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RIVER CHANNEL PATTERNS: A GEOGRAPHIC ANALYSIS

By

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CHAPTER I

INTRODUCTION

Purpose of This Study

River channel patterns, "the aspect of a stream channel as seen from the air, on a map,"[1] pose several fundamental problems which have defied satisfactory explanation. Such problems include adequate classification of channel patterns, together with why, and under what conditions, particular channel pattern types occur. In recent years, the literature on the subject has varied from broad deductive overviews of geographers such as W. M. Davis at the turn of the century, to detailed analytical studies performed by civil engineers and hydrologists using complex statistical tools, working in the laboratory on flume experiments, or on the micro-scale in the field. Thus, the modern trend in the study of channel patterns, as indeed in fluvial geomorphology as a whole, has been first, a shift from the general to the specific, and second, a shift away from the field of geography. It is the intention of the present study to reexamine the above mentioned problems employing a geographic approach. It proposes to take a broad overview, analogous to that attempted by Davis, but retaining the quantitative, empirical approach perfected by subsequent workers.

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[1] J. C. Brice, "Streams," Laboratory Studies in Geology, No. 207 (1962), 1.

The overview involves a consideration of fields of study beyond the sphere of hydrology or civil engineering, but which, nevertheless, have a direct bearing upon fluvial processes. This study, then, in keeping with fundamental geographic methodology, is a synthesis incorporating such diverse disciplines as climatology and geology with hydrology and geomorphology. Herein lies the immense value of geography in the realm of research; a value which is sadly neglected, even by geographers themselves. As intended, this interdisciplinary synthesis brings into meaningful relationship important factors largely overlooked in previous studies.

In the past, the majority of field studies concerning channel patterns have confined themselves to restricted geographic environments, and consequently conclusions reached can only be valid in terms of the geographical conditions obtaining in those specific areas where the studies were carried out. It is illustrated in this paper that a spatial approach covering a wide variety of geographic environments is valuable in the establishment of general principles regarding the occurrence of channel pattern types which are devoid of any geographic bias.

It is the intention of this paper to demonstrate the significance of a geographic approach in resolving some of the apparent contradictions that can arise from more confined viewpoints, in a spatial sense as well as an academic one, and also to give a better overall appreciation of the controls acting upon channel patterns and their variation over space.

More specifically, the present research is directed primarily toward the significance of climatological relationships in the occurrence of various types of channel pattern. The purpose of this study is to investigate the hypothesis that the spatial distribution of channel pattern type is related to climate. The rationale for this hypothesis, which is examined in more detail later, is that climate affects the spatial variation in the discharge variability of rivers; and that discharge variability in turn contributes to channel pattern determination.

Format of the Study

First, the problem of definition and classification of channel patterns, together with the associated problem of terminology, are considered; and an alternative scheme of channel pattern description is forwarded. This scheme, being quantitative in nature and avoiding the traditional classificatory process, is more precise and comprehensive than previous schemes. By this scheme, each and every channel pattern can be described, precisely, without the need for subjective decisions regarding whether or not a particular channel pattern meets all the requirements of a particular class.

Next follows a brief review of the literature concerning channel patterns, with a particular emphasis on that part of it relating to the supposed relative importance of the various factors which contribute to the occurrence of differing channel pattern configurations. This paper illustrates the contradiction and confusion that have arisen therefrom and demonstrates, that by resorting to the climatic base of river channel patterns, many of these contradictions can be resolved and a more meaningful overview obtained.

In attempting to substantiate the hypothesis that the distribution of channel pattern types is controlled by climate, a spatial analysis of the relationship between climate, discharge variability, and channel pattern is presented. In order to quantify and define these relationships in more mathematical terms, a series of regression analyses are also carried out.

The relationship of channel pattern to climate having been assessed on a spatial level, it is then reviewed in a temporal sense in an investigation of the correlation of paleoclimatic change with the existence of geomorphic evidence of corresponding channel pattern changes.

CHAPTER II

DEFINITION AND CLASSIFICATION OF RIVER CHANNEL PATTERNS

Inadequacies of Previous Classificatory Schemes

River channel patterns are commonly classified into meandering, braided, and straight.[1] There are several major disadvantages with this scheme.

First, it is not comprehensive; it is not inclusive of all channel pattern configurations. For example, implicit in most definitions of a meandering stream is that is possesses at least a minimum degree of sinuosity, even though the minimum requirement is by no means agreed upon, and is quite often not even stated in a particular study. A meander is also normally required to display a relatively uniform recurrence of S-shaped curves, normally associated with the meandering process; though again, the minimum required degree of uniformity is undetermined. Finally, a meandering pattern is associated only with the floodplain section of a stream, where it experiences no confining valley walls and is then free to change the position of its channel periodically. Thus, Matthes defines a meandering stream as: "Any letter S-shaped channel pattern, fashioned in alluvial materials, which is free

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[1] L. B. Leopold and M. G. Wolman, "River Channel Patterns: Braided, Meandering and Straight," United States Geological Survey Professional Paper, 282B (1957).

to shift its location and adjust its shape as a part of a migratory movement of the channel as a whole down the valley." He goes on to state: "Mere tortuity, or crooked channel alignments are not classed as meanders."[2] Werner's definition is somewhat similar: "The continually changing sinuous course developed by silt bearing streams in erodible alluvial sediments."[3] From the above discussion, it is clear that the generally accepted trifold classification into meandering, braided, and straight does not include ingrown or incised meanders with confining valley walls.[4] Nor does it include those patterns which have a high degree of sinuosity, but which lack any regular uniformity of curves. Conversely, streams that have a regular uniformity of curves, but a relatively low degree of sinuosity are also excluded from this scheme. Leopold, Wolman, and Miller attempted to broaden the scheme slightly by distinguishing between sinuous and meandering streams, their dividing line being a sinuosity of 1.5 (channel length divided by valley length).[5] This represents only a minor improvement. Furthermore, although the work of Leopold, Wolman, and Miller must be commended for its use of quantitative criteria in this connection, the value of 1.5 is purely

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[2] G. H. Matthes, "Basic Aspects of Stream Meanders," Transactions of the American Geophysical Union, XXII (1941), 632.

[3] P. Werner, "On the Origin of River Meanders," Transactions of the American Geophysical Union, XXXII (1951), 898.

[4] See G. H. Dury, Face of the Earth (Middlesex, England: Penguin Books Inc., 1959), pp. 97-98 for a distinction between these two channel pattern types.

[5] L. B. Leopold, M. G. Wolman, and J. P. Miller, Fluvial Processes in Geomorphology (San Francisco: W. H. Freeman and Co., 1964), p. 281.

arbitrary and holds no geomorphic significance. Werner also earlier recognized the difficulty of classifying rivers with low sinuosities and introduced his own term: "The earlier meander stages, that is before the development of loops, may be designated serpentines."[6]

Several workers have formulated alternative classificatory schemes. Schumm, for example, distinguishes between five classes of stream channel patterns: tortuous, irregular, regular, transitional, and straight.[7] The distinction between the first three is made by virtue of the regularity of changes of direction, or in other words, degree of approximation to the meandering form. The last two classes are distinguished on the basis of varying degrees of sinuosity. Dury recognizes eight classes: meandering, braided, straight, straight simulating, delta distributary, anabranching, reticulate, and irregular.[8] Even this Dury thought to be incomplete. Although these classifications are certainly more comprehensive, they suffer from the inherent subjectivity involved in their interpretation and application.

The second major problem encountered in channel pattern classification is the transitional nature of the majority of stream channel patterns and the difficulty of erecting definable boundaries between each type. Schumm, for example recognized the existence of "a continuum

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[6] Werner, "On the Origin of River Meanders," p. 898.

[7] S. A. Schumm, "The Sinuosity of Alluvial Rivers on the Great Plains," Bulletin of the Geological Society of America, LXXV (1963), 1089.

[8] G. H. Dury, "Relation of Morphometry to Run-off Frequency," in Water, Earth and Man, ed. by R. J. Chorley (London: Methuen and Co., LTD., 1969), p. 419.

of channel patterns."[9] Leopold and Wolman also realized that "there is a gradual merging of one pattern into another."[10] Consequently, many naturally occurring channel patterns possess elements of two or more channel pattern types within a single pattern. Thus, for example, a braided river may have a meandering overall plan or may have meandering anabranches. Conversely, a meandering river may have channel bars or small islands in its channel. Truly meandering, braided, or straight streams in nature are in the minority; most channel patterns are transitional, rendering any classificatory scheme highly tenuous.

A final objection that may be raised in regard to channel pattern classification is in connection with the standard terminology used. The recognition by many authors of a straight channel pattern is unjustifiable. In reality, all river sections above two or three miles in length show some deviation, however small, from a straight line path, and thus possess some degree of sinuosity. W. M. Davis asserts: "No straight river occurs in a state of nature."[11] In practice, straight is used to refer to those streams which have a low degree of sinuosity in comparison to a meandering stream and is thus a grossly misleading term. A braided river is "one which flows in two or more anastomosing channels around alluvial islands."[12] Although the definition would appear

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[9] Schumm, "The Sinuosity of Alluvial Rivers on the Great Plains," p. 1089.

[10] Leopold and Wolman, "River Channel Patterns: Braided, Meandering and Straight," p. 1.

[11] W. M. Davis, "Development of River Meanders," Geological Magazine, X (1903), 4.

[12] Leopold and Wolman, "River Channel Patterns: Braided, Meandering and Straight," p. 53.

straight forward, the term braid (being analogous to a braid of hair) implies a highly anastomosing stream, and streams that have only occasional channel islands are not commonly regarded as braided.

This standard terminology is unsatisfactory, inadequate, and is dropped from the present study.

Descriptive Indexes

Sinuosity, in general terms, is a quantitative measure of the deviation of the actual path of a river channel from an equivalent straight line course, and it is normally expressed as a numerical value derived by dividing the former by the latter. This value has a possible theoretical lower limit of 1.0 for a straight channel course and on occasions can exceed 4.0 or more, but the value for the greater majority of naturally occurring streams lies in the range 1.1 to 1.8. More specifically, the procedure adopted for obtaining values for sinuosity varies slightly from author to author as recorded in Table 1.

Table 1

MEASURES OF SINUOSITY

$\frac{\text{Length of a channel in a given curve}}{\text{Wavelength of the curve}}$ -- Leopold and Langbein, 1968

$\frac{\text{Thalweg Length}}{\text{Valley Length}}$ -- Leopold, Bagnold, Wolman, and Brush, 1960

$\frac{\text{Stream Length}}{\text{Valley Length}}$ -- Schumm, 1963

$\frac{\text{Channel Length}}{\text{Length of Meander Belt Axis}}$ -- Brice, 1964

In practice, the values obtained from each of these indexes varies very little. All measure, essentially, the same thing; the only real difference is one of expression. All of these indexes have one major disadvantage--they can only be applied to those rivers, or parts of rivers, which have extensive floodplains. Confined streams, no matter how sinuous they may be, whose valley sides extend to its banks cannot be described using established sinuosity indexes. The value for sinuosity in these cases can never exceed 1.0, for stream length is equal to valley length. Mueller recognized this problem and formulated his own scheme of indexing sinuosity in an attempt to overcome it.[13]

This scheme involves the recognition of three types of sinuosity. Total sinuosity is computed by dividing channel length of a particular stretch of stream by the crow-fly distance for the same stretch, regardless of the configuration of the valley. Total sinuosity is comprised of two component parts--hydraulic sinuosity and topographic sinuosity--which vary in their relative proportion depending upon the degree to which a stream is confined. Topographic sinuosity is valley length divided by crow-fly length, while hydraulic sinuosity is stream length divided by valley length. Thus, for confined streams which possess no floodplains, topographic sinuosity is a maximum and hydraulic sinuosity is a minimum; while for unconfined streams which have wide floodplains, hydraulic sinuosity is a maximum and topographic sinuosity a minimum.

