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PHYSICAL INFLUENCES ON FLOW SERIAL CORRELATION

William J. Stolte
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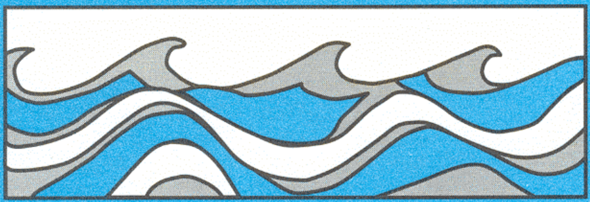

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Technical Report No. 27
June 1969

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LIST OF SYMBOLS

α	the constant in the baseflow recession exponential function
σ_{q_i}	the standard deviation of the flow q_i
σ_{q_{i+1}/q_i}	the standard error of estimate of q_{i+1} given q_i
q_{i+1}	flow for the year i+1
q_i	flow for the year i
ρ	the serial correlation coefficient for the generation model
b	the regression coefficient of the generation equation.

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Due to the critical illness of Professor Campbell, the principal investigator, supervisory functions in the latter phases of the study were undertaken by Professor E. P. Richey also of the Department of Civil Engineering. The valuable aid of Professor D. Wooldridge of the Department of Forest Sciences at the University of Washington and Professor J. S. Gladwell of Washington State University is gratefully acknowledged.

ABSTRACT

The effects of basin geometry and water storage capacity, rainfall, snow accumulation, and snowmelt on the lag-one monthly and annual serial correlation in the streamflow of Western Washington are examined by means of contouring and multivariate analyses. It is found that rainfall, snow accumulation, and snowmelt strongly influence the variation in the monthly flow serial correlation from basin to basin while the corresponding influence of basin geometry and water storage capacity is quite weak. The effect of these factors on the annual flow serial correlation is indirect and difficult to explain.

KEY WORDS: Hydrology, Runoff, Serial Correlation, Streamflow, Synthesis.

CHAPTER 1

INTRODUCTION

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 and unwise actions inevitably give rise to undesirable results. These reactions may be regarded as due to this philosophy of exploitation, and they 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 more and more damaging as the development of flood plains accelerates while the occupants do not give due consideration to the consequences of this action, namely, the possible submersion of municipal and industrial 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 order governing the world. In hydrology an urgent necessity now is that a careful study be made 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 discussion is necessary at this point of how streamflow is put to use and the problems that have occurred from this usage. Some of the major uses of the water are in hydroelectric power, irrigation, flood control and the dissipation of pollutants, both thermal and chemical. The problems that occur are caused by conflicts of interest between competing users and by the variation of the water supply in relation to the users' needs. An example is the use of the multi-purpose 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 pollutant dissipation purposes 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. The problems involved become more acute every year since there is an increasing rate of growth of agricultural, urban and industrial complexes, both on and off the flood plain land, which put higher stress on each of the uses.

Wise development of water resources is inherently a complex problem, and is further complicated by the fact that not enough is known about the behavior of river flow. What the hydrologist needs for a better approach to the problem is to learn more about what influences river-flow behavior, thereby gaining a new stance for attempting to predict this behavior. Obviously, flows of any type are caused by a complex series of circumstances about which little is known; this lack of knowledge prevents the accurate formulation of deterministic relationships. It is difficult to overemphasize the complexity of hydrologic relationships. The long sequence of causes and effects which produces the flow regime is very complex. However, the variation in recorded flows usually follows approximately the Gaussian error curve. Both this consideration and the great difficulty encountered in developing a plausible detailed faithful description of the physical factors at work in the flow regime encourages the use of statistics as a tool of investigation. Regrettably the limitations inherent in the statistical approach are easily forgotten. This leads to a probabilistic description of the universe which ignores the fact that statistics is merely a way of analysing the end results of a series of complex interactions.

The statistics used in hydrology can range from the relatively simple to the very complex. A method often used in describing a series of flows -- whether yearly peak flow, daily flows, monthly average flows, or annual runoff is frequency analysis. This allows the determination of the average frequency of occurrence of a flow of a certain magnitude, but the method has limitations since the occurrence of an extreme flow in a short period of time (usually less than 50 years) often will be ascribed a frequency much greater than its true value. A closer approximation of the true frequency of occurrence would be obtained if the length of record were much longer. This more accurate approximation is necessary if chaotic development of water resources is to be avoided.

Planning would be much enhanced if there were enough data to allow accurate knowledge of the frequency of extreme events. Since the creation of historical data is impossible, many hydrologists are focusing attention on the generation of synthetic data. Since historical records belong to a statistical distribution that can be defined by certain parameters, data having the same statistical qualities as the historical data can be generated and then used to extend our knowledge of the river flow regime. The statistical parameters usually of concern are the mean, the standard deviation, the coefficient of skew, and kurtosis. Furthermore, in recent years the realization has grown that the series of measured flow values form a time series in which there is a relationship between consecutive flows, expressed in the serial correlation coefficient; the residual variation is measured by the standard error of estimate. Given the average flow, the serial correlation coefficient, and the standard deviation of the flow, it is then possible to set up a statistical model describing the historical flow records, 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 a closer determination of the frequency of unusual flow occurrences, is a promising technique in the hydrologist's bag of tricks.

However, the fact that at least thirty observations of a phenomenon have been found necessary before an hydrologic sample is statistically significant and useable for the determination of the necessary statistical parameters limits the usefulness of the technique: thirty years of historical records may not be available for many of the smaller rivers. Such a situation, coupled with the consideration that the statistical parameters are merely a means at getting to the basic knowledge of the hydrologic factors at work in the river basin, leads to the desirability of determining the basic physical factors governing the flow regime. An accurate description of the relationship between these statistics and the physical parameters known to be influential in the flow regime of a river would facilitate the prediction of these parameters for streams with insufficient length of record.

The purpose of the research program under discussion has been to find the physical causes of the serial correlation effects in river flows. The flows studied were the annual and monthly flows defined as the average flow rate passing a certain river station during the applicable time period. Throughout this report, this definition is implied in the use of the terms, monthly and annual flows. Monthly serial correlation coefficients vary from month to month and in turn are different from the annual serial correlation coefficient in that monthly serial correlation coefficients tend to be higher and are subject to greater variation. Since the annual flows are the weighted average of the monthly flows by the above definition, it is likely that the annual serial correlation is a function of the monthly serial correlations. In this case the physical explanation of the variation in the monthly serial correlations on a geographical basis will be more meaningful than the same type of explanation for the annual serial correlation. In anticipation of this circumstance efforts were directed mainly to the explanation on a physical basis of the geographical variation in monthly serial correlations with less emphasis attached to the physical causes of annual serial correlation except as a check on the underlying assumption. What will be required later is an investigation into the mathematical relationship between annual and monthly serial correlations.

CHAPTER II

FACTORS AFFECTING STREAMFLOW

A drainage basin can be conceived of as being a complex system in which the rainfall is the input and the resulting river flow is the output. Both the initial nature of the input and the characteristics of the system which convert it into output, in this case the statistics of the rainfall and the pertinent characteristics of the basin itself, will have an effect on the nature of the output or flow. Of these two factors, the statistics of the rainfall are likely to be the most important and therefore will be discussed first.

A. Rainfall

Significance: The importance of the rainfall factor has long been recognized and is generally illustrated in the article by Howe, Slaymaker and Harding (1966) who analyzed the reasons for the occurrence of more extreme floods in Wales than had occurred in the past. They arrived at the conclusion that although land use practices had changed such that rainfall would run off at a greater rate, this was not the main factor. Most important of all was the fact that the nature of the rainfall had changed in recent times such that higher intensity storms were occurring with greater frequency than was formerly the case. Although floods are not the present topic of concern the underlying principle that changes in rainfall are the primary factors causing changes in runoff and the characteristics of the basin are secondary is probably also valid for annual and monthly flows, and was checked in the research. It is thus necessary that in the study of flows, sufficient data on associated rainfall must be available in order that the processes be understood correctly.

Distribution: Having established the importance of the rainfall factor, it would be beneficial to discuss the nature of rainfall and the physical factors affecting its distribution and variation. Basic to the understanding of the nature of rainfall is a knowledge of its macroscopic distribution. Although this topic lies properly in the field of meteorology it is very closely related to hydrology. Caffey (1965) states that the factors influencing distribution of rainfall are the source of moisture, topographic effects, convergence effects, variations due to frontal activities, convection factors, and the influence of evapotranspiration. His attempts to isolate these influences did not meet with great success, which illustrates that rainfall is caused by very complex forces, and also shows the difficulties inherent in attempting to express rainfall characteristics in terms that will facilitate explanations of flow variations.

The topographic effects important in the spatial distribution of rainfall have been investigated by Schermerhorn (1967) in a study limited to the western part of Oregon and Washington. The three main topographic features which influence precipitation in this area are the shielding effects of barriers in the path of the storm which result in rain shadows, the orographic effects caused by barriers to the lee side of the station, and the latitude of the location. The former two depend very much on and are defined by the usual storm direction which in this case was from the southwest. Therefore barriers southwest of the station would have the effect of decreasing the rainfall at the location while barriers to the northeast of the location would tend to increase the precipitation. The latitude factor causes the rainfall to decrease with higher latitudes.

The author reports that much of the regional variation in the rainfall is explained by these three factors.

Snow: The above discussion has dealt mainly with the flows caused by precipitation in the form of rain, but in much of the continent melting snow will affect the monthly flow distribution in the spring. Quick (1965) reports on the factors affecting snowmelt rates and although his discussion is limited to floods the conclusion can be drawn that temperature and extent of the snowpack are of great importance in annual and monthly flows also. Considering the nature of the drainage basins in the Pacific Northwest, it appears obvious that some monthly flows are affected directly and strongly by snowmelt, and less directly by snow accumulation since snow accumulation consists of storage which will alter the flow pattern during the period it occurs. The amount of snowfall which occurs in the winter will have a strong effect on the serial correlations in flows for both this period and the period when this snow melts. Snowfall is indexed to a certain degree by temperatures. Blodgett (1967) found that the average number of degree days below freezing at a particular locality was associated with the variation in the serial correlation from month to month for that locality. Considering the underlying cause of this relationship it is apparent that this temperature factor does index snow accumulation and snowmelt, but the relationship is not consistent in that low temperatures may be associated with a high pressure system producing little precipitation or else associated with low pressure systems producing great amounts of precipitation. It is possible that the latter case is the most common and overshadows the effects of the former condition.

B. Drainage Basin Factors

Drainage Area: Drainage area is strongly related to flow regime variation from basin to basin. Its importance should be intuitively obvious, since the larger the catchment area the greater amount of rainfall caught and the larger the magnitude of flow. This applies to flows of all durations from daily to annual. In addition to this simple relationship between area and flow, there is another more subtle effect of area on the flow. As discussed by McGuiness, Harrold, and Amerman (1961), McGuiness and Harrold (1962), and Hely (1964) the area of the drainage basin will have a strong additional effect on flows because the stream size, and thus the degree of incision of the stream into the soil, is determined by the area of the basin. The higher the degree of incision the more aquifers the stream taps and the larger the groundwater component of the flow, which is a cause of flow persistence. This factor is recognized by the common terming of streams as perennial or intermittent.

Groundwater Storage: Since depletion of the groundwater storage of the basin, or as it is usually called baseflow recession, can be thought of as being a time series of flows with an exponential relationship between succeeding flows, it seems reasonable that the constant in the relationship should be closely related to the serial correlation of the stream.

It is well known that the baseflow recession curve tends to remain constant with time within a certain drainage basin, and that it varies from basin to basin. This curve is of a logarithmic nature such that it can be expressed as a constant slope on logarithmic paper. The storage remaining in the basin at a certain time is a function of the flow at that time and the slope of the logarithmic curve. The baseflow recession curve has the characteristic that $q_{i+1} = kq_i$ where i+1 is the period (usually 1 day) following the period i, and k is a constant. Since baseflow recession is an exponential decay function, the term "k" can be replaced by $e^{-\alpha}$ where α is a constant with dimensions of time^{-1}. Although the use of the term "k" is more common there is much to be said for the use of the exponential form since it implies that baseflow recession is an exponential decay function while "k" does not. Assume a flow q_0 for day 0. Then the flow q_t t days after day 0 is $e^{-\alpha t}q_0$ or $q_t = e^{-\alpha t}q_0$.

But $\ln(q_t) = -\alpha t + \ln(q_0)$ where $-\alpha$ is the absolute value of the slope of the line derived by plotting ln(q) versus time. The storage remaining in a basin is the integration of all the flows occurring to time infinity.

$$\text{Thus storage} = \int_{t=0}^{\infty} q_t dt = \int_{t=0}^{\infty} e^{-\alpha t} q_0 dt$$

$$= q_0 \int_{t=0}^{\infty} e^{-\alpha t} dt = q_0 \left. \frac{e^{-\alpha t}}{-\alpha} \right|_{t=0}^{\infty}$$

$$\text{STORAGE} = \frac{q_0 (e^{-\alpha})^{\infty}}{-\alpha} - \frac{q_0 (e^{-\alpha})^{0}}{-\alpha} = \frac{q_0}{\alpha} \text{ cfs-days}$$

It is thus apparent that storage remaining in a basin is a direct function of the slope of the baseflow recession curve. From this derivation it is quite obvious that the storage capacity of a basin and thus theoretically the degree of persistence in flows is a function of the value "k".

The cause of this baseflow recession lies in the storage capacity of the basin, either in the underlying rock aquifers or in the soil layer. In the Pacific Northwest it is generally conceded that in the mountainous streams with underlying impervious rocks, the soil horizon provides the major part of the storage capacity of the basin. This consideration leads to the conclusion that the baseflow recession of many of the streams in the Pacific Northwest is a combination of depletion of storage in aquifers and in the soil mantle overlying the bedrock.

An important basin characteristic is the basin infiltration capacity of the basin and the storage capacity of the soil formation. The former will be an influential factor for flows of any time period from daily to annual. Reich (1965), and Reich and Hiemstra (1965) although dealing mainly with flood flows on small drainage basins indicate that the infiltration capacity is a direct function of the soil type and the vegetation cover and show that it can be quantified by classification of the bare soil cover and the condition and type of vegetation cover. The type of data required for this classification is not usually available. Occasionally the infiltration capacity of the basin is taken as a residual to explain the leftover variation in the correlation relationship developed. On the other hand, Blodgett (1967) used a geologic map to classify the soil types of the basins which he investigated and then assigned numerical values with the lowest values signifying the most permeable material to the highest values denoting highly impervious material. Blodgett found that this geological index was significantly related to the monthly variation in the serial correlations of the monthly flows that he investigated.

Geometry: While the infiltration and storage capacity of the basin is a major part of the response of the basin to the incoming rain, the rate of overland or channel runoff will affect the length of time that the rain has to infiltrate and thus the amount of ground water storage. The factors which affect this rate of runoff are discussed in Reich (1965), Reich and Hiemstra (1965), Kinnison and Colby (1945), and Benson (1962b). Rapid runoff is encouraged by an efficient conveyance system which in hydrology is represented in part by a high number of channels both large and small such that the overland flow does not have far to travel before it reaches a channel. The drainage density is a measure of how far overland flow has to go to reach a channel, but is likely too complex a factor to be used extensively. The relationship between velocity of flow and channel slope is too well known to require any discussion. Blodgett (1967) used a channel slope term which was the ratio of the difference in elevation, between the gauging station and the point of intersection of the stream and the mean basin elevation, to the length of the stream between these two points. This term was found to be associated with monthly variation in monthly flow serial correlation. Given the orientation of a basin, the slope will also determine to some degree the amount of sunlight the basin receives depending on the time of the year, which will then affect the rate of runoff, and hence the serial correlation in the flow.

A factor that tends to increase the rate of flow into ground storage is the surface storage measured by the area of the lakes and ponds since it will serve to slow down the rate of runoff. This is affirmed by Kinnison and Colby (1945), and Benson (1962b). Blodgett (1967) found that the storage area provided by the lakes and ponds in a basin is related to monthly serial correlation characteristics. Other factors which affect flows but whose effects are extremely hard to analyse and quantitize are the shape, length, and configuration of the basin and the distance that the water must travel before reaching the outlet. All these factors have some individual effect, but are so highly related to one another that it is difficult to separate them. However, the influence of these factors on monthly and annual flow serial correlation is probably small due to their short term nature.

Related Studies: Numerous investigators, among them Bodhaine and Thomas (1964), Patterson (1964), and Hulsing and Kallio (1964) have analysed the relationship between the nature of drainage basins and the characteristics of flood frequency curves. The basin factors found to be most associated with flood frequency variation were the total area of the basin, its slope, the area of lakes and ponds as a percentage of the total basin area, some measure of the temperature, rainfall intensity over the basin, and some measure of the orographic effects in the basin. This list conforms well to the conclusions drawn in the previous discussion. Not every factor will be influential in every basin and furthermore many of these factors are interrelated. However, the use of these factors would be a good starting point in the analysis of the influence of basin characteristics on the serial correlation characteristics of streams.

Probably the article dealing most specifically with the cause of serial correlation is the one written by Benson and Matalas (1967). In it they determine the relationship between the statistical parameters of annual and monthly flows and drainage basin parameters in the Potoma River basin. Their stated reason for doing so was that these parameters could then be obtained for basins that are ungaged or which have insufficient record to allow the accurate determination of these parameters. The statistical parameters correlated were means, standard deviation, skew coefficients and lag one serial correlation coefficients for annual and all monthly flows. The physical factors which they used were the drainage basin area, the percentage of this area which was forested, the mean annual precipitation, the slope of the main channel, the annual snowfall, and the surface storage of the basin due to lakes and ponds. It is to be noted that it was concluded from previous discussion that although all these factors are required, other factors such as the orientation, elevation, temperature, geology, slope of the base flow recession curve, and mean annual discharge were also required for a complete description of the influences acting upon the flow regime. The authors found that the mean and the standard deviation of monthly and annual flows were significantly related to the factors included in the analysis, but that the serial correlation of the annual flows was so small (average 0.045) that it was not significantly different from zero. In their analysis of the relationship between the monthly serial correlation coéfficients and the basin factors they found that the factors which were associated with the statistical parameters of monthly flows did not vary consistently from month to month and concluded that the relationships developed may be somewhat questionable. However, the authors did not explain what variation in the regression equations would have been considered consistent and did not include the regression equations between the basin factors and the flow statistics. This then prevents the evaluation of the questionableness of the associations between flow statistics and basin characteristics.

The result of the type of study done by these authors is that statistical parameters can be obtained from commonly available data which does not require the availability of long term periods of record. Furthermore, the reliability of the coefficients derived in this manner would be higher than if the coefficients had been derived from even a fairly long record.

Summary: In summary the major factor which influences streamflow is the general nature of the rainfall which in turn is affected by the usual source of the moisture, the general nature of the majority of the storms, the latitude and elevation of the basin, and the orographic effects. Expression of these factors could be included in mean annual precipitation and basin orientation and elevation. In this study latitude was assumed to be insignificant since variation in this parameter throughout the area studied was small. Important parameters not expressly related to rainfall include the drainage area of the basin, percentage of this area occupied by lakes and ponds, baseflow recession characteristics, and the amount and type of vegetation although this factor is very difficult to determine with the limited data available. Of secondary importance is the capacity of the basin to dissipate the runoff resulting from storms, as expressed in terms of the channel and land slope, the stream density, and to a lesser degree, the basin shape. The initial list of factors used in the analysis included mean annual precipitation, basin orientation, elevation, area, percentage of this area occupied by lakes and ponds, baseflow recession slope, channel slope, and geology. This list was expanded as work progressed. The relation of the serial correlation of flows to the preceding parameters were investigated by some of the statistical techniques discussed in the following chapter.

CHAPTER III

STATISTICS OF FLOW ANALYSIS

Sample Size: In a statistical evaluation of data, a most important consideration is the amount of data available. A sample is taken to be representative of the total population of possible values, but if the sample is too small it may not fulfill this function. It is commonly accepted that a minimum of thirty observations of a parameter is necessary before this set of data is statistically significant. An insignificant sample size does not necessarily imply that no information is obtainable from the sample. It only indicates that the information and conclusions drawn from the sample may not be trustworthy. Obviously, the statistical significance of the sample will vary as the number of observations it includes. The main problem of hydrologic investigations of a statistical nature is that there often is insufficient data to allow the derivation of dependable values for statistical parameters.

Statistical Parameters: The means and standard deviations of samples are easy to determine and to work with. They exhibit a fair amount of stability and are quite easy to test by standard techniques. The same cannot be said for the coefficient of skew and even less so for the coefficient of kurtosis. Although Matalas and Benson (1968) derived a test for the significance of the skewness coefficient which depended only on the sample size, Fiering (1967) states that the skew is difficult to handle mathematically and that it is unimportant in some cases. Furthermore, Martig (1968) in his studies of the statistics of mean annual flows on the Columbia River found that the data was significantly skewed, but that the deletion of a small random bit of data caused the values of skew to change very significantly, from which he concluded that tests for skewness of mean annual flow are very unstable and thus do not justify a great amount of attention.

Annual flow records constitute one population of data but this is not the case with monthly flows where each month has a data population distinct from the other eleven. This means that the statistical moments will vary from month to month, a fact verified by Benson and Matalas (1967), and Roesner and Yevdjevich (1966). A significant fact they bring out is that the coefficients of skew all varied significantly from the normal which indicates that if flow is to be synthetically generated, the skew of the population must be considered. Harms and Campbell (1967) suggest that the log transformation be used in the generation of synthetic monthly flows and discuss the transformation in detail concluding from comparisons between generated and actual data that the proposed model is operationally valid. The log generation equation for the lag one model is $\ln(q_{i+1}) = a + b \ln q_i + RS$ where q_{i+1} is the flow for period $i + 1$ and q_i is the flow for the period i, a and b are constants of the equation, R is the random deviate of mean 0 and standare deviational, and S is the standard error of estimate of the equation. The logs of the monthly flow are closer to a normal distribution than the actual flow values since the latter are skewed by the existence of a lower limit to the flow. The log transformation reduces the effect of this lower limit, but does not make physical sense since the equation as transformed back is $q_{i+1} = aq_i^b e^{RS}$. Thus the log model is a purely empirical one.

It is obvious that the log transformation will not serve to transform each month's flow population into a normal distribution because of the varying skew coefficients. What should be done with the remaining lack of normalcy in the transformed data is somewhat unclear. Harms and Campbell did not deal with this problem. Roesner and Yevdjevich (1966) attempted to deal with variation in moments, but did not concern themselves with the skewness. Apparently this subject has not been developed to any great degree.

