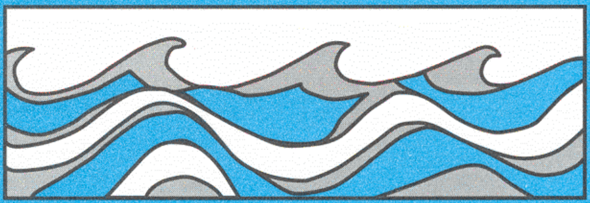
University of Washington
Department of Civil and Environmental Engineering

FLOW SERIAL CORRELATION & RELATED STREAMFLOW GENERATION MODELS

William J. Stolte
Eugene P. Richey



Water Resources Series
Technical Report No. 29
June 1970

Seattle, Washington
98195

Department of Civil Engineering
University of Washington
Seattle, Washington 98195

FLOW SERIAL CORRELATION & RELATED STREAMFLOW GENERATION MODELS

William J. Stolte
Eugene P. Richey

Water Resources Series
Technical Report No. 29

June 1970

FLOW SERIAL CORRELATION AND RELATED STREAMFLOW GENERATION MODELS

A Completion Report of Project Number
43-34-10E-3992-3018
of the Office of Water Resources Research
Under Annual Allotment Agreement
Number 14-01-0001-1416
July 1, 1969, to June 30, 1970

University of Washington
Seattle, Washington 98105

William J. Stolte and Eugene P. Richey
June 1970

TABLE OF CONTENTS

LIST OF TABLES

Tables within body of text

Tables in Appendix A

LIST OF FIGURES

LIST OF FIGURES (cont.)

Page No.

LIST OF SYMBOLS

Q	annual flow
$\overline{Q}$	mean annual flow
B	regression coefficient of single lag annual flow generation model
R	random deviate of mean of 0 and standard deviation of 1
S	standard error of estimate of single lag annual generation model
i	subscript designating the year
j	subscript designating the months of year i
L	subscript designating the months of year i + 1
t	subscript designating days in the baseflow recession relationship
q	monthly flow
$\overline{q}$	mean monthly flow
a	regression constant for single lag monthly generation model
b	regression coefficient for single lag monthly generation model
s	standard error of estimate of single lag monthly generation model
ρ	lag one serial correlation coefficient for annual flows
n	lag number in the Markovian model
N	number of years of record
m	weighted average factor-the number of days in the month divided by the number of days in the year
σ_Q^2	variance of annual flows
x	daily flow in baseflow recession relationship
k	baseflow recession constant
α	constant in exponential decay formulation of baseflow recession

ACKNOWLEDGEMENTS

The work upon which this report is based was supported by funds provided through the United States Department of the Interior, Office of Water Resources Research, as authorized under the Water Resources Research Act of 1964. Included in the work was a two year project entitled "Serial Correlation in Annual Stream Runoff" and a one year study entitled "Persistence in Seasonal Stream Runoff". This report supercedes and includes the progress report entitled "Physical Influences on Flow Serial Correlation" submitted in fulfillment of the last half of the two year contract specified above.

The two year project was initially conceived by Professor Thomas H. Campbell who provided an abundance of valuable aid and direction in the period before his death. Supervision of the one year project was then assumed by Professor Eugene P. Richey who saw the entire effort to its completion. The valuable aid of Professor David D. Wooldridge of the College of Forest Resources of the University of Washington, Professor John S. Gladwell of Washington State University, and Professor John W. Van Ness of the Department of Mathematics of the University of Washington is also gratefully acknowledged.

ABSTRACT

The goal of the research was to investigate both the mathematical and physical aspects of flow generation processes. The mathematical aspect of the study indicated that the statistics of annual and monthly flows are intrinsically related. Therefore it is desirable that generated monthly flows should yield acceptable annual flows. Multiple regression equations incorporating from 1 through 12 preceding flows as predictor variables were used to generate monthly flows from which annual flows were derived. The statistics of both the monthly and annual flows gained by this process were compared to those of the recorded flows in order to determine the accuracy of flow generation by these models and to choose the most acceptable model. It was found that the lag 1 model was the most desirable but that it had deficiencies in some respects. The physical aspect of flow generation was studied by determining the physical causes of, and prediction equations for, a poorly understood component of the lag 1 flow generation model, namely, the lag one serial correlation coefficient. It was found that the influence of climate on the serial correlation coefficient strongly predominates over that of basin characteristics in the region studied. It was concluded that groundwater storage was not of great importance in the variation in the flow serial correlation from basin to basin. It was also found that the prediction equations for the lag one serial correlation coefficient were deficient in some respects and could not be used with great confidence. More work is needed in developing accurate indices of the various physical causes influencing the flow regime. These results are not necessarily applicable to other regions where climatological and geographic conditions are different from those of Western Washington.

KEY WORDS: Hydrology*, Runoff, Stochastic*, Basin Parameters*,
Climatic Factors.

CHAPTER I

INTRODUCTION

Problems in Hydrology

The subspecialty of water resources is the study of the limited but significant role that water plays in the life of man. In his development of water resources, man has often shown a deplorable disregard for the reactions that must result from continued thoughtless exploitation of the world around him. Since the world is a balanced system, unwise actions inevitably give rise to undesirable results which are becoming more and more apparent in the deterioration of our environment.

As river pollution increases and industries and irrigation systems are set up which are dependent on water that may or may not be available when needed, more and more attention is being given to water management. Not only is a scarcity of water causing concern, but floods are becoming increasingly damaging as the urban and industrial development of flood plains accelerates without due consideration given by flood plain occupants to the possible submersion of facilities beneath the swirling waters of high river flows. Obviously much regrettable dislocation has resulted from man's rebellious attempts to impose his will on creation rather than letting his activities be guided by the built-in order of the world. It is now more necessary than ever before that hydrologists make a careful study of the nature of river flows, of factors that influence these flows, and of the reaction that can be expected in the drainage system after a proposed course of action is implemented, so that distresses may be ameliorated and future activity wisely planned.

Some of the major uses of the water are in power generation, irrigation, flood control and the dissipation of particulate, biological and thermal pollutants. Some of the problems that occur are caused by conflicts of interests between these competing users and by the variation of the water supply in relation to their needs. An example is the use of the multipurpose dam. The irrigation industry may need the stored water at the same time that there is a high demand for power generation. However, the optimal release schedule of the water for the dissipation of pollutants may be considerably different than that for irrigation or power. Furthermore, flood control considerations may dictate an entirely different schedule of releases than either the power, irrigation, or pollutant dissipation needs would indicate. These problems become continually more acute since the increasing rate of growth of agricultural, urban and industrial complexes both on and off the flood plain land puts higher stress on each of the uses.

The difficulty of wise development of water resources is magnified by a lack of knowledge about the behavior of river flow. A more complete knowledge about the complex series of circumstances producing river flows would provide a new stance for accurately formulating deterministic relationships from which behavior of river flows could be predicted. Eventually the state of the art in hydrology may reach that point where the cause and effect relationships within a drainage basin are known in enough detail to enable the prediction of very short term, e.g. daily flows. This idealized state is far from being realized at present, although there are several deterministic models based upon a knowledge of rainfall and runoff mechanics. However, application of these deterministic techniques is still limited to small, individual basins because of the volume and detail of data needed to apply them.

Statistical Approach

In view of this limitation to the deterministic models, the hydrologist is forced into a statistical approach in the planning of water resources development. Frequency analysis is often used to describe a series of flows, such as annual peak flows (instantaneous values), monthly (average) flows, and annual (average) flows. This method allows the determination of the average frequency of occurrence of a flow of a certain magnitude, but has limitations in that the occurrence of an extreme flow in a short period of record often will be ascribed a frequency much greater than its true value. A closer approximation of the true frequency of occurrence could be obtained from a longer flow record. Greater accuracy in approximation of flow variability is necessary if chaotic development of water resources is to be avoided.

Since the creation of historical data is impossible, many hydrologists are focusing attention on the generation of synthetic data. Historical flow records belong to a statistical distribution that can be defined by the mean, the standard deviation, the coefficient of skew, and the kurtosis. In recent years the realization has grown that continuously measured flow values form a time series in which there is a relationship between consecutive flows. This relationship is quantified by the serial correlation coefficient while the residual variation is expressed by the standard error of estimate. Given the flow mean, the standard deviation, and the serial correlation coefficient; and disregarding skew for the moment, it is possible to set up a statistical model which can be used to generate new values of flows that will have the same statistical distribution as the original flow values. This process which allows a numerically unlimited extension of the available data and hence a closer determination of the frequency of unusual flow occurrences, is a useful technique in the hydrologist's bag of tricks. Other methods of streamflow simulation were not studied. Of the three parameters yielding the generation equation, the serial correlation has been given the least attention; therefore, the lag one serial correlation coefficient was chosen for detailed study.

Research Requirements

The research was limited to the study of the characteristics of monthly and annual flows. Each of the flows belongs to a different statistical distribution since they are the product of physical causes which vary with time. In light of this reasoning, it was concluded that thirteen different statistical distributions required study. Since annual flows are mathematically the weighted average of the monthly flows the latter flows should yield a great deal of information about the former. This condition can be generalized to apply to all types of flows with differing time bases. Since short term flows contain a great deal of information about longer term flows, it is desirable that studies be concentrated on flows of the shortest possible time base. As the body of hydrologic knowledge grows, statistical analysis will concern itself with flows of progressively shorter time base. The ultimate end of this process would be when the instantaneous flow was the subject of the inquiry. However, this is extremely unlikely since instantaneous flows by definition have an infinitesimally small time base. It is also highly probable that deterministic models will be developed to a higher degree of practicability thus obviating some of the need for the statistical approach.

Although both monthly and annual flows are used in water resources planning the former are of more value since most water resources planning applications require, at the minimum, knowledge of monthly rather than annual flow distributions. To satisfy this requirement the most useful procedure would be the generation of monthly flows from which the annual flows could be derived.

Since flow generation is intended to yield more information about the variability in flows, a prime requirement of the generation process is that the original statistics of both the monthly and the annual flows be preserved in the generated data. The lag one generation equation is not the only model available. As is discussed later, the existence of a relationship between two consecutive flows should lead to relationships between multiple consecutive flows. This leads to different generation equations, commonly termed multi-lag models, which incorporate a varying number of predictor flows. A major goal of the research program was to determine the relative accuracy of these different models in producing flows of the same statistical characteristics as the original flow data.

All generation equations are based on the statistics of the original flow records which are usually very limited in length. A problem inherent in the use of a limited flow record is that it may not accurately reflect the effects of the causative influences operative on a flow regime over a long period of time. The applicability of generation equations derived from a short length of flow record to long-term generation may therefore be questionable. This problem can be reduced somewhat by setting a minimum, usually 30 years, to the number of years of record used to derive the generation equations. Although this minimum does not guarantee accurate representation of long term conditions it does reduce the amount of deviation that could be expected.

The requirement for adequate flow records curtails the general usefulness of flow generation techniques in water resources planning since most streams have less than 30 years of flow record available. This problem could be circumvented by developing equations to predict the components of the generation equation from generally available climatological and basin parameters. A major part of the research was directed towards developing such equations for the lag one serial correlation coefficient. Another reason for this phase of the research was that an analysis of the physical causes of the flow statistics may lead to a greater understanding of hydrologic relationships.

Research Objectives

The overall purpose of the research was to investigate the nature of flow generation techniques related to flow serial correlation. The research was divided into different phases, each dealing with a different aspect of the total purpose. The first phase was devoted to determining the relationships between the statistics of the annual and monthly flows which derives from the relationship between the flows themselves. The fact that annual and monthly flows have a common basis in the instantaneous flows led to the second phase of the research, namely, the determination of which of several available monthly flow generation models yields the most accurate monthly and annual flows. The third phase of the research dealt with the development of prediction equations for the lag one flow serial correlation. The reasons for this research included the necessity of explaining the flow serial correlation in terms of the causative factors within the hydrologic cycle and, in view of the lack of sufficient flow records on many stream, the necessity of being able to predict this factor from numerical indices of these causes.

Research Viewpoint

It is commonly considered that there are two main approaches to the study of hydrology, usually termed deterministic and probabilistic. The deterministic approach deals with the theoretical relationships between the causative factors operative within the hydrologic cycle and the resulting streamflow. The probabilistic approach studies exclusively the statistical characteristics of the streamflow. The separation between these two approaches may not be as absolute as it first appears to be. A study of the relationships between the causative physical factors and the resulting flow regime must inevitably arrive at a point where present day knowledge ends such that deterministic relationships cannot be formulated for the remaining physical phenomena. For example, this point is reached when the physical causes of the precipitation regime are being considered. The lack of knowledge of the physical regime beyond this point necessitates the use of statistics to describe the precipitation input. Therefore, in every hydrologic study there must enter some element of the probabilistic approach. In the view of the writer, a probabilistic approach should not be employed until absolutely necessary and that basic hydrologic research should not be content with merely a statistical description of the flow regime when it is possible to either develop deterministic relationships between the flow regime and the statistically described precipitation input, or else to find deterministic causes for the statistical characteristics of the streamflow.

Throughout the research the basic premise has been that all the relevant statistical parameters of the streamflow are primarily the product of physical causes. Errors can occur in the measurement of flows, precipitation and basin characteristics. Although errors in measurement of these various data may introduce an element of variation, its magnitude is totally unknown. The approach taken in the research was to assume that both the statistical values subjected to analysis and those resulting from the analyses were completely the result of physical causes, thereby ignoring the variation in the parameters due to error in measurement. Ignoring this variation must lead to a loss of some of the validity and transferability of the results of the analyses. However, it can be assumed that the main thrust of the results is valid whereas this is not true for some of the individual results.

The samples of data studied included both the flow records of individual streams, and flow and basin characteristics for a large selection of streams. The concept of the flow regime utilized in this research included the assumption that neither the specific characteristics of flow record samples nor those pertaining to the selection of streams were necessarily transferable to flow records from a different time period and other streams. The general conclusions and information gained should be applicable to other regions where the same general hydrologic regime exists, and to other periods of time.

Specific applications of the general point of view outlined above existed in different aspects of both the second and third phases of the research. The second phase involved the derivation of generation models from the flow records of several streams. These models were then used to generate flows whose statistics were then compared to those of the recorded flows from which the generation equations were derived. Model accuracy was rated on the basis of the divergence of the statistics of the generated flows from those of the recorded flows. No consideration was given to whether these divergencies were significant in the traditional statistical sense. The numerical values were accepted as representing the differing accuracies of the models even though it was realized that the use of random numbers in such a model must give rise to variations in generation accuracy not due to the nature of the model. However, the number of flows generated was quite large and it was assumed that variations due to the use of random numbers was small.

In that phase of the research concerning itself with the investigation of the physical causes of the lag one flow serial correlation, the values of the serial correlations was assumed to be totally the product of physical causes. That part of these values resulting from errors of measurement of the flows was ignored. The analysis of the causes of flow serial correlation involved the use of statistical analysis techniques closely related to multiple regression methods of analysis. Indicated associations between the independent and dependent variables were assumed to reflect the actual influence of the indexed physical cause on the flow serial correlation. Strong and weak associations were assumed to reflect strong and weak influences respectively, even though tests of significance would probably find the weak associations to be statistically insignificant.

In summary, a deterministic use of statistics involves two problems. The first is that if variation in statistical parameters is considered to be primarily the result of physical causes, statistical tests of significance are not applicable since they assume that all variation is random unless otherwise indicated. Secondly, the component of the variation in the statistical parameters due to error in measurement is not quantifiable in most cases and must be ignored. However, the presence of this component of variation must reduce the general accuracy of the results. The approach selected in the research was to consider all statistical values to be the product of physical causes while at the same time recognizing that the presence of measurement error reduces the validity of the results.

Format

The format of the report is as follows. Chapter II is a discussion of the statistical aspects of the study and includes a literature review dealing with pertinent statistical concepts and the problems involved in statistical flow generation. An attempt is made to determine the cause of these problems and to pose possible directions research should take to solve them. A discussion of the general climatic and basin conditions of the region studied serves as an introduction to Chapter III which is a review of literature dealing with aspects of the hydrologic cycle specific to the region studied.

Chapter IV deals with the selection of the detailed problems to be studied and the procedures used in analysing them. (Most of the computer programs used in the analyses were either available from previous local studies or else were developed by the writer. These programs are available from the Department of Civil Engineering, University of Washington). The chapter is structured such that discussion deals first with verification of the derived relationships between the statistics of annual and monthly flows, then with the selection of acceptable generation models, and finally with the analysis of the relationships between basic physical influences and the monthly and annual flow serial correlations. This order of discussion is also followed in the delineation of the results in Chapter V and in the discussion of the results and the accompanying primary conclusions in Chapter VI. Chapter VII attempts to integrate the conclusions into the main body of hydrologic thought and to determine their implications.

CHAPTER II

CONSIDERATIONS OF FLOW STATISTICS

A. General Considerations

Sample Size

The use of a small sample to represent the long term regime is the underlying foundation of a statistical study of physical relationships. The degree of accuracy of sample representation depends on the size of the sample since large samples tend to include a greater selection of causal interactions than do small ones. The sample size required for adequate representation of the phenomena studied is commonly considered to be 30. It is not true that smaller samples are completely meaningless nor that larger samples are absolutely trustworthy. Any sample can be a poor representation of the long term regime. In this sense the sample size minimum is somewhat of an artificiality; however, it serves as a convenient criterion of sample value.

The size of a sample of measured flows equals the number of years of record, which for most streams in the Pacific Northwest is less than 50 and in many cases less than 30. The widespread lack of adequate flow records puts a severe crimp on the use of statistical methods in hydrologic analysis.

Statistical Parameters

Description of a statistical sample is accomplished by the derivation of values for the mean, the standard deviation, the coefficient of skew and the kurtosis. The mean is merely the average of the observed values while the standard deviation is a measure of variability about the mean. The coefficient of skew is a measure of the asymmetry of the distribution curve, while the kurtosis is an expression of its peakedness. The mean is the simplest of these terms while the kurtosis is the most complex. Usually, the mean and the standard deviation are the most important terms; they are the easiest to work with and represent the basic information required about the distribution. The skewness and the kurtosis are refinements designed to better define the distribution but can be very difficult to work with. Matalas and Benson (1968) derived a simple test of the significance of the skewness coefficient which depended only on sample size but Fiering (1967) states that skewness is difficult to handle mathematically and is unimportant in some cases. Martig (1968) in his study of the mean annual flows of the Columbia River found that the flow data was skewed, but that the deletion of a randomly selected small bit of data caused the values of skew to change markedly. From this he concluded that tests for skewness of annual flows are very unstable. Therefore considerations of skewness in annual flows were not included in the research.

Annual flows form one population of data whereas changes in the flow regime from month to month result in 12 monthly flow distributions, each with its own statistical parameters. This is affirmed by Benson and Matalas (1967) and Roesner and Yevdjevich (1966). These authors bring out the point that the skewness of monthly flows is quite marked which must then affect the validity of monthly flow generation models not altered to account for skewness. The skewness is mainly the result of the truncating effect of the lower limit of the flow. Harms and Campbell (1967) suggest the use of a log transformation of the monthly flows prior to the derivation of the generation equation and discuss its effect on the results of some experimental work. They conclude from a comparison between actual and generated flow data that the log transformation model is operationally valid.

The logs of monthly flows are nearer to a normal distribution than the actual flow values because the log transformation reduces the truncating effect of the lower flow limit. However, this transformation is strictly empirical in nature since exponentiation of the logarithmic equation yields a multiplicative equation which is devoid of physical meaning. Varying skewness from month to month will prevent the log transformation from normalizing all monthly flow populations. What approach to take towards the remaining lack of normalcy in the transformed data is somewhat unclear. Harms and Campbell did not deal with this problem, and the attempts of Roesner and Yevdjevich (1966) to deal with variation in moments did not include skewness considerations. The scope of the research did not allow an investigation of this problem. It was therefore assumed that the log transformation of the monthly flows sufficed to eliminate any gross reduction in the validity of the generated monthly flows due to skewness.

The higher the order of the statistical parameter the more difficult it is to determine its effects and to compensate for them. If the skewness of flow is found to be rather unwieldly, then it is to be expected that the kurtosis of the flow will be even more difficult to incorporate into the structure of the generation models. For this reason, the effects of kurtosis on flow generation procedures have been disregarded.

B. Serial Correlation

Introductory Description of Generation Models

Along with the well known statistical parameters discussed above, the property of flow persistence is also an important part of flow generation techniques. Flow persistence is the property of relatedness between successive flows. The strength of the relationship is measured by the serial correlation coefficient. The relationship can be expressed by an equation derived from linear regression. The scatter of values about the resulting regression line is measured by the standard error of estimate which is the square root of the amount of variance in the original data not explained by the relationship.

The equation both describes the actual flow sequence and also can be used to generate synthetic data which is statistically the same as the original data.

Specific Applications of Generation Techniques

Some of the potential uses of generation techniques have been discussed already. One of the major ones is in the study of the reservoir storage demands under the adverse conditions caused by extreme flows. In this application the generation process was found by Yevdjevich (1967) and Fiering (1967) to produce realistic data and valuable results. Chow and Ramaseshan (1965) used serial correlation generation methods to generate rainfall which was then routed through the drainage basin. Reasonable correspondence was found between actual data and the results of this approach. These specific applications indicate that generation techniques are a valuable aid in water resources planning.

Model Generation Limitations

The two most significant and far-reaching limitations of flow generation techniques are a result of the derivation of the generation equation from limited records. The first limitation stems from the fact that the magnitude of the deviation of the sample from the long term regime cannot be determined. Since the generation equations are derived from a sample, the generated flows will have statistical parameters centering on those of the sample rather than of the long term regime. Furthermore the statistics of the generated and actual flow data will never fully coincide because of the limited length of the generated flow. Therefore the divergence of both the generated from the sample data and the sample data from the long term regime will be possible sources of error. This limitation must be kept in mind when using generated flows for water resources analysis because it is impossible to make corrections for it.

At best a partial solution is to strive for a large sample to serve as a basis for as much generated flow data as possible.

The second significant limitation stems from the variation in the flow regime with time. These changes, usually referred to as nonstationarity in the flow regime, result from changes in the importance of the underlying causes of the flow regime. They could be produced by either the activities of man as in logging operations, land clearing programs, and soil conservation efforts; or else by unpredictable changes in rainfall patterns. Howe, Slaymaker and Harding (1966) investigated a case in Wales where floods were becoming increasingly more severe and frequent, a condition commonly attributed to man-made changes in the basins. Although man-made changes were partially responsible, they were quite secondary to the changes in the rainfall regime of the area which were causing more frequent and severe storms that produced the undesirable changes in flow. The nonstationarity of the flow regime caused by man-made changes in the basin could possibly be predicted. On the other hand, if there is a change in the precipitation regime, due either to human activity or to unknown causes, it would be very difficult to predict either the time of occurrence, or the direction of the resulting variation in the runoff regime.

This discussion of the limitations of the generation process points out some of the difficulties that can arise in the use of generated data. It must be appreciated that the results of generating techniques cannot be trusted implicitly and must be handled with proper circumspection even though they can be a great help in water resources development.

Single Lag Generation Model

The single lag generation model, or the lag one model, is based on the assumption that any given flow is related to the single previous flow only. The corresponding regression equation representing the single annual flow distribution is

$$Q_{i+1} = \overline{Q} + B*(Q_i - \overline{Q}) + R*S \tag{1}$$

where Q_{i+1} is the flow for year i + 1, $\overline{Q}$ is the average of the lagged flows, Q_i is the flow for year i, B is the regression coefficient, R is a random deviate from a population with mean 0 and standard deviation of 1, and S is the standard error of estimate. In the generation process Q_i will be the previously generated flow or some assumed beginning value and Q_{i+1} the flow generated by the equation. The corresponding equation for the monthly flow is

$$q_{j+1} = a_{j+1} + b_{j+1} * q_j + R*s_{j+1} \tag{2}$$

where for month j + 1, q_{j+1} is the flow, a_{j+1} and b_{j+1} are the regression constant and coefficient, and s_{j+1} is the standard error of estimate. q_j is the flow for the preceding month j. Since q_j and q_{j+1} do not belong to the same distribution the regression constant and coefficient and the standard error of estimate vary from month to month and therefore must be subscripted.

Multilag Considerations

Specific references to a particular model have so far been limited to the lag one model, mainly because of its simplicity. However, according to the traditional Markov chain any flow is related to an infinite number of preceding flows. If the relationship between two consecutive flows of the same population is measured by the correlation coefficient "ρ", then mathematically the relationship between single flows two periods removed is measured by a correlation coefficient of "ρ^2", or in general, the relationship between single flows "n" periods removed is measured by a correlation coefficient of "ρ^n" The relationship between flows infinitely removed is based on the relationship between immediately consecutive flows. In reality the relationships between flows removed by several periods are not such simple functions of the lag one serial correlation coefficient. However it still remains that single flows are related to several preceding flows. This is the justification of the multilag model in which several predictor flows are used in the generation model.

Although there is little literature dealing specifically with multilag generation models, there is some discussion of closely related concepts. Matalas (1963) suggests that the annual runoff can be expressed as a function of the rainfall of preceding years. If all flows are a function of the preceding rainfall, then each flow must also be related to the preceding flows. Another related study is by Chow and Ramaseshan (1965) who used a multilag model to generate rainfall which was then used to determine the resulting runoff. However, neither of these studies deals directly with the nature of the multilag model. Possible reasons mentioned by Matalas (1967) are that usually there is not enough data to warrant a higher order flow generation chain and also that the mathematics involved in the relationship becomes excessively complicated.

In specific application to flow generation, Yevdjevich (1967) used the two degree multilag model in a study of the mean range of flow. Fiering (1967) acknowledges the possible value of multilag models when he mentions that higher order chains may be useful. Le Feuvre (1965) also discussed the validity of multilag concepts. The approaches of these authors is mainly mathematical. Using an empirical approach, Martig (1968) studied the use of the multilag model in the generation of annual flows for 25 streams and found a tendency for equations with five, six, or seven "independent" flows to provide the most explanation of the variation in the "dependent" flow. Although the physical cause of this result was not determined, it does provide some justification for considering multilag models as possible alternatives to the single lag model.

In light of the results obtained from the studies mentioned it is evident that it might be profitable to investigate the nature of the multilag model. The authors cited dealt mostly with annual flows whereas the research program was mainly concerned with the relationship between monthly and annual flows. Relating multilag annual flow generation models to multilag monthly flow generation models was much beyond the scope of the research, but a study of models for generating monthly flows from which annual flows could be derived was quite feasible.

Statistical regression techniques were used to determine both the lag one and the multilag monthly flow generation models. For the lag one model simple linear regression analysis was used and for the multilag models multiple regression techniques were employed. These standard least squares techniques have long been used for many types of analyses. For a full discussion of the mathematics involved see Ford (1953) or any standard introductory statistics textbook. In the multiple regression equation, the unbroken sequence of preceding flows becomes the series of predictor variables in the regression equation. The interdependence of these "predictor variables" is undesirable from the viewpoint of linear regression but its effect was ignored since this interdependence is the very essence of the multilag model.

Harms and Campbell Monthly Model

The study by Harms and Campbell (1967) discussed earlier illustrates the need for an investigation into the relationship between annual and monthly flow statistics. In their model the generated monthly flows were adjusted so that the weighted average of the 12 monthly flows would equal a simultaneously generated annual flow. The purpose of this adjustment was to guarantee the accuracy of the statistics of the annual flows resulting from the generated monthly flows. However, they did not fully investigate the effect of this adjustment on the statistics of the monthly flows. There is no guarantee that the generated monthly flows have statistics approximating those of the actual flow data. It could not be expected that the serial correlation between the flows of the last month of one year and the first month of the succeeding year would equal that of the recorded flows since each of these flows would have a different adjustment. More importantly variation in monthly flows could be distorted by the adjustment. As an example, a very infrequent large monthly flow in conjunction with low flows for the other months and a large generated annual flow could cause the large monthly flow to be adjusted upward appreciably. The frequency of such large flows would be misrepresented. Generally the adjustment process could distort generated flow data. An investigation is required into the relationship between annual and monthly flows to determine that monthly model, either single lag or multilag, which can be used to generate acceptable monthly flows from which equally acceptable annual flows can be derived. This would eliminate the need for annual flow generation. A large part of the research was directed toward eliminating the artificial separation between monthly and annual flows when the two flows are so intrinsically related.

Annual to Monthly Flow Relationship

The relationship between annual and monthly flows derives from the fact that the instantaneous flows are the common source. The relationship between the annual and monthly flows leads to a relationship between their statistics. Let Q_i be the annual flows and q_{ij} be the monthly flows where i designates the year and j the month. Then the mean of the annual flows is:

$$\bar{Q} = \sum_{i=1}^{N} Q_{i/N} \qquad (3)$$

but

$$Q_i = \sum_{i=1}^{N} m_j\, q_{i,j} \qquad (4)$$

where m_j equals the number of days in month j divided by the number of days in the year. Therefore,

$$\bar{Q} = \sum_{i=1}^{N} \sum_{j=1}^{12} m_j \frac{q_{i,j}}{N} \qquad (5)$$

$$\bar{Q} = \sum_{j=1}^{12} m_j \sum_{i=1}^{N} \frac{q_{i,j}}{N} \qquad (6)$$

$$\bar{Q} = \sum_{j=1}^{12} m_j\, \bar{q}_j \qquad (7)$$

where $\bar{q}_j$ is the average flow of month j. The variance of the annual flow is:

$$\sigma_Q^2 = \sum_{i=1}^{N} (Q_i - \bar{Q})^2 \qquad (8)$$

$$\sigma_Q^2 = \sum_{i=1}^{N} \left(\sum_{j=1}^{12} m_j\, q_{i,j} - \sum_{j=1}^{12} m_j\, \bar{q}_j\right)^2 \qquad (9)$$

If the monthly flows were not related to each other the variance of the annual flow would be a simple additive function of variances of the monthly flow, but this is not the case; the variance of annual flows is a function of both the variance and the covariance of the monthly flows. The lag one serial correlation coefficient "ρ" is a function of the mean, the standard deviation and the cross product of the annual flows as shown by:

$$\rho = \frac{\sum_{i=1}^{N-1} Q_{i+1} * Q_i - \sum_{i=2}^{N} Q_{i+1} \sum_{i=1}^{N-1} Q_i / N - 1}{\sqrt{\left[\sum_{i=2}^{N} Q_{i+1}^2 - \frac{\left(\sum_{i=2}^{N} Q_{i+1}\right)^2}{N-1}\right]\left[\sum_{i=1}^{N-1} Q_i^2 - \frac{\left(\sum_{i=1}^{N-1} Q_i\right)^2}{N-1}\right]}} \tag{10}$$

The product of $\sum_{i=2}^{N} Q_{i+1}$ and $\sum_{i=1}^{N-1} Q_i$ is a function of the means while the denominator is a function of the variances. Since both the mean and the variance have already been shown to be functions of monthly statistical parameters, it only remains to prove that the same condition applied to the initial factor in Equation 10.

$$\sum_{i=1}^{N-1} Q_{i+1} * Q_i = \sum_{i=1}^{N-1} \left(\sum_{L=1}^{12} m_L q_{i+1,L}\right) \left(\sum_{j=1}^{12} m_j q_{i,j}\right) \tag{11}$$

$$\sum_{i=1}^{N-1} Q_{i+1} * Q_i = \sum_{i=1}^{N} \sum_{j=1}^{12} \sum_{L=1}^{12} m_j m_L q_{i+1,L} q_{i,j} \tag{12}$$

All the symbols have been previously defined except for L, which indicates the month for year i + 1. Equation 12 shows that the cross-product of the annual flows is a function of the cross-products between the monthly flows of two consecutive years. Since all the components of Equation 10 are functions of monthly statistics, it can be concluded that the serial correlation in annual flow is also a function of monthly flow statistics.

It has just been demonstrated that the pertinent statistics of the annual flows are a function of the statistics of the monthly flows. The purpose of the derivations was to demonstrate that there is a functional mathematical relationship between the statistics of annual and monthly flows. This condition is a strong motivation for research into the use of monthly generation models which will also produce acceptable annual flows since it indicates the need for an integral approach toward generation of flows of differing time bases.

In light of the scarcity of flow records on many streams, it is desirable to be able to predict components of the generation equations from basic physical basin data. It was assumed that research would provide a clear indication of which monthly model would produce acceptable annual and monthly flows. Finding both the physical factors affecting the lag one monthly serial correlation and the resulting prediction equations would contribute to the prediction of the entire generation equation. Chapter III will deal with the physical factors which can be expected to influence the flow regime and therefore the serial correlation. Methods of adequately quantifying these phenomena for purposes of numerical analysis will also be discussed.

CHAPTER III

PHYSICAL PHENOMENA AFFECTING STREAMFLOW

Nature of the Study

There are two main approaches to the study of the physical causes of the characteristics of the flow regime. The first commonly uses statistical analysis techniques to gain a microscopic overview of the main factors affecting many basins, while the second is more macroscopic, concentrating on the relationships existing within a small individual basin. The former approach utilizes the gross variations existing between basins as indicators of the nature of the factors affecting the flow regime. The latter approach attempts to correlate theoretically predicted flow regime behaviour to that actually observed within a small basin. The theoretical nature of the deterministic formulations representing the flow regime require much detailed data to describe the hydrologic interactions. This is illustrated by the theoretic formulations, derived by Fiering (1967) describing the relationships between flow serial correlation and groundwater storage and carryover in precipitation. Operational use of these derivations is impossible at present. Comparison of the actual flow regime behaviour with that predicted allows successive modifications to be made to the theory and thus the formulation.

The statistical approach is entirely empirical. Statistical regression techniques are used to detect the cause of the observed variations in the flow regime from stream to stream. Numerical indices of the pertinent physical causes are derived and then regressed against the desired characteristics of the flow regime. On a regional basis wide variations exist in the underlying physical causes of the flow regime resulting in wide variations in its characteristics. Wide variation tends to nullify the effects of errors in the numerical indices of the physical causes and therefore these indices do not have to be highly refined. Hence requirements in terms of efforts and resources are considerably less for the empirical approach than for the theoretical approach. It was decided that in view of the limited resources available for this study, the empirical approach was more appropriate than the theoretic approach.

The most well-known examples of the empirical approach to the study of the regional variations in flow regime characteristics are the studies done by the United States Geological Survey on flood frequencies. The publications in this series include Bodhaine and Thomas (1964), and Hulsing and Kallio (1964), whose efforts were concentrated on streams in Washington and Oregon. The basic purpose of these studies was to facilitate the prediction of flood frequencies without the need to rely on flow records. The method included the determination of a regional dimensionless flood frequency relationship applicable to all streams in the region and the development of an equation relating the mean annual flood to the characteristics of the climate and the basin. The product of the predicted mean annual flood and the ordinates of the dimensionless flood frequency relationship yields the predicted flood frequency relationship for the particular basin of interest. The basic difference between the work done by the USGS and the research program undertaken is that the former is concerned with peak flows while the latter is concerned with monthly and annual flow serial correlations.

A commentary on the value of the United States Geological Survey work is given by Benson (1962) who discusses the validity of the assumptions underlying a regional approach to studying flow characteristics. Although his discussion is in terms of floods, it has general application to all regionalized studies of flow characteristics. An important conclusion of this article is that the results of the regionalized approach may be used in preference to those obtained from actual flow records because the regionalization process averages out the random variations inherent in the flow record. Obliteration of these random variations allows a more reliable estimate of the true state of affairs. According to the point of view taken in the research, the concept of random variation must be rejected since any statistical parameter is the product solely of physical causes and is not subject to random variation. However, it is possible that limited flow records may less accurately reflect the results of long term physical processes than would a regionalized approach. On the other hand, individual basin records may give information about characteristics unique to that particular basin not available from the regionalized approach. Therefore either limited flow records or regionalized results may yield valuable information depending on the specific circumstances.