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[13] J. E. Mueller, "An Introduction to the Hydraulic and Topographic Sinuosity Indexes," Annals of the Association of American Geographers, LVIII, No. 2 (1968).

This can be restated in terms of topographic control[14] (exercised by the restraining influence of valley walls): such that in the former case topographic control is a maximum, and in the latter case it is a minimum (Fig. 1). All the indexes in Table 1 measure only hydraulic sinuosity, whereas all sinuosities are affected by topographic control to some extent for, as Leighley pointed out, streams become prisoners of the valleys they cut and occupy.[15] However, for many rivers, such as the lower Mississippi which has a very wide floodplain, the amount of effect valley sides have in determining sinuosity is negligible.

Mueller's approach represents, to the mind of the present author, a tremendous step forward; and his basic idea regarding topographic control upon sinuosity will be employed as a tool to aid quantitative description of channel patterns in this research. However, a major shortcoming of Mueller's work is that he concerned himself with classification. He attempts to distinguish between a sinuous and a meandering pattern, experiencing all the attendant difficulties of such a task that have been discussed earlier. Furthermore, Mueller disregards the braided pattern from his classificatory scheme as he considers it to be "generally a local quality."[16] Anastomosity in stream channel patterns is far too common and persistent a feature to be ignored and is as fundamental to any consideration of channel patterns, as a whole, as is sinuosity.

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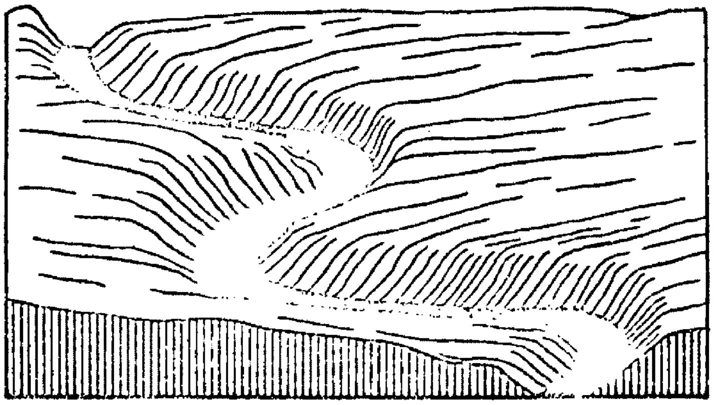
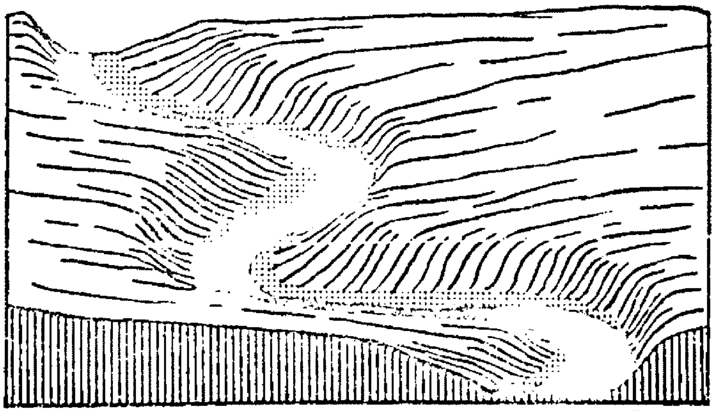
[14] A numerical value for topographic control can be derived from the formula: $\frac{\text{topographic sinuosity-1}}{\text{total sinuosity-1}} \times 100$

[15] J. B. Leighley, "Meandering Arroyos of the Dry Southwest," Geographical Review, XXVI (1936).

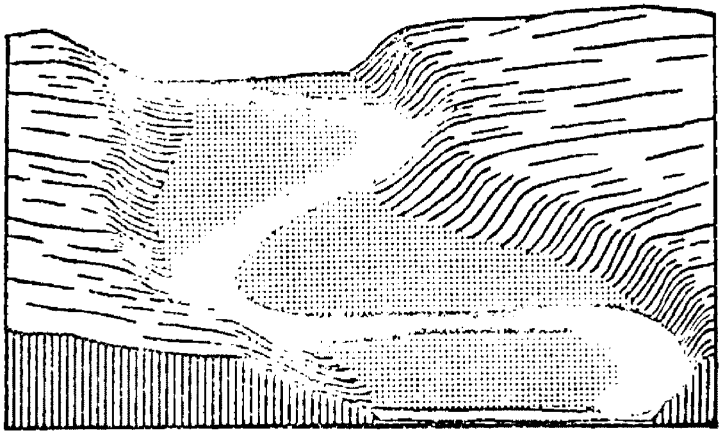
[16] Mueller, "An Introduction to the Hydraulic and Topographic Sinuosity Indexes," p. 373.



(A) Stream confined;
topographic control maximum.



(B) Stream partially confined;
topographic control intermediate.



(C) Stream unconfined;
topographic control minimum.

Fig. 1.--Channel-valley relationship in three hypothetical stream sections. Topographic sinuosity is replaced with hydraulic sinuosity as river floodplain expands.

To the author's knowledge, no established index of anastomosity exists in the literature. Consequently, an original index that will be outlined later is employed in this study.

Comprehensive Scheme for Channel Pattern Description

It is suggested that all streams can be adequately described, as regards their channel pattern characteristics, in terms of three numerical values: total sinuosity, involving any deviation from a straight line; percentage of topographic control of that sinuosity; and anastomosity which takes all channel islands into account. Throughout the remainder of this study, particular stream patterns will be referred to in the following manner: for example, 2.43(66)0.73, (Bluestone River near Pipestem, West Virginia--Fig. 2).

The first figure is total sinuosity; the figure in parenthesis, topographic control; and the final figure, anastomosity. From these figures, it may be deduced that the Bluestone River is a highly sinuous river with a restricted floodplain and a small degree of anastomosity.

This scheme is considered to be more valuable than existing schemes in that it is totally comprehensive; and that, furthermore, it negates the need for an unsatisfactory classification of channel patterns into straight, sinuous, meandering, or braided.

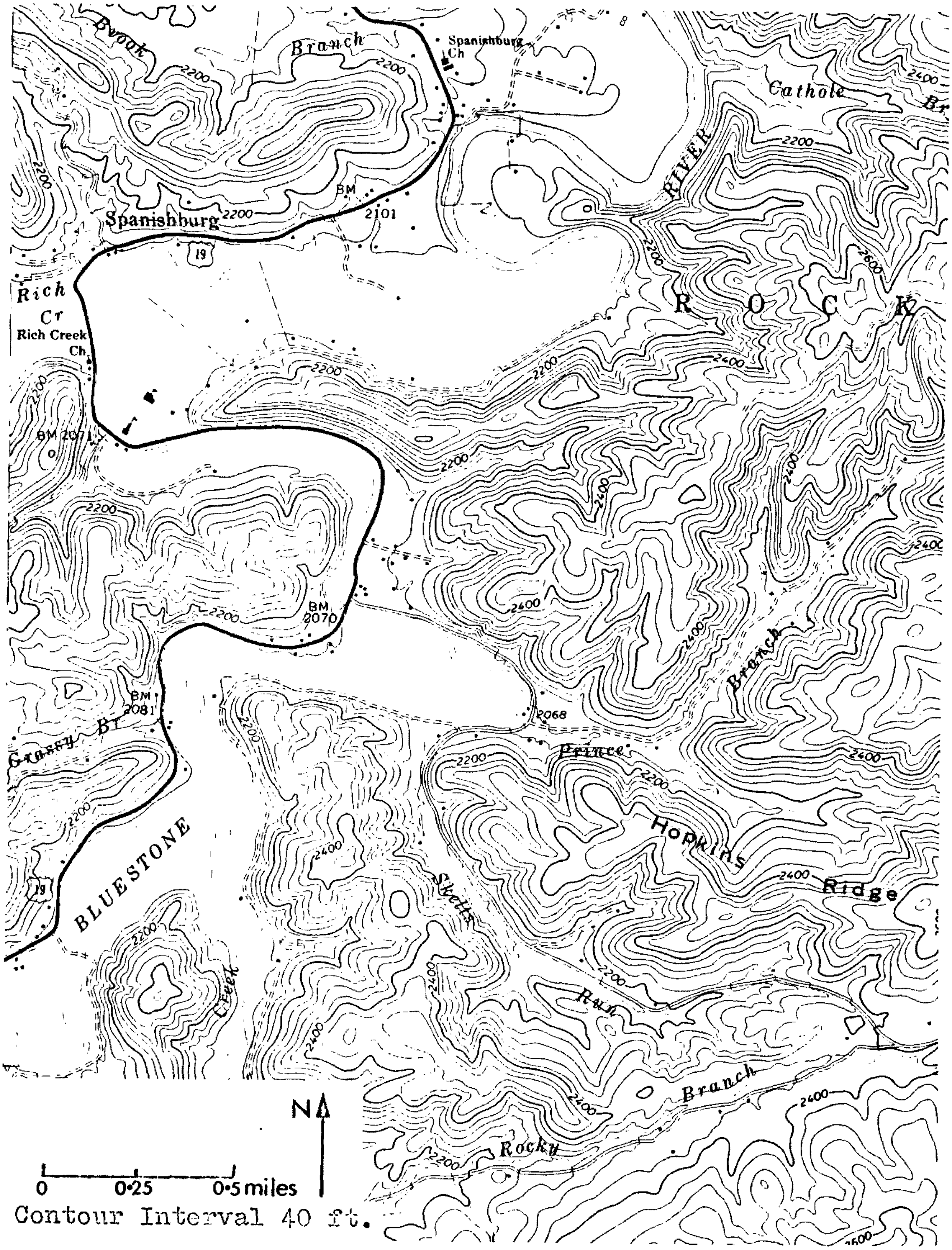


Fig. 2.--Athens Quadrangle, West Virginia, showing the Bluestone River, near Pipestem, 2.43(66)0.73. Note the variance between hydraulic sinuosity-1.2525-and topographic sinuosity-1.9423.

CHAPTER III

REVIEW OF THE LITERATURE

Direction of Current Research

Research into river channel patterns over the past century has taken three broad related forms. First, the development of theories to explain channel patterns, especially the meandering type; second, attempts to establish relationships between elements of symmetry of the meandering pattern; and finally, the analysis of the relative importance of the factors contributing to the occurrence of one or another type of pattern.

Theories concerned with river channel patterns have developed from the simple deductive explanations of von Baer[1] and Davis,[2] to complex analytical schemes involving transverse oscillations,[3] sine generated curves and random walk models,[4] thermodynamic analogies,[5] and

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[1] K. E. von Baer (1860) quoted in P. Werner, "On the Origin of River Meanders," p. 898.

[2] Davis, "Development of River Meanders."

[3] Werner, "On the Origin of River Meanders."

[4] L. B. Leopold and W. B. Langbein, "River Meanders and the Theory of Minimum Variance," United States Geological Survey Professional Paper, 422H (1968).

[5] A. E. Scheidegger, "A Thermodynamic Analogy for Meander Systems," Water Resources Research, III, No. 4 (1967).

and kinematic waves.[6] A comparative analysis of these theories poses several interesting questions, but such an analysis is beyond the scope of this geographic study.

Several workers have attempted to establish relationships between the elements of symmetry of meanders, such as wavelength, amplitude, radius of curvature, and hydraulic variables such as width and discharge. This has been done, for instance, by Jefferson,[7] Bates,[8] Schumm,[9] and particularly by Leopold and co-workers (Leopold and Maddock;[10] Leopold and Miller;[11] Leopold and Wolman[12]).