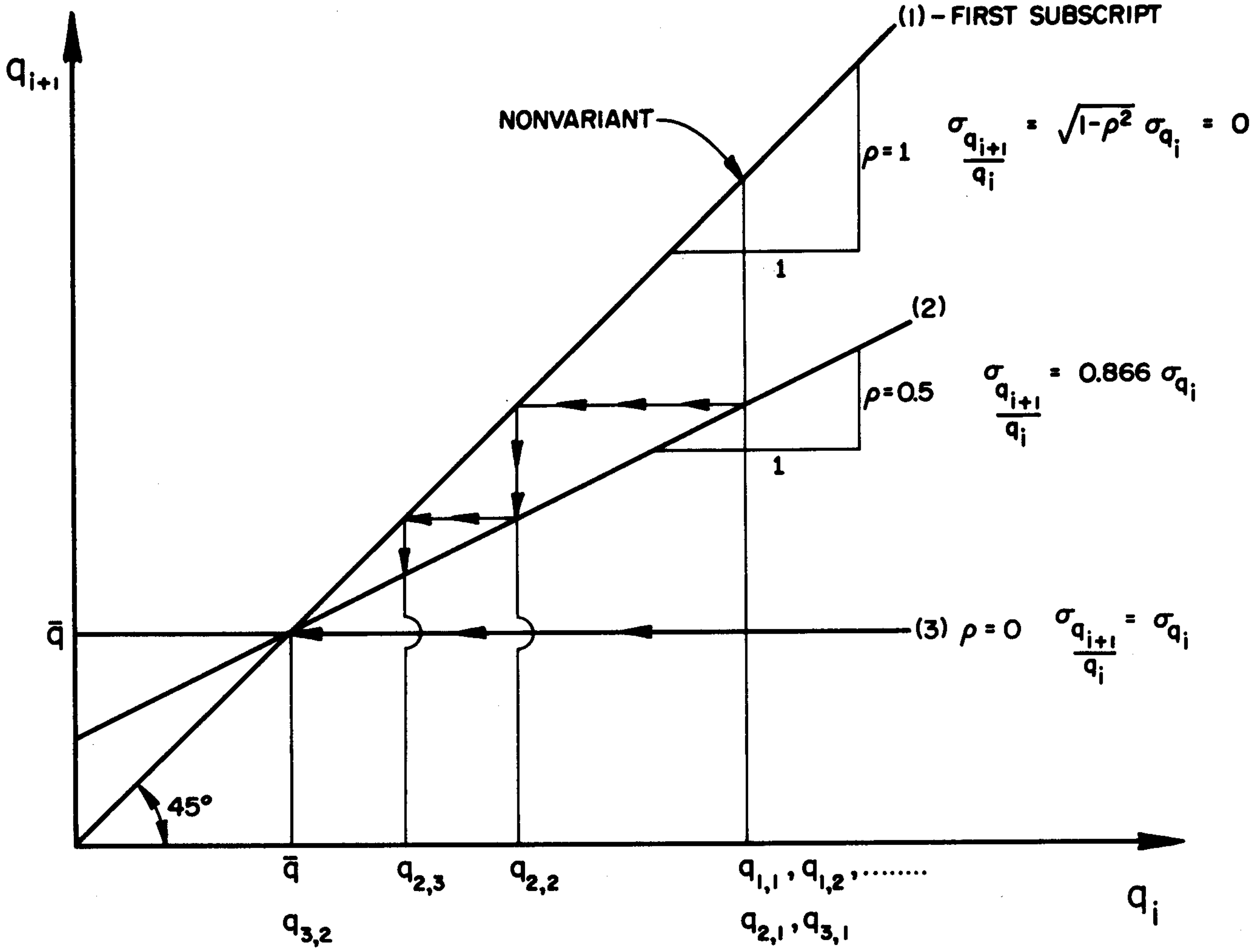
Since the complexity of analysis of statistical moments increases with the order of the moment, the problems encountered in dealing with skewness will be accentuated when kurtosis is being considered.

A. Serial Correlation

Generation Model: Of more importance than the previously discussed statistical moments is the property of the persistence in flows, or serial correlation, which can be defined generally by saying that the flow of previous years will affect to some extent, depending on the various factors, the flow of the following year. The strength of the relationship is measured by the serial correlation coefficient which is derived from linear regression of historic flows against the preceding flows. The scatter about the resulting regression line is measured by the standard error of estimate. Incorporating both the serial correlation and the standard error of estimate into an equation allows the generation of synthetic data which is statistically the same as the original historic data. The standard error of estimate is the square root of the amount of the variance in the original data which is not explained by the serial correlation, or mathematically $\sigma_{q_{i+1}/q_i} = \sqrt{(1-\rho^2)}\ \sigma_{q_i}$ where σ_{q_{i+1}/q_i} is the standard error of estimate, ρ is the serial correlation coefficient and σ_{q_i} is the standard deviation of the lagged data.

In the lag-one model where historic flow depends on the single previous flow only the regression equation representing historic flow is $q_{i+1} = q + b(q_i - q) + t\sigma_{q_{i+1}/q_i}$ where q_{i+1} is the historical flow for the year i+1, q is the average of the lagged flows, q_i is the historical flow for year i, b is the regression coefficient, t is the corresponding random deviate from a population with mean 0 and standard deviation of 1. In the generation process q_i will be the previously generated flow or some assumed beginning value and q_{i+1} is the flow generated by the equation. The equation for the single lag model for annual flow only has several interesting characteristics which will be discussed in relation to the following figure.

The essential features of this regression model are that $b = \rho$ and $\sigma^2_{q_{i+1}} = \sigma^2_{q_i}$ if the amount of data is large enough to damp out the effect of the lag in the data, this condition being assumed in the following discussion. Since the standard error of estimate depends on the serial correlation coefficient, it will become smaller as the slope of the line increases. This indicates that for high values of the correlation coefficient, the persistence effects have less tendency to move the flow value towards the mean than is the case for low values of the persistence properties. However, the fact that the standard error of estimate varies inversely as the serial correlation coefficient means that for low values of the



q_{i+1}
(1) - FIRST SUBSCRIPT
NONVARIANT
$\rho = 1$
$\sigma_{\frac{q_{i+1}}{q_i}} = \sqrt{1-\rho^2}\,\sigma_{q_i} = 0$
1
(2)
$\rho = 0.5$
$\sigma_{\frac{q_{i+1}}{q_i}} = 0.866\,\sigma_{q_i}$
1
$\bar{q}$
(3) $\rho = 0$
$\sigma_{\frac{q_{i+1}}{q_i}} = \sigma_{q_i}$
45°
$\bar{q}$
$q_{3,2}$
$q_{2,3}$
$q_{2,2}$
$q_{1,1}, q_{1,2}, \ldots\ldots$
$q_{2,1}, q_{3,1}$
q_i

serial correlation coefficient the random effect is large and offsets the tendency for the persistence effects to bring the flow value back to the mean. What this would seem to indicate is that the flow of a river is quite stable about the mean for any value of the serial correlation coefficient since the random element offsets the persistence effects in the flow. The lag one annual flow model was chosen to demonstrate this condition because of its simplicity but similar effects would occur for the monthly model and multidimensional models.

Uses of Generated Data: The applications, both potential and actual, of serial correlation statistics have a wide scope. An important application of this method already in practice is in the prediction of the storage needed behind a dam for a given withdrawal schedule, thus facilitating the best planning and use of a reservoir such that adverse effects resulting from extreme flow conditions could be minimized. This topic is discussed by Yevdjevich (1967) and Fiering (1967) who find that the generating method gives realistic data and valuable results. In addition to their two applications Chow and Ramaseshan (1965) used the technique in a different manner in that the serial correlation was not done on the flows but on the causative rainfall. The rainfall was generated and then routed through the drainage basin with accompanying extractions and additions to account for the losses to groundwater, evapotranspiration and other sinks, and contributions from groundwater to the flow. The authors stated that reasonable results were achieved. It is evident that this generation technique will be a valuable addition to the techniques available to hydrologists in their planning for wise use of the water resources of the country.

Model Limitations: The mathematics dealing with the model can become very complex, especially in regard to ensuring that the statistics of the generated data are the same as the statistics of the original data. Fiering (1967) gives an excellent discussion of the subject with his main concern being the derivation of the statistics of the flow given the statistics of the rainfall, the rainfall-runoff relationship, and the carryover characteristics of the aquifer; however, his mathematical development was stopped at the second moment, since higher moments require information not available at present. He does develop the serial correlation coefficient of the flow for situations wherein both the holdover effect of the groundwater storage and the persistence effects in the rainfall contribute to the serial correlation in the flows. The mathematical derivations are general but the information needed to use them are usually unavailable. This severely limits the possible applications of his work.

Of possible importance is the consideration that the serial correlation characteristics of the flow actually reduce the amount of information in the sample about its moments. Matalas (1963a) discusses the matter and gives expressions for the statistical methods which take this phenomenon into account and later (1967b) goes into the problem in more detail; however, this seems to be a new development since not much attention has been paid to it in the literature.

A significant comment made by Matalas (1967b) is that the generality and representativeness of the generated data is limited because the generation equation is frequently based on a small sample. There are two considerations involved here: (1) statistically speaking the magnitude of the deviation of the small sample from the large population of historic flows from which it is drawn cannot be determined. This places one limitation on the representativeness of the generated data since its moments will vary about the moments of the historic data, and not necessarily about the true moments of the total population, and (2) apart from this statistical consideration, a greater limitation is the nonstationarity of a flow regime or in other words the time variance of the moments of the flow. The factors influencing the flow regime may change, thus causing all the statistical moments of the flow to vary which leads to invalidation of the generated values.

Variations in the flow regime could be produced by either the activities of man as in logging operations, clearing of land, soil conservation; or else by unpredictable changes in rainfall patterns. As discussed previously in a different context the latter case is illustrated by Howe, Slaymaker and Harding (1966) who investigate a case of nonstationarity of flow in Wales where floods were becoming increasingly more severe and frequent. This was commonly attributed to manmade changes in the basins which as the authors state was partially true, but of a very secondary nature, because most importantly the rainfall regime of the area had been changing such that storms were more frequent and severe thus producing the undesirable changes in flow. The main point in this discussion of small sample nonrepresentativeness and nonstationarity of flow regime is that the results of the serial correlation generating methods cannot be trusted implicitly and must be handled with proper circumspection at the same time that they would be of great help in water resources development. Little can be done about either problem.

Multi-lag Considerations: Different from, but closely related to, the serial correlation generation model is the method discussed by Matalas (1963b) where he suggests that the annual runoff can be expressed as a function of the rainfall of preceding years and sets up a regression equation that expresses the flow as a linear function of the rainfall of the previous m years, where m is the carryover period. The main purpose of his research was to investigate the statistics of the distribution of the flow relative to the distribution of the causative rainfall. The mathematical derivations indicated that the water retardation properties of the basin act as stabilizing influence in that they cause the flow to have a smaller standard deviation and skewness than the original rainfall. This confirms the conclusion reached previously that rainfall statistics will influence to some extent the statistics of runoff.

Though we have been discussing simple serial correlation, this is a limited case and may not reflect completely the actual occurrences in flow. In this light an interesting aspect of the previously mentioned article is that the use of m year carryover model carries in it the implicit assumption that the single lag Markov model may not be representative of the true serial correlation of the stream. Furthermore, since the flow is highly related to preceding rainfall, flow instead of rainfall could be used in a multi-lag model. Surprisingly enough, this idea has not had much airing in the literature surveyed. A possible reason for this is given by Matalas (1967a) who states that there is usually not enough data to warrant a higher order chain and that the mathematics of the relationship becomes too complicated to justify. What is commonly done in the literature is the calculation of the simple correlation coefficient between flows of lag n years apart for different values of n, but this approach does not give any information on the multiple serial correlation coefficient of the multi-lag model.

Although no thorough analysis of the multi-lag Markov chain is evident in the literature, some attention has been given to the problem. Yevdjevich (1967) in a study of the mean range of linearly dependent normal variables, recognizes the value of the two degree Markov chain in hydrologic problems and uses it to determine the statistics of the mean range of flow. Chow and Ramaseshan (1965) used a multi-lag model in their prediction of flow from serially correlated rainfall, and Fiering (1967) in his study of the ranges of generated values of variables, also mentions this technique of the higher order chains as possibly being a viable method.

The multi-lag model for annual flows has been investigated by Martig (1968) who studied the multiple regression model which assumed that q_i is a linear function of q_{i-1}, q_{i-2}, . . . and q_{i-n}. He studied the validity of the higher order model for twenty-five streams for lags up to $n = 12$, and found that the model of about the sixth order ($n = 5$, 6, or 7) tended to give the best results. He found twelve streams in which the standard error of estimate decreased with increasing lag down to a minimum at either the 5, 6, or 7 lag model. Furthermore for the thirteen streams where the lag 1 model was the best, the tendency for increase in standard error of estimate with increasing lag usually was broken at the same point (lag 5, 6, or 7). It is apparent that in some instances the lag one model may not be completely representative of real occurrences and so this limitation must be kept in mind. However, the research completed was limited in scope to a study of lag-one serial correlation.

B. Multiple Correlation Techniques.

Multiple Regression: In order to derive the serial correlation coefficients, the flow data must be subjected to multiple regression analysis. Furthermore, if these serial correlation coefficients are to be explained in terms of the physical characteristics of the drainage basin, the same type of analysis must be done on the derived drainage basin data and the coefficients themselves. Basically most statistical techniques depend to a certain extent on the multiple regression model which is based on the least squares criterion. For a full discussion of the mathematics involved see Ford (1953) or any standard statistics text.

Limitations of Multiple Regression: However, the basic multiple regression technique has many inherent disadvantages, the greatest one being that interdependence of the predictor variables makes interpretation of results difficult. Many of the physical factors influencing serial correlation discussed previously are subject to this condition and yet each can add additional information to the prediction that the other factors cannot. As demonstrated by Wallis (1965) this interdependence of the predictor variables leads to considerable instability in the derived regression equation thus jeopardizing the validity and the significance of the regression coefficients of the various predictor variables.

The difficulties involved with the problem of the instability of the regression model resulting from the inter-dependence of the predictor variables, can be circumvented by the use of other techniques of multiple regression. Some of these techniques were tested by Wallis (1965), who took a known mathematical relationship and used as parameters in the relationship, predictor variables which are quite intercorrelated, and then developed regression equations with these variables by utilizing the ordinary multiple regression model, principal component analysis, varimax rotation, and other techniques. The results of these methods are then analyzed as to their usefulness and applications, and it was found that the principal components analysis is quite useful and reduces the disadvantages inherent in the multiple regression model.

Examples of the use of the statistical techniques mentioned are quite common in the literature. For instance, the simple multiple correlation model has long been used in the extension of the data of a particular stream by correlating it to the data of a nearby stream. In most cases, the simple multiple regression model is used without adding a random element to the regressed value to account for the variance that is not common to both streams. According to Matalas and Jacobs (1964) if this random element is not included a correlation coefficient of 0.8 or more is necessary before the regressed data is as statistically informative as when the random element is included in an equation for which the correlation coefficient is 0.5. This indicates that the random element should be included in prediction by multiple regression. A problem with these prediction techniques is that the statistical parameters of the predictor variables will be included in the generated data. Although techniques to eliminate this deficiency discussed by Fiering (1964) and Matalas (1967b) are too complex to utilize, it is necessary to keep these limitations in mind in any work in this area.

Another illustration from the literature of the use of some of the more complex methods in hydrology is given by Gladwell and Hastay (1967) in their study of a cloud-seeding program on the Skagit River. The difference between the actual runoff and that predicted by the control variables was tested as to its significance. The control variables were chosen to minimize the risk of transposing undesirable statistical characteristics into the predicted data. These control variables were interrelated, the effect of which was reduced by the use of principal components analysis.

The main topic of discussion is the influences of drainage basin and rainfall characteristics on serial correlation. A considerable amount of work using a different approach has already been done on drainage basin influences on river flows by the U.S. Geological Survey in their efforts to relate the characteristics of the flood frequency curves to the physical aspects of the basin. An excellent discussion of the approach used by this organization is given by Benson (1962a) who describes how the method, termed the flood index method, evolved. The assumption underlying the procedure is that the characteristics of the flow of each stream are part of a statistical sample and that the process of regionalization will cause the statistical variations to average out, thus giving a better indication of the true statistics of the floods. The author also states that in some cases the results of the regionalization process may be more dependable than the information garnered from individual streamflow records. There is an inherent limitation in their work in that it is slanted towards practical use rather than to describe the actual physical processes of the drainage system. However, the concept that measured statistical parameters may actually be bits of data from another statistical population may be very pertinent in a study of what influences flow serial correlation.

CHAPTER IV

PROCEDURE

As previously stated the prime purpose of the research was to discover the physical influences acting on serial correlation of both annual and monthly flows. This required the derivation of numerical indices of the basin factors previously concluded to be important. This section of the report deals with this activity. Some preliminary comments will be made on the significance of some of these indices and the specific reasons why the form of some of these indices had to be changed, generally because of index inconsistency, unrepresentativeness, or insensitivity to the related phenomenon. Also some of the data was changed in form because of considerations of availability of the raw data and degree of reproducibility and standardization of the index of that data.

Area Studied: The area studied was that in Washington bounded on the west by the Pacific and on the east by the Columbia River. Precipitation conditions vary from the predominantly rainfall regime of the coastal areas to the strong snow influences in the higher mountainous regions. Rainfall patterns throughout the region are strongly affected by the mountains with which this region abounds. Similar rainshadow effects occur in the lee of both the Olympic and the Cascade mountain ranges while orographic conditions exist on the western slopes of both mountain ranges. The Puget Sound lowlands have a more subdued precipitation regime than the mountain slopes. Soil conditions vary from the exposed bedrock of the upper mountain regions to the deep glacial deposits which occur sporadically throughout the Puget Sound lowlands.

It was thought at the beginning of the research program that several streams of Eastern Washington should be included in the analysis, but further study indicated that the conditions in this region were so divergent from those existing in Western Washington that the inclusion of these extreme conditions might bias the study. Furthermore precipitation data was not as readily available, and the density of streamflow record was not as high in the eastern as in the western part of the state. Therefore, streams in non-mountainous areas of Eastern Washington were not included in the analysis. Extending the study beyond the bounds of Washington State was not feasible because of the added problems of data collection and the probability of regime differences.

Flow Records: The streamflow record used in the study was subject to the following criteria: (1) The record must be continuous for at least 30 years, (2) the record must be unaffected by diversion or regulation, (3) the streams chosen must give adequate geographical coverage, and (4) the records must be of good quality. Most of the 40 streams chosen, listed in Table I with their period of available record, conformed to these criteria. However, it is apparent from the Table that several streams do not have 30 years of record. These were included so that geographical coverage, as shown in Figure 26, would be more complete, in which case one criterion overruled another.

It is to be noted that the Hoh river is shown to have a continuous record from 1931 to 1967. Data for the last four years are not actually recorded data, but were statistically generated for the following reasons. The original site of the gauging station was discontinued in September 1964, but for three years prior to that time another gauging station had been in operation at another station on the river which then constituted the new site for the river after the old one had been discontinued. This provided for three years of overlapping records between the two stations which was then used to establish the regression relationship between the flows at the two sites. This relationship was utilized to generate the flows which would have occurred at the old site from 1963 to 1967 if the old station had still existed. Although the relationship was not perfect in that there was some variation in the flows at the old site not explained by the flows at the new site, the relationship was close enough (the correlation coefficient equalled .99) to allow the identification of the generated flow with the actual flow in the river at that station. Even though the relationship was so close, a random element was still included in the generated flows to account for the variation in the flows at the old site not occurring in the flows at the new station.

Initially all available stream flow records were used in the study which led to the use of varying length of record from stream to stream. Comparison of the annual serial correlation coefficients derived from these records, and those found by Gladwell (1969) from records of the 1934 to 1966 period, indicated several major discrepancies which must be attributed to nonstationarity in the flow records, or else to statistical variation resulting from the different time periods used. Existence of these variations in the data quite possibly could bias the results of the analysis. Therefore, only the data from 1934 to 1966 was used so that the length and period of record were the same for all streams in the study.

Model Transformations: As previously discussed, annual flows are almost normally distributed so that generation using normally distributed random numbers is proper. However, the monthly flows are distributed with large skewness which precludes generation using normally distributed random numbers without some modifications to the model. The logs of the monthly flows are closer to a normal distribution than the flows themselves. Therefore the serial correlations of the logs of the flows, not the flows themselves, have been regressed against basin characteristics. It is to be noted that the research was limited to a study of serial correlation in flows, whereas more information is required for the development of a generation model.

Precipitation Indices: Since precipitation has the strongest influence on the variation of flow serial correlation it was necessary that some index of it be included as a predictor variable. Mean annual precipitation was originally used since Blodgett (1967) found that mean annual precipitation derived from point values of precipitation measured at gages in or near the basins, was closely related to flow serial correlation. However, these values of precipitation are of poor quality since they may be based on varying periods of record which do not accurately represent the precipitation that occurs over a large area. For these reasons mean annual precipitations were obtained from Gladwell and Mueller (1967), a contour map of mean annual precipitation for the State of Washington. The contour values were drawn from data which had been corrected for elevational influences on precipitation, necessary since most of the precipitation gages are at the lower elevations and fail to measure the higher precipitations at the higher elevations. Lack of a correction for elevation may lead to an indicated value of mean annual precipitation occurring in a basin which is less than the equivalent depth of runoff. It is recognized that measured point precipitation values are only indices of the actual precipitation falling on a given area.

Later it was decided that mean annual precipitation could not index monthly effects with enough sensitivity and that mean monthly precipitation was required. These were obtained from carded data received from Gladwell (1969) which included measured values from a constant period of record for all gages, (see Figure 27) thus introducing some homogeneity into this precipitation index. However, this was point data and as such had no more than an indexing quality. Furthermore this technique of indexing precipitation is regrettably influenced by the arbitrary choice of representative gages.

As the direction of the research developed it became obvious that precipitation serial correlations affect flow serial correlations. To derive the former statistics the monthly precipitation data mentioned previously was statistically analysed and the lag one serial correlation coefficient for the annual and monthly precipitations obtained. Representative values of these coefficients were obtained for each basin by averaging the serial correlation for point stations. The precipitations were not subjected to the log transformation applied to the flow records prior to the analysis because the statistics of precipitation are unknown and any analysis in this direction was beyond the scope of the research and not because the precipitations are necessarily normally distributed. This situation dictates that the simplest alternative be used which in our case was a statistical analysis which paid no heed to the higher moments of the precipitation statistical distribution.

<u>Snow Index</u>: A large part of the region under study is subject to snow

accumulation while glaciers occupy the upper areas of several basins. Since flows are strongly affected by snow accumulation and snowmelt, some index of this phenomenon must be included as a predictor variable if the variation in serial correlation is to be adequately understood. In this study the average amount of snowfall occurring within a basin for the months of October, December, and February were used. Snowfall for other periods showed no association with flow serial correlation. These snow factors, the average of measured point snowfalls, are a very crude index of a phenomenon as complex as snow storage and snowmelt, but was the best that could be done under the circumstances. Some related indices were the mean annual temperature, basin orientation, and basin slope.

It should be remembered that many of the variables to be discussed are interrelated to a high degree. An example of this is the situation just previously mentioned, namely the relatedness of snowfall to mean annual temperature, basin orientation and basin slope. This same condition of interdependence holds true for all the indices used as predictor variables. This is understandable in light of the fact that there are only a few basic phenomena at work in a basin and that it is the many facets of these phenomena that are being indexed. It is thus to be expected that the predictor variables will overlap to some degree.

Mean annual temperature is but a crude index of a strong influence. In place of this index, Blodgett (1967) used the average annual number of degree days below freezing and found that it had strong associations with flow serial correlation. However, the derivation of this index would have entailed an excessive amount of time. Although its inclusion may have been desirable, only the easily obtainable mean annual temperature was included as a predictor variable.

Basin orientation relative to true north indexes the relative amount of sunlight the basin receives and will affect the rate of snowmelt or accumulation. This factor was indexed by Blodgett (1967) by the azimuth in radians of the orientation vector relative to true north. Inherent in this form is a discontinuity at true north where the orientation changes abruptly from 6.28 to 0. This weakness ruins any attempt to find the real relationship between orientation and flow serial correlation. To cure this weakness, the cosine of the angle positioning the orientation vector with respect to true north was used as the orientation index. Since the cosine is a continuous function all discontinuities were eliminated and the differing effects occurring in north (+) and south (-) were indexed. However, this orientation of the cosine also assigns the same conditions to due east and due west facing basins. In view of the effect of the mountains on the precipitation patterns of east and west facing basins, another orientation index, incorporating the cosine of the angle between the orientation vector and a vector pointing southwest, the predominant storm direction in Washington, was included as a predictor variable. Preliminary analysis showed that this orientation of the basin relative to the predominant storm direction was not associated with flow serial correlation to any significant degree. Therefore only the orientation of the basin relative to true north was used as a predictor variable in the final analysis.

Basin slope was calculated as the difference in elevation between the gauging station and the intersection of the mean basin elevation contour and the stream. All values for this factor were obtained from Bodhaine and Thomas (1964) and Hulsing and Kallio (1964).

Values for mean basin elevation and mean annual discharge were also contained in these two works. Although Blodgett (1967) found mean basin elevation to be closely related to flow serial correlation this factor was also related to many other indices and much difficulty was experienced in sorting out its influence. In the final analysis it was decided that this factor was not amenable to physical interpretation and therefore deleted from the array of predictor variables. A similar problem was encountered in the interpretation of the effect of mean annual discharge so it too was deleted from the array.

