks nor had it been tested with Willamette peak flows.

Mean basin elevation has been reported as being related to mean annual floods and by Lystrom (1970) as being positively correlated to peaks of other return intervals. As has been repeatedly pointed out, this isn't necessarily so. Furthermore, the headwater elevations were hypothesized as controlling the distributions by being only an occasional contributing area to peak flows. Contrasting to this opinion is Harr's (1976), "It is doubtful that normal clearcutting practices in the headwater areas of western Oregon have any appreciable effect on downstream flooding."

Total watershed relief is usually thought to provide an index for the lift given to travelling air masses, thus serving as a climatic index. Not only has a relationship between distribution and total relief been untested but the results suggest a different interpretation.

#### 4. Forest Cover and Soil

Conflicting results have been reported for soil and forest cover influences on floods. For example, December flows in the Oregon Coast Range could not be correlated with a soil permeability index according to Orwig (1973). He found permeability is important for summer flows, reflecting the fact that during the winter, "soils in the area are usually thoroughly wetted and are passing most of the rainfall input to streamflow." (Orwig, 1973:62). Lystrom's equations reflect an inverse relationship with peak flows of all return intervals for western Oregon streams. Soil permeability has not been examined as an influence on the distribution of floods, to this author's knowledge.

Forest cover has been repeatedly shown to be a significant influence on water yields through influences on transpiration (hence, soil moisture) and snow melt rates (by micro-climate changes), but Lystrom reported forest cover as insignificant for "large" western Oregon streams. Harr, et al. (1975) concluded from a literature review that increases in peak flows due to timber harvesting do not occur in western Oregon except during fall peaks.

In contrast, Anderson and Hobba (1959) suggested that clear-cutting in two major drainages in western Oregon increased peak flows 13 to 56 percent. Leaf's (1975) data showed annual water yield increases with about 37 years required for full recovery. His model shows even greater increases in peak flows but models are human concepts.

Soil and forest cover are significant for small drainages but not large basins. "Overland flow rather than the effect of channel flow is a dominating factor affecting the peak runoff," of small watersheds, according to the American Geophysical Union's Committee on Runoff (1957:374). "Consequently, a small watershed is very sensitive to high intensity rainfalls of short duration, and to land use."

These factors, soil and forest cover, needed to be explored as an influence on both flood magnitude and distribution for large watersheds in western Oregon. Former studies had inadequately approached these problems.

#### D. Summary of Research Problems

The overriding problem which leads to other flood estimation problems is the technique called "regionalization," which is actually a data aggregation technique. This technique prohibits exploration of stream-to-stream differences in flood distributions. Secondly, distributions should be related to watershed and climate factors but these relationships heretofore had been largely unexplored.

Although flood frequency is highly significant in making land use decisions, questionable regional frequencies have usually been assigned, in contrast to analysis of each stream's frequency. Similarly, the identification of frequency regions within broader hydrologic regions has often been foregone in favor of magnitude regions. Such is the case in the Willamette River basin.

Furthermore, inaccurate estimations of extreme peak flows result from regionalization and measures of equation reliabilities have been falsely high. These equations have essentially the same "independent" variables for all selected return intervals and both experience and common sense suggest this is not necessarily true.

A second area which may lead to low estimation capabilities is in the realm of variable selection. Inclusion of many variables in estimation equations tends to estimate gauged streams disproportionately better than ungauged, ignore secondary factors due to cross-correlation, and therefore does not necessarily identify the most significant variables.

Certain basin-wide descriptors of basin geometry are often not considered; for example, hypsometry, local relief (and land slope), head-water elevation, watershed shape, exposure, and total basin relief and slope. Some of these variables, most notably shape, have been shown by Tolle (1974) and others, to be important in other areas but have been ignored in the Willamette drainage. In addition, they had not been examined in conjunction with flood distribution or frequency.

Climatic factors are intuitively obvious as controls for flood distribution and magnitude controls but storms are difficult to index with any accuracy. Distributions of weather events are nearly impossible to evaluate on a basin-by-basin basis due to a lack of climate stations. Antecedent conditions have also not been addressed, including soil moisture conditions, snow conditions,

or precipitation duration.

Conflicting results concerning the influence of soil and forest cover on floods exist, even within western Oregon. These variables had been inadequately explored as controls of flood magnitude in large basins and not at all as controls of flood frequency and distribution.

### III. OBJECTIVES

Based on the foregoing research problems the following objectives were established.

1. Show that significant stream-to-stream differences in peak flow frequency distributions exist within the Willamette River basin.
2. Identify peak flow distribution regions, in contrast to peak flow magnitude regions.
3. Interpret causes of peak flow distribution (frequency) regions.
4. Develop an estimation technique to regionalize stream-to-stream differences in peak flow distributions based on physical hydrology variables; bypassing the aggregation technique called "flood frequency regionalization."
5. Incorporate precipitation into flood frequency evaluation.
6. Test the significance of variables commonly used with flood magnitude equations for explanation of flood distributions.
7. Test the significance of alternate variables in flood magnitude equations for their respective utility in estimating peak flow frequency distributions.
  - a. headwater elevation
  - b. watershed relief
  - c. basin hypsometry
  - d. terrain ruggedness
  - e. watershed shape

- f. basin orientation
- 8. Test the significance of forest cover and soil permeability on the frequency distribution of peak flows from "large" watersheds.
- 9. Improve upon the existing mean annual peak equations of the Willamette River basin.

These objectives were subject to the following three constraints: The variables selected approximate the mechanics of the hydrologic systems; the final model makes sense hydrologically; and the variable indices are easily measured or obtainable. This last constraint was imposed so that use of the methodology developed herein would be more likely.

## CHAPTER TWO      THEORY AND HYPOTHESES

## I. GENERAL THEORY

The general hypothesis examined in this research was that flood distributions of streams are related to the hydrophysical character of each stream's basin. The goal pursued and met was to define flood frequency and distribution regions by measurable indices of physical character, in contrast to estimating by median ratios. Physical character is meant to include basin size, watershed shape, land slope, relief, elevation, hypsometry, orientation, soil permeability, forest cover and precipitation.

The hypothesis is based on previous findings as summarized in the first chapter, and on theoretical considerations. For convenience of discussion relationships between flood flows and basin geometry can be grouped into: 1) the continuity of flowing water within a basin; 2) genetic expressions of landforms as they relate to geology and climate; and 3) controlling influences of specific elements of basin geometry on flood flows.

More specific hypotheses are introduced on a variable-by variable basis following this general hypothesis and an overview description of the study area.

A. Continuity of Flow

Playfair's law explains the continuity of flowing water within a basin (Playfair, 1802):

"Every river appears to consist of a main trunk, fed from a variety of branches, each running in a valley proportioned to its size, and all of them together forming a system of valleys connecting with one another, and having such a nice adjustment of their declivities that none of them join the principal valley either on too high or too low a level; a circumstance which would be infinitely improbable if each of these valleys were not the work of the stream which flows in it."

This law suggests that measurements of watershed characteristics, particularly topography, should index significant stream flow-related factors. Floods are commonly assumed to be intimately related to valley forming processes through erosion, transportation, and desposition.

#### B. Genetic Expressions of Landforms

Landforms are created (and destroyed) by the interaction of climatically driven processes operating on geologic materials. Differences in either geology or climatology are reflected in differences in topography. For example, Melton (1957) determined that valleyside slopes and drainage density are related to climate and to properties of mantle and vegetal cover. Chorley (1957) found that his climate-vegetation index is closely correlated to selected elements of basin geometry. Those relationships indicate the indexing potential of geology-climatology combinations by watershed geometry.

#### C. Controlling Influences

Not only is the geometry of the terrain related to past hydrologic events and to the underlying materials but geometry itself influences flow magnitudes and rates. Additionally, certain

geometry elements index climate, such as elevation and watershed orientation. Slope, areal extent, and drainage network can influence either the size of the flow events, the timing, or, most likely, both.

Because each storm could interact with a given geometry in a different manner, the variability of flows has been hypothesized to relate to watershed geometry. Also resulting from that hypothesis and from knowledge that elevation and orientation do not precisely index climate, an attempt to investigate more direct climatic indexes was included.

A third area of probable controls indicated by previous work is forest cover and soil condition. Both were correctly thought to influence peak flows of the Willamette River basin's larger streams. Due to known and/or suspected influences of cover and soil condition on peaks from small drainages and due to the nature of this investigation, separate indices were included for examination which proved to be significant.

## II. PHYSICAL GEOGRAPHY OF THE STUDY AREA

### A. Introduction

A brief introduction of the physical geography will assist one in understanding the hypothesis and variable selection. The Willamette River basin was selected for study because it has 31 streams with 20 years of concurrent peak flow records (1941-1960), which allowed stream-to-stream comparison of peak flow distributions. These flows were not influenced by diversions or other similar kinds of practices and the drainages are mostly within forested lands.

### B. Flood Weather

The annual peaks occur almost totally within the November through March period, when approximately 70 percent of the annual precipitation occurs. Rain is the dominant form of the Coast Range and other lower elevations. Snowfall totals in the Cascades increase sharply with elevation above about 2000 feet (600 meters) elevation.

The winter storms result from mid-latitude cyclonic systems moving eastward with warm, moist marine air invading the system from southerly directions. Precipitation is often spread out over hundreds of miles, blanketing much or all of the basin. Winter peaks are associated with either a series of fairly rapidly moving occluded systems or with quasi-stationary fronts. Often the result is a two to four day precipitation "event" of varying intensity. The extreme annual peaks are rain-on-snow or rain-on-

frozen or saturated mantle events. "Almost without exception, the destructive floods west of the Cascades are the result of warm rain falling at relatively high altitudes on previously accumulated snow" (Hulsing and Kallio, 1964:7). Resulting peaks are usually of short duration with flashy hydrographs. The Army Corps of Engineers (1948) also noted "broad-crested" floods with back-to-back precipitation events.

Winds associated with the winter storms are almost always from the south-southwest. "Speeds of 49 mph can be expected on the valley floor at least every other year, 60 mph at least every ten years, and 75 mph every 25 years. There are little or no official records at higher elevations but from limited unofficial information it appears that velocities of 100 mph may occur across some of the more exposed high ridges and peaks each year." (Pacific Northwest River Basins Commission, 1969).

From the above description, assumptions were made that basin rise, elevation, and basin orientation are probably important modifiers of winter storm precipitation form and magnitude. For that reason, basin rise, elevation, and basin orientation were examined as controls of peak flow magnitudes and distributions.

#### C. Terrain and Physiographic Regions

Elements of terrain are represented in this study by morphometric indices but physiographic regions define areas of similar terrain. Each region is characterized by similar topography, climate, geology, soils, and plant cover and differ from each other for those same characteristics.

The Coast Range is characterized by steep slopes in the headwater areas and gentle slopes in the lower elevations. Streams have many rapids and falls in their headwater reaches but their gradients flatten as they emerge into the Willamette Trough. The streams are cut deeply into the terraces and sloping lands. Elevations range from 200 to 4000 feet (60 to 1200 meters).

The High Cascades is a narrow (5 to 10 miles) but long (130 miles) plateau topped by recent alpine glaciated volcanic cone peaks (State Water Resources Board, 1963:8). Elevations range from below 6000 to over 9000 feet (1800 to 2700 meters). Streams have relatively steep gradients (as much as 1500 feet in five miles) and have valleys with typically steep-walled flat-bottomed character of alpine glacier troughs. Often wet meadows are found which probably act as water storage areas, desynchronizing flows from tributaries. In addition, internally drained basins occur at upper elevations due to alpine geomorphic processes operating on permeable volcanics.

Western Cascade region is defined here to have peaks less than 6000 feet and extend on its western edge to the Willamette Trough. Streams are more typically integrated dendritic, have gentler gradients, and are in older, less permeable materials.

The Willamette Lowland is characterized by gently sloping terrain and channels with well developed flood plains.

These physiographic regions, by definition, delineate different complexes of climatic, lithologic, soil, and mosaics

of plant communities in addition to the terrain differences noted above. For these reasons, an attempt was made to define flood frequency sub-regions by these physiographic regions.

D. Subsurface

The permeability of the subsurface was also handled in a quantitative manner, but as noted above, varies with physiographic province. The Coast Range consists predominantly of large areas of poorly permeable sandstone, shale, and mudstone (Willamette Basin Task Force, 1969). Hydrologic response is quick on these basins. In contrast, the High Cascades are underlain by highly permeable young volcanic rocks. Most of the Western Cascades is underlain by andesitic lava, breccia, and tuff of the Sardine Formation which have moderate recharge and moderate to low permeability capacities. The Willamette Lowland has slowly permeable alluvial and marine deposits.

### III. Specific Hypotheses

The major variables effecting winter floods are precipitation, surface character, and subsurface character. Figure 4 below lists important attributes of each variable with the arrows indicating direction of influence.

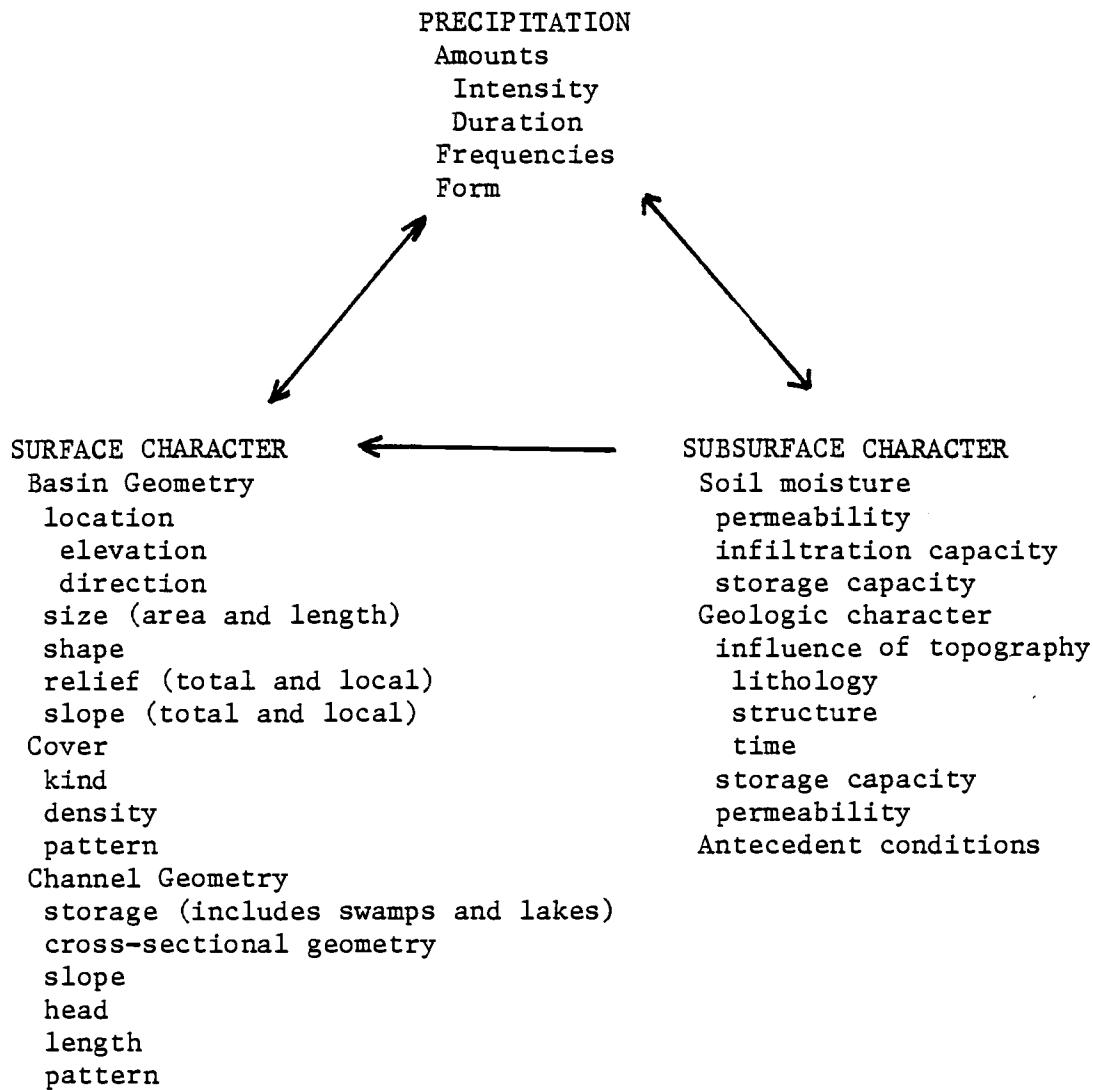


Figure 4: Attributes of the three major variables which influence flood frequency.

#### A. Drainage Basin Geometry Hypotheses

The first and foremost objective was to test for the effects of selected drainage basin geometry elements upon flood frequency. Flood frequency was measured as the slope of the flood frequency curve in this research. Hypotheses associated with each element of basin geometry follow. It is important to note at this time that almost all flood equations to date are based predominately upon morphometric variables.

##### 1. Drainage Size

Drainage basin size was hypothesized as being positively correlated to the slope of the flood frequency curve. That is, larger basins were expected to have disproportionately larger extreme peaks compared to their average sized peaks. This hypothesis was made for two interrelated reasons. First, larger land areas have greater opportunity for storage so the entire land area of big basins was hypothesized to contribute only during extremely large events. Second, synchronization of major tributaries was thought to be less common in larger basins than smaller basins, leading to larger year-to-year variations of peak flows from the larger basins.

This hypothesis differs from research before it by hypothesizing a changing relationship between drainage area and peak flows. Previous studies treated the influence of area as one which affects the relative sizes of peak flows from stream-to-stream but not as one which affects the relative sizes of peaks from a given basin.

## 2. Watershed Shape

Watershed shape has been shown by previous studies to correlate with peak flow magnitudes (Horton, 1932; Morisawa, 1958; Wong, 1963, 1971; Askew, 1970; and Tolle, 1974). The interpretation made is that watershed shape influences concentration times of surface runoff and synchronization of those flows (Figure 5). Streams of fan-shaped or circular basins have shorter travel routes from the headwater areas than do streams of elongated basins. The hypothesis was that short, fan-shaped basins should have larger peak flows on the average but that elongated basins would have disproportionately larger extreme peaks. The expected graphical result was gentle flood frequency curves for short, fan-shaped basins and steep flood frequency curves for elongated basins.

## 3. Terrain Ruggedness

Land slope was hypothesized to relate to flood frequency curves because concentration times of runoff are expected to vary with slope. Furthermore, land slope had the possibility of influencing the relative sizes of peak flows by being highly significant for given magnitudes and frequencies of peak flow events and less significant for others.