Although this line of study is extremely fruitful, adequate summaries of it are common in the literature on channel patterns;[13] and any consideration of it, being outside the main purpose of the present

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[6] L. B. Leopold and W. B. Langbein, "River Channel Bars and Dunes-Theory of Kinematic Waves," United States Geological Survey Professional Paper, 422L (1968).

[7] M. Jefferson, "Limiting Width of Meander Belts," National Geographic Magaine, XIII (1902).

[8] R. E. Bates, "Geomorphic History of the Kickapoo Region, Wisconsin," Bulletin of the Geological Society of America, L (1939).

[9] S. A. Schumm, "Meander Wavelength of Alluvial Rivers," Science, CLVII (1967).

[10] L. B. Leopold and T. Maddock, Jr., "Hydraulic Geometry of Stream Channels and Physiographic Implications," United States Geological Survey Professional Paper, 252 (1953).

[11] L. B. Leopold and J. P. Miller, "Ephemeral Streams--Hydraulic Factors and Their Relation to the Drainage Net," ibid., 282A (1956).

[12] L. B. Leopold and M. G. Wolman, "River Meanders," Bulletin of the American Geological Society of America, LXXI (1960).

[13] For example, see A. E. Scheidegger, Theoretical Geomorphology (Berlin: Springer Verlag, 1969), pp. 14ff.

study, would be superfluous. The major purpose of this research is to analyze the factors which influence the form of channel patterns and to what extent these factors may have a bearing upon any implications of spatial variations of channel pattern type.

Relative Importance of Factors Controlling Channel Pattern

From analysis of the literature, the broad hydraulic variables which are considered to have a major effect in determining channel patterns are as follows: Width-depth ratio of a stream; stream bank and bed resistance; sediment load (amount and character); gradient; and nature of discharge.

Width-depth ratio is undoubtedly important in regulating the degree of sinuosity and anastomosity. It is an empirical fact that "Braided reaches, taken as a whole are wider and shallower than individual reaches carrying the same flow,"[14] and that greater sinuosities occur with small width-depth ratios.[15] The existence of this relationship is readily observable and requires little discussion. Problems arise, however, in attempting to determine the nature of this relationship.

For example, Dury prefers high width-depth ratio as the major contributing factor in the formation of the anastomosing pattern; the increased hydraulic radius resulting in increased bed shear and, thus,

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[14] Leopold and Wolman, "River Channel Patterns: Braided, Meandering and Straight," p. 53.

[15] Leopold, Wolman, and Miller, <u>Fluvial Processes in Geomorphology</u>, p. 296.

deposition of channel bars dividing stream flow.[16] Schumm, on the other hand, argues that it is the formation of channel bars initially, causing concentration of erosion at the banks, which is responsible for increased width.[17]

The relative resistance of the banks of a stream as compared to that of the stream bed also appears to be a strong contributing factor. It is evident, however, that this factor is intimately related to width-depth ratio. Streams that have a resistant bed, but weak banks, will tend to be wide and shallow favoring anastomosity. Alternatively, those streams which possess strong banks and relatively weak beds will be deep and narrow, promoting sinuosity rather than anastomosity. Thus, there appears to be an equilibrium between bank resistance and width, for as Lane pointed out, the greater the width-depth ratio, the greater will be the ratio of velocity acting on the bottom to that acting on the sides of the channel.[18] Mackin favors bank resistance as the key factor in determining channel pattern.[19] Fahnestock, however, thought that this factor was relatively unimportant in producing the channel patterns observed of the White River in Washington State.[20] Here, anastomosing

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[16] Dury, Face of the Earth.

[17] Schumm, "The Sinuosity of Alluvial Rivers on the Great Plains."

[18] E. W. Lane, "Stable Channels in Erodible Material," Transactions of the American Society of Civil Engineers, CII (1937).

[19] J. H. Mackin, "Cause of Braiding by a Graded River," Bulletin of the Geological Society of America," LXVII (1957).

[20] R. K. Fahnestock, "Morphology and Hydrology of a Glacial Stream, White River, Mt. Rainier, Washington," United States Geological Survey Professional Paper, 422A (1963).

and sinuous sections of the river alternate through a stretch where there are no discernible changes in the nature of the channel banks.

The amount and character of the sedimentary load carried by a stream has been considered by many authors to be of prime importance in controlling the nature of its channel pattern. Anastomosity in streams is often associated with an overloaded state, and hence aggradation. Thus, Hjulstrom maintains, "A fundamental fact for understanding the braiding of rivers is the great sedimentary load they carry."[21] Similarly, in Russell's view, "Available load seems to be the factor separating meandering streams from braided streams."[22]

However, contrary to these views, Leopold and Wolman conclude that anastomosity is not necessarily an indication of excessive total load.[23] They also indicated that aggradation can take place without anastomosity.[24] Fahnestock, in his study of the White River channel patterns, observed that active anastomosity was associated with net degradation.[25] Matthes asserted that meandering takes place in both aggrading and degrading streams.[26] Thus, it would appear that the

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[21] F. Hjulstrom, "The Geomorphology of the Alluvial Outwash Plains of Iceland and the Mechanics of Braided Rivers," Proceedings of the Eighth General Assembly, Seventeenth International Congress, International Geographic Society, (1952), 310.

[22] R. J. Russell, "Louisiana Stream Patterns," Bulletin of the American Association of Petroleum Geologists, XXIII, No. 8 (1939), 1200.

[23] Leopold and Wolman, "River Channel Patterns: Braided, Meandering and Straight."

[24] Ibid.

[25] Fahnestock "Morphology and Hydrology of a Glacial Stream, White River, Mt. Rainier, Washington."

[26] Matthes, "Basic Aspects of Stream Meanders."

under-loaded or the over-loaded state of rivers is not inherently characteristic of either anastomosity or sinuosity, and that aggradation and degradation do not appear to be basic factors in the formation of channel patterns.

The importance of sediment load in channel pattern determination would seem to be related more to stream competence rather than capacity, or to caliber of sediment load rather than overall amounts. Schumm stresses the importance of the relative proportion of traction load and suspension load: "Another possible distinction between straight (i.e., anastomosing) and sinuous streams is in the proportions of the components of total sediment load. In a wide, shallow channel much of the sediment transported is in the form of bed load. In a narrow, deep channel most of the sediment transported is wash load."[27] Leopold, Wolman, and Miller observed in flume experiments that anastomosity occurs in preference to sinuosity with the addition of poorly sorted sediment, the coarse fraction which the river cannot move being concentrated into bars at the center of the stream.[28]

Sediment load characteristics as a whole are closely linked with the other factors controlling channel pattern that have so far been discussed. For example, the more coarse the grains comprising the channel, the more susceptible are the channel banks to collapse under the influence of gravity and undermining by the stream. On the other hand, coarse grained channel beds are protected from erosion, for only on very seldom

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[27] Schumm, "The Sinuosity of Alluvial Rivers on the Great Plains," p. 1089.

[28] Leopold, Wolman, and Miller, Fluvial Processes in Geomorphology.

occasions does the stream have the required energy to lift into suspension large particles from the bottom.

These conditions lead to wider and shallower channels and, consequently, increasing probability of anastomostiy. By the same virtue, the finer the sediment, the deeper the stream, and the greater the sinuosity. Wolman and Brush, undertaking flume experiments using two median sizes of sand (0.67 mms and 2 mms), discovered that channels in the coarse sand tended to widen and aggrade with increased discharge, rather than deepen as occurred with channels in the fine sand.[29] Schumm observed that the higher the percentage of silt and clay in natural channels, the more cohesive were the banks and, consequently, the smaller the width-depth ratio.[30]

Gradient is another factor which is considered to be of considerable importance, though again the degree of importance attached to it varies from author to author. Leopold and Wolman contend that anastomosing reaches, taken as a whole, are steeper than undivided reaches carrying the same flow. They base this conclusion upon a log/log plot of bankfull discharge against channel slope for seventy streams where a regression line ($S=0.06Q^{-0.44}$) separates meandering from braided streams.[31] This is meaningless for, although they clearly define

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[29] M. G. Wolman and L. C. Brush, Jr., "Factors Controlling the Size and Shape of Stream Channels on Coarse Noncohesive Sands," United States Geological Survey Professional Paper, 282G (1961).

[30] S. A. Schumm, "The Shape of Alluvial Channels in Relation to Sediment Type," ibid., 352B (1960).

[31] Leopold and Wolman, "River Channel Patterns: Braided, Meandering and Straight," p. 59.

meandering streams (sinuosity 1.5), nowhere in their work do they present the criteria they used in defining a braided stream. Furthermore, consideration of channel slope as a causative factor in channel pattern formation is also meaningless as it is, itself, dependent upon sinuosity. A highly sinuous stream will naturally have a smaller value for channel slope than a less sinuous stream, assuming valley gradient to be the same in both cases. Valley gradient is a far more significant parameter in this connection as its value is independent of channel pattern. Although Schumm could find no progressive change of sinuosity with valley gradient from his research in the Great Plains,[32] the results of the present author's research, conducted over a much wider area, indicate that a meaningful relationship does in fact exist between valley gradient and channel pattern.

Discharge is indisputably one of the most important hydraulic variables controlling channel morphology. The significance of discharge in controlling the dependent hydraulic variables, particularly width, depth, and velocity, is well documented.[33] However, there exists some dispute as to which characteristic of discharge is the most significant with special reference to channel patterns.

As a result of his research, Schumm came to the conclusion that "discharge does not affect the sinuosity of the channel."[34] However,

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[32] Schumm, "The Sinuosity of Alluvial Rivers on the Great Plains."

[33] M. G. Wolman, "The Natural Channel of the Brandywine Creek, Pennsylvania," United States Geological Survey Professional Paper, 271 (1955).

[34] Schumm, "The Sinuosity of Alluvial Rivers on the Great Plains," p. 1089.

Schumm considered only mean annual discharge which, in geomorphic terms, has little meaning. The smallest rills display the same characteristics of channel morphology and channel pattern as do the largest rivers.

The degree of importance attributed to variability of discharge in respect to channel pattern again varies depending upon the author concerned. D. J. Doeglas, for example, favors this factor to the exclusion of all others: "Large and sudden variations in run-off seem to form braided rivers. A more regular run-off throughout the year gives a meandering river. The gradient and the available sediment load seem to be of little importance."[35] However, after research on the channel patterns of the White River, Fahnestock concludes that "rapid discharge variation is eliminated as a cause for braiding in most streams."[36]

Dependent, Semi-Dependent and Independent Variables

From this brief review of the literature pertaining to the possible relative contributions of individual factors to channel pattern form, two common features readily stand out--confusion and contradiction. Morisawa, for example, in the final analysis can only conclude: "Sinuosity probably results from a number of interacting factors, or at one time and under certain conditions meanders arise from one cause, and under other conditions they occur for a different reason."[37]

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[35] D. J. Doeglas, "Meandering and Braided Rivers," Geologie en Mijnbouw, XIII, No. 9 (1951), 298.

[36] Fahnestock, "Morphology and Hydrology of a Glacial Stream, White River, Mt. Rainier, Washington," p. 58.

[37] M. Morisawa, Streams (New York: McGraw-Hill Book Co., 1968), p. 141.

This confusion arises largely from the failure of many authors to recognize the differing degrees of independence of the variables they deal with and, thus, the tendency to become entangled in a discussion of dependent variables. Table 2 shows the relationship and degree of dependency of the variables so far discussed. They have been classified into independent, semi-dependent, and dependent after the manner of Bloom.[38] However, in all other respects the scheme differs markedly from his. As can be seen, the dependent variables--width-depth, anastomosity-sinuosity, channel gradient, and bank resistance--are characterized by reflexive relationships and a very complex interdependency. Up to present, it has been impossible to establish a causative relationship between them. Workers who have attempted to do this have been faced with the "chicken and egg" problem; the hopeless task of separating cause and effect. By the same virtue, any attempt to isolate a dependent variable and to determine the intensity of its relationship with another dependent variable is rendered unrealistic and, consequently, conclusions vary from author to author.