According to previous discussion the rate of storage depletion of a basin is indexed by the slope of the baseflow recession curve. Instead of using this slope which showed no association with flow serial correlation, as an index the inverse of the log of this slope was used. The inverse of the log of the slope is also the constant in the exponential decay function presented earlier in the report. This constant was found to be associated with flow serial correlation. Changing the form of a variable by some mathematical transformation usually adds complexity to its interpretation, but in this case the greater logic in the more complex form justified its use.

Blodgett (1967) developed a factor indexing the geologic condition of a basin which was found to be related to flow serial correlation. The inclusion of this index as a predictor variable in this study was a logical step considering that the geologic structure of a basin largely determines the available groundwater storage which in turn affects the carryover in flow. This geologic index was derived from the State Department of Conservation geologic map of the State of Washington published in 1961. The carryover of flow from one year to the next as measured by the annual serial correlation coefficient may be in part a function of the groundwater storage remaining at the end of the water year, relative to direct runoff. The relative magnitude of the groundwater component of the flow can be indexed by the average ratio of the maximum to the minimum flow within the water year. The expected relationship of this variable to annual flow serial correlation was not apparent, but a relationship did exist between this ratio and some of the monthly serial correlations which led us to retain this predictor variable.

Perhaps the ratio of the total annual discharge to available storage capacity calculated using the slope of the baseflow recession curve and a representative initial flow, would have been a better index of the effect of the available groundwater storage on the flow carryover effects of the basin. This is a logical deduction from the relationship between the slope of the baseflow recession curve and the storage in the aquifer. According to that derivation, the storage in the aquifer is a function of the flow at the time and the baseflow recession slope. The ratio of the storage available to the total annual flow is a function then of the slope of the curve, some representative flow at any one time and the total flow within the year. However, time did not allow the use of an index incorporation both the ratio variable and the recession constant variable.

It is commonly assumed that the area of a drainage basin occupied by lakes and ponds will influence the streamflow characteristics of that basin since the presence of lakes and ponds will serve to decrease the rate of runoff and increase the amount of infiltration into underlying groundwater storage. An index of this effect is the percentage of the surface area occupied by lakes and ponds which was included in the research as a predictor variable. The source of this information was Bodhaine and Thomas (1964) and Hulsing and Kallio (1964).

The size of the drainage basin has an effect on the serial correlation in flow since the larger the basin the longer it takes for phenomena occurring in the upper reaches of the basin to appear at the gauging station, thus possibly influencing carryover effects in monthly flows. Probably a more significant aspect of the influence of basin size is its relationship to the degree of incision of the river into underlying storage aquifers. Greater basin area is associated with greater river incision and larger groundwater additions to flow, leading to greater carryover in flow. Basin area in square miles was included as a predictor variable.

The final array of the predictor variables used and their values are included in Table II and III.

Serial Correlation Contours: Although techniques of statistical analysis are indispensable in a study of relationships between various phenomena, an inherent disadvantage of this approach is that the mathematical results are difficult to visualize. It is also to be noted that many of the flow serial correlation coefficients listed in Table IV are quite small, and if taken separately, can be considered insignificant. However, it is obvious that each basin is not complete in itself, but will be subject to a part of the geographical variation over the whole region if indeed such a variation does occur. Therefore, to complement the statistical analysis and to determine the geographical variation in the annual and monthly serial correlations, as well as to discover consistencies and variations in flow serial correlation patterns from month to month, contours of annual and monthly flow serial correlations were drawn. Furthermore since the statistical analysis showed, as discussed later, that flow serial correlations are influenced by some precipitation serial correlations, October, November, December, April, May, and September precipitation serial correlations were also drawn. Fortunately the time consuming and error prone process of manual contouring was avoided by the use of a computer program in conjunction with an IBM computer. Although many of the random errors to which manual contouring is subject to were avoided, the program required some constraints that could not be filled due to the nature of the data and also time and finance limitations. Therefore, some of the contour maps contain small anomalies which though undesirable, do not severely curtail the value of the maps, since the overall patterns of serial correlation variation are unaffected. This fact was deduced from the comparison of these computer drawn maps with some manually contoured maps, completed prior to the use of the computer program. The information available from these maps is a valuable adjunct to the results obtained from the statistical analysis of the main body of data.

CHAPTER V

RESULTS

In this section of the report, the results of both the contouring and statistical analysis will be presented. Discussion will deal initially with the underlying approach to the interpretation of the statistical analysis after which the results of the contouring will be discussed. Special attention will be paid to the seasonal patterns in the variation of the flow serial correlation (hereafter referred to as FSC) and also to some of the specific features of these patterns which may have an explainable physical basis. The results of the statistical analysis will then be presented such that the influence of each individual major physical phenomenon, first the most important and last the least important, will be delineated month by month. Therefore, the results of the associations of precipitation, the precipitation serial correlation (hereafter referred to as PSC), the effects of snowfall, snowpack, and also snowmelt, and basin storage will be presented in that order. The discussion of the PSC will also include the results of the contouring of the several PSC deemed to be of interest and relevance to the explanation of the variation in the FSC.

The results of the study are based on an interpretation of statistical studies which make much use of the correlation coefficient. A statement of the basis of interpretation of these statistical results is desirable and necessary. If each of the streams studied is considered as part of a total sample, the statistical analysis is based on a sample of 40 observations. For a sample of this size a correlation coefficient of approximately 0.3 is required before the relationship is considered significant. However, the governing philosophy of this study does not strictly conform to this criterion. In a study of this nature many small associations may occur in several consecutive months as a group and have a plausible physical rationale and thus, although not significant, can be of interest. On the other hand, even if very strong statistical associations, for which no plausible physical explanation is evident, occur they are of no interest since this association though not a statistical accident, gives no information and is probably due to some unknown indexing quality of the variables. Although no attempt has been made to rigorously test the significance of all the associations found, their relative magnitudes are considered in making a judgement as to the overall importance of the physical phenomenon indexed by the independent variable.

A. Contouring

The discussion of the FSC contours does not include a detailed description of the smaller variations since many of these details are beyond the scope of present day knowledge of FSC. The purpose of the contouring has been to determine the large scale patterns of variation while paying special attention to any consistency in the patterns. Determination of the physical reasons for the existence of these patterns in many cases is beyond the scope of this project and, therefore, only generalized conclusions will be drawn. Another purpose of the contouring has been to ascertain whether small serial correlation coefficients indeed merit discussion in the light of the lack of statistical significance of these coefficients. If the small coefficients do fall into regional patterns which are consistent from month to month then it is quite probable that a study of these coefficients is worthwhile.

FSC Contours: Figures 7 through 19 show that contours of FSC have similar patterns of variation within certain groups of months. These groups or seasons include September through March, excluding November, April through June, and July and August. Contour patterns of November and annual FSC do not conform to any of the seasonal patterns.

September through March: The FSC contours during this period generally have a north-south orientation except for a northwest-southeast orientation along the Pacific coast. The highs centered on the Chambers Creek and Dungeness basins are fairly consistent throughout the period. The Pacific coast tends to have low FSC while high FSC occur along the eastern border. The low that consistently appears in the Stillaguamish region has the form of a band with an east-west orientation in December and February, but is shorter and has a north-south orientation in September, October, January, and March. Generally the magnitude of the FSC is fairly constant from October through December, is quite low in January and February, then increases in March.

April through June: During this period the orientation of the contours along the coastline tends to be northwest-southeast, but changes to east-west along the eastern border. A high is centered on the Chambers Creek basin while an adjacent low is located over the Mount Rainier region. The configuration of the contours includes a low in the southwestern and northeastern corners and a high in the southeastern corner. The intensity of variation for this period is somewhat lower than that for the September through March period and the patterns of variation are less regular. The magnitude of the FSC increases from April to June.

July and August: The contour density is low during July and August and no strongly predominant orientation of the contours occurs. Lows are centered near the Chambers Creek and Satsop basins and a high occurs around the Dungeness basin. This season is similar to the September through March period in that there is a high in the southeastern corner of the region. The magnitude of the FSC is very high during this period.

November and Annual: These two contour maps do not resemble any of the other maps. Contour density is fairly light for both maps. November FSC is dominated by an extensive low centered on the Duckabush basin. The orientation of the annual FSC is similar to that occurring during the September through March period. The variation in annual FSC is somewhat opposite to that occurring during the months in that there is a low instead of a high in the southeastern corner.

Common to almost all the periods is the trend toward low FSC on the Pacific coast and high FSC in the east, and a more or less north-south orientation of the contour lines.

B. Statistical Analysis

Precipitation Amounts: The bottom half of Figure 1 shows that the association of precipitation to monthly FSC has a seasonal variation. From January through March the association of precipitation to FSC is quite large, but does not consistently increase or decrease. From March through June this relationship decreases in strength until a minimum is reached in June. From June through September the strength of the relationship rises steadily after which from September through December it decreases to a minimum in December. All these relationships are negative which means that the FSC decreases with increasing precipitation. A similar relationship holds between the precipitation and the PSC (Table IV).

Precipitation Serial Correlation: The contour maps of October, November, December, April, May, and September PSC (Fig. 20 through 25) show that there is little consistency in the geographical variation of PSC. However, there is a tendency for low PSC to occur in the southeastern corner of the region. The general orientation of the contour lines is probably more north-south than east-west, though not strongly so.

The top half of Figure 1 shows that the cumulative amount of variation in FSC explained by PSC is very large. However, only the associations between the PSC and the FSC of the same month can be considered. From October through December the associations between FSC and PSC are positive, quite strong, but decreasing (lower part of Fig. 3). During April and May there is an association, also positive and fairly strong, between PSC and FSC while September PSC and FSC are significantly, but negatively related. There is a change in sign of the associations between the monthly FSC and April and May PSC from the winter to the spring months. September PSC has considerable negative associations to the FSC from April through September while the association of September PSC to the annual FSC is positive. Both April and May PSC have a negative relationship to the annual FSC.

Snowfall: Mean annual temperature and the average October, December, and February snowfall are considered to be indices of winter snow conditions. These average snowfalls, grouped together, allow a crude inference as to the influence of the general snow condition on FSC. Mean annual temperature is more amenable to specific interpretation and, therefore, its associations will be considered individually.

Average snowfall is generally associated with annual, October, November, December, and February FSC. (Fig. 4). The relationships are significantly large in all cases except for the annual and the October FSC. Although the relationship to October FSC is small it is part of a sequence of associations and therefore will be considered. No such rationale exists for the relationship of snowfall to annual FSC and their association will be ignored.

Mean annual temperature is negatively related to annual, October, November, December, January, and March FSC. (Fig. 4). The small negative relationship to September FSC will be ignored because there is no logical reason for its existence known at present. Only the relationship of mean annual temperature to December FSC is significantly large, but the fact that these associations occur as a group during the winter months warrants their consideration.

Basin Variables: Basin geology is positively related to annual FSC, but negatively associated with the December, April, May, June and August FSC. (Fig. 5). The association is quite strong in the case of annual, April, May and August FSC, but small for December and June FSC. There is a decrease in the associations from a maximum in April to a minimum in June thereby making an interesting sequence.

The associations of the recession variable do not show any grouping tendencies, but occur throughout the year. (Fig. 5). A significant positive relationship occurs between this variable and the annual FSC while a fairly large negative relationship exists between this variable and the January FSC. Smaller negative associations occur during March, June and September. Although the associations are somewhat spread out throughout the year they do occur mainly in the winter and spring months.

The ratio variable is insignificantly related to the annual, October, January, and April FSC, but significantly and negatively associated with February, May, June and August FSC. (Fig. 5). There is an increasing strength of association between this variable and the FSC from January to February and also from April through June.

None of the associations between the basin area and the annual and monthly FSC are significantly large. (Fig. 6). However, small, but decreasing associations occur between this variable and the October through December FSC. There is also a very small association of this variable to August FSC which will be ignored since it is not part of a sequence of associations. Probably the most interesting associations of drainage area to monthly FSC are included in the sequence from October through December.

The percentage of the area occupied by lakes and ponds has no significant relationships to the FSC. (Fig. 6). The small associations that do exist are positive and occur during October, January, February, March, August, and September. The associations from January through March are low in January, reach a maximum in February, and decrease to a minimum in March. The sequence from August through October has its maximum in August, its minimum in September, and rises again a bit in October.

Basin slope has a significant positive relationship with January

FSC and other smaller positive associations with February, August, and September FSC. (Fig. 6). There is also an insignificant association between this variable and the November FSC. The sequence of January and February includes stronger associations than the August and September sequence. The associations decrease from January to February and also August to September.

Basin orientation has significant positive associations with December FSC and smaller positive associations to November, March and May FSC. (Fig. 6). The strength of the associations decreases from November to December.

Summary: To comment generally on the total array of variables, it may be stated that the effect of precipitation on FSC is fairly strong from September through December in that both the amount of precipitation and the PSC have strong relationships to the FSC although the strength of the relationships decreases from September through December. There is a trend from March through July of decreasing influence of precipitation on FSC. Mean annual temperature is related to monthly FSC for the September through December period as are the other indices of snow conditions although it must be noted that these patterns have breaks in them and do not rise or fall as consistently as the precipitation and PSC associations for the same period. The less important variables such as the drainage area, the percentage of the area occupied by lakes and ponds, the basin slope, and the basin orientation tend to be related only to the FSC of the winter and summer months and do not show any associations with the FSC of the spring months. The relationships of the recession variable do not show any discernable pattern, while the associations of the ratio variable have a random aspect and also show grouping tendencies with an increasing trend from April through June. The relationship between the geologic variable and the various FSC are strongest in the spring months and increase from April through June. This general discussion brings out the point that the associations of many of the predictor variables with the FSC tend to follow seasonal lines.

CHAPTER VI

DISCUSSION AND CONCLUSIONS

Introduction: Both the statistical analysis and the FSC contours indicate that variation in FSC occurs along seasonal lines. Although the seasonal patterns indicated by the contour maps differ somewhat from those suggested by the statistical analysis, the degree of conformity between the two patterns is great enough that information obtained from the contours adds to that obtained from the statistical analysis. The patterns indicated by the statistical study will determine the organization of this report while the results of the contouring will be used in conjunction with the results of the statistical analysis to determine the physical factors affecting annual and monthly FSC. The discussion of the physical influences affecting the FSC will deal with the following periods in order; October through December, January through March, April through June, and July through September.

October through December: The geographical variation in the FSC as shown by the contours is similar for October and December, but not for November. The probable reason for the divergence of the patterns of November FSC from those of October and December is that November flows are subjected to fluctuating conditions relative to October flows. This could cause the differing contour patterns, but one would also expect these differences to appear in the results of the statistical analysis, a condition which does not exist.

October through December form a sequence during which it is evident that precipitation in the form of both rain and snow is a dominating influence on the variation in the FSC. Rainfall increases throughout this period which has the effect of decreasing the FSC. However, snowfall also increases during this period and has the opposite effect of increasing the FSC. The influence of snowfall and fresh snowpack is inferred from the associations between the FSC and the snowfall variables, the mean annual temperature, and the basin orientation.

These two conditions compensate for each other thereby producing the condition of relative constancy of FSC magnitude with respect to time, not location. That the influence of rainfall is such as to decrease the FSC is shown by both the lower FSC in the low elevation basins indicated by the low contour values in the low elevation and coastal basins which receive the greatest rainfall, and the associations of the precipitation variables with the FSC. The decrease in the associations between the precipitation and the FSC throughout this period is almost matched by the increase of association between the snowfall variables and the FSC which suggests that the two effects may be compensatory. The positive associations of the snowfall variables indicate that a fresh snowpack increases the FSC while the negative associations of precipitation variables indicates that increasing rainfall decreases the FSC.

Precipitation serial correlation is also significantly and positively related to October through December FSC. The contours of the PSC are quite different from the FSC contours in that the PSC patterns are not as regular as the FSC patterns and PSC values are lower in magnitude. This indicates that most of the characteristics of the FSC contours originate from influences acting on the precipitation after it has fallen. There is a similarity between the FSC and PSC contours in that the variation in both tends to be east-west throughout most of the area and that high values tend to occur in the east and low values along the coast. That PSC is associated with FSC only from October through December and also April and May, may be because from October through December the soil moisture is in a state of partial depletion and the flow of water through the soil serves to transfer the PSC into the FSC to some degree, and in April and May the snowpack may serve as a soil matrix.

The nature of the basin storage has little influence throughout this period as shown by the association of the geologic recession and ratio variables. Basin area, percentage of this area occupied by lakes and ponds, and basin slope have small associations during this period, which do not contradict the previous conclusion. This lack of association between basin storage variables and the FSC is rather strange considering the depleted state of the soil and aquifer storage. It does not appear unreasonable that the depleted state of these reservoirs should have an effect on the transference of the PSC to the FSC, but it does seem strange that the variables intended to index this effect do not have more significant relationships to the FSC.

January through March: The contours of FSC during this period have a north-south orientation with the high values occurring on the east boundary of the region and the low values occurring along the Pacific coast. This pattern is due to the fact that the lowest FSC occurs in the lower basins where the rainfall is the highest, especially along the Pacific coast which is the nearest to the storm tracks while the highest FSC occur at higher elevations where snow conditions hold. These considerations indicate that rainfall has the strongest effect on FSC. The association of mean annual temperature to January FSC, December snowfall to February FSC, basin orientation to March FSC and the lack of any other associations which could be attributed to snowfall indicates that the snowfall is not important. However, it is logical to conclude, and this is not contradicted by the statistical analysis, that the snowpack has a strong influence on the FSC. This is indicated by the presence of high FSC in the high mountainous regions where the depth of snowpack is the greatest. Snowpack depth increases during this period, but the relative conditions from basin to basin apparently do not change drastically.

The general increase of FSC from January to March further indicates that rainfall has a strong decreasing effect on FSC since the rainfall decreases while the FSC increases. The PSC has no association to the FSC during this period from which it can be concluded that the conditions have changed from the former period of October through December in that the conditions of the storage reservoirs and the snowpack have changed. It is possible that the recharged condition of the storage reservoirs prevents the transference of the PSC into the FSC and that the existence of a more substantial snowpack also affects this condition.

The associations between the FSC and the basin recession variable, the percentage of the area occupied by lakes and ponds, and the ratio variable indicate that during January through March the influence of the basin storage is present. However, the positive association of the basin slope to the FSC is contrary to the expected relationship. There is no coherent logical reason why basin storage should affect FSC during the winter. It is quite possible that the relationship between elevation and FSC is being indexed by these associations, since all the associated variables are strongly related to basin elevation. The most probable condition is that the basin storage is not affecting the FSC, but the variables which indicate this condition are merely indexing elevational influences.

April through June: The contour patterns for this season are different from those in the previous seasons in that although a low still exists along the Pacific coast, the orientation of the contours along the eastern border is east-west while a high exists in the southeastern corner and a low in the northeastern corner. This east-west orientation is probably due to different snowmelt characteristics between the northern and the southern streams. A most significant departure from previous months is that high FSC now occur at the lower elevations while the lower FSC occur at the higher elevations. This is an increasing trend from April through June and is due to decreasing rainfall and consequently increasing FSC in the lower basins. During this period most of the flow originates from snowmelt at higher elevations thus causing the lower FSC in these areas.

April and May FSC are associated with PSC because the crystallized snow now acts in the same capacity as the soil during the storage depleted period from October through December when the PSC were also associated with the FSC. In June the snowpack has been so modified by the melting process that the pack can no longer act as a soil matrix and thus the PSC and FSC are not associated during this month. Why the storage action of the snowpack on the soil should cause the transference of PSC into the FSC is unknown at this time. Basin storage capacity appears to be a little more influential than in the previous months as shown by the relationships between the geologic variable and the April, May, and June FSC. The strength of this relationship is at a maximum in April and a minimum in June. The recession variable is weakly related to the June FSC. It is difficult to explain these associations in term of basin storage since during this period most of the flow comes either from rainfall or snowmelt and, therefore, would not be strongly influenced by the characteristics of basin storage. It is also difficult to explain these associations of the geologic variable in terms of its relationship to elevation. No satisfactory conclusion can be reached as to the meaning of the associations of these variables to the FSC during this period.

July through September: The contour density is low in August and July, but high in September. The magnitude of the FSC is very high in July and August, but considerably lower in September. There is no predominate orientation of the contours in July and August, but a fairly strong north-south orientation of the September FSC contours exists with low values occurring along the Pacific coast and high values along the eastern border. All these conditions can be explained in terms of rainfall in that the low rainfall during July and August has little effect on the FSC, thus accounting for the high values, the lack of a predominate orientation, and the low degree of variation throughout the region. However, in September the rainfall is much more substantial and because of this the orientation of the contours is once again north-south, the contour density is high with the low values occurring along the Pacific coast, the region of high rainfall.

These conclusions are borne out by the associations between precipitation and the FSC, very weak in July increasing to very strong in September. The strength of the association between precipitation and August FSC is high enough to arouse expectations of differences between August and July FSC contours, but this does not occur so possibly the difference in rainfall conditions between July and August is not high enough to affect the contours.

During July and August, the low FSC occurring around the Thunder Creek and the Puyallup and Carbon rivers is probably due to the influence of glacial meltwater. Possibly this also occurs in the Olympic streams, but less intensely. However, there are other glaciated basins which do not show these contour patterns, possibly because the glaciers are smaller in these streams and, therefore, are less influential.

July and August FSC and PSC are unrelated, but September PSC is negatively related to FSC. This association may be of the same nature as the positive associations between the PSC and FSC of October, November, and December, but the negative nature of the relationship is difficult to explain. Other points where September is different than most of the other months includes the positive relationship between precipitation and PSC and the negative relationship of September PSC to the FSC of the spring and summer months. These anomalies lead to the conclusion that September rainfall is different from the rainfall of the other months for some unknown reason.

August FSC is weakly related to the drainage area, percentage of this area occupied by lakes and ponds and the geologic variable. This seems to indicate that both the soil and aquifer storage of the basin has some influence on the FSC. This probably stems from depletion of storage occurring during this period. July FSC is not related to any of the basin factors which in conjunction with the lack of associations to rainfall and FSC suggests that some phenomenon is active during this period which has not been indexed. This phenomenon may be related to the last of the snowmelt or else glacial melting. September FSC is weakly related to the recession variable which indicates that the soil storage capacity of the basin is of some influence.

Annual: The contour patterns of annual FSC are somewhat similar to those for the period of April through June, but lows tend to occur where monthly highs are located and the highs where the monthly lows are located. Furthermore the associations of the geologic and recession variables are both positive while for the monthly FSC these associations are negative. These positive associations indicate that high FSC are associated with low storage capacity which is contrary to expectations. Annual FSC is weakly related to February snowfall which may or may not indicate any influence of snow conditions on annual FSC. Annual FSC is not related to either the annual precipitation nor the annual PSC and, therefore, precipitation has no direct influence on the FSC. There are many associations between monthly PSC and the annual FSC which indicates that precipitation has an unknown indirect effect. In summary, the annual FSC has no clear explainable physical basis. This leads to the consideration that since the annual flows are the weighted average of the monthly flows, it is possible that annual FSC is also partly a mathematical function of the monthly FSC.

Summary: An overall conclusion that can be drawn from the studies made is that the monthly FSC are overwhelmingly influenced by precipitation, in the form of both snow and rain. Rainfall has the tendency to decrease the FSC while a fresh snowpack has a tendency to increase FSC, a crystallized snowpack causes the transference of PSC into the FSC in a manner similar to that of a fairly dry soil, while snowmelt decreases the FSC. Throughout the year soil and aquifer storage have little directly observable influence on the FSC although some small effects on the FSC may be inferred from the action of the variables indexing other phenomena. Although the monthly FSC can be fairly well explained in terms of physical phenomena acting on the basin, annual FSC have no known physical explanation.

LIST OF REFERENCES

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

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

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

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

5. 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.

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

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

8. Fiering, M.B., "Multivariate Technique for Synthetic Hydrology", Journal of the Hyd. Div. of the ASCE, Vol. 90, #HY5, Sept. 1964, Part 1, p. 43.