Matalas and Gilroy (1968) developed detailed mathematical relationships which facilitate the decision as to whether regionalized estimates of the characteristics of the flow generation equation or the characteristics obtained from limited flow records should be used. No specific component of the equation was investigated and the results are generally applicable to all flow regime characteristics. The basic criterion they used was the relative magnitudes of the variances in the values obtained by either source. Although the mathematics are quite involved, the results could be useful when equations have been developed for the prediction of the components of the generation equation. Since the research was only a preliminary step towards this goal it was felt that considerations of the relative value of predicted flow serial correlations versus those obtained from flow records were not required.

Geographic Area Studied

The streams studied were in the area of Washington State bounded on the west by the Pacific Ocean and on the east by the Columbia River. The climate of the area is mainly dominated by the Pacific Ocean and variations are due mostly to the topography. The majority of the precipitation-producing storms come from the southwest. The coastal regions receive from 50 to 100 inches of rainfall per year. Both the Olympic and the Cascade mountain ranges cause high precipitations to the windward sides and rainshadow effects to their leeward sides. Maximum precipitations reach 200 inches per year in the Olympic range and 150 inches per year in the Cascade range. In the Olympic rainshadow, precipitations reach a minimum of 20 inches per year or less. Precipitation in the Puget Sound lowlands averages approximately 40 inches per year. That part of the region in the Cascade rainshadow receives approximately 60 inches per year. Localized areas receiving high precipitations include Mount Rainier. The southeast part of the region may receive as little as 20 inches per year. In general, precipitation varies widely throughout the region studied.

Since a marine climate predominates, the greatest proportion of the precipitation occurs in the winter. The relative warmth of the ocean compared to that of the air causes high evaporation rates and consequently makes available a great volume of precipitable water vapor. Even though moderate temperatures prevail throughout the region, the freezing level is quite low much of the winter, leading to great amounts of snow at elevations of 3,000 feet or more. This snowpack has a profound effect on the flow regime since it tends to reduce the maximum flows at the time of precipitation but causes subsequent increases in flow rates during the snowmelt period of May, June, and July. The high amounts of snowfall in the Cascade range result in a significant amount of glacation in some of the basins. Glaciers store moisture for several years and also increase the flow during July and August. Apart from the Cascade glaciers there are a few glaciers in the Olympic range and at high elevation on Mount Adams and Mount St. Helens. The glaciers on Mount Rainier strongly affect the runoff regimes of the streams draining its slopes.

Forests are quite dense throughout much of the region except for the southeastern section which has sparse vegetation. Dense forestation is associated with a soil mantle of high permeability and moisture-holding capacity. At the higher elevations of most of the streams studied the soil mantle is the main water-bearing material because of the dense impermeable underlying bedrock. Bare rock out-croppings are fairly common at the highest elevations. In the Puget Sound lowlands and other low elevation areas, ice age glaciation has left some deep deposits of material ranging from permeable sands and gravels to dense impermeable tills. Some of these deposits store substantial amounts of water, but the general importance of this storage is secondary to that of the storage capacity of the soil mantle.

The streams included in the study were chosen from all parts of the region in order to provide a representative sample. These drainage basins tend to be small, averaging about 250 square miles in area, because drainage of the mountainous regions directly into the ocean allows little opportunity for small streams to join to form large ones. Since the streams drain mainly mountainous regions they tend to have steep slopes and rocky beds.

A general conclusion gained from this discussion is that conditions vary greatly throughout the region. The climate varies from humid to semiarid. Density of vegetation for that reason also has a wide range. The presence of both mountains and lowlands causes variations in basin moisture storage characteristics. The literature will be reviewed with specific application to the effect the conditions within the region would have on the flow regime.

A drainage basin is a complex system which converts precipitation input into the river flow output. The characteristics of both the input and the conversion system will have an effect on the nature of the flow output. The characteristics of the conversion system are a function of the physical features of the drainage basin. The large amounts of precipitation common within the region likely have a more important effect on the characteristics of the flow than would the characteristics of the basin.

A. Climatological Characteristics

Significance

The general importance of precipitation as a factor in the flow regime is illustrated by Howe, Slaymaker, and Harding (1966) who analyzed the reasons for an increasing frequency of occurrence of extreme floods in Wales. They concluded that although changes in land use practices had led to an increase in runoff rates, the increasingly severe flooding conditions were due to changes in the precipitation regime. The precipitation regime is probably just as influential in the marine climate of Western Washington. If precipitation has such a strong effect on peak instantaneous flows, a similar influence will be exerted on the monthly and annual flows studied. It is therefore imperative that the general influence of precipitation on the flow regime be adequately indexed by precipitation data.

Precipitation Distribution

The factors influencing changes in the distribution and amounts of precipitation are discussed by Caffey (1965). These included the primary source of moisture, orographic and rainshadow effects resulting from topography, convergence, convection, frontal activities, and evapotranspiration. His attempts to study each factor separately did not meet with great success. Precipitation is the result of many very complex interactions which are hard to quantify. It is to be expected that this will result in difficulties in developing suitable precipitation indices but even partial success could provide a great deal of information on the effect of precipitation on flow serial correlation.

The effect of topography on the spatial distribution of precipitation in the Western Oregon and Washington has been investigated by Schermerhorn (1967). He found that much of the regional variation in precipitation was due to the main storm direction, topographic barriers in relation to this storm direction and the latitude. The discussion of the precipitation regime at the beginning of this chapter confirm his conclusions regarding the effects of storm direction and topography. The region studied does not include a wide range in latitude and so its effect is not likely to be strong compared to that of storm direction and topography.

Most studies dealing with the effect of the precipitation on the flow regime are not concerned with the serial correlation in the flow so naturally the serial correlation in the precipitation is of no concern. Given the problem of determining the causes of variation in flow serial correlation and the fact that precipitation is a predominant influence on the flow regime, it follows that the precipitation serial correlation should be considered a possible influence on the flow serial correlation and included as a factor in the research.

Snow Accumulation and Snowmelt

The previous discussion has dealt with precipitation in general; precipitation in the form of snow exerts a different influence than that of rain.

Runoff resulting from rainfall is affected mainly by basin characteristics, to be discussed later, while runoff from snowmelt is controlled mainly by climate and climate-related factors, and affected secondarily by basin characteristics.

Storage by snow accumulation reduces the effective drainage area at the time of precipitation. The main bulk of the snow pack melts during the spring season. The snowline fluctuates considerably throughout the winter which means that there is a continuous cycle of snow accumulation and melting. Extreme floods may occur when high rainfall occurs in conjunction with snowmelt. However, this short-term cycle of accumulation and melting has little effect on the monthly flow regime. Snowmelt has a predominant influence on the flow regime and therefore the flow serial correlation, when the major part of the snow pack melts during the months of May, June and July.

The factors affecting snowmelt and resulting floods as discussed by Quick (1965) are also likely to be very relevant to the influence of snowmelt on flow serial correlation. The high albedo of the snowpack minimizes the amount of thermal energy entering it from solar radiation, and the low temperature of the rain falling on the snowpack prevent much snowmelt from the thermal energy of the rain. The main sources of energy are conduction of heat from the air into the snowpack and the release of the latent heat of vaporization resulting from condensation of water vapor on the snowpack. Wind induced turbulence plays a large role in the effectiveness of both of these sources of energy, as does air temperature. The condition of the snowpack also has a strong influence on snow melt rates. Macroscopically, maximum flood-producing conditions occur when an extensive snowpack at near melting temperatures is subjected to a prolonged sharp rise in air temperature.

The internal mechanics are complex due in part to the many variations in governing conditions which can be expected. There is a dearth of quantitative data which necessitated the use of very crude and simplistic indices of factors such as snowfall and air temperature. Blodgett (1967) found that the annual average number of degree days below freezing was associated with the variation in the serial correlation from month to month and with location. The nature of his analysis did not allow the determination of whether this factor was most closely associated with snowmelt or snow accumulation. In either case, these results do point out that air temperature may be a valuable index of snow conditions within a basin.

The expected effect of snowmelt on the flow serial correlation would be a reduction in the flow serial correlation. The large volumes of water added to the flow in an inconsistent manner from month to month can only serve to decrease the relationship between the monthly flows affected. As snowmelt proceeds, the snowpack will decrease in size. The accompanying reduction in resulting runoff will have a smaller effect on the flow serial correlation.

Glacial Melt

During the summer months of July, August, and September, melting of the glaciers and high elevation snowpack occurs. A comparison of Figures 1 and 2, obtained from the United States Geological Survey in Tacoma, Washington shows the difference between the monthly flow hydrograph for streams with and without glaciers and permanent snowpacks. Figure 1 is the hydrograph of the South Fork Nooksack River and Figure 2 is the hydrograph of Thunder Creek. These two streams are almost adjacent but the South Fork Nooksack River has no glaciers or perennial snowfields while Thunder Creek does. The difference between the two hydrographs should be due mainly to the effect of glaciers and perennial snowfields on the flow regime. The flow of the South Fork Nooksack River is high during May and June but decreases considerably in July, while Thunder Creek flows continue high through July followed by relatively small decreases to August and September flows. The continuing high Thunder Creek flows through July, August and September are due to glacial melt including melting of perennial snowfields since the flows of the South Fork Nooksack indicate that during this time the melting of lower elevation snowpacks is minimal. Glacial melting is controlled by the same factors as snowmelt and its effect on the flow regime will probably be similar to that of snowmelt. Therefore it is to be expected that glacial melting will cause a decrease in the flow serial correlation. The areal extent of a glacial mass is readily definable so it may be possible to index glacial volume rather than climate as was the case for the snowmelt occurring earlier in the year.

B. Drainage Basin Characteristics

In traditional hydrologic thought a simplified view of the effect of the drainage basin on rainfall input includes the concept of overland flow, interflow and groundwater flow. As is commonly known, overland flow is that part of the runoff which flows over the surface of the land; groundwater flow is a result of the depletion of aquifer storage; and interflow is that part of the infiltrated rainfall which travels to the streams by way of the zone above the water table. Although these are oversimplified concepts, it may be beneficial to discuss flow serial correlation in their context.

Overland flow is the most rapid form of runoff and would not be expected to be a factor in the carryover in streamflow from one month to the next. Groundwater storage depletion provides the slowest form of runoff since generally the infiltrated rainfall must traverse both the unsaturated zone and the saturated aquifer. Because of this factor, groundwater flow is not subject to rapid variation unless both the saturated and unsaturated zones form a continuous system in tension. In this case, precipitation may release the tension and thus allow discharge from the aquifer. Generally speaking however, groundwater flow provides a consistency in the flow which could be expected to contribute to the flow serial correlation. The runoff from interflow probably has sufficient consistency to provide a contribution to the flow serial correlation. Interflow requires a longer period of time to reach the stream than does overland flow but a shorter period of time than groundwater flow. Although separation of total flow into phases is somewhat of an artificiality, a literature review following these divisions would be useful.

Overland Flow

According to Reich (1965), Reich and Hiemstra (1965), Kinnison and Colby (1945), and Benson (1962b), the main factors affecting overland flow include drainage density and basin geometry. The drainage density is an index of runoff conveyance efficiency of the basin. The geometry of the basin includes land and stream slopes which affect rate of runoff, and the length of the main channel which affects the time of concentration. Depression Storage in the form of lakes and ponds serves to delay the flow in opposition to the effect of the slope. The shape of the basin will have a strong influence on the form of the overland flow hydrograph. Blodgett (1967) found both channel slope and depression storage to have some effect on the monthly variation in flow serial correlation.

Inclusion of easily obtainable indices of these factors provides a check on the assumption that overland flow is of little significance in the problem studied. Both stream slope and depression storage surface area are easily obtained from topographic maps. On the other hand, data on the basin shape and drainage density is not readily available which puts it beyond the scope of the present study. Stream length is probably adequately indexed by basin area in the fairly homogeneous geographic area studied.

Interflow

Since interflow is that portion of the infiltrated precipitation that is not incorporated into groundwater storage, it must be a function of both the capacity of the soil mantle to absorb the precipitation and that of the bedrock to absorb the infiltrated moisture. In the region studied, the soil mantle is very permeable and has a high storage capacity. The soil mantle acts as a storage reservoir, recharging during the high precipitation periods and depleting during the dry season. Thus this depletion has some of the characteristics of groundwater flow. The factors governing the recharge and depletion of the soil moisture storage are the infiltration capacity of the soil and the soil storage capacity which in turn are governed by the vegetative cover and the soil type. Although Reich (1965) and Reich and Hiemstra (1965) show that infiltration capacity can be quantified by classification of these two factors, the data required is prohibitive in scope. Several attempts were made to index vegetative cover but were discontinued because too much time would be required to develop an index sensitive to the relatively small variation in vegetative conditions throughout the regions studied. Similar problems were encountered in indexing soil types. The importance of indexing infiltration rates is reduced by the fact that the permeable soil in densely forested areas is capable of absorbing all but the most intense rainfalls. The inclusion of a few lightly-forested basins in the research makes an index of infiltration capacity and soil storage capacity desirable and therefore it was unfortunate that none could be developed. The capacity of the bedrock to absorb moisture is a function of the rock type which will be discussed later in reference to groundwater storage.

Groundwater Flow

Generally there are three factors which affect the proportion of the stream flow originating from groundwater storage: the rate of recharge of the aquifer, the storage capacity of the aquifer, and the availability of storage. The recharge rate of the aquifer is dependent on rainfall, infiltration, and percolation rates. Infiltration rates have just been discussed in reference to interflow and soil moisture storage.

The groundwater storage capacity of an aquifer is partly a function of its permeability -- a property that was indexed by Blodgett (1967) for some of the streams studied. The index was derived from a map of the geologic structures of the region. By and large the basins of the area are underlain by impermeable bedrock and there is little variation in aquifer permeability. Blodgett's results indicated however, that this index of aquifer storage did associate to some degree with the variability in the monthly flow serial correlations.

The availability of groundwater storage to the stream is related to the degree of incision of the stream into the aquifer. The relationship of groundwater flow to basin area is discussed by McGuiness, Harrold, and Amerman (1961), McGuiness and Harrold (1962), and Hely (1964), who found that in many regions in the eastern and midwestern United States, stream incision is generally a function of the drainage area. Since groundwater flow could contribute to the carryover in monthly flow, it is possible that basin area as an index of stream incision could be associated with flow serial correlations even though the region being studied is much different in some respects than that studied by the above authors.

Baseflow Recession

The cumulative effect of the infiltration capacity of the basin, the storage capacity of the aquifer, and the accessibility of aquifer storage is expressed in the characteristics of the resulting streamflow which follows an exponential decay law and is called baseflow recession. Baseflow recession forms a time series and as such could be expected to have some effect on the carryover in monthly flows. A common expression of this time series is

$$x_{t+1} = kx_t \tag{1}$$

where x is the daily flow, t designates the day, and k is a factor constant with time for a particular basin. Since baseflow recession is an exponential decay function, the term "k" can be replaced by $e^{\alpha t}$ where α is a constant. Although the term "k" is used more commonly than $e^{\alpha t}$, the latter expresses more clearly the exponential decay nature of the relationship. If the flow is x_0 for day 0, then the flow x_t t days later is $e^{-\alpha t}$ x_0, i.e.

$$x_t = e^{-\alpha t} x_0 \tag{2}$$

where t is in days.

But

$$\text{Ln}(x_t) = -\alpha t + \text{Ln}(x_0) \tag{3}$$

is a linear equation in t with coefficient $-\alpha$ and constant $\text{Ln}(x_0)$, both of which can be derived by plotting Ln(x) versus time. The groundwater storage at time 0 can be found by integrating all succeeding flows occurring to time infinity. Thus STORAGE

$$= \int_{t=0}^{\infty} x_t \, dt \tag{4}$$

$$= \int_{t=0}^{\infty} q_0 \, e^{-\alpha t} \tag{5}$$

$$= q_0 \left| \frac{e^{-\alpha t}}{-\alpha} \right|_{t=0}^{\infty} \tag{6}$$

$$= \frac{q_0}{\alpha} \tag{7}$$

The above discussion is predicted on the premise that the portion of the flow due to groundwater inflow may be isolated from the total hydrograph. This may be difficult because, according to Hall (1968), there are many sources producing flows with exponential decay characteristics. These sources include lakes and ponds, snowmelt and glacial melt, and channel, bank and soil moisture storage. In the region studied the runoff from glaciers, the snowpack, and the soil mantle undoubtedly affect the nature of what appears to be baseflow recession.

Although the separation of flow into phases facilitates a discussion of the effects of the basin on the flow, too rigid an adherence to this format can lead to a distorted view of the interactions which exist within a basin. Any one particle of water may exist in any of the phases at different stages in its transport. For example, the water may initially flow over the surface of the land but if surface depressions cause a sufficient loss in velocity, the water may infiltrate and travel some distance in the interflow phase. The particle may then either reappear upon the surface as overland flow or else may reach the groundwater table. Intersection of the water table with the ground surface may again cause the water to travel in either the interflow or overland phase. It is obvious that these phases may be a result of definition more than of physical conditions.

In the area studied the phase distinctions become unimportant because the main bulk of storage may not be in the rather impermeable bedrock but in the highly permeable soil mantle. Throughout most of the region studied, few storms produced rainfall intensities greater than the infiltration capacity of the soil mantle. This is especially true for the densely forested areas.

Methods of Analysis

Investigation of the influence of the various physical factors discussed requires adequate indices of these factors and also suitable methods of analysis. The standard multiple regression analysis is a commonly used technique but it has disadvantages when used to analyse interrelated variables. Interpretation of its results is confused by strong interdependencies among the variables, a hallmark of many of the available indices of physical influences on the flow regime. For example, elevation indexes almost all basin and climatological conditions in the region studied. Basin slope varies with elevation and is therefore likely to be associated with indices of either snowmelt or glacial melt. Another index associated with elevation is aquifer permeability since rock outcroppings are common at higher elevations. Precipitation increases markedly with elevation due to topographic effects. The strength of these interrelationships will vary considerably. Determining the true importance of each physical factor is extremely difficult when its index is related to other factors.

In addition to causing confusion in the interpretation of results, the interdependence of the indices also leads to other deficiencies in the results of multiple regression analysis. As demonstrated by Wallis (1965) interdependence of the predictor variables leads to considerable instability in the derived regression equation, resulting in a loss of validity and significance.

These difficulties can be circumvented to an appreciable degree by the use of some modification of basic multiple regression, as shown by Wallis (1965). The technique most applicable to the research program was principle components analysis in combination with varimax rotation. In the principle components analysis orthogonal, or independent, components are derived from the original variables. In the varimax rotation these components are rotated, with little loss in orthogonality, so that each is maximally associated with one original variable. A full description of these procedures is included in Harman (1960). Wallis found that this procedure alleviated many of the problems associated with the use of multiple regression techniques.

The value of the basic principle components approach has been established in practice. Gladwell and Mastay (1967) investigated the effect of a cloud-seeding program on the flows of the Skagit River in Washington State. A prime requirement of such a study is that there must be some way to evaluate the significance of resulting changes, if any, in the runoff. This requires dependable control variables which in the study mentioned included the runoff of several adjacent streams, and precipitations at several locations. A regression equation using these control variables was developed to predict the flow on the treated stream under original conditions. It was found that these control variables were highly interrelated and that the ordinary multiple regression analysis techniques were unsuitable. Instead, principle components analysis was used and found to produce satisfactory results.

Related Studies

A study of the physical factors affecting the statistics of monthly and annual flows in the Potamac River basin has been done by Benson and Matalas (1967). In many respects their work is very similar to that done in this program. Included among the statistics studies were the serial correlations of monthly and annual flows. The purpose of their study was to develop equations to predict flow characteristics for streams having inadequate records.

The indices the authors used to explain the variation in the flow statistics were the drainage area, the percentage of forested area, the mean annual precipitation, the annual snowfall, the slope of the main channel, and the surface storage provided by the lakes and ponds within the basin. The authors found that the annual flow serial correlations were very nearly zero, so that attempts to explain the variation in this factor were of no value. Their analysis showed that the relationships between the monthly serial correlation coefficients and the basin factors did not vary consistently from month to month and therefore they concluded that the relationships indicated were questionable. It can be assumed that relationships which contradicted the expected physical processes were rejected as unsatisfactory. This apparent lack of success may be due to the nature of the region studies and is not necessarily the result of all such studies. The authors' rejection of unsatisfactory relationships is in agreement with the point of view taken in this research that the variation in a statistic is totally due to physical causes and not the result of chance.

Summary

It can be concluded from the discussion of this chapter that climatological characteristics of the region dominate the flow regime to a large degree and that the characteristics of the basin are somewhat secondary. The climatological characteristics relevant to the variation in flow serial correlation are the precipitation amounts, the precipitation serial correlation, the snowfall, and glacial volume. Basin aquifer storage is the prime basin characteristic which needs indexing. Facets of aquifer storage include recharge rates, actual storage volume available, and the accessibility of storage to the stream.

CHAPTER IV

PROCEDURES

Specific Purposes

The purpose of the first phase of the research was to find the mathematical relationship between the statistics of annual and monthly flows. The development of the formulations for the means, standard deviations, and lag one serial correlations was included in Chapter II.

The purpose of the second phase of the research was to empirically test the lag one through twelve multilag monthly models to ascertain which of these would generate monthly flows and subsequently derived annual flows most closely approximating the original recorded flows. The judgement was based on the correspondence between the means, standard deviations and lag one serial correlations of the generated and actual flows. The nature of the study precluded the discovery of reasons for the performance characteristics for any particular model. An investigation of the influencing physical factors would be too extensive to include in the research program.

Although such a full fledged investigation was impossible, a beginning step in this direction was made by studying the physical factors influencing the lag one flow serial correlation. The third phase of the study included both the development of indices of the basic physical factors influencing the flow regime, and the analysis of the relationships of these indices to the lag one flow serial correlation. The purpose was first to develop equations with which the lag one flow serial correlation could be predicted from commonly available physical data. This would eliminate any dependence on short flow records. The second more general purpose was to gain more knowledge about the physical influences acting within the region studied.

A. Annual to Monthly Statistical Relationships

The mathematical relationships between annual and monthly flow statistics were derived in Chapter II. Substitution of numerical values into the formulations for a few sample streams merely verifies the accuracy of the formulations and helps develop some appreciation for the relationship. This substitution was done for the annual flow cross-products. Actual values for the monthly and annual parameters were substituted into the right and left sides, respectively, of Equation 12, Chapter II, for the Chehalis and South Fork Skykomish Rivers. These streams were randomly selected.

B. Monthly Multi-lag Model Accuracy

The flow records of four streams were subjected to a standard multiple regression analysis which yielded the components of the various multi-lag generation equations. These components were fed into a computer program which generated 500 years of monthly flows for each model and stream. The monthly and annual flow statistics derived for each of these sequences were then compared to those of the original flows. This allowed the selection of the most acceptable model.

The streams chosen for this analysis were the Chehalis River, the South Fork Skykomish River, Thunder Creek, and the Wenatchee River. Their identification numbers are listed in Table 1 and their locations are shown in Figure 3. The Chehalis River drains a coastal and inland region having relatively few mountains and thus the rainfall patterns are not greatly altered by topography. The basin recieves little snowfall and has no long term snow accumulation. The South Fork Skykomish River originates at the divide of the Cascade mountains. Much of the basin is covered by extensive snowpack during the winter but glacial activity is minimal. The precipitation patterns within the basin are governed to a large degree by the rise in land elevation towards the headwaters. This causes high precipitations over much of the basin. Thunder Creek is also located on the western side of the Cascade mountains but drains a higher area than does the South Fork Skykomish River. It is subject to precipitation and snowpack conditions similar to those of the South Fork Skykomish River. The condition which sets Thunder Creek apart from the South Fork Skykomish River is its high degree of glaciation. The Wenatchee River differs from the other three in that it drains an area to the leeward side of the Cascade mountain range. It recieves high precipitations in the upper regions of the basin but decreasing precipitation in the lower reaches. Much of this precipitation falls as snow. In summary, the streams chosen represent a wide range of precipitation, snow accumulation and glaciation conditions.

Since flow statistics are an expression of the effects of physical causes on the flow regime, variations from stream to stream in the strength of different physical causes could be reflected in the general accuracy of flow generation by each model. This may cause differences between streams in the accuracy of a model relative to the other models. The purpose of the study was to make a general conclusion as to which model was the most accurate in the generation of monthly and derivative annual flows. Therefore, the conclusion must be based on information covering the widest range of conditions existing within the region for which the conclusion is assumed to be reliable. The four streams studied were chosen with a view to satisfy this requirement. The study was limited to an empirical determination of the most accurate model for flow generation and did not attempt to investigate the effect of different physical conditions on the accuracy of each model.

The general lack of knowledge about multi-lag generation processes made it difficult to decide which model should be studied. Considering that flows belong to a continuous interrelated time series, it seemed reasonable to include as "independent" variables the sequence of consecutive flows immediately preceding the "dependent" flow. This decision limited the research to a study of the lags one through n multilag models, where the n lag model is the most complex. A decision was then required as to what the maximum value of n should be. The lag 12 model where n equals 12 was chosen as the most complex model because it includes the entire yearly cycle in the "independent" variables. There was no justification for inclusion of any model of greater complexity.

Standard multiple regression techniques were used to obtain the components of each of the 12 models for each of the 12 monthly flow distributions for each of the four streams. The components of interest were the regression constant, the regression coefficients, and the standard error of estimate.

A computer program was developed which generated the flow data from the regression equations, then derived the statistics of each of the monthly flow distributions and the derived annual flow distribution, and then compared the statistics of the generated flows to those of the original flow data. A large sample of generated flow records was required so that errors in the generated data could be assumed to be due to inadequacies in the model. This would eliminate the problem of deciding if the lack of accuracy in the generated data was due to the divergence of the sample from the original flow data or to deficiencies in the mechanics of the generation model. Financial considerations served as the upper limit to the amount of data generated since the cost of running the computer program would vary with the length of record generated. It was decided that 500 years of generated record would satisfy both financial limitations and the requirements of record length.

Analysis of model generation accuracy was accomplished by a comparison between the means, standard deviations and the lag one serial correlations of the actual and generated monthly and annual flows. From a practical point of view, the mean and the standard deviation are more important than the serial correlation because they are an expression of the flow characteristics most critical in water resources planning. Flow serial correlation is much more difficult to understand in a physical context than the mean and standard deviation. Determination of model accuracy relative to this statistic could yield valuable information and increase understanding of its nature. This would facilitate the research on the physical causes of flow serial correlation.

The need for this research into model generation accuracy arose from the fact that annual and monthly generation models are usually considered independently. This ignores the fact that annual and monthly flows have a common basis in the instantaneous flows and therefore should be considered in relation to each other. Since the generation of monthly flows is usually more important than the generation of annual flows, a model is required which will generate accurate monthly flows from which equally accurate annual flows can be derived. This eliminates the need for the generation of annual flows and satisfies the need for viewing annual flows and monthly flows in relation to each other.

In light of these requirements the program output for each stream and model consisted of the means, standard deviations, and serial correlations for the generated and actual annual and monthly flows, the errors in the statistics of the generated flows, and these errors as a percentage of the original statistics. What is referred to as the actual error is the difference between the values of the statistics of the recorded and generated flows. This error as a percentage of the value for the recorded flows is called the percentage error. The actual and percentage errors were averaged over all periods for each model to allow a judgment on model accuracy. The actual and percentage errors were also averaged over all models for each period to provide information on the variations between periods in model generation accuracy. This yielded information on the accuracy of the annual flows derived from the generated monthly flows. Furthermore, it provided information on seasonal trends in monthly generation accuracy and indicated months having anomalous generation characteristics. These results could then be correlated to some degree to the results of the physical prediction study.

C. Physical Prediction Study

Dependent Variable

The study of the physical causes of the regional variation in flow serial correlation* required the selection of streams to be analyzed, the derivation of the FSC of these streams, the derivation of numerical indices of the important physical influences, and the analysis of the relationships between the indices and the FSC. The streams selected are listed in Table 1, (Appendix A), the indices used are listed in Table 2 (Appendix A), and the FSC are listed in Table 3 (Appendix A). The validity of the resulting prediction equations was checked by comparing predicted versus actual values of FSC for three randomly selected check streams not used in the regression analysis.

---

*Flow serial correlation will hereinafter be referred to as FSC.

The 40 streams listed in Table 1 include the check streams, namely, the South Fork Skokomish, the Greenwater, and the Sultan Rivers. The flow records of all the streams selected were required to meet the following criteria: (1) the records must be continuous for an adequate period of time, preferably 30 years, (2) the flow must be relatively unaffected by diversion or regulation, (3) the streams must provide adequate coverage of the geographical region studied, and (4) the records must be of good quality. Several streams with less than 30 years of available records were included to provide adequate geographical coverage.

Although the Ash River station is listed as having a continuous record from 1934 to 1966, it was actually discontinued in September 1964. Three years prior to this date another station was set up on this river. Using approximately 36 monthly flows measured at both stations, a regression equation was developed with which the flow at the old station for the period after discontinuation was predicted from that of the new. The correlation coefficient was so high (0.99) that it could safely be assumed that the predicted flows were of the same statistical distribution as the measured flows.

Initially the PSC values were derived from all available continuous records but comparison of these values with those derived by Chriswell (1969) for a base period from 1934 to 1966 indicated several major discrepancies. These could only be attributed to the varying length of flow records indicating that the strengths of the causative physical influences varied with time. This variation could bias the results of the research since a non-homogeneous flow regime is treated as being homogeneous. Therefore the standard base period was adopted. For purposes of eliminating skewness, the serial correlations of the logs of the monthly flows were found, not those of the flows themselves. Although the total research program was designed to eliminate the need for an annual flow generation model, annual FSC based on actual annual flows were also studied. Determination of the physical causes of both the annual and monthly FSC would lead to a greater knowledge of the interrelationships between annual and monthly flows.

Precipitation Indices

Chapter III has established that precipitation has a strong influence on flow regime characteristics. Precipitation-related indices included the means and serial correlations of annual and monthly precipitations. Blodgett (1967) derived mean annual precipitations by averaging the precipitation records of several individual gages near each basin studied. Unfortunately, most precipitation gages are located at the lower elevations resulting in consistently underestimated basin precipitation. An isohyetal map prepared by Gladwell and Mueller (1967) provided annual precipitation values which reflected the influence of precipitation with elevation.

The monthly precipitations and the annual and monthly precipitation serial correlations* were derived by averaging values of these variables from several precipitation stations. Preliminary results indicated that the annual FSC was not related to the annual PSC derived in this manner. This tended to contradict the results of a study by Gladwell (1969). The annual PSC was contoured and its values obtained for each basin. Derived in this manner it was found to be related to the annual FSC as expected. To check whether this condition would hold true for the monthly PSC, the values of this statistic for October, November, December, April, May and September

---

*Precipitation serial correlation will hereafter be referred to as PSC.

were also derived from contour maps. For these months the cruder form of the variable had already been shown to be related to the respective FSC. If deriving the PSC from contour maps was more desirable than getting it from point values, its relationship to the FSC for these months should show clearly the effect of using a different source for its values. Little change occurred in these relationships from which it was concluded that monthly PSC derived from averaging point values were satisfactory for this study. Therefore the other monthly PSC were not subjected to contouring procedures.

According to Schermerhorn (1967) the orientation of a basin relative to the major storm paths strongly affects its precipitation regime. In this study orientation was indexed by the cosine of the angle between a basin directional vector and the southwest vector, the southwest being the major origin of precipitation-yielding storms in the region. The basin vector was that line directed from the point of intersection of the stream channel and the mean elevation contour, to the gaging station. Preliminary analysis indicated that this index was not simply related to the FSC of any period. Although this result was unexpected, the range of efforts required to allow this variable to make it more sensitive to basin conditions was prohibitive.

Snow Influence

Snow accumulation and snow melt are important factors in the flow regime. They are difficult to index since the necessary data such as the average volume of moisture stored in the snowpack during each month of the year, is not available. This necessitates the use of some other index. Several different possibilities were investigated including the average number of degree days below freezing which Blodgett (1967) found to be associated with the regional variation in the variability of monthly FSC. Difficulties in the derivation of this index from limited climatological data resulted in its rejection. The readily available mean annual temperature was used instead but was likely not as sensitive. It may have been wiser to derive the degree days index. Average monthly snowfall was obtained for each basin by averaging records of point gauges near the basin.

More general indices of snow conditions used in the study included basin slope, and basin orientation relative to true north. This orientation factor differed from that previously discussed only in the direction of the reference vector. Basin slope was the average rise of the stream in feet per mile between the gauging station and the point of intersection of the main channel and the mean basin elevation contour. This index was obtained from Bodhaine and Thomas (1964) and Hulsing and Kallio (1964). Both slope and orientation are related to the amount of solar radiation a basin receives. North oriented basins receive less solar radiation during winter months than do south facing basins. Streams with steep slopes will receive less sunlight than a basin with mild slopes during the snowmelt period. Although solar radiation is not a direct factor in snowmelt it may affect air temperatures and therefore snow conditions.

Another factor undoubtedly related to general snow conditions is basin elevation which has previously been shown to be related to a host of other variables. The strong interdependencies between basin elevation and most of the primary causes of variation in the flow regime prevented its inclusion as an index of snow conditions.

Glaciation Index

The significant degree of glaciation of several of the basins studied makes it almost certain that this factor will have a strong influence on the variation in FSC from basin to basin. The presence of both retreating and advancing glaciers in the same region indicates that glacial activity is a complex phenomenon which may be difficult to index. A mitigating factor is that glacier volumes and surface areas change very slowly and that delineation of glacier boundaries is a relatively simple process. Glacier volumes are impossible to obtain from available information. The influence of glaciers on the flow regime was adequately indexed by the area of glaciers in a basin as a percentage of total basin area. The required data not obtainable from the United States Geological Survey were derived from topographic maps.

Groundwater Storage

The most logical source of carryover in stream flow was concluded in Chapter III to be groundwater storage. This stimulated efforts to develop adequate indices of the infiltration capacity of the basin, the storage capacity of the aquifer itself, and the availability of the aquifer storage to the stream.

The sum total of all these conditions is represented by the characteristics of baseflow recession. Initially, the ratio "k" between the successive flows of the recession was used as an index but was not found to be strongly associated with the geographical variation in any of the FSC. It was thought that taking the inverse of "k" would more correctly represent the storage function of Equation 7, Chapter III. The expected result of stronger associations to the FSC did not materialize. To insure that the lack of relationship between groundwater storage conditions and the FSC was not due to an inadequate index, its form was changed once more. The beginning flow of the baseflow recession in a particular year was obtained for each stream. Along with the exponential decay constant, it was substituted into Equation 7, Chapter III, to obtain a storage index. Although this storage value was only applicable to the particular year used, variations in this value from basin to basin would reflect general variation in groundwater storage capacity. The considerable effort expended in these attempts to index basin storage was justified by the importance of arriving at firm conclusions about the effect of groundwater storage.

Indices of the three different aspects of groundwater storage were also developed but not to any high degree of accuracy and sensitivity. Blodgett's (1967) index of the aquifer storage capacity was based on the permeability of the underlying bedrock as obtained from the State Department of Conservation geologic map of the State of Washington published in 1961. Extension of this numerical index to streams not included in Blodgett's work was accomplished with the aid of Gladwell (1969).