Hudziekewicz (1968) demonstrated mean land slope to have a positive correlation with mean annual peak for 23 sample streams of the Willamette basin, but local relief had not been examined for such a correlation, nor had either variable been examined in conjunction with flood frequency or with low frequency peaks.

In addition, Tolle (1976) found that unit area winter peak magnitudes in northwestern Montana are powerfully controlled by land slope. For example, the standard errors of the 10- and 20-year peaks are one and nine percent, respectively for equations which relate land slope to peak flows per square mile. Winter peaks in this area are similar to the winter rain-on-snow flood events studied herein. Tolle found that the influence of land slope of flood magnitude increased with return interval of the event, suggesting a relationship between flood frequency and land slope.

Although local relief and local slope have been lumped together in this discussion, they are two different attributes. To clarify the difference the following statement is made: Small local relief can be associated with very rugged topography, hence large local slope values; large local reliefs can be associated with low slopes and precipitous slopes, yielding average-sized average land slopes.

#### 4. Elevation

Elevation is the only geometry element thus far examined which has been demonstrated to influence the slope of the flood frequency curve. Thomas, Broom, and Cummins (1963) found a positive correlation in the Snake River basin, but did not attempt to explain the physical significance.

Three of the possibilities that exist were examined in this research: precipitation magnitude, precipitation intensity, and precipitation form. In general, precipitation increases with

elevation in the Willamette basin, but so does snowfall. In fact, snow increases not only as an absolute amount but as a percentage of the total annual precipitation (Army Corps of Engineers, 1956). To complicate the picture, high intensities are associated with the low elevations of the Willamette Lowland and precipitation of the High Cascades is less than that of parts of the lower, Western Cascades.

In addition, the mean basin elevation was not necessarily the best or most important elevation parameter. Headwater elevation, because it reflects snow conditions, was hypothesized to be the more important "control" of the flood frequency situation.

Lystrom (1970) reported that mean basin elevation is directly correlated to magnitudes of all frequencies in western Oregon, using regionalization to obtain the peak flow magnitude-frequency relationships. In contrast, the assumptions and hypotheses tested here were that for long return interval events, the higher elevation streams either respond similarly to low elevation streams, or, due to increased water contribution from snowmelt (disproportionate contribution), respond more strongly to precipitation input than low elevation streams. This would change the flood frequency from stream to stream. The hypothesis can be stated as such: A positive correlation exists between flood frequency (slope of the flood frequency curve) and headwater elevation.

In addition to testing the above hypothesis, an attempt was made to explain which precipitation characteristic best explains

the significance of elevation: mean precipitation magnitude, mean precipitation intensity, and/or mean snow depth. These characteristics, of course, are not the only possible precipitation characteristics of importance.

Precipitation variables are also not the only characteristics which might explain the importance of elevation, but arguments suggesting they are (the most likely characteristics of importance) are contained in the following paragraphs. Furthermore, Hewlett, et al. (1977) made a strong inference from their work that rainfall intensities are of little value in predicting storm flow volume in forested areas.

##### 5. Hypsometric Integral

The hypsometric curve represents an elevation-area relationship such that at any point along the curve a percentage elevation of the total (percent of the total relief) and an associated percentage of the total drainage area above and below that elevation can be identified. The curve gives a graphic representation of the relative distributions of elevations in a basin and the relative percentage of total basin area associated with given relative elevations. See Figure 6.

Neither this property nor the hypsometric integral (the area beneath the curve) has been used as independent variables in flood hydrology studies. These indices are integrating measures of basin geometry and were examined in this work for that reason. Hydrophysically, a relationship between the distribution of elevations

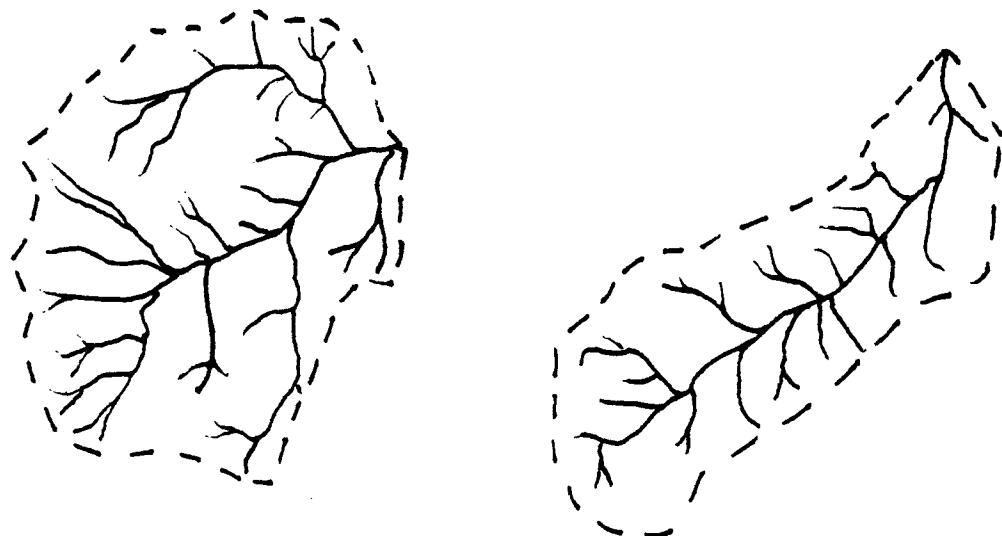


Figure 5: Comparison of Idealized Watershed Shapes. On the left a fan-shaped or circular basin is illustrated and on the right an elongated basin is illustrated. Watershed shape was hypothesized to be related to time-of-concentration.

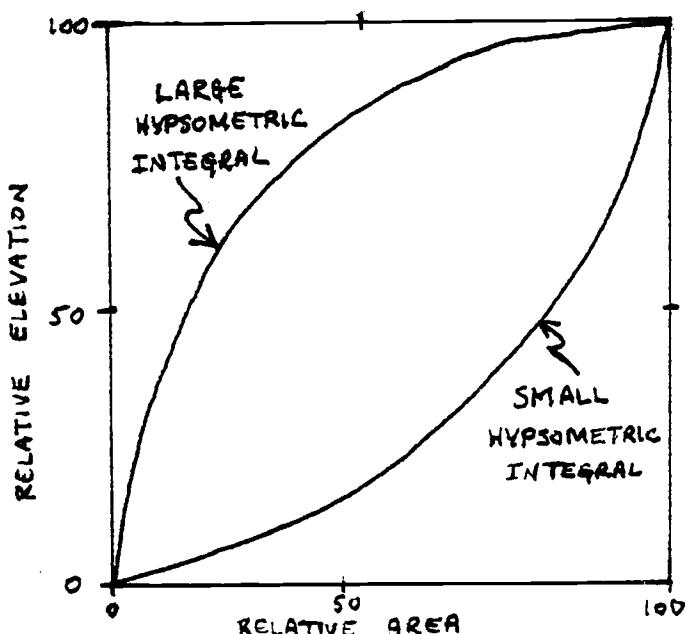


Figure 6: Comparison of two idealized hypsometric curves. The area beneath the curve is the hypsometric integral and is usually expressed as a percentage of the total area within the diagram.

in a drainage and snow hydrology was postulated.

#### 6. Orientation (aspect)

The orientation of a basin is strongly related to precipitation and to snow melt rates. For those reasons orientation was examined as an independent variable.

Rain-bearing winds in the Willamette basin during the flood season (November through March) typically occur from the south, west and directions in between. During average flood events exposure may play an important factor in the flood hydrology, but during extreme flood events, precipitation events last for several days. It was postulated that south-to west-facing basins would have larger average sized peak flows than basins of differing orientations but that little difference would be present during extreme peaks. The flood frequency curves were expected to demonstrate this difference.

Orientation was postulated to further complicate the peak flows by influencing snow melt rates. Southerly exposures accumulate less snow and melt earlier than northerly exposures, influencing runoff timing and magnitude.

Precipitation magnitude and intensity were examined to further refine the understanding of the hypothesized influence of basin orientation on flood frequency distributions and any identified correlations. These climate variables are discussed in the subsequent section.

## 7. Percent Storage Area

The hypothesis made was that percent surface storage area should be positively correlated to large flood events because the surface water in storage was thought to contribute disproportionately large volumes of water very quickly to large peak flow events. The mean event, in contrast, was thought to be inversely related to percent surface storage area. This hypothesis was based on the assumption that lakes and ponds serve as sinks and diminish the average peak flow. The hypothesis also stems from Lystrom's (1970) results concerning western Oregon streams, in which the Willamette basin is found.

### B. Climate

#### 1. General

Two climate variables were examined because each had the potential to explain differences in distributions more directly than the morphometric variables, mean annual precipitation and the average two-year 24-hour maximum precipitation intensity for the basins. It was believed that elevation and basin orientation tend to integrate individual climatic factors and thus provide a composite index. Also, use of specific climate variables was expected to help clarify why a given morphometric variable correlated (or didn't correlate) with the descriptive flood statistics. The goal of the thesis was to develop a new method

and to demonstrate that slopes of flood frequency curves vary with climatic and basin characteristics. Direct use of climate data and of published data are consistent with that goal. In addition, the variables selected are easily obtainable, making use of the method more likely.

## 2. Storm Precipitation

Mean annual maximum storm precipitation was hypothesized to vary inversely with the slope of the flood frequency curve. This hypothesis was proposed because larger average annual peak flows should be associated with larger average rainfalls, but exceptionally large precipitation events in the Willamette River basin result in large rainfalls "everywhere". That is, long duration quasi-stationary occluded fronts or a series of rapidly moving fronts deliver approximately equal precipitation totals throughout the Willamette basin. This set of conditions would result in steep flood frequency curves for basins with smaller average storms, and conversely.

Lystrom found that the two-year, 24-hour maximum precipitation intensity is positively related to peak flows of all return intervals. My thesis is that Lystrom's findings are attributable to the effects of "regionalizing" (aggregating) the flood record and of including too many variables in the final regression equation, without critically examining each additional variable.

## 3. Mean Annual Precipitation

Mean annual precipitation (M.A.P.) was investigated for

similar reasons as was mean storm precipitation. In addition to being roughly proportional to mean storm size, however, M.A.P. is known to be related to mean snowfall and is a measure of overall basin wetness. Not only does total snowfall increase with a rise in elevation and mean annual precipitation (M.A.P.), but a larger percentage of the M.A.P. is snow as M.A.P. becomes larger.

The interpretation of results presented herein is that M.A.P. is a measure of antecedent conditions. Without elaborating prematurely on that interpretation, it can be said that soil moisture and snow pack are related to M.A.P.

Similar to the hypothesis about mean storm size, M.A.P. was hypothesized to be inversely related to the slope of the flood frequency curve. Basins which have wet soils, ripe snow packs, or larger than average annual peak storms were hypothesized to be no more "wet" than other basins during the extreme peaks. This was believed because of the nature of the extreme winter peak flow related storms in the Willamette River basin.

In support of the antecedent conditions interpretation is Hewlett et al.'s (1977) research. They showed that precipitation intensity only accounted for 4.7 percent of the total variation in log peak flows for the Coweeta Experimental Watershed. This watershed is located in western North Carolina which is a rainfall peak flow area. They found total storm rainfall, antecedent flow, season of the year (winter or summer), and duration of the rainstorm accounted for 86.4 percent of the total variation in storm flow.

This suggests that if M.A.P. is important, it is important as an index of antecedent conditions.

Comparison of extreme rainfall statistics could be profitable if those statistics could be accurately measured with enough precision. This is not the case, however.

#### C. Forest Cover and Soil Hypotheses

##### 1. Forest Cover

Although percent forest cover was not found by Lystrom (1970) to be an important control of peak flow of any of his selected frequencies for western Oregon streams, many people believe forest cover has a very significant control of peak flows. Because of the controversial nature and possible influence of forest cover on peak runoff and for reasons that follow, percent forest cover was re-examined as an influence on the mean peak flow and on the slope of the flood frequency curve.

Rothacher (1970) demonstrated increases in water yield from west-slope Cascade streams following timber harvesting. Most of the increase occurred during the fall, but winter peaks increased as well. Whipkey (1965), Hewlett and Hibbert (1967), and Harr, et al. (1975) have attempted to explain the increase in water yield in terms of soil permeability and expanding drainage densities. In other reports water yield increases are attributed to changes in interception and/or changes in snow storage.

If changes in forest cover affect runoff principally by logging practices and the associated decrease in soil permeability,

one could anticipate a different set of flood frequency curves given a certain forest cover condition than if interception and snow storage alone are the dominant mechanisms by which forest cover influences peak runoffs.

If changes in forest cover affect runoff principally by changes in interception and snow storage, one would need to know whether just the average peak flow event, just the extreme events, or both were affected.

Admittedly, this simplistic discussion does not consider differences among tree species, cutting patterns, exposures, or any of the other conditions through which forest cover has been supposed to influence snow via the energy budget. The major thrust of this research, however, was to test the impacts of drainage basin geometry elements on the slope of the flood frequency curve. In addition, at the outset of this research the author incorrectly did not anticipate that a crude index, such as percent forest cover, would be a significant factor. Percent forest cover was included partially due to data availability and partially due to the reasons stated above.

## 2. Soil Permeability

Soil permeability was reported to have an inverse relationship with western Oregon peak flows at all return intervals examined. (Lystrom, 1970). In contrast, Orwig (1973) found that soil permeability did not influence December flows of Oregon coastal streams but is important for summer months, "reflecting the fact that soils

in the area in December are usually thoroughly wetted and are passing most of the rainfall input to streamflow." (Orwig, 1973:62)

Lystrom's (1970) results seem more applicable to the Willamette River basin because Willamette streams were included in his analysis and not in Orwig's; because Lystrom had a larger sample size; and because soil permeability intuitively appears to be important to the average peak flow event. During many extreme events, however, Willamette basin soils are saturated, and may be frozen, and/or snow-covered. This suggests that soil permeability takes on less significance as return interval increases.

In contrast to Lystrom's (1970) findings, therefore, soil permeability is hypothesized as having a positive correlation with the slope of the flood frequency line. This means that streams with high average basin soil permeabilities were expected to have smaller average peaks but their extreme peaks were expected to be unaffected by soil permeability, thus having steeper flood frequency curves.

#### D. Channel Geometry

Channel geometry was rejected as being a possible source of variation in peak flows for two reasons. First of all, the basins vary in size from about 30 square miles to 600 square miles. The influence of size is thought to overpower influences of channel geometry. Second, channel geometries are more a function of peak flows than vice-versa. The channel geometry of a stream may change after each large peak, thus being related mostly to the last large

peak rather than to the distribution of all peaks, large and small.

The exception to the rejected influence of channel geometry was the hypothesized influence of channel slope. Channel slope probably influences water travel time which may vary with the amount of quick flow. Quick flow, in turn, was thought to vary with the size of the storm.

Benson (1959, 1962) and Wong (1971) found that channel slope correlates with peak flows. In contrast Lystrom and Brush (1961) found a lack of correlation. Johnson and Omang (1976) identified an inverse relationship between peak flows and channel slope.

#### E. Flood Frequency Sub-regions

The fourth objective of this research was to examine the Willamette River basin for flood frequency sub-regions. The State Engineer (1971) identified three sub-regions: Coast Range, Cascades, and streams below 1000 feet in elevation. These regions, however, are flood magnitude regions in contrast to regions of differing flood frequency distributions. The similarity of frequency distributions is noted by the same multipliers for the return intervals for each regional curve. The curves differ only in their magnitudes.

The hypothesis examined in this research was: There are four flood frequency regions within the Willamette basin -- Coast Range, Willamette Lowland, Western Cascades, and High Cascades. This hypothesis means that multipliers of each return interval would be different for each region.

The Coast Range streams receive the highest precipitation on

the average, which may explain their relative magnitude. At the outset of this research, it was not known which factors best differentiated the Coast Range streams from the other, so a flood frequency hypothesis was not feasible. However, as an example, if mean precipitation is the most significant factor one would expect the most gentle flood frequency curves to be associated with the Coast Range and the steepest to be associated with the low elevation streams, regardless of the mountain range. Unfortunately, too few low elevation sample streams are available to allow a conclusive research design.

The initial four regions selected were based primarily on physiographic differences, which is consistent with the primary hypothesis of this research; i.e., stream-to-stream differences in flood frequency result from basin-to-basin differences in morphology. The frequency/sub-region hypothesis was normative due to the complexities involved but pursuance of the first three objectives of this research allowed interpretation of why flood frequency sub-regions in the Willamette basin exist.

#### F. Median Annual Peak (M)

In an effort to learn more about peak flows and to develop a better predictive equation than existed prior to this effort, predictive equations were developed for the mean of the log peak flows, "M". Hudziekewicz (1968) and the State Engineer have developed the only previous formulas for the Willamette basin. The State Engineer included drainage area as the only "independent

variable". Hudziekewicz included area and land slope, but only included low elevation streams and five years of record. Furthermore, Hudziekewicz did not explore soil permeability, forest cover, storm precipitation, hypsometric integral, or several other potentially important variables.

Lystrom (1970) explored the commonly used variables (by U.S.G.S.) but included so many variables in his final equation that the results are hydrophysically suspect. His equations were for all of western Oregon.

For those reasons and the lack of high estimation capabilities, the median annual peak was re-explored. Area, of course, was assumed to be dominant but drainage length also indexes drainage size so it too was included.

Climate variables include mean annual precipitation as an index for total basin wetness and mean annual 24-hour precipitation intensity as an index of storm magnitude. The mean of the logarithms, "M", was hypothesized to be larger for larger precipitation values.

"M" was expected to be inversely related to elevation; in contrast to Lystrom's findings. The poor predictability of Lystrom's model is partially attributed to not narrowing the region of study such that elevation indexed something other than an increase in precipitation, and partially due to using so many variables in the final equation. The hypothesis made here was that because higher elevations have predominantly snow inputs, rather than rainfall-runoff peak flow generators, lower median annual peaks

were expected. Watershed shape and local relief are related to concentration times. Short, circular basins and rugged terrain with steep slopes were expected to yield higher peak flows per unit area on the average than elongated basins with gentle slopes.

Forest cover and soil permeability are related to near-surface and surface water storage. As soil permeability decreased, higher peaks were expected due to greater and faster quick flow. Snow water equivalents and snowpack melt rates are related to forest cover. Soil compaction is also related to forest cover. As forest cover decreased, higher peaks were expected.

Percent surface area in lakes, ponds, and streams was expected to have a dampening effect on peak flows. Lakes and ponds generally serve as sinks for rapid runoff.

Hypsometry and basin relief were explored because they are significant geometrical elements of a drainage basin. Specific hypotheses were normative for these two variables.