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

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

11. Gladwell, J.S., "Private Communications" 1969.

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

13. Gladwell, J.S., and A.C. Mueller, "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.

14. 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.

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

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

17. 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.

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

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

20. Matalas, N. C., "Autocorrelation of Rainfall and Streamflow Minimums", USGS Prof. Paper 434-B, 1963a.

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

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

23. Matalas, N. C., "Mathematical Assessment of Synthetic Hydrology", Water Resources Research, Vol. 3, #4, 1967b, p. 937.

24. 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.

25. 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, Jan. 1961, p. 1-13.

26. 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.

27. Patterson, J. L., "Magnitude and Frequency of Floods in the U.S.", USGS Water Supply Paper, #1681, 1964.

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

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

30. 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.

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

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

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

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

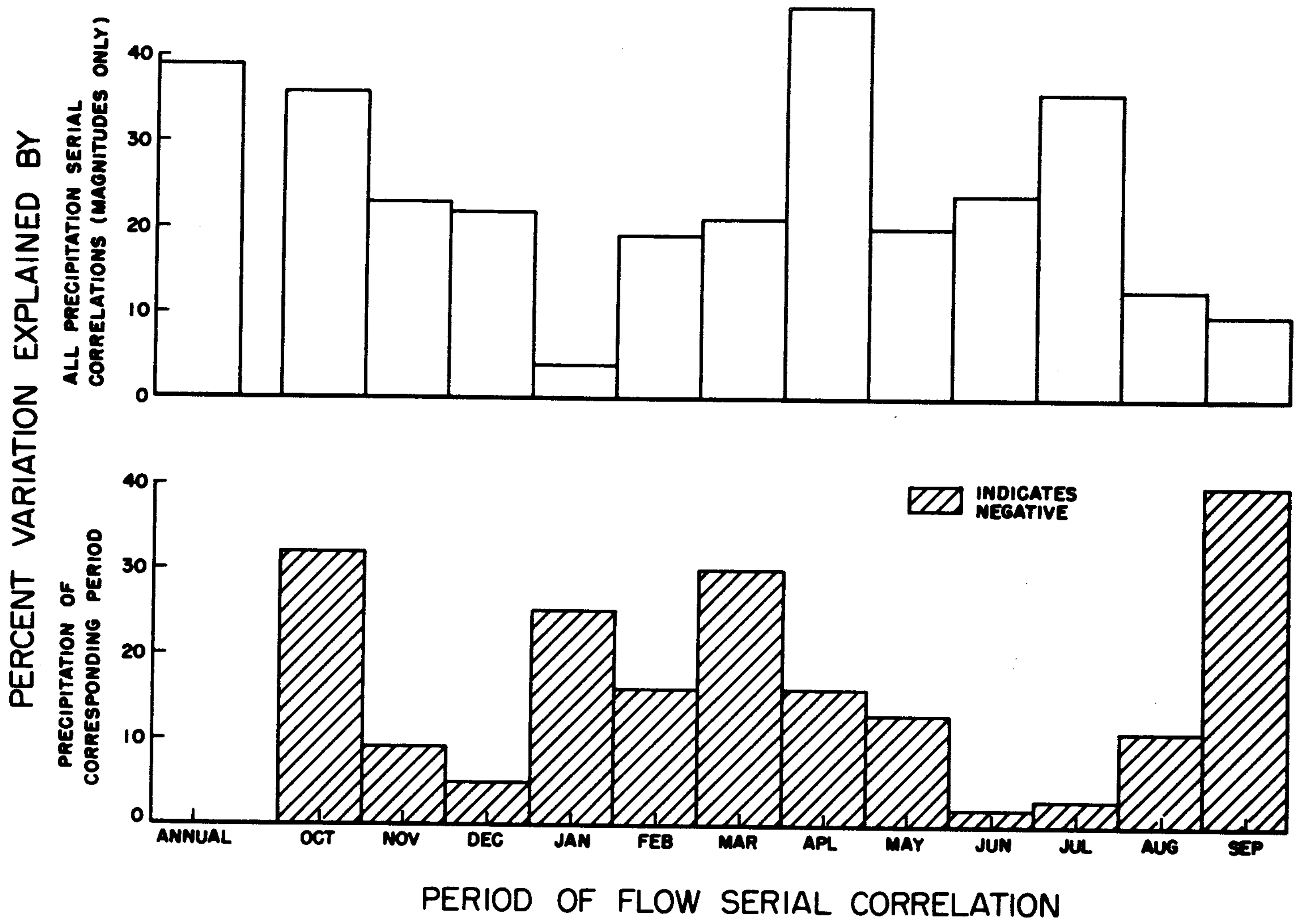


FIGURE 1. ASSOCIATIONS BETWEEN FLOW SERIAL CORRELATIONS AND 1) PRECIPITATION AMOUNTS, AND 2) ALL PRECIPITATION SERIAL CORRELATIONS.

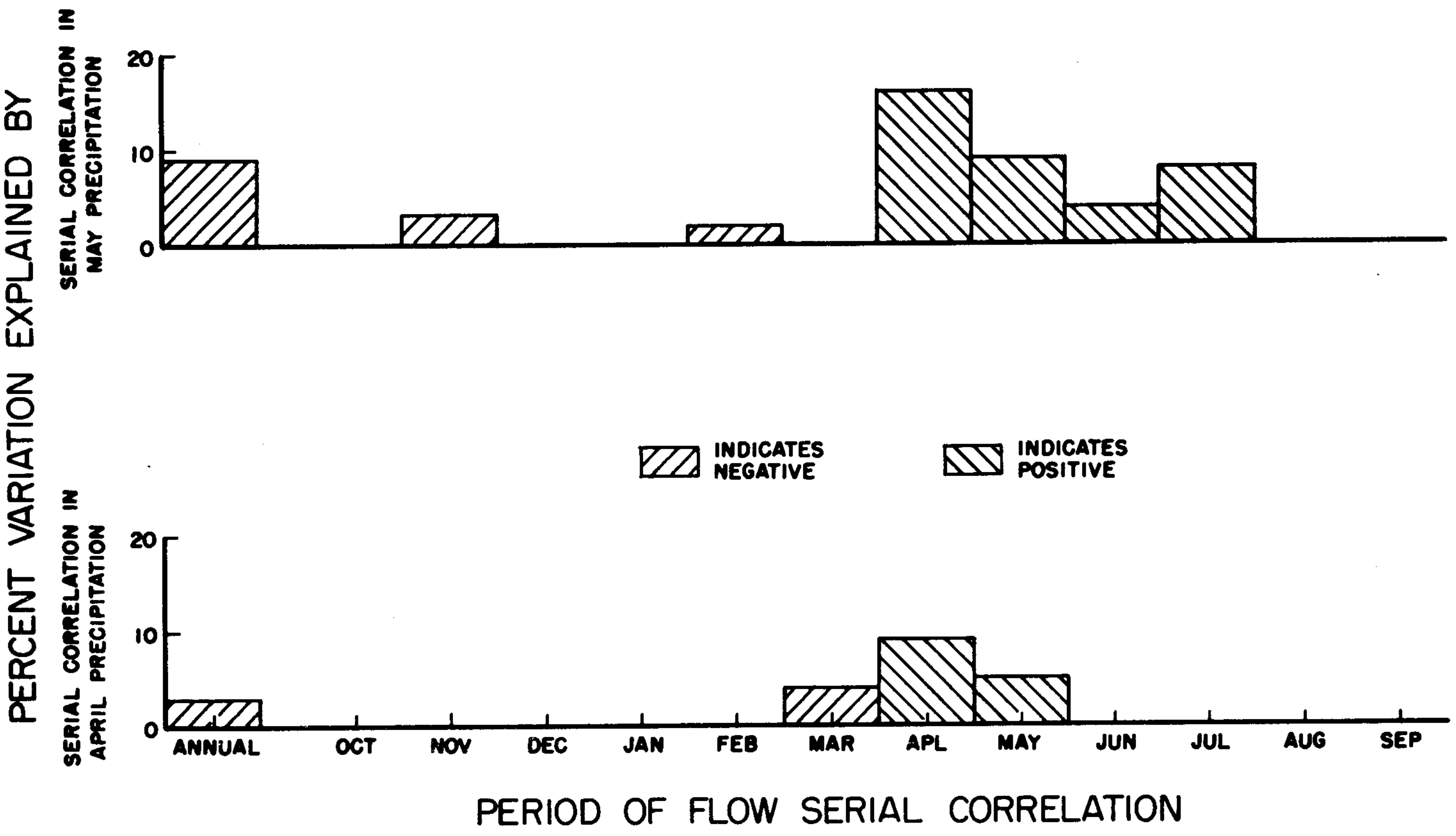


FIGURE 2. ASSOCIATIONS BETWEEN FLOW SERIAL CORRELATIONS AND 1) MAY PRECIPITATION SERIAL CORRELATION, AND 2) APRIL PRECIPITATION SERIAL CORRELATION.

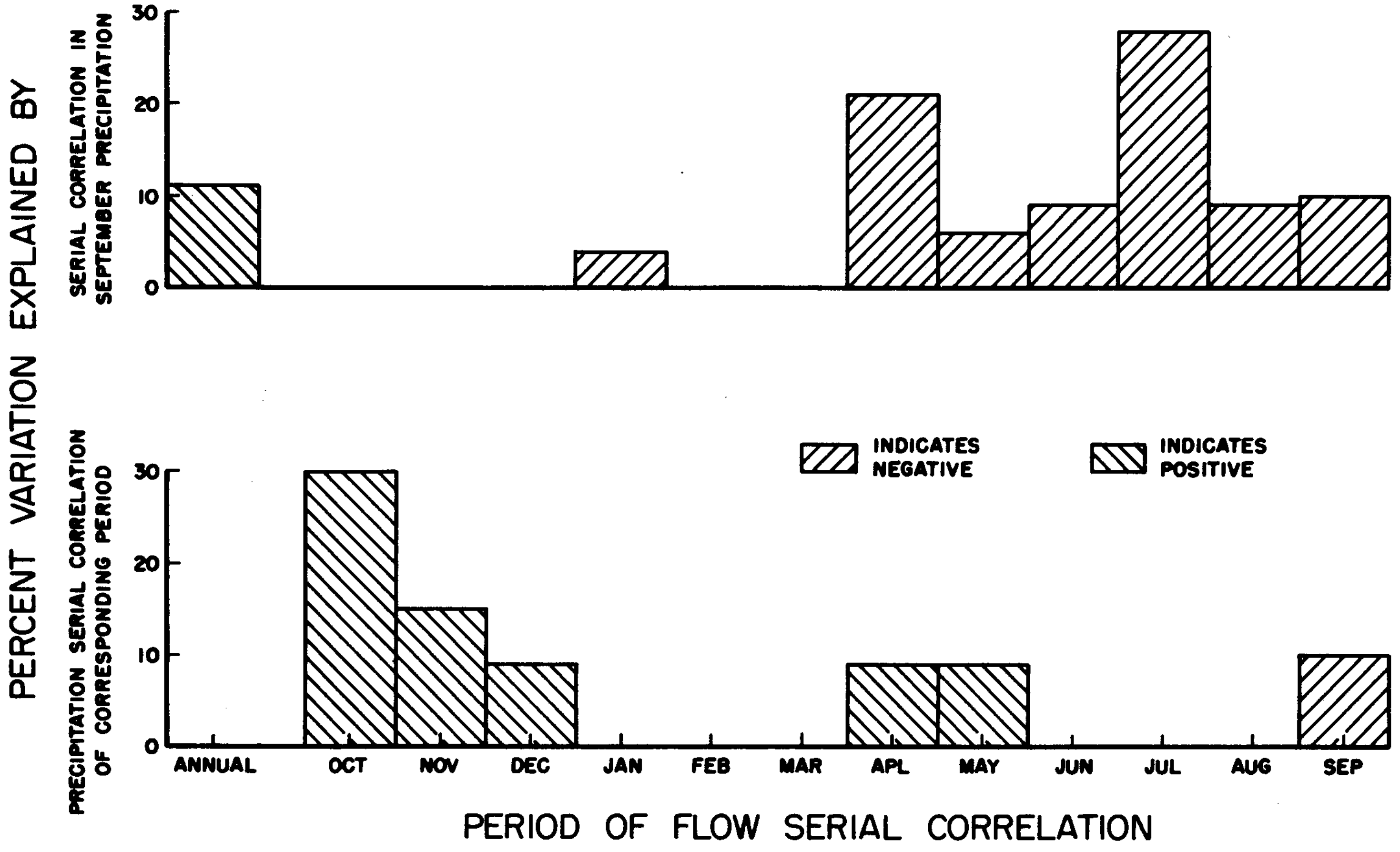


FIGURE 3. ASSOCIATIONS BETWEEN FLOW SERIAL CORRELATIONS AND 1) CORRESPONDING PRECIPITATION SERIAL CORRELATION, AND 2) SEPTEMBER PRECIPITATION SERIAL CORRELATION.

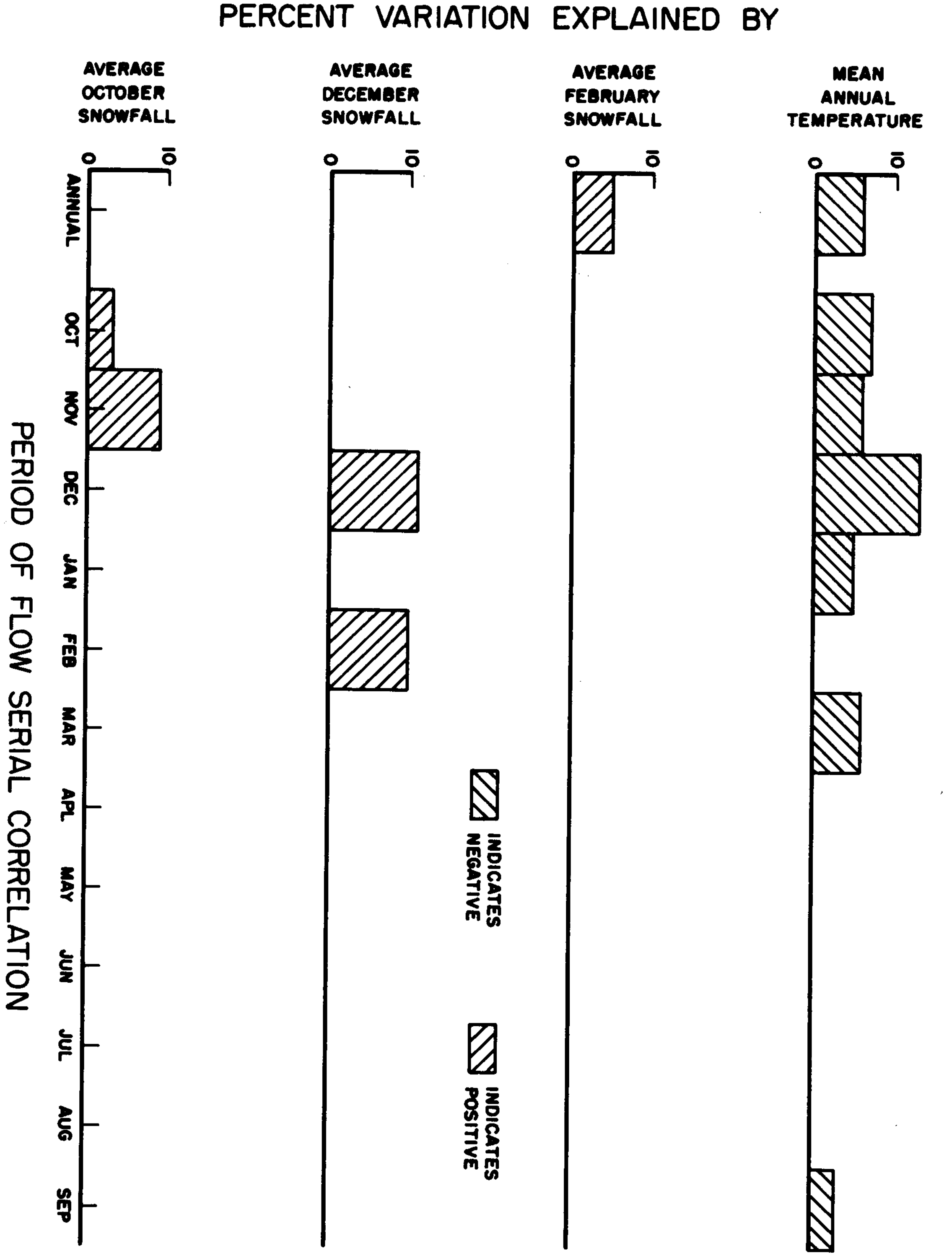


FIGURE 4. ASSOCIATIONS BETWEEN FLOW SERIAL CORRELATION AND SNOW ACCUMULATION INDICES AND MEAN ANNUAL TEMPERATURE.

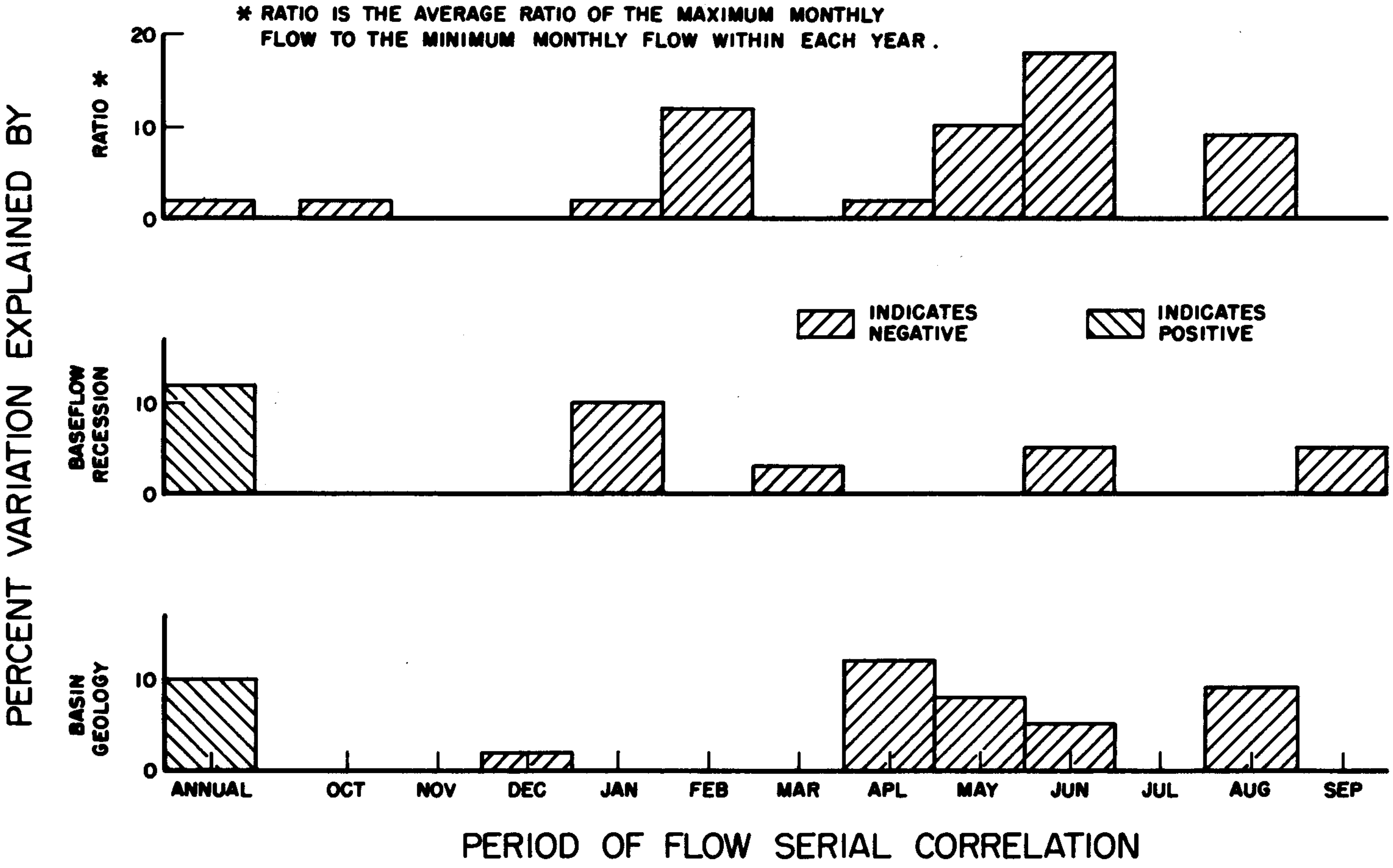


FIGURE 5. ASSOCIATIONS BETWEEN FLOW SERIAL CORRELATION AND THE RATIO, RECESSION, AND GEOLOGIC VARIABLES.