Another aspect of the influence of groundwater contributions to flow is the infiltration capacity of the basin. The relevant factors in this case are the time available for infiltration as affected by stream slope and depression storage, and the soil porosity which governs the maximum rates of infiltration. Although stream slope has previously been mentioned in connection with snow conditions, during the summer months it may affect groundwater storage. Stream slope and depression storage indices were obtained from Bodhaine and Thomas (1964) and Hulsing and Kallio (1964). Most of the region is heavily vegetated which results in a high soil porosity that is subject to little variation. Little variation in infiltration capacity must lead to little variation in the flow regime. Some attempts were made to find an index of vegetation but they met with little success due mainly to a lack of easily obtainable data. The last aspect of the influence of groundwater storage on the flow regime is the availability of the storage to the stream. As discussed in Chapter III, basin area is an index of stream incision in some regions. Although it is not known for certain whether a similar condition exists for the region studied, basin area will be assumed to be an index of stream incision and thus groundwater storage availability. The results should indicate both the validity of the assumption and the importance of this factor in the variation in the FSC.

D. Analysis Techniques

Contouring

Studying the regional variation in the FSC logically led to the contouring of the FSC of each period, thereby providing a visual expression of this variation. Fortunately the time consuming and error prone process of manual contouring was avoided by the use of the IBM 1130 computer program, "Numerical Surface Techniques and Contour Map Plotting", No. 1130-CX-11X, described in IBM publications No. H20-0356-0 and No. H20-0357-0. Although many of the errors which manual contouring is subject to were avoided, the program required some constraints that could not be fulfilled due to limitations of time, finances, and data. This resulted in small anomalies in the contours which did not significantly affect their value. Some of the PSC were also contoured in order to facilitate a comparison of their patterns to those of the FSC for periods when mathematical analysis showed them to be related. This allowed a visual determination of common variation.

Multi-variate Analysis

A simplified version of the computer program developed by Wallis (1965b), incorporating principal components analysis and varimax rotation, was used to analyse the relationships between the FSC and the numerical indices. This analysis technique facilitated the identification of extraneous interrelationships and the deletion of duplicating variables from the array of all possible indices. The deletion of these duplicating indices reduced the number of indices needed to explain the variation in the dependent variables. The final result of this process was that for each FSC there existed a set of indices which were almost independent of each other but still capable of explaining nearly the same amount of the variation in the FSC as the full array of indices were capable of. During the research numerous analyses were done as old indices were rejected or improved upon and new ones added as suggested by the results of a previous run.

CHAPTER V

RESULTS

A. Relationship Between Monthly and Annual Statistics

The importance of finding the relationships between annual and monthly flow statistics lies in the resulting emphasis on the intrinsic relationship between the statistics of flows of different time bases. This is expressed in the derivation of the mathematical relationships between the statistics of annual and monthly flows given in Chapter II. The monthly and annual flow cross-products were substituted into the right and left sides respectively of Equation 12, Chapter II. The values substituted are too numerous to include in this report. The results of the substitution were that there was a difference of 6.6% for the Chehalis River, and 0.13% for the South Fork Skykomish River, between the annual flow cross-products obtained from the annual flow records and those obtained from the monthly flow cross-products.

B. Model Comparison

Table Included

The results of the model comparison include Table 4 (Appendix A), which lists the percentage error in each statistic averaged over all periods for each model. The table is sectioned to allow comparison between streams, of model error in each statistic, the average of the three statistics, and the average of the mean and the standard deviation. Model ratings based on the errors found in Table 4 are included later in this chapter.

Table 5, 6 and 7 (all in Appendix A) deal with a comparison of the averagemodel generation accuracy for different periods. Table 5 lists the average model error for each period and is divided into a section for each stream and the average of the four streams. This format was taken to allow a comparison of the differing levels of average model error for each period, occurring between the statistics of a particular stream. Table 6 is a rating of the periods based on the errors in Table 5 and follows the same format. These ratings are also included in Table 7, but grouped differently to facilitate the comparison of period ratings relative to a particular statistic, from stream to stream.

Model Errors

Table 4 shows that the error in the mean is generally very small, usually less than 10%. For the Chehalis River the minimum error of 3% in the mean occurs for the lag three model while the maximum error of 10% is produced by the lag 12 model; for the South Fork Skykomish River comparable figures are 2% and 46% for the lag five and lag nine models respectively; similar figures for Thunder Creek are 1% and 3% for the lag seven model and lag 11 model; for the Wenatchee River, the values are 2% and 4% for the lag seven and lag 12 models; and for the average of the four streams the errors are 3% and 15% for the lag five and lag nine models. The errors in the generated means tend to be higher for the Chehalis River and the South Fork Skykomish River than for Thunder Creek and the Wenatchee River. The low magnitude of the errors in the means is associated with little variation from model to model and from stream to stream.

The differences between the standard deviations of the generated and recorded flows can be very high regardless of the stream considered. For the Chehalis River a minimum error of 22% and a maximum error of 58% are produced by the lag three and the lag 12 models respectively; for the South Fork Skykomish River comparable figures are 16% and 63% for the one lag and lag nine models respectively; for Thunder Creek the minimum and maximum errors are 9% and 29% for the lag one and lag 11 models respectively; for the Wenatchee River the errors range from 13% to 37% for the lag one and lag 11 models respectively; and for the four stream average the figures are 10% and 42% for the lag three and lag 12 models. The errors tend to be higher for the first two streams above than for the last two streams. It is interesting to note that these errors have a much wider range than the errors in the means even though their minimum values are of a similar magnitude.

The errors in the PSC tend to be higher and vary more widely than those in the standard deviations. For the Chehalis River the lag 10 and lag nine models are associated with minimum and maximum errors of 50% and 77% respectively; for the South Fork Skykomish River the figures are 13% and 27% for the lag two and lag 10 models; for Thunder Creek the error range produced is from 17% to 35% for the lag 12 and lag one models; for the Wenatchee River the most accurate model is the lag 12 with an error of 10% while the least accurate is the lag one with an error of 20%; for the four stream average minimum and maximum errors of 20% and 38% are produced by the lag 12 and lag nine models respectively. The Chehalis River has much larger range of error than the other three streams.

Variations in general model accuracy from stream to stream are indicated by the average of the errors in the means, standard deviations, and PSC referred to as the three statistic average. For the Chehalis River the lag one model is the most accurate with an error of 33% while the lag nine model is the least accurate with an error of 54%; for the South Fork Skykomish River the minimum and maximum errors of 12% and 45% are associated with the lag two and lag nine models respectively; for Thunder Creek the comparable figures are 12% and 17% for the lag three and lag 10 models; for the Wenatchee

RMS of the errors ranges from a minimum of 10% for the lag three model to a maximum of 17% for the lag 11 model.

Since practical model accuracy is governed more by the errors in the means and standard deviations than by those in the RMS, the average of the errors in these two statistics, also called the two statistic average, are included in the results. For the Chehalis River minimum and maximum errors of 19% and 34% are associated with the lag three and lag 12 models respectively; for the South Fork Skykomish River the corresponding figures are 9% and 51% for the lag one and lag nine models; for Thunder Creek the figures are 5% and 15% for the lag one and lag 11 models; and for the Wenatchee River the figures are 6% and 29% for the lag one and lag 11 models.

Model Ratings:

Model ratings were obtained on basis of the errors discussed above, and are presented in the following tables, one table for each statistic. The numbered values found in the tables refer to the lag number of the models and are presented in order of decreasing model accuracy. Reference to model complexity is related to the assumption that the greater the number of preceding flows used in the model, the more complex it is considered to be. The model sequences for the means are shown in Table 8.

Table 8

Model Accuracy with Respect to the Means*

Chehalis River	3	5	8	1	2	6	4	7	10	11	9	12
So. Fk. Skykomish River	5	2	6	1	8	7	3	10	4	11	12	9
Thunder Creek	7	6	10	5	2	9	1	12	8	3	4	11
Wenatchee River	7	2	10	5	6	9	1	8	3	4	11	12
Four Stream Average:	5	2	6	1	3	8	7	10	4	11	12	9

---

*Model Number Sequence in Order of Decreasing Model Accuracy

Generally, for the Chehalis and South Fork Skokomish Rivers, the simpler models tend to be most accurate, while the more complex models tend to be the least accurate. This is opposite to the trend for Thunder Creek and the Wenatchee River where most of the more complex models are fairly accurate and the simpler models such as the lag one, three and four models tend to be inaccurate. The sequence of the four stream average follows that of the South Fork Skokomish River rather closely. The absence of strong similarities between the sequences of the different streams is probably associated with the generally low errors and their narrow range of variation.

The sequences of decreasing model accuracy for the standard deviations are shown in Table 9.

Table 9

Model Accuracy with Respect to the Standard Deviations*

Chehalis River	3	1	4	2	5	6	8	7	9	11	10	12
So. Fk. Skokomish River	1	3	2	5	4	6	8	7	10	12	11	9
Thunder Creek	1	3	2	6	4	5	9	8	7	10	12	11
Wenatchee River	3	1	2	5	4	6	8	7	10	9	12	11
Four Stream Average	3	1	2	5	4	6	8	7	10	9	11	12

---

*Model Number Sequences in Order of Decreasing Model Accuracy

Strong similarities exist between the sequences of different streams. There is a very strong tendency for the simpler models to be the most accurate and the more complex models to be the least accurate. Not surprisingly, the sequence of the four stream average does not differ greatly from the sequence of any single stream. The model rating sequences for the standard deviations are much more consistent from stream to stream than they are for the means. The tendency for the simpler models to be the most accurate is also much stronger for the standard deviations than for the means.

The sequences of decreasing model accuracy with respect to the FDC are shown in Table 10.

Table 10

Model Accuracy with Respect to the Serial Correlation*

Chehalis River	10	6	1	12	11	4	7	8	5	2	3	9
So. Fk. Skykomish River	2	4	5	7	9	12	8	11	1	5	3	10
Thunder Creek	12	11	3	6	5	2	9	7	4	8	10	1
Wenatchee River	12	11	9	6	3	7	8	10	4	2	5	1
Four Stream Average	12	11	6	10	4	7	5	1	8	2	3	9

---

*Model Number Sequences in Order of Decreasing Model Accuracy

This set of sequences shows no strong similarities between streams. There is a tendency for the more complex models to be the most accurate for the Chehalis River, Thunder Creek, and the Wenatchee River while the simpler models tend to be the most accurate for the South Fork Skykomish River. These sequences do not have a tendency toward the definite groupings found in the standard deviation ratings. The means and standard deviations are best approximated by the simpler models while on the whole the FDC is best approximated by the more complex models.

Table 11 shows the sequences of decreasing model accuracy with respect to the average of the three statistics.

Table 11

Model Accuracy with Respect to the Four Statistic Average*

Chehalis River	1	6	4	3	10	5	8	2	7	11	12	9
So. Fk. Skykomish River	2	1	5	3	6	4	8	7	10	11	12	9
Thunder Creek	3	6	2	5	9	4	7	1	12	8	11	10
Wenatchee River	3	2	6	5	9	8	1	4	10	7	12	11
Four Storm Average	6	3	1	2	4	5	8	7	10	11	12	9

---

*Model Number Sequence in Order of Decreasing Model Accuracy

There is a general tendency for the more complex models to be the most inaccurate and the simpler models to be the most accurate. These sequences resemble the standard deviation sequences fairly closely.

The sequences of decreasing model accuracy for the average of the means and standard deviations are shown in Table 12.

Table 12

Model Accuracy with Respect to the Two Statistic Average*

Chehalis River	3	1	4	2	5	6	8	7	11	10	9	12
So. Fk. Skykomish River	1	3	2	5	6	4	8	7	10	11	12	9
Thunder Creek	1	2	6	3	5	4	9	7	8	10	12	11
Wenatchee River	1	2	5	3	6	4	8	9	10	7	12	11
Four Storm Average	3	1	2	5	4	6	8	7	10	11	12	9

---

*Model Number Sequence in Order of Decreasing Model Accuracy

Since the errors of the standard deviations tend to be higher than those of the means it is not surprising that these sequences resemble the standard deviation sequences rather closely in that simpler models are the most accurate while the more complex models are the least accurate.

In summary there are several generalizations which can be deduced from the model errors and model settings. The means are reproduced with considerable accuracy by all the models for all the streams. The standard deviations are reproduced with fairly high accuracy by the simpler models but poorly reproduced by the more complex models. The serial correlations are reproduced with fair accuracy by the more complex models but with poor accuracy by the simpler models. The generated flows of the Chehalis River tend to be more in error than those of the other streams.

Period Errors

Table 5 (Appendix A) shows that the errors in the means of the generated monthly and annual flows of the Chehalis River are less than 10% for all but the November period. The errors, for this stream, in the standard deviations are much higher for almost all the periods, ranging from a low of 7% for December to an exceedingly high of 200% for November. PSC generally have the same magnitude of error as the standard deviations, ranging from a minimum of 4% for July to an extremely high 400% for January. The most interesting results for the Chehalis River are the large error in the standard deviation for the month of November, and the extremely large error in the January PSC. It is also important to note that annual errors are generally not larger than monthly errors.

The errors in the means of the generated flows of the South Fork Skykomish River are fairly small, ranging from a minimum of 3% for April to a maximum of 16% for July. However, they are still slightly larger than those for the Chehalis River. Errors in the standard deviations range from a minimum of 11% for September to a maximum of 86% for November. The error in the PSC reaches a maximum of 65% in the generated annual flows, and a minimum of 2% in August flows. The magnitudes of the errors in the standard deviations and PSC tend to be smaller for this stream than for the Chehalis River. The interesting features for this stream are that maximum errors occur in the November standard deviations and annual FSC and that the July and August FSC are fairly accurate.

The error in the means of the generated flows of Thunder Creek reached a very low maximum of 3%. Consistent with the case for the Chehalis and South Fork Skykomish Rivers the greatest error in the standard deviations, 37%, occurs in November flows. It reaches a minimum of 8% for October. The errors for the other periods are all 20% or less. A similarity exists between Thunder Creek and the South Fork Skykomish insofar as the maximum error in the serial correlation occurs in the annual flows for both streams with values of 75% and 65% respectively. The error in serial correlations of Thunder Creek flows are also high, reaching 60% for January. The most interesting of the results for Thunder Creek are that a high standard deviation error occurs in November flows and a high serial correlation error occurs in January and annual flows. The magnitudes of all errors are lower for this stream than for either the Chehalis River or the South Fork Skykomish River.

The errors in the means of the generated flows for the Wenatchee River are all less than 10%. The error magnitudes of the standard deviations are similar to those for Thunder Creek, reaching a maximum of 41% in the November flows and a minimum of 9% in the September flows. The FSC of the generated flows are generally fairly accurate since error levels are usually less than 10% and reach a minimum of 1% in August flows. The maximum error, 53%, occurs in the annual FSC, as it did for the South Fork Skykomish River and Thunder Creek. June FSC also has a high error of 41%. Error levels are about the same for the standard deviations and the serial correlations. The most interesting features of the results for the Wenatchee River are that error levels of the means are quently low the maximum standard deviation error is found in November flows and the maximum FCD error occurs in annual flows.

In summary the following trends should be noted. For all the streams the maximum error in the standard deviation occurs in the quartered November flows. The error in the MD is the highest for the annual flows for all streams except for the Cedar River for which January MD is greatest in error. Generally speaking, the statistics of the quartered July through October flows are the most accurate. Errors in the means and standard deviations of annual flows are generally of the same order as those of other periods. These general results are also indicated by the averages of the errors of the four streams.

Table 6 (Appendix A) is constructed by ranking in order that period ratings may be compared from the statistics of each stream. The values in the table from 1 to 13 are the numerical ratings of the periods, higher numerical values indicating less accuracy.

For the Cedar River there is a tendency for the summer, i. e. June, July, August, and September, flows to have the most accurate statistics. The mean statistics are also fairly accurately approximated but those of October, November, January and February are poorly approximated. These trends hold for all the statistics which indicated a degree of consistency in period ratings among the statistics of this stream.

The degree of consistency of period ratings from statistic to statistic is somewhat less for the South Fork Skykomish River since June and August are the only periods with reasonably constant ratings for all three statistics. Standard deviations from December through May tend to have a uniform accuracy.

For Thunder Creek the only periods with similar ratings for all three statistics are October, November, and June. There is little uniformity in the ratings of several groups of months.

For the [illegible] River, the December, February, August and September periods tend to have consistent ratings from statistic to statistic. It is interesting to note that similar to the [illegible] River the summer months generally tend to have high ratings regardless of the statistic. The lack of consistency in the [illegible] ratings of the individual streams carries over into the average of the four streams since for this average, only the late summer periods have consistent ratings for all three statistics.

The period ratings of Table 7 (Appendix A) are mentioned to enable comparisons of period ratings between different streams for each statistic. The only trends worth considering in the period ratings with respect to the means are the relatively constant ratings from stream to stream of November, January, August and September periods.

The outstanding feature of the standard deviation ratings is that very consistently the standard deviations of November flows are the least accurate. April ratings also tend to be poor. The FSC in both the annual and January flows have consistently poor ratings while July and August ratings are rather consistently good.

In summary, from the information derived from the period ratings, it is obvious that no strong patterns are present except for isolated periods; the most notable inaccuracies were in November standard deviations and annual and January FSC. Also of interest is the weak tendency for the statistics of the flows of the summer months to be more accurate than those of the flows of other periods.

C. Study of Regional Variation in Flow Serial Correlation

1. Flow Serial Correlation Contours

The FSC contours included in Figures 5 through 17 indicate similarities in FSC contour patterns from September through March excluding November, April through June, and July and August. The contours of annual and November FSC do not fit into any of these groups. The description of the results of these contours will be limited to a delineation of the main patterns since most of the details will be too complicated to explain in physical terms.

September through March Contours

The contours during this season (excluding November) generally have a north-south orientation except for a northwest-southeast orientation along the Pacific coast. The highs centered on the Chambers Creek and [illegible] basins are fairly constant for all months. The FSC values are low along the Pacific coast but high in the Cascade region. The low in the Stillaguamish basin region occurs consistently for all the months in this season. Generally the FSC are fairly constant at moderate values from October through December, become quite low in January and February, and then increase in March.

April through June Contours

During this period the orientation of the contours tends to be northeast-southwest along the Coast and east-west along the eastern border. There is a high centered on the Chambers Creek basin and a low over the adjacent Mount Rainier region. There is also a low in the southwestern and northeastern corners and a high in the southeastern corner. The contour density is somewhat lower than that for the September through March season and the patterns of variation are less regular. The magnitude of the FSC increases from April through June.

July and August Contours

The contour density is low during July and August and there is no predominant orientation of the contours. Lows are centered near the Chambers Creek and Satsop basins and a high occurs around the Dungeness basin. The usual high exists in the southeastern corner of the region. The FSC are very high during this period.

November and Annual Contours

These two contour maps do not resemble any of the other maps. Contour density is fairly light for both periods. November FSC is dominated by an extensive low centered on the Duckabush basin. The orientation of the annual FSC is similar to that occuring during the September through March season except that there is a low instead of a high in the southeastern corner.

2. Physical Prediction Study

This section will deal with the results of the multivariate analysis shown in Figures 19 through 23. The discussion will deal with each of the major phenomena affecting the flow regime, i. e. climatological influences, groundwater storage and the characteristics of the basin surface. The data relating to the effect of the climatological characteristics of the region on the FSC are contained in Figures 18, 19, 20 and 21. Figure 19 shows the associations of FSC to the precipitation, the FSC of the same period as the FSC with which it is associated and FSC of the previous period. Figure 20 shows the associations of the FSC with the snowfall, the mean annual temperature, and the basin orientation. Figure 21 shows the associations of FSC with the percentage of glacierized basin area. Figures 21 and 22 show the association of the FSC with the basin related indices. Figure 21 shows the associations of the FSC with the basin geology while Figure 22 shows the associations of FSC with the other variables indexing the groundwater storage characteristics of the basins, namely the basin area, the baseflow recession factor, the basin slope, and the percentage of basin area occupied by depression storage. The latter two indices more directly index the characteristics of overland flow than those of groundwater storage. In the following discussion the phrase "strength of association" will be frequently used. By this is meant the degree to which the index variable is associated with the FSC as measured by the percentage of the variation in the FSC also occurring in the index variable.

Climatological Indices

A major index of the climatological condition of the basins is the precipitation whose associations with the FSC are shown in Figure 19. The strength of these associations is cyclical reaching minima of 0% and 1% for June and November FSC respectively and maxima of 41% and 33% for September and March respectively. All the associations of precipitation with monthly FSC are negative, indicating that increasing precipitation is associated with decreasing FSC. The association of mean annual precipitation with annual FSC is a positive 9%. In this case increasing precipitation is associated with increasing FSC, contrary to the case for monthly FSC.

Another important index of the general effect of precipitation on the flow regime is the PSC of the same period as the FSC whose associations with the FSC are shown in Figure 19. All the associations are positive with the exception of the September period. The positive associations indicate that the higher the serial correlation in the precipitation, the higher will be the serial correlation in the flow. The strongest associations of the PSC with the FSC are for the annual, October, November, and December periods, explaining from 20% to 30% of the variation in the FSC. Weak associations of less than 10% occur with the March through June, and

September FSC. A notable feature of these associations is that they occur in seasonal groupings of October through December and March through June. An important result is that annual PSC is strongly associated with the annual FSC.

Although October, November, December, April, May, September, and annual PSC were all contoured, only the contours of October PSC, Figure 18, are included in the results. This is because only October PSC contours show any resemblance to the FSC contours; common features of the October PSC and FSC are that both increase in an easterly direction resulting in a high in the southeastern corner of the map. Also, the contour density for both is rather light. For the other periods the PSC contours tend to be very patterned around a minimum number of highs and lows, whereas the FSC contours tend to have few regional patterns and include many localized highs and lows.

It is possible that the carryover in precipitation from one period to another may extend over into a third period and therefore each PSC may be associated with more than one FSC. For this reason Figure 19 includes the associations of the FSC with the PSC of the preceding period. This factor is negatively associated with the February, March and August FSC and positively with the May and June FSC. Only the association of the February PSC with March FSC exceeds 10% in value.

Another important climatological variable in the region studied is the general influence of snow, indexed to some degree by the snowfall, the mean annual temperature, and the basin orientation. The associations of these variables with the FSC are shown in Figure 21. The snowfall is associated with the annual, October, November, December, and February FSC. The magnitudes of the associations are positive and in no case reach 10%. The positive nature of the associations indicates that high FSC tends to be associated with high snowfall. The mean annual temperature is negatively associated with the annual and September through March FSC. The negative nature of the associations indicates that high FSC is associated with lower temperatures and therefore to greater snowfalls, which is in agreement with the associations of the snowfall with the FSC. The associations of the basin orientation to the November, December and May FSC are all positive which indicates that FSC is higher in north-facing basins than in south-facing basins. The strengths of the snowfall, mean annual temperature, and basin orientation associations are all less than 10%.

The influence of glaciers on the flow regime is indexed in this study by the percentage of basin area covered by glaciers whose associations with the FSC are shown in Figure 21. This variable is associated with all but the October FSC. The only positive associations occur with December through March FSC, indicating that for these periods, glaciers are associated with high FSC. From December through June the associations are all less than 10% in magnitude. The association with November FSC is a fairly high 12%. This variable is strongly associated with July, August, and September FSC, reaching a maximum of 45% in July. The positive association of 10% with the annual FSC is also of interest.

Groundwater Storage Considerations

Groundwater storage was divided into its different aspects of infiltration capacity, aquifer storage capacity, and availability of the storage to the stream. Basin slope and depression storage index both the infiltration capacity of the basin and the effects of the basin surface on the characteristics of the overland flow. Basin geology and the baseflow recession factor index the aquifer storage capacity, and the basin area indexes the accessibility of this storage to the stream.

Figure 21 shows that basin slope associates positively with the January, February, August, and September FSC and negatively with the April FSC. Positive associations indicate that high FSC are associated with high slopes and therefore with lower infiltration capacities and higher rates of overland flow. The strength of the associations, highest in January, February and August, is in all cases less than 10%. Figure 21 also shows that associations occur between depression storage and all but the annual, October, November and May FSC. Only with February FSC does the strength of association exceed 5%. All associations are positive indicating that FSC increases with increasing depression storage, hence higher infiltration rates and reduced overland flow velocity.

According to Figure 22, the basin geology is associated with only the May and June FSC, with magnitudes of 11% and 7% respectively. These associations are negative which indicates that low values of this index, and therefore high aquifer permeabilities are associated with high FSC. Also according to Figure 22, the baseflow recession variable is not strongly associated with any FSC. The magnitudes of the association are 1% for November, April, and July FSC and 5% for the August FSC. The associations are negative for the November and April FSC and positive for the July and August FSC. A negative relationship indicates that the FSC decreases with increasing storage.

As shown by Figure 22, drainage area is positively associated with the October through December, FSC, decreasing from a high of 5% during October to a low of 2% in December. The positive nature of the association indicates that FSC increases with increasing basin area and hence greater accessibility of storage.

Strength of Prediction Equations

The total percentage of variation in the FSC explained by the indices is shown in Figure 23. This percentage is at a maximum of approximately 70% for February and September FSC, decreasing to approximately 60% for the annual, October, November, December and March FSC. It is further reduced to approximately 50% for the May, July and August FSC, and 40% for the January and April FSC. It reaches a minimum of 33% for the June FSC. Perfect predictability of the FSC was obviously not reached, nor was this surprising in view of the complexity of the problem.

As a consequence of the imperfection of the equations the actual FSC values used in the analysis did not completely correspond to those indicated by the regression equations. The errors, or residuals, were included in a subsequent analysis to determine the relationships between these residuals and the dependent and independent variables. Relationships between the residuals and the independent variables would violate the assumptions of the analysis and would make the results questionable. Fortunately the residuals were found to be unrelated to the independent variables. They were negatively related to the dependent variable which indicated that high FSC tend to be underestimated and low FSC tend to be overestimated. It was not surprising that the residuals were related to the FSC since the residuals incorporated the variation in the FSC not explained by the rest of the indices.

The components of the prediction equations are listed in Table 13 (Appendix A). Table 2 (Appendix A) includes the values of the indices for the check streams which when substituted into the prediction equations, give the results listed in Table 14 (Appendix A). These results for the South Fork Skokomish, the Greenwater, and the Sultan Rivers include the actual FSC, the predicted FSC, and the difference between these two values. The highest errors for the South Fork Skokomish River occur in the predicted January and the September FSC, which have weak and strong prediction equations respectively. The minimum errors occur in November, December, April and July FSC and show little relation to the strength of the prediction equations. The errors in the FSC of the Greenwater River are greatest when the prediction equation is weakest, as would be expected. This is shown by the larger errors in the predicted April, May, and June FSC. For the Sultan River the maximum errors occur in December and June FSC which have strong and weak equations respectively. The minimum errors occur in the predicted annual and October FSC, both of which have fairly strong equations.

The negative relationship between the errors and the FSC can also be checked by the results of these independent predictions. Contrary to the predicted relationship, positive and negative errors occur for both high and low FSC values in the case of the South Fork Skokomish River. In the case of the Greenwater River the relationship is upheld by the negative errors occurring in the high FSC values from April through August and the positive errors occurring in the low-valued March and January FSC. For the Sultan River the expected relationship is shown by the overestimation of the small annual FSC and October through April FSC, and the underestimation of the larger June and July FSC. Large errors over 0.10 occur in the October, January, March, May, June, August, and September FSC of the South Fork Skokomish River; in the April, May, June, and August FSC of the Greenwater River; and in the December through March FSC and June FSC of the Sultan River. These errors were not expressed in terms of percentages because of the large, misleading values resulting from the division of a small error by an equally small FSC value.

CHAPTER VI

DISCUSSION OF RESULTS AND PRIMARY CONCLUSIONS

A. Relationship Between Monthly and Annual Statistics

The small errors of 6% and 0.1% resulting from the substitution of appropriate values into both sides of Equation (12), Chapter II, expressing the relationship between annual and monthly flow cross-products indicate that the equation for the annual flow cross-product is correctly formulated. From this it can be concluded that the statistics of any time averaged flow distribution are intrinsically related to and derivable from the statistics of flows of a smaller time base. This holds important implications for the proper attitude required in the use of, for example, monthly and annual flows in water resources development.

B. Model Accuracy and Ratings

Model accuracies are discussed in this section wholly within the context of the empirical applicability of the models to flow generation. Physical reasons for the characteristics of model accuracy are much too complex to be studied within the scope of the research. Some of the more outstanding features of the period ratings may have a counterpart in the physical prediction aspect of the research which provides somewhat of a weak tie of this phase of the study into the study of physical causes of FSC. The relationships between this phase of the research and the physical prediction phase strengthen the confidence held in the results of both.

Model Errors

The range of errors in the means is very small since the maximum error of any stream is 15%, except for the 44% error of the lag nine model for the South Fork Skykomish River. Errors in the means cannot play a large role in the selection of the most acceptable model, since the error to be expected is usually negligible. This also leads to the conclusion that the mechanics of the generation process were not subject to inadvertent human error and therefore the results can be accepted as providing correct information.

Whereas the errors in the means are small and have a narrow range of values, the errors in the standard deviations range from minimum values of 10% to 20% to maximum values from 30% to 60% depending on the stream. The minimum errors are acceptable in hydrologic usage, whereas the errors of the least accurate models would severely reduce the reliability of the generated flow. There is undoubtedly a physical reason for the fact that for the Chehalis and South Fork Skykomish Rivers, the maximum model error is approximately 60% while for Thunder Creek and Wenatchee River, the maximum error is approximately 30%. Unfortunately there is no possibility at the present of determining what this reason is. The rather large range in the error places considerable importance on the choice of the model to be used for flow generation since a bad choice can lead to gross error. This is further accentuated by the fact that the errors discussed are averaged over all periods and that errors in the standard deviations of the flows of individual periods may be considerable higher than the average.

The errors in the FSC do not follow the same patterns as those in the standard deviations. For the standard deviations, the Chehalis and South Fork Skykomish Rivers tended to have a common error level and range as did Thunder Creek and the Wenatchee River. In the case of the serial correlations, the Chehalis River is different from the other three streams in that its error range, 50% to 97%, is much greater than that for the other three streams whose errors have a combined range of 10% to 35%. The error range for the average of the four streams reflects mainly those of these three streams. It is interesting to note that the magnitudes of the errors in the FSC are generally greater than those in the standard deviations which in turn are generally larger than those in the means. This leads to the conclusion that the degree of error in the statistics of the generated flows depends on the complexity of the statistic.

General model accuracy is indicated by the errors in the average of the three statistics. These errors reflect mainly the errors in the standard deviations and FSC since these errors are the largest. Over all, the statistics of the generated Chehalis River flows are subject to the greatest error followed closely by those of the generated South Fork Skykomish River flows. The statistics of the generated flows of Thunder Creek and the Wenatchee River contain less error. It must be concluded that the accuracy of model generation varies considerably from stream to stream.

The flow characteristics of most interest in practical water resources analysis are the average of the flow and the variability of the flow about this average. The errors in the means and standard deviations are therefore of interest. They reflect mainly the influence of the errors in the latter because of their higher values. The Chehalis and South Fork Skykomish Rivers have a combined error range of 9% to 54% compared to values of 5% to 20% for Thunder Creek and the Wenatchee River. Practical application of model generation may be limited by the variability between models and between streams. However if the most acceptable model is comparably accurate from stream to stream, its use in flow generation for all streams in the region may be very valuable. Individual models and their rating will be discussed in the following section in terms of consistency of ratings from statistic to statistic and from stream to stream.

Model Ratings

Having discussed general error levels and ranges, it is necessary to discuss the ratings of the accuracy of each model in the reproduction of the proper statistics of their generated flow. Factors to be taken into consideration are the variation in model ratings from stream to stream for each statistic and from statistic to statistic for each stream. The low error levels and ranges of the means reduces the importance of the ratings of models with respect to this statistic and also results in a lack of consistency in the ratings. This lack of consistency is evidenced by both a lack of similarity in ratings between streams and also by the fact that neither the complex nor the simple models have a tendency to be the most accurate.

On the other hand the errors in the standard deviations are considerably less for the simpler models than for the more complex models. There is also a very definite trend for this condition to be applicable to all the streams studied. In detail, the most accurate models are consistently the one, two, and three lag models, which have relatively low error levels. It can be concluded that the use of one of the three simplest models in flow generation will yield flows with acceptably accurate standard deviations for all streams. This most certainly is of great value to the hydrologist concerned with flow generation.

The ratings of the models with respect to the serial correlation indicate that the more complex models have a weak tendency to be more accurate than the simpler models. This tendency is not nearly so strong as the opposite trend in the standard deviations. The FSC ratings also have less consistency from stream to stream than do the standard deviation ratings. This is shown by the fact that FSC ratings for the South Fork Skykomish are contrary to those of the other streams. It can be concluded that the more complex models are generally the most accurate with respect to the FSC but that this general rule may not hold for all streams studied. Since this parameter could be of secondary importance in the generated flows, these results may be of theoretical interest only. Certainly if the FSC is of great importance, the reliability of the generated data of any model is questionable.

The model ratings with respect to the average errors of all three statistics indicate that the simpler models generate the most accurate flow data while the more complex models are the least acceptable in this respect. This indicates that the standard deviations are predominant in this average. Inconsistencies between streams appear to be quite significant since the ratings of the average of the four streams do not strongly coincide with those of the individual streams. The model ratings with respect to the average errors of the means and standard deviations definitely follow the standard deviation ratings. This is especially shown by the high ratings of the simpler models. It can be concluded that standard deviation errors are the most dominant.

The general consistency of model ratings from statistic to statistic is very low. For the means, models of medium complexity are the most accurate, for the standard deviations the simpler models are the most accurate; and for the FSC the more complex models tend to be most accurate. The result of this lack of consistency is that no single model will generate data in which all the statistics are highly accurate. It is necessary therefore, to develop criteria for choosing an acceptable model. These criteria were alluded to in previous discussion but will now be discussed in detail. The serial correlation in generated flows is of little concern to the water resources planner since its major application lies in flow generation processes. Hydraulic structures are designed with a built-in safety factor which is intrinsically connected to the probability of extreme events capable of rendering the structure unsafe. The probability of extreme events is directly a product of the variability in the flow, and therefore the standard deviation and also the means of the flow. It is evident that the means and the standard deviations of the generated flows must closely approximate those of the original flow data if the generation model is to be suitable for practical hydrologic use. The errors in the means are smaller and have a lower range than do the errors in the standard deviations. A less than optimal model with respect to the means will result in minor errors while the same condition for the standard deviation could result in gross errors. Therefore it is necessary that the model chosen be capable of generating flows with acceptable standard deviations.

Another consideration relevant to model acceptability is model complexity in relation to the current degree of insight into generation mechanics. It has been stressed that presently little is known about multi-lag generation techniques whereas considerably more is known about the single lag generation model. Since an understanding of the nature of the generation process facilitates the proper use of such techniques, simpler models are more desirable than complex ones if the errors produced by the former are comparable to those of the latter. This would involve more of an intuitive than a quantitative judgement.

The criteria therefore, applying to model acceptability are model simplicity and model accuracy relative to the standard deviation in the generated flows. The most accurate models with respect to the standard deviations are the lag three, one, and two models in that order. Table 15 below gives the error averaged over all periods for each of these models for each of the streams.

Table 15

Standard Deviation Errors for Selected Models

	Lag 1 Model	Lag 2 Model	Lag 3 Model
Chehalis River	32.12%	34.46%	21.66%
So. Fk. Skykomish River	16.24%	18.90%	17.34%
Thunder Creek	8.77%	9.87%	9.75%
Wenatchee River	12.83%	13.68%	13.75%
Four Stream Average	17.49%	19.23%	15.63%

This table indicates that the differences in the errors for the three models are quite small for all streams except the Chehalis River for which the lag three model is considerably more accurate than the other two. According to the accuracy criterion, it must be concluded that the lag three model is the most acceptable. However, it was concluded that the simplicity of the lag one model was more valuable than the increased accuracy of the lag three model. Until further information on the nature of the multilag model is available, the lag one model must be considered the most acceptable for monthly flow generation. The variability in the accuracy from stream to stream as exemplified above by the Chehalis River, is a factor which must be taken into account in its use. Considerable error in the parameters of the generated data may result from both the differences in model errors between streams and the less than optimal nature of the lag one model. The actual errors occurring in the statistics for each stream studied will be given after variations in the period errors are discussed in the following section.