## CHAPTER THREE RESEARCH DESIGN

## I. GENERAL METHOD

The hydrologic cycle, including flood hydrology, is so complex that a complete mechanistic model of it will not be achieved in the near future. Furthermore, there exists an inadequate understanding of the variables involved. Consequently, an alternative approach to gaining more understanding of flood hydrology in general, and of flood frequencies in particular, is to measure observable variables which appear pertinent to explaining flood frequencies, determine correlations, and interpret relationships.

This study uses that method and examines variables from a wide range of flood situations and conditions. The results will hopefully provide a better understanding of flood frequencies and an improved estimation capability. The estimation techniques are based on easily measured variables that appear to be physically as well as statistically significant.

The general approach is to measure and compare the flood frequency curve properties (slope and location of the flood frequency curve of each stream) to selected hydrophysical characteristics of each stream's basin. The characteristics examined are those which were hypothesized to be significant flood controlling features of the system and which could be meaningfully indexed in an efficient manner. These are the independent variables and are easily obtainable and capable of being accurately measured.

The comparisons are both statistical and graphical. Map inspection and analysis of variance allowed preliminary regionalization. Multiple regression of non-linear variables and graph analysis allowed relationships to be examined which might otherwise have been missed by simple linear correlation and regression.

Strong correlations are described by numerical equations developed by the method of least squares. Multivariate numerical models of the data at hand were also developed to determine secondary influences on residuals. The coefficient of determination is used in this report to measure the value of using a regression equation. The coefficient of determination ( $R^2$ ) is defined as the proportion by which the error variance (square of the standard error of estimate) has been reduced by use of the regression equation. The standard error (root mean square error) of the estimates made from a regression equation is a measure of reliability of those estimates and, therefore, of the regression equation. Standard errors (S.E.) of logarithms are not meaningful because S.E. are calculated by arithmetic processes. For that reason logarithmic standard errors were not calculated for the slope of the flood frequency curve. Standard errors were calculated for comparative purposes for selected frequencies of peak flows because that variable can be converted to arithmetic values.

The hydrophysical system is the drainage basin, including geomorphic attributes, is represented by morphometric measures and by a soil permeability index. Climatic influence, including

antecedent conditions, is indexed by morphometric measures such as various elevation indices and basin orientation, by estimated precipitation values, and by percent forest cover.

Morphometric values are easily obtainable. Published data which are readily available are used rather than remeasured from primary data sources. This is because the goals of this research were to develop a new methodology and attain new understandings of the mechanisms involved rather than challenging existing measurements. Furthermore, use of published data eliminates researcher bias, which is especially important for climate variables. Climate indices are subject to researchers' bias because the values are not measured, but instead are estimated by extrapolation of point data over areas, making heavy reliance upon the researchers' professional judgment necessary.

Dependent variables, the slope and position of the flood frequency curve, are numerically represented by the standard deviation and the mean of the logarithms of each stream's peak flows, as was explained in Chapter One. The Willamette Drainage Basin was selected as the area of study for several reasons:

1. The basin is well documented, has a reasonably accurate flood peak record for over 40 basins during a time period of such length (20 years) that a flood frequency index could be developed for each basin. (Swift, 1966)
2. A large number of these basins (34) were free of peak flow regulation during a selected period of record

- (1941 to 1960).
3. Most (31) of the basins are mapped at a uniform scale by expert cartographers. U.S.G.S. 15 minute topographic maps were used (scale 1:62,500 and compiled during the latter half period of record from aerial photographs with spot field checks of the elevations).
  4. The Willamette Basin is considered part of a larger hydrologic region according to the U.S.G.S. This meant that differences between basins should be identifiable from local (basin) differences rather than overwhelming regional hydrologic factors.
  5. Existing Willamette basin flood estimation equations have large standard errors. Lystrom (1970) reported standard errors of 46% for the two-year peak and yet the Willamette has a very good flood record.

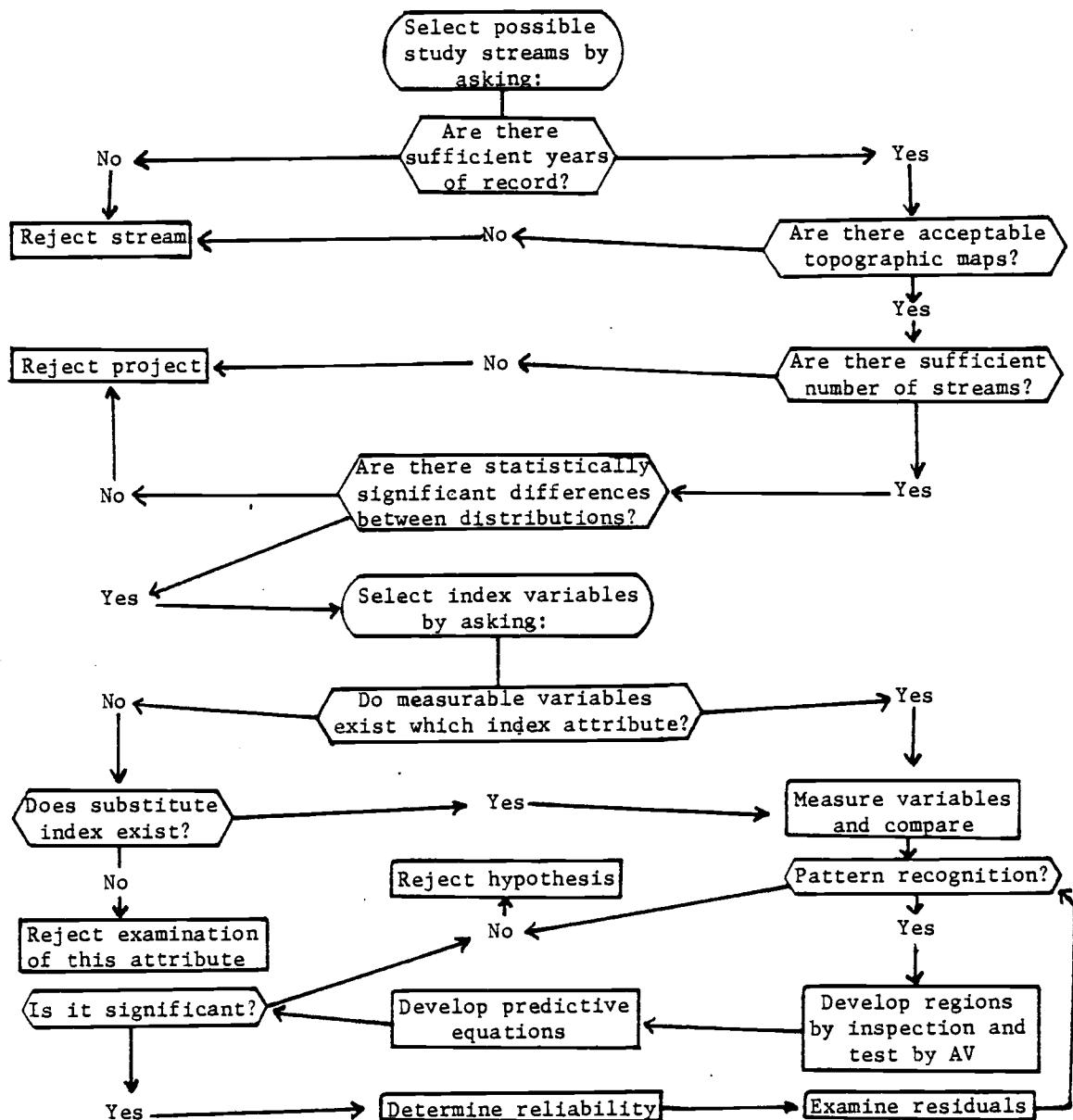


Figure 7: Flow diagram of method

## II. FLOOD FREQUENCY

### A. Dependent Variables

The basic flow data are contained in U.S. Geological Survey (U.S.G.S.) Water-Supply Papers. Annual instantaneous peaks from 31 Willamette River basin streams of the twenty water years' period 1941 through 1960 were selected on the basis of Swift's (1966) Analysis referenced earlier.

A flood is defined by the U.S.G.S. (Langbein, 1949) as the instantaneous peak discharge during a given water year. Using the U.S.G.S. definition, the annual flood peaks from a stream comprise its "annual series". A flood can also be defined as that magnitude equal to or in excess of a given stage. Floods so defined in the latter manner comprise the "partial duration series".

Langbein (1949) demonstrated that for return periods of four or five years or longer, floods defined by the annual series and by the partial duration series generally have the same magnitude. Defining a flood by the annual series has several advantages. First, very high frequency, small magnitude peaks are thus partially screened from the data base. This allows a focus upon variables that truly account for differences in the flood frequency curves. Second, independence of events does not become a problem with the annual series definition as it could with the partial duration series. Third, and of importance to the measurement technique used in this report, annual floods are part of a true population. The significance of this will be made clearer from the discussion of the flood

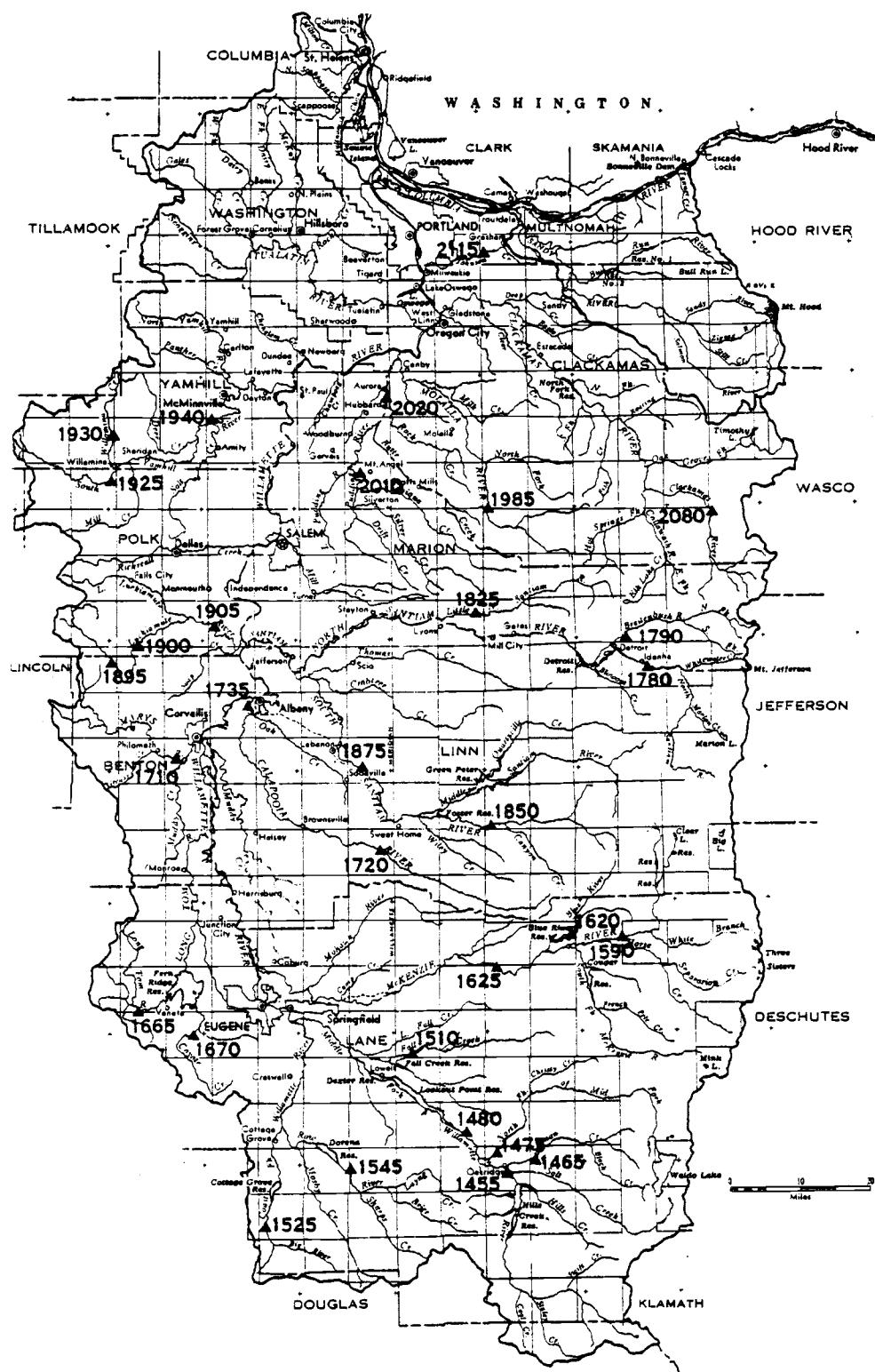


Figure 8: Map of station locations. See following page for key. The base map was provided by Oregon State Water Resources Board (undated).

## KEY TO FIGURE 8

Solid triangles indicate location of the gauging stations.  
 The four digit codes are the last four digits of U.S.G.S.  
 assigned station numbers.

<u>Station Number</u>	<u>Drainage</u>
1455	Middle Fork Willamette River above Salt Creek, near Oakridge, Oreg.
1465	Salmon Creek near Oakridge, Oreg.
1475	North Fork of Middle Fork Willamette River near Oakridge, Oreg.
1480	Middle Fork Willamette River below North Fork, near Oakridge, Oreg.
1510	Fall Creek below Winberry Creek, near Fall Creek, Oreg.
1525	Middle Fork Willamette River at Jasper, Oreg.
1545	Row River above Pitcher Creek at Star.*
1590	McKenzie River at McKenzie Bridge, Oreg.
1620	Blue River near Blue River, Oreg.
1625	McKenzie River near Vida, Oreg.
1665	Long Tom River near Noti, Oreg.
1670	Coyote Creek near Crow, Oreg.
1710	Mary River near Philomath, Oreg.
1720	Calapooya River at Holley*
1735	Calapooya River at Albany*
1780	North Santiam River below Boulder Creek, near Detroit, Oreg.
1790	Breitenbush River above Canyon Creek, near Detroit, Oreg.
1825	Little North Santiam River near Mehama, Oreg.
1850	South Santiam River below Cascadia, Oreg.
1875	South Santiam River at Waterloo, Oreg.
1895	Luckiamute River near Hoskins, Oreg.
1900	Luckiamute River at Pedee, Oreg.
1905	Luckiamute River near Suver, Oreg.
1925	South Yamhill River near Willamina, Oreg.
1930	Willamina Creek near Willamina, Oreg.
1940	South Yamhill River near Whiteson, Oreg.
1985	Molalla River above Pine Creek, near Wilhoit, Oreg.
2010	Pudding River near Mount Angel, Oreg.
2020	Pudding River at Aurora, Oreg.
2080	Clackamas River at Big Bottom, Oreg.
2115	Johnson Creek at Sycamore, Oreg.

\* These stations have new names since 1960,  
 but the codes remain the same.

frequency index.

The twenty-year record was used for two reasons: 1) At least ten years are needed to estimate the standard deviation with any degree of precision. 2) Concurrent records permit comparison, thus avoiding artificially created "records" by correlation and losing the unique flood frequency identification of any short-term stream record.

The 31 streams examined have drainage areas larger than 25 square miles. The same basin was used so as to not introduce large climatic variation into the data. The same scale was selected so that morphometric differences are less likely to be cartographic differences. The areal dimension criterion is necessary because experience suggests that small basins respond differently than basins larger than 25 square miles.

#### B. Slope of the Flood Frequency Curve (S value)

As explained in chapter one, the slope of the flood frequency curve is approximated numerically by the standard deviation of the logarithms of the peak flows. This numerical indexing of frequency allows one to attempt quantitative estimations which, in turn, allows more precise estimates of extreme events.

Definition of extreme events from known data is made from the following equation:

$$q = M + SK$$

where;  $q$  = the logarithm of the peak flow of  
the selected frequency

M = the mean of the logarithms of the peak flows

S = the standard deviation of the logarithms of the peak flows

and K = frequency or probability factor of the selected return interval.

In practice K varies with the coefficient of skewness but is assumed to be zero or have a regional constant in this study because too few years of record are available to accurately estimate the skewness of each stream.

#### C. Median Annual Peak Flow (M)

The mean of the logarithms or the median annual peak flow is also a dependent variable in this research because of the need to estimate it for use in the equation given above. The mean of the logarithms (M) is the median annual peak flow and it is analogous to, but not identical to, the y- intercept value, a, in the standard regression equation:  $y = a + bx$ . M is not the y- intercept because peak flows of zero do not occur in humid climates. The K factor (its analogous part is X in the standard regression equation) allows for peak flows of higher frequency and smaller magnitude than M.

The so-called mean annual flood and the two-year peak flow are similar to M in value and frequency. For that reason the standard error and coefficient of determination for M are compared to the published standard error and  $R^2$  value for the two-year

peak (Lystrom, 1970) and the mean annual flood (Hudziekewicz, 1968), respectively.

### III. INDEPENDENT VARIABLES

#### A. Basin Geometry

"Morphometry may be defined as analysis of the configuration of the earth's surface and of the shape and dimensions of its landforms." (Clark, 1966:235) The main elements of area, relief, and orientation are broken down into the following elements for this study: drainage size, relief, slope, hypsometric integral, watershed shape, elevation, surface storage, and direction.

Each of these elements was measured directly from U.S.G.S. 15 minute quadrangle topographic maps (1:62,500 scale) by the author or by Lystrom (1970). This allows numerical indices of each element to be derived at a uniform scale for all basins examined. The numerical indices of each element of drainage basin geometry can then be graphically and numerically compared to the slope of the flood frequency.

#### B. Drainage Size

##### 1. Area

Basin area is measured as that area of the drainage basin which is represented by projection onto a plane surface, the 15 minute map. The boundary of the basin is taken to be the topographic divide, known as the watershed, even though exact coincidence of topographic divides and hydrologic divides often doesn't exist. The investigator believes the 28 square mile minimum size of the basins to be such that the disagreement between the watershed and subsurface hydrologic boundaries is negligible and within measuring error.

Measurement of basin area (A) was by planimeter and is reported in U.S.G.S. Water-Supply Paper 1318 (U.S.G.S., 1963).

## 2. Length

Drainage basin length is also an important index of both stream and basin size. The following horizontal length measures were gathered: watershed length, basin length, and longest stream channel length. See Figure 9.

Watershed length ( $L_w$ ) is defined and measured as the longest chord which can be constructed connecting the basin mouth (defined by the gauging station) to the watershed. The watershed is defined here, after common Canadian usage, to be the topographic divide. This allows straight-forward distinction from "drainage basin", the area within the watershed, to be made.

Basin length, designated ( $L_b$ ) is the longest chord which connects any two points on the watershed. As can be anticipated, watershed length and drainage basin length are often the same. However, a difference occurs often enough to warrant distinction. Both watershed length and basin length are measured and expressed in miles to the nearest tenth of a mile. Repeated measurements are made to insure maximum precision.