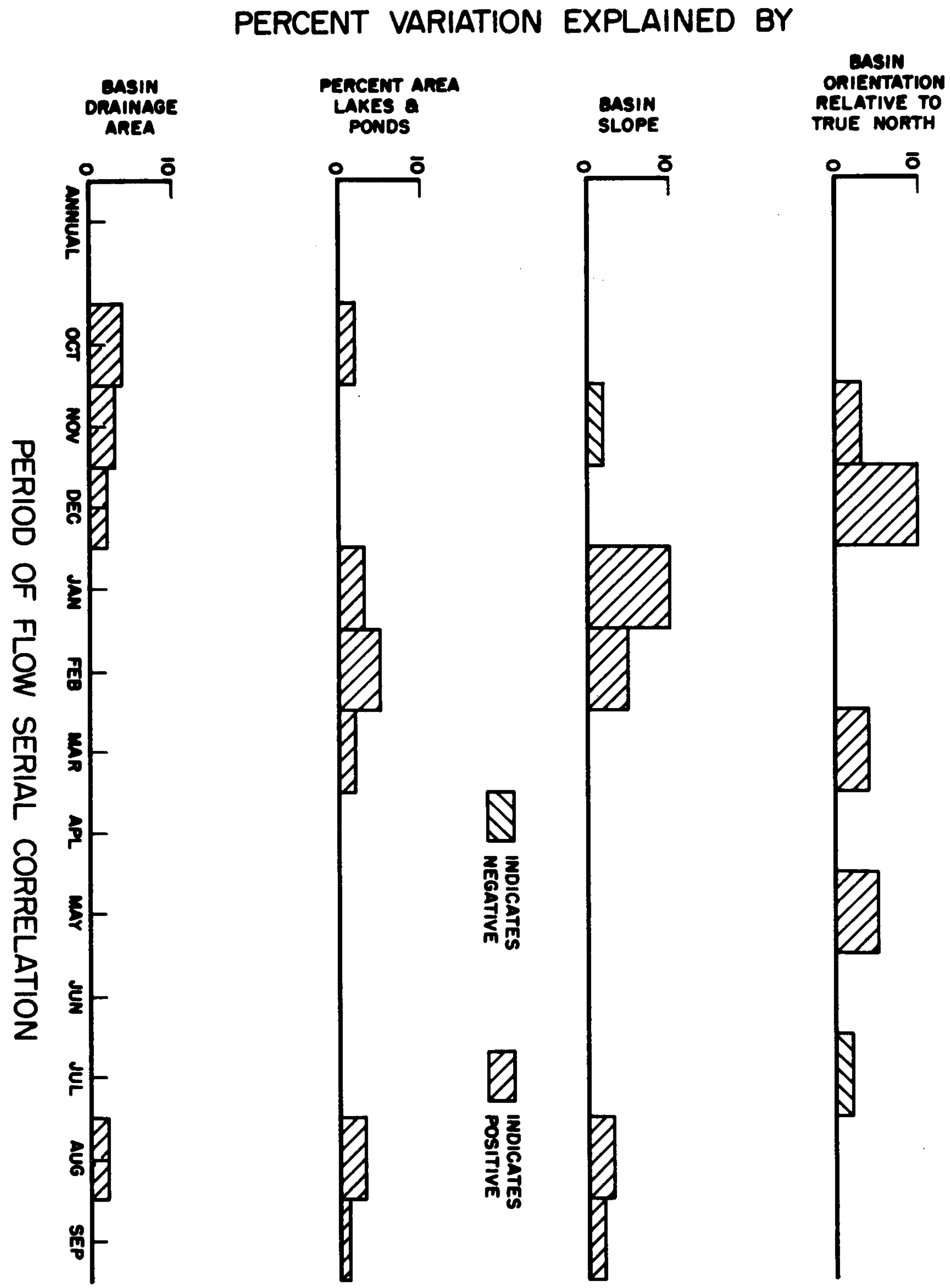
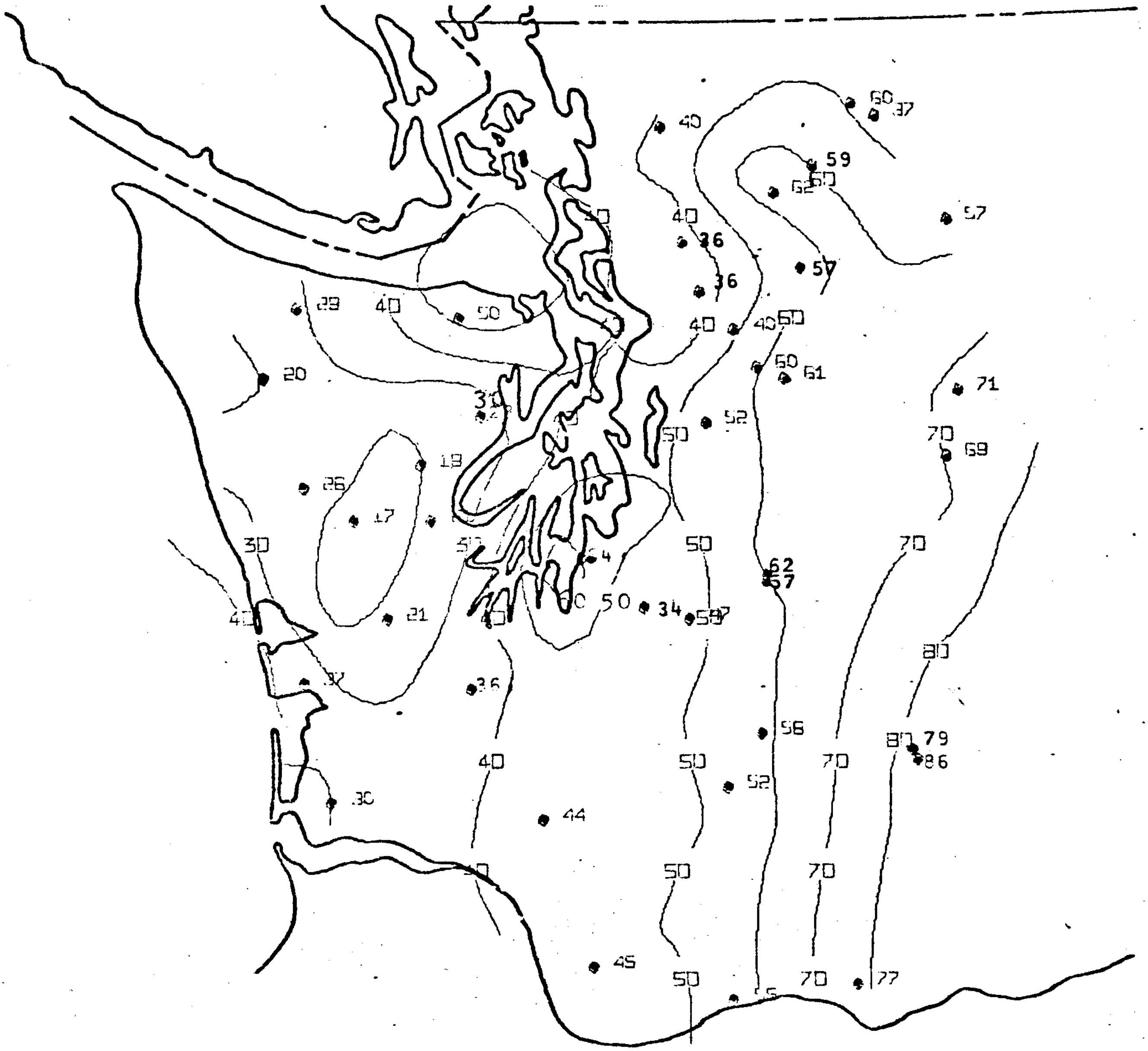


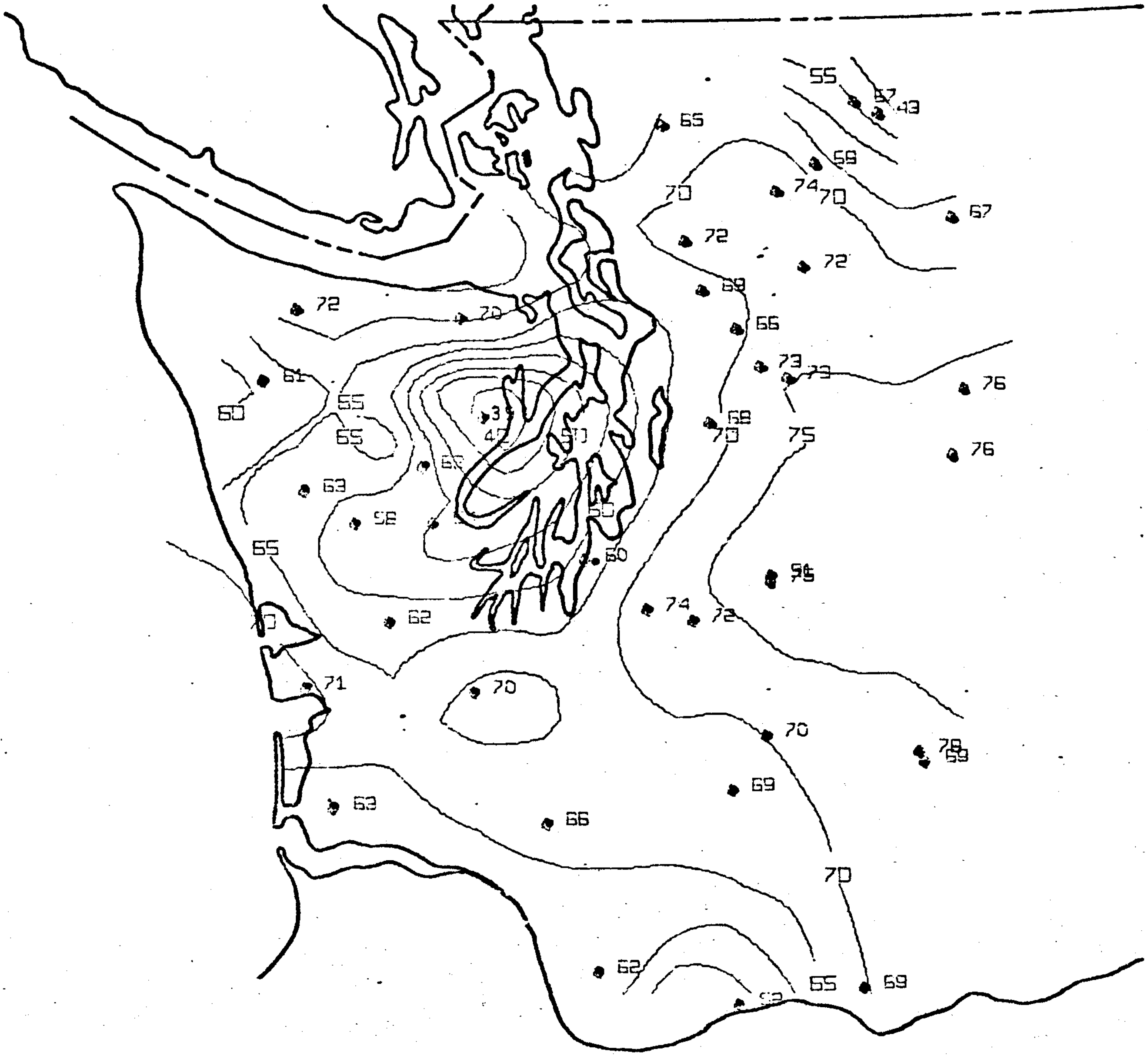
FIGURE 6. ASSOCIATIONS BETWEEN FLOW SERIAL CORRELATION AND THE BASIN SLOPE, THE DRAINAGE AREA, THE LAKES & PONDS VARIABLE, AND THE BASIN ORIENTATION.



All values marked are 100 times the actual serial correlation values

CONTOUR INTERVAL - 10

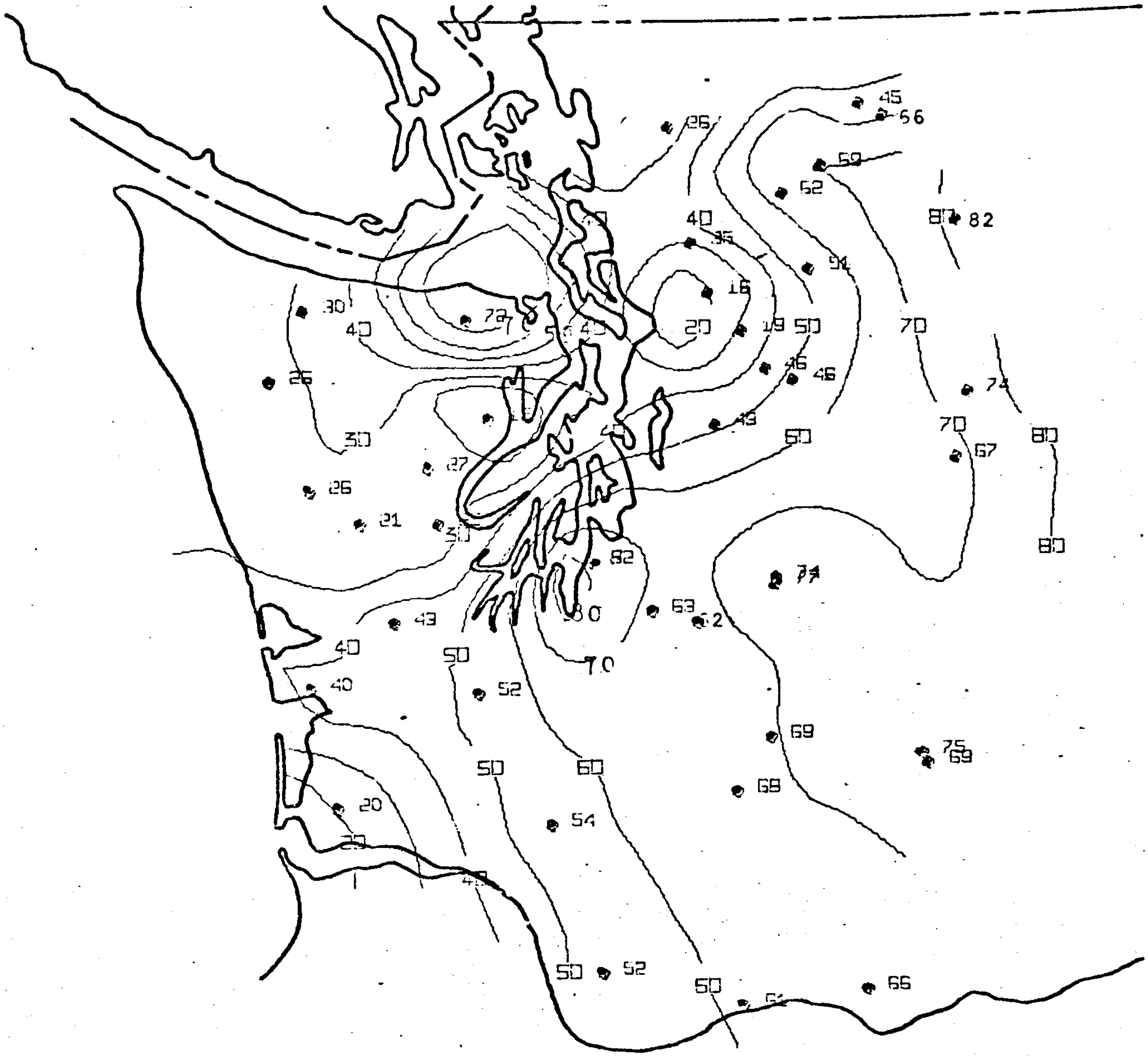
FIGURE 7
SERIAL CORRELATION IN OCTOBER FLOWS OF WESTERN WASHINGTON



All values marked are 100 times the actual serial correlation values

CONTOUR INTERVAL - 5

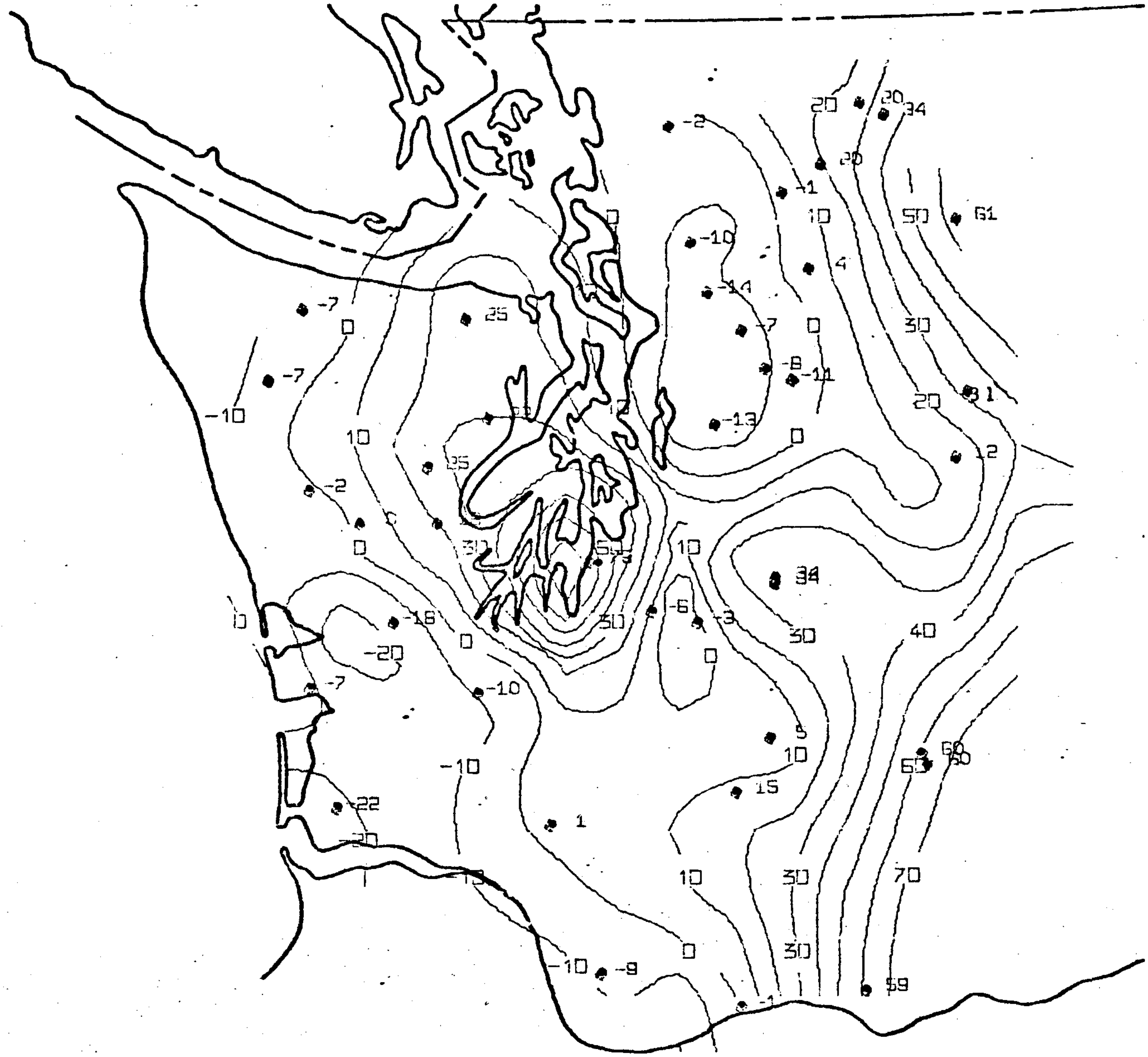
FIGURE 8
SERIAL CORRELATION IN NOVEMBER FLOWS OF WESTERN WASHINGTON



All values marked are 100 times the actual serial correlation values

CONTOUR INTERVAL - 10

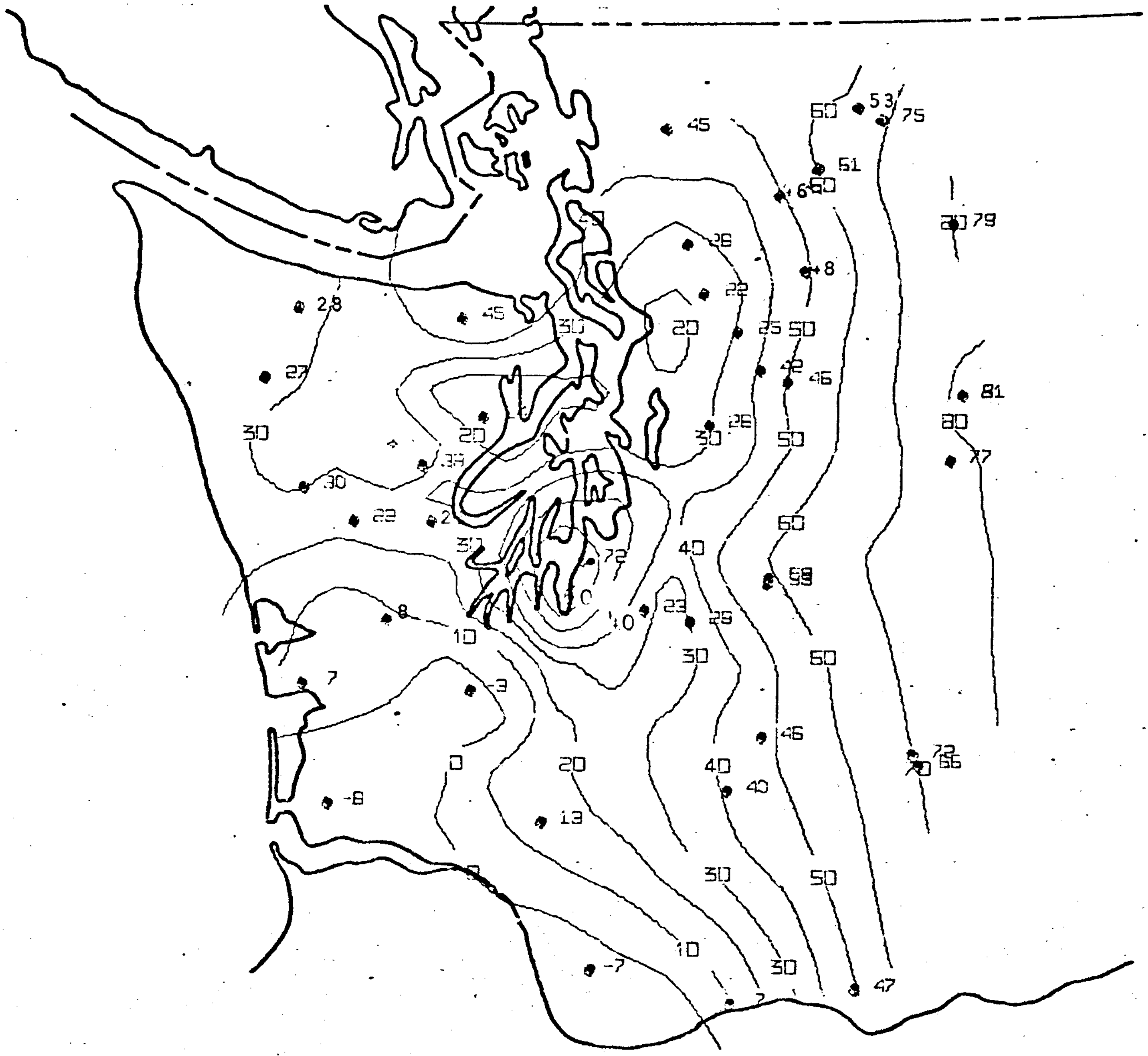
FIGURE 9
SERIAL CORRELATION IN DECEMBER FLOWS OF WESTERN WASHINGTON



All values marked are 100 times the actual serial correlation values

CONTOUR INTERVAL - 10

FIGURE 10
SERIAL CORRELATION IN JANUARY FLOWS OF WESTERN WASHINGTON



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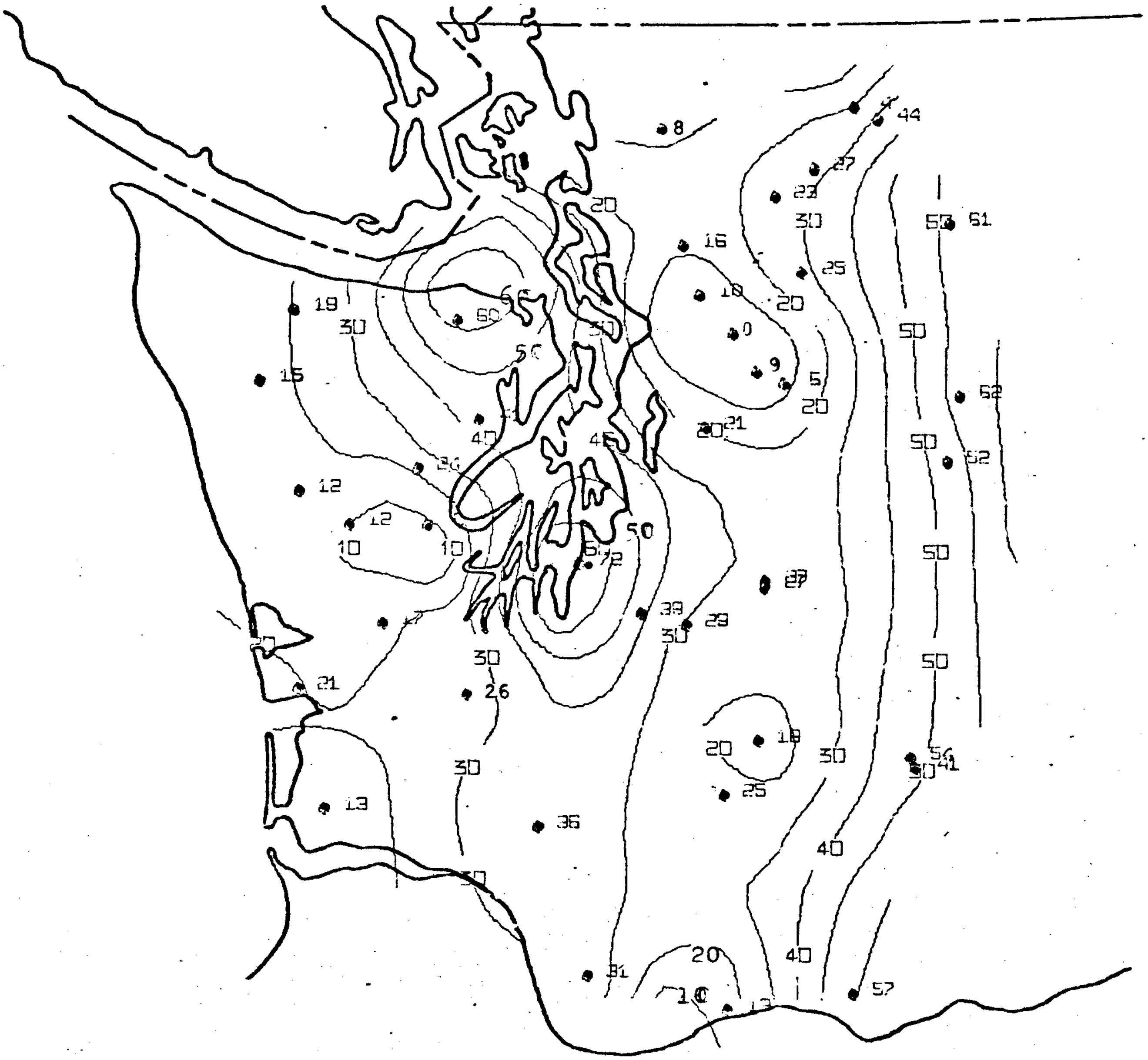
CONTOUR INTERVAL - 10