Period Ratings

The purpose of this discussion is to determine from the relative differences in error levels between periods any seasonal tendencies in average generation accuracy and any consistencies in such tendencies from statistic to statistic. Determination of isolated periods whose flows are subject to anomalously large errors is also important in order that the limitations of flow generation are clearly outlined. Another question to be answered by the results is whether the errors in the statistics of the annual flows derived from the generated monthly flows are of the same magnitude as those in the statistics of the generated monthly flows. It should be noted that the period errors discussed are obtained by averaging, for each period, the errors of all the models. Period errors for individual models may vary considerably from the average.

The means of the generated flows of all periods are quite accurate, usually subject to errors of less than 10%. This indicates that there is little variation in the level of errors in the means from period to period consistent with the lack of variation in these errors from model to model. An exception to the general low level of error in the means is the 31% error in the means of the November flows of the Chehalis River. This may reflect both the generally larger errors in the flows of the Chehalis River and the tendency noted below to large error in generated November flows. Overall it can be concluded that the means of only the generated November flows will likely be subject to substantial error.

It is apparent from the results that the errors in the standard deviations vary widely from period to period. The minimum errors of approximately 10% are acceptably small while the maximum values of 200% are totally unacceptable. This wide variation serves to emphasize that the standard deviations in the generated data of some of the periods may be grossly in error. The errors in the standard deviations of generated November flows are, for all streams, larger than those for any other period. The abnormal nature of these errors is highlighted by the relatively low error values for the September, October, and December flows. A possible reason for this is that November flows are somewhat transitional in nature, spanning the change from a rainfall dominated flow regime to one strongly influenced by snowfall. The anomalous nature of November flows is also evidenced in the contours of November FSC to be discussed later. It is also to be noted that the standard deviations of July and August flows tend to be quite accurate.

With respect to the FSC errors, the points of interest are that the maximum errors occur in the annual and January flows and the minimum errors occur in the flows of the summer months. A possible explanation for this lies in the magnitudes of the FSC themselves. Relatively high percentage errors would result from small actual errors in the low-valued annual and January FSC, shown in Figures 5 and 9, while low percentage errors would result from relatively high actual errors in the high June, July and August FSC, shown in Figures 14, 15, and 16.

Observations can be made about the period errors in general. The errors tend to be higher for the Chehalis and South Fork Skykomish Rivers than for Thunder Creek and the Wenatchee River. It must be concluded that error levels can vary considerably from stream to stream for reasons which unfortunately, are not known. Generation accuracy can vary from period to period, generally being most accurate for the summer months. This may be due to the stable regime of flows occuring during this period. These error variations from stream to stream and from period to period must be considered in the use of flow generation techniques.

The results indicate that the statistics of the annual flows have generally the same accuracy as those of the generated monthly flows. Specifically the means of the annual flows are as accurately reproduced as those of the monthly flows. An intuitively logical reason for this accuracy is that the mean is a relatively simple characteristic of the flow and as such is easily carried through the monthly to annual flow transformation. The errors in the standard deviation of annual flows are fairly large for some streams but do not approach the maximum values for the monthly flows. The errors in the annual FSC are generally higher than those in the monthly flows. It appears that the means and standard deviations are fairly well preserved in the transformation process from monthly to annual flows but that serial correlation is not. If the serial correlation in the generated annual flows is of little importance it can be concluded that annual flows can feasibly be derived from the generated monthly flows. This means that an acceptable monthly flow generation model will satisfy requirements for both annual and monthly generated flows in water resources applications.

Individual Errors for Streams Studied

The discussion of errors averaged over all models for each period has provided some insight into the seasonal variations in the errors of the periods. It also has provided some insight into the nature of the annual flows derived from the generated monthly flows. Previously in this chapter, the lag one model was chosen as the most acceptable model. The actual errors of this model for each stream and statistic are presented in Table 16 (Appendix A). The errors in the means and standard deviations are listed as a percentage of the original values of these statistics while the errors in the FSC are presented as merely the difference between the statistics of the original and generated flows since low values of the original FSC caused distorted values in the percentage errors.

The only major error in the means occurs in the November flows of the Chehalis River. At 33% this error is large enough to cause problems in the practical use of the generated flows. Since an error of this magnitude occurred for only one stream, it can be tentatively concluded that this repetition in other streams within the region would not be too common. However, it would be advisable to excerise caution in the use of generated November flows.

The important errors in the standard deviations are mainly those of the generated November flows. The magnitudes of the errors range from a high of 225% for the Chehalis River to a low of 20% for the Wenatchee River. In water resources applications requiring accurate estimates of flow variability, the generated November flows of Thunder Creek and the Wenatchee River may be acceptable but not those of the Chehalis and South Fork Skykomish Rivers. It appears that accurate means and standard deviations in generated November flows are not totally attainable with the use of the models studied. Other relatively large but possibly acceptable errors in the standard deviations occur in the annual and March flows of the Chehalis River and the March flows of Thunder Creek and the Wenatchee River. None of these errors reach the extreme magnitudes of those found in the November flows of the Chehalis and south Fork Skykomish Rivers, so they could be acceptable.

Although the accuracy of the FSC was not considered to be an important criterion of model acceptability, it is possible that some applications would require knowledge of the errors to be expected in this statistic. Table 16 shows an interesting feature of the serial correlation errors not seen in the previous results. Regardless of the value of the FSC in the original annual flows of the four streams, it is negligibly small in the annual flows derived from the generated monthly flows. From this it can be concluded that deriving annual flows from generated monthly flows does not allow for the preservation of the annual FSC. Serious errors also occur in the FSC of April, May, June, and September flows for the Chehalis River; January and February flows for Thunder Creek; and June flows for the Wenatchee River.

An overall conclusion which can be made about the results of generating flows by means of the lag one model is that they are generally satisfactory but subject to large errors in the standard deviations and FSC of a few of the monthly flows. The value of generation techniques in water resources planning leads to the conclusion that notwithstanding some of the large errors that can occur, the lag one model is still a valuable tool if proper precautions are taken to reduce the detrimental effect of such errors. These results also affirm the suitability of deriving annual flows from generated monthly flows, thus eliminating any need for an annual flow generation model.

C. Physical Prediction Study

The results of both the FSC contour and the multivariate analysis will be discussed as a unit with a view to determining the physical influences which affect the magnitude and geographical variation in the FSC. The results of the multi-variate analysis should cast light on, and be affirmed by, the results of the contours. Initial discussion will deal with the general effect of the active hydrologic factors in order to determine what gives rise to FSC and also what detracts from it. Following this will be a specific delineation of the variation in the strength of each of these factors from month to month. The FSC contours will be discussed at the same time, specifically in the context of the dominant factors affecting the FSC variation shown in the contour. It must be emphasized that the conclusions gained from the prediction study are only applicable to regions having climatological and geographical conditions similar to those of Western Washington. Such regions might well include the west coast from Alaska to California.

The associations of the numerical indices with the FSC are either positive or negative indicating that the indexed physical phenomenon either adds to or detracts from the magnitude of the FSC. The wide variation in the magnitudes of the FSC from period to period and from location to location should be explainable in terms of additive or subtractive physical causes. The additive physical causes can be regarded as sources of FSC. Determination of these sources is one of the purposes of this study.

A general impression of the variation in the serial correlation from month to month can be obtained from the FSC contours shown in Figures 5 through 17. The FSC is highest during July and August and decreases to a low in January and February. It is to be noted from Table 16 (Appendix A), that both the flow magnitude and variability are at a minimum during the summer months but increase to a maximum during the winter months. Low FSC values occur when the means and standard deviations of the flows are at a maximum leading to an apparent negative correlation between the FSC and the flow means and standard deviations. It is tempting to think of the association of high FSC with low standard deviations as a causal relationship, but this is not necessarily true. The correlation coefficient is operationally a product of the covariance and the inverse of what can be considered to be the average variance of the two variables involved. Any reduction in the variance will lead to a higher correlation coefficient providing there is no corresponding reduction in the covariance. In the particular case under discussion the reduction in the variance of flows from the winter to the summer months does not guarantee that there will be the smaller reduction in the covariance required to produce the higher serial correlation coefficients during the summer. Furthermore, explaining variation in the FSC in terms of variation in other statistical parameters does not do justice to the underlying physical causes of variation in FSC. Although variation in the standard deviation must be rejected as a cause of variation in FSC, the non-causal relationship between the serial correlation and the standard deviation may be an important consideration in determining the source of FSC. A possible reason for this relationship is that if the source or sources of serial correlation are weak they will be easily over-ridden by the less consistent variability in the sources of high flows, namely rainfall, snowmelt, and glacial melt. This would result in a reduction in FSC during periods when flow variability is high.

The results show that precipitation increases are associated with decreases in the FSC whereas both the snowfall and the PSC have opposite associations. Snowfall at higher elevations usually occurs in conjunction with rainfall at lower elevations. The immediate runoff resulting from the rainfall serves to decrease the FSC whereas the moisture stored in the form of snow does not run off for some time. This delay in the runoff leads to higher serial correlation values for basins receiving snowfall than for basins without snowfall. However the melting of the accumulated snow will serve to reduce the FSC. Therefore, the increase in FSC caused by snow accumulation is later matched by a decrease in FSC caused by snowmelt. The associations of the PSC with the FSC occur during October, November, and December when precipitation and thus flow, is increasing. If PSC was associated with decreasing flow it could be said to be an index of the effect of flow levels on the FSC. Since this is not the case, it must be considered a source of FSC even though the exact physical relationship between the two variables is not known. PSC is also a source of March, April, and May FSC.

In addition to the PSC of the same month as the FSC, the PSC of the month preceding that of the FSC was also included in the study to see if there existed a Markovian relationship between consecutive PSC which could lead to associations between the FSC and several PSC. The associations of this PSC with the FSC were negative for February, March and August, and positive for May and June. The indices involved are the January, February, July, April, and May PSC respectively. The existence of a Markovian relationship was refuted by the multivariate analysis results which indicated that the consecutive PSC tended to be unrelated. It is possible that the FSC may be associated with the PSC of the previous period because of some influence of the drainage basin on the resulting runoff. However, the relationships involved are complex and poorly understood. Factors contributing to the difficulty in interpretation of the associations are that they are not all of the same sign and that their strength varies from a fairly high level in February to low values in May and August.

Since the PSC of the previous period is a characteristic of the precipitation, it is fairly certain that it is not indexing some physical condition of the basin. It is independent of the other indices which means that it could be included in the prediction equation without compromising the understanding of the nature of the influences acting on the FSC. Although it serves to emphasize the complexity of the effects of precipitation on the flow regime, it may also provide information for future researchers investigating this area of study.

The associations of glacierized area to FSC indicate that glacial melt from June through September serves to decrease the carryover in the flow whereas from December through March the small positive associations indicate that glacierized basins tend to have higher FSC than nonglacierized basins. The latter associations are probably similar to those of the snowfall from October through December, i. e. a reduction in flow leading to an increase in FSC. The positive association between the glacierized area and the annual FSC can be plausibly explained in terms of the long delay between when the snow falls on the upper surface of the glacier and when the ice melts in the ablation zone. In this sense, glaciers could be a source of annual FSC.

Groundwater storage is usually an important aspect of the runoff regime. The literature reviewed included several references to the logical importance of groundwater storage in FSC. However, it has been pointed out that in the region studied there is little storage capacity in the underlying bedrock. For this reason it has been postulated that groundwater storage is not a significant source of FSC. The proof of the postulate lies in the nature of the associations of the indices of groundwater storage with the monthly and annual FSC. The associations of these indices which include basin slope, basin geology, depression storage, drainage area, and the baseflow recession factor, with the FSC will be discussed in relation to the accuracy or inaccuracy of the above postulate. The positive associations of the basin slope with the January, February, August and September FSC mean that high slopes are associated with higher flow carryover. This certainly does not reflect the relationship of slope to infiltration rates and volume of groundwater storage. Basin slope is not indexing groundwater storage in these associations. The only negative association of the basin slope is with the April FSC. April flows result mainly from precipitation and snowmelt. In relation to these flow sources the relative importance of groundwater additions to the flow would be very small. However, it is possible that weak effects of groundwater storage are being indexed here. Depression storage is associated with all but the October, November, and May FSC. Of these associations all of which are positive only those with the February and August FSC are of considerable strength. The positive nature of the associations indicate that depression storage has the expected function of increasing the carryover in flow. Considering the high flow volumes occurring during the rainfall and snowmelt periods, depression storage probably increases FSC by introducing regularity into the streamflow rather than by its effect on infiltration rater. However during the low flow summer months depression storage may affect FSC through its effect on infiltration rates. It appears reasonable to conclude that only the association of depression storage with August FSC reflects an important influence of groundwater storage.

Basin geology was intended to be a measure of the storage capacity of the basin aquifers but the lack of associations of this variable with the summer FSC indicates that this is may not be true. The negative associations with May and June FSC mean that basins with more permeable bedrock tend to have higher FSC as would be expected if groundwater storage was being indexed. However, it does not seem reasonable to expect groundwater storage to be a strong influence during the period of high runoff from snowmelt. A more probable explanation for these associations is that the basin geology is related to elevation and therefore to snowmelt to some extent.

The baseflow recession variable was designed to be an index of the storage available in the aquifer at the beginning of the depletion period. Its positive associations with the July and August FSC indicate that greater storage is associated with higher values of FSC. The small negative associations of this variable with the November and April FSC are unexplainable in physical terms and therefore must be disregarded. The associations with July and August FSC are relatively weak and indicate that the influence of storage is rather small. Although storage is shown to be a source of FSC, it does not appear to be solely responsible for the existence of very high FSC during the summer months. Confusion about the nature of this variable is introduced by the fact that in its derivation the initial flow taken as the beginning of the recession period was for most of the streams, a daily flow in April. April is not usually considered to be the beginning of the baseflow recession period. A possible reason for this early occurrence of what appears to be baseflow recession is that the exponential decay characteristics of snowmelt are being indexed. These characteristics would then grade into the glacial melt decay function and then into groundwater storage depletion. It can be concluded that notwithstanding the apparent incongruities in the baseflow recession factor, this factor does index aquifer storage to some degree and that aquifer storage does have a small effect on FSC during July and August.

Basin area is assumed to index both stream length and the accessibility of aquifer storage to the stream. This variable is positively but weakly associated with the October, November, and December FSC only. The positive aspect ot the relationship means that as expected larger basins tend to have higher FSC. It would be expected that the predominant influence of precipitation on the flow regime would reduce the effects of groundwater storage until they were almost negligible. It is possible that basin area as related to stream length may be associated with a regulatory effect on the flow which tends to increase the FSC. This alternative explanation for these associations is somewhat weak however and it is still possible that groundwater storage accessibility may have a weak influence on the October, November, and December FSC.

In summary it can be concluded that groundwater storage and its related aspects do have a weak influence on the flow regime. Basin slope affects infiltration rates during April and thereby April FSC. Basin geology may or may not influence May and June FSC. Its exact effect is unknown because of its ambiguous nature. During the months when high flows occur, depression storage increases the FSC by introducing regularity into the stream flow. Its only effect on infiltration rates occurs during

July and August when it serves to increase the FSC. Groundwater accessibility possibly affects the October, November and December FSC. The baseflow recession variable is associated with July and August FSC indicating that the total effect of infiltration rates, storage capacity, and storage accessibility is to increase July and August FSC. None of the above relationships are strong. The general conclusion must be that groundwater storage, though possibly having some influence on the FSC, is not the major source of the FSC of any period.

Attributing the weakness of the associations of the indices of groundwater characteristics with the FSC to deficiencies in the indices is unacceptable. Many of the indices of the other physical phenomena are as crude, if not more so, as those indexing the groundwater characteristics. Yet they show strong associations with the FSC of various periods. It can be concluded that if the physical influence being indexed is of major importance, the sensitivity of the index is of secondary importance. On the other hand if the physical influence is of limited significance the index must be very sensitive if its influence is to be discovered. The latter appears to be the case for groundwater storage.

As an overall conclusion to the search for the sources of FSC, it must be stated that only precipitation serial correlation and groundwater storage have been found to act as partial sources of monthly FSC. The former is of major importance while the latter is quite minor. PSC does not influence the same FSC as the groundwater storage does. Therefore it must be concluded that the sources of FSC vary throughout the year. It is evident that flow addition from such sources as rainfall and snowmelt cause a decrease in the monthly FSC, indicating a relative weakness in the physical causes of FSC. Annual FSC is partially caused by the storage function of glaciers.

Detailed Analysis of Associations

The foregoing discussion dealt primarily with the nature of the influence of each of the major physical phenomena on the FSC. Following is a detailed discussion of the variation in the strengths of these influences from month to month. The results of both the contouring and the multivariate analysis indicate that a logical breakdown of the twelve months would be into seasons including October through December, January through March, April through June, and July through September. The results for the September FSC indicate that it may be included in both the October through December and the July and August seasons. It is included with the July and August periods since its similarities are greatest with this season. Annual FSC is discussed separately.

October through December FSC

In the results of the multivariate analysis both precipitation and PSC show strong associations with the FSC during this season from which it can be concluded that precipitation as a general physical phenomenon dominates the flow regime. Mean monthly precipitation is strongly associated with October and December FSC but not with November FSC. It is apparent that both October and December FSC are precipiatation dominated but apparently November FSC is not. From previous discussion of the results of both the model testing and the contouring studies it was concluded that November was an anomalous month. It was previously postulated that the cause of the abnormality of November flows was that they are somewhat transitional in nature. This is shown in Table 16 (Appendix A) by major differences between the November and October flow means and standard deviations for the Chehalis, South Fork Skykomish and Wenatchee Rivers. The association of the PSC with the November FSC does not show this phenomenon since it fits in with the steady increase in the strength of the associations of this variable with the FSC from October through December. It is not known why the anomalous nature of November flows does not affect the association between November FSC and PSC. However, it must be concluded that some of the physical factors affecting November FSC are quite different than those affecting October and December FSC.

It can be speculated that a flow regime change occurs in November. The unsaturated state of the soil mantle initiated during the day summer months may persist through October even though considerable precipitation falls during this period. If the soil reaches a state of saturation in November, it would be expected that runoff during November would not be subjected to the regulatory action of the soil mantle and thus would be subject to more variation than October flows. It must be noted from Table 16 that November flow means and standard deviations are more like those of September flows than October flows; there is not a large change in the flow regime from November to December. November FSC will be anomalous because October and November flows belong to two different regimes. The October and December FSC will not be anomalous because for each, the flows involved belong to the same regime. This could account for the anomalous results for the contouring and multivariate analysis for November FSC compared to those of the October and December FSC. The inaccuracy of November flow generation compared to that of October and December flow generation may also be due to the regime change since generation is based on the use of preceding flows as predictor variables. October flow generation is based on preceding flows belonging to the same regime. This is not true for November flow generation. December flow generation includes November flows as predictor variables. These belong to the same regime but for multi-lag models, flows belonging to a different regime are also included in December flow generation. The latter flows may not have a strong effect on the results of the generation process, thus possibly allowing accurate December flow generation. These deductions, although speculative, may be of value.

The weak associations of snowfall with the October through December FSC indicates that it has some influence on the flow regime during this period. The positive nature of these associations has been surmised to indicate that snowfall serves to decrease the flow relative to that occurring from basins which do not receive snowfall. The weakness of the associations leads to the conclusion that snowfall does not greatly affect these FSC. The associations of the mean annual temperature with the FSC also indicate that snowfall is associated with higher FSC values during the period and again the weakness of the associations indicates that snowfall is not of great importance. Neither the snowfall nor the mean annual temperature associations show the effects of the anomalous nature of November flows. Basin orientation is weakly associated with the November and December FSC in such a way that north-facing basins have higher FSC than do south-facing basins - another indication of the weak influence of snowfall.

The anomalous nature of November flows is also indicated by the negative association between the glacierized area index and the November FSC. The strength of the association is relatively high and means that glaciers have a fairly strong detractive effect on the FSC. A remotely possible reason for this may be that an "Indian summer" effect during November could result in the melting of glaciers with an accompanying reduction in the FSC. However this does not appear to be reasonable since the sudden change in the November flow means and standard deviation occurring for the other three streams shown in Table 16 does not occur for the highly glacierized Thunder Creek. It appears that the transitional nature of November flows bears some unknown relationship to the presence of glaciers in the basin. The expected association of glacierized area to the FSC during this period would be positive in nature meaning that glaciation is associated with higher FSC since glaciation would be strongly related to snowfall. This expectation is fulfilled by the weak positive association of this variable with the December FSC. Groundwater storage has previously been concluded to have a weak influence on the FSC of this period as shown by the associations of the drainage area with the FSC.

Most of the results of the multivariate analysis are mirrored in the contour patterns of the FSC of this period. The variation in the precipitation itself is clearly reflected in the FSC contours. The coastal and Olympic basins which receive much rainfall have low serial correlations while the Cascade basins subject to snowfall and therefore less runoff tend to have higher FSC. These observations do not apply to the anomalous November FSC contours. No reason has been found for the dominance of the Duckabush basin in November FSC contour patterns. October PSC tend to have the same pattern as October FSC while this is not the case for November and December PSC.

In summary it can be concluded that precipitation and precipitation serial correlation are both important factors in the geographical variation in FSC. The effect of the precipitation is modified somewhat by its occurrence in the form of snow rather than rain. Very definitely, there is a regime change from October to November which probably also strongly affects the influence of glaciers on the FSC.

January through March FSC

By far the most important influence on the FSC during this period is that indexed by the precipitation. The associations between precipitation and the FSC are strongly negative which means that the FSC is decreased by increasing precipitation. This is also indicated by the contour maps which show that January FSC are very small in the lower Cascade basins and the west Olympic basins. The influence of PSC disappears entirely in January and February and reappears, although weakly, in March. Why this factor should be strong and inconsequential in the January through March season is not known at present.

The association between the snowfall variable and the February FSC indicates that snowfall causes higher FSC for this month. It would be expected that January FSC would be similarily affected, but apparently such is not the case since no associations exists between the snowfall and the January FSC. Possibly this condition is reflected in the contours where the lows in the January and March FSC associated with rainfall are not as strong in the February FSC. The association of mean annual temperature with the January through March FSC indicate that colder basins have a weak tendency towards higher FSC. This may reflect the effects of either snowfall or the snowpack condition. The associations of mean annual temperature probably indicate that January and March FSC may be affected by snowpack conditions whereas its association with February FSC probably reflects the effects of snowfall. The effect of the snowpack may result from the fact that freezing elevations vary widely throughout the winter. This in turn causes the snowpack to be rained on rather frequently. The rainfall must find its way through the snowpack before it can reach the stream, and in so doing may be regulated somewhat by the storage capacity of the snowpack.

Positive, weak associations occur between the basin slope and the January and February FSC indicating that steeper basins have higher FSC. The possibility that these associations might be related to groundwater storage has already been discounted and the suggestion was made that these associations are due to the fact that basin steepness varies with basin elevation and therefore with the degree of snow accumulation.

In summary, it can be concluded that for this season precipitation in the form of rainfall has a predominant influence on the FSC, causing very low values of the FSC. Snowfall and the presence of accumulated snow have a minor effect on the FSC. Precipitation serial correlation has no effect on the FSC.

April through June FSC

As shown by the associations of precipitation to the FSC of this season, the influence of precipitation on the flow regime decreases from a high value in April to negligible levels in June. The likely reason for this is that precipitation is decreasing and some other source of flow is becoming more important. It is likely that the flow resulting from snowmelt increasingly overshadows that of rainfall until in June precipitation is not associated with the FSC at all. Throughout this season PSC is positively associated with the FSC. These associations begin in March at a low strength reaching a peak in May and decreasing again in June. It must be concluded that PSC once again is a source of FSC.

There are weak negative associations of the glacierized area with the April, May and June FSC. The association with the June FSC is the strongest. The negative aspect indicates that the effect of the glaciers has changed from one of causing an increase in the FSC to that of causing a decrease in the FSC. This is no doubt due to glacial melting and the resulting additions to the flow. That maximum strength of the associations during this season is reached in June is not surprising since it would be expected that glacial melting increases throughout the period from a very low level in April.

The positive association between the basin orientation and the May FSC can be attributed to the fact that north-facing basins receive the least sunlight. This results in lower snowmelt rates than those which occur in south-oriented basins. Less snowmelt results in lower flow and therefore higher FSC. At first glance the lack of similar associations with April and June FSC contradicts this statement. However, during April snowmelt contributes only a small amount of the flow and therefore any secondary factor affecting snowmelt would have little influence on the flow regime. Supporting evidence for this statement arises from the relatively strong associations between precipitation and April FSC which indicate that precipitation is still a predominant influence on the flow. Basin orientation may not be associated with June FSC because during June snowmelt has become a rather universal phenomenom experiencing little variation from basin to basin arising from basin orientation. The high degree of snowmelt is indicated by the lack of any association between precipitation and June FSC. Therefore only in May are the conditions such that basin orientation will influence the flow regime to any detectable degree.

As concluded previously, the associations of basin slope, depression storage, and aquifer storage with the FSC indicate that groundwater storage may have a weak effect on the FSC of this season. The nature of basin geology did not allow firm conclusions to be made regarding its association with May and June FSC.

In summary, it can be concluded that the influence of precipitation becomes decreasingly important from April through June as snowmelt becomes increasingly important. Some glacial melt also occurs at this time although its effect is fairly small. Groundwater additions to the flow are not thought to be of any importance.

July through September FSC

As shown by the associations of their respective indices, glacial melt and precipitation are the dominant influences on the FSC for this season. The strength of the associations between precipitation and the FSC increases from a low level in July to an extremely high level in September. The strength of the associations between the glacierized area and the FSC is extremely high in July, considerably lower in August and again relatively high in September. In the region studied precipitation is low in July, but increases through August and September. This results in a corresponding increase in the strength of the associations of precipitation with FSC. The influence of glacial melt on the FSC would be expected to be at a maximum in July and decreasing through August and September. Not only would the decreasing rate of glacial melt from August to September serve to reduce its influence but the increase in precipitation would also contribute to the decrease in influence. Expectations are contradicted by the increase in the strength of the associations between glacierized area and FSC from August to September. The reason for this increase is unknown at present. It has been concluded that the influences of precipitation and snowmelt are somewhat competitive, the one increasing while the other decreases. The same would be expected of glacial melting and precipitation influences. However both these variables are strongly associated with September FSC. It may be possible that rainfall during September is limited mainly to non-glaciated basins, in which case glacial melt and rainfall are not competitive influences in the same basin, as appears to be the case during the snowmelt period. As concluded previously, August but not September FSC is influenced by groundwater storage characteristics. This could indicate that August is somewhat of a transitional month between the predominately glacial melt July regime and the mixed precipitation and glacial melt September regime.

The effects of precipitation and glaciers show up strongly in the contours of the FSC of these months. The non-glaciated streams have very high July and August FSC compared to the low values of the glaciated streams, such as Thunder Creek and the Cascade, Puyallup, and Carbon Rivers. Contour density is low in July FSC but increases in August and September FSC, mainly due to increasing precipitation. The effect of increasing precipitation is also evident in the low values of August and September FSC for the coastal basins.

The associations of precipitation with October FSC are weaker than those with September FSC. The glacierized area has no association with October FSC. Apparently the lower air temperatures in October cause glacial melting to cease. It probably also causes some of the precipitation to fall in the form of snow. This may be responsible for the decrease in the influence of precipitation on the FSC from September to October. It can be concluded that the precipitation and glacial melt regime of the July through September season changes to a precipitation and snowfall regime in October.

In summary it can be concluded that July FSC is predominantly influenced by glacial melting while precipitation is a relatively weak influence. However, the latter increases from July through September, until in September it is considerably more dominant than the melting of glaciers. These factors are clearly reflected in the respective FSC contours.

Annual FSC

Strong positive association between annual PSC and FSC indicates that even though the magnitudes of the annual FSC are very low, they are partially the result of the influence of PSC. Mean annual precipitation is positively associated with annual FSC. The positive aspect of the association is in contradiction to the negative associations of precipitation with monthly FSC. The nature of the mathematical relationship between monthly and annual flows and precipitation is not known well enough to firmly conclude that the association of precipitation with annual FSC is a product of similar monthly associations. The PSC association is stronger than would be expected from the associations of PSC with the monthly FSC. However, both the annual and the monthly associations are positive. It must be concluded that precipitation has an important influence on annual FSC which must be related in some manner to the influence of precipitation on monthly FSC.

The associations of the snowfall and mean annual temperature with the annual FSC may indicate that snowfall has an influence on the FSC but it is difficult to explain the physical nature of the relationship. The positive association of the glacierized area with the annual FSC indicates that the presence of glaciers increases the FSC. This may be due to the fact that it may take years before the precipitation falling on the accumulation zone of a glacier ever reaches the stream. This could introduce some carryover in annual flows. This condition does not depend on the relationship between annual and monthly flows. It is possible that this positive association is a result of the similar negative associations with the April through September FSC. Not enough is known about the mathematical relationship between annual and monthly FSC to determine if the influences of the physical factors on annual FSC are a result of the corresponding influences on monthly FSC. More generally, it is difficult to develop a clear understanding of the physical basis of time averaged flows when all such flows are mathematically derivable from averaged flows of a shorter time base.

The strong association of the PSC with the annual FSC suggest that this factor may be a stronger source of FSC than is indicated in the results for the monthly FSC. As mentioned in Chapter IV only a few of the monthly PSC were contoured. Deriving values of this index from contour maps for all months may have provided greater information about the influence of precipitation serial correlation and also certainly would eliminate the uncertainty over its influence during the months when none is indicated.

Prediction Equations

The results show that generally the strength of the prediction equation has less apparent relationship to the error in the predicted FSC than would be expected. This may be due to the uniformity on the strengths of many of the equations. It is unlikely that the check streams do not conform to the regime described by the prediction equation since the predicted negative relationship between the error magnitudes and the FSC levels did occur in the check data. The negative relationship between error magnitude and FSC magnitude indicated poor estimation of extreme values, a condition common to most hydrologic studies.

For the South Fork Skokomish River, the errors in the October, January, March, May, June and August FSC could be expected to introduce large errors in flows generated by an equation utilizing predicted FSC. This is also true for the errors in the April, May, June and August FSC of the Greenwater River and the June FSC and the December through March FSC of the Sultan River. Generally the predicted FSC of the winter and spring months are most subject to error, although this is only weak trend. It must be concluded that the errors in the predicted values of the FSC are of sufficient magnitude to cast doubts on the practicality of using predicted FSC in the lag one flow generation model. Further research into the cause of both chronological and geographical variation in the FSC would have great value in refining the prediction equations to a point where their use becomes practical. Furthermore, comparison of flows generated by equations utilizing predicted FSC to those generated by a model derived from flow records would yield valuable insights into the errors to be expected in the generated flows.

CHAPTER VII

SUMMARY AND IMPLICATIONS

A. Summary

The results and conclusions of the three phases of the research are interrelated. It has been determined that since annual flows are a mathematical average of the monthly flows the statistics of the annual flows are a product of the statistics of the monthly flows. Therefore, the generation of monthly flows with statistics closely approximating those of the actual monthly flows should yield annual flows with similarly accurate statistics. This was found to be the case in the study of model accuracy.

Specifically, the research done into the accuracy of the various models indicates that the lag one model is preferable to any of the other models studied. The main criterion for this choice was that the means and standard deviations of the generated flows should be as accurate as possible since these two parameters are of the most importance in water resources development. It was found that for this model the accuracy of the means of all generated flows was quite high while the general accuracy of the standard deviations was somewhat lower. Specifically the errors in the standard deviations of the generated November flows were quite high and might prove to be a limitation in the practical use of this model. For the other periods the errors were within acceptable limits.

The fact that the lag one model was found to be the most acceptable increases the value of the results of the study of the causes of geographical and chronological variation in the lag one flow serial coreelation coefficient for streams in Western Washington. The purposes of this research were to find the sources of FSC, the physical factors influencing their magnitude and variation and also to find practical prediction equations for each monthly FSC based on easily available indices of basic hydrologic and climatological factors.

The search for the sources of flow serial correlation yielded no completely satisfactory answer although it was found that precipitation serial correlation is an important source. It may even be more important than indicated by the results because of deficiencies in the index. An important conclusion gained is that contrary to common expectations groundwater storage is neither a major source of FSC nor does it contribute materially to the geographical variation in the FSC.

The results indicate that any factor which tends to increase flow levels, decreases the FSC. This is true for precipitation, snowmelt, and glacial melt which are the important flow sources in the region studied. It can be speculated that the source or sources of FSC are of minor strength and that their effects are easily obliterated by the high flows resulting from less consistent sources. It could not be determined fully whether the physical causes of annual FSC derive from those of the monthly FSC.

The indices of the physical phenomena used in the prediction equation account for 30% to 70% of the variation in the annual and monthly FSC. The use of FSC predicted from the equations in the lag one generation model may lead to gross errors in the generated flows. Future research should concentrate on finding more representative indices which would lead to more accurate prediction equations. Experimental usage of the lag one generation equations utilizing predicted FSC would provide valuable insights into the accuracy of a predicted generation model. None of the results of the prediction study are necessarily applicable to regions subject to climatological and geographical conditions different from those of Western Washington.

B. Implications of Conclusions

Practical

The practical implications of the research completed are fairly obvious. That the annual flows are a product of the monthly flows is common knowledge but the corollary that annual flow statistics are a mathematical function of the monthly flow statistics is not commonly considered in flow generation applications. This inherent relationship between annual and monthly flow statistics implies that monthly flow generation should also yield acceptable annual flows. This was found to be a characteristic of the lag one model. Use of the model obviates any necessity for annual flow generation models. This holds valuable implications for water resources planning. The study of the errors in the use of the various models increases the confidence that can be placed in the use of the lag one model. The discovery of its weaknesses serves to prevent unwarranted use of its results.

Attempts to predict lag one FSC on the basis of indices of physical phenomena were not entirely successful since a check showed that the predicted FSC could be considerably in error. Use of predicted FSC in the flow generation model would probably yield seriously deficient flow data. However, the development of these equations is a beginning towards development of more accurate equations to predict the entire generation equation from quantitative basin data. A totally predictable generation equation would eliminate the dependence of hydrologists on recorded flows in their efforts to determine the flow characteristics necessary for proper water resources development. Although such development would still be limited to applications requiring annual or monthly flows only, further efforts should be expended in developing the field of daily flow generation. However, daily flow could possibly be better obtained in the future by use of deterministic techniques.

Basic Implications

The broader implications of the results of the research are somewhat less obvious than the practical implications. The mathematical relationship between annual and monthly flow statistics leads to the general conclusion that all time averaged flows are a function of similarly averaged flows of a shorter time base. This ultimately points to the fact that the source of all time-based flows is the instantaneous flow. Although trivial from an intuitive point of view, this conclusion serves as a necessary reminder that statistically averaged flows have meaning only when thought of in terms of actual instantaneous flows and thus must constantly be related back to reality. Consistent statistical logic based on the mathematical relationship between all flows of different time bases serves to make all such flows part of a coherent whole which has its basis in the observable physical instantaneous flows.