Length of the longest channel ( $L_s$ ) is measured along the channel from the gauging station to the basin divide. Horton (1945) called the path from the fingertip of the main stream as displayed on the maps to the divide "mesh length". It is believed that this non-channelized segment above the mapped

stream channel should be appropriately included as part of the main stream because water from this most distant source (from the gauge) is assumed to contribute to flood peaks.

This makes  $L_s$  a measure of distance and relates to the longest time of concentration for any point within the drainage basin, and thus related to flood peak concentration time. Longest channel length, as described, has been measured by U.S.G.S., "in accordance with guidelines given by the Water Resources Council (1968) or taken in part from the various River Mile Index publications prepared by the Hydrology and Hydraulics Committee of the Pacific Northwest River Basins Commission (1963-1968)" (Lystrom 1970:14). An exception to the above published data was Marys River above gauge 14-1710. It was measured by map measurer because the "main" channel measured below was not the longest channel.

### 3. Basin Relief

Following Strahler (1952), Coates (1958) and Melton (1958a), basin relief ( $R_b$ ) is the vertical distance between the mouth of the basin and the highest point in the basin.  $R_b = E_m - E_o$  where  $E_m$  is the maximum elevation and  $E_o$  is the elevation at the stream gauging station.

Watershed relief may also be defined as the vertical difference between the basin mouth and the headwater elevation.  $R_w = E_w - E_o$  where  $E_w$  = elevation in the basin where the longest stream originates and  $E_o$  is defined as before. Both measurements were made and the difference in results of the two made it possible to make more detailed hydrologic interpretation.

### C. Slope

Terrain slope has been measured many different ways. Total basin slope indices can be easily derived from basin relief and length indices already presented: watershed relief ( $R_w$ ), basin relief ( $R_b$ ), watershed length ( $L_w$ ), basin length ( $L_b$ ), and longest stream length ( $L_s$ ). Combinations of these size measures used to compute terrain slope are:  $R_w/L_w$ ,  $R_b/L_w$ ,  $R_w/L_b$ ,  $R_b/L_b$ ,  $R_w/L_s$ , and  $R_b/L_s$ .  $R_b/L_w$ ,  $R_w/L_b$ , and  $R_b/L_s$ , however, are not nearly as meaningful as the other three. The three combinations used to define terrain slope are called: watershed slope  $S_w = \frac{R_w}{L_w}$ , basin slope  $S_b = \frac{R_b}{L_b}$ , and slope of the longest stream  $S_s = \frac{R_w}{L_s}$ . In addition, a "critical" slope of the main channel ( $S_c$ ) was measured by Lystrom (1970), in which the upper 15% and lower 10% of the

channel were ignored and slope computed for the channel between.

#### D. Terrain Ruggedness

##### 1. Local Relief

Local relief was determined by the author by measuring relief in feet per square mile. A grid system of squares was laid over the map and maximum and minimum elevation values were read from sample squares. Interpolated values were estimated wherever either of these extreme values could not be directly read.

A ten percent systematic sampling of the total basin area was made in this manner. Basin areas of less than 100 square miles could have too few samples by this method, so the spacing of samples was adjusted for small basins such that at least 12 samples were taken from each basin. This resulted in sample densities of 15 to 40 percent of the basin area. The only basin with as few samples as 12 is Johnson Creek with about 28 square miles of planimetric area. The minimum elevation was subtracted from the maximum for each sample and these computed values averaged for the drainage basin. This yields mean relief per square mile, called local relief in this paper.

##### 2. Average Land Slope

Average land slope was measured in feet per mile. Perhaps most meaningful would have been an average ridge-to-valley (or stream channel) slope. This approach is not systematic or "duplicable", however, because the "nearest" ridge-tops and valley bottoms can vary with scale or observer.

Equally good conceptionally, and far superior in practice, is Wentworth's (1930) mean slope per mile technique. This was the method the author used in this study. A grid system of square mile blocks is overlaid on each drainage basin. A system of north-south, east-west and diagonal (NE-SW and NW-SE) lines is constructed within each square mile block. Contour crossings are counted and recorded for each of the lines for each sample square mile. The observations of the diagonal line are corrected to unit distance (one mile). All four sample contour crossing observations are then averaged. In order to determine the average land slope ( $S_m$ ) in terms of the tangent of the average slope angle the following equation is applied:

$$S_m = \frac{\text{mean number of contour crossings per mile} \times \text{contour interval}}{3361}$$

The number 3361 relates to the conversion of feet to miles and a theoretical average tangent. The contour intervals need not be the same with this method; however, scale changes may introduce a bias in precision involved.

#### E. Elevation

Elevation indices included in this study are: mean basin elevation ( $\bar{E}$ ), headwater elevation ( $E_w$ ), and maximum basin elevation ( $E_m$ ). Mean elevation could have been computed by averaging the maximum and minimum elevation values of each sample square mile observed for the local relief measurements. Instead, Lystrom's (1970) values were used to allow a comparison of flood

results. The measurement of mean elevation by Lystrom is described on page

Headwater elevation ( $E_w$ ) is the elevation of the head of the longest stream channel. It was measured by the author to the nearest ten feet, which meant that estimation by the noting of local land slope was often necessary because contour intervals varied from 25 to 80 feet.

Maximum basin elevation ( $E_m$ ) was the highest observed elevation in any basin. As such, it was often the same as headwater elevation, but it served two functions. First, maximum elevation was used to delineate Western Cascades from High Cascades. Those basins with a maximum elevation less than 6000 feet are part of the lower, western Cascade physiographic province. Second, differences in correlation results of headwater and maximum elevations allowed the identification of a flood hydrology attribute.

#### F. Hypsometric Integral

Hypsometric curves were computed two ways: an elevation-relief ratio (ER) and the hypsometric integral (HI). Wood and Snell (1960) and Pike (1963) obtained a simple arithmetic expression called the elevation-relief ratio (ER) which Pike and Wilson (1971) demonstrated to be mathematically identical to the hypsometric integral:

$$ER = \frac{(\text{mean elevation minus minimum elevation})}{R}$$

Two "R" values can be used here. Basin relief ( $R_b$ ) is perhaps the most obvious value, is the true total relief of the basin,

and was used by the author in this study. Watershed relief ( $R_w$ ), on the other hand, avoids the possible pitfall of over-weighting the ratio unduly in favor of a single, isolated high peak of small surface area. An isolated high peak may not contribute a proportional elevation area to the true hypsometric curve as the associated ER ratio would suggest. Both ER ratios have been calculated and are examined. The former, however, gives a truer picture.

Also computed is an approximate hypsometric curve from sample elevation points. Strahler is commonly credited with first devising the hypsometric integral as: "a solid bounded on the sides by the vertical projection of the basin perimeters and on the top base by parallel planes passing through the summit and mouth respectively." (Strahler, 1952:1119) Strahler's method of measuring contour line lengths and areas between successive contours is very tedious and has led to attempts to simplify the approximation, most notably by Chorley and Morley (1959) and Haan and Johnson (1966). Hypsometric curves are cumulative frequency curves of basin elevations rotated 90 degrees. Haan and Johnson (1966) used this knowledge to develop a curve based on random sampling of elevations. Although Clark (1966) criticized sampling for this purpose, he had in mind sample spot elevation estimates. These tend to be peak elevations and thus are not representative of the area. This author's interpretation is that both sets of authors are correct.

A point of disagreement this investigator has with Haan and

Johnson concerns sampling technique. Because the samples are meant to be representative elevations of sample areas, systematic areal sampling is undertaken. Maximum and minimum elevations are noted within each square area and an average is computed. Each sample square is one mile on a side and equi-distant from neighboring squares. Each average elevation, then, is an average elevation of a unit area.

The sample average elevations are then ordered by magnitude with ties receiving successive rank numbers. The mouth elevations and maximum basin elevations are included in this list, such that with order number plotted against elevation and both axis being of equal length, a percentage area versus percentage elevation curve results. The area beneath the curve is the hypsometric integral (HI):

$$HI = \int_{Eo}^{Em} \text{Area}$$

The area under the curve is measured and reported as a percentage of the total area (of the equal-axis-length graph).

#### G. Watershed Shape

Watershed shape was indexed in four ways. Form ratio suggested by Horton (1932) was computed by dividing the drainage area ( $A$ ) by the square of the basin or watershed length. In Strahler's (1968) symbols:

$$\text{Shape 1} = \frac{A}{(L_b)^2} \quad \text{and} \quad \text{Shape 2} = \frac{A}{(L_w)^2}$$

Elongation ratio, suggested by Schumm (1956), was determined by dividing the diameter ( $D_c$ ) of a circle with the same area as the basin in question, but the basin length. In symbols:

$$\text{Shape 3} = \frac{D_c}{L_b} \quad \text{and Shape 4} = \frac{D_c}{L_w} \quad \text{where } D_c = 2\sqrt{A/\pi}.$$

Ratios so calculated are dimensionless. Fan-shaped or circular watersheds have indices which approach unity. Long, narrow watersheds have indices which approach zero. These four shape indices were calculated and measured by the author for this study.

#### H. Orientation

Orientation, an index of exposure, was measured three different ways: stream direction, vector direction of the basin water movement, and basin orientation. Names, definitions, and measurement of each orientation variable are explained below.

##### 1. Stream Direction (Ds)

Stream direction was determined by measuring one mile segments starting at the headwaters of the longest stream, progressing downstream to the mouth. A pair of dividers, calibrated to the unit distance, was used to determine the length and a protractor was used to measure the azimuth in degrees from north towards which the stream was flowing. The dividers disengaged the operator from having to measure a sinuous stream with unknown cartographic error and, at the same time, provided a reasonable smoothing effect.

##### 2. Watershed Orientation (Dw)

Vector direction of the water movement or watershed orientation, was determined along the watershed length chord. Watershed direction is defined as the downstream compass direction in degrees of the longest chord connecting the mouth to some distant point on the watershed.

### 3. Basin Orientation (Db)

Basin orientation, on the other hand, is the downstream compass direction in degrees along the longest chord that can be constructed which connects two points on the watershed (Lb).

The three orientation indices, Ds, Dw, and Db, were plotted with flood frequency values on polar coordinate graph paper. Frequency values of higher values were plotted further from the center, allowing visual interpretation of the results. See Figure 10 for an illustration of the definitions.

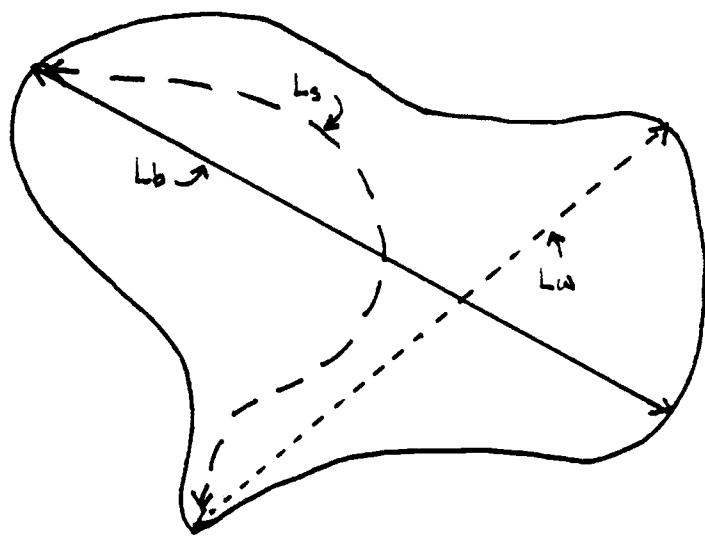


Figure 9: Length measurements.

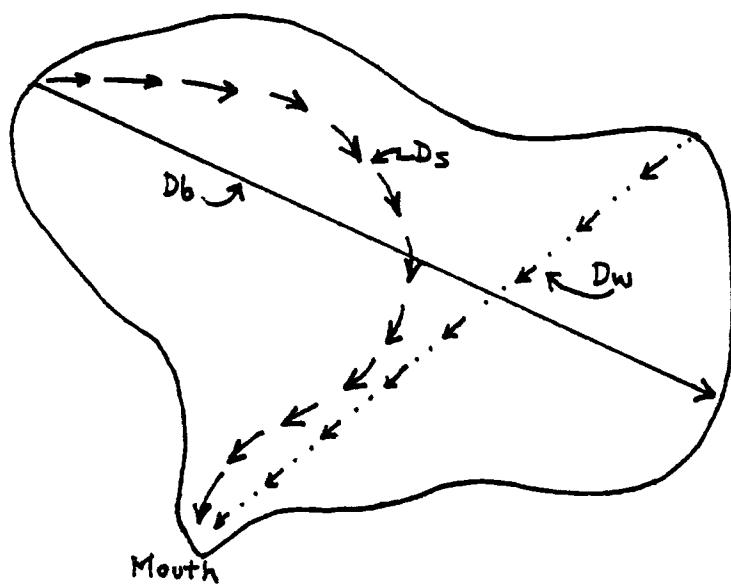


Figure 10: Three orientation variables illustrated.

#### IV. SUBREGIONS

Basin location is closely related to direction because streams from the Coast Range are generally east-flowing and streams from the Cascades are west-flowing. Four locations or subregions were identified: Coast Range, Willamette Lowland, Western Cascades, and High Cascades.

Basin location was examined by plotting flood frequency values on a map of the Willamette basin. This allowed a visual inspection of elevation regions and latitudinal zonation, as well as physiographic regions. An analysis of variance was performed to test for groupings. Because only two groups segregated out in the analysis, location was numerically indexed by use of an indicator (dummy) variable. The use of an indicator variable allowed location to be accounted for in multiple regression. The Willamette Lowland and Cascade streams made up one group and the Coast Range streams the other group.

## V. PUBLISHED DATA

### A. Introduction

Lystrom (1970) examined nine "independent" variables in an effort to explain peak flow magnitudes of various return intervals. Those variables used from Lystrom's work are identified in Table 1.

### B. Climate

The climate variables were derived originally from three sources and reported by Lystrom (1970). Mean annual precipitation expressed in inches was "determined from an isohyetal map prepared by the U.S. Weather Bureau River Forecast Center, Portland, Oregon, using adjusted climatological data (1930-1957) and values derived by correlation with physiographic factors" (Lystrom, 1970:14).

Precipitation intensity was determined from the U.S. Weather Bureau's (1961) "Rainfall Frequency Atlas of the United States". It is defined as the maximum 24-hour rainfall having a recurrence interval of 2 years (Lystrom, 1970:14). This is the so-called two-year 24-hour maximum precipitation intensity.

Ratios between precipitation delivered during extreme peak flows to that delivered during average peak flows would have been ideal to test certain hypotheses. Basin-by-basin analysis of point precipitation information extrapolated over large areas is not reliable enough to use as input variables in a scientific design. Few mid- and high-elevation weather stations exist. It was necessary to use two-year, 24-hour intensity data from very small scale maps or to introduce operator bias or error into

developing the more desirable data. Results of this research support the expected applicability of interpreting these relationships.

The winter temperature index was determined from the U.S. Weather Bureau publication, "Climatography of the United States", by Stearnes (1960). It is defined as the mean minimum January temperature in °F (Lystrom, 1970:14).

#### C. Geometry Variables

The geometry variables, area of lakes and ponds and mean basin elevation, were determined from "the most recent quadrangle maps available" (Lystrom, 1970:14). The surface water storage area was the total area of lakes and ponds expressed as a percentage plus one percent. Although not explained by Lystrom, the one percent addition accomplished two objectives: It accounted for the percentage of area which occurs as streams, and it also eliminated the possibility of non-zero statistics for those basins without lakes or ponds, allowing logarithmic transformations.

"Mean basin elevation was "determined from (a) quadrangle map of a practical scale by laying a grid over the map, recording the elevation at each grid intersection, and averaging those elevations. The grid spacing was selected to give at least 25 intersections with the basin boundary" (Lystrom, 1970:14). It was expressed in thousands of feet to the nearest ten feet.

#### D. Soil Permeability

Soil permeability index values "were determined from a

map compiled from computed values of soils indexes according to procedures described by the Soil Conservation Service (1959; 1964). Data for these computations were derived from soils-association and land-use maps included in the Columbia North-Pacific Framework Study (unpublished manuscript). Data were also furnished by the Soil Conservation Service staff, State Office, Portland, Oregon" (Lystrom, 1970:14).

#### E. Forest Cover

Forest cover, "as shown on the most recent quadrangle maps available", is that percentage area of the basin covered by forests (Lystrom, 1970:14). The one percent addition eliminated non-zero forest cover variables, thus allowing logarithmic transformations.

<u>Variables</u>	<u>Dimensions</u>	<u>Source</u>
Drainage area	$(\text{Length})^2$	U.S.G.S. (1963)
Basin length	Length	Map measurement
Watershed length	Length	Map measurement
Channel length	Length	Lystrom (1970)
Form ratio	Dimensionless ratio	Map measurement
Elongation ratio	Dimensionless ratio	Map measurement
Basin relief	Length	Map measurement
Watershed relief	Length	Map measurement
Local relief	$(\text{Length})^{-1}$	Map measurement
Average land slope	Dimensionless percentage	Map measurement
Basin slope	Dimensionless ratio	Map measurement
Watershed slope	Dimensionless ratio	Map measurement
Channel slope	Dimensionless ratio	Map measurement
Channel slope	Dimensionless ratio	Lystrom (1970)
Mean basin elevation	Length	Lystrom (1970)
Maximum basin elevation	Length	Map measurement
Headwater elevation	Length	Map measurement
Hypsometric integral	Dimensionless ratio	Map measurement
Elevation-relief ratio	Dimensionless ratio	Map measurement
Watershed orientation	Degrees	Map measurement
Basin orientation	Degrees	Map measurement
Stream orientation	Degrees	Map measurement
Percent area in surface water	Dimensionless percentage	Lystrom (1970)
Soil permeability	Length	Lystrom (1970)
Percent forest cover	Dimensionless ratio	Lystrom (1970)
Mean annual precipitation	Length	Lystrom (1970)
Precipitation intensity	Length/time	Lystrom (1970)
Slope of the flood frequency curve	$\log \frac{(\text{length})^3}{\text{time}}$	Calculated from U.S.G.S. flow records
Median annual peak flow	$\log \frac{(\text{length})^3}{\text{time}}$	Calculated from U.S.G.S. flow records

Table 1: Variables: dimensions and sources.