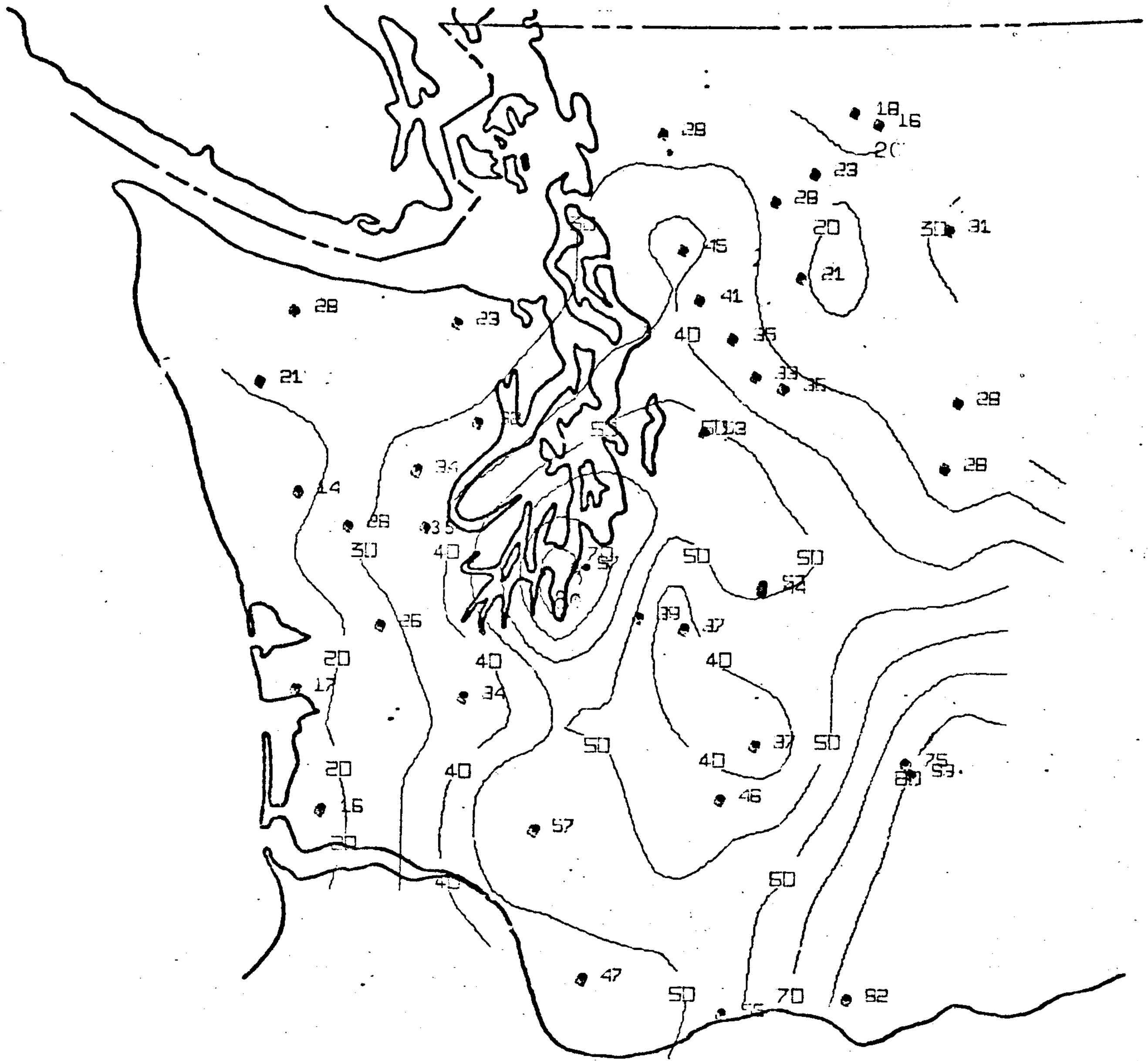
FIGURE 11
SERIAL CORRELATION IN FEBRUARY FLOWS OF WESTERN WASHINGTON



All values marked are 100 times the actual serial correlation values

CONTOUR INTERVAL - 10

FIGURE 12
SERIAL CORRELATION IN MARCH FLOWS OF WESTERN WASHINGTON



All values marked are 100 times the actual serial correlation values

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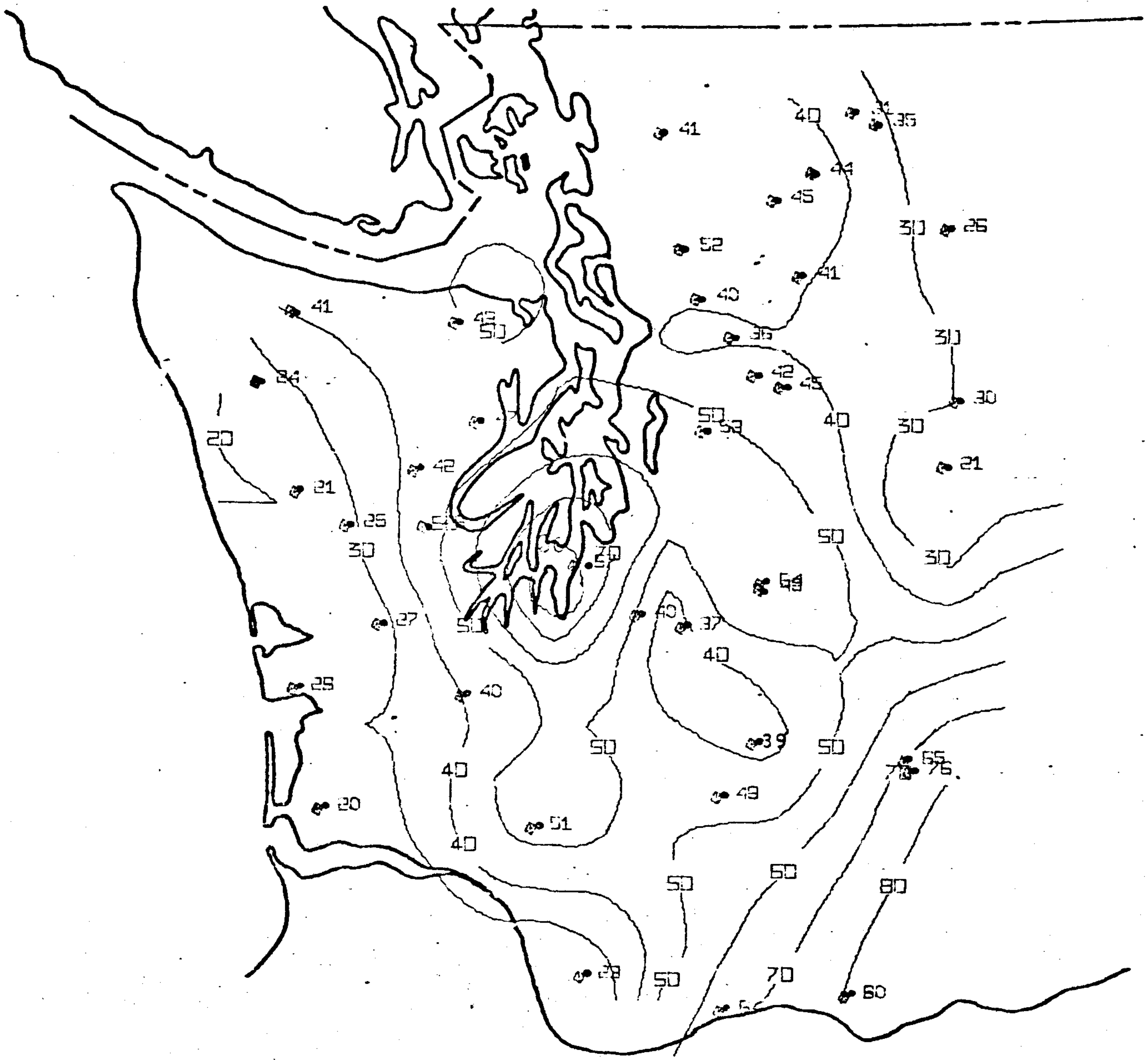
FIGURE 13
SERIAL CORRELATION IN APRIL FLOWS OF WESTERN WASHINGTON



All values marked are 100 times the actual serial correlation values

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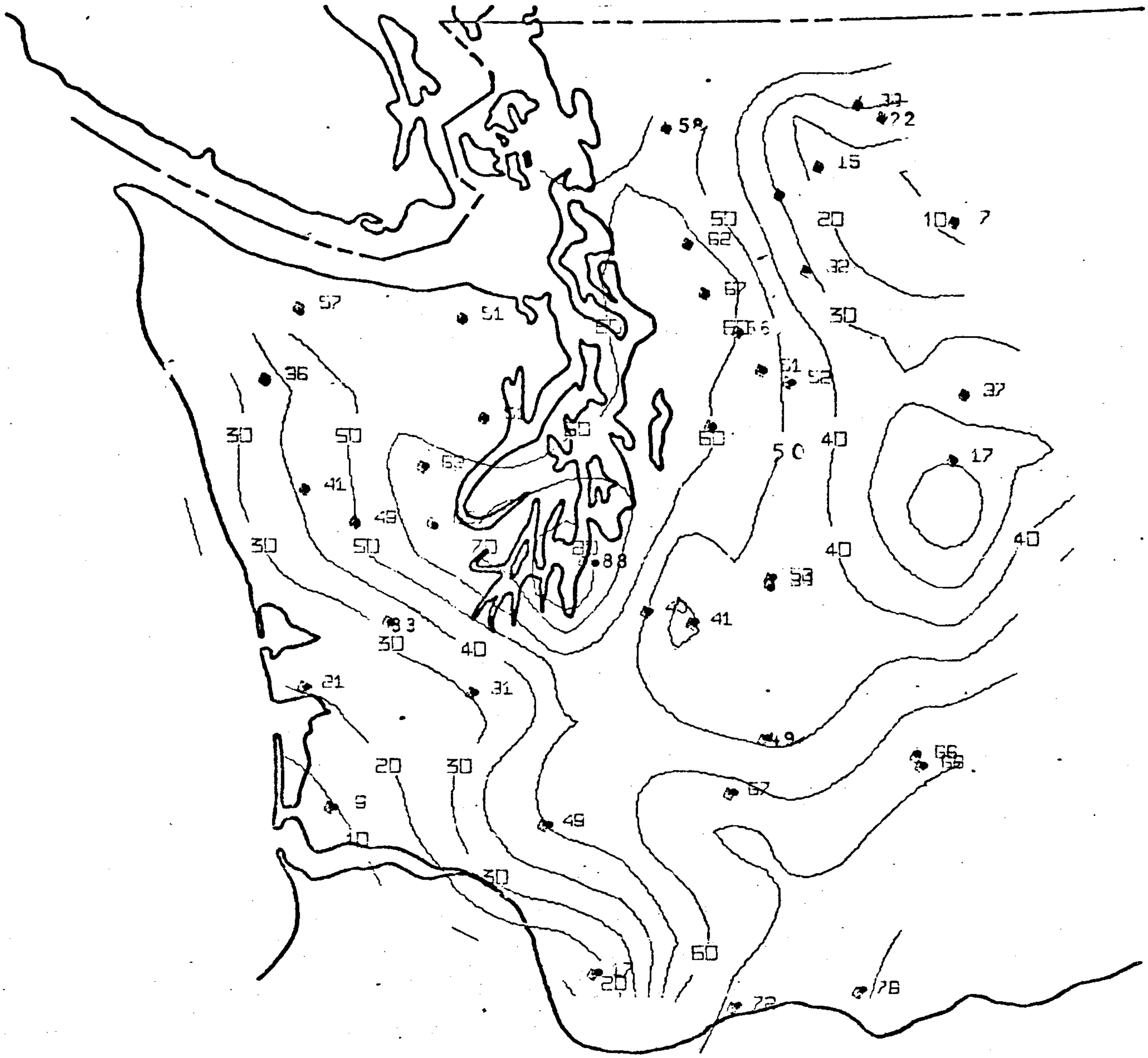
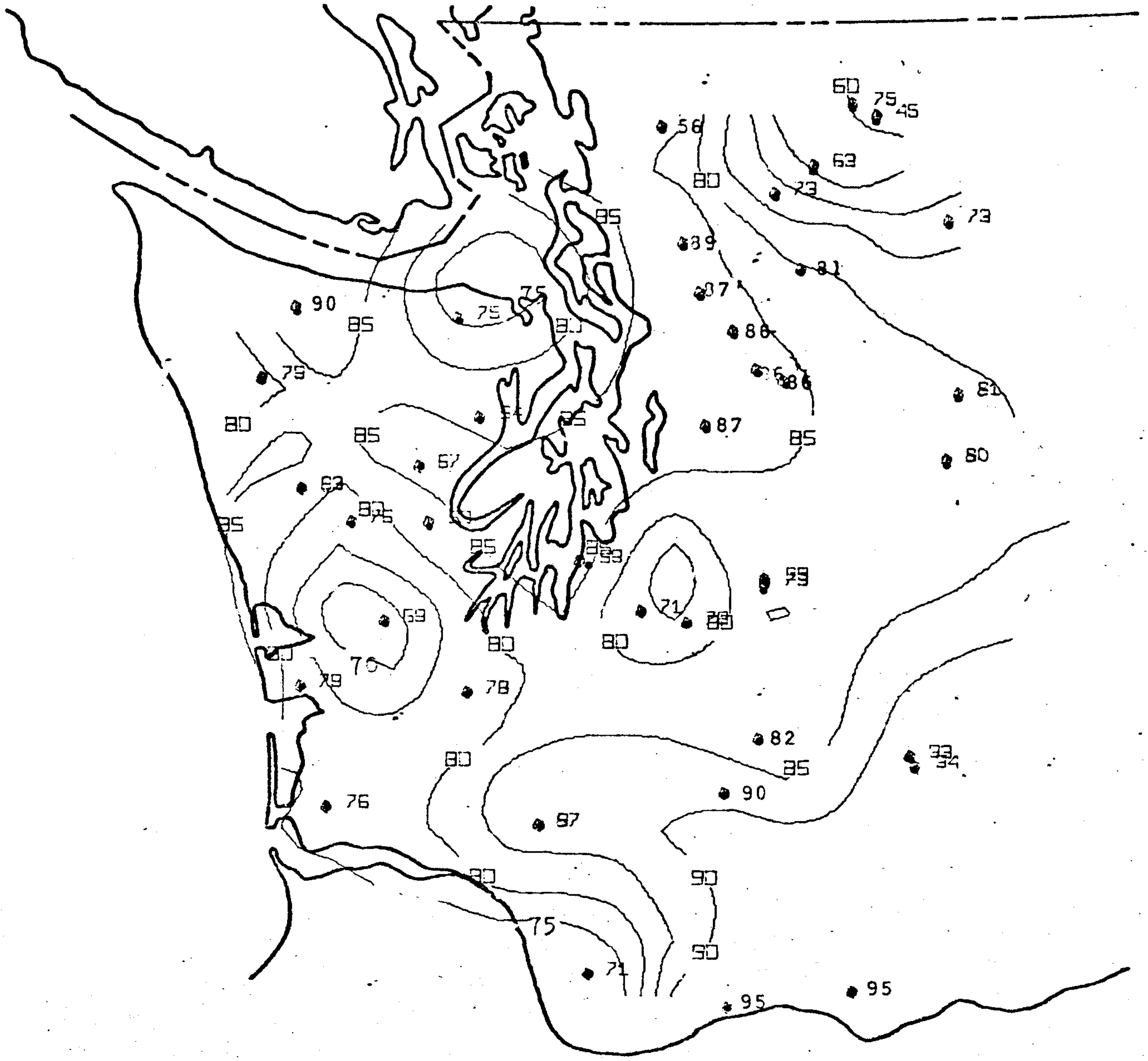
FIGURE 14
SERIAL CORRELATION IN MAY FLOWS OF WESTERN WASHINGTON