The desirability of viewing statistical parameters in terms of the underlying physical reality led to the multivariate analysis study of the physical factors affecting FSC. In the introduction a statement was made delineating the approach taken in this research regarding the use of probabilistic criteria in the analysis of the results. A specific aspect of this position was that the serial correlations of the flows should not be subjected to tests of significance because a study of the physical basis of this parameter could not include the assumption that its variation is the result of chance occurrence. A similar attitude was taken toward the use of tests of significance in relation to the associations of the indices with the FSC. Such associations, regardless of strength were considered of value if they reflected an intuitively logical physical process. The strength of the association was considered to be indicative of the strength of the influence of the physical factor on the flow serial correlations.

Associations which could not be physically explained were considered to index some unknown physical influence.

The results of the prediction study give some indication that this approach was valid. Specifically, the magnitudes of the FSC have little bearing on the percentage of the variation in the FSC explained by the prediction equation. This can be verified by noting that the strengths of the prediction equations for the generally low-valued annual, December, January, February, March and April FSC are as high as those for the very high July and August FSC. This would not be the case if statistically "insignificant" FSC had no meaning. It must be concluded that regardless of their magnitudes, flow serial correlations are the product of physical causes and as such cannot be disregarded on the basis of statistical insignificance.

In general statistical models are very useful in describing the flow distribution when deterministic descriptions are not available. However, it is apparent that statistical models are very limited in scope since the regime they attempt to describe is essentially deterministic and not probabilistic in nature. Therefore the concept of random variation has its value as an operational tool but it is necessary to remember that this variation is not truly random, but merely the product of poorly understood physical processes. The goal of hydrologic research must always be the more detailed delineation of the physical processes; the more detailed this delineation becomes, the less reliance need be placed on statistical techniques. It may almost be said that the use of statistical techniques is equivalent to opening the back door to knowledge.

LIST OF REFERENCES

Benson, M.A., "Evolution of Methods for Evaluating the Occurrence of Floods", USGS Water Supply Paper, 1580-A, 1962a.

Benson, M.A., "Factors Influencing the Occurrence of Floods in a Humid Region of Diverse Terrain", USGS Water Supply Paper 1580-B, 1962b.

Benson, M.A., and Matalas, N.C., "Synthetic Hydrology Based on Regional Statistical Parameters", Water Resources Research, Vol. 3, #4, 1967, p. 931.

Blodgett, J.C., "Persistence Properties of Mean Monthly Flows from Selected Watersheds in Washington", Unpublished Master of Science Degree Thesis, University of Washington, 1967.

Bodhaine, G.L., and Thomas, D.M., "Magnitude and Frequency of Floods in the United States", Part 12, Pacific Slope Basins in Washington and Upper Columbia River Basin, USGS Water Supply Paper 1687, 1964.

Caffey, J.E., "Inter-station Correlations in Annual Precipitation and in Annual Effective Precipitation", Hydrology Papers, No. 6, Colorado State University, June 1965.

Chow, V.T., and Ramaseshan, S., "Sequential Generation of Rainfall and Runoff Data", ASCE Water Resources Engineering Conference, March 1965.

Fiering, M.B., "Streamflow Synthesis", 1967, Harvard University Press, Cambridge, Massachusetts.

Ford, P.M., "Multiple Correlation in Forecasting Seasonal Runoff", Department of the Interior, Bureau of Reclamation, Engineering Monographs #2, June 1953.

Gladwell, J.S., "Personal Communications", 1969.

Gladwell, J.S., and [illegible], M., "A Statistical Evaluation of the Skagit River Cloud Seeding Project", report prepared for the State of Washington Weather Modification Board, July 14, 1967.

Gladwell, J.S., and Mueller, A.C., "Water Resources Atlas of the State of Washington", Part of the State of Washington Water Research Center coordinated study, "An Initial Study of the Water Resources of the State of Washington", Vol. II, Chart II-4, 1967.

Hall, F.R., "Baseflow Recessions - A Review", Water Resources Research, Vol. 4, #5, 1968, p. 973.

Harms, A.A., and Campbell, T.H., "An Extension to the Thomas-Fiering Model for the Sequential Generation of Streamflow", Water Resources Research, Vol. 3, #3, 1967, p. 653.

Harman, H.H., "Modern Factor Analysis", University of Chicago Press, Chicago, 1960

Hely, A.G., "Areal Variations of Mean Annual Runoff", Journal of the Hyd. Div., ASCE, HY5, Sept. 1964, p.61.

Howe, G.M., Slaymaker, H.O., and Harding, D.M., "Flood Hazard in Mid-Wales", Nature, London, Vol. 212, #5062, Nov. 5, 1966.

Hulsing, H., and Kallio, N.A., "Magnitude and Frequency of Floods in the United States", Part 14, Pacific Slope Basins in Oregon and Lower Columbia River Basin, USGS Water Supply Paper 1689, 1964.

Kinnison, H.B., and Colby, B.R., "Flood Formulas Based on Drainage Basin Characteristics", Transactions of the ASCE, Vol. 110, 1945, p. 849.

Le Feuvre, A.R., "An Investigation of the Effect of Multiple Event Carryover on Hydrologic Data Analysis", ASCE Water Resources Engineering Conference, Mobile, Alabama, March 8-12, 1965.

Martig, K.W., "Serially Correlated Annual Streamflow Synthesis", Unpublished Master of Science Degree Thesis, University of Washington, 1968.

Matalas, N.C., "Statistics of a Runoff-Precipitation Relation", USGS Prof. Paper 434-D, 1963.

Matalas, N.C., "Time Series Analysis", Water Resources Research, Vol. 3, #3, 1967, p. 817.

Matalas, N.C., and Benson, M.A., "Note on the Standard Error of the Coefficient of Skewness", Water Resources Research, Vol. 4, #1, 1968, p. 204.

Matalas, N.C., and Gilroy, E.J., "Some Comments on Regionalization in Hydrologic Studies", Water Resources Research, Vol. 4, #6, 1968, p. 1361.

McGuiness, J.L., Harrold, L.L., and Amerman, C.R., "Hydrogeologic Nature of Streamflow on Small Watersheds", Journal of the Hydraulic Division of the ASCE, Vol. 87, HY1, 1961, p. 1-13.

McGuiness, J.L., and Harrold, L.L., "Seasonal and Areal Effects on Small Watershed Streamflow", Journal of Geophysical Research, Vol. 67, #11, Oct. 1962, p. 4327.

Quick, M.C., "River Flood Flows-Forecast and Probabilities", Journal of the Hyd. Div. of the ASCE, May 1965, Vol. 91, HY3, p.1.

Reich, B.M., "Estimating Flood Peaks from Small South Africa Catchments", Journal of Hydrology, Vol. 3, 1965, p.231-253.

Reich, B.M., and Hiemstra, L.A.V., "Tacitly Maximized Small Watershed Flood Estimates", Journal of the Hyd. Div. of the ASCE, May 1965, Vol. 91, HY3, p.217.

Roesner, L.A., and Yevdjevich, V.M., "Mathematical Models for Time Series of Monthly Precipitation and Monthly Runoff", Hydrology Papers, #15, Colorado State University, Oct.1966.

Schermerhorn, V.P., "Relations Between Topography and Annual Precipitation in Western Oregon and Washington", Water Resources Research, Vol. 3, #3, 1967, p. 707.

Wallis, J.R., "Multivariate Statistical Methods in Hydrology - A Comparison Using Data of Known Functional Relationship", Water Resources Research, Vol. 1, #4, 1965a, p. 447.

Wallis, J.R., "Wallyl....A Large, Principal Components Regression Program with Varimax Rotation of the Factor Weight Matrix", U.S. Forest Service Research Note, PSW 92, 1965b.

Yevdjevich, V., "Mean Range of Linearly Dependent Normal Variables with Application to Storage Problems", Water Resources Research, Vol. 3, #3, 1967, p. 663.

Appendix A

Tables

TABLE 1

DRAINAGE BASINS INCLUDED IN STUDY

Stream Name & Gauging Site*	Identification Number	No. Years of Record
Naselle R. near Naselle	12-0100	33
North R. near Raymond	12-0170	33
Chehalis R. near Grand Mound	12-0275	33
Satsop R. near Satsop	12-0350	33
Wynoochee R. above Save Creek near Aberdeen	12-0360	33
Quinault R. at Quinault Lake	12-0395	33
Hoh R. near Spruce	12-0410	33
Soleduck R. near Fairholm	12-0415	33
Dungeness R. near Sequim	12-0480	33
Duckabush R. near Brinnon	12-0540	29
North Fork Skokomish R. below Staircase Rapids near Hoodsport	12-0565	33
South Fork Skokomish R. near Union	12-0605	33
Chambers Creek below Leach Creek, near Steilacoom	12-0915	22
Puyallup R. near Orting	12-0935	33
Carbon R. near Fairfax	12-0939	33
White R. at Greenwater	12-0970	33
Greenwater R. at Greenwater	12-0975	33
South Fork Skykomish R. near Index	12-1330	33
Skykomish R. near Gold Bar	12-1345	33
Sultan R. near Startup	12-1375	33
Snoqualmie R. near Carnation	12-1490	33
South Fork Stillaguamish R. near Granite Falls	12-1610	33
North Fork Stillaguamish R. near Arlington	12-1670	33
Thunder Creek near Newhalem	12-1755	33
Stetattle Creek near Newhalem	12-1775	33
Cascade R. at Marblemount	12-1825	33
Sauk R. above Whitechuck R. near Darrington	12-1860	33
Sauk R. near Sauk	12-1895	33
South Fork Nooksack R. near Wickersham	12-2090	33
Stehekin R. at Stehekin	12-4510	33
Wenatchee R. at Plain	12-4570	33
Icicle Creek above Snow Creek near Leavenworth	12-4580	31
North Fork Ahtanum Creek near Tampico	12-5005	33
South Fork Ahtanum Creek at Conrad Ranch near Tampico	12-5010	33
Klickitat R. near Pitt	14-1130	33
Wind R. near Carson	14-1285	33
East Fork Lewis R. near Heisson	14-2225	33
Cowlitz R. at Packwood	14-2265	33
Cispus R. near Randle	14-2325	33
Toutle R. near Silver Lake	14-2425	33

*See also Figure 3 for geographic locations.

Table 2 Array of Index Variables

River Name	Average Precipitation in inches for the Period Indicated									
	Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
Naselle	113.3	9.3	13.4	15.2	14.2	12.4	10.6	6.4	3.8	3.2
North	88.5	6.8	9.6	10.7	10.3	8.6	7.4	4.8	3.0	2.5
Chehalis	68.2	5.8	8.4	9.1	8.5	7.1	6.1	3.9	2.4	2.1
Satsop	116.0	10.4	14.4	16.9	15.8	13.0	11.1	7.3	4.3	3.1
Wynoochee	140.3	10.4	14.4	16.9	15.8	13.0	11.1	7.3	4.3	3.1
Quinault	184.6	13.4	18.4	21.5	19.6	16.0	13.3	9.1	5.7	4.2
Hoh	154.6	12.3	16.5	19.6	17.7	14.4	12.3	8.5	5.1	3.8
Soleduck	100.9	9.7	13.4	16.1	15.0	11.7	9.9	6.6	3.9	2.9
Dungeness	58.6	2.5	4.1	4.4	4.1	3.4	2.6	1.8	1.7	1.7
Duckabush	112.1	4.0	7.1	7.5	7.4	6.0	4.5	2.8	2.1	2.0
N.F.Skokomish	142.9	7.9	12.6	13.6	13.2	10.1	8.3	5.0	2.7	2.0
S.F.Skokomish	131.0	7.9	12.6	13.6	13.2	10.1	8.3	5.0	2.7	2.0
Chambers Creek	37.9	3.8	5.6	5.8	5.4	4.4	3.7	2.6	1.7	1.6
Puyallup	64.2	6.0	8.7	9.3	8.2	7.0	5.7	4.1	3.0	2.7
Carbon	91.6	4.4	6.0	6.2	5.5	4.7	4.1	3.3	2.5	2.5
White	72.0	6.0	8.6	9.4	8.1	6.9	6.1	4.8	3.6	3.4
Greenwater	94.6	6.0	8.6	9.4	8.1	6.9	6.1	4.8	3.6	3.4
S.F.Skykomish	120.4	7.9	11.8	13.1	11.2	9.8	8.1	5.9	4.0	3.3
Skykomish	117.5	5.4	7.4	7.3	6.8	5.9	5.0	4.3	3.6	3.3
Sultan	86.1	5.4	7.4	7.3	6.8	5.9	5.0	4.3	3.6	3.3
Snoqualmie	104.5	7.2	9.8	10.2	9.1	7.7	7.2	5.6	4.2	4.0
S.F.Stillaguamish	121.4	3.4	4.6	4.6	4.4	3.7	3.2	2.4	2.3	2.3
N.F.Stillaguamish	81.6	8.1	11.3	12.5	11.7	9.2	7.7	5.3	3.5	3.0
Thunder Creek	114.8	8.4	10.8	12.6	10.5	8.7	6.5	4.7	2.8	2.3
Stetattle Creek	123.1	8.4	10.8	12.6	10.5	8.7	6.5	4.7	2.8	2.3
Cascade	124.8	8.4	10.8	12.6	10.5	8.7	6.5	4.7	2.8	2.3
Sauk nr. Darring.	139.9	7.5	10.2	11.2	10.2	8.3	7.0	4.8	3.3	2.8
Sauk nr. Sauk	121.8	7.5	10.2	11.2	10.2	8.3	7.0	4.8	3.3	2.8
S.F.Nooksack	108.3	5.8	7.4	8.0	7.2	5.9	5.3	4.0	2.8	2.6
Stehekin	96.9	3.2	5.9	6.5	5.6	4.5	2.8	1.4	1.0	1.0
Wenatchee	81.5	3.5	5.8	6.6	5.8	4.6	3.5	2.1	1.5	1.2
Icicle	74.5	2.2	3.7	4.3	4.1	3.1	1.9	1.1	1.0	1.1
N.F. Ahtanum	50.5	1.2	2.2	2.6	2.3	1.8	1.2	.9	.7	.9
S.F.Ahtanum	54.2	1.2	2.2	2.6	2.3	1.8	1.2	.9	.7	.9
Klickitat	34.5	2.1	3.8	4.2	4.2	3.1	2.4	1.3	.9	.9
Wind	99.0	8.2	15.2	17.3	15.6	12.9	11.2	6.5	3.7	2.3
E.F. Lewis	94.6	7.3	10.7	12.2	11.2	9.1	8.2	5.2	3.4	2.7
Cowlitz	89.4	6.6	9.7	10.8	9.0	7.6	6.4	4.7	3.4	3.1
Cispus	85.4	5.2	8.4	9.3	8.1	6.6	5.5	3.7	2.6	2.3
Toutle	85.6	4.3	6.5	7.0	5.7	5.1	4.6	2.9	2.3	2.1

TABLE 2 (cont.)

River Name	Average Precipitations (cont.)			Precipitation Serial Correlation				
	July	Aug.	Sept.	Ann.	Oct.	Nov.	Dec.	Jan.
Naselle	1.5	2.0	3.4	.04	-.06	.18	.06	0
North	1.1	1.6	2.6	.11	.05	.16	.06	.11
Chehalis	.8	1.4	2.3	.03	.03	.38	.12	.05
Satsop	1.8	2.4	4.3	.02	-.05	.12	-.04	.01
Wynoochee	1.8	2.4	4.3	.02	-.11	.11	-.15	-.04
Quinault	2.4	3.0	5.5	.12	-.11	.11	-.15	0
Hoh	2.4	2.6	4.7	.12	-.15	.17	-.11	-.08
Soleduck	1.9	2.1	3.6	.22	.07	.22	.10	-.01
Dungeness	.8	.8	1.2	.15	.05	.15	.05	.12
Duckabush	.8	.9	1.4	.04	-.04	-.03	-.11	.33
N.F. Skokomish	1.0	1.3	2.7	-.02	-.08	-.02	-.13	0
S.F. Skokomish	1.0	1.3	2.7	-.03	-.08	0	-.13	0
Chambers Creek	.8	1.0	1.7	0	.15	.10	.18	.06
Puyallup	1.2	1.5	2.8	.22	.23	.42	.09	.07
Carbon	1.1	1.3	2.2	.20	.22	.41	.13	.01
White	1.4	1.6	3.0	.16	.33	.35	.28	-.16
Greenwater	1.4	1.6	3.0	.10	.20	.38	.28	-.16
S.F.Skykomish	1.3	1.7	3.6	.25	.13	.36	.02	-.06
Skykomish	1.5	1.8	2.9	.22	.09	.31	0	-.11
Sultan	1.5	1.8	2.9	.09	.05	.17	.07	-.06
Snoqualmie	1.7	2.0	3.7	.07	.01	.28	.09	-.16
S.F.Stillaguamish	1.0	1.2	1.8	.10	-.03	.13	.07	.2
N.F.Stillaguamish	1.3	1.8	3.6	.16	-.01	.20	.05	-.36
Thunder Creek	1.4	1.8	2.6	.18	.05	.26	.11	-.2
Stetattle Creek	1.4	1.8	2.6	.09	.10	.26	.06	-.2
Cascade	1.4	1.8	2.6	.14	.01	.28	.06	-.2
Sauk nr. Darring	1.3	1.8	3.4	.20	.02	.27	.03	-.36
Sauk nr. Sauk	1.3	1.8	3.4	.16	-.04	.23	.03	-.36
S.F.Nooksack	1.3	1.7	3.0	.14	.12	.28	.03	.02
Stehekin	.4	.6	1.2	.15	-.06	.25	.13	-.18
Wenatchee	.5	.6	1.4	.27	-.02	.36	.25	-.2
Icicle	.3	.5	.8	.25	.24	.46	.12	.15
N.F.Ahtanum	.3	.4	.5	.15	.53	.40	.12	.15
S.F.Ahtanum	.3	.4	.5	.12	.53	.37	.16	.15
Klickitat	.3	.3	.7	-.05	.44	.20	.25	.11
Wind	1.0	1.2	2.9	.14	.33	.17	.16	.13
E.F.Lewis	1.3	1.7	3.1	.02	.25	.18	.12	.08
Cowlitz	1.1	1.7	3.0	.21	.08	.37	.15	.05
Cispus	.7	1.2	2.2	.18	.38	.34	.16	.06
Toutle	.8	1.4	2.0	.27	.15	.41	.14	.13

TABLE 2 (cont.)

River Name	Precipitation Serial Correlation							
	Feb.	Mar.	Apr.	May	June	Jul.	Aug.	Sept.
Naselle	-.1	.22	-.11	.02	-.22	.26	-.19	-.02
North	0	.19	-.15	-.04	-.24	.2	-.15	.10
Chehalis	-.07	.15	.02	-.04	-.27	.13	-.04	.03
Satsop	-.03	.13	-.18	-.02	-.2	.26	-.2	.05
Wynoochee	.01	.17	-.14	-.01	-.23	.24	-.14	-.01
Quinault	-.02	.19	-.12	.01	-.26	.17	-.07	-.02
Hoh	.07	.05	-.08	.03	-.26	.29	-.16	.03
Soleduck	.09	.08	-.08	.03	-.23	.22	-.16	.04
Dungeness	-.02	.12	-.10	.04	-.01	.15	-.13	.07
Duckasbush	-.04	.34	-.14	.01	-.07	.17	-.01	-.01
N.F.Skokomish	-.04	.25	-.13	0	-.04	.32	-.1	-.02
S.F.Skokomish	-.04	.25	-.16	0	-.04	.32	-.1	-.02
Chambers Creek	-.16	.21	-.12	0	.09	.25	.01	.14
Puyallup	-.15	.14	-.04	-.02	-.02	.29	-.1	.12
Carbon	-.13	.18	-.07	-.02	-.09	.29	-.11	.11
White	.02	.07	-.22	-.03	-.17	.4	-.15	-.15
Greenwater	.02	.07	-.21	-.06	-.17	.4	-.15	-.13
S.F.Skykomish	.07	.15	.12	-.04	-.1	.19	-.06	.10
Skykomish	.08	.13	.11	-.05	-.13	.21	- 16	.08
Sultan	.08	.03	.09	-.07	-.13	.27	-.11	.09
Snoqualmie	-.06	-.02	.12	-.02	-.24	.35	-.06	.02
S.F.Stillaguamish	.15	.24	0	-.03	-.03	.06	.03	.12
N.F.Stillaguamish	.01	-.11	.04	-.01	-.36	.16	-.11	.19
Thunder Creek	.12	-.07	.09	-.05	-.22	.14	-.2	.30
Stetattle Creek	.12	-.07	.25	-.03	-.22	.14	-.2	.41
Cascade	.12	-.07	0	-.04	-.22	.14	-.2	.20
Sauk nr. Darring	.01	-.11	.03	-.08	-.36	.16	-.11	.12
Sauk nr. Sauk	.01	-.11	-.04	-.06	-.36	.16	-.11	.14
S.F.Nooksack	-.01	.13	.15	.07	-.17	.17	-.22	.33
Stehekin	-.12	.2	-.19	-.03	-.07	-.05	.03	.13
Wenatchee	-.1	.28	-.13	-.03	-.11	.19	.02	.11
Icicle	-.39	.34	.09	.01	.21	-.08	-.14	.05
N.F.Ahtanum	-.2	.25	.18	.03	.05	.06	-.22	-.15
S.F.Ahtanum	-.2	.25	.19	.03	.05	.06	-.22	-.15
Klickitat	-.16	.27	.12	.18	-.19	.03	-.16	-.03
Wind	-.16	.22	.02	.07	-.19	.17	-.31	.01
E.F.Lewis	-.23	.11	.09	.06	-.11	.35	-.39	0
Cowlitz	-.12	.03	-.08	0	-.08	.33	-.17	-.08
Cispus	-.13	.18	-.07	-.10	.06	.22	-.26	-.04
Toutle	-.31	.09	.04	.07	-.07	.34	-.33	.08

TABLE 2 (cont.)

River Name	Average Snowfall in Inches during:				
	Oct.	Nov.	Dec.	Feb.	Year
Naselle	0	0	0	0	.13
North	0	.33	.86	.5	6.23
Chehalis	.12	.49	1.81	1.4	10.95
Satsop	0	1.14	1.88	1.68	16.18
Wynoochee	0	1.14	1.88	1.68	16.18
Quinault	0	.25	.41	.22	8.12
Hoh	0	.64	2.92	2.69	21.95
Soleduck	0	.42	1.4	1.51	12.42
Dungeness	0	.47	.22	.68	5.52
Duckasbush	0	.78	1.25	.55	7.07
N.F.Skokomish	.04	1.54	3.34	3.97	29.91
S.F.Skokomish	.04	1.54	3.34	3.97	29.91
Chambers Creek	0	.3	.54	1.44	5.69
Puyallup	.86	5.92	16.58	19.21	98.16
Carbon	0	.83	1.43	1.81	10.46
White	1.76	9.87	19.75	16.21	102.56
Greenwater	1.76	9.87	19.75	16.21	102.56
S.F.Skykomish	3.17	25.45	60.59	47.38	269.23
Skykomish	0	.44	2.12	2.68	11.73
Sultan	0	.44	2.12	2.68	11.73
Snoqualmie	0	2.12	5.83	5.99	27.16
S.F. Stillaguamish	0	.77	2.	.64	8.18
N.F. Stillaguamish	.06	2.57	7.24	8.39	50.9
Thunder Creek	.08	2.36	13.12	6.13	48.09
Stetattle Creek	.08	2.36	13.12	6.13	48.09
Cascade	.08	2.36	13.12	6.13	48.09
Sauk nr. Darring	.03	2.02	5.61	6.25	41.34
Sauk nr. Sauk	.03	2.02	5.61	6.25	41.34
S.F.Nooksack	0	.76	2.94	2.82	21.59
Stehekin	.06	16.13	28.54	19.29	116.92
Wenatchee	.06	9.94	18.09	11.41	72.73
Icicle	1.03	13.06	28.06	21.63	127.37
N.F. Ahtanum	.38	5.39	12.93	7.2	58.09
S.F. Ahtanum	.38	5.39	12.93	7.2	58.09
Klickitat	.04	3.16	13.68	6.68	55.86
Wind	0	4.08	8.05	10.75	44.87
E.F.Lewis	0	.58	2.1	1.81	12.65
Cowlitz	.59	4.37	11.65	14.93	75.12
Cispus	.02	2.34	10.04	7.09	50.45
Toutle	0	.4	.46	.35	5.42

TABLE 2 (cont.)

River Name	% Area Lakes and Ponds	Basin Slope - Ft/Mi	% Area Glacierized	Drainage Area-mi^2
Naselle	.01	52	0	54.8
North	.01	11	0	219.
Chehalis	.03	13	0	895.
Satsop	.25	13	0	299.
Wynoochee	.01	89	0	74.1
Quinault	2.08	79	.068	264.
Hoh	.10	96	4.975	208.
Soleduck	.48	131	0	83.8
Dungeness	.06	217	0	156.
Duckasbush	.30	191	0	66.5
N.F.Skokomish	.17	294	0	57.2
S.F.Skokomish	.25	94	0	76.3
Chambers Creek	1.68	16	0	104.
Puyallup	.82	88	3.494	172.
Carbon	.25	107	7.316	78.9
White	.46	93	5.611	216.
Greenwater	.27	124	0	73.5
S.F.Skykomish	.90	102	.425	355.
Skykomish	.73	87	.403	535.
Sultan	.40	132	0	75.
Snoqualmie	.69	43	.064	603.
S.F.Stillaguamish	.08	76	0	119.
N.E.Stillaguamish	.01	60	0	262.
Thunder Creek	.10	234	14.190	105.
Stetattle Creek	.47	582	2.336	21.4
Cascade	.17	143	4.250	168.
Sauk nr. Darring.	.13	120	1.013	152.
Sauk nr. Sauk	.01	53	2.173	714.
S.F.Nooksack	.29	114	0	103.
Stehekin	.28	160	3.424	344.
Wenatchee	1.30	79	.548	591.
Icicle	.48	82	0	193.
N.F.Ahtanum	.01	155	0	68.9
S.F.Ahtanum	.01	221	0	24.8
Klickitat	.09	41	.325	1297.
Wind	.03	85	0	225.
E. F. Lewis	.01	87	0	125.
Cowlitz	.45	167	2.564	287.
Cispus	.15	122	1.205	321.
Toutle	.93	68	.225	474.

TABLE 2 (cont.)

River Name	Mean Annual Temp.	Geologic Variable	Baseflow Recession Variable	Basin Orientation
Naselle	50.6	4.0	87.3	-.753
North	51.0	2.8	62.3	.028
Chehalis	51.2	3.0	27.5	.882
Satsop	50.1	2.2	112.7	-1.000
Wynoochee	50.1	2.7	233.9	-.943
Quinault	50.8	3.8	218.3	-.558
Hoh	49.2	3.9	153.6	-.082
Soleduck	49.0	3.9	130.8	.643
Dungeness	49.3	3.9	35.2	1.000
Duckasbush	50.5	4.0	101.8	-.342
N.F.Skokomish	50.8	4.0	204.2	-.989
S.F.Skokomish	50.8	4.0	325.9	-.783
Chambers Creek	51.4	1.8	23.8	.680
Puyallup	50.3	2.8	49.7	.658
Carbon	46.6	3.3	72.0	.433
White	43.7	3.4	64.2	.960
Greenwater	43.7	4.0	100.5	.680
S. F. Skykomish	49.9	3.7	76.1	266
Skykomish	52.4	3.7	103.9	.332
Sultan	52.4	3.7	80.0	.000
Snoqualmie	50.1	3.2	89.6	.360
S.F. Stillaguamish	50.5	3.2	104.9	.284
N.E.Stillaguamish	48.5	3.2	87.9	.148
Thunder Creek	49.1	3.8	54.9	.912
Stetattle Creek	50.1	4.0	58.9	-.572
Cascade	50.1	3.7	119.7	.406
Sauk nr. Darring.	48.5	3.2	111.6	.596
Sauk nr. Sauk	48.5	3.0	160.5	.835
S. F. Nooksack	47.4	3.7	88.5	-.249
Stehekin	48.6	3.8	107.0	.488
Wenatchee	43.6	3.6	78.4	-.659
Icicle	48.0	4.0	139.1	-.496
N F. Ahtanum	48.2	3.6	57.4	.209
S.F. Ahtanum	48.2	3.0	65.3	.229
Klickitat	46.6	3.2	68.4	-1.000
Wind	47.8	3.6	196.9	-.939
E. F. Lewis	49.7	3.7	150.0	.078
Cowlitz	49.4	3.8	104.4	-.936
Cispus	50.3	3.7	181.2	.360
Toutle	49.6	3.7	147.7	.167

Table 3 Array of Dependent Variables

River Name	Serial Correlation in Flows of Indicated Period									
	Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
Naselle	.13	.30	.63	.20	-.22	-.08	.13	.16	.20	.09
North	.25	.37	.71	.40	-.07	.07	.21	.17	.28	.21
Chehalis	.13	.36	.70	.52	-.10	-.03	.26	.34	.40	.31
Satsop	.16	.21	.62	.43	-.18	.08	.17	.26	.27	.33
Wynoochee	.10	.17	.58	.21	0	.22	.12	.28	.25	.49
Quinault	.27	.26	.63	.26	-.02	.30	.12	.14	.21	.41
Hoh	.22	.20	.61	.26	-.07	.27	.15	.21	.24	.36
Soleduck	.23	.29	.72	.30	-.07	.28	.19	.28	.41	.57
Dungeness	.27	.50	.70	.72	.25	.45	.60	.23	.49	.51
Duckabush	.10	.28	.39	.15	.29	.14	.41	.32	.47	.51
N.F.Skokomish	.15	.19	.63	.27	.25	.39	.24	.34	.42	.63
S.F.Skokomish	.17	.21	.54	.25	.18	.23	.05	.35	.46	.65
Chambers Ck.	.01	.64	.60	.82	.79	.72	.72	.87	.87	.88
Puyallup	.20	.34	.74	.63	-.06	.23	.39	.39	.40	.40
Carbon	.24	.47	.72	.62	-.03	.29	.29	.37	.37	.41
White	.35	.57	.75	.77	.34	.55	.27	.44	.49	.39
Greenwater	.30	.62	.81	.74	.34	.59	.27	.57	.64	.53
S.F.Skykomish	.25	.61	.73	.48	-.11	.46	.06	.36	.45	.52
Skykomish	.28	.60	.73	.46	-.08	.42	.09	.33	.42	.51
Sultan	.21	.40	.66	.19	-.07	.25	0	.35	.36	.66
Snoqualmie	.19	.52	.68	.49	-.13	.28	.21	.53	.53	.60
S.F.Stillaguamish	.26	.36	.69	.16	-.14	.22	.10	.41	.40	.67
N.F.Stillaguamish	.26	.36	.72	.35	-.10	.28	.16	.45	.52	.62
Thunder Creek	.35	.37	.43	.66	.34	.75	.44	.16	.35	.22
Stetattle Creek	.36	.60	.67	.45	.20	.53	.04	.18	.31	.39
Cascade	.31	.59	.68	.69	.20	.61	.27	.23	.44	.15
Sauk nr. Darring.	.30	.57	.72	.51	.04	.48	.25	.21	.41	.32
Sauk nr. Sauk	.30	.62	.74	.62	-.01	.46	.23	.28	.45	.33
S.F.Nooksack	.11	.40	.65	.26	-.02	.45	.08	.28	.41	.58
Stehekin	.35	.57	.67	.82	.61	.79	.61	.31	.26	.07
Wenatchee	.41	.71	.76	.74	.31	.81	.62	.28	.30	.37
Icicle	.38	.69	.76	.67	.12	.77	.52	.28	.21	.17
N.F. Ahtanum	.10	.79	.78	.75	.60	.72	.54	.75	.65	.66
S.F. Ahtanum	.06	.86	.69	.69	.60	.66	.41	.83	.76	.68
Klickitat	.00	.77	.69	.66	.59	.47	.57	.82	.80	.78
Wind	.09	.55	.52	.61	-.01	.07	.13	.55	.64	.72
E. F. Lewis	.04	.45	.62	.52	-.09	-.07	.31	.47	.23	.17
Cowlitz	.16	.44	.66	.54	.01	.13	.36	.57	.51	.49
Cispus	.15	.52	.69	.68	.15	.40	.25	.46	.49	.67
Toutle	.37	.58	.70	.69	.05	.46	.18	.37	.39	.49

Table 3 (cont.)