<u>Symbol</u>	<u>Variable</u>
"S" value	Slope of flood frequency curve or the standard deviation of the logarithms of the annual peak flows
M	Mean of the logarithms of the annual peak flows
A	Drainage area in square miles
Lb	Basin length in miles
Lw	Watershed length in miles
Ls	Channel length of longest channel in miles
Rb	Basin relief in feet
Rw	Watershed relief in feet
R1	Local relief in feet per square mile
Sw	Watershed slope in feet per mile
Sb	Basin slope in feet per mile
Sm	Average land slope as a percent
Eo	Month elevation in feet
E	Mean basin elevation in feet
Ew	Headwater elevation in feet
Em	Maximum elevation in feet
HI	Hypsometric integral as a percentage
ER	Elevation-Relief ratio
S <sub>1</sub>	Basin form ratio
S <sub>2</sub>	Watershed form ratio
S <sub>3</sub>	Basin elongation ratio
S <sub>4</sub>	Watershed elongation ratio
Dw	Watershed orientation in degrees
Db	Basin orientation in degrees
Ds	Stream orientation in degrees
Sp	Soil permeability in inches
Fc	Percent forest cover
M.A.P.	Mean annual precipitation in inches
I <sub>2,24</sub>	Precipitation in inches per 24 hours
% St	Percent surface area in streams, ponds and lakes

Table 2: Symbols of variables.

## CHAPTER FOUR RESULTS

## I. GENERAL

Analysis and interpretation demonstrate that statistically significant stream-to-stream differences in peak flow curves exist for streams within one drainage basin. These differences are reflected in differences of "S" values or slopes of the flood frequency curves.

Differences between "S" values are related to specific hydrophysical characteristics of each drainage basin. Because of that, peak flow frequency regionalization by drainage basin characteristics can be accomplished in the same manner that peak flow magnitudes have been regionalized. This contrasts with the traditional frequency regionalization technique which utilizes median ratios. Predictive equations to accomplish this new regionalization method are developed and presented. The variables which prove most useful are climatic indices and soil and forest cover indices. However, these are secondary and tertiary influences on peak flow magnitude, where the primary influences, drainage area and terrain ruggedness, remain important for all frequencies and sizes of annual peak flows. An interpretation made here is that these primary flood influences become more important with an increase in the size and corresponding decrease in the frequency of a peak flow event.

Also of importance is the effect of climate-related

topographic variables, such as watershed relief, elevation, and drainage basin orientation, on peak flows. The most significant influence exhibited is by watershed relief. For those drainages above the Willamette lowland, which possess a distinctly different flood climatology, total relief measures the internal (within basin) variability of precipitation before and during peak-flow-related weather events. Large differences lead to large year-to-year differences in peak flows and, in that manner, to steep flood frequency curves.

Basin orientation is correlated with precipitation intensity and with differential snow accumulation rates (primarily through the heat budget). More extreme peaks, in contrast, result from storms which deliver a large amount of water to all basins, yielding flood frequency curves, the slopes of which are dependent upon basin orientation.

Mean basin elevation is a highly significant inverse influence on the median annual flood (M.A.F.). During the average peak flow event less water is released from the snowpack from higher elevation basins than is released from rain on saturated mantles of the lower elevation. Flood frequency curves of higher elevation basins are steeper, however. The correlation between headwater elevation and the "S" value is more prominent than for mean basin elevation, and thereby demonstrates two relationships. First, as elevation increases, more extreme events are required to release the snowpack. Second, during more extreme peaks

the entire drainage basin contributes proportionately.

Mean annual precipitation is inversely correlated with the "S" value. The interpretation made here is that M.A.P. indexes antecedent moisture conditions and average total storm volumes. Antecedent moisture conditions refer to the composite condition of soil moisture and snow water (ripe or not and total water equivalencies).

Surface water area, expressed as a percentage of the total drainage area, is a minor but statistically significant control of the peak flow distribution. Lakes and impoundments (all natural in this study) act as moderators on average peak flows but are even more significant flow reducers of more extreme peaks. In that manner, the percent area of surface water bodies influences the slope of the flood frequency curve.

In addition to results of the frequency investigation generalized upon above, peak flow magnitude was re-investigated. Predictive equations were developed which are superior to existing equations. For example, the coefficient of determination ( $R^2$ ) developed in this research for the median annual flood is about 95 percent with a standard error of 16 percent. This equation has only four independent variables, in comparison to Lystrom's equation with seven variables and a standard error of 46 percent. Lystrom did not report  $R^2$  values. Hudziekewicz's formula was developed from limited data (five years of record to define the M.A.F.) with an associated  $R^2$  of 70 percent. Hudziekewicz did

not report a standard error. Both equations with three independent variables presented herein have  $R^2$  values of over 90 percent and yet have standard errors of 21 percent.

The flood magnitude equations reemphasize the significance of terrain roughness reported in a few earlier works, but largely neglected in most flood formulas, most notably in U.S. Geological Survey investigations. Terrain roughness is represented by average land slope or by average local relief (per square mile) in these equations. Traditionally, slope variables used in flood formulas are some measure of channel slope and these formulas generally have large standard errors associated with them.

The finding that geomorphic characteristics best explain within-region differences of mean peak flow magnitude but that climate and soil/cover variables best explain within-region differences in distributions, may explain universal relationships heretofore misrepresented or misconceptualized. This research incorporates climate into flood estimation procedures in a manner not previously reported. Antecedent moisture conditions and within-basin variation in climatology appear to be particularly important.

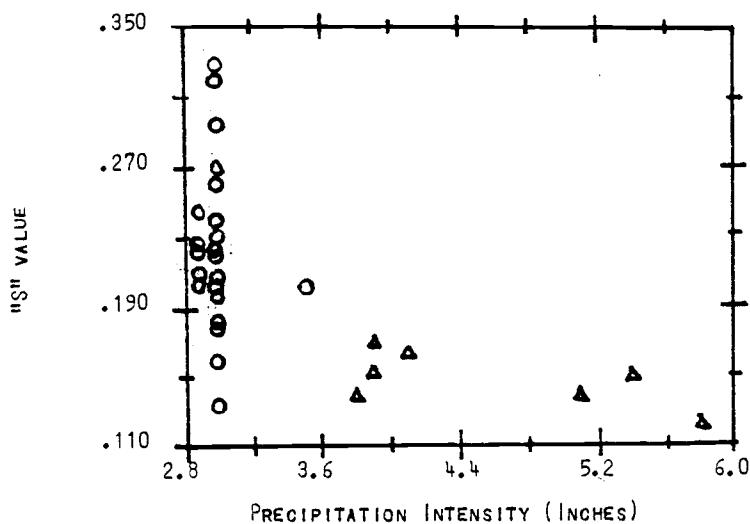


Figure 11: Scatter diagram of precipitation intensity (two-year, 24-hour maximum) against "S" value.  $\blacktriangle$  -- indicates Coast Range streams.  $\circ$  -- indicates Cascade or Lowland stream.

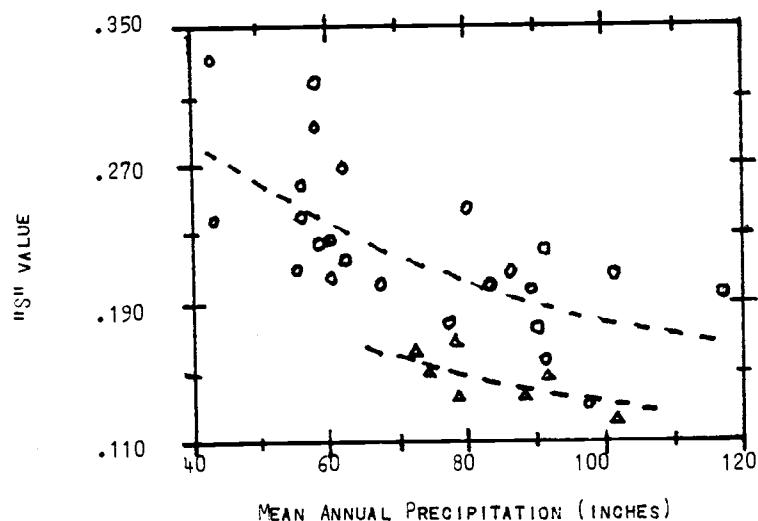


Figure 12: Scatter diagram of mean annual precipitation against "S" value. Dashed lines indicate regression lines of Coast Range streams (lower curve) and Cascade streams (upper curve) where  $S = \frac{C}{(M.A.P.)^P}$ .  $\blacktriangle$  -- indicates Coast Range streams.  $\circ$  -- indicates Cascade or Lowland stream.

## II. REGIONALIZATION

### A. Physiographic Regions

Differences between flood frequency curves of the Coast Range and Cascade streams are demonstrated both by map inspection and by analysis of variance results. Figure 12 is a scatter diagram which shows curves for the Cascades and the Coast Range relating M.A.P. to the "S" value. Rivers in the Cascades have steeper flood frequency curves. This is attributed to two major differences between the two sub-regions; precipitation intensity and snow climatology.

Steeper flood frequency curves relate to the ratios between extreme frequency peak flows to higher frequency peak flows. This can be caused by a) comparatively smaller high-frequency events, b) comparatively larger extreme-peak flow events, or c) both.

In the case of the Cascades in general both conditions are occurring because those basins have lesser average maximum precipitation intensities, and, or secondary importance, higher elevation. The Cascades generally have higher elevations ( $r = +0.54$  for mean elevation and  $+0.46$  for headwater elevation) which indicate a potential snow water equivalency addition to peak flows. This latter point will be explained shortly.

The Coast Range basins have larger precipitation intensities than the Cascade basins ( $r = -0.87$ ), but this is true only for the average peak flow events. The more extreme peaks result from three-to-five-day quasi-stationary occluded fronts

releasing both rain and heat onto a snow-covered surface. During these conditions, the snow pack ripens and releases water through melt, rather than absorbing much of the precipitation. Due to the widespread nature of these storm systems, which often cover hundreds of miles, there is little basin-to-basin difference in total precipitation.

Unfortunately, climate data are not extensive or detailed enough to analytically assess this interpretation. In further support of it, however, precipitation intensity is the only variable, of over 30 measured, which strongly correlates with location. The definition of "strong correlation" in this report is a correlation coefficient with an absolute value of greater than 0.60.

Of interest are the correlations between basin orientation, precipitation intensity, and the "S" value. These suggest that precipitation intensity and basin orientation are directly related. Watershed orientation and "S" have a correlation coefficient of +0.63.

#### B. Elevational Regionalization

##### 1. General Trend

Flood frequency curves are steeper for higher headwater elevations due to the increased contribution of headwater areas to peak flows during extreme peak flow events. Ignoring for a moment the low elevation outliers, the simple linear correlation coefficient between "S" and headwater elevations is +0.71.

The low elevation outliers belong to a different flood frequency region as will be explained below. See Figure 14.

The contribution of high elevation headwater areas to only extreme peaks could be attributed solely to the nature of the weather events creating extreme flows, (i.e., the long duration occluded fronts). This condition would allow runoff from the most extreme tributaries to contribute to peaks of Willamette basin rivers.

Other factors seem to be operating, however, though these are in addition to those presented above. Snow melt from headwater areas is an important condition for extreme events, whereas for the "mean annual flood" much of the runoff is from storm precipitation. At higher elevations during an "average" peak flow event, precipitation may be snow or rain which is absorbed by an existing snowpack or permeable, volcanic soil.

Elevation in this instance indexes snow depth and the associated water content. This is supported by the correlation between the mean daily minimum temperature for January reported by Lystrom (1970) (a winter temperature index) and mean basin elevation. The correlation coefficient ( $r$ ) for the streams studied herein is -0.86 and between headwater elevation and Lystrom's mean basin winter temperature index  $r = -0.82$ . Furthermore, the correlation ( $r$ ) between the S.C.S.'s mean January snow water equivalency and elevation for Willamette stations is +0.90 and is demonstrated in Figure 15.

Headwater elevation could also index air uplift due to basin rise or soil permeability and in one or both of these ways influence "S". The correlation between headwater elevation and watershed relief is +0.98 and between headwater elevation and the soil permeability index +0.85. Basin rise increases upward air flow patterns and resulting precipitation totals. "S" decreases with increases in precipitation, eliminating that interpretation because basin rise and "S" are positively correlated ( $r = +0.30$ ), although weakly.

In addition, mean annual precipitation and elevation are insignificantly correlated ( $r = +0.17$ ), though precipitation intensity and elevation are significantly correlated ( $r = -0.47$ ). This latter correlation is attributed primarily to the locations of the Cascades and the Coast Range with regard to the winter storms and only secondarily to a causal elevation-intensity relationship.

Soil permeability, in contrast, is a contributing factor to the influence that headwater elevation has on the slope of the flood frequency curve. Although soil permeabilities for headwater areas are not recorded, the very strong correlation between mean basin elevation and mean basin soil permeability ( $r = +0.90$ ) support this. Furthermore, both large soil permeabilities and high elevations tend to suppress average peak flows per unit area. Permeability loses significance as an influence on the peak flows associated with more extreme events

while headwater elevation takes on greater significance. The soil permeability influence will be discussed more completely in a following section.

A third area of possible hydrophysical significance is the correlation between headwater elevation and local relief ( $r = +0.64$ ). Local relief, however, is an insignificant influence on "S" ( $r = +0.05$ ).

Mean basin elevation is also directly related to the slope of the flood frequency curve ("S"). In simple correlation, the pattern is weak ( $r = +0.31$ ) as shown in Figure 17.

In multiple regression, however, mean basin elevation shows itself a strong influence. It is positively correlated with "S" and explains an additional 22 percent of the stream-to-stream variability in "S" values. In simple regression M.A.P. explains almost 46 percent and in multiple regression mean basin elevation and M.A.P. explain 68 percent.

## 2. Lower Subregion

Below about 2900 feet headwater elevation the peak flow climatology is so radically different than above 3000 feet, that large streams with headwaters below this threshold are not part of the same flood distribution region. This difference is attributed primarily to the snow pack providing insignificant storage of water equivalency available to peak flows for the lower area. This lower "subregion" is primarily a rainfall flood region with seasonally impermeable, saturated soils. Frequently, the regional water table is at or near the

surface during peaks.

### 3. Higher Subregion

Above about 8000 feet a third hydrologic subregion exists. This region has permanent ice fields and internal drainage. The internal drainage results primarily from alpine ice-sculptured terrain and the extra-permeable recent volcanics contribute to subsurface flow. The net result of these conditions and associated climate conditions are low peak flows per unit area and a comparatively low year-to-year difference in peak flow volumes. The comparison in this case is made with flood records of streams with maximum elevation areas just below the 8000 foot threshold.

A third result of these climatically and geologically related conditions is that areas located above 8000 feet (2400 meters) elevation do not significantly contribute to peak flows of even extreme frequencies. This knowledge allows one to refine the effective contributing area of these upper drainages. Figure 13 demonstrates the outliers above 8000 feet (maximum elevation).

### 4. Basin Relief

Watershed relief has the most significant correlation with "S" ( $r = +0.75$ ). This correlation is only  $+0.27$  with all observations, but examination of the 28 streams located above 3000 feet (headwater elevation) allows the significance of watershed relief to become readily apparent (Figure 16).

Watershed relief has moderate correlations with several other attributes, but the interpretation becomes obvious when

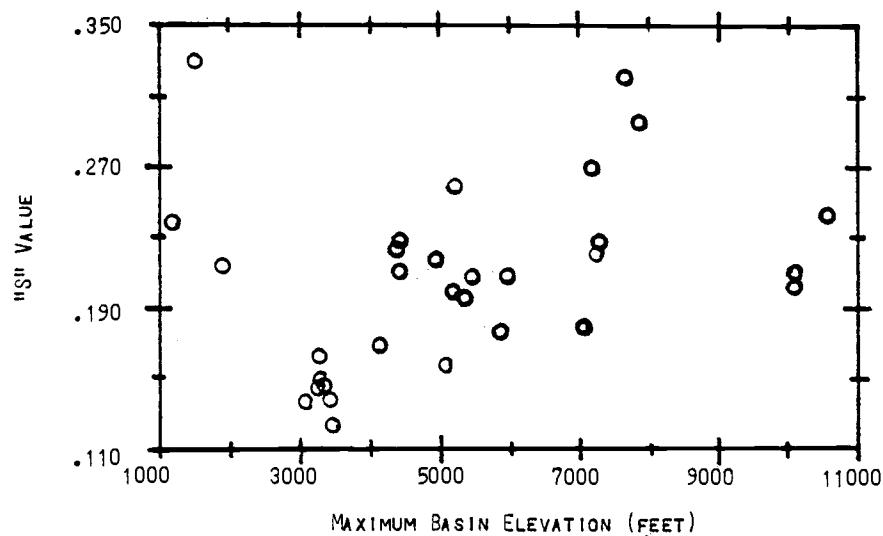


Figure 13: Scatter diagram of maximum basin elevation against "S" value. All 31 observations are included.

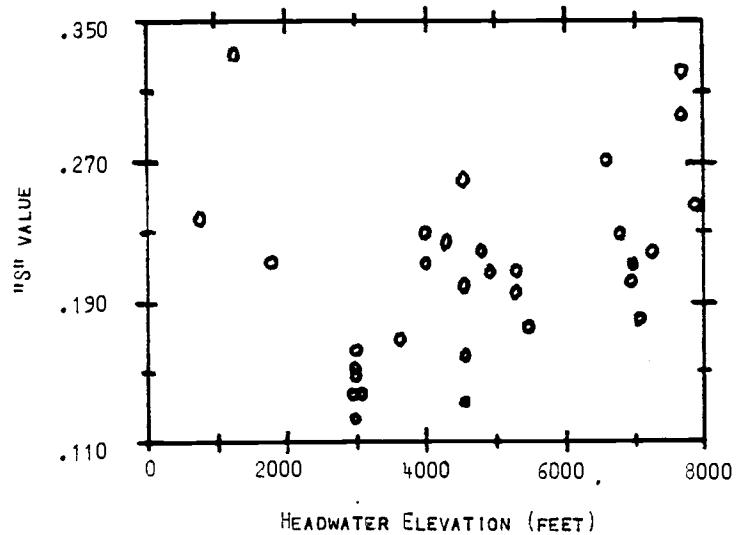


Figure 14: Scatter diagram of headwater elevation against "S" value. All 31 observations are included.