All values marked are 100 times the actual serial correlation values

CONTOUR INTERVAL - 10

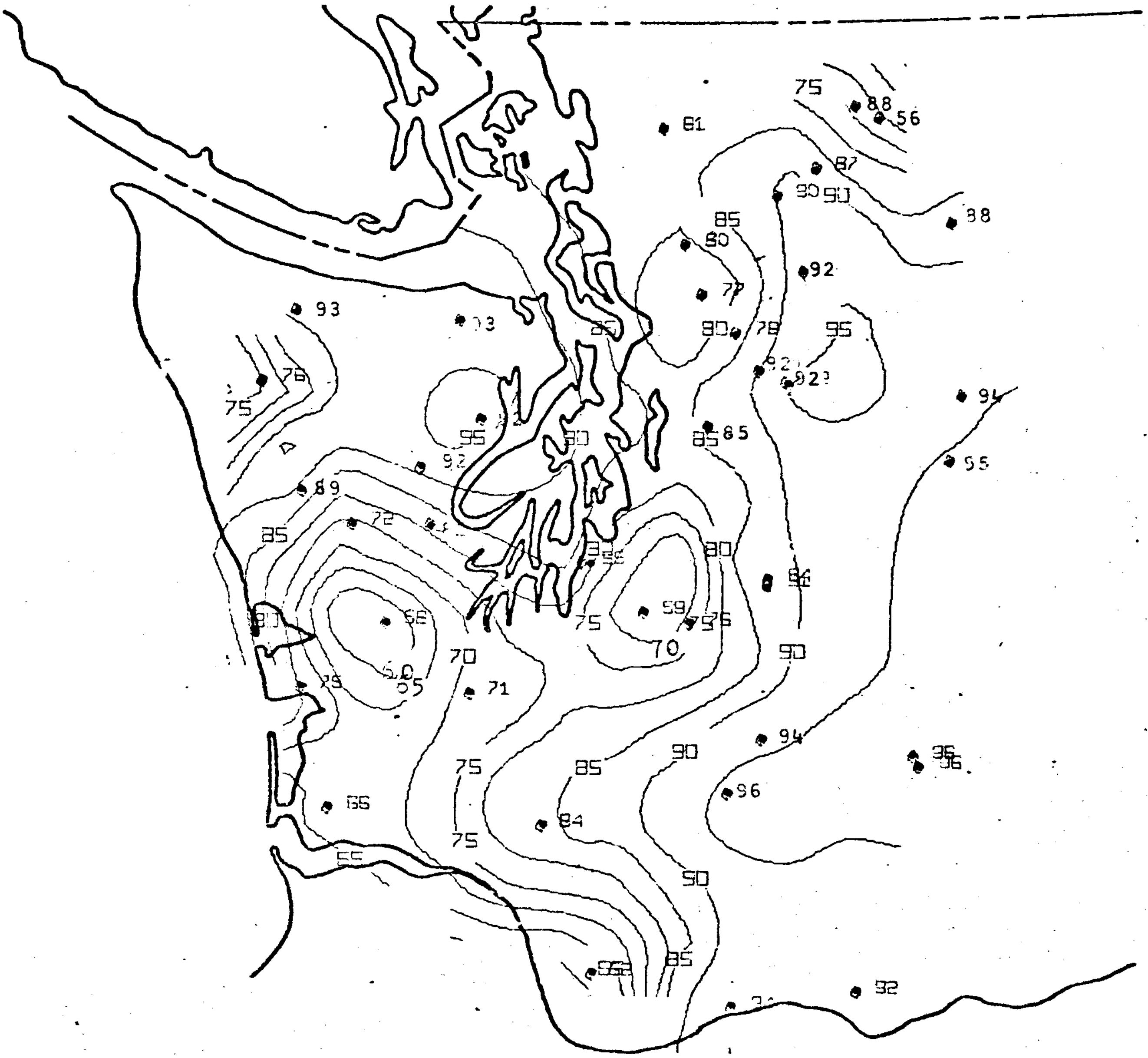
FIGURE 15
SERIAL CORRELATION IN JUNE FLOWS OF WESTERN WASHINGTON



All values marked are 100 times the actual serial correlation values

CONTOUR INTERVAL - 5

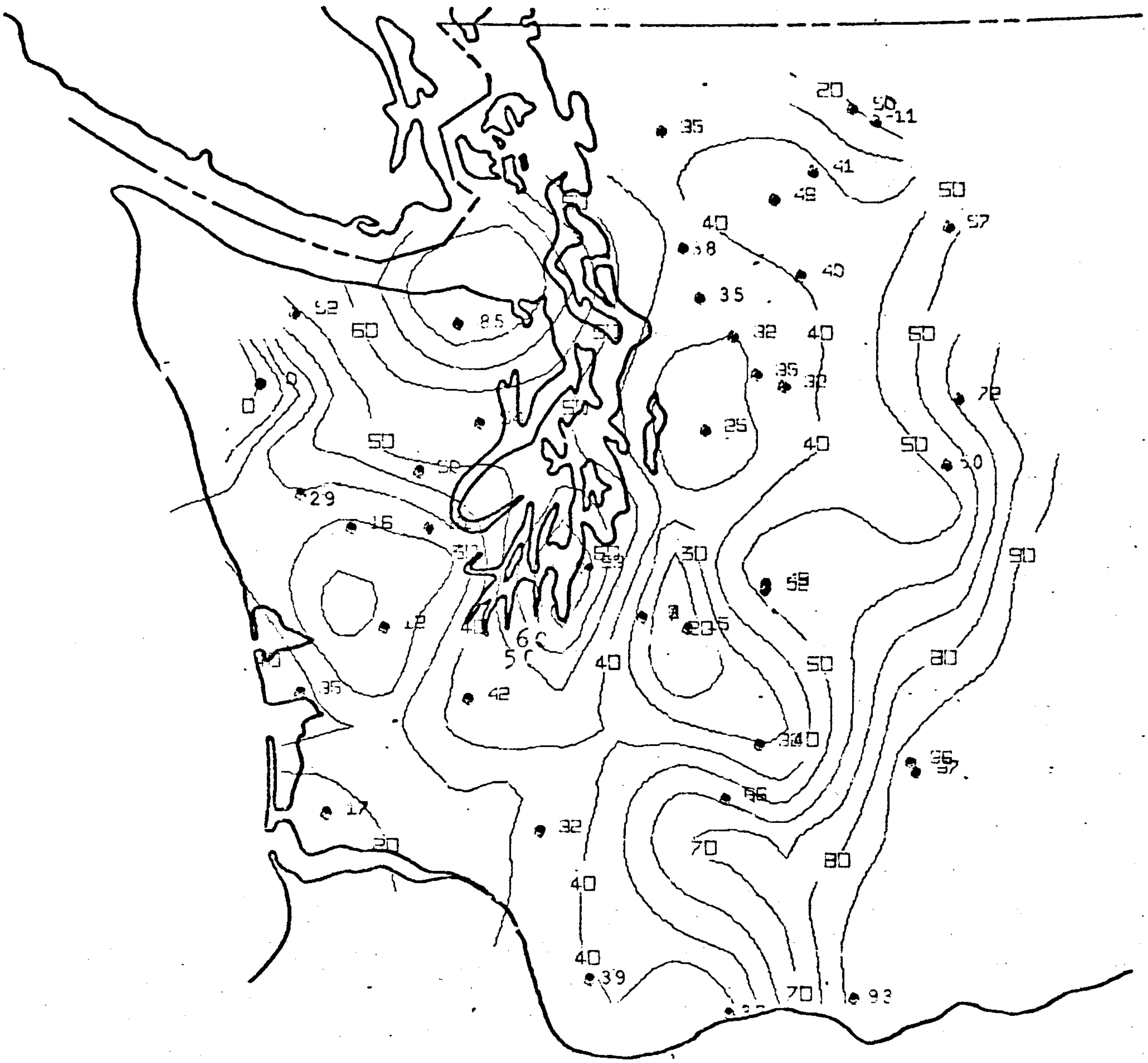
FIGURE 16
SERIAL CORRELATION IN JULY FLOWS OF WESTERN WASHINGTON



All values marked are 100 times the actual serial correlation values

CONTOUR INTERVAL - 5

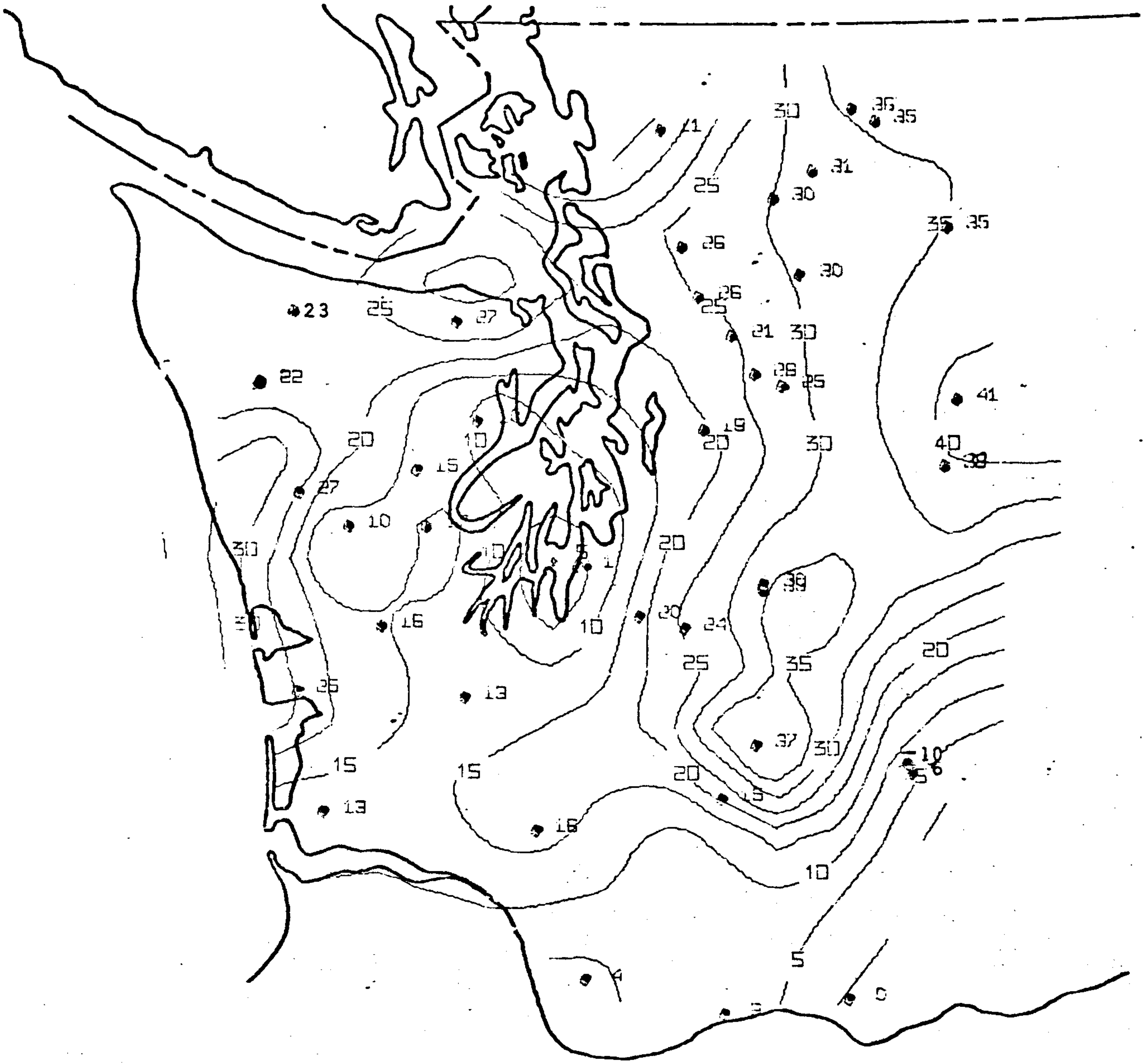
FIGURE 17
SERIAL CORRELATION IN AUGUST FLOWS OF WESTERN WASHINGTON



All values marked are 100 times the actual serial correlation values

CONTOUR INTERVAL - 10

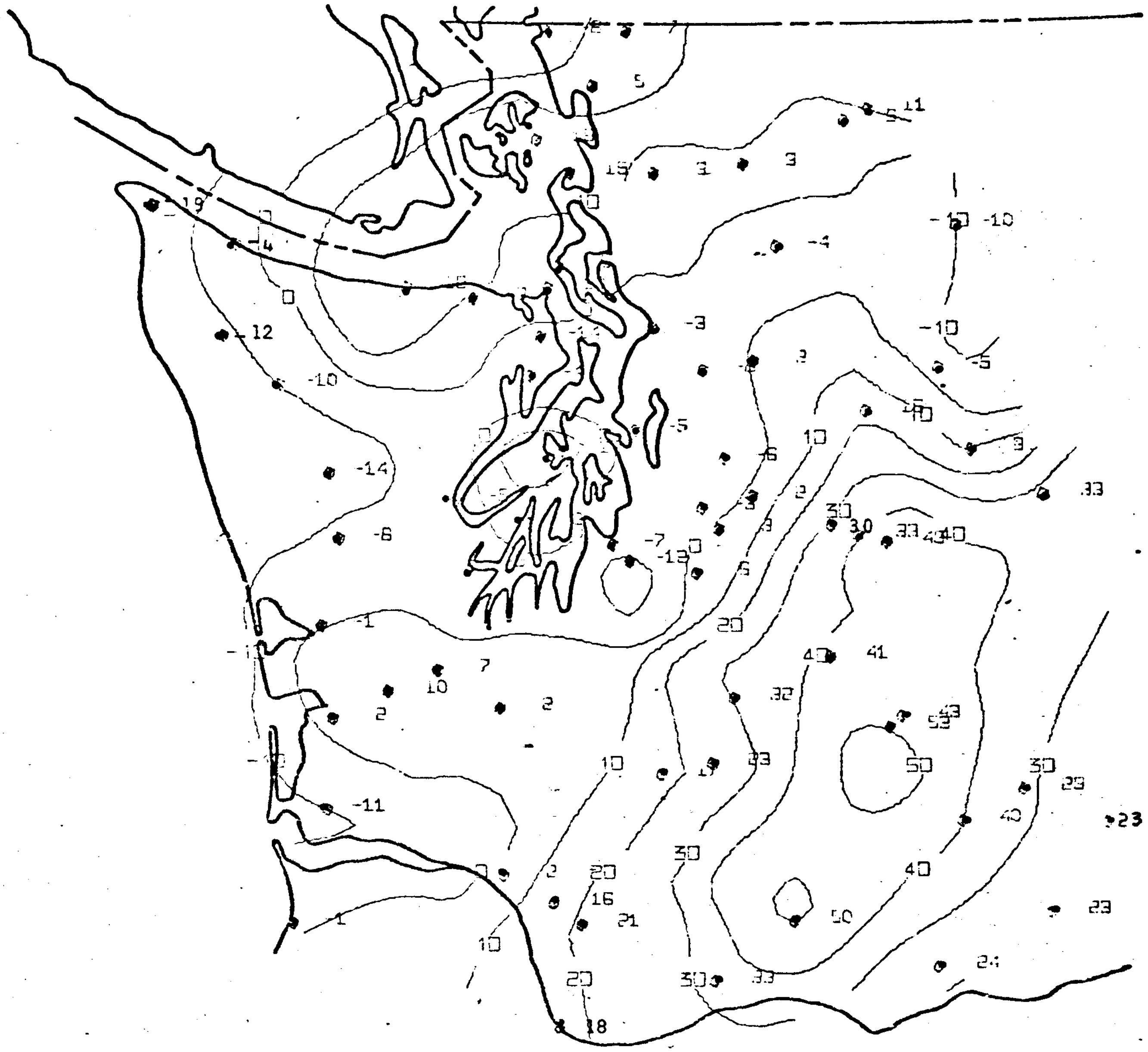
FIGURE 18
SERIAL CORRELATION IN SEPTEMBER FLOWS OF WESTERN WASHINGTON



All values marked are 100 times the actual serial correlation values

CONTOUR INTERVAL - 5

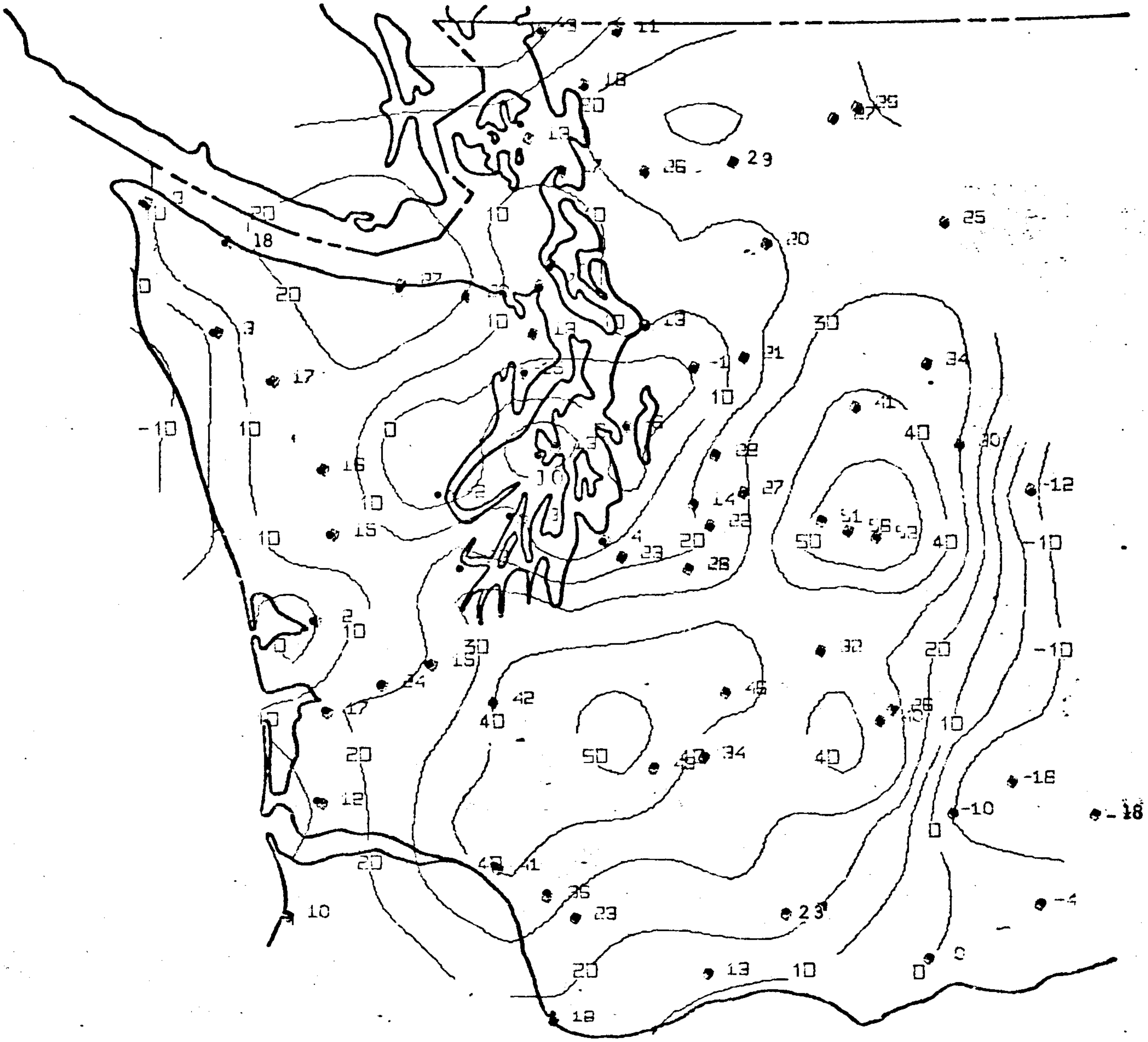
FIGURE 19
SERIAL CORRELATION IN ANNUAL FLOWS OF WESTERN WASHINGTON



All values marked are 100 times the actual serial correlation values

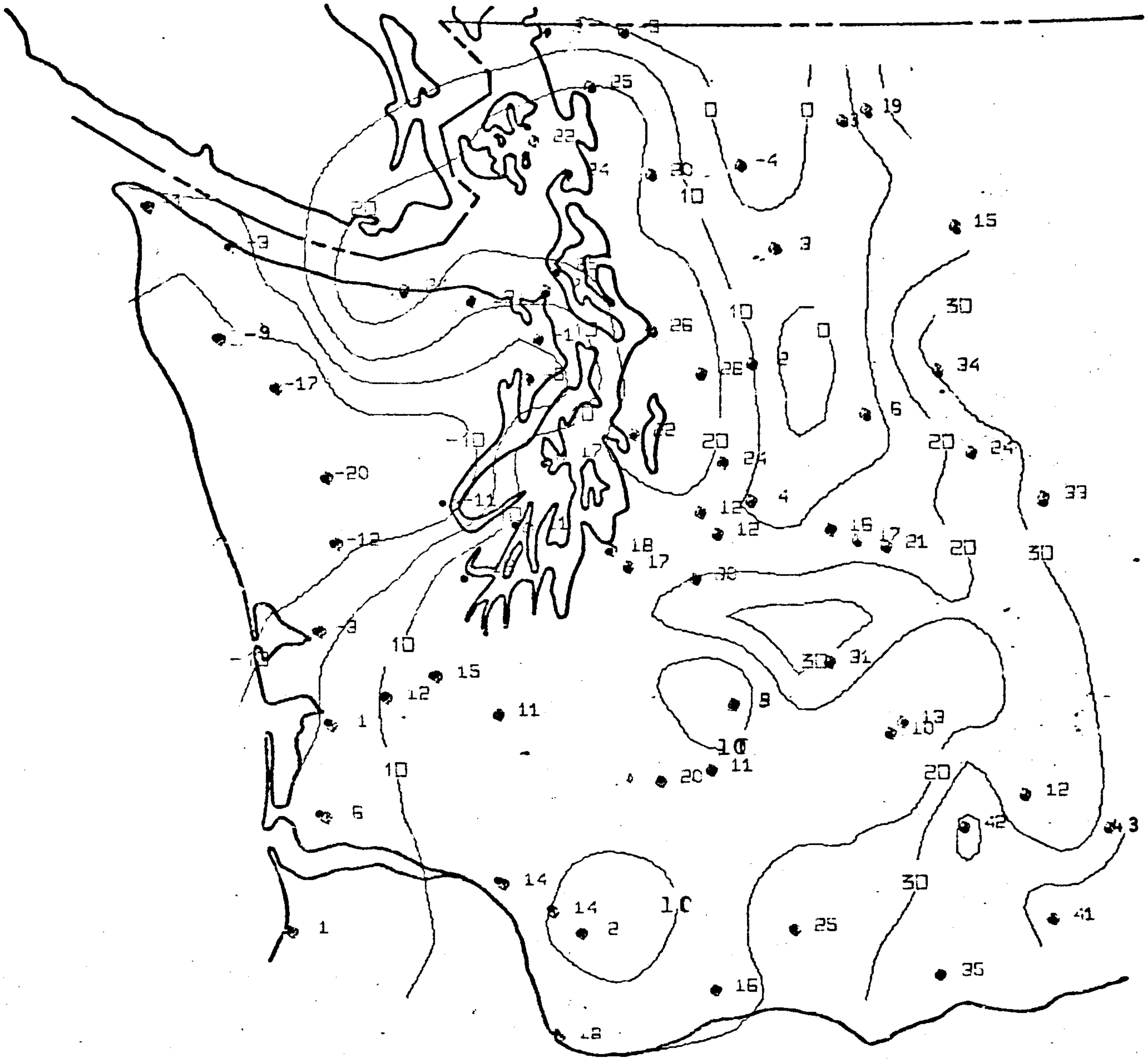
CONTOUR INTERVAL - 10

FIGURE 2 C
SERIAL CORRELATION IN OCTOBER PRECIPITATIONS IN WASHINGTON



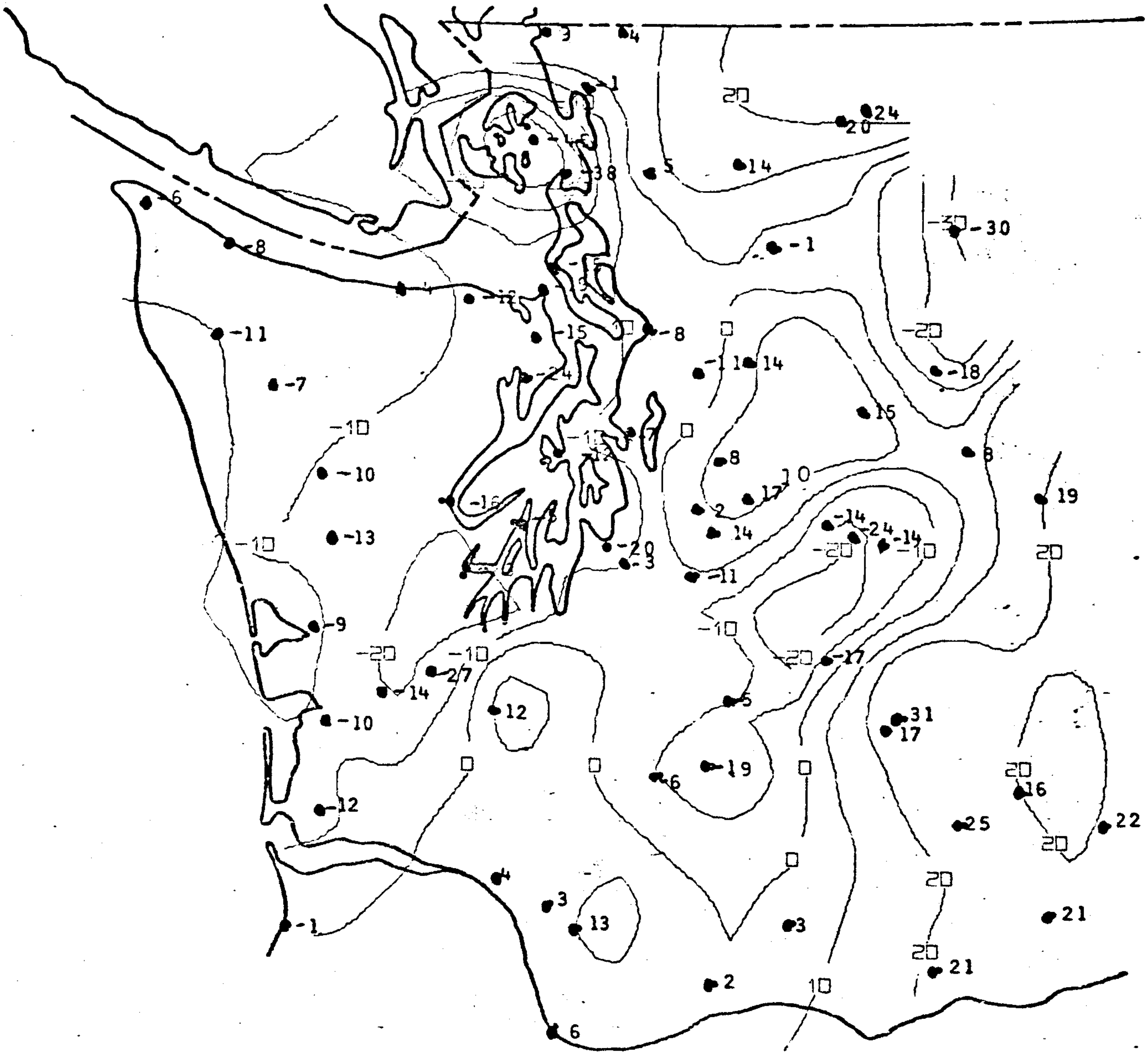
All values marked are 100 times the actual serial correlation values
CONTOUR INTERVAL - 10

FIGURE 21
SERIAL CORRELATION IN NOVEMBER PRECIPITATIONS IN WASHINGTON



All values marked are 100 times the actual serial correlation values
CONTOUR INTERVAL - 10