The semi-dependent variables--valley gradient, sedimentary load, and variability of discharge--together control the dependent variables. They are not characterized by the intimate association displayed by the dependent variables and are, for all practical purposes, unrelated one to the other. Consequently, at this level, the establishment of causative relationships with dependent variables is justified.

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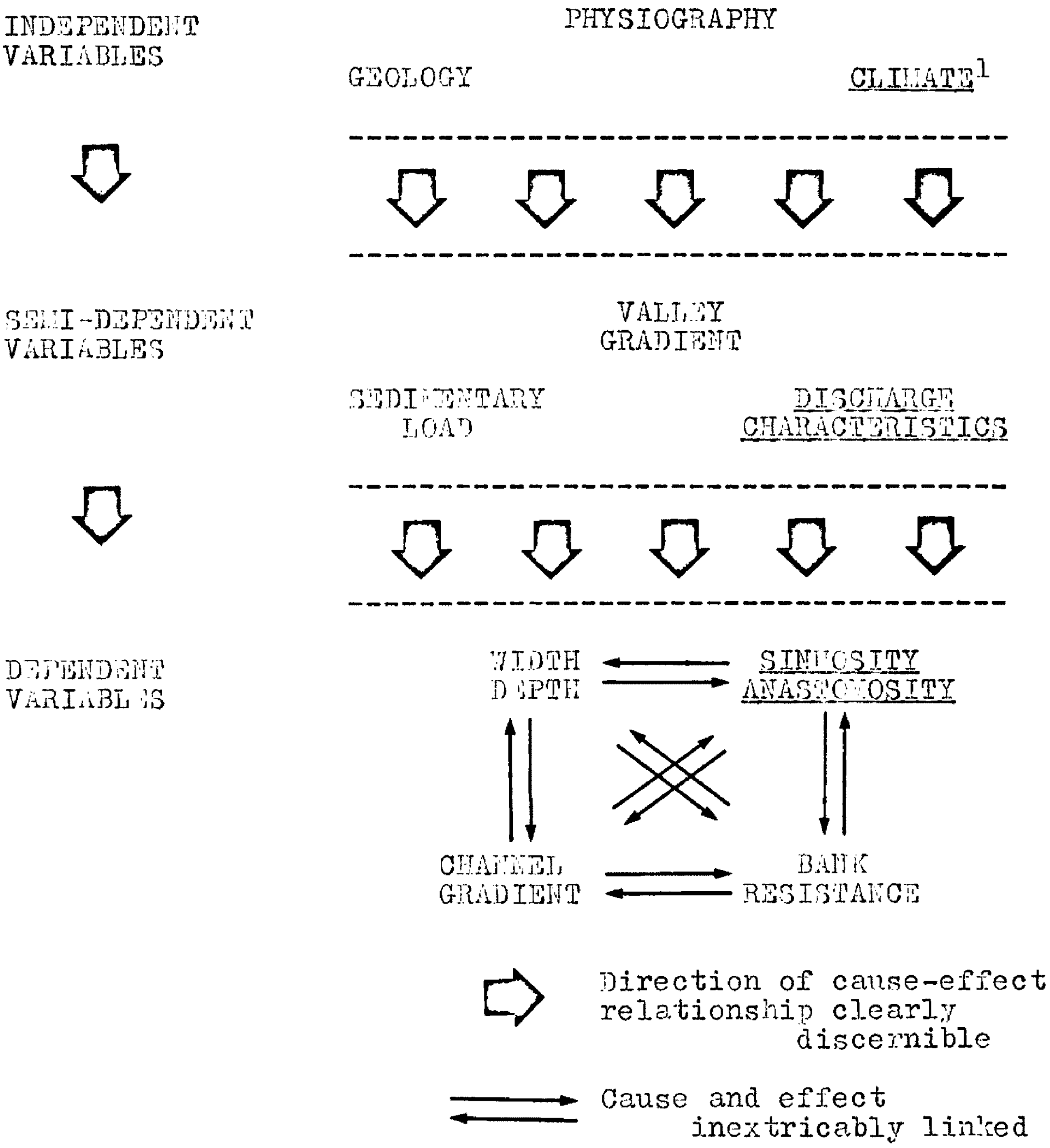
[38] A. L. Bloom, The Surface of the Earth (Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1969), pp. 64-66.

TABLE 2

THE RELATIONSHIP BETWEEN SOME OF THE MAJOR VARIABLES AFFECTING CHANNEL PATTERN



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[1] The relationship between the underlined variables is the major concern of the present research.

Most research concerning the controls upon and the relationship between hydraulic variables stop at this point and consider discharge, sediment load, and valley gradient as independent variables. This present research broadens the scope beyond the boundaries of the hydraulic system to include a consideration of the factors which in turn control the hydraulic independent variables.

These hydraulic variables then become demoted to semi-dependent variables. The independent variables now become climate, physiography, and geology. Since neither the independent nor the semi-dependent variables are mutually interrelated, cause and effect relationships between these two levels are especially well defined. The primary value of considering these independent variables is in obtaining a more meaningful insight into the controls upon the dependent hydraulic variables. A great deal of the contradiction that has arisen regarding the relative importance of one or another of the semi-dependent variables in determining anastomosity-sinuosity results from the fact that field research into this problem in the past has been conducted in a wide variety of differing geological, physiographical, and climatological regions; and thus the results are not comparable. It is evident that the relative importance of each of the semi-dependent variables in controlling channel pattern varies spatially in accordance with spatial variations in the independent variables. Herein lies the justification for a spatial analysis of channel patterns as it relates to the spatial variation of independent variables.

Climatic Base of River Channel Patterns

To the author's knowledge, there is only one comprehensive study of the effect of climate on channel pattern.[39] In Hjulstrom's study, based upon experimental research by Friedkin,[40] he argues that climate controls the discharge of rivers; and that in turn the degree of turbulence is proportional to discharge. He then hypothesizes that meander wavelength is directly proportional to the degree of turbulence. On these lines, he attempts to relate climate to sinuosity. However, his conclusions are based purely on surmise; no empirical proof of the relationship between channel pattern and climate is presented. This study aims, by empirical research and quantitative analysis, to investigate this relationship in more detail and to examine the validity of a climatic base for river channel patterns. It is hypothesized here that climate controls channel pattern, primarily through the medium of variability of discharge.

A rationale for this may be sought in two possible mechanisms. First, "Rapidly fluctuating changes in stage contribute to the instability of the transport regime and to erosion of the banks."[41] Second, under conditions of highly variable discharge there is a greater need for temporary storage of sedimentary load in the form of channel bars

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[39] F. Hjulstrom, "Climatic Change and River Patterns," Geografiska Annaler, H I-2 (1949).

[40] J. F. Freidkin, A Laboratory Study of the Meandering of Alluvial Rivers (U.S. Waterways Engineering Experiment Station 40, 1945).

[41] Leopold, Wolman, and Miller, Fluvial Processes in Geomorphology, p. 294.

during periods of relatively low flow. In any event, irregularity of discharge favors a relative increase in the width of the stream.[42]

Variability of discharge is known to be a feature of arid and semi-arid areas, due largely to the irregularity and intensity of rainfall in these regions, together with the comparative lack of vegetation.[43] Discharge variability is also a feature of cool, continental climates where annual temperature range is most marked (Fig. 3a). Here, annual snow-melt causes high flows in spring and high evaporation rates lead to low flows in the late summer and fall.

The relationship of channel patterns to climate is further strengthened by more subtle climatic controls. For example, in the climatic regions where variability of discharge is most marked, mechanical weathering appears to preside over chemical weathering. In the cool, temperate continental regions freeze-thaw activity is most significant, decreasing in relatively higher and lower latitudes.[44] The large, diurnal temperature range that is characteristic of arid and semi-arid regions (Fig. 4a) may also be significant in promoting mechanical weathering; though this process, involving rapid expansion and contraction, is open to some question. Ollier considers this process to be effective: "In arid regions, there is likely to be less chemical

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[42] P. Birot, The Cycle of Erosion in Different Climates, trans. by C. Ian Jackson and Keith M. Clayton (London: B. T. Batsford LTD., 1968), p. 45.

[43] V. A. Conrad, Methods in Climatology (Mass.: Harvard University Press, 1946).

[44] J. K. Fraser, "Freeze-thaw Frequencies and Mechanical Weathering in Canada," Arctic, XII (1959).

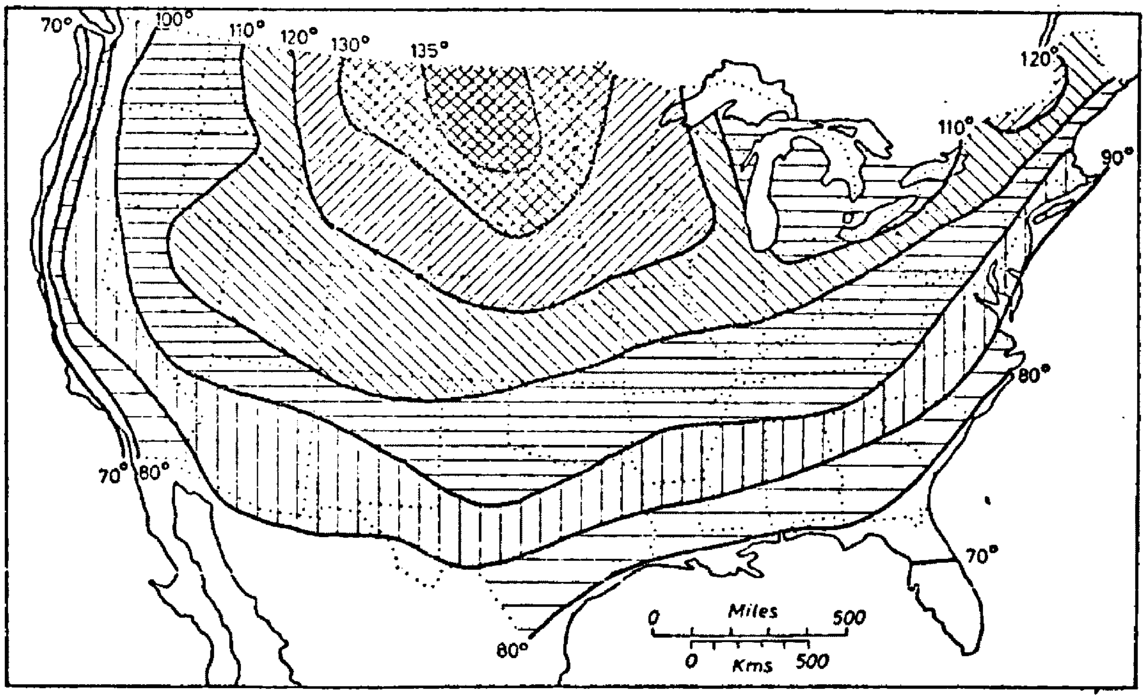

Fig. 3a.--Average annual temperature range, U.S.A.; degrees Fahrenheit. (after Visher 1945)