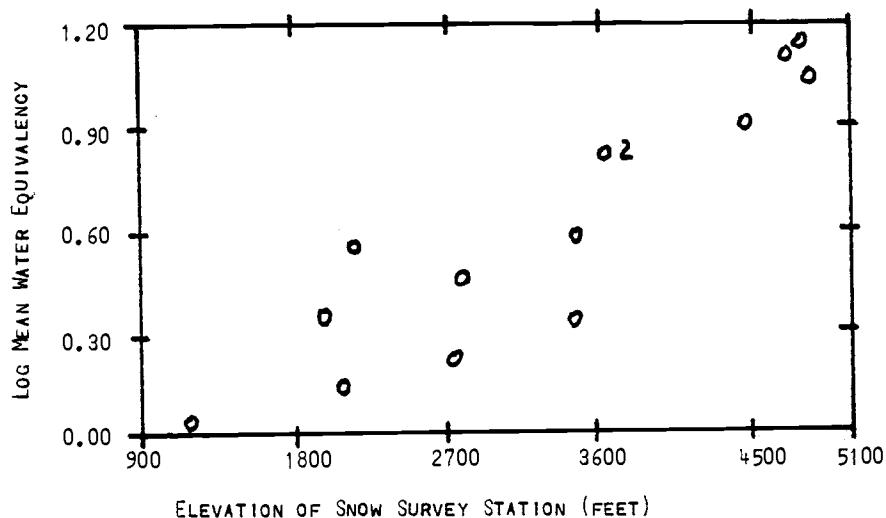


Figure 15: Scatter diagram of elevation of snow survey station against mean of the logarithm of the January water equivalents. Stations are predominantly located in the Cascades but a few are located in the Coast Range. The correlation coefficient is +0.90.

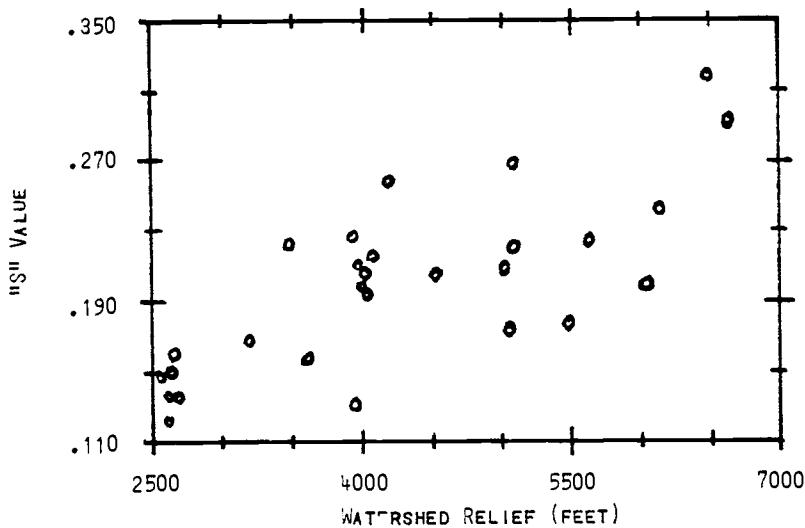


Figure 16: Scatter diagram of watershed relief against the "S" value. The 28 plotted observations are those streams that have headwaters above 3000 feet elevation. The correlation coefficient is +0.75.

one considers the details. Watershed relief is an index of within-basin variance of climatically-differing contributing areas to peak flows. The strongest correlation, (+0.98), is with headwater elevation. To assign separate significances to these variables may appear suspect, but the interpretations merge and support each other. First, mean annual precipitation and mean 24-hour maximum annual precipitation intensity have insignificant and moderate correlations, respectively, with watershed relief ( $r = +0.14$  and  $-0.44$ ). Although the winter temperature index presented by Lystrom has a strong inverse correlation with watershed relief ( $r = -0.73$ ), its correlation with headwater elevation ( $r = -0.82$ ) and with average basin elevation ( $r = -0.86$ ) are more significant both statistically and hydrophysically.

Watershed relief, in this case, indexes the total variability of winter temperature and, therefore, snowpack conditions within a drainage basin. This means large differences in snowpack water equivalencies, snow ripening conditions, and precipitation form exist within basins that have large total reliefs. The result in terms of flood hydrology and, in particular, flood frequency curves, is larger variance in peak flows. This means steeper flood frequency curves should result, which is what happens.

For drainages with headwater elevations above 2900 feet, total watershed relief alone explains over 56 percent of the stream-to-stream variability in slopes of the respective flood frequency curves. In Chapter Five, a model is presented

which incorporates watershed relief, mean annual precipitation, and percent surface storage area. That model explains 86 percent of the stream-to-stream differences in "S" for Willamette River basin streams with headwaters above 2900 feet elevation.

It should be noted that drainage area does not account for very much stream-to-stream variability in "S" ( $r^2 = 4\%$ ), even though it could index internal differences in source area, much like relief does. This is because large areas can be similar in flood hydrology conditions, but drainages with large reliefs can be only rarely.

#### C. Regionalization by Mean Annual Precipitation

##### 1. General

Mean annual precipitation (M.A.P.) can be used to approximate "S" (slope of the flood frequency curve) in a regression equation,  $r^2 = 45\%$ . M.A.P. is inversely correlated to "S" and is interpreted to index general antecedent moisture conditions and average storm volumes associated with annual peak flows.

The inverse relationship between "S" and M.A.P. ( $r = -0.68$ ) is due to large differences in antecedent moisture conditions between basins for average peaks but, due to the type of weather events and added flow contribution from headwater areas, during extreme events a greatly decreased basin-to-basin difference in antecedent conditions exists.

That mean annual precipitation indexes antecedent moisture conditions is shown by several correlations. First, M.A.P. and

mean precipitation intensity are weakly correlated ( $r = +0.32$ ).

Both, however, are inversely related to "S". Second, M.A.P. and precipitation intensity have additive influences on "S", as is shown by multiple regression ( $R = 0.84$ ), suggesting that each variable indexes different attributes.

Third, the only three factors to which M.A.P. is meaningfully correlated with an absolute value of the correlation coefficient of 0.5 or greater are: soil permeability ( $r = 0.51$ ), percent forest cover ( $r = 0.50$ ) and channel slope ( $r = 0.52$ ). Though these variables influence the amount and flow rates of water in storage within a watershed, soil permeability and forest cover interact with M.A.P. in nonlinear equations to be best estimators of "S". Furthermore, these variables do not explain "S" at a significant level in simple linear correlation. The simple correlation coefficient between soil permeability and "S" is 0.09 and between percent forest cover and "S" is 0.13. Neither correlation is statistically significant. This means the equations truly express interaction between independent variables.

The interpretation is that the M.A.P. and forest cover and the M.A.P. and soil relationships define antecedent conditions. This interpretation is discussed more completely in following sections.

## 2. Precipitation Intensity

Precipitation intensity, an index of mean storm precipitation and M.A.P., an index of antecedent conditions, explains

over 70% of the stream-to-stream differences in slopes of the flood frequency curves (the coefficient of determination,  $R^2 = 70\%$ ).

Precipitation intensity can be substituted for by the binary location variable as explained in section II-A of this chapter.

This substitutability is further indicated by scatter diagram where streams of the Coast Range and the Cascade Mountains are plotted with different symbols (Figure 11) and by the multiple correlation coefficient of 0.84.

Separate equations for the two precipitation intensity sub-regions can be developed, but only seven observations define the Coast Range sub-region. This lessens the confidence level for the Coast Range estimate. The pooled observations (Coast and Cascade) makes the assumptions that the slope of the regression line is better estimated by more observations and that the main difference between the two groups lies in relative magnitudes. Inspection of the scatter diagram (Figure 12) suggests that those assumptions are not precisely correct but are approximately correct.

Substitution of precipitation intensity itself for the binary variable, which represents two precipitation intensity regions, does not improve the predictive capability ( $R^2$  is still about 70%) but is more specific in terms of cause and effect. The disadvantage, of course, is that mean annual maximum 24-hour precipitation intensity is difficult to assess accurately.

### 3. Influence of Soil Permeability

It was previously indicated that soil permeability does not correlate with "S" in simple regression ( $r = +0.09$ ) but in combination with M.A.P. in nonlinear multiple regression, soil permeability is a strong secondary influence. The percent stream-to-stream variability in "S" explained by the regression equation improves from 45 percent to 75 percent with the addition of soil permeability. This means the residuals from the simpler equation are almost half accounted for by soil permeability. The addition of soil permeability (partial F test) is significant at the 99 percent confidence level.

Of particular interest is the lack of correlation between "S" and soil permeability when examined in simple regression ( $r = +0.09$ ). Considering that lack of correlation and the observed strong influence soil permeability has in combination with mean annual precipitation upon "S", soil permeability is interpreted as a measure of quick flow available to flood peaks.

Basins with higher average soil permeabilities have lesser average flood peaks and as the event becomes more extreme, the permeable soils contribute more water, but do it through both surface and subsurface flow. This added contribution may be disproportionately larger with an extreme event because of the additional storage of free water often associated with permeable, volcanic rocks and soils. This soil influence should be more significant in more humid antecedent moisture conditions, which is precisely what the equation suggests.

Furthermore, soil permeability varies directly with elevation ( $r = +0.90$ ) but is only weakly associated with the mean storm precipitation index. The interaction of soil permeability and snow water (indexed by elevation), another measure of stored water available for storm runoff, suggests two things.

First, it is possible that too much influence is being attributed to soil permeability when, in fact, both snow and soil moisture conditions contribute. The correlation coefficient between soils and headwater elevation is +0.85. Because soil permeability is not correlated with "S" in simple regression but headwater elevation is, the interpretation made here is that both influences are important, but soil permeability is important as an interactive variable with mean annual precipitation to define antecedent moisture conditions.

Second, soil permeability as an input variable is a stronger predictor than elevation. This was shown by the multiple regression results presented previously.

Another variable that could, but isn't, interpreted as partially accounting for the significance of soil permeability is local relief. The correlation coefficient between local relief and soil permeability is +0.80. Because "S" does not vary with local relief and because the influences should be opposite upon surface runoff concentration times, soil permeability must be considered to be an important influence (on "S") on its own merit.

The overall results are that antecedent conditions are

defined primarily by precipitation and soil permeability. General relationships exist which link variances of peak flow to annual precipitation and soil permeability further modifies the effect of antecedent moisture conditions. With extreme peak flow events antecedent conditions become nearly alike from basin-to-basin thus offering little explanation of stream-to-stream differences in runoff.

#### 4. Forest Cover Influence

Forest cover also interacts with mean annual precipitation in a multiple regression model to index antecedent moisture conditions and, in that manner, quick flow to average-sized peaks. As with the interaction in the multiple regression model of mean annual precipitation with soil permeability, M.A.P. and forest cover together assume low significance in defining basin-to-basin differences during extremely large peak flows. These influences result in an estimation equation which shows that flood frequency curves are steeper for streams whose basins have a higher percentage forest cover. That equation accounts for 73 percent of the stream-to-stream variance in "S".

The relationship of forest cover to "S" is dependent upon mean annual precipitation, suggesting that forest cover is not just a secondary variable but is an interactive modifier of the characteristic that M.A.P. is partially indexing, antecedent moisture conditions. This is the same kind of relation as soil permeability has with M.A.P.

In fact, forest cover is strongly related to two basin characteristics which could explain its significance. The correlation between soil permeability and forest cover is strong ( $r = +0.75$ ). The correlation of percent forest cover with headwater elevation is less strong, but statistically significant ( $r = +0.52$ ). This means that percent forest cover could partially index the influence of these two variables. Both of these variables, as we've already seen, influence water availability to peak flows (antecedent moisture conditions).

Forest cover probably relates to the slope of the flood frequency curve for much the same reasons as do soil permeability and elevation. First, soil compaction from heavy equipment and from road construction are commonly associated with timber harvest. It is through soil compaction that many West Coast hydrologists believe timber harvest influences peak flows, especially lower magnitude fall season peaks.

Where the interpretations differ for this study are that annual peaks, sometimes of sizable magnitudes, often occur in the October and November period. Related to this, most hydrologists, including the author, did not believe that either soil character or land treatment greatly influenced annual peaks from large drainages (i.e., greater than 25 square miles) due to the sizes of the events and areas involved.

Second, forest cover influences water equivalency, of the snowpack and thereby influences the amount of water available to a peak flow event. Ingebo (1955) demonstrated in the Northern

Rockies a consistent 35 to 40 percent decrease in water equivalency for snow survey sites with complete forest canopy compared to open sites. This difference is attributable to many different physical processes but can be simplified to two without much loss of understanding. First, interception consistently accounts for 10 percent or more "loss" from the ground's snowpack. With longer duration storms, such as occur with more extreme peaks in the Willamette basin, the percentage intercepted tends to be smaller.

Second, the microclimate under a canopy, including the soils, tends to differ from openings. This is more true during the early part of the flood season than in midwinter. The microclimate difference, including reradiation from the trees, establishes differences in antecedent snowpack differences including temperature and this influence necessarily varies from storm-to storm. Forest cover also varies with M.A.P. ( $r = +0.50$ ) but this correlation does not account for the influence of forest cover. The interactive nature of M.A.P. and forest cover in the multiple regression model indicates that the influence of forest cover varies with M.A.P. and modifies it rather than indexing it.

Two similar variables that correlate strongly with forest cover but do not directly explain the significance of it are local relief (feet/square mile) and percent average land slope. Neither of these variables influence "S" so that relationship can be ignored for this interpretation.

It should be noted that there is a lack of correlation between forest cover and the location variable ( $r = -0.01$ ) and also no correlation between forest cover and precipitation intensity ( $r = +0.08$ ). This means the equations that included the M.A.P. and forest cover and M.A.P. and precipitation intensity have different hydrophysical interpretations. This lends further support to the interpretation that forest cover influences antecedent conditions as a modifier of annual precipitation (itself an index of seasonal precipitation) and in that way influences the slope of the flood frequency curve.

### III. OTHER BASIN GEOMETRY INFLUENCES

Most of the basin geometry elements are not influential factors in determining the slope of the flood frequency curve. A few, however, have minor influences worthy of mention.

#### A. Size

Watershed relief, watershed length, drainage area are all indexes of drainage size. The consistent, though low positive correlation of the length and area variables with "S" supports a hypothesis made earlier. The correlation coefficients between watershed relief, watershed length, and drainage area with "S" are, respectively, +0.27, +0.24, and +0.21. This means the flood frequency curves are steeper with larger drainages and that this influence is secondary to the influences of antecedent moisture conditions and mean storm size already identified. The primary influences of flood magnitude, area and terrain roughness, increase in significance as the duration of the storm increases due to increasing water contributions to peak flows from steeper, headwater areas. This is consistent with findings presented earlier. The correlation of watershed relief with "S" ( $r = +0.75$ ) for mid and high elevation streams was explained earlier.

#### B. Slope

Influences which are not easily understood are the influence of an overall basin slope index,  $Rw/A$ , on "S" ( $r = -0.28$ ) and the influences of local relief on "S" ( $r = +0.05$ ) and average land slope ( $r = -0.13$ ) on "S". At first glance these correlations

appear inconsistent with the previous interpretations. However, because elevation changes from an inverse influence on flood magnitude to a direct influence with an increase in return interval, elevation supplants the local terrain roughness variable and thereby supports both general and specific interpretations made herein.

#### C. Watershed Shape and Hypsometric Integral

Two variables hypothesized to influence the slope of the flood frequency curve but found to be insignificant are watershed shape ( $r = +0.02$ ) and hypsometric integral ( $r = 0.21$ ). Neither variable influences peak flow magnitudes in the Willamette River basin. This immediately indicates a low probability of influencing "S". This lack of peak flow influence results from overwhelming influences of terrain roughness upon concentration times. It was through concentration times that both these variables, shape and hypsometric integral, had been hypothesized to influence "S".

Watershed shape is not a control of concentration times in the Willamette River basin because, unlike in the Appalachians and the Umpqua River basin, large differences between watersheds do not exist. This creates the situation whereby watershed shape is not a sensitive enough variable to influence peak flows.

Hypsometric integral, in contrast, does reflect differences between basins and has a statistically significant, although weak, correlation with "S". The correlation is largely attributed

to its correlation with average basin elevation ( $r = +0.70$ ). Large hypsometric integrals are associated with higher average elevations, thus snow water equivalencies, but the headwater elevation correlation to hypsometric integral is weaker ( $r = +0.47$ ), thus making the hypsometric integral less useful as a predictive or explanatory variable. The elevation-relief ratio is also related to average relief per square mile ( $r = 0.83$ ) showing a geometrical attribute of the Willamette basins, but not explaining differences in flood distributions. The correlation between the "S" value and the hypsometric curve is statistically insignificant.

#### D. Terrain Influences - Conclusion

Several morphometric indices explain variations in within-region differences of peak flow distributions. These are: watershed relief, headwater elevation, watershed orientation, and percent area of surface water. Except for the last mentioned variable, these morphometric variables directly index climate. However, watershed relief does not index orographic uplift, as might be suspected, but instead indexes within-basin variance of climatic conditions and, therefore, source areas of peak flow runoff. Drainages with small watershed reliefs have similar antecedent conditions and storm characteristics throughout, whereas, drainages with large reliefs are apt to have large year-to-year differences in contributing source areas for peak flows.

Headwater elevation areas are infrequent contributing

sources to peak flow, especially in the higher elevations of the Willamette basin. During extreme events these headwater areas contribute disproportionately large water volumes because during these events snowpacks change from being storage areas for precipitation to being source of runoff areas. Furthermore, synchronization of flood volumes from throughout the drainages occurs during these extreme peaks.

Orientation of the watershed correlates with year-to-year peak flow distributions significantly during average-sized peak events but insignificantly during extreme peaks. During extreme peaks, factors such as differences between north-slope and south-slope and water delivered by storms take on less significance because the storms are widespread in both time and space.

#### IV. PREDICTION OF THE FLOOD FREQUENCY CURVE'S SLOPE

The variables involved and the prediction equations have been presented in general form. They are presented here for quick reference and for emphasis.

##### A. Equation 1

The equation with the highest prediction capability ( $R^2 = 76\%$ ) for all 31 streams (all elevations) is:

$$(1) "S" = \log e \left[ -0.38141 + 0.04981 (\text{Sp}) + \frac{13.382}{(\text{M.A.P.})^{0.7}} \right]$$

This equation and those that also include mean annual precipitation are considered to be sound primarily due to the inclusion of M.A.P. Many investigators, particularly statisticians, realize that 20 years of record is a very limited sample by which to describe the variance of a population ("S" is the positive square root of the variance). Three factors, one of them mean annual precipitation, tend to erase this complaint.

First of all, mean annual precipitation is a direct inclusion of water input into a flood frequency formula and it is, perhaps, the most accurate precipitation index one will have for hydrologic investigations. Second, the investigation used 20 years of concurrent record for all sample streams. The significance of M.A.P. is more than just for comparison of streams during these years.

The significance lies in indexing (in contrast to defining) antecedent conditions. The lack of needed precision to achieve results with predictive abilities at the 99 percent confidence levels

further points to the value of these equations.

Third, soil permeability has significance to the water balance. It directly influences the amount of water available for peak flows.