River Name	Serial Correlation in Flows of Indicated Period		
	July	Aug.	Sept.
Naselle	.76	.66	.17
North	.79	.75	.35
Chehalis	.78	.71	.42
Satsop	.69	.58	.12
Wynoochee	.76	.72	.16
Quinault	.83	.89	.29
Hoh	.79	.76	0
Soleduck	.90	.93	.52
Dungeness	.75	.93	.85
Duckabush	.84	.95	.54
N.F.Skokomish	.87	.92	.50
S.F.Skokomish	.83	.82	.21
Chambers Creek	.89	.85	.83
Puyallup	.71	.59	.09
Carbon	.79	.76	.15
White	.73	.81	.52
Greenwater	.89	.94	.49
S.F.Skykomish	.86	.92	.32
Skykomish	.86	.92	.35
Sultan	.86	.78	.32
Snoqualmie	.87	.85	.25
S.F.Stillaguamish	.87	.77	.35
N.F.Stillaguamish	.89	.80	.38
Thunder Creek	.45	.56	-.11
Stetattle Creek	.75	.88	.50
Cascade	.63	.87	.41
Sauk nr. Darring	.81	.92	.40
Sauk no. Sauk	.73	.90	.48
S.F.Nooksack	.86	.81	.35
Stehekin	.73	.88	.57
Wenatchee	.81	.94	.72
Icicle	.80	.95	.50
N.F. Ahtanum	.93	.96	.96
S.F. Ahtanum	.94	.95	.97
Klickitat	.95	.92	.93
Wind	.95	.94	.37
E.F. Lewis	.71	.62	.39
Cowlitz	.87	.84	.32
Cispus	.90	.96	.66
Toutle	.82	.94	.32

TABLE 4

MODEL ERRORS IN %

Model No.	1	2	3	4	5	6	7	8	9	10	11	12
Stream												
MEANS												
Chehalis R.	5.0	5.2	3.2	5.8	4.5	5.4	7.3	4.9	9.8	8.6	8.6	10.8
S. F. Skykomish R.	2.8	2.4	3.5	4.8	2.4	2.6	3.4	3.2	44.2	3.7	5.2	6.8
Thunder Ck.	2.0	1.7	2.4	2.7	1.6	1.3	1.2	2.2	1.9	1.5	3.3	2.1
Wenatchee R.	2.6	2.3	3.4	3.8	2.4	2.4	2.2	2.8	2.5	2.4	4.2	4.6
4 Stream Average	3.1	2.9	3.1	4.3	2.7	2.9	3.5	3.3	14.6	4.1	5.3	6.1
STANDARD DEVIATIONS												
Chehalis R.	32.1	34.5	21.7	32.4	35.1	39.5	45.7	40.9	53.8	54.8	54.1	58.1
S. F. Skykomish R.	16.2	18.9	17.3	21.8	19.6	22.6	28.3	26.2	63.0	32.0	41.1	47.8
Thunder Ck.	8.8	9.9	9.8	12.2	12.9	10.7	15.9	15.6	14.8	21.5	28.9	26.9
Wenatchee R,	12.8	13.7	13.8	17.0	14.0	17.2	22.2	18.1	19.8	20.9	36.6	33.7
4 Stream Average	17 .5	19.2	15.6	20.9	20.4	22.5	28.0	25.2	37.9	32.3	40.2	41.6
SERIAL CORRELATIONS												
Chehalis R.	62.0	84.0	84.2	69.3	74.7	61.1	70.8	74.5	96.9	50.5	67.4	64.9
S. F. Skykomish R.	21.8	13.4	23.3	18.0	22.0	19.4	20.3	21.0	20.3	27.2	21.3	20.6
Thunder Ck.	34.5	24.5	22.9	28.0	23.7	23.1	25.9	28.8	25.7	29.2	16.9	16.8
Wenatchee R.	20.2	15.4	13.5	15.2	15.7	12.1	14.0	14.8	10.1	14.9	9.8	9.7
4 Stream Average	34.6	34.3	36.0	32.6	34.0	28.9	32.7	34.8	38.3	30.5	28.9	28.0
3 STATISTIC AVERAGE												
Chehalis R.	33.1	41.2	36.4	35.9	38.1	35.3	41.2	40.1	53.5	38.0	43.4	44.6
S. F. Skykomish R.	13.6	11.6	14.7	14.9	14.6	14.9	17.3	16.8	42.5	20.9	22.6	25.0
Thunder Ck.	15.1	12.0	11.7	14.3	12.7	11.7	14.3	15.5	14.2	17.4	16.4	15.3
Wenatchee R.	11.9	10.5	10.2	12.0	10.7	10.6	12.8	11.9	10.8	12.7	16.9	16.0
4 Stream Average	18.4	18.8	18.3	19.3	19.0	18.1	21.4	21.1	30.3	22.3	24.8	25.2
AVERAGE OF MEAN AND STANDARD DEVIATION												
Chehalis R.	18.1	19.8	12.4	19.1	19.8	22.5	26.5	22.9	31.8	31.7	31.3	34.5
S. F. Skykomish R.	9.5	10.7	10.4	13.3	11.0	12.6	15.8	14.7	53.6	17.8	23.2	27.3
Thunder Ck.	5.4	5.8	6.1	7.5	7.2	6.0	8.5	8.9	8.4	11.5	16.1	14.5
Wenatchee R.	7.7	8.0	8.6	10.4	8.2	9.8	12.2	10.4	11.2	11.6	20.4	19.2
4 Stream Average	10.2	11.1	9.4	12.6	11.6	12.7	15.8	14.2	26.2	18.2	22.5	23.9

TABLE 5
PERIOD ERRORS IN %

Period Statistic	Ann.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
					CHEHALIS R.								
Mean	6.5	6.7	31.0	3.0	5.1	5.4	4.5	6.2	5.7	3.6	2.7	1.5	3.9
Standard Deviation	72.6	52.5	196.9	7.3	50.1	31.0	31.4	29.1	19.2	12.3	12.3	19.7	10.2
Serial Correlation	82.2	36.1	8.1	15.9	408.4	125.4	19.7	83.1	13.3	75.4	4.0	5.6	54.9
					S. F. SKYKOMISH R.								
Mean	3.4	6.2	10.2	10.3	6.5	3.9	4.4	3.0	6.8	9.1	16.2	5.8	6.0
Standard Deviation	35.8	35.3	86.1	15.3	26.1	29.2	15.4	19.8	24.1	34.4	39.2	12.2	11.5
Serial Correlation	65.3	5.7	11.5	11.3	43.8	12.6	45.3	13.1	10.6	21.8	3.1	2.3	23.0
					THUNDER CREEK								
Mean	0.7	1.7	3.0	2.3	2.6	3.1	3.8	3.1	1.8	1.2	0.7	0.6	1.3
Standard Deviation	10.8	7.7	34.0	10.6	10.2	19.7	20.9	10.7	17.7	12.9	16.4	13.5	18.2
Serial Correlation	74.8	6.3	29.5	24.1	59.4	3.8	11.8	28.4	10.5	18.7	4.1	6.6	46.7
					WENATCHEE R.								
Mean	1.4	3.5	3.1	2.6	2.7	2.5	5.8	3.5	1.8	2.6	5.3	2.2	1.7
Standard Deviation	17.6	11.5	41.3	14.9	13.4	12.1	32.6	12.5	20.1	30.3	28.8	12.9	8.6
Serial Correlation	53.5	5.5	4.7	5.5	15.1	5.0	7.2	16.8	14.4	41.1	5.2	0.8	4.6
					4 STREAM AVERAGE								
Mean	3.0	4.5	11.8	4.6	4.2	3.8	4.6	4.0	4.0	4.1	6.2	2.5	3.2
Standard Deviation	34.2	26.8	89.6	12.0	25.0	23.0	25.1	18.0	20.3	22.5	24.2	14.6	12.1
Serial Correlation	68.9	13.4	13.5	14.2	131.7	36.7	21.0	35.4	12.2	39.2	4.1	3.8	32.3

TABLE 6

RATINGS OF PERIOD ERRORS STREAM BY STREAM*

Period Statistic	Ann.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
						CHEHALIS R.							
Mean	11	12	13	3	7	8	6	10	9	4	2	1	5
Standard Deviation	12	11	13	1	10	8	9	7	5	3	4	6	2
Serial Correlation	10	7	3	5	13	12	6	11	4	9	1	2	8
						S. F. SKYKOMISH R.							
Mean	2	7	11	12	8	3	4	1	9	10	13	5	6
Standard Deviation	11	10	13	3	7	8	4	5	6	9	12	2	1
Serial Correlation	13	3	6	5	11	7	12	8	4	9	2	1	10
						THUNDER CK.							
Mean	2	6	10	8	9	12	13	11	7	4	3	1	5
Standard Deviation	5	1	13	3	2	11	12	4	9	6	8	7	10
Serial Correlation	13	3	10	8	12	1	6	9	12	7	2	4	11
						WENATCHEE R.							
Mean	1	11	9	7	8	5	13	10	3	6	12	4	2
Standard Deviation	8	2	13	7	6	3	12	4	9	11	10	5	1
Serial Correlation	13	7	3	6	10	4	8	11	9	12	5	1	2
						4 STREAM AVERAGE							
Mean	2	9	13	10	8	4	11	5	6	7	12	1	3
Standard Deviation	12	11	13	1	9	7	10	4	5	6	8	3	2
Serial Correlation	13	4	5	6	12	10	7	9	3	11	2	1	8

* LOWEST NUMERICAL VALUES IN TABLES INDICATE LOWEST ERROR

TABLE 7
RATINGS OF PERIOD ERRORS STATISTIC BY STATISTIC*

Period Stream	Ann.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
						MEANS							
Chehalis	11	12	13	3	7	8	6	10	9	4	2	1	5
S. F. Skykomish	2	7	11	12	8	3	4	1	9	10	13	5	6
Thunder	2	6	10	8	9	12	13	11	7	4	3	1	5
Wenatchee	1	11	9	7	8	5	13	10	3	6	12	4	2
4 Stream Average	2	9	13	10	8	4	11	5	6	7	12	1	3
						STANDARD DEVIATIONS							
Chehalis	12	11	13	1	10	8	9	7	5	3	4	6	2
S. F. Skykomish	11	10	13	3	7	8	4	5	6	9	12	2	1
Thunder	5	1	13	3	2	11	12	4	9	6	8	7	10
Wenatchee	8	2	13	7	6	3	12	4	9	11	10	5	1
4 Stream Average	12	11	13	1	9	7	10	4	5	6	8	3	2
						SERIAL CORRELATIONS							
Chehalis	10	7	3	5	13	12	6	11	4	9	1	2	8
S. F. Skykomish	13	3	6	5	11	7	12	8	4	9	2	1	10
Thunder	13	3	10	8	12	1	6	9	5	7	2	4	11
Wenatchee	13	7	3	6	10	4	8	11	9	12	5	1	2
4 Stream Average	13	4	5	6	12	10	7	9	3	11	2	1	8

* LOWEST NUMERICAL VALUES IN TABLE INDICATE LOWEST ERROR

TABLE 13
FSC PREDICTION EQUATIONS

			Period			
	Ann.	Oct.	Nov.	Dec.	Jan.	Feb.
% Variation Explained	56	62	59	65	43	68
Regression Constant	0.29128	1.16791	.98639	.20213	1.35352	1.37632
			REGRESSION COEFFICIENTS			
VARIABLE						
Precipitation	.00105	-.00023	.00002	-.0001	-.0003	-.00037
PSC	.67158	.35577	.39368	1.0534	-	-
PSC of Previous Period	-	-	-	-	-	-.46709
Snowfall	.00021	.03495	.00085	.0030	-	.00467
Mean Annual Temperature	-.00595	-.01259	-.00842	.0050	-.02214	-.01836
Basin Orientation	-	-	.03086	.0135	-	-
Glacierized Area	.00876	-	-.01476	.0149	.0067	.01292
Basin Slope	-	-	-	-	.00068	.00063
Basin Geology	-	-	-	-	-	-
Depression Storage	-	-	-	.0444	.1007	.14834
Drainage Area	-	.00012	.00002	-	-	-
Baseflow Recession Factor	-	-	-.00007	-	-	-

TABLE 13 (cont.)
FSC PREDICTION EQUATIONS

			Period				
	Mar.	Apr.	May	June	July	Aug.	Sept.
% Variation Explained	61	41	50	30	53	53	74
Regression Constant	.64984	.61593	.90225	.81734	.86348	.87110	2.12291
			REGRESSION COEFFICIENTS				
VARIABLE							
Precipitation	-.0003	-.00045	-.0004	.0002	-.00042	-.00092	-.00124
PSC	.16181	.47099	1.2014	.3972	-	-	-.37214
PSC of Previous Period	-.45801	-	.1949	1.1837	-	-.10815	-
Snowfall	-	-	-	-	-	-	-
Mean Annual Temperature	-.00531	-	-	-	-	-	-.02794
Basin Orientation	-	-	.0853	-	-	-	-
Glacierized Area	.01449	-.0083	-.0050	-.0130	-.02215	-.01173	-.03869
Basin Slope	-	-.00054	-	-	-	.00034	.00055
Basin Geology	-	-	-.1015	-.1040	-	-	-
Depression Storage	.06128	.04019	-	.0251	.02076	.06680	.06399
Drainage Area	-	-	-	-	-	-	-
Baseflow Recession Factor	-	.00019	-	-	.00016	.00071	-

TABLE 14
RESULTS OF CHECK OF FSC PREDICTION EQUATIONS

STREAM		S. F. SKYKOMISH RIVER			GREENWATER RIVER			SULTAN RIVER		
Period	% Variation Explained	Actual FSC	Predicted FSC	Error	Actual FSC	Predicted FSC	Error	Actual FSC	Predicted FSC	Error
Annual	56	0.17	0.08	-0.09	0.30	0.32	0.02	0.21	0.22	0.01
October	62	0.21	0.33	0.12	0.62	0.65	0.03	0.40	0.41	0.01
November	59	0.54	0.54	0	0.81	0.81	0	0.66	0.62	-0.04
December	65	0.25	0.19	-0.06	0.74	0.70	-0.04	0.19	0.49	0.30
January	43	0.18	-0.08	-0.26	0.34	0.25	-0.09	-0.07	0.12	0.19
February	68	0.23	0.18	-0.05	0.59	0.59	0	0.25	0.38	0.13
March	61	0.05	0.21	0.16	0.27	0.25	-0.02	0	0.21	0.21
April	41	0.35	0.34	-0.01	0.57	0.26	-0.31	0.35	0.43	0.08
May	50	0.46	0.29	-0.17	0.64	0.30	-0.34	0.36	0.31	-0.05
June	30	0.65	0.46	-0.19	0.53	0.34	-0.19	0.66	0.37	-0.29
July	53	0.83	0.88	0.05	0.89	0.83	-0.06	0.86	0.82	-0.04
August	53	0.82	0.99	0.17	0.94	0.81	-0.13	0.76	0.81	0.05
September	74	0.21	0.45	0.24	0.49	0.57	0.08	0.32	0.37	0.05

TABLE 16
ERRORS IN STATISTICS OF FLOWS GENERATED BY LAG ONE MODEL.

Period Source	Ann.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
CHEHALIS - MEANS													
Recorded Data	2836	989	4062	6263	6423	6188	4456	2850	1424	744	347	221	279
Generated Data	2965	1002	5389	6033	6311	6421	4625	2972	1487	744	344	224	288
% Difference	4.6	1.3	32.7	-3.7	-1.8	3.8	3.8	4.3	4.4	0	-0.7	1.4	3.0
CHEHALIS - STANDARD DEVIATIONS													
Recorded Data	633	734	2641	3455	2989	2613	1923	1352	695	455	127	63	167
Generated Data	1020	864	8608	3251	3566	2761	2354	1552	722	371	122	69	152
% Difference	61.3	17.7	225.9	-5.9	19.3	5.6	22.4	14.8	3.8	-18.4	-3.9	9.6	-9.0
CHEHALIS - SERIAL CORRELATION COEFFICIENTS													
Recorded Data	.13	.22	.62	.51	-.02	-.03	.20	.18	.36	.16	.73	.66	.25
Generated Data	-.04	.25	.59	.45	-.06	.02	.22	.30	.46	.32	.76	.67	.44
Actual Difference	-.17	+.03	-.03	-.06	-.04	+.05	+.02	+.12	+.12	+.16	+.03	+.01	+.19
S.F. SKYKOMISH - MEANS													
Recorded Data	2460	1795	2784	3115	2413	2045	1818	2957	4454	4298	2224	830	777
Generated Data	2485	1787	3084	2978	2302	2054	1764	2950	4581	4435	2254	837	798
% Difference	1.0	-0.5	10.8	-4.4	-4.6	0.5	-3.0	-0.2	2.8	3.2	1.3	0.8	2.7
S.F. SKYKOMISH - STANDARD DEVIATIONS													
Recorded Data	492	1061	1428	1575	1448	1031	656	781	1167	1638	1304	456	507
Generated Data	568	1191	2574	1357	1446	1124	535	854	1270	1918	1386	410	456
% Difference	15.6	12.2	80.3	-13.9	-0.1	9.0	-18.4	9.3	8.8	17.1	6.3	-10.2	-10.1
S.F. SKYKOMISH - SERIAL CORRELATION COEFFICIENTS													
Recorded Data	.25	.56	.60	.42	-.16	.44	.07	.33	.41	.41	.80	.92	.26
Generated Data	.02	.54	.66	.48	-.08	.51	.09	.34	.50	.53	.84	.89	.28
Actual Difference	-.23	-.02	+.06	+.06	+.08	+.07	+.02	+.01	+.09	+.08	+.04	-.03	+.02

TABLE 16 (contd.)

Period Source	Ann.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
				THUNDER CREEK - MEANS									
Recorded Data	617	509	382	319	237	212	184	404	912	1301	1315	958	641
Generated Data	614	504	399	315	227	208	176	390	920	1298	1299	958	650
%Difference	-0.4	-1.1	4.5	-1.3	-4.2	-2.1	-4.8	-3.6	0.9	-0.3	-1.2	0	1.5
				THUNDER CREEK - STANDARD DEVIATIONS									
Recorded Data	85	178	230	161	134	134	83	173	244	306	222	145	114
Generated Data	79	160	302	163	126	134	62	145	256	313	227	149	118
% Difference	-7.5	-10.5	31.5	1.2	-5.8	0	-25.1	-16.2	4.7	2.2	2.1	3.3	3.5
				THUNDER CREEK - SERIAL CORRELATION COEFFICIENTS									
Recorded Data	.35	.38	.32	.50	.19	.71	.36	.15	.37	.20	.45	.56	-.11
Generated Data	-.01	.34	.42	.68	.37	.75	.44	.12	.39	.26	.45	.54	-.02
Actual Difference	-.36	-.04	+.10	+.18	+.18	+.04	+.08	-.03	+.02	+.06	0	-.02	+.09
				WENATCHEE RIVER - MEANS									
Recorded Data	2273	960	1338	1332	1046	1006	1087	2823	6066	6420	3375	1125	639
Generated Data	2264	917	1369	1302	996	967	1013	2701	6167	6521	3386	1123	646
% Difference	-0.4	-4.5	2.3	-2.2	-4.8	-3.9	-6.7	-4.3	1.7	1.6	0.4	-0.1	1.1
				WENATCHEE RIVER - STANDARD DEVIATIONS									
Recorded Data	531	588	894	823	550	634	582	1252	1695	2038	1743	547	252
Generated Data	555	491	1081	806	531	591	373	1005	1836	2440	1918	521	216
% Difference	4.7	-16.4	20.9	-2.1	-3.3	-6.7	-35.9	-19.7	8.3	19.7	10.0	-4.7	-14.3
				WENATCHEE RIVER - SERIAL CORRELATION COEFFICIENTS									
Recorded Data	.41	.71	.68	.67	.25	.75	.55	.26	.29	.24	.74	.94	.73
Generated Data	.05	.66	.66	.71	.32	.82	.60	.24	.35	.40	.79	.92	.69
Actual Difference	-.36	-.05	-.02	+.04	+.07	+.07	+.05	-.02	+.06	+.16	+.05	-.02	-.04

Appendix B

Figures

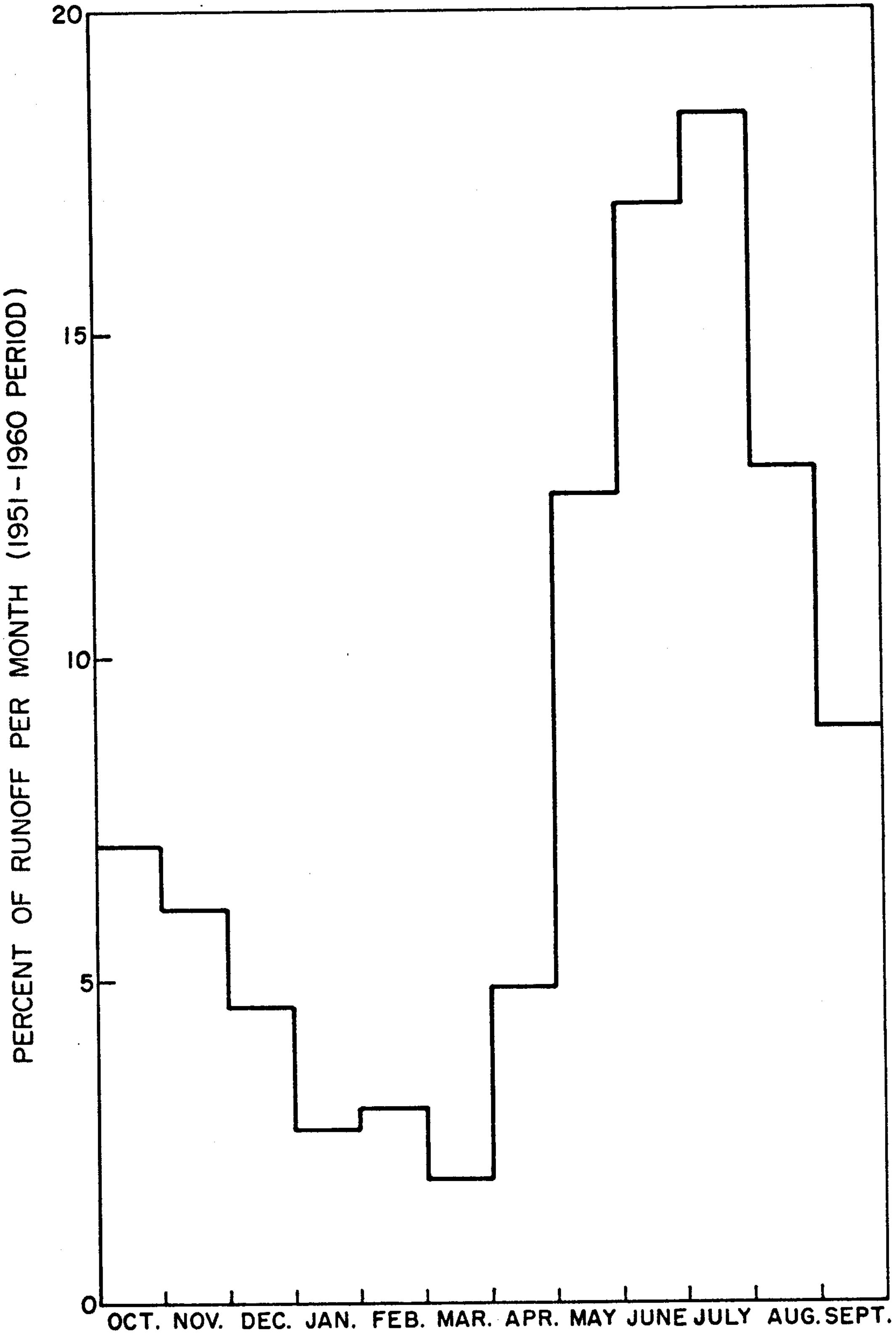


FIGURE 1. MONTHLY HYDROGRAPH FOR THUNDER CREEK NEAR NEWHALEM, WASHINGTON

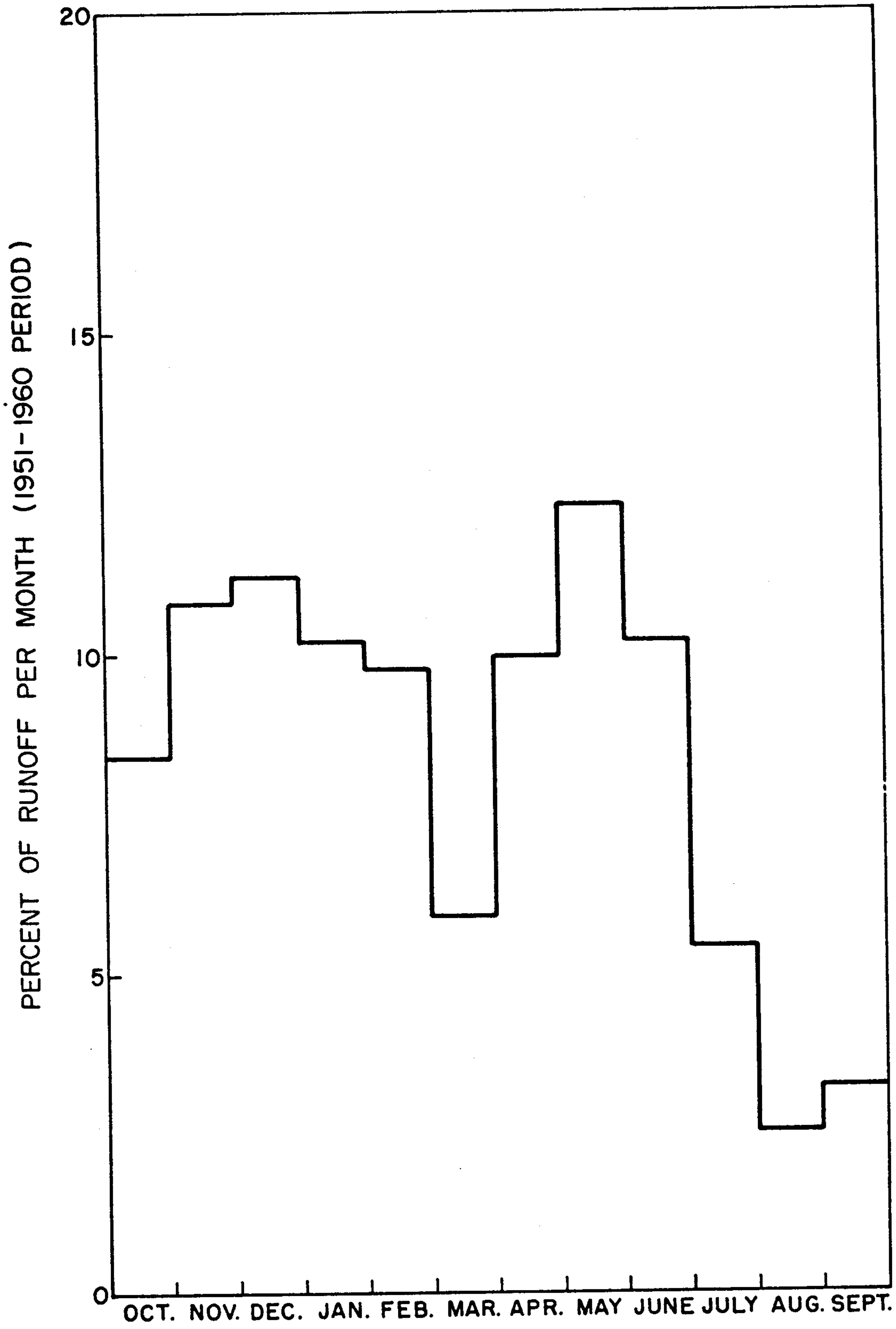
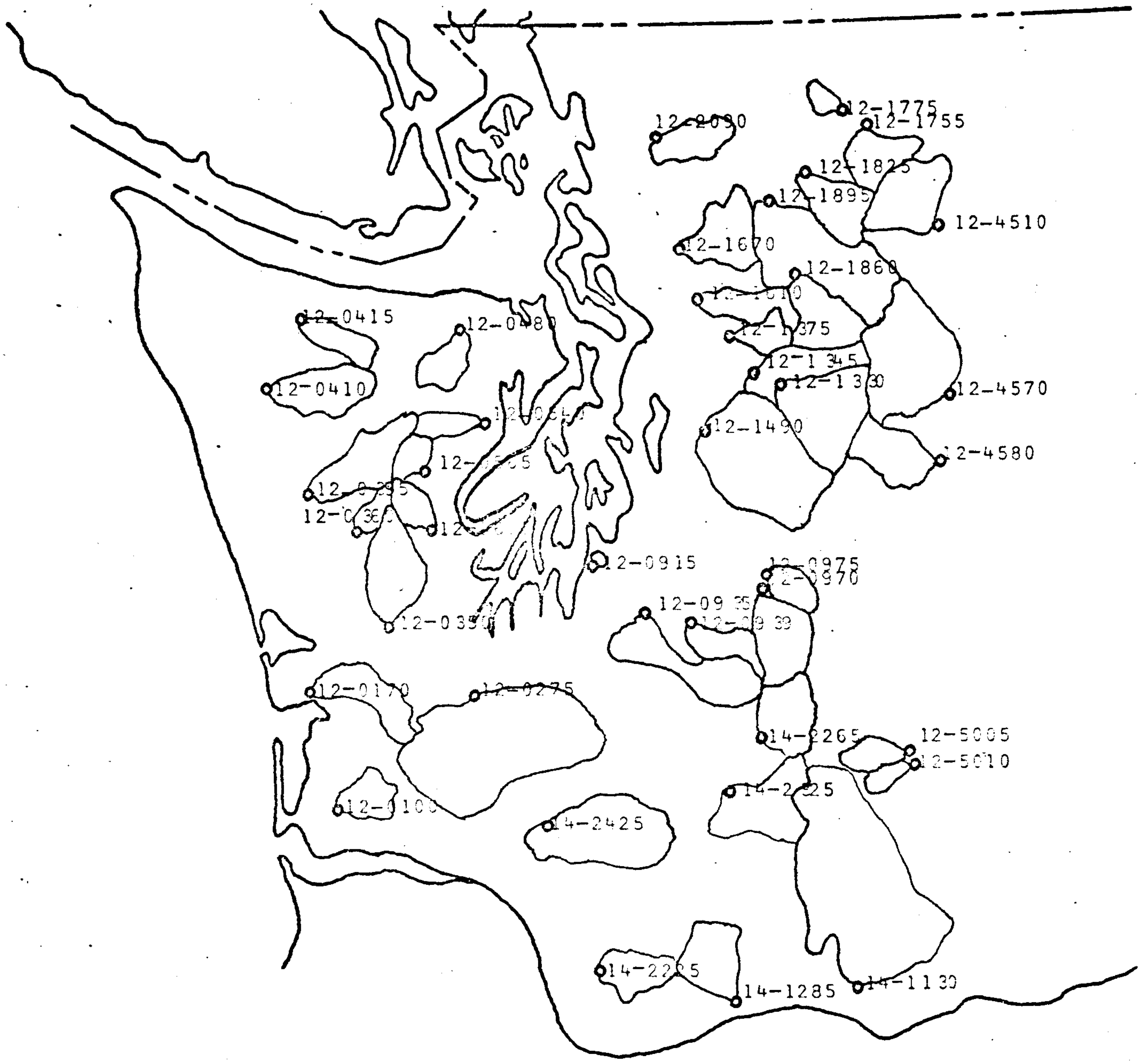
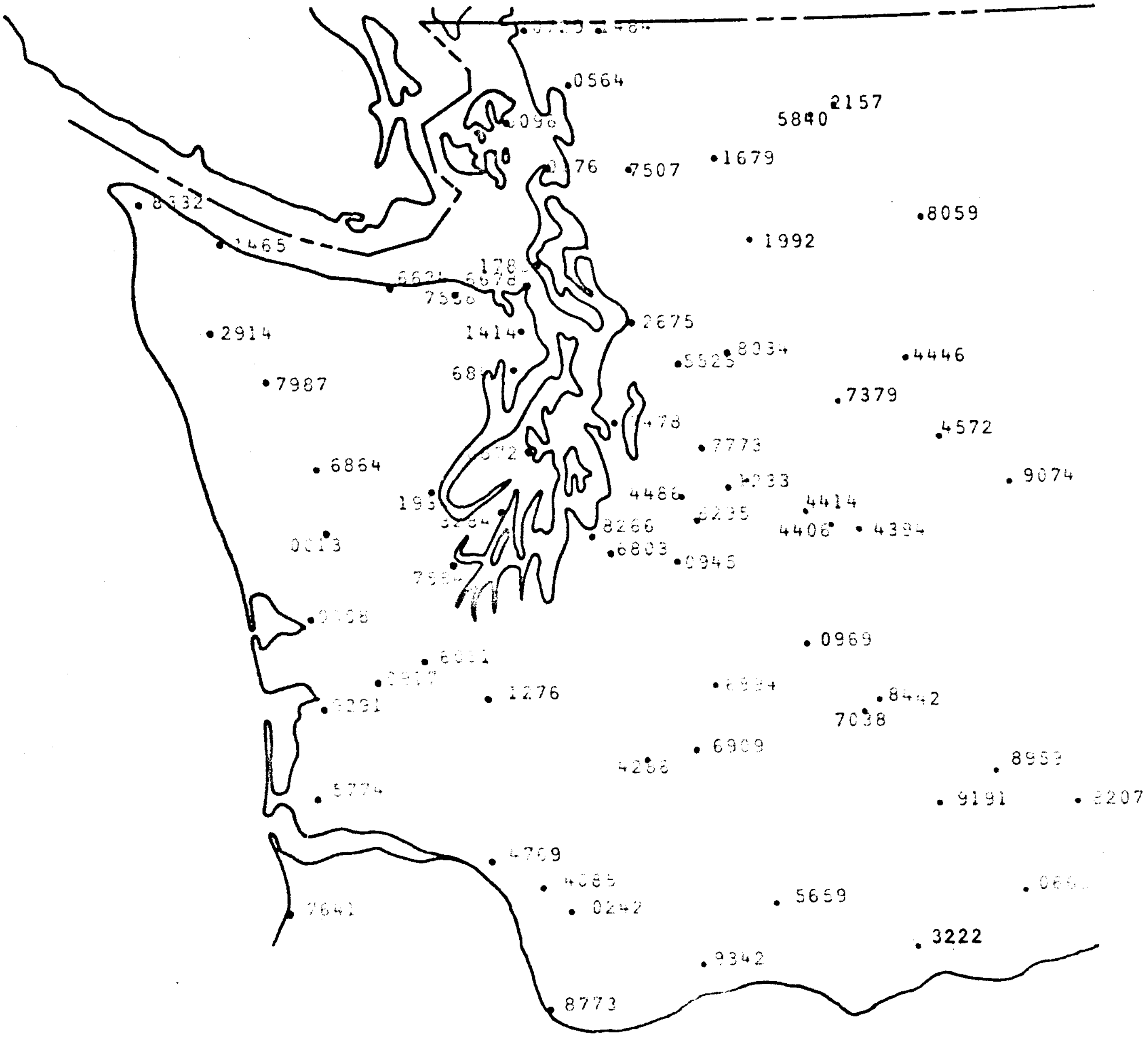


FIGURE 2. MONTHLY HYDROGRAPH FOR THE SOUTH FORK NOOKSACK RIVER NEAR WICKERSHAM, WASHINGTON



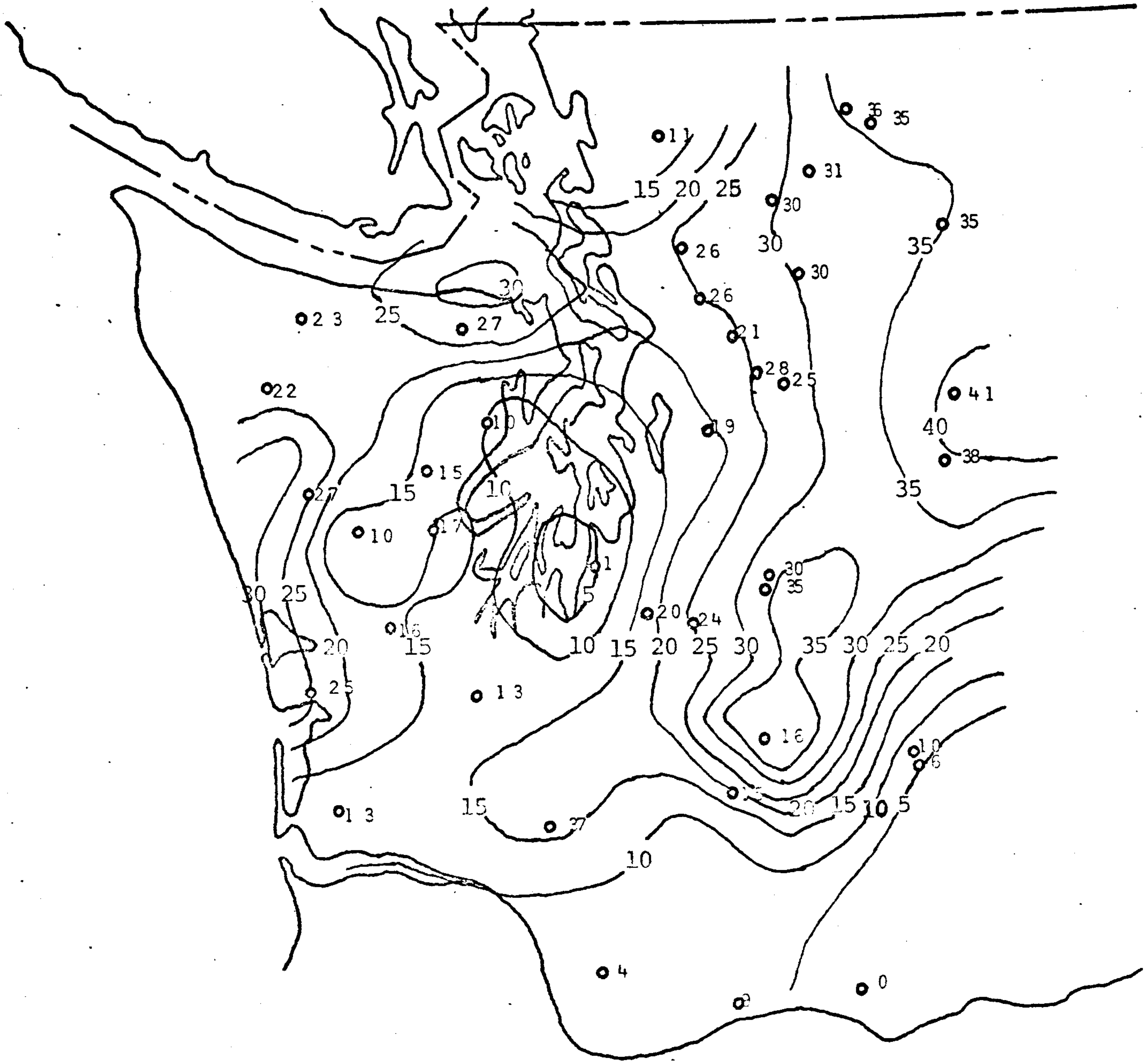
U.S. Geological Survey Identification Numbers