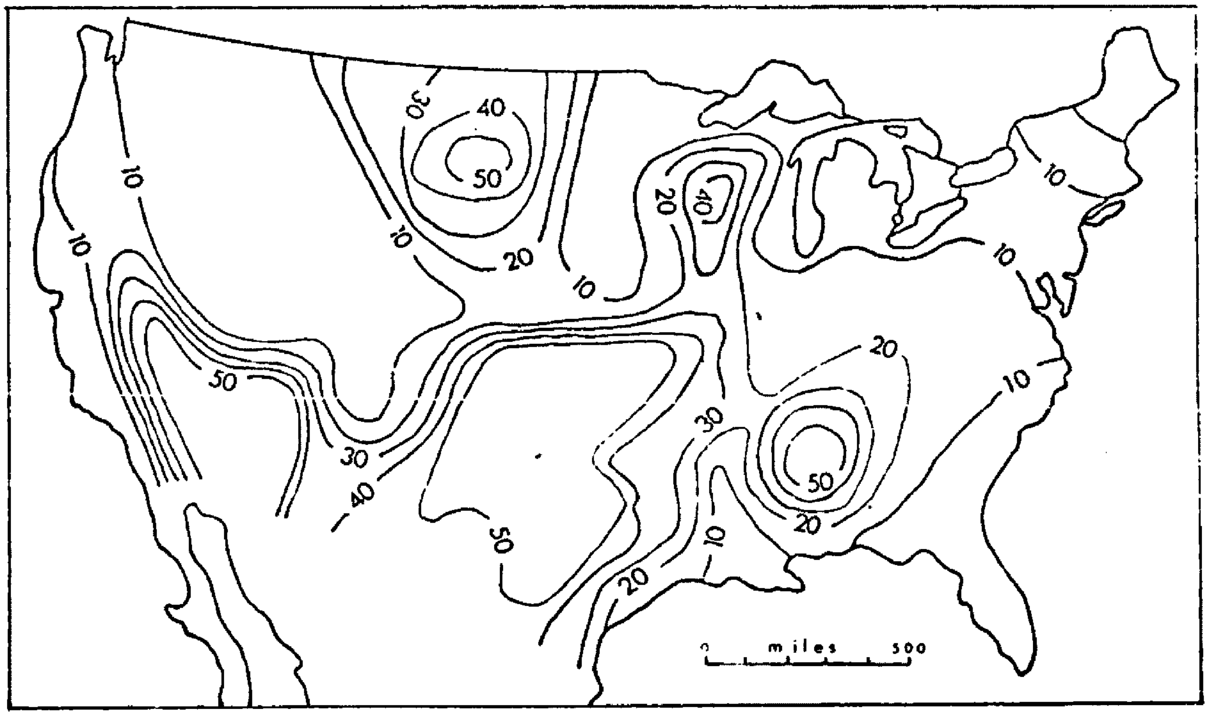

Fig. 3b.--Average annual discharge variability, U.S.A.

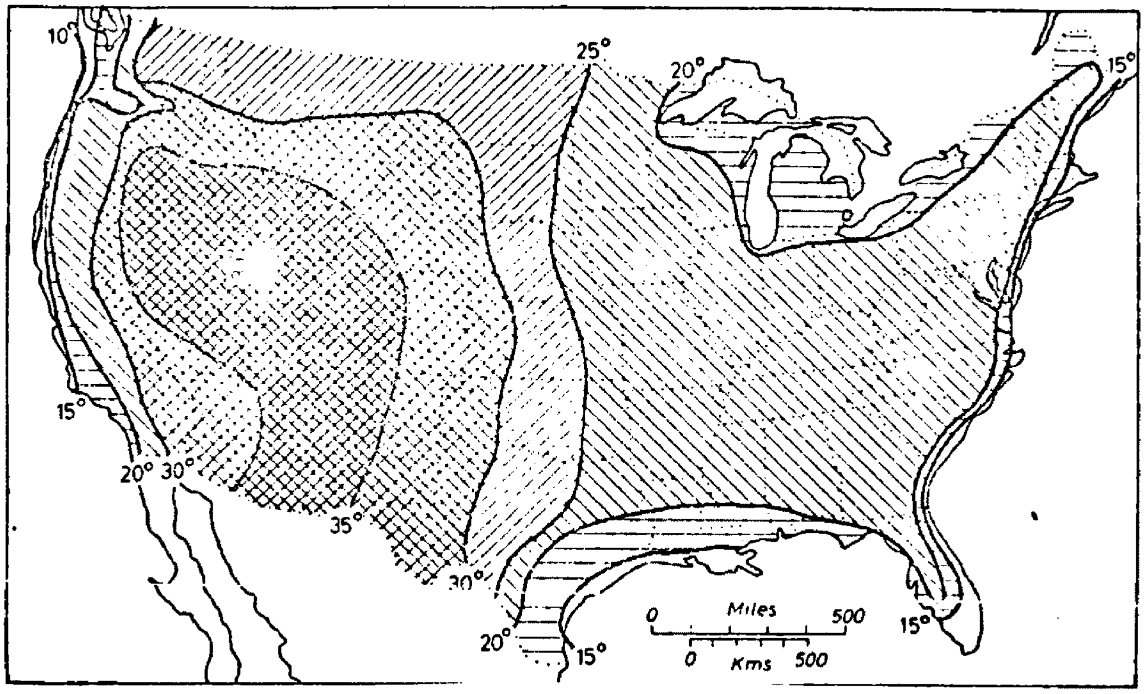

Fig. 4a.--Average daily temperature range in the shade, U.S.A.; degrees Fahrenheit. (after Visher 1945)

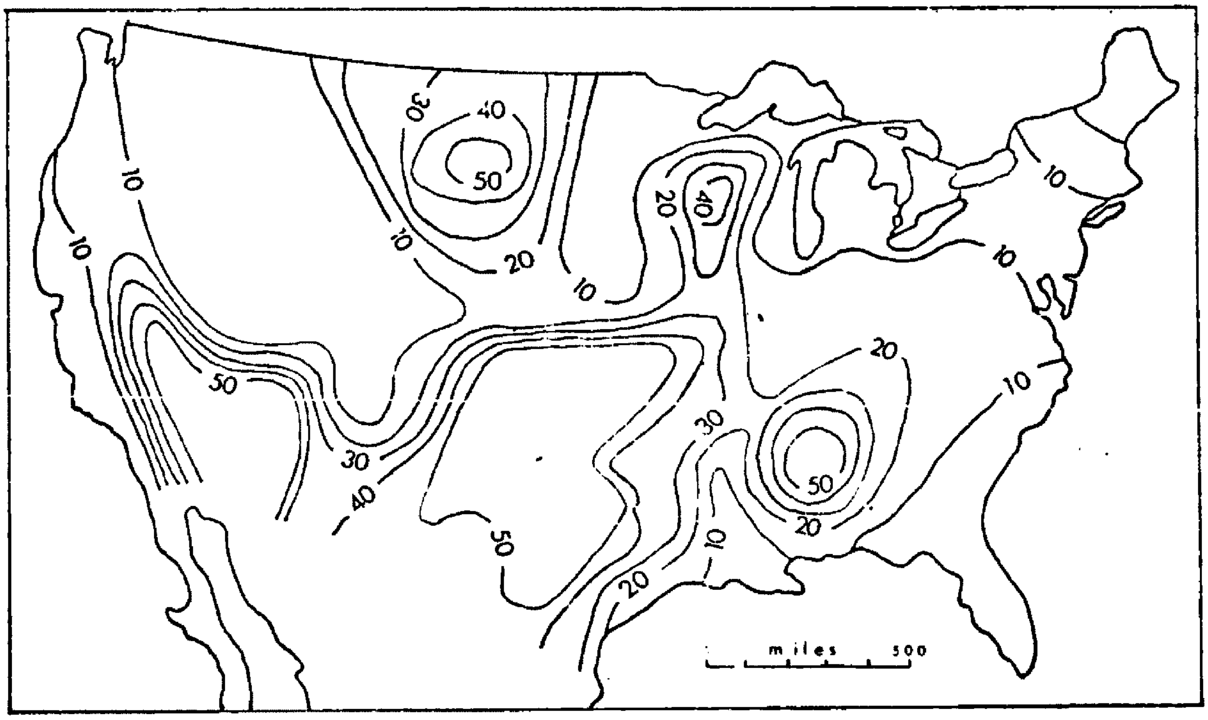

Fig. 4b.--Average annual discharge variability, U.S.A.

weathering. There is much physical weathering, often producing large angular debris."[45] Peltier,[46] on the other hand, following Blackwelder,[47] discounted insolation weathering in desert areas and omitted it from his scheme of weathering in different climates. Mechanical weathering products tend to be composed, in large part, of coarse, rudaceous material.[48] This means that the sediment load of the rivers flowing through a region of mechanical weathering will be characterized by large grain caliber and a correspondingly high proportion of traction load in relation to dissolved or suspended load. These conditions tend to favor anastomosity over sinuosity. Elsewhere in the more humid marine climates, increased moisture and shorter periods of temperatures below freezing hasten chemical reactions, and the relative importance of mechnaical fracturing is reduced.[49] Here sinuosity is favored above anastomosity, due to the character of sediment load in these regions.

Climate also affects channel pattern, via its control over vegetation density. In arid and semi-arid regions where vegetation density is small, variability is intensified due to the reduction of

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[45] C. D. Ollier, Weathering (Edinburgh: Oliver and Boyd LTD., 1969), p. 111.

[46] L. Peltier, "The Geographic Cycle in Periglacial Regions as it is Related to Climatic Geomorphology," Annals of the Association of American Geographers, XL (1950).

[47] E. Blackwelder, "The Insolation Hypothesis of Rock Weathering," American Journal of Science, XXVI (1933).

[48] K. I. Lukashev, Lithology and Geochemistry of the Weathering Crust, trans. from Russian by N. Kaner (Jerusalem: Israel Program for Scientific Translations, 1970), p. 162.

[49] Leopold, Wolman, and Miller, Fluvial Processes in Geomorphology, p. 40.

rainfall interception. Even more significant in this connection is that the relative sparsity of vegetation along river edges means that the river banks are more susceptible to erosion. This factor further intensifies the probability of high values of anastomosity in regions of high discharge variability in semi-arid and continental climates and conversely high values of sinuosity in regions of low discharge variability in humid marine climates.

CHAPTER IV

THE STUDY

Research Methods

To evaluate the hypothesis as stated in the preceding chapter, fifty-four separate observations were made, ranging in location over the entire continental United States and covering a wide variety of climatic, physiographic, and geologic environments.[1] Climate over the study area varies from cold continental to humid sub-tropical; physiography, from high rugged mountains to flat coastal plains; and geology, from resistant impermeable pre-Cambrian igneous and metamorphic rocks to recent unconsolidated alluvial gravel. This wide variety of conditions ensures that any conclusions derived from the data thus obtained are valid with respect to any geographic environment and are not biased towards one particular set of conditions, as might be the case with a more reduced study area.

In order to remove any personal bias from the selection of sample sites to be used in the study, a random sampling technique was employed. This involved the superimposition of a one-inch grid over a 1:20,000,000 map of the United States, on a Albers Equal Area Projection, and aligned along the 100th meridian (Fig. 5). "Stochastic anchor points" were established at every intersection of the one-inch interval

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[1] A list of the sites sampled, together with their locations, is given in Appendix I.