#### B. Equation 2

The second most powerful equation ( $R^2 = 73\%$ ) also reflects antecedent moisture conditions.

$$(2.) "S" = \log e [2.3356 + 0.0485 (Fc) - 0.475 (\ln M.A.P.)]$$

This equation is both more meaningful and less meaningful than it may first appear to be. It is less meaningful because percent forest cover changes over time and engineering decisions must be based on available data. The equation becomes more meaningful when used as a management tool. Coupled with the flood magnitude equations, which also include the two "independent" variables, the effect of canopy modification on peak flows from large streams can be estimated.

#### C. Equation 3

A third equation includes both antecedent moisture and mean annual storm indexes. The coefficient of determination is 67%.

$$(3.) "S" = \frac{3.8292}{(M.A.P.)^{0.50697} (I_{2,24})^{0.65289}}$$

#### D. Equation 4

A fourth equation simplifies the mean annual storm index by using a binary location variable, and, at the same time increases the measured prediction ability;  $R^2 = 70\%$ .

$$(4.) \quad "S" = \frac{C}{0.51644}$$

(M.A.P.)

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where;  $C = 1.43515$  for Coast Range  
 and  $C = 1.96938$  for Cascades and Lowlands

#### E. Watershed Relief Models

Because those basins with headwater elevations below 3000 feet belong to a separate flood frequency region, equations were developed from data representing 28 streams located above that elevation. The simplest model relates watershed relief to "S" and explains 56 percent of the stream-to-stream variability in "S".

$$(5.) \quad "S" = K \left[ 6.8137 \times 10^{-5} (Rw) - 0.16735 \right]$$

where  $K$  = conversion constant from natural logarithms to base 10 logarithms, (i.e.,  $\log e$  or 0.43429) and watershed relief is expressed in feet.

A more complex equation (nonlinear and multiple variables) explain 78 percent of the stream-to-stream differences in "S". This equation is of approximate value to equation 1 which explains 76 percent but is based on all elevations rather than limited population.

$$(6.) \quad "S" = K \left[ 0.15885 + 5.7844 \times 10^{-5} (Rw) + \frac{6.3798}{0.66} \right]$$

(M.A.P.)

where  $K$  = conversion constant equal to  $\log e$ , or 0.43429.

$Rw$  = watershed relief in feet

and M.A.P. = mean annual precipitation in inches

An inverse power (0.66) of M.A.P. is not the best expression

of the influence M.A.P. has on the residuals of the equation (6.) so a correction factor can be applied which increases the power of the predictive equation to 83 percent.

$$(7.) "S" = \log e \left[ 5.7679 \times 10^{-5} (Rw) + \frac{24.132}{0.66} + 9.0305 \times 10^{-3} (\text{M.A.P.}) - 1.8999 \right]$$

The inclusion of the second M.A.P. expression means this is still a three-variable equation and that M.A.P. raised to the -.66 power overestimates the inverse influence of antecedent conditions (as expressed by M.A.P.). The relative sizes of the coefficients (24.31 and 0.009) continue to demonstrate the significance of the inverse relationship.

The best predictive equation adds percent area in surface water (percent of the total area in streams, lakes, and ponds). The negative correlation disproves the original hypothesis but still supports a more general hypothesis. The original hypothesis was that a positive correlation was expected.

The inverse relationship between "S" and the percent area in surface water suggests that lakes and ponds become more important as retardants to peak flows for more extreme peaks. This, of course, contrasts with the belief that lakes and ponds deliver quick flow during the extreme events. The best explanation is that those drainage basins with large percent areas in surface water have lakes especially in the headwaters, which continue to retard peak flow contribution past that point in the stream system. Examination of Willamette basin streams, especially the High Cascade streams, supports this conclusion.

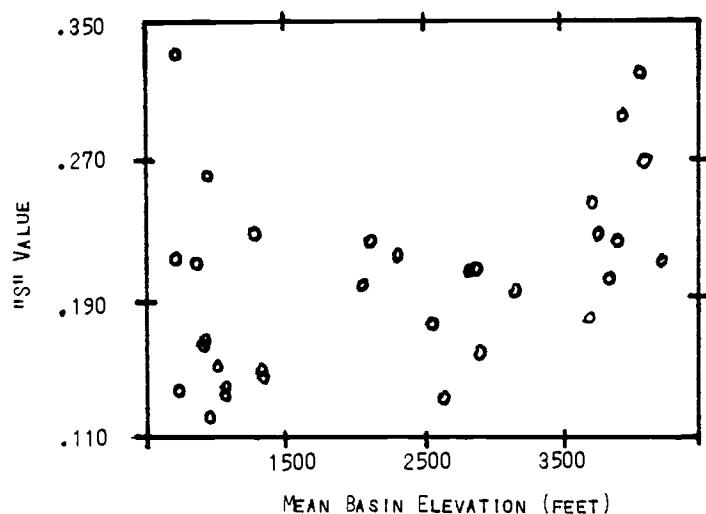


Figure 17: Scatter diagram of mean basin elevation and "S" value. All 31 observations are included.

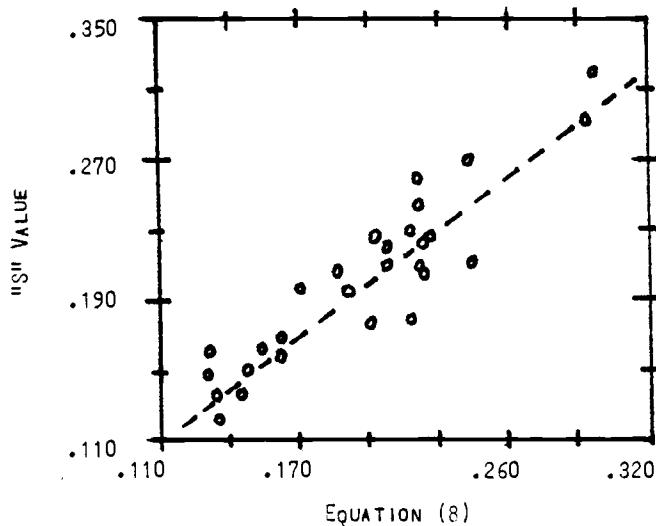


Figure 18: Scatter diagram of estimation equation 8 against observed "S" values. Observations are for all streams with headwater elevations above 3000 feet. The  $R^2$  value is 86%.

The equation explains 86 percent of the Willamette River basin's stream-to-stream variations in "S" (limiting the population to those 28 streams with headwaters above 3000 feet elevation).

$$(8.) \text{ "S" = } \log e \left[ 6.5291 \times 10^{-5} (\text{Rw}) + \frac{25.909}{0.66} (\text{M.A.P.}) - 2.8589 \times 10^{-2} (\% \text{St}) - 2.0289 \right]$$

where "S" = slope of the frequency curve

Rw = watershed relief in feet

M.A.P. = mean annual precipitation in inches

% St = percent of the total area in lakes, ponds, and streams

## V. MEDIAN ANNUAL FLOOD (M) ESTIMATORS

A. General Review

To properly introduce this section three previously introduced topics are re-introduced. First, flood frequency distributions are estimated by the first three moments of the sample logarithms such that:

$$Q = \text{antilog } q \quad \text{and}$$

$$q = M + SK$$

where  $M$  = mean of the logarithms

$S$  = standard deviation of the logarithms

$K$  = frequency value based on probabilities of near normally distributed populations (the variance from true normality being estimated by the sample skewness coefficient)

Section IV presented several estimation techniques to evaluate "S". Improvement of all of these estimators over the traditional regionalization (data aggregation) technique was demonstrated therein.

This section's purpose is to introduce several equations to estimate "M". These estimators are improvements over existing published equations for two-year peaks or the "mean annual flood" in terms of standard error or coefficient of determination (percent variation explained by the regression equation), respectively.

Hudziekewicz's (1968) model explains 70 percent of the stream-to-stream variations in the mean annual flood. He identifies three "independent" variables as positively correlated to mean

annual floods in the Willamette River basin: basin area, basin length and average land slope. Obviously, basin area and basin length are not independent but for predictive purposes (in contrast to statistical or to explanatory purposes), the lack of independence is not critical.

Lystrom's (1970) model is for all western Oregon and was thought, therefore, to not be the best possible model of the Willamette River basin, a more narrowly defined subregion of western Oregon. In addition, Lystrom's model has a standard error of 46 percent and includes seven "independent" variables. The variables which positively correlate with peak flow are: drainage area, elevation, mean annual precipitation, precipitation intensity, and a winter temperature index. Inversely correlated to the mean annual flood are percent (of the basin) surface water storage, and soil permeability. Lystrom made no attempt to eliminate redundancies, such as elevation and winter temperature, or to interpret the variables included or not included in his models.

#### B. Equation 9

The least powerful model presented here is superior to both Hudziekewicz's and to Lystrom's.

$$(9.) \quad M = \frac{k}{(E)} \frac{(log e)^{P_1}}{(e)^{P_2}} \frac{(A)^{P_3}}{(Sm)^{P_4}}$$

$$\text{where } K = 2.1258$$

$$P_1 = 9.7565 \times 10^{-2}$$

$$P_2 = 0.1173$$

$$P_3 = 3.8340 \times 10^{-2}$$

The coefficient of determination is 90.2 percent compared to Hudziekewicz's 70 percent. The standard error from this model is 21 percent compared to Lystrom's 46 percent.

This equation shows that as drainage area and average land slope of the drainage basin increases so does "M". Stepwise regression was used to develop these equations so the additional steps allow more interpretation. Step one related drainage basin area to "M". Step two correlated average land slope to the residuals, which are defined by:  $(\ln "M") - (\ln \text{area} + \text{constant})$ . Because subtracting logs is equivalent to arithmetic division, the residual has the dimensions of cubic feet/second, square mile

or  $\frac{L^3}{T}$ , or  $L/T$ . Length divided by time is the definition of velocity. Step two added land slope which dimensionally is length divided by length, a dimensionless ratio. Step two, therefore, shows that dimensionally as slope increases so does velocity,

The third step, which adds elevation, shows results which differ from Lystrom's. His equation says M.A.F. increases with elevation. The results given here demonstrate a more hydrophysically reasonable interpretation: the effectiveness of average flood-related storms are ameliorated by snow. This occurs because the higher elevations have larger snowpacks which can absorb a larger absolute amount of precipitation prior to ripening. Extreme events, in contrast, are larger for higher elevation watersheds, which is consistent with Lystrom's findings. It should be kept in mind that Lystrom studied the entire western Oregon area so that his findings which relate

elevation to peak flow may have validity at that scale of regionalization.

C. Equation 10

More powerful, in terms of prediction is, model 10:

$$(10.) M = (\log e) (e)^{[K + C_1 (A)^P + C_2 (R1) - C_3 (Fc)]}$$

The equation explains 92.4 percent of the stream-to-stream variations in "M". Local relief substitutes for local slope in this model with just a slight loss in predictive power.

Percent forest cover is not a substitute for mean elevation in the same sense that local relief and average land slope are for each other. Although forest cover and elevation are positively correlated, which is consistent with the substitution theme, the correlation ( $r = +0.64$ ) is not powerful. Furthermore, percent forest cover is hydrophysically meaningful on its own merits.

Basins with lesser percent forest cover have larger "M" values. This may result from changes in soil permeability due to soil compaction associated with road building, tractor logging, and site preparation, from decreased transpiration allowing soils to be saturated earlier in the water year, and an altered microclimate. Snow in forest openings tends to have greater snow-water equivalents due to reduced interception and less melting from re-radiation from trees. Also, the soil tends to freeze more easily in an exposed site in the fall before an insulating snow pack accumulates, contributing to "quick flow".

The added explanation attributable to percent forest cover is only seven percent, but this additional explanation is significant at above the 99 percent confidence level. The comparison of seven percent is made to the simpler model of a general form:

$$(11.) \quad M = (\log e) (e)^{[K + C_1 (A)^P + C_2 (Sm)]}$$

#### D. Equation 12

The next best model explains 94.7 percent of the stream-to-stream variability in "M".

$$(12.) \quad M = \frac{(1.1855) (M.A.P.)^{0.058785} (A)^{0.10327} (R1)^{0.14309}}{(\bar{E})^{0.078}}$$

The addition of M.A.P. is only significant at the 95 percent confidence level but the hydrophysical significance of this variable is obvious. Although drainage area indexes the total volume of water available for peak flow runoff, M.A.P. shows basin-to-basin differences per unit area, which is consistent with the results reported earlier. The interpretation is that M.A.P. indexes antecedent conditions more than mean storm precipitation, however, due to all the reasons stated earlier in this chapter.

The major weakness of this model and the one which follows is that both break a "rule of thumb" which states that regression models should be limited to one independent variable per ten samples. Model (12.) is, however, consistent with Lystrom's more general model for western Oregon with respect to mean annual precipitation. Furthermore, it has a more reasonable hydrophys-

ical interpretation when applied to the Willamette River basin.

E. Equation 13

Mean annual precipitation can also be added to model 10 to yield the best predictor. The equation explains 95.4 percent of the variability in "M".

$$(13.) \quad M = (\log e) (e) \left[ K + C_1(A)^{P_1} + C_2(Rl) - C_3(Fc) - \frac{C_4}{(M.A.P.)^{P_2}} \right]$$

where;	$K = 1.0563$	$C_4 = 1.3776$
$C_1 = 0.7458$	$P_1 = 0.0875$	
$C_2 = 3.7174 \times 10^{-5}$	$P_2 = 0.6$	
$C_3 = 1.3714 \times 10^{-4}$		

## CHAPTER FIVE COMPARISONS WITH PREVIOUS WORK

## I. GENERAL

Although only one study of flood frequency curves has been identified (Thomas, Broom, and Cummins, 1963) several comparative statements to previous reports can be made. The development of estimation equations is, of course, an original and primary result of this investigation and it differs from the traditional regionalization technique. The significance of certain variables, most notably watershed relief, elevation, mean annual precipitation, storm intensity, soil permeability, forest cover, watershed shape, hypsometry, terrain roughness, and drainage size, have comparative significance to previously reported findings.

## II. MEDIAN RATIOS OR PREDICTIVE EQUATIONS

This is the first study which attempted to identify controlling hydrophysical factors of the slope of the flood frequency curve. The only comparison to previous work must be to results which would be obtained by using the traditional "regionalization" method.

Using +0.211 as a measure of "S" (the median ratio of the sample 31 streams for the 1941-1960 time period) the following comparisons can be reported for selected peaks.

$$\text{Standard Error} = \sqrt{\frac{(o-e)^2}{n-1}}^{\frac{1}{2}}$$

EQUATION	10-Year Peak	25-Year Peak	50-Year Peak
M = M, S = Equation (1)	8%	11%	12%
M = M, S = Equation (7)	6%	8%	10%
M = M, S = Equation (8)	6%	8%	9%
Median Ratio Know M, S = 0.2110	16%	21%	25%
M = Equation (13); S=Equation(1)	18%	18%	18%
M = Equation (13); S=Equation(7)	16%	16%	16%
M = Equation (13); S=Equation(8)	15%	15%	14%
Lystrom (1970)	46%	46%	40%

TABLE 3

This shows clearly the improvement in predictive capability when using any of the equations presented herein. Equation (1) demonstrates the significant difference in slopes (of the frequency curves) between the Coast Range and the Cascades.

This difference contrasts with curves reported by the Oregon

State Engineer (1971). In that report three subregions of the Willamette River basin were also identified. Owing to the identical slopes of the three curves but differences of slope positions, the curves should have been identified as flood magnitude subregions. The State Engineer's report labelled the subregions as flood frequency regions which is an incorrect, though traditional, interpretation. These flood frequency subregions are, therefore misnomers of the curves presented. Lystrom's work did not identify magnitude differences between the subregions within western Oregon.

The standard errors of estimate for the ten-year, twenty-five-year, and fifty-year peaks are significant in several ways. First, they clearly demonstrate that flood distributions are predictably related to the basin characteristics of the drainages from which they flow. Second, the method developed here is superior to results reported that used the traditional regionalization procedure. Third, the traditional regionalization technique has been demonstrated to lack hydrologic rationale. Fourth, a "good" measurement of a given flow is as large as ten percent (U.S.G.S.). Considering the measuring error involved with extreme peaks, these results can be considered to be within measuring error.

### III. ELEVATION REGIONALIZATION

Regionalization by elevation agrees in general with Thomas, Broom, and Cummins' (1963) findings for the Snake River basin. For both the Willamette and the Snake River basins, flood frequency curves become steeper with an increase in elevation. In the Willamette, correlation analysis allowed the interpretation that changes in the slope of the flood frequency curve are due to snow hydrology differences. Specifically, these include snow water equivalencies, precipitation form of differing storm types and duration, and time of snowpack ripening. Thomas, Broom, and Cummins (1963) did not attempt an interpretation.

The Willamette basin study reported here, differs from the Snake study findings in several ways. First, headwater elevation, not mean elevation, is more significantly related to "S" in the Willamette basin. This is interpreted as a difference between winter season rain-on-snow floods associated with long duration precipitation events of the Willamette drainage and spring season snow-melt peaks of the Snake drainage. In addition, headwater areas contribute positively rather than "negatively" for the more extreme peak events. During average peaks the higher elevation headwater areas act dominantly as either snowfall addition areas or temporary storage areas for rainfall. A second difference between the Snake study and Willamette study is the identification of additional variables which index hydrophysical conditions that influence flood distributions ("S" values).

#### IV. ANTECEDENT CONDITIONS

Major findings of this research which differ from previous works center about antecedent conditions. Such conditions have not been successfully indexed in very many studies and they account for stream-to-stream differences in flood frequency distributions. Furthermore, most studies which have developed flood equations have lacked precipitation input variables and lack interpretations of the variables that are included in the equations.

This study regionalized flood frequency distributions by mean annual precipitation. Mean annual precipitation is interpreted here to be an index of antecedent moisture conditions for a drainage. Soil permeability and percent forest cover also influence the frequency distribution of peak flows and index antecedent moisture conditions in an interactive manner with M.A.P. in the multiple regression equation. In addition, historically both soil and forest cover characteristics have been thought of as being of insignificant importance for peak flows from large drainages. Lystrom's work is an exception to this in that he reported soil permeability as inversely related to peak flow magnitudes in western Oregon.

This study showed that percent forest cover and soil permeability influence average peaks but lose significance as the size of the hydrometeorological event increases. Lystrom's work suggested forest cover is not significant in western Oregon.

## V. WATERSHED SHAPE AND THE HYPSOMETRIC CURVE

Horton (1932) introduced watershed shape as a probable control of concentration times during peak flow events but results of the present research show that watershed shape is insignificant. Tolle (1974) reported watershed shape as a significant control for the Umpqua drainage. Neither Lystrom nor Hudziekewicz examined this variable.