FIGURE 3. DRAINAGE BASINS INCLUDED IN THE STUDY



U.S. Weather Bureau Identification Numbers

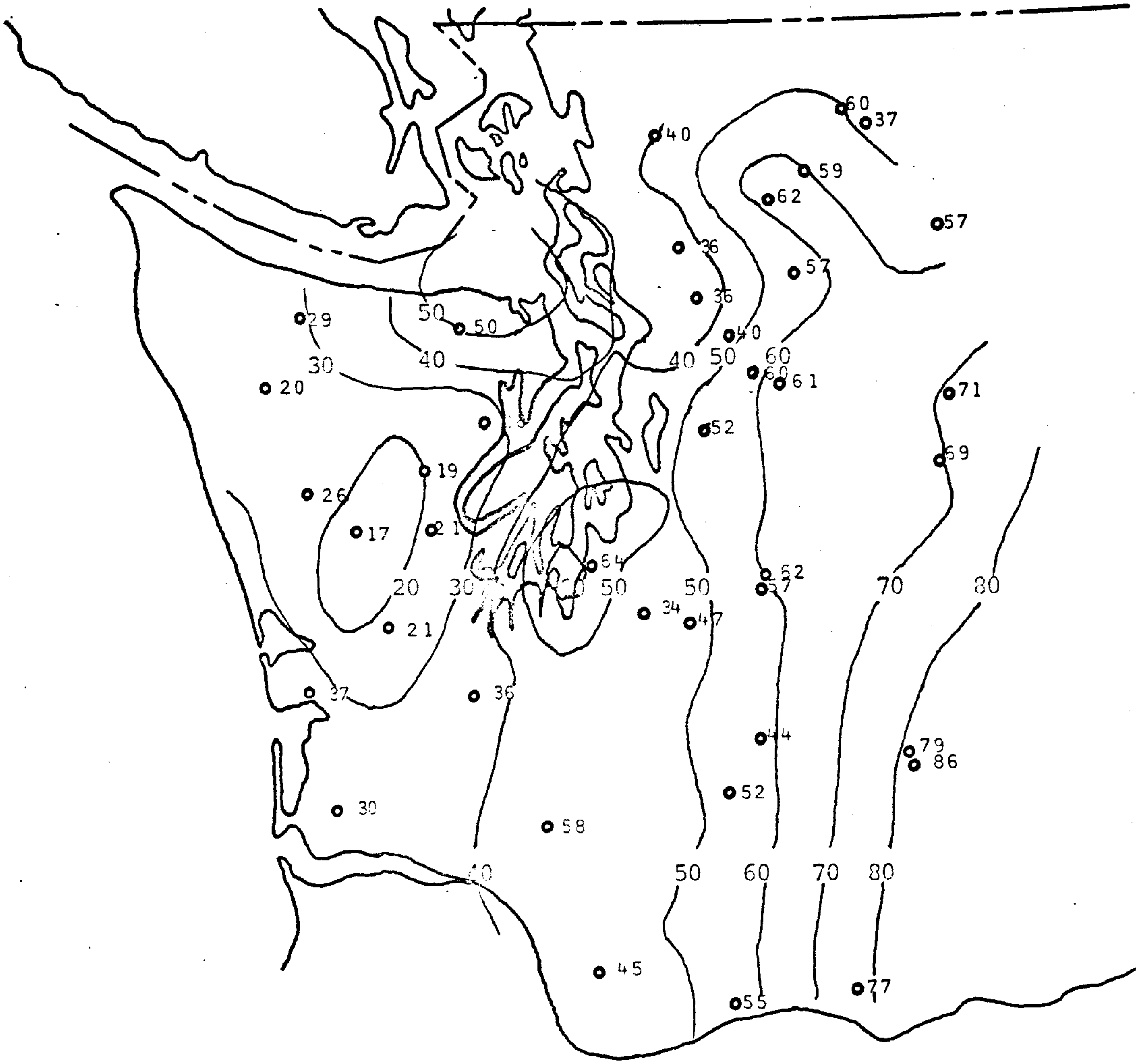
FIGURE 4. PRECIPITATION STATIONS INCLUDED IN THE STUDY



All values indicated are 100 times actual serial correlations

CONTOUR INTERVAL - 5

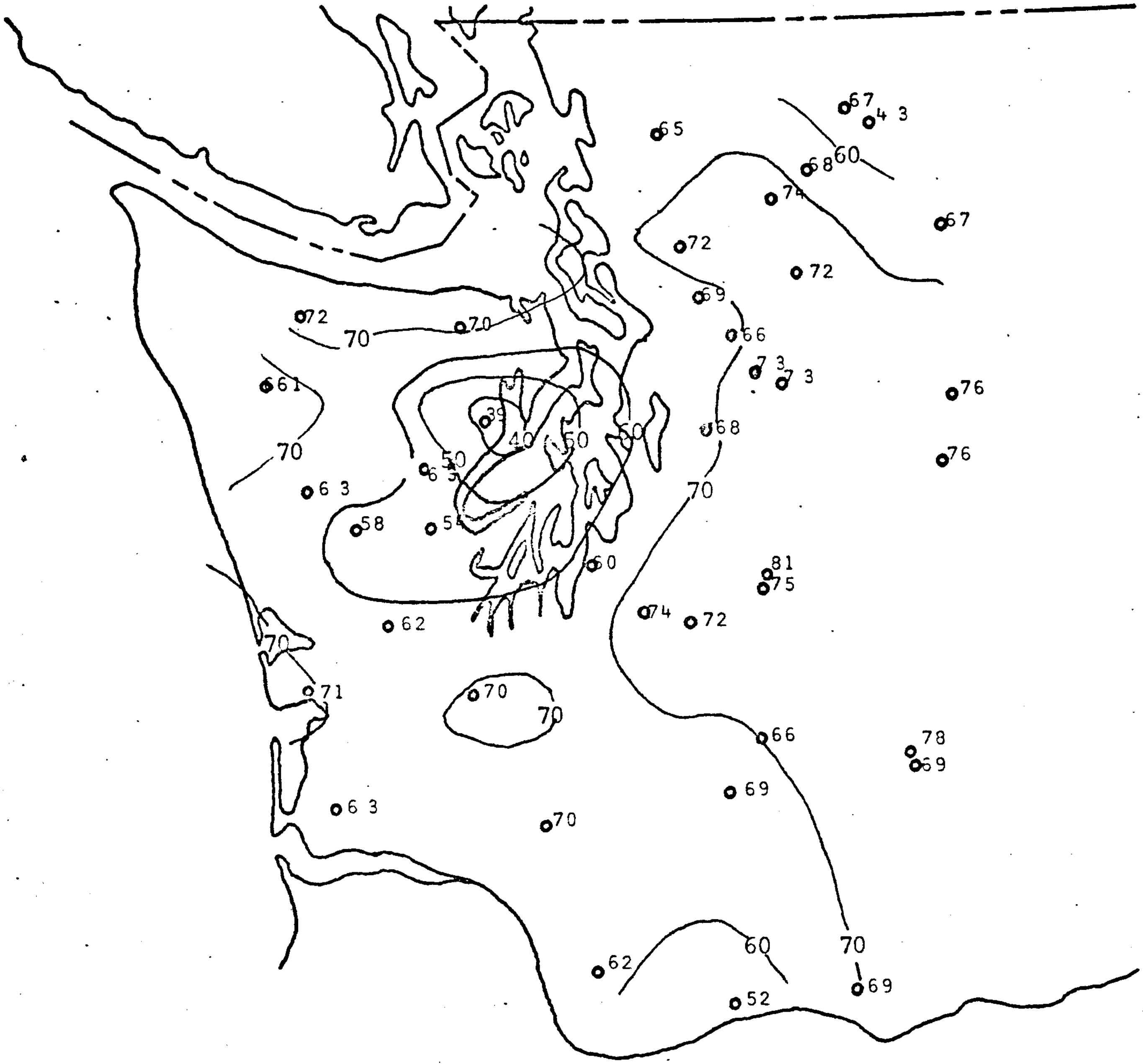
FIGURE 5. CONTOURS OF ANNUAL FLOW SERIAL CORRELATIONS



All values indicated are 100 times actual serial correlations

CONTOUR INTERVAL - 10

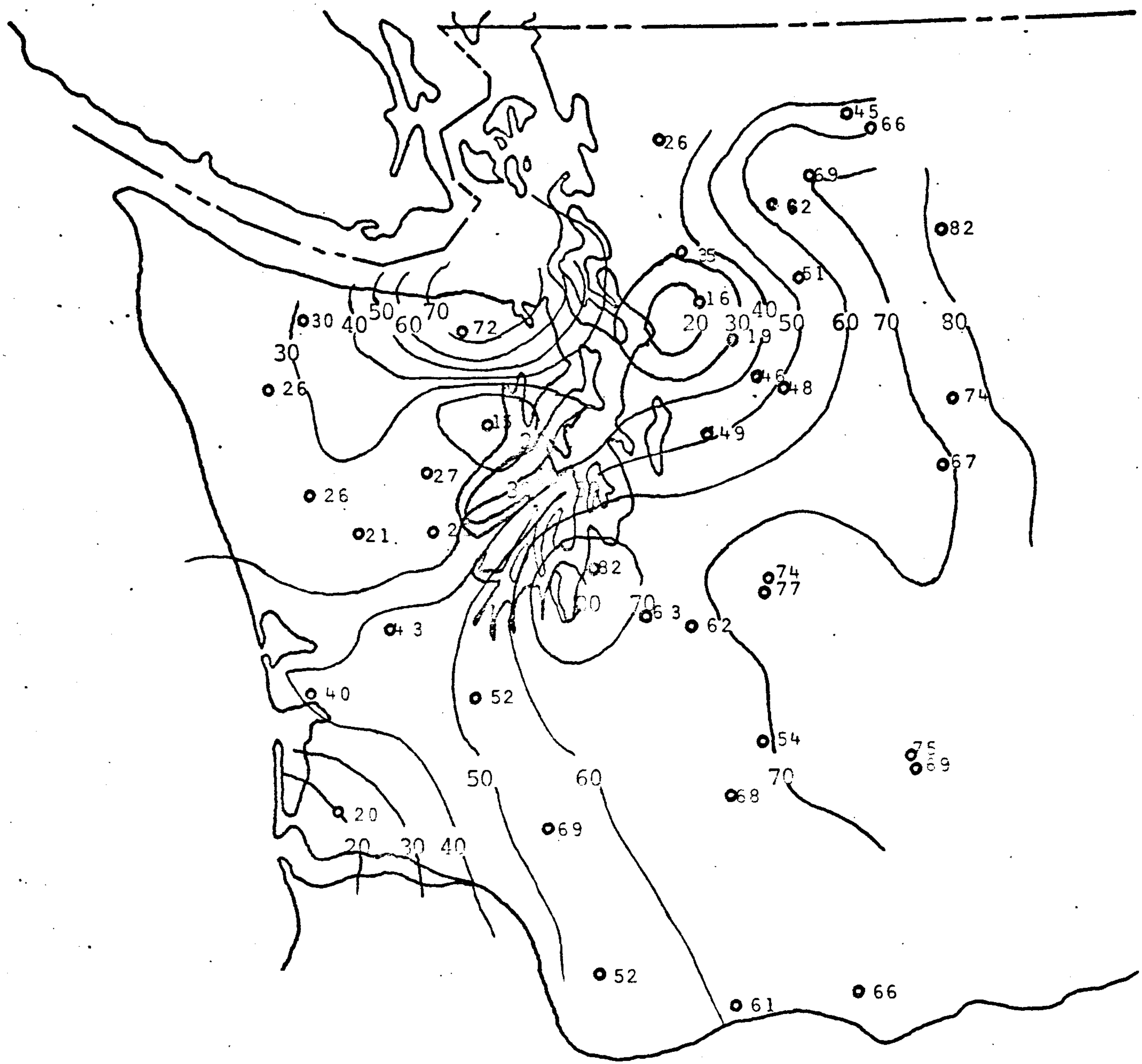
FIGURE 6. CONTOURS OF OCTOBER FLOW SERIAL CORRELATIONS



All values indicated are 100 times actual serial correlations

CONTOUR INTERVAL - 10

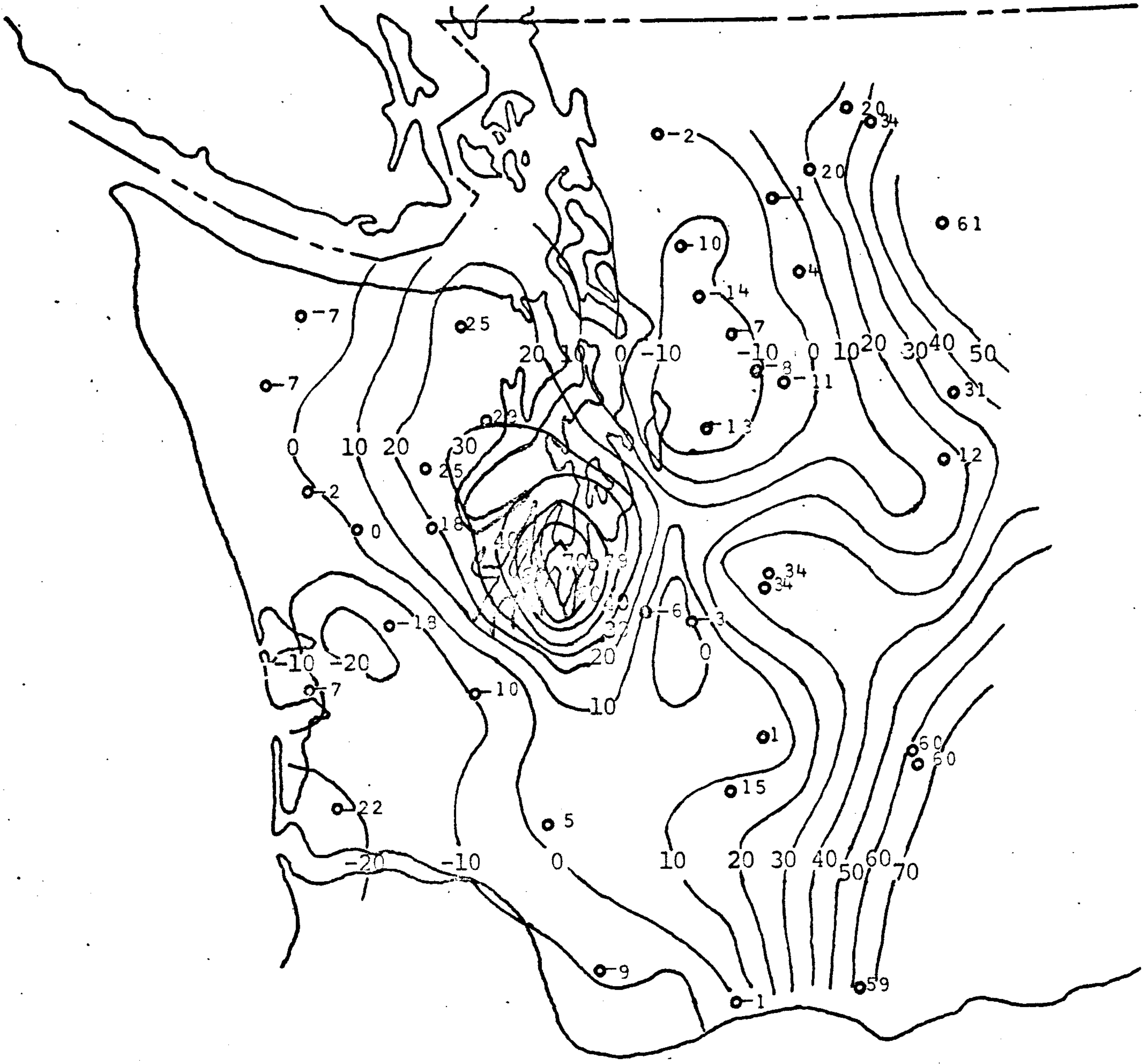
FIGURE 7. CONTOURS OF NOVEMBER FLOW SERIAL CORRELATIONS



All values indicated are 100 times actual serial correlations

CONTOUR INTERVAL - 10

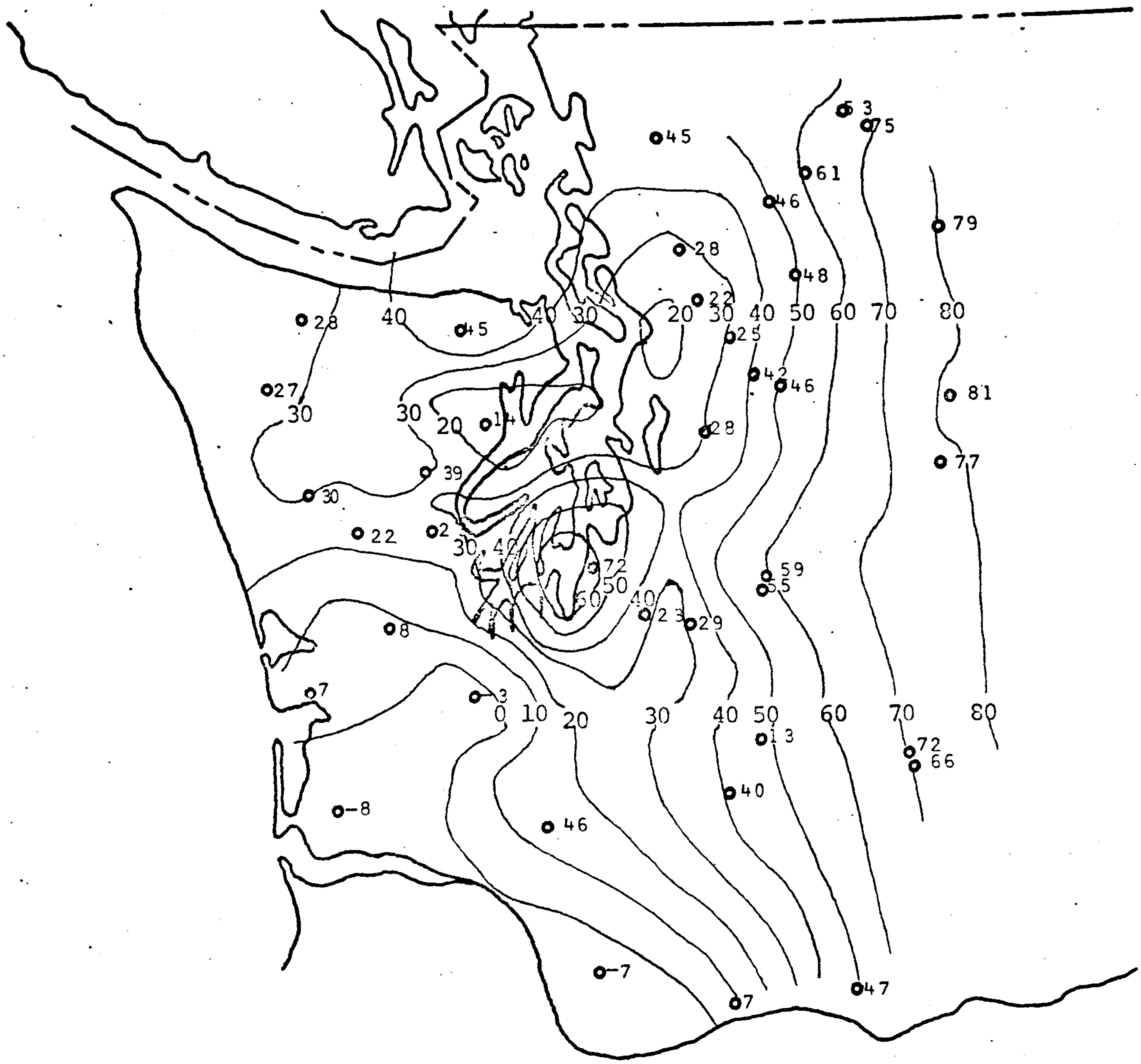
FIGURE 8. CONTOURS OF DECEMBER FLOW SERIAL CORRELATIONS



All values indicated are 100 times actual serial correlations

CONTOUR INTERVAL - 10

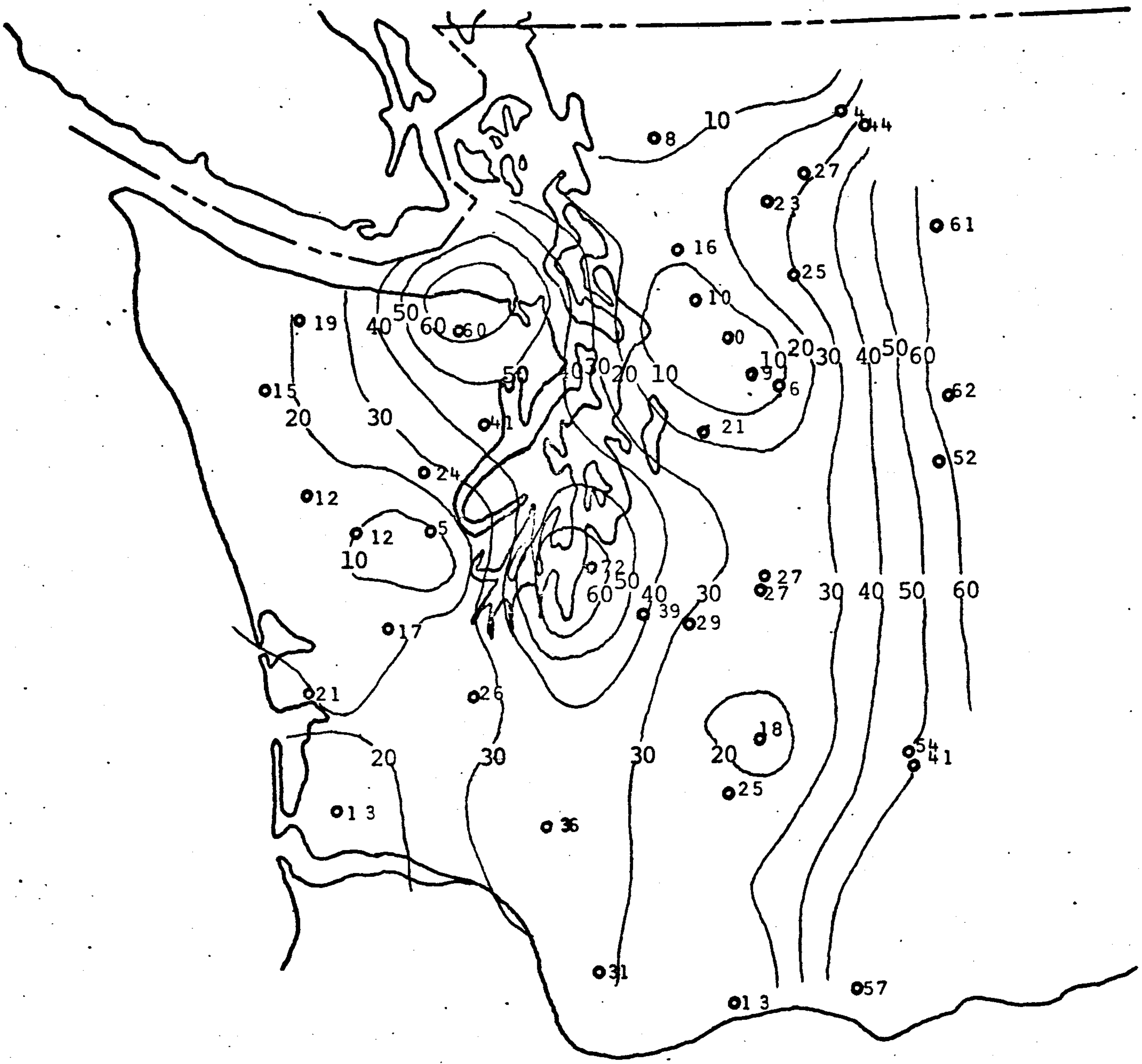
FIGURE 9. CONTOURS OF JANUARY FLOW SERIAL CORRELATIONS



All values indicated are 100 times actual serial correlations

CONTOUR INTERVAL - 10

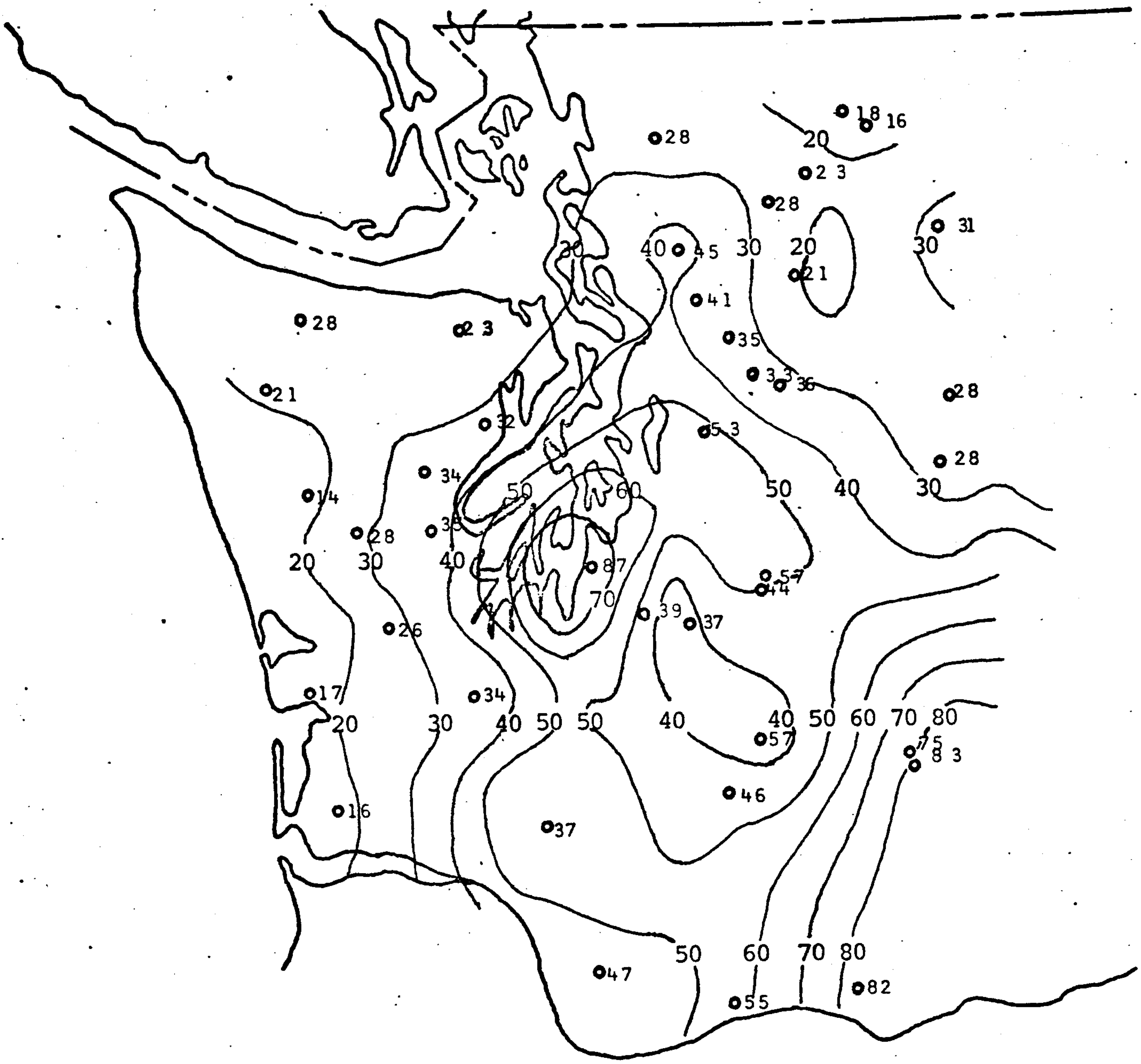
FIGURE 10. CONTOURS OF FEBRUARY FLOW SERIAL CORRELATIONS



All values indicated are 100 times actual serial correlations

CONTOUR INTERVAL - 10

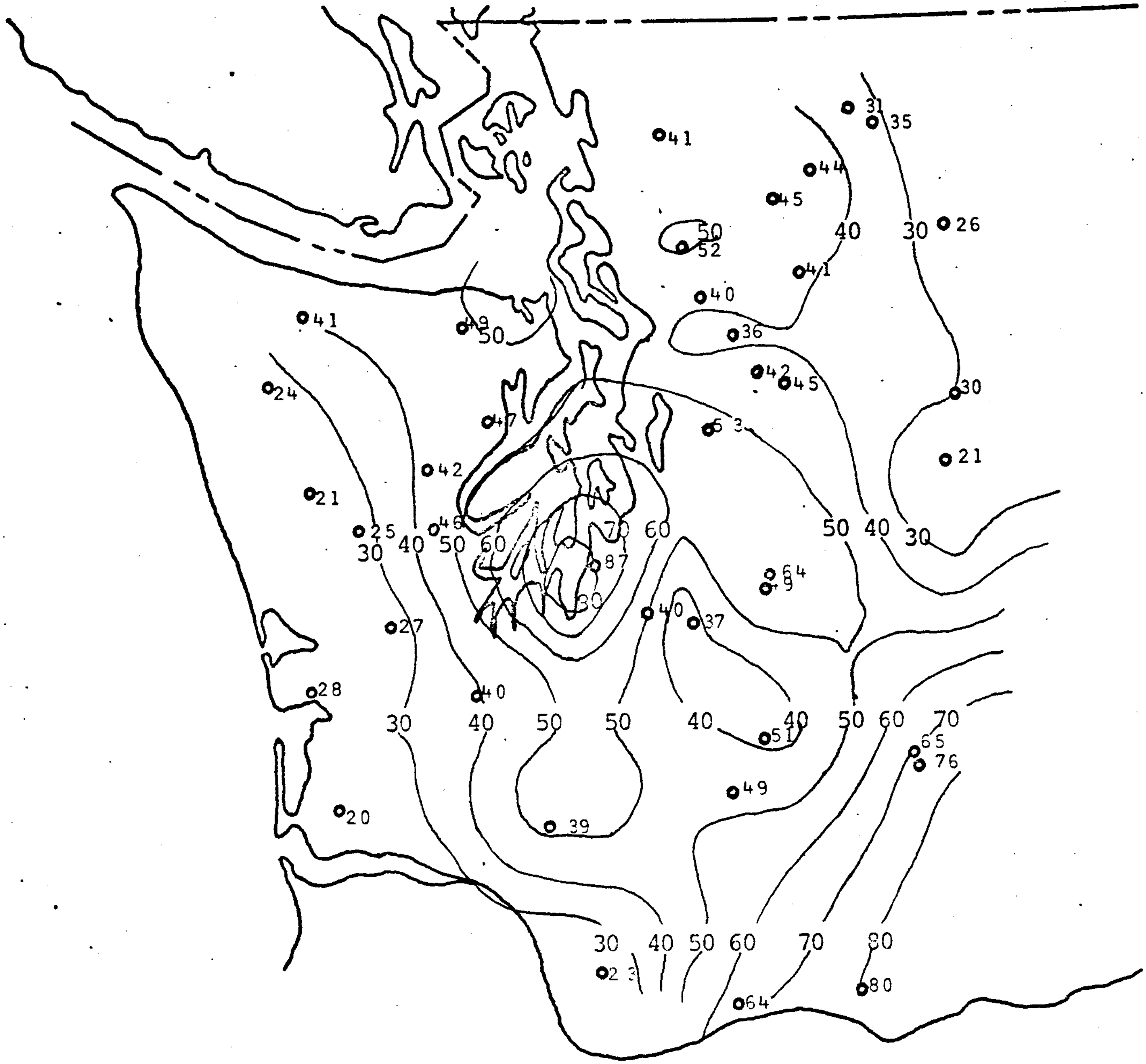
FIGURE 11. CONTOURS OF MARCH FLOW SERIAL CORRELATIONS



All values indicated are 100 times actual serial correlations

CONTOUR INTERVAL - 10

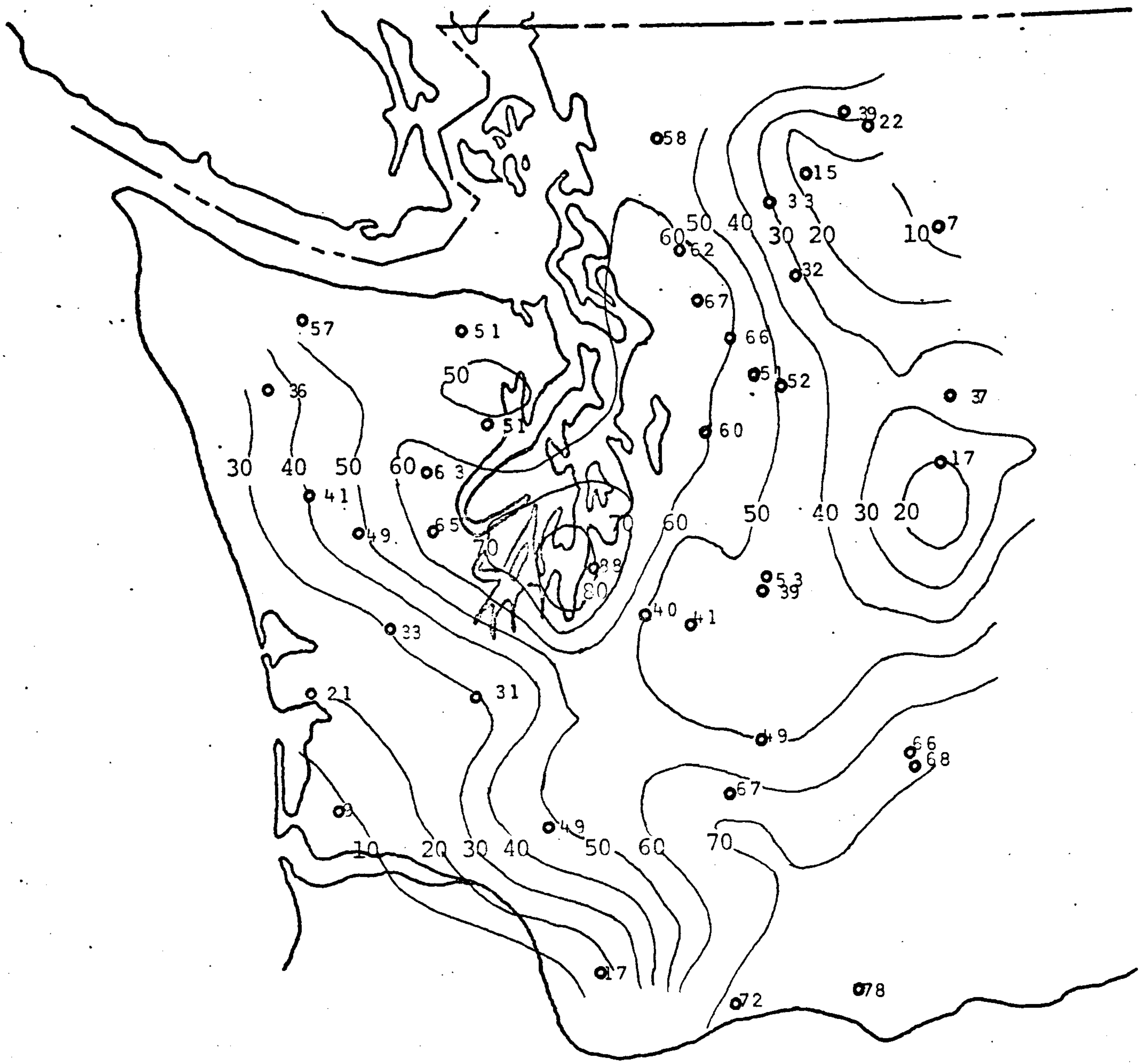
FIGURE 12. CONTOURS OF APRIL FLOW SERIAL CORRELATIONS