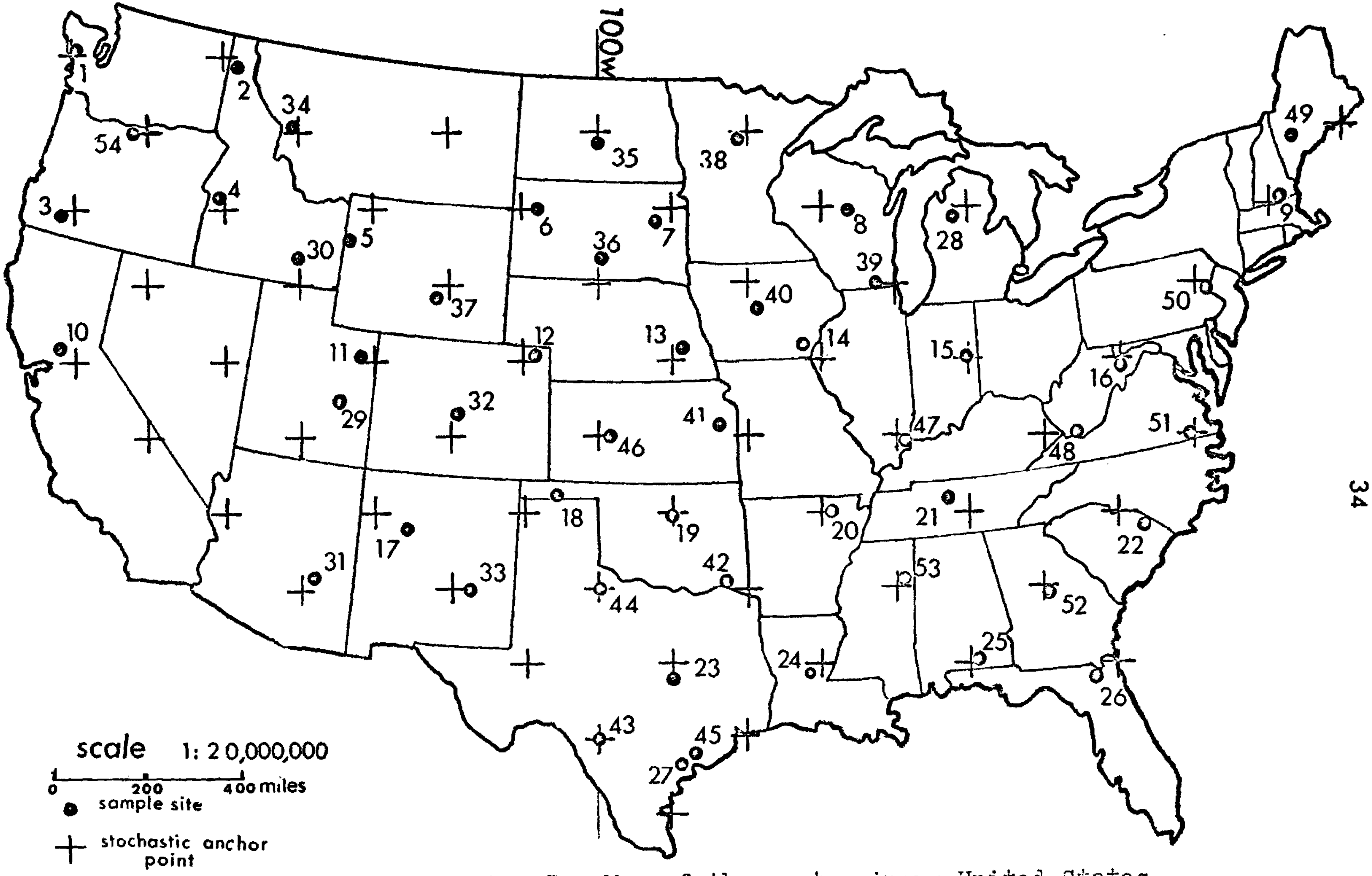

Fig. 5.--Map of the conterminous United States showing the location of sample sites and illustrating the method of sampling employed. (Explanation of the site numbers appears in appendix I)

lines and at the center of each one-inch square. Sample sites were then chosen at the nearest practicable point to each of the stochastic anchor points; the practicality of a prospective sample site being governed largely by availability of data. To be eligible for selection, a site had to possess a gauging station on a stretch of river ten miles long as the crow flies. This stretch had to be free of any major tributaries. The streams also had to be sufficiently large so that both banks appeared on a 1:24,000 topographic map, rather than just being represented by a single blue line. This stipulation was made so that small islands and channel bars in the stream would be represented on the map. The gauging station had to have a record dating back to at least 1951. If a suitable sample site fulfilling all these conditions could not be found within a radius of 270 miles[2] from the stochastic anchor point, then it was abandoned. In all, six stochastic anchor points had to be abandoned, five of them being located in the arid southwest where streams were unsuitable for use in the study.

Data concerning details of river channel pattern at each of these fifty-four sites were derived from the United States Geological Survey 7.5 Minute Topographic Series. While topographic maps clearly represent channel pattern in its gross form and provide a more convenient, simply derived, and inexpensive source of data than could be obtained from ground fieldwork or from aerial photographs, a certain amount of accuracy has to be sacrificed. This loss of accuracy results from the generalization of the topographic maps themselves and also from

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[2] The mean distance between stochastic anchor points.

the precision limitations imposed by the scale of the maps which exclude the finer details of the channel pattern configuration.

From the topographic maps, two fixed points ten miles apart as the crow flies were established on each chosen stretch of river. The gauging station always provided one of these fixed points. Whether the other fixed point was established upstream or downstream of the gauging station depended upon which of the two sections of the river had the least tributaries entering it, the least amount of riverside urban development, and the availability of maps. Total sinuosity was computed by dividing by ten the total length of the channel (in miles) that occurred between the two fixed points.[3] Topographic sinuosity was computed by dividing by ten the total length of the valley (in miles) that occurred between the two fixed points.

$$\text{Total sinuosity} = \frac{\text{Channel length}}{\text{Crow-fly length}}$$

$$\text{Topographic sinuosity} = \frac{\text{Valley length}}{\text{Crow-fly length}}$$

In those cases were no floodplain is evident from the map or where the river is deeply incised into its floodplain, valley length has the same value as channel length; and consequently, topographic sinuosity has the same value as total sinuosity. In those cases where the floodplain is very wide or where the valley is very shallow, valley length is, for all practical purposes, the same as crow-fly length, and topographic sinuosity has the minimum value of 1.0. Hydraulic sinuosity is computed by dividing channel length by valley length.

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[3] All cartometric measurements were made with a Dietzgen map measure.

$$\text{Hydraulic sinuosity} = \frac{\text{Channel length}}{\text{Valley length}}$$

By definition its value varies inversely with topographic sinuosity.

A practical problem arises in deciding how deeply a stream has to be incised into its floodplain beyond which point it is considered a valley within a valley. It was arbitrarily decided that floodplain incision had to be more than thirty feet before the innermost valley length was used in preference to floodplain length in the computation of the sinuosity indexes. In cases such as this, channel pattern becomes more confined as channel length is closer to the value for valley length. Hydraulic sinuosity, therefore, is diminished, topographic sinuosity increased, and topographic control has a higher value.

Percentage topographic control is calculated from the following formula:

$$\frac{\text{Topographic sinuosity} - 1}{\text{Total sinuosity} - 1} \times 100\%$$

A value for anastomosity for each river section was calculated by dividing the number of islands that occurred in a given stretch by valley length, the result being expressed as bifurcations per mile. Only permanent bifurcations were employed in the computation of this index. Seasonal anabranches, represented on the map by broken blue lines, were omitted.

$$\text{Anastomosity} = \frac{\text{Number of bifurcations}}{\text{Valley length}}$$

Channel gradient at each site was also derived from the topographic maps by measuring the distance between contour/river intersections, the result being expressed as elevation change in feet, per foot of river distance. Valley gradient at each site was computed by multiplying hydraulic sinuosity by channel gradient, this being a more convenient method than direct measurement.

The values for discharge variability used in this study were processed from the data recorded in the United States Geological Survey Water Supply Papers for the ten-year period, October 1951 to October 1960.[4] From these data, two coefficients of discharge variability were formulated. The first of these, indicating annual variability, was computed for each site by taking a mean over the ten years of annual peak discharge divided by annual mean discharge. A second coefficient, indicative of long-term variability in discharge, was obtained from the standard formula for coefficient of variation, the value being expressed in per cent.

$\text{C.V.} = \frac{\sigma}{\bar{x}} \times 100$ where $\bar{x}$ denotes the mean of peak discharges and σ denotes the standard deviation from this mean

In addition to the fifty-four sample sites used in the study, values for discharge variability were also obtained for six abandoned stochastic anchor points in order to complete the overall picture of discharge variability for the United States as a whole.

The values of all these indexes and coefficients for each sample site are included in Appendixes II, III, and IV.

Spatial and Quantitative Analysis of the Relationship Between Channel Pattern and Climate

Figs. 3 and 4 show the spatial relationship between annual variability of discharge and climate. Figs. 3b and 4b showing annual

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[4] This particular time period was chosen as it corresponds to the period when most of the topographic maps were drawn up or revised.

discharge variability were compiled from data collected in connection with the present research. Fig. 3a showing annual temperature range is an indication of marine or continental type climates. Fig. 4a showing diurnal temperature range indicates those areas of greatest aridity. From comparison of these maps, close similarities in the pattern of spatial variation may be discerned.

The isoline for the annual variability of discharge value of ten in Figs. 3a and 4b excludes regions where climate has a strong marine influence. These regions include the southeastern part of the continent, together with the Gulf Coast, most of the East Coast, and most of the West Coast except for Oregon and Washington where annual snowmelt in the Cascades contributes significantly to variability in discharge. In addition, the Great Lakes region lies outside the ten isoline due to the moderating influence on climate of the Great Lakes themselves. The greater part of the Rocky Mountains also has annual discharge variability below ten, as their elevation reduces the continental influence on climate; yet snowfall in this region is not high enough to cause a high variation in discharge. It may be noticed that the margins of the Rocky Mountains region are characterized by steep gradients of discharge variability associated with sharp changes in elevation and corresponding changes in evaporation rates in these areas.

Areas of extreme discharge variation occur characteristically in the central portion of the United States where the continental effect upon climate is at its most extreme, and also in the arid southwest part of the continent. Rather anomolous high discharge variability occurs in

Alabama, Mississippi, and Tennessee which might possibly be explained in terms of the convective storm activity in these states.

Although it is evident from comparison of Figs. 3a with 3b and 4a with 4b that annual discharge variability is in fact a close hydrological response to climatological conditions, no attempt is made in this study to analyze this relationship quantitatively; this must be left for future research. Before this relationship can be researched further, however, more comprehensive climate data will have to be used. Temperature range is employed in this research, as an indication only, of certain climate types. However, it must be recognized that climate is composed of several other parameters, besides temperature range, which also must be taken into account in a more detailed study. This research succeeds only in demonstrating that the relationship between climate and discharge variability is a viable one; before any firm conclusions can be reached, the data base must be greatly expanded. Furthermore, insofar as other factors are involved in affecting the spatial relationship between climate and discharge variability, their effect upon this relationship must be investigated in some detail before its precise nature can be determined.

The phenomenon of interference (processes or features that transgress climate boundaries)[5] is important in partially obscuring the spatial relationship between climate and discharge variability, even though it does not reduce the efficacy of climate in controlling discharge variability. In this study, this phenomenon takes the form of

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[5] A. Cholley, "Morphologie Structurale et Morphologie Climatique," Annales de Geographie, XLIX (1950).

certain rivers passing through several climatic regions. In these cases, the regime of the river represents an aggregation of all the characteristics of flow imparted to the river as it passes through each climatic region, and as a result the river's regime is only partially related to any one of these climatic regions.[6] The effect of interference is often neglected in climatic geomorphologic studies; and the obscurity of the climate-landform relationship is misinterpreted as climate's relative incompetence in controlling landform distribution, in comparison to other supposedly more important factors.

To some extent also, other independent variables besides climate affect the spatial variation of discharge variability.

Geology affects discharge variability through lithological variations. Drainage basins that have a high proportion of permeable rocks can be considered analogous to a sponge or a reservoir of water. This tends to reduce the extremes of discharge normally perpetrated by climate, by absorbing water during periods of high rainfall and by releasing groundwater into the river during periods of drought.

Physiography is also effective in determining discharge variability. In high altitude areas, snow melt may greatly contribute to the nature of stream flow; but this is really a climatic factor. However, the nature of the physiography can affect the variability of stream flow directly, as well as through its effect on climate. For example, drainage basins which have high relief tend to accentuate discharge

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[6] R. P. Beckinsale, "River Regimes," in Water, Earth and Man.

extremes generated by extremes in precipitation by an increase in the speed of overland flow as a result of steeper slopes.