Watershed shape is not a significant control of concentration times in the Willamette basin for two reasons. First, there are no large differences between basins. Large basin differences did exist for the Umpqua and in the Appalachian highlands. Second, terrain roughness, whether measured by local relief per unit area or by average land slope per unit distance, is an overpowering control of concentration times.

Hypsometric curves were examined and found to not influence peak flow distributions. This property had not been examined previously as a peak flow control.

## VI. SUMMARY

Relationships between selected watershed variables and the descriptive statistics of the flood distributions for 31 streams in the Willamette River basin were explored. Predictive equations are presented which explain 86 percent of the stream-to-stream variability in "S", the slope of the flood frequency curve, and about 95 percent of the variability in "M", the median annual flood and the first moment.

Statistically significant differences in "S" exist between individual drainages within the Willamette River basin. The differences can be explained in terms of watershed and climate variables. This explanation allows a regionalization of flood frequency curves based on indices of watershed and climate variables and it allows bypassing the traditional "regionalization" technique which aggregates flood records by correlation of those records.

Determinants for the subregions of the Willamette basin are interpreted primarily to be differences in source areas and antecedent moisture conditions and, secondarily, in mean storm size. Antecedent moisture conditions and precipitation intensity tend to influence the relative sizes of average peaks but lose significance in explaining differences between streams for the more extreme peaks. In this manner the relative sizes of extreme peaks to average peaks vary with average antecedent conditions by basin.

Antecedent moisture conditions are indexed by mean annual precipitation interacting with soil permeability or percent forest cover. They are also indexed by elevation.

Higher precipitation areas with impermeable or saturated soils have more gentle flood frequency curves, mainly because those areas have wetter antecedent moisture conditions on the average but little basin-to-basin differences in antecedent moisture conditions exist for extreme events. Storms associated with winter peak flows in the Willamette River basin are low intensity, long duration, mid-latitude fronts.

Elevation indexes winter temperatures and snow accumulations. Flood frequency curves become steeper with increases in elevation because of different snow hydrologies for average peak flows than the snow hydrologies for extreme flows. At higher elevations, average peak flows are ameliorated because the snowpack takes longer to ripen. Snow melt is diminished, a process which is affected by the lower temperatures of the higher elevations. Extreme peak flows from these higher elevations are disproportionately larger due to the greater available snow water equivalencies.

Watershed relief is the most significant influence on the temporal distribution of peak flows. It alone explains over half the stream-to-stream differences in "S". Streams with small total relief have small differences in hydrologic conditions, allowing more synchronization of runoff within the

watershed. Smaller differences between extreme and average flood peaks in these basins result. In contrast, large watershed reliefs are equivalent to large internal differences within a watershed in average hydrologic conditions. Non-synchronization of peak flow runoff results in small peak events. During extreme events synchronization occurs. This interpretation contrasts with two more traditional ones. First, basin relief is usually thought to index orographic precipitation - an interpretation which may be correct but which does not explain peak flow distributions nor is it consistent with results reported herein.

The second non-traditional interpretation, is that basin relief, rather than drainage length, basin area, or watershed shape, best indexes internal differences in synchronization of peak flow because basin relief explains the existence of different hydrologic conditions. Apparently hydrologic condition is more important than travel time in explaining differences in peak flows for a given drainage.

Two variables do not exhibit significant influences on peak flows. These are hypsometric integral and watershed shape. Other variables, such as average land slope and soil permeability, apparently have greater influence on concentration times. Average elevation and headwater elevation, as separate variables rather than as an integrated variable (hypsometric curve), influence peak flows in predictable manners.

Terrain ruggedness, indexed by either local relief or

land slope, is a highly significant control of concentration times and, therefore, of peak flow magnitudes. This agrees with Hudziekewicz's (1968) and Tolle's (1976) work but has been a largely ignored basin attribute in flood hydrology studies.

## VII. CONCLUSIONS

The predictability of flood frequency curves (flood distributions) coupled with the knowledge of important peak flow controls, allow two overall flood hydrology interpretations. These agree well with intuitive arguments but are often overlooked due to the research methods commonly employed.

Of most importance is the recognition that antecedent moisture conditions and the meteorological events common to given areas control the relative sizes of peaks in different areas. Second, the regression equations which leave out precipitation (both antecedent to and during the storm) are correct. Those equations explain differences between streams within similar physiographic, precipitation, and antecedent moisture conditions.

The method developed herein is applicable to areas with flood records on many streams. Future research should focus upon verification of these results. Of particular value is the applicability of the method to those areas with two or more flood populations, such as the west side of the Northern Rockies. The frequency distribution estimator will allow a quantitative analysis of the relationship between extreme peaks of one population and "average" peaks of a different population.

In those areas with only a few streams of long record, the traditional regionalization technique will still have to be used. The relationship between precipitation and flood distributions, however, suggests that optimization of flood hydrology studies is

in the realm of more streams of record in contrast to more years of record on long-term records. Also, estimations of future precipitation will allow future flood distributions to be estimated.

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## APPENDICES

## Title: Descriptive Flood Statistics

<u>U.S.G.S.</u>		<u>M</u>	<u>S</u>	<u>Location</u>
<u>Gage No.</u>				
1455		4.085	.320	1
1465		3.568	.270	1
1475		3.923	.227	1
1480		4.488	.295	1
1510		4.025	.218	1
1525		3.577	.224	1
1545		4.047	.207	1
1590		3.835	.210	1
1620		3.792	.196	1
1625		4.485	.202	1
1665		3.475	.214	1
1670		3.619	.331	1
1710		3.742	.169	0
1720		2.785	.199	1
1735		4.080	.260	1
1780		3.901	.245	1
1790		3.784	.180	1
1825		4.066	.133	1
1850		4.094	.208	1
1875		4.624	.176	1
1895		3.476	.149	0
1900		3.803	.152	0
1905		4.019	.164	0
1925		3.950	.123	0
1930		3.556	.138	0
1940		4.304	.138	0
1985		3.856	.159	1
2010		2.761	.229	1
2020		3.905	.211	1
2080		3.505	.222	1
2115		2.981	.239	1

0 = Coast Range

1 = Cascade Mountains and Willamette Lowland

Source: U.S.G.S. Water Supply Papers (calculated from 1941-1960 W.Y. data)

## Title: Surface Diversion Factors

<u>U.S.G.S. Gage No.</u>	<u>Surface Storage Area (Percent)</u>	<u>Soil Permeability</u>	<u>Forest Cover (Percent)</u>
1455	1.34	5.2	96
1465	1.51	5.0	98
1475	5.23	4.6	91
1480	2.38	4.9	95
1510	1.00	3.7	92
1525	1.00	3.4	80
1545	1.05	3.2	93
1590	1.45	5.1	85
1620	1.00	5.6	97
1625	1.27	5.3	91
1665	1.07	1.9	79
1670	1.00	1.7	61
1710	1.00	1.9	83
1720	1.00	4.3	88
1735	1.00	1.9	32
1780	1.60	5.4	93
1790	1.19	5.5	93
1825	1.39	4.5	96
1850	1.03	5.5	93
1875	1.02	4.5	87
1895	1.00	3.3	96
1900	1.00	1.8	90
1905	1.00	2.1	79
1925	1.08	3.2	85
1930	1.00	3.6	86
1940	1.10	2.1	48
1985	1.02	3.8	81
2010	1.04	1.8	48
2020	1.02	1.5	31
2080	1.22	5.6	98
2115	1.07	0.7	37

Source: Lystrom (1970)

## Title: Altitude/Area Indices

<u>U.S.G.S.</u> <u>Gage No.</u>	Hypsometric Index (Percent)	Watershed ER-Ratio	Basin ER-Ratio	Watershed Relief/Area (ft/mile <sup>2</sup> )	Basin Relief/Area (ft/mile <sup>2</sup> )
1455	41.25	.445	.455	16	16
1465	48.75	.525	.475	44	49
1475	45.75	.476	.436	23	25
1480	42.75	.451	.441	7	7
1510	36.50	.408	.393	22	23
1525	34.48	.371	.361	47	49
1545	39.50	.493	.393	19	24
1590	33.50	.509	.323	16	25
1620	45.00	.479	.471	54	55
1625	30.13	.494	.324	7	10
1665	33.00	.253	.236	16	17
1670	37.63	.402	.315	9	12
1710	20.50	.209	.182	21	24
1720	34.50	.384	.329	38	44
1735	16.38	.177	.154	12	13
1780	30.38	.341	.239	29	41
1790	41.50	.394	.394	51	51
1825	45.75	.514	.433	35	42
1850	46.50	.467	.449	26	27
1875	39.25	.431	.407	8	8
1895	37.88	.359	.325	76	84
1900	27.25	.280	.255	24	26
1905	25.75	.263	.237	12	13
1925	31.88	.263	.224	20	24
1930	33.25	.272	.272	42	42
1940	21.88	.233	.200	6	7
1985	48.50	.571	.498	38	44
2010	24.50	.299	.269	19	21
2020	18.00	.201	.181	8	9
2080	36.75	.357	.357	38	38
2115	40.75	.539	.324	19	32

Source: topographic maps

## Title: Elevation Measurements

<u>U.S.G.S.</u> <u>Gage No.</u>	<u>Mean*</u> <u>Basin Elevation</u>	<u>Headwater Elevation</u>	<u>Maximum Basin Elevation</u>
1455	4080	7660	7660
1465	4140	6600	7140
1475	3760	6760	7290
1480	3970	7660	7820
1510	2320	4760	4920
1525	2120	4270	4360
1545	2850	4900	5930
1590	4220	6920	10090
1620	3170	5280	5350
1625	3850	6920	10090
1665	740	1780	1880
1670	730	1260	1510
1710	930	3600	4100
1720	2060	4520	5190
1735	950	4520	5190
1780	3720	7840	10500
1790	3720	7020	7020
1825	2640	4520	5240
1850	2870	5280	5460
1875	2560	5460	5750
1895	1310	2980	3250
1900	1010	2980	3250
1905	910	2980	3290
1925	950	2950	3430
1930	1060	3050	3060
1940	750	2950	3430
1985	2910	4510	5050
2010	1280	4000	4430
2020	860	4000	4430
2080	3900	7220	7220
2115	520	770	1130

\*Source: Lystrom (1970)

Remainder: topographic maps

## Title: Size Indices by Drainage Basin

<u>U.S.G.S. Gage No.</u>	<u>Drainage* Area (In Sq. Miles)</u>	<u>Watershed Length (In Miles)</u>	<u>Basin Length (In Miles)</u>	<u>Longest* Channel Length (In Miles)</u>
1455	392	29.6	32.8	42.1
1465	117	16.7	17.6	24.7
1475	246	27.5	28.6	51.0
1480	924	37.6	43.8	53.3
1510	186	23.4	23.4	27.0
1525	72	12.3	15.0	16.4
1545	211	19.2	19.9	24.0
1590	348	23.3	29.9	30.8
1620	75	12.4	12.6	14.7
1625	930	36.7	44.0	54.6
1665	89	11.9	17.2	18.3
1670	95	11.1	14.2	23.3
1710	159	18.7	21.4	42.9
1720	105	24.4	25.9	30.5
1735	372	47.9	47.9	72.9
1780	216	20.7	21.8	35.7
1790	106	18.4	19.9	21.8
1825	110	22.5	22.5	29.5
1850	174	19.4	19.8	23.5
1875	640	39.5	43.0	49.4
1895	34	9.7	9.8	15.2
1900	115	11.8	18.5	28.7
1905	240	21.0	22.1	44.9
1925	133	14.8	17.8	21.0
1930	65	10.5	13.4	15.1
1940	502	30.2	31.8	49.9
1985	97	13.9	15.3	17.8
2010	204	25.3	25.6	35.4
2020	479	30.9	32.6	67.7
2080	136	15.5	17.8	19.3
2115	28	11.0	11.2	13.8

\*Source: Lystrom (1970)

Remainder: topographic maps

## Title: Slope Indices by Drainage Basin

<u>U.S.G.S. Gage No.</u>	<u>Watershed Slope (Feet/Mile)</u>	<u>Basin Slope (Feet/Mile)</u>	<u>Local Relief (Feet)</u>	<u>Avg Land Slope (Tan of Angle)</u>
1455	218	197	1566	0.485
1465	310	325	1666	0.364
1475	208	219	1222	0.292
1480	179	157	1448	0.349
1510	176	183	1328	0.347
1525	278	234	1166	0.320
1545	211	255	1510	0.418
1590	236	290	988	0.229
1620	326	327	1618	0.424
1625	165	210	1247	0.335
1665	116	86	650	0.231
1670	80	80	561	0.166
1710	181	181	690	0.212
1720	162	180	1309	0.384
1735	91	104	644	0.159
1780	302	409	1213	0.261
1790	296	274	1653	0.462
1825	172	204	1591	0.414
1850	233	237	1518	0.383
1875	129	125	1271	0.351
1895	268	293	1147	0.344
1900	231	162	867	0.382
1905	133	141	711	0.226
1925	183	179	780	0.230
1930	260	205	799	0.275
1940	95	105	573	0.179
1985	268	279	1521	0.367
2010	153	168	509	0.140
2020	127	134	337	0.098
2080	333	290	813	0.194
2115	49	80	388	0.097

Source: topographic maps

## Title: Channel Slope Indices by Drainage Basin

<u>U.S.G.S.</u>	<u>Main Channel</u>	<u>Windsorized*</u>
<u>Gage No.</u>	<u>Slope</u> <u>(Feet/Mile)</u>	<u>Channel Slope</u> <u>(Feet/Mile)</u>
1455	153	75.0
1465	210	89.7
1475	112	112.0
1480	126	64.5
1510	153	43.5
1525	208	58.0
1545	169	98.3
1590	179	44.6
1620	275	145.0
1625	111	58.3
1665	76	13.1
1670	38	10.9
1710	79	13.4
1720	131	64.6
1735	60	21.1
1780	175	93.3
1790	250	180.0
1825	131	77.4
1850	192	102.0
1875	103	35.7
1895	171	115.0
1900	95	39.5
1905	62	17.8
1925	129	40.5
1930	181	124.0
1940	57	9.4
1985	210	83.1
2010	109	72.3
2020	58	23.6
2080	267	136.0
2115	39	31.9

\*Source: Lystrom (1970)

## Title: Total Relief Indices

<u>U.S.G.S. Gage No.</u>	<u>Maximum Basin Relief (In Feet)</u>	<u>Watershed Relief (In Feet)</u>
1455	6455	6455
1465	5722	5178
1475	6260	5730
1480	6883	6729
1510	4282	4122
1525	3507	3417
1545	5077	4038
1590	8666	5501
1620	4117	4043
1625	9229	6064
1665	1486	1386
1670	1131	886
1710	3873	3376
1720	4657	3992
1735	5004	4339
1780	8907	6251
1790	5444	5444
1825	4587	3865
1850	4695	4515
1875	5387	5085
1895	2867	2596
1900	3001	2730
1905	3115	2803
1925	3189	2713
1930	2741	2735
1940	3343	2867
1985	4271	3730
2010	4312	3876
2020	4360	3924
2080	5159	5159
2115	901	542

Source: topographic maps

Title: Watershed Shape Indices  
(All dimensionless ratios)

U.S.G.S. Gage No.	Watershed Form Ratio	Basin Form Ratio	Watershed Elongation Ratio	Basin Elongation Ratio	Stream Elongation Ratio
1455	.447	.364	.534	.482	.375
1465	.420	.378	.517	.490	.349
1475	.325	.301	.455	.438	.245
1480	.654	.482	.645	.554	.455
1510	.340	.340	.465	.465	.403
1525	.477	.320	.551	.452	.413
1545	.572	.533	.604	.582	.483
1590	.641	.389	.639	.498	.483
1620	.488	.472	.557	.548	.470
1625	.690	.480	.663	.553	.446
1665	.631	.302	.634	.438	.412
1670	.772	.472	.701	.548	.334
1710	.455	.347	.538	.470	.235
1720	.176	.157	.335	.316	.268
1735	.162	.162	.321	.321	.211
1780	.504	.455	.566	.538	.328
1790	.313	.268	.446	.413	.377
1825	.217	.217	.372	.372	.284
1850	.462	.444	.543	.532	.448
1875	.410	.346	.511	.469	.409
1895	.365	.357	.482	.477	.307
1900	.826	.336	.725	.463	.298
1905	.544	.491	.589	.559	.275
1925	.607	.420	.622	.517	.438
1930	.587	.360	.611	.479	.425
1940	.550	.496	.592	.562	.358
1985	.502	.414	.565	.514	.441
2010	.319	.311	.540	.445	.322
2020	.502	.451	.565	.536	.258
2080	.566	.429	.600	.523	.482
2115	.233	.225	.385	.378	.307

Source: Topographic maps

## Title: Direction Indices

<u>U.S.G.S. Gage No.</u>	<u>Watershed Direction (Degrees)</u>	<u>Basin Direction (Degrees)</u>	<u>Stream Direction</u>
1455	319	309	NW
1465	286	291	NW
1475	255	298	W
1480	319	005	NW
1510	260	260	W
1525	308	306	NW
1545	301	013	NW
1590	192	151	S
1620	210	208	SW
1625	230	355	W
1665	174	174	S
1670	347	269	NW
1710	147	168	E
1720	288	295	NW
1735	303	303	NW
1780	322	329	W
1790	267	279	W
1825	260	260	W
1850	274	283	W
1875	264	260	W
1895	136	136	SE
1900	295	300	SE
1905	284	321	SE(E)
1925	136	165	SE
1930	200	239	S
1940	062	071	E
1985	275	271	W
2010	304	303	NW
2020	326	286	NW
2080	331	335	NW
2115	281	274	W

Source: Topographic maps

## Title: Climate Indices

U.S.G.S. Gage No.	Mean Annual Precipitation (inches)	Two-Year, 24- Hour Precipit- ation Intensity (inches)	Mean Minimum January Temperature(°F)
1455	58	3.0	24
1465	62	3.0	24
1475	58	2.9	25
1480	58	3.0	25
1510	62	3.0	31
1525	56	3.0	33
1545	60	3.0	31
1590	86	2.9	20
1620	117	3.0	26
1625	83	2.9	23
1665	67	3.5	31
1670	43	3.0	32
1710	78	3.9	31
1720	89	3.0	31
1735	56	3.0	33
1780	80	2.9	20
1790	77	3.0	23
1825	97	3.0	27
1850	101	3.0	27
1875	90	3.0	28
1895	91	5.4	30
1900	74	3.9	30
1905	72	4.1	31
1925	101	5.8	30
1930	88	5.1	29
1940	78	3.8	30
1985	91	3.0	27
2010	60	3.0	31
2020	55	3.0	33
2080	91	2.9	20
2115	43	3.0	32

Source: Lystrom (1970)