All values indicated are 100 times actual serial correlations

CONTOUR INTERVAL - 10

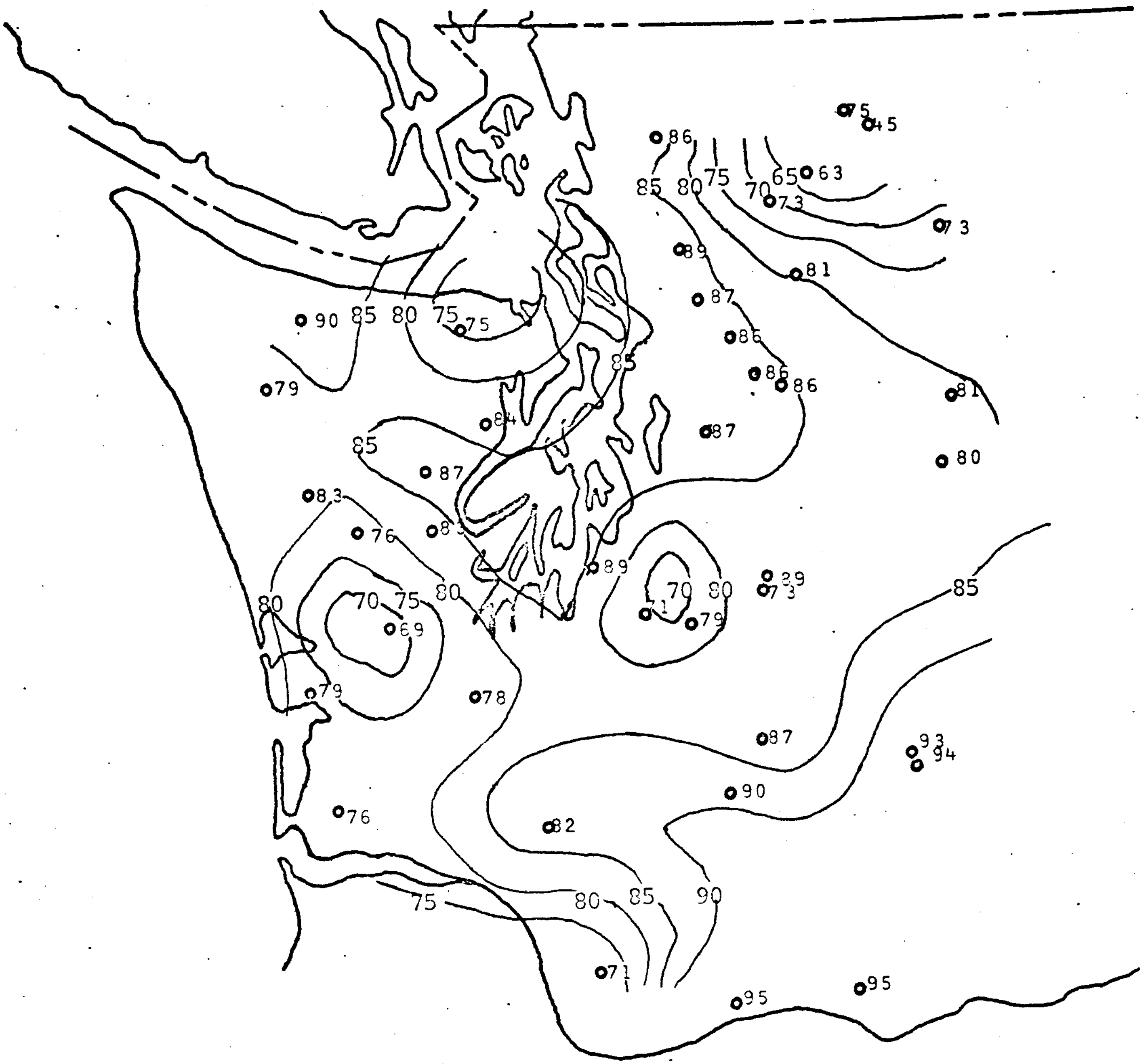
FIGURE 13. CONTOUR OF MAY FLOW SERIAL CORRELATIONS



All values indicated are 100 times actual serial correlations

CONTOUR INTERVAL - 10

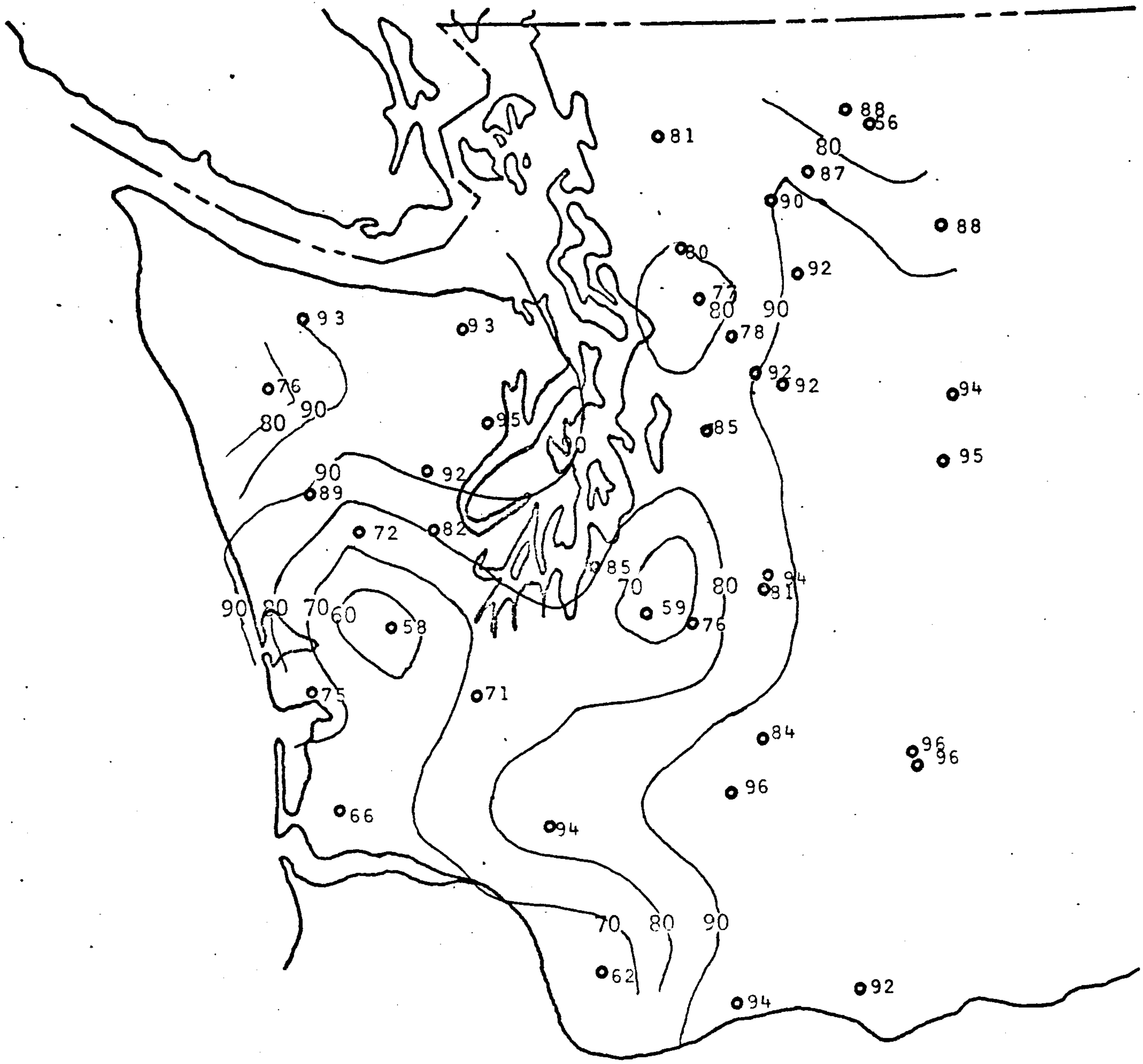
FIGURE 14. CONTOURS OF JUNE FLOW SERIAL CORRELATIONS



All values indicated are 100 times actual serial correlations

CONTOUR INTERVAL - 5

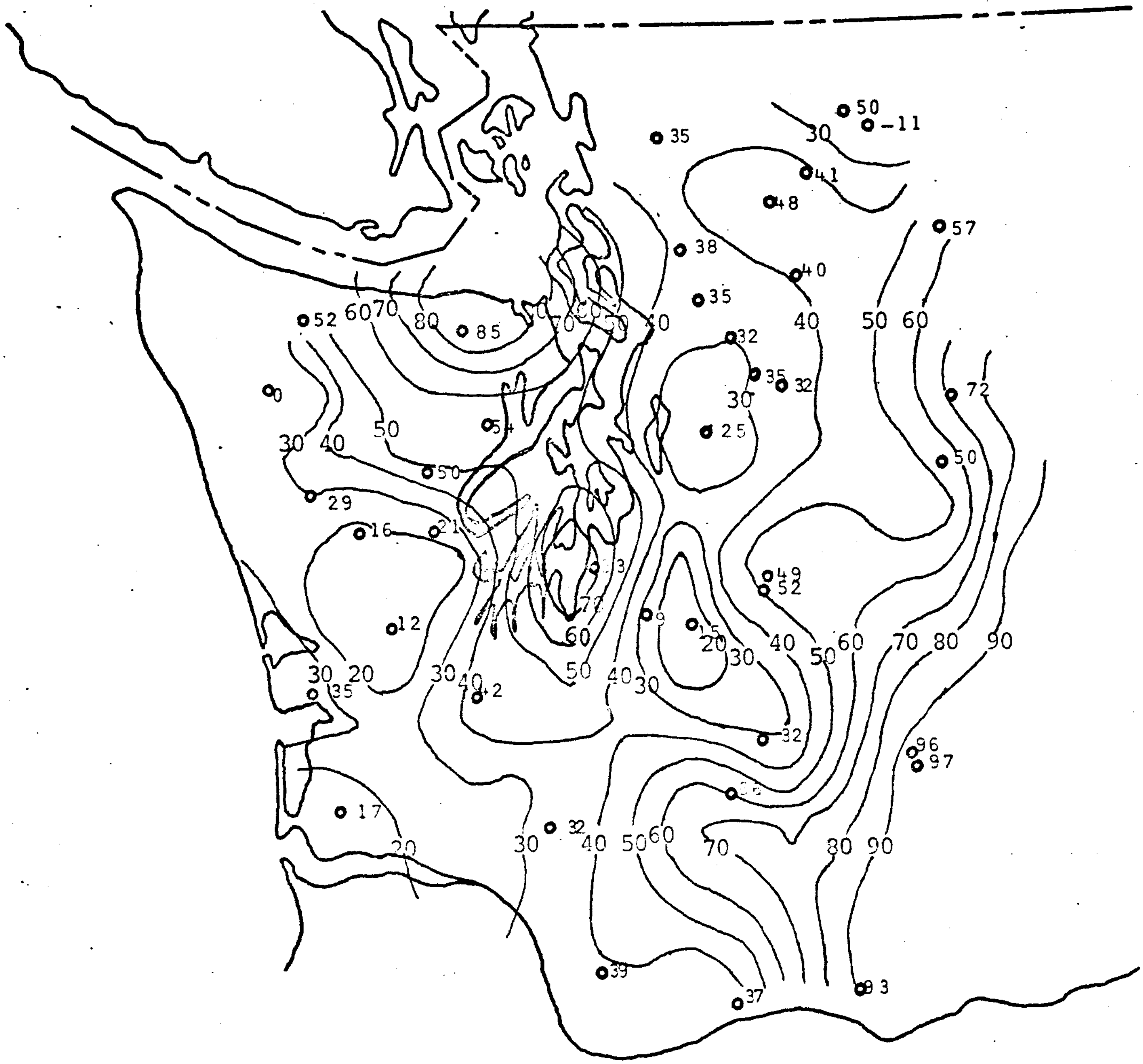
FIGURE 15. CONTOURS OF JULY FLOW SERIAL CORRELATIONS



All values indicated are 100 times actual serial correlations

CONTOUR INTERVAL - 10

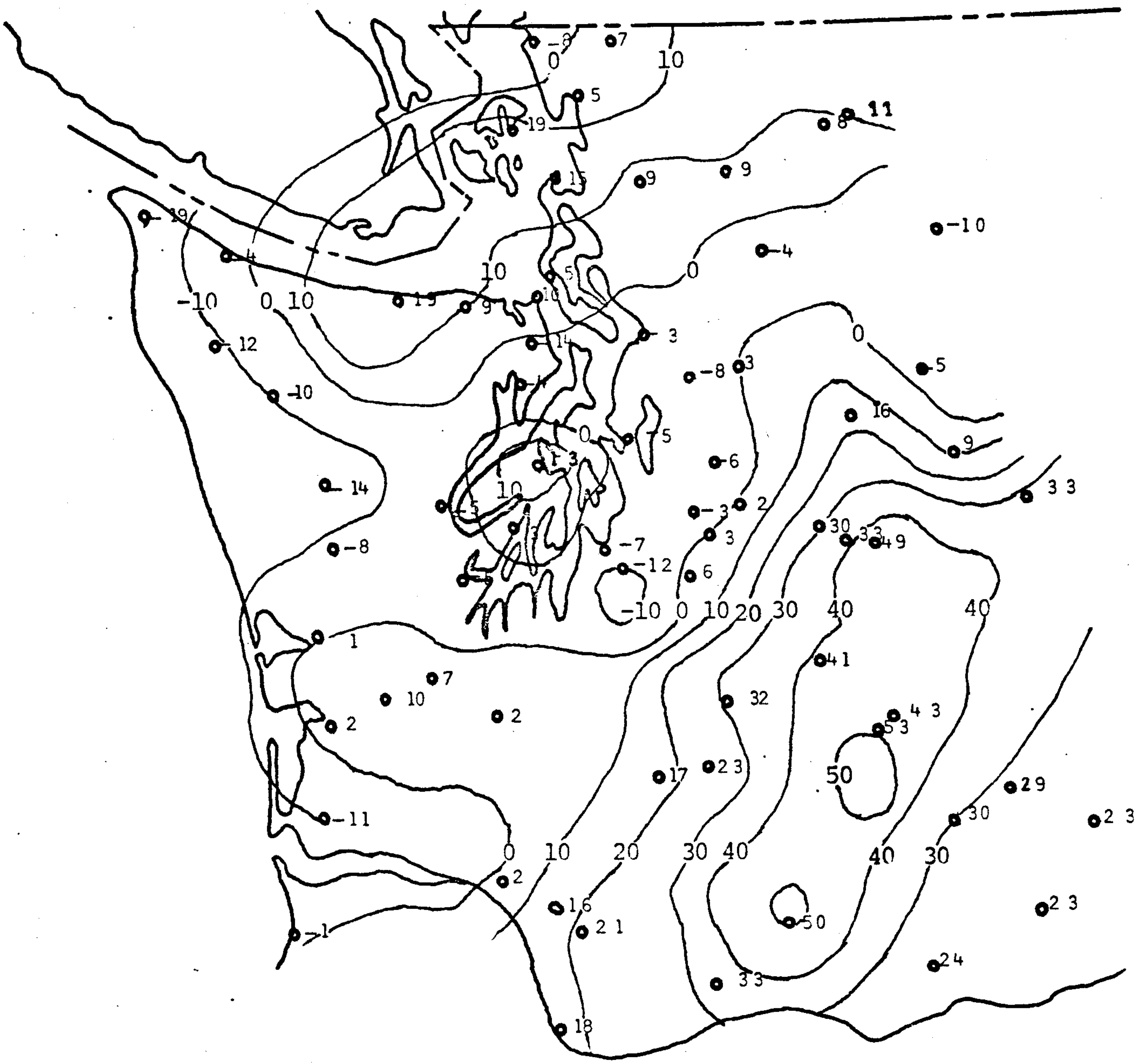
FIGURE 16. CONTOURS OF AUGUST FLOW SERIAL CORRELATIONS



All values indicated are 100 times actual serial correlations

CONTOUR INTERVAL - 10

FIGURE 17. CONTOURS OF SEPTEMBER FLOW SERIAL CORRELATIONS



All values indicated are 100 times actual serial correlations

CONTOUR INTERVAL - 10

FIGURE 18. CONTOURS OF OCTOBER PRECIPITATION SERIAL CORRELATIONS

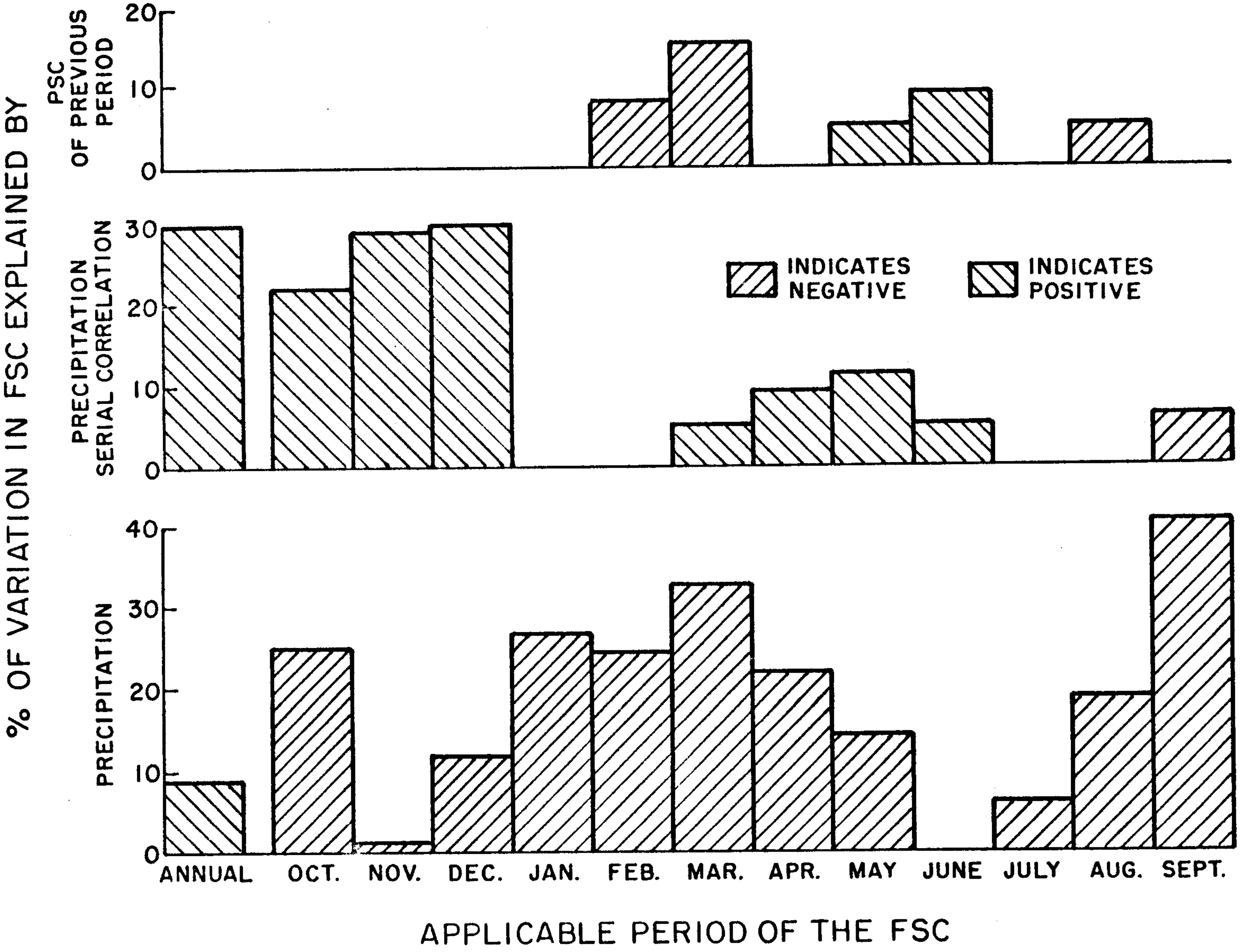


FIGURE 19. ASSOCIATIONS OF THE SPECIFIED INDICES WITH THE ANNUAL AND MONTHLY FSC

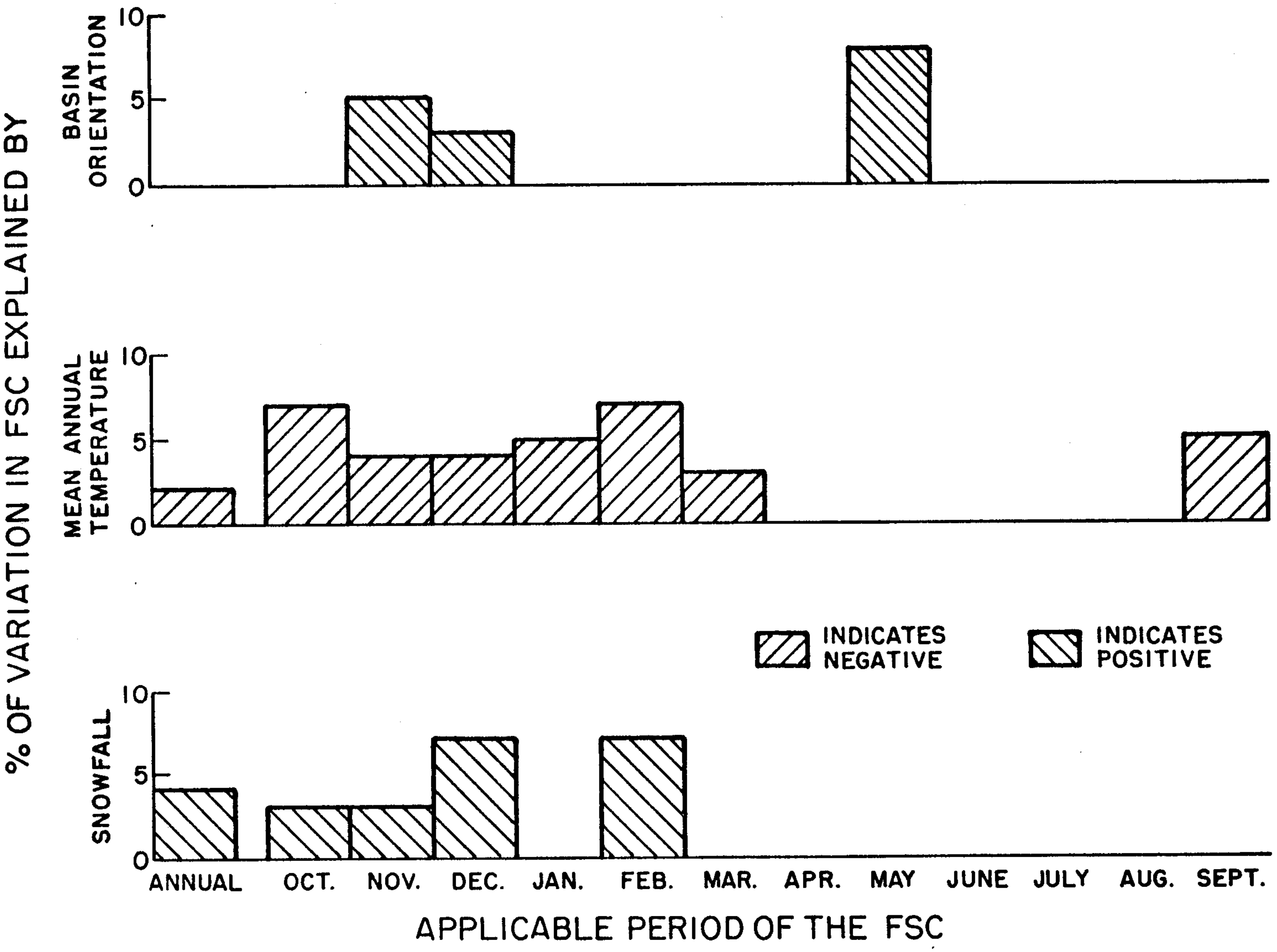


FIGURE 20. ASSOCIATIONS OF THE SPECIFIED INDICES WITH THE ANNUAL AND MONTHLY FSC

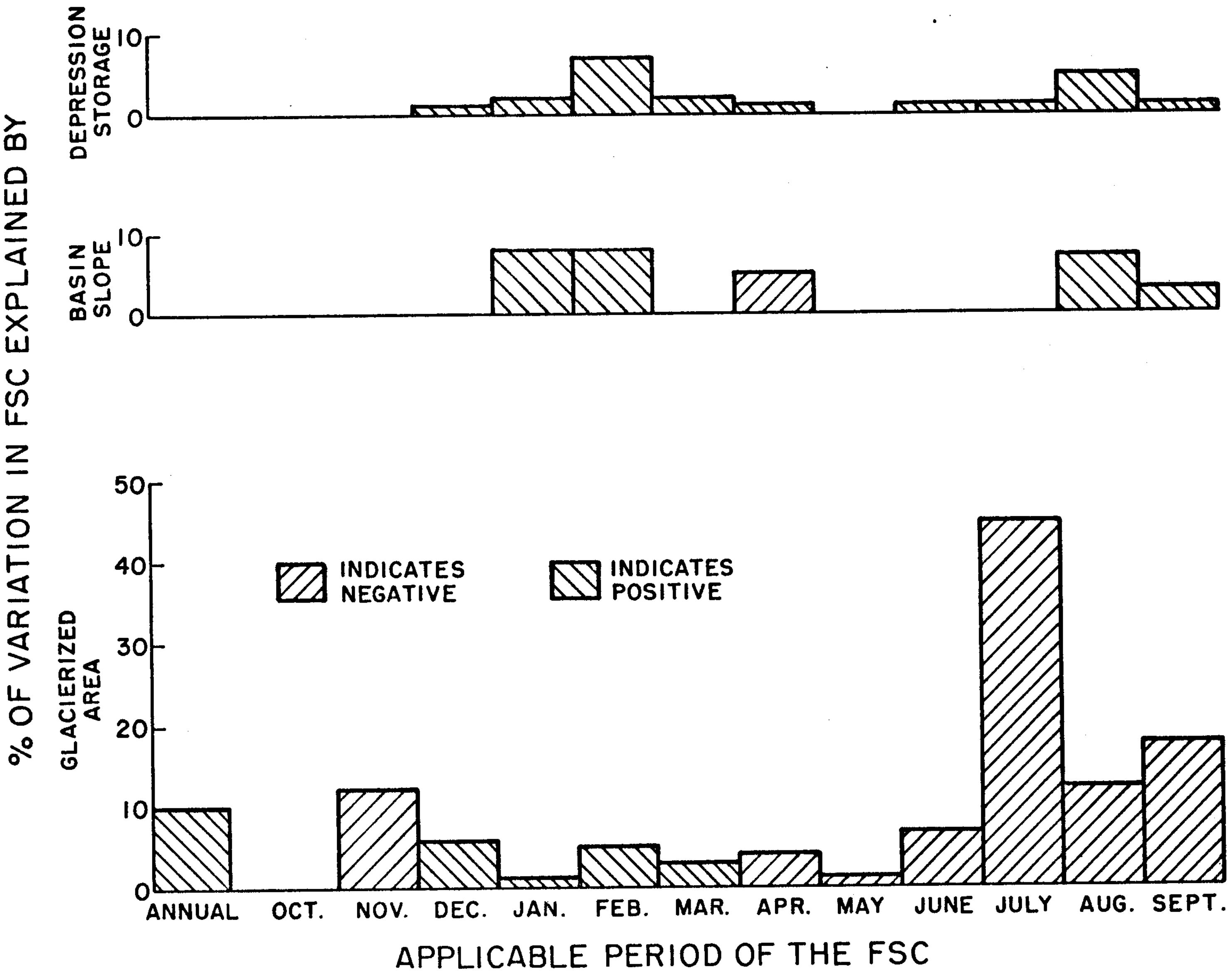


FIGURE 21. ASSOCIATIONS OF THE SPECIFIED INDICES WITH THE ANNUAL AND MONTHLY FSC

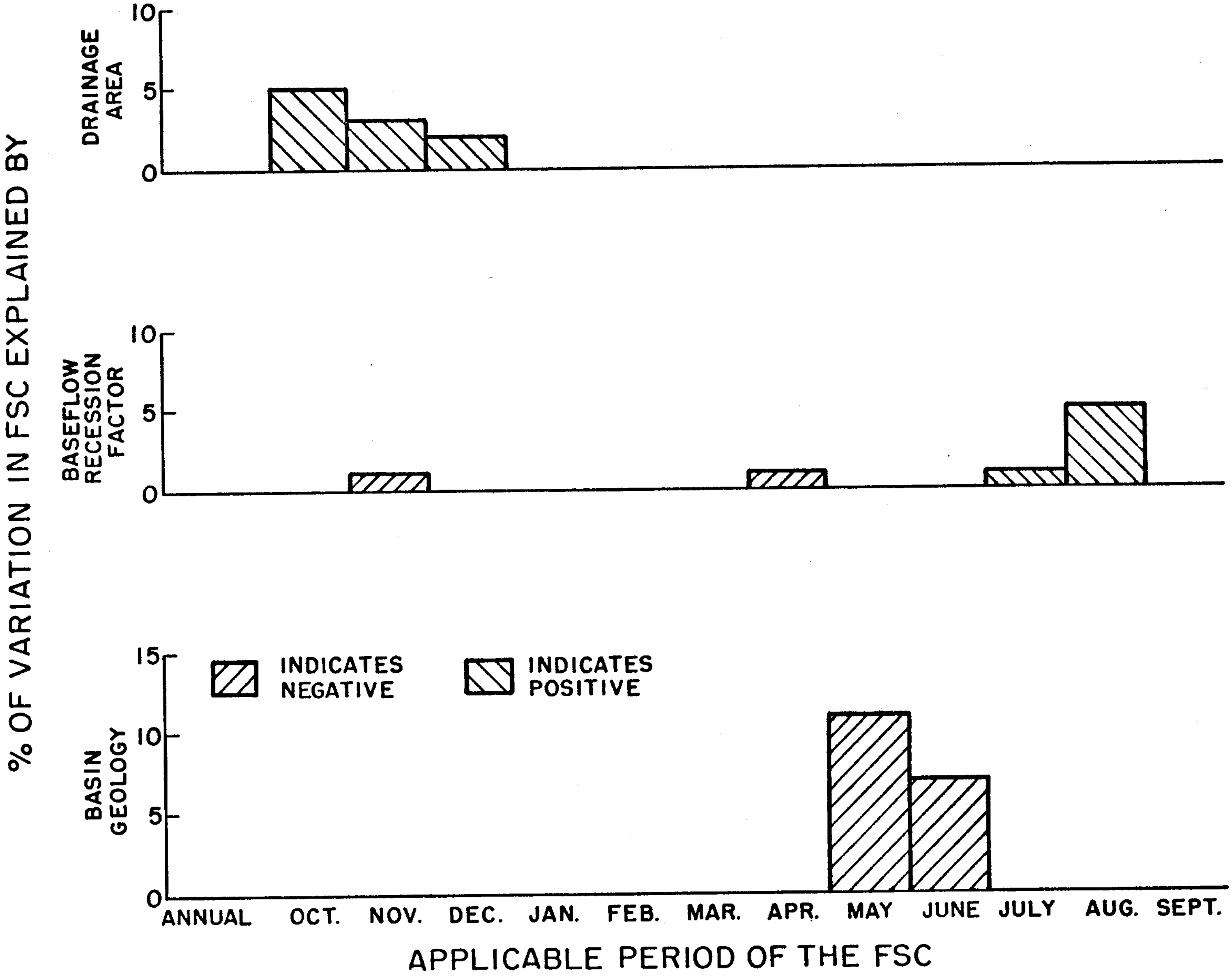


FIGURE 22. ASSOCIATIONS OF THE SPECIFIED INDICES WITH THE ANNUAL AND MONTHLY FSC

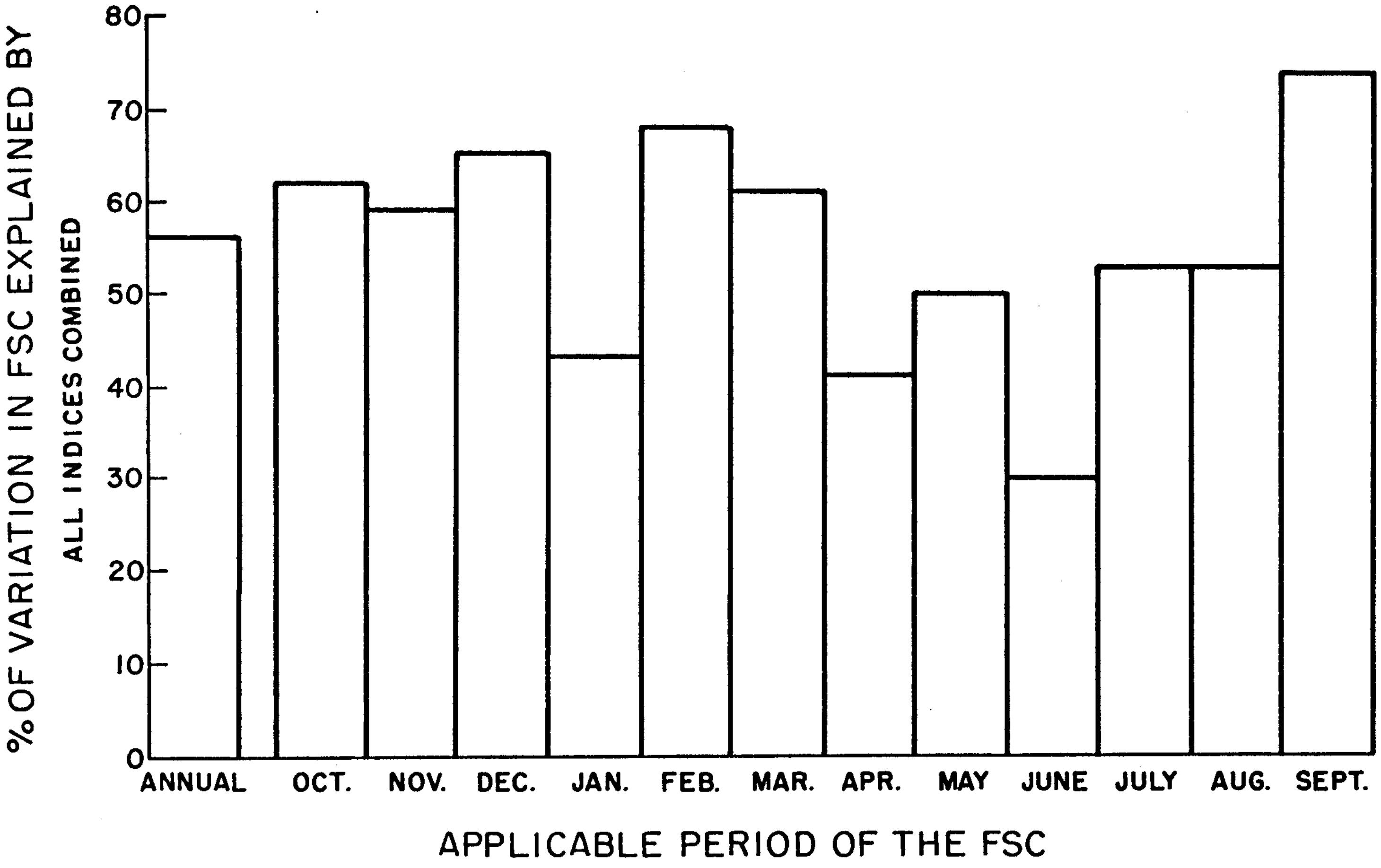


FIGURE 23. ASSOCIATIONS OF THE SPECIFIED INDICES WITH THE ANNUAL AND MONTHLY FSC