The effect of all these factors on the spatial variation of discharge variability must be analyzed before the nature of the relationship between climate and discharge variability can be realistically evaluated. The present research merely reveals the existence of this relationship. If a spatial association between variability of discharge and channel pattern can be demonstrated, then climate can be seen to possess some importance in controlling channel pattern distribution. Fig. 6 shows the spatial relationship between annual discharge variability and channel pattern.

Of the fifty-four streams sampled, fourteen showed no evidence of anastomosity. These are plotted on the map in Fig. 6. It is evident that they are clustered in the regions of low discharge variability. Eleven of them lie in the regions where annual discharge variability is below the value of ten; whereas if their distribution were purely random and being totally unaffected by discharge variability, only five would be likely to be located in these regions. Only one out of a total of fourteen lies above the thirty isoline, whereas there would be four of them if the distribution were not preferentially located in areas of low discharge variability.

With hydraulic sinuosity, a spatial association with discharge variability is also evident, but it is not as well defined as is the case of anastomosity. Those streams which have a hydraulic sinuosity of 1.5 or more are plotted on the map in Fig. 6. In conventional terminology, these would be termed meandering streams. Out of seventeen, seven lie

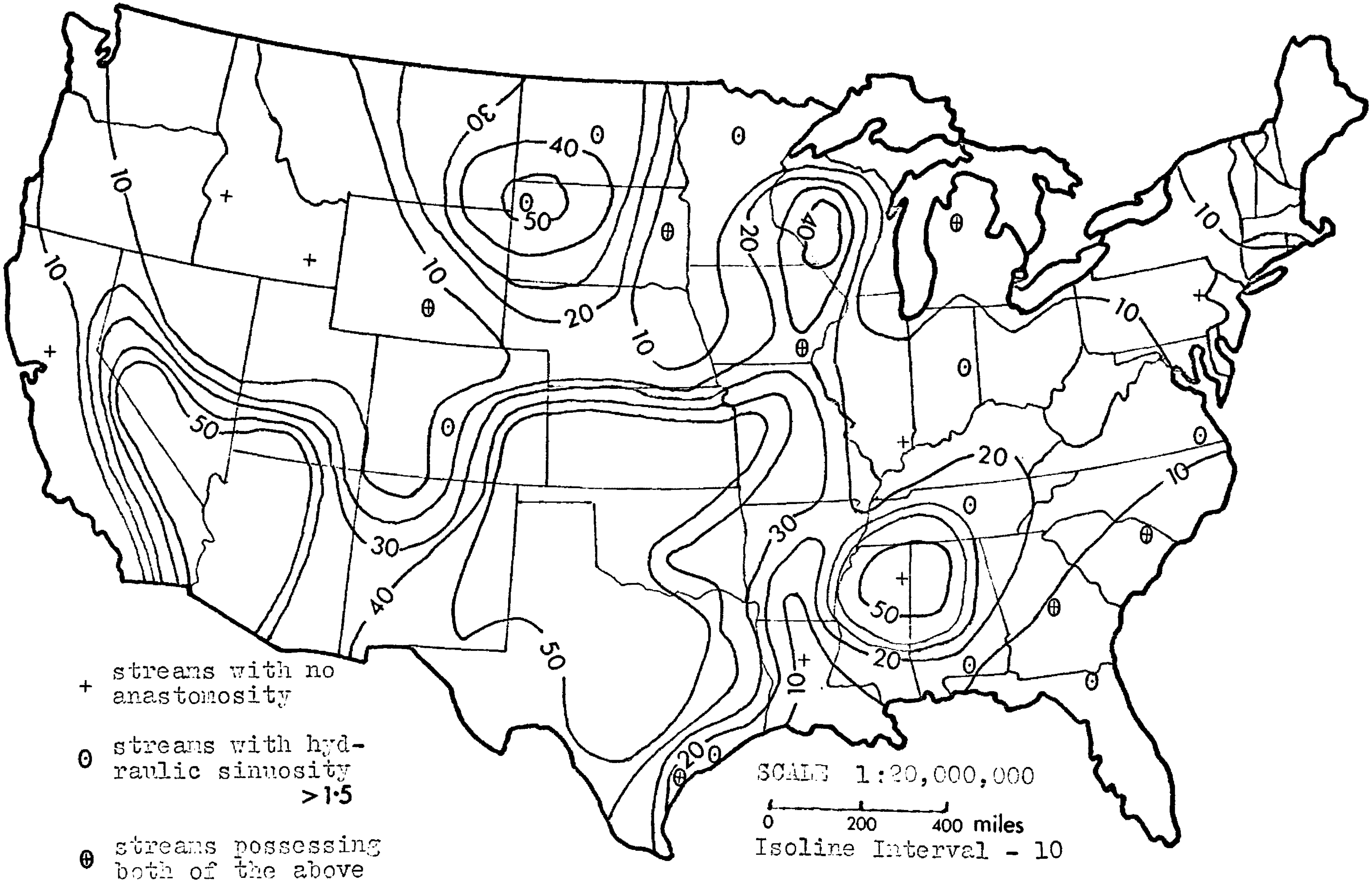

Fig. 6.--Average annual discharge variability, U.S.A., 1951-60, indicating the spatial relationship with channel pattern.

outside the ten isoline, though only six would be expected in a random distribution. Only two lie in the region where annual discharge variability is above thirty; whereas if the distribution of these highly sinuous streams were random and not preferentially located in regions of low discharge variability, at least four would be located here.

Of the fifty-four stream sections sampled, seven have both hydraulic sinuosity above 1.5 and no evidence of anastomosity. Five of these seven lie below the ten isoline with none at all existing above the thirty isoline.

From this spatial analysis, it is apparent that non-anastomosing and highly sinuous streams are preferentially located in areas of low discharge variability. In these regions where annual and diurnal temperature ranges are small, a humid marine type climate prevails.

The converse to this, that anastomosing streams and streams with low values of sinuosity occur more commonly under conditions of high discharge variability, is also apparent from analysis of Fig. 6. Nine of the stream sections sampled in this study lie in areas where annual discharge variability is above fifty. Only one of them displays evidence of anastomosity, and only one has a sinuosity exceeding 1.5.

Although there is a relative paucity of data pertaining to channel pattern in the semi-arid southwest compared to other regions of the United States, it can be inferred that here, too, anastomosing streams and streams with low sinuosity are more common due to the conditions of discharge variability in this region.

These findings support the hypothetical model presented earlier in Chapter III, but they are by no means conclusive. Before a hypothesis of this magnitude can be validated at an acceptable level of confidence, much more intensive research, employing a very much enlarged data base, will have to be performed, as well as a more intensive investigation into the relative importance of the other factors which also have a bearing upon the problem. This study is merely a preliminary investigation to illustrate the value of the methodological procedure employed. However, the results of the investigation have shown that the effect of climate upon the distribution of channel pattern type merits more intensive research.

Regression analyses were performed upon the data used in this study in an attempt to place the relationship between discharge variability and channel pattern on a statistical basis. A positive correlation coefficient of 0.27 was obtained from the log/log regression of anastomosity and annual discharge variability and a negative correlation coefficient of 0.20 from the log/log regression of hydraulic sinuosity and annual discharge variability.

The correlation of channel pattern to long-term variability of discharge is much poorer than in the case of annual variability, indicating possibly that frequency of discharge variation is relatively more important than magnitude in channel pattern determination, though more intensive research would have to be carried out before any firm conclusions could be reached on this point.

All of these values, however, failed to reach any acceptable level of significance. This does not indicate that the relationship between discharge variability and channel pattern does not exist, but rather that there is no significant progressive variation between the two variables. The poor correlation coefficients do not mean that discharge variability is ineffective in controlling the distribution of channel pattern types in comparison to other more potent factors, but rather that the relationship between the two is too complex to be revealed by regression analysis, as undertaken in this study.

The complexity of this relationship is caused largely by the phenomenon of succession (the imprint of past climates on existing geomorphological features).[7] This, like the phenomena of interference, is inherent in any study of this kind which attempts to relate climate to landform and has been responsible to a large degree for the relative unpopularity of climatic geomorphology. In this study, succession manifests itself as a time lag of channel pattern response to climatic change. Present channel patterns are not entirely adjusted to present climatic conditions due to an inherent resistance to morphological change. The degree of resistance to channel pattern change and, consequently, the amount of time lag in channel pattern adjustment varies spatially.

It depends largely upon the spatial variation of the degree of topographic control exercised by restraining valley sides which, in turn, is dependent upon such factors as tectonic activity which can be responsible for stream incision and absence of floodplains in certain areas.

In addition to topographic control, degree of resistance also depends to a large extent upon the strength of the channel banks and the intensity of discharge variation acting upon them. Thus, resistance and

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[7] Cholley, "Morphologie Structurale et Morphologie Climatique."

time lag would be expected to be a minimum where topographic control is absent, where banks are composed of unconsolidated material, and where intensity of discharge variation is a maximum. Such conditions might be expected to arise, for example, in proglacial streams. Fahnestock reported that the channel patterns of the White River, emanating from the Emmons Glacier in Washington State, change with great rapidity in response to large diurnal fluctuations in discharge accompanying glacial melting.[8] In other cases, such as a deeply incised stream course, channel pattern modifications are likely to be exceedingly slow and channel pattern form would be unlikely to bear any relationship to the channel pattern forming factors obtaining at present.[9]

Before a more detailed analysis of the relationship between discharge variability and channel pattern can be attempted, information regarding channel bank resistance for each sample site must also be compiled so that allowance may be made for time lag in channel pattern adjustment.

In addition to discharge variability, other semi-dependent variables also have a bearing upon channel pattern. Before the strength and nature of the relationship between discharge variability and channel pattern can be fully evaluated, it is necessary also to investigate the spatial relationship of these other factors with channel pattern.

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[8] Fahnestock, "Morphology and Hydrology of a Glacial Stream, White River, Mt. Rainier, Washington."

[9] Mueller, "An Introduction to the Hydraulic and Topographic Sinuosity Indexes."

Amount and caliber size of the sediment load of streams is controlled largely by climate. However, it is also controlled partly by geology. Certain rock types characteristically weather into larger fragments than other rock types, and this is likely to be reflected in the character of the sediment load of the river passing through the region. Physiography is also capable of affecting the character of the sediment load of rivers. Corbel demonstrated by empirical and quantitative evidence that drainage basins in mountainous areas produce more detritus than those on the plains, and furthermore that a relatively greater proportion of it is in the form of traction load.[10]

Valley gradient is determined almost entirely by physiography and bears no relationship to climate. Most workers in this field agree that valley gradient is extremely important in channel pattern determination, and the findings of the present research corroborate this. Regression analyses carried out in conjunction with the present research yielded a positive correlation coefficient of 0.4393 (alpha level of significance 99.999%) with valley gradient and anastomosity, although the correlation with hydraulic sinuosity failed to reach any acceptable level of significance. However, the importance of valley gradient does not detract seriously from the importance of discharge variability in this connection, but rather the two factors are complementary. Discharge variability and valley gradient together largely determine variability in velocity of a stream, as velocity depends essentially upon discharge and

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[10] J. Corbel, "Vitesse de l'Erosion," _Zeitschrift fur Geomorphologie_, III, No. 1 (1959).

slope.[11] However, it must be recognized that this gives an indication only, and that factors such as width-depth ratio and channel roughness also have a bearing on stream velocity. The variability of velocity of a stream is more significant than simply variability of discharge in relation to the mechanisms outlined earlier. Variability of velocity is more closely related to channel bank erosion and also to the temporal variation in competency of a stream and the need for periodic traction load storage in the form of channel bars. Valley gradient largely controls the degree of the velocity of a stream while discharge variability controls variability of velocity. Thus, valley gradient and discharge variability work hand in hand in determining channel pattern. However, it can be appreciated that the role of valley gradient is subordinate to that of climate, acting in such a way as to decrease or intensify the control of discharge variability over channel pattern. Increased valley gradient works to make variability in discharge more effective in determining sinuosity and anastomosity.