FIGURE 22
SERIAL CORRELATION IN DECEMBER PRECIPITATIONS IN WASHINGTON

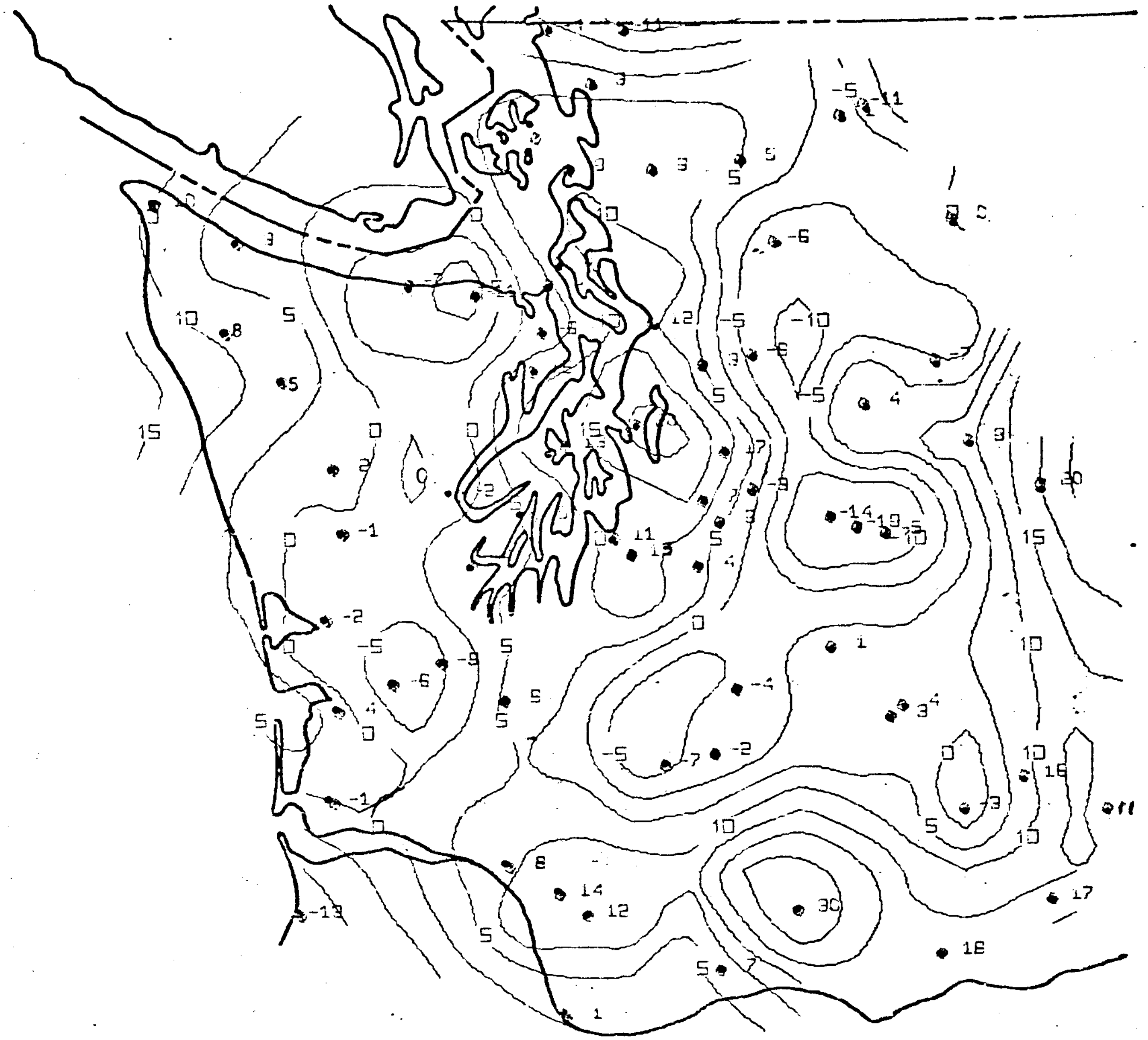


All values marked are 100 times the actual serial correlation values

CONTOUR INTERVAL - 10

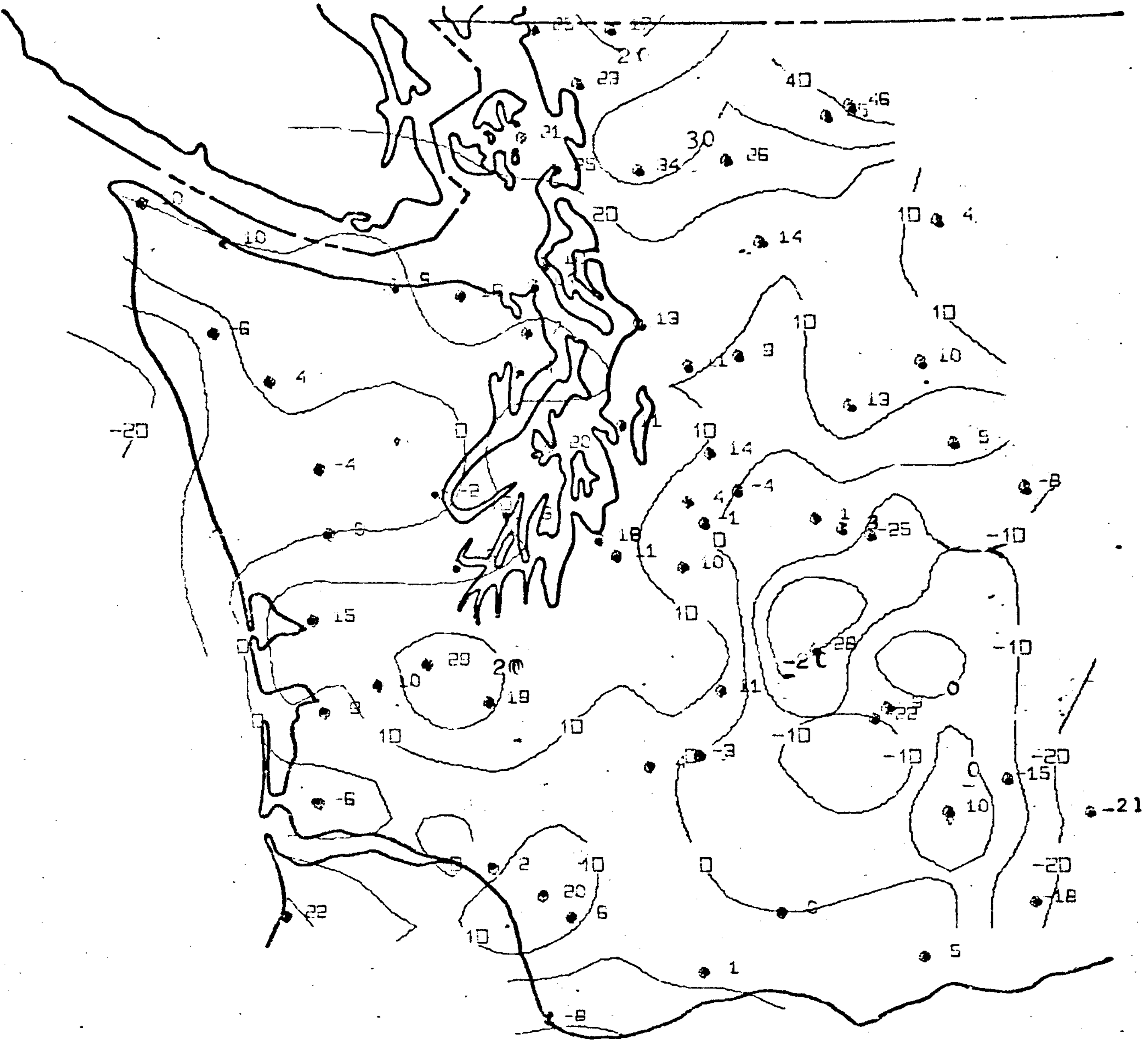
FIGURE 23

SERIAL CORRELATION IN APRIL PRECIPITATIONS IN WASHINGTON



All values marked are 100 times the actual serial correlation values
CONTOUR INTERVAL - 5

FIGURE 24
SERIAL CORRELATION IN MAY PRECIPITATIONS IN WASHINGTON



All values marked are 100 times the actual serial correlation values
CONTOUR INTERVAL - 10

FIGURE 25
SERIAL CORRELATION IN SEPTEMBER PRECIPITATIONS IN WASHINGTON

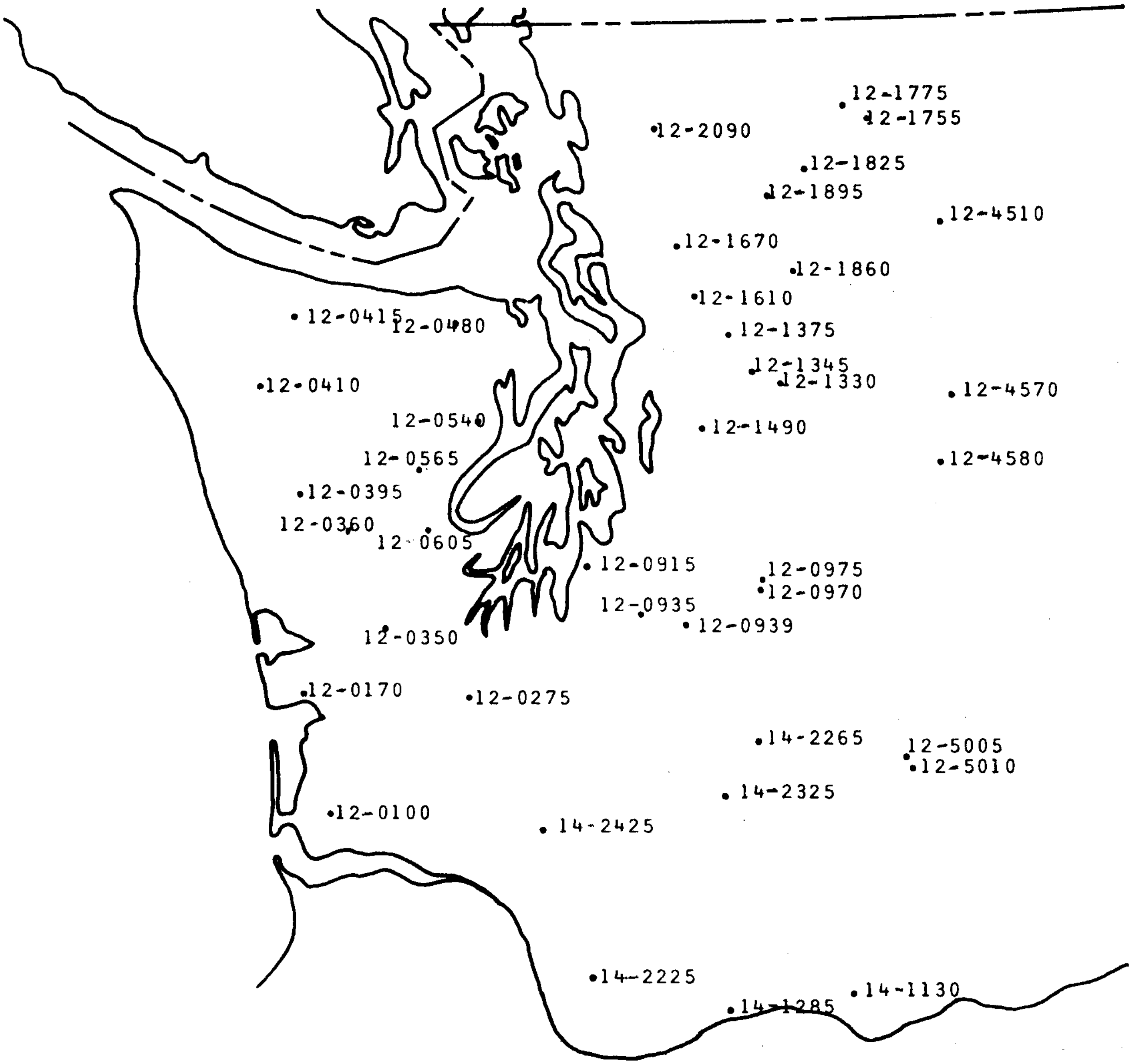


FIGURE 26 Location and Identification Number of Drainage Basins Studied

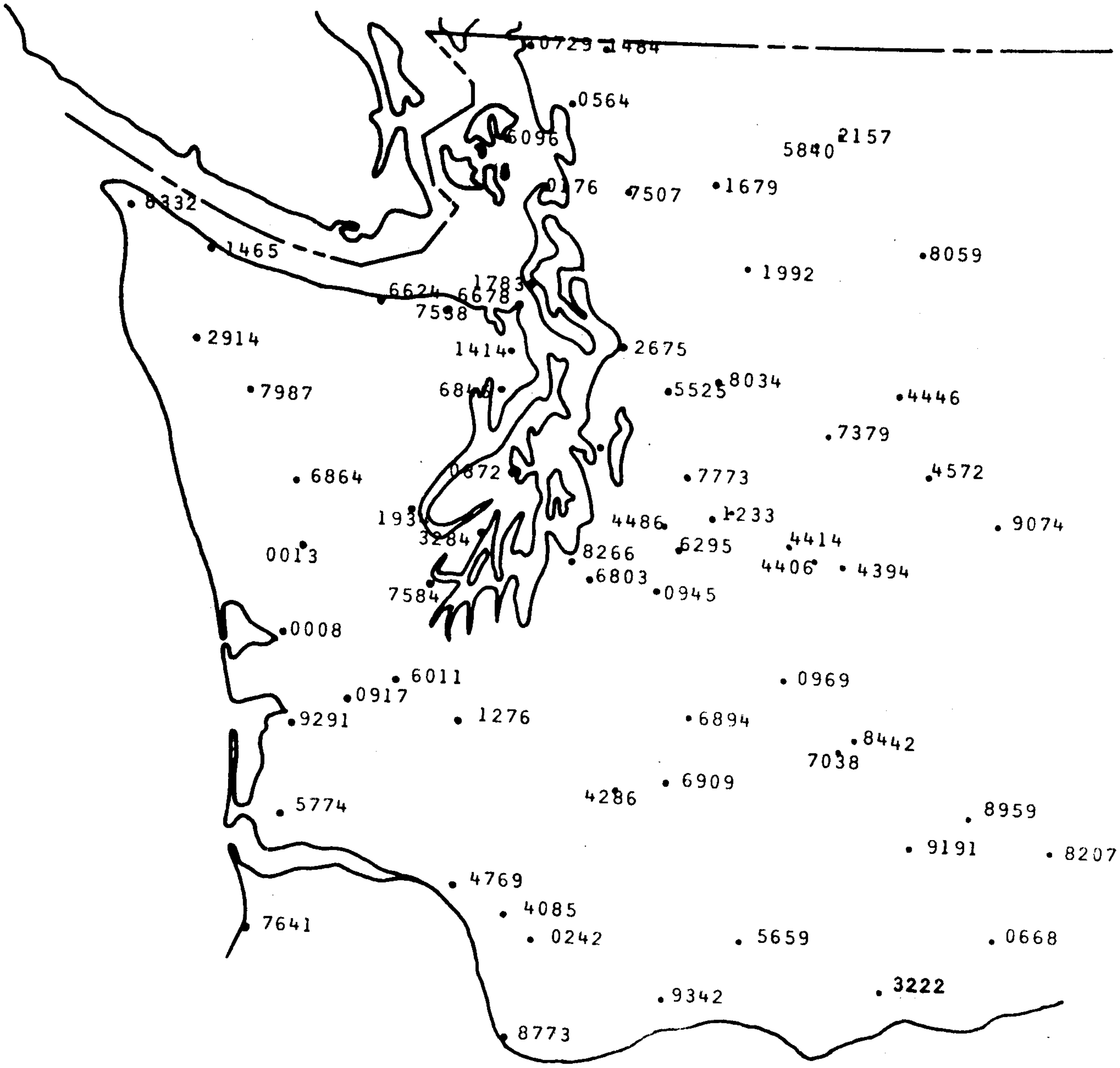


FIGURE 27 Location and Identification Number of Precipitation Stations

TABLE I

Stream Name & Gauging Site*	Identification Number	No. Years of Record
Naselle R. near Naselle	12-0100	38
North R. near Raymond	12-0170	40
Chehalis R. near Grand Mound	12-0275	39
Satsop R. near Satsop	12-0350	38
Wynoochee R. above Save Creek near Aberdeen	12-0360	42
Quinault R. at Quinault Lake	12-0395	56
Hoh R. near Spruce	12-0410	37
Soleduck R. near Fairholm	12-0415	34
Dungeness R. near Sequim	12-0480	44
Duckabush R. near Brinnon	12-0540	29
North Fork Skokomish R. below Staircase Rapids near Hoodsport	12-0565	43
South Fork Skokomish R. near Union	12-0605	37
Chambers Creek below Leach Creek, near Steilacoom	12-0915	22
Puyallup R. near Orting	12-0935	37
Carbon R. near Fairfax	12-0939	38
White R. at Greenwater	12-0970	37
Greenwater R. at Greenwater	12-0975	38
South Fork Skykomish R. near Index	12-1330	56
Skykomish R. near Gold Bar	12-1345	39
Sultan R. near Startup	12-1375	33
Snoqualmie R. near Carnation	12-1490	39
South Fork Stillaguamish R. near Granite Falls	12-1610	37
North Fork Stillaguamish R. near Arlington	12-1670	39
Thunder Creek near Newhalem	12-1755	37
Stetattle Creek near Newhalem	12-1775	34
Cascade R. at Marblemount	12-1825	39
Sauk R. above Whitechuck R. near Darrington	12-1860	37
Sauk R. near Sauk	12-1895	37
South Fork Nooksack R. near Wickersham	12-2090	37
Stehekin R. at Stehekin	12-4510	41
Wenatchee R. at Plain	12-4570	56
Icicle Creek above Snow Creek near Leavenworth	12-4580	31
North Fork Ahtanum Creek near Tampico	12-5005	36
South Fork Ahtanum Creek at Conrad Ranch near Tampico	12-5010	37
Klickitat R. near Pitt	14-1130	39
Wind R. near Carson	14-1285	33
East Fork Lewis R. near Heisson	14-2225	38
Cowlitz R. at Packwood	14-2265	37
Cispus R. near Randle	14-2325	38
Toutle R. near Silver Lake	14-2425	37

*See also Figure 26 for geographic locations.

Table II 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 II (cont.)

River Name	Average Precipitations (cont.)			Serial Correlation in Precipitation of indicated period.					
	July	Aug.	Sept.	Oct.	Nov.	Dec.	Apr.	May	Sept.
Naselle	1.5	2.0	3.4	-.06	.11	.04	-.07	-.07	.08
North	1.1	1.6	2.6	.05	.16	.08	-.19	-.03	.19
Chehalis	.8	1.4	2.3	.06	.27	.13	-.10	-.02	.19
Satsop	1.8	2.4	4.3	-.05	.09	-.08	-.11	-.02	.08
Wynoochee	1.8	2.4	4.3	-.08	.15	-.12	-.13	-.01	0
Quinault	2.4	3.0	5.5	-.14	.16	-.20	-.10	.02	-.04
Holt	2.4	2.6	4.7	-.11	.10	-.13	-.09	.08	-.01
Soleduck	1.9	2.1	3.6	-.08	.11	-.06	-.10	.06	.02
Dungeness	.8	.8	1.2	.05	.04	.05	-.18	.04	.11
Duckabush	.8	.9	1.4	-.04	-.15	-.05	-.24	.18	.04
N.F.Skokomish	1.0	1.3	2.7	-.05	-.02	-.11	-.16	-.02	-.02
S.F.Skokomish	1.0	1.3	2.7	-.05	-.02	-.11	-.16	-.02	-.02
Chambers Creek	.8	1.0	1.7	-.09	.14	.18	-.12	.13	.14
Puyallup	1.2	1.5	2.8	.10	.35	.13	-.04	.06	.11
Carbon	1.1	1.3	2.2	-.03	.26	.24	-.07	.10	.11
White	1.4	1.6	3.0	.05	.25	.21	.02	.07	.05
Greenwater	1.4	1.6	3.0	.05	.25	.21	.02	.07	.05
S.F. Skykomish	1.3	1.7	3.6	.16	.41	.06	.15	.04	.13
Skykomish	1.5	1.8	2.9	-.03	.10	.15	.02	-.03	.10
Sultan	1.5	1.8	2.9	.03	.21	.02	.14	-.08	.09
Snoqualmie	1.7	2.0	3.7	-.06	.28	.24	.08	.17	.14
S.F.Stillaguamish	1.0	1.2	1.8	-.03	.13	.26	-.08	.12	.13
N.F.Stillaguamish	1.3	1.8	3.6	-.04	.20	.03	-.01	-.06	.14
Thunder Creek	1.4	1.8	2.6	.10	.26	.11	.22	-.05	.41
Stetattle Creek	1.4	1.8	2.6	.10	.26	.11	.22	-.05	.41
Cascade	1.4	1.8	2.6	.10	.26	.11	.22	-.05	.41
Sauk nr. Darring.	1.3	1.8	3.4	-.04	.20	.03	-.01	-.06	.14
Sauk nr. Sauk	1.3	1.8	3.4	-.04	.20	.03	-.01	-.06	.14
S.F. Nooksack	1.3	1.7	3.0	.09	.28	.08	.10	.07	.30
Stehekin	.4	.6	1.2	-.10	.25	.15	-.30	0	.04
Wenatchee	.5	.6	1.4	-.05	.34	.34	-.18	-.07	.10
Icicle	.3	.5	.8	.09	.30	.24	.08	.09	.05
N.F. Ahtanum	.3	.4	.5	.53	.40	.10	.17	.03	-.22
S.F. Ahtanum	.3	.4	.5	.53	.40	.10	.17	.03	-.22
Klickitat	.3	.3	.7	.37	.12	.30	.12	.24	.03
Wind	1.0	1.2	2.9	.33	.13	.16	.02	.07	.01
E.F. Lewis	1.3	1.7	3.1	.21	.23	.02	.13	.12	.06
Cowlitz	1.1	1.7	3.0	.32	.46	.08	-.05	-.04	.11
Cispus	.7	1.2	2.2	.23	.34	.11	-.19	-.02	-.03
Toutle	.8	1.4	2.0	.02	.41	.14	.04	.08	.02

Table II (cont.)

River Name	Average Snowfall in inches during		Mean Annual Temp.	Geologic Variable	Baseflow Recession Variable	Basin Orientation	% Area Lakes & Ponds
	Oct.	Dec.					
Naselle	0	0	50.6	4.0	- 23.1	- .753	.01
North	0	0.86	51.0	2.8	- 29.4	.028	.01
Chehalis	.12	1.81	51.2	3.0	- 19.3	.882	.03
Satsop	0	1.88	50.1	2.2	- 23.5	-1.000	.25
Wynoochee	0	1.88	50.1	2.7	- 53.0	- .943	.01
Quinault	0	.41	50.8	3.8	- 26.2	- .558	2.08
Hoh	0	2.92	49.2	3.9	- 24.6	- .082	.10
Soleduck	0	1.40	49.0	3.9	- 40.5	.643	.48
Dungeness	0	.22	49.3	3.9	- 17.6	1.000	.06
Duckabush	0	1.25	50.5	4.0	- 18.3	- .342	.30
N.F. Skokomish	0	3.34	50.8	4.0	- 21.0	- .989	.17
S.F.Skokomish	0	3.34	50.8	4.0	- 35.9	- .783	.25
Chambers Ck.	0	.54	51.4	1.8	- 27.4	.680	1.68
Puyallup	.86	16.58	50.3	2.8	- 14.1	.658	.82
Carbon	0	1.43	46.6	3.3	- 17.8	.433	.25
White	1.76	19.75	43.7	3.4	- 17.2	.960	.46
Greenwater	1.76	19.75	43.7	4.0	- 35.6	.680	.27
S.F.Skykomish	3.17	60.59	49.9	3.7	- 11.3	.266	.90
Skykomish	0	2.12	52.4	3.7	- 17.1	.332	.73
Sultan	0	2.12	52.4	3.7	- 10.0	.000	.40
Snoqualmie	0	2.12	50.1	3.2	- 15.3	.360	.69
S.F.Stillaguamish	0	2.00	50.5	3.2	- 18.1	.284	.08
N.F.Stillaguamish	.06	7.24	48.5	3.2	- 13.7	.148	.01
Thunder Ck.	.08	13.12	49.1	3.8	- 20.1	.912	.10
Stetattle Ck.	.08	13.12	50.1	4.0	- 10.9	- .572	.47
Cascade	.08	13.12	50.1	3.7	- 24.3	.406	.17
Sauk nr. Darring	.03	5.61	48.5	3.2	- 15.6	.596	.13
Sauk nr. Sauk	.03	5.61	48.5	3.0	- 26.7	.835	.01
S.F. Nooksack	0	2.94	47.4	3.7	- 18.2	- .249	.29
Stehekin	.06	28.54	48.6	3.8	- 22.5	- .488	.28
Wenatchee	.06	18.09	43.6	3.6	- 20.6	- .659	1.30
Icicle	1.03	28.06	48.0	4.0	- 22.2	- .496	.48
N.F. Ahtanum	.38	12.93	48.2	3.6	- 22.2	.209	.01
S.F. Ahtanum	.38	12.93	48.2	3.0	- 36.0	.229	.01
Klickitat	0	13.68	46.6	3.2	-102.2	-1.000	.09
Wind	0	8.05	47.8	3.6	- 53.0	- .939	.03
E.F. Lewis	0	2.10	49.7	3.7	- 29.7	.078	.01
Cowlitz	.59	11.65	49.4	3.8	- 20.0	- .936	.45
Cispus	.02	10.04	50.3	3.7	- 46.0	.360	.15
Toutle	0	.46	49.6	3.7	- 33.3	.167	.93

Table II (cont.)

River Name	Basin Slope Ft/Mi	Ratio Variable	Drainage Area mi^2
Naselle	52	29.9	54.8
North	11	46.2	219
Chehalis	13	46.8	895
Satsop	13	19.5	299
Wynoochee	89	14.5	74.1
Quinault	79	9.9	264
Hoh	96	4.6	208
Soleduck	131	13.7	83.8
Dungeness	217	5.5	156
Duckabush	191	8.8	66.5
N.F.Skokomish	294	12.6	57.2
S.F.Skokomish	94	17.9	76.3
Chambers Creek	16	5.8	104
Puyallup	88	4.0	172
Carbon	107	5.0	78.9
White	93	5.0	216
Greenwater	124	12.0	73.5
S.F.Skykomish	102	10.6	355
Skykomish	87	9.9	535
Sultan	132	11.8	75
Snoqualmie	43	9.9	603
S.F.Stillaguamish	76	12.0	119
N.F.Stillaquamish	60	11.4	262
Thunder Creek	234	11.5	105
Stetattle Creek	582	8.5	21.4
Cascade	143	6.6	168
Sauk nr. Darring.	120	8.1	152
Sauk nr. Sauk	53	5.5	714
S.F. Nooksack	114	9.9	103
Stehekin	160	19.6	344
Wenatchee	79	14.4	591
Icicle	82	74.7	193
N. F. Ahtanum	155	13.7	68.9
S. F. Ahtanum	221	9.3	24.8
Klickitat	41	4.5	1297
Wind	85	15.4	225
E. F. Lewis	87	33.3	125
Cowlitz	167	8.3	287
Cispus	122	8.0	321
Toutle	68	10.8	474

Table III Array of Dependent Variables

River Name	Serial Correlation in Flows of Indicated Period									
	Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
Naselle	.93	.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 III (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	.96	.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 IV Correlation Between Precipitation and Precipitation Serial Correlation for Period Indicated

Period	Correlation Coefficient
Annual	+0.0426
October	-0.4565
November	-0.3099
December	-0.6812
January	-0.2532
February	+0.3681
March	-0.2633
April	-0.0648
May	-0.1923
June	-0.5749
July	-0.4969
August	-0.1130
September	+0.1799