The efficacy of the semi-dependent variables, sediment load and valley gradient, in affecting channel pattern form is undeniable. Furthermore, climate only partially controls sediment load and has no affect upon valley gradient, although this is offset to some degree by the complementary nature of valley gradient and discharge variability in terms of channel pattern determination. However, succession is undoubtedly the greatest single factor responsible for obscuring the spatial relationship between discharge variability and channel pattern.

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[11] _Ibid_., p. 5. "La vitesse du courant depend essentiellement de la pente et du debit."

From the results of this research, it is clearly evident that the spatial distribution of channel patterns is affected, to some degree, by climate, so that certain channel pattern types occur more commonly in particular climates. However, it is equally evident that a great deal more research is required before the degree to which climate controls channel pattern can be established and the precise nature of the relationship determined.

CHAPTER V

RIVER CHANNEL PATTERNS AND CLIMATIC CHANGE

Evidence of Channel Pattern Change

There is abundant evidence in the literature that river channel patterns have changed in nature in relatively recent times. This has been substantiated by observations associated with the present study. Such evidence that may be readily discernible from a topographic map includes abandoned river channels with sinuosities that have a marked variance with those of the present stream channel, or the existence of several approximately contemporaneous cut-offs, in close proximity, which together have significantly reduced sinuosity (Fig. 7). Evidence for river channel pattern adjustments also takes the form of channel islands in streams with incongruously high degrees of sinuosity (Fig. 8).

This sort of evidence would seem to indicate that in recent times there has been a trend towards a reduction in sinuosity and a corresponding increase in anastomosity.

The degree of change varies spatially, largely as a function of the spatial variation in topographic control and channel bank resistance. Where topographic control or bank resistance is at a maximum, there is unlikely to be any evidence of channel pattern modification, and in these locations channel pattern will bear little relation to the independent and semi-dependent variables which control sinuosity and anastomosity in unconfined situations. Although the original course of

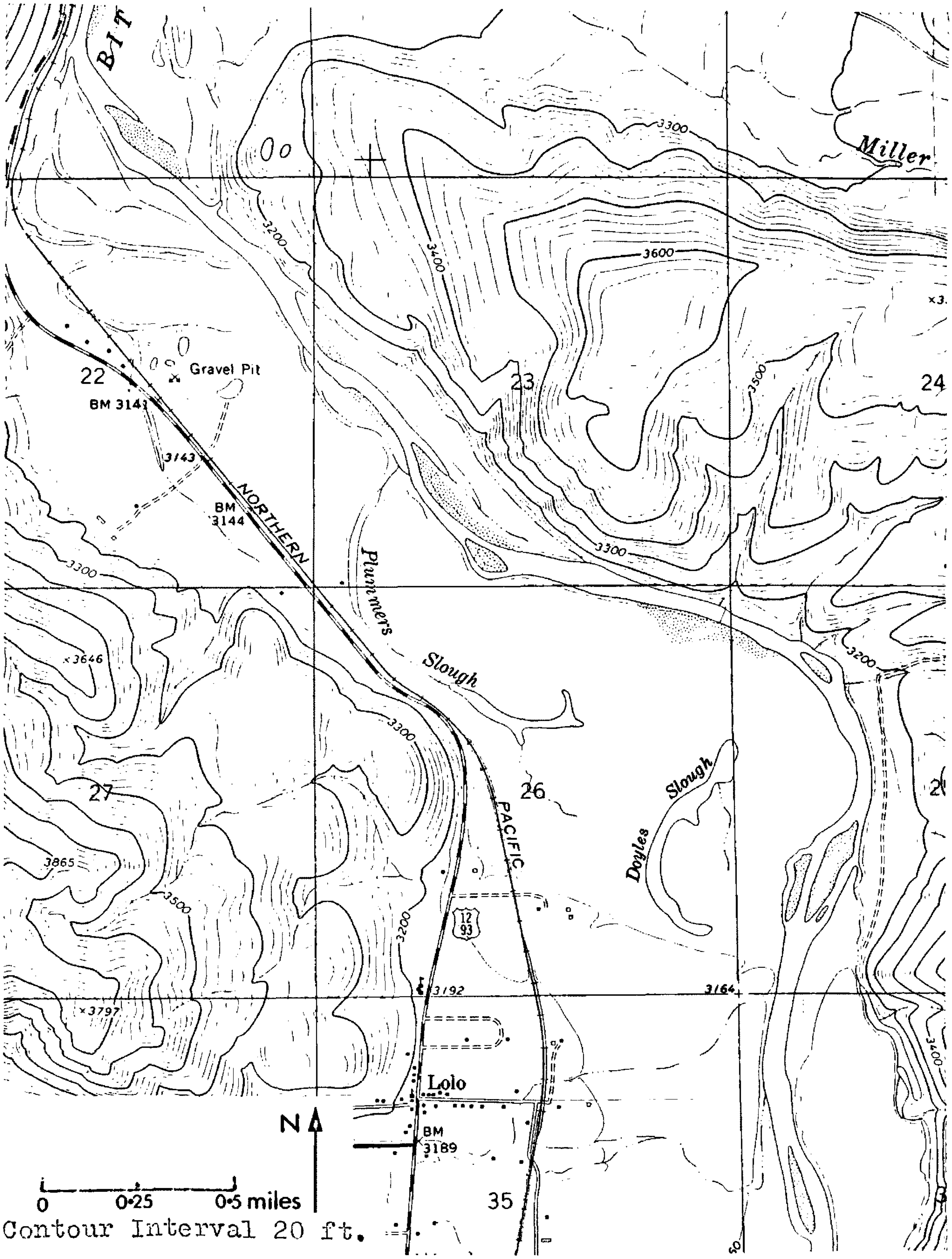
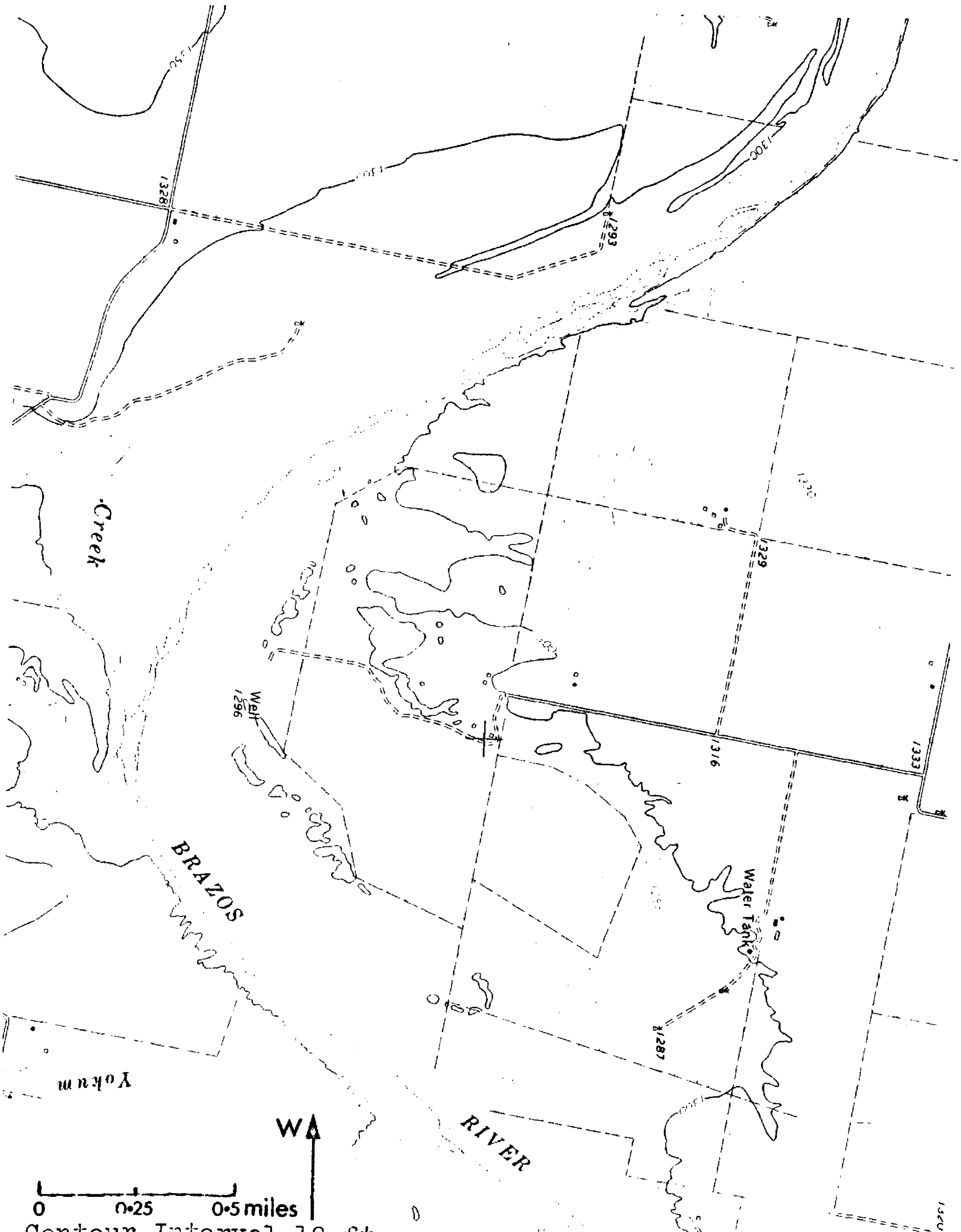


Fig. 7.--Southwest Missoula Quadrangle, Montana, showing the Bitterroot River, near Missoula, 1.21(20)2.42. Note the several approximately contemporaneous cut-offs which together considerably reduce the sinuosity of the river. Note also the high degree of anastomosity.



Contour Interval 10 ft.

Fig. 8.--Bomarton Quadrangle, Texas, showing the Brazos River, near Seymour, 1.19(0)0.91. Note the uniformity of the river's sinuosity, and the incongruity of the anastomosity which appears to be a relatively recent development. From this association it may be deduced that channel bank resistance is very strong.

the river may have been determined by these factors in the past, it is more than likely that due to temporal changes in these factors the channel pattern of a river would be very different if not confined by valley walls.

In conditions more favorable to extensive channel adjustments, evidence of fundamental channel pattern modification clearly indicate the direction of change. The Bitterroot River, for example, near its confluence with the Clark Fork at Missoula, Montana, has at some time reverted from a highly sinuous river to a relatively straight one with a high degree of anastomosity (Fig. 7).

Several other authors have also recognized this trend from geomorphological evidence in the field. Schumm, for example, noted that "Many modern channels have changed from meandering to straight."[1] More specifically, McLaughlin described how the Cimarron River in Kansas changed its pattern from a deep meandering channel to a broad anastomosing channel after the flood of 1914.[2]

These changes would seem to indicate that in the western United States, at least, the climate is becoming drier, resulting in an increased variability of discharge. Data collected from tree rings, rainfall and runoff records, lake levels and sediments, and historical records corroborate this.[3]

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[1] Schumm, "The Sinuosity of Alluvial Rivers on the Great Plains," p. 1097.

[2] T. McLaughlin, "Accelerated Channel Erosion in the Cimarron Valley of Southwest Kansas," Journal of Geology, LV (1947).

[3] For example, see E. Antevs, "Rainfall and Tree Growth in the Great Basin," American Geographical Society Special Publication, 21 (1938).

With the aid of detailed analysis of paleochannels, longer extrapolations of paleoclimatic events is possible. Fisk, for example, attempted to relate the change from the braided to the meandering state of the Mississippi River, evidenced in abandoned channels, to the amelioration of climate following the Pleistocene glaciation.[4] However, due to the several other factors which also bear upon river channel patterns and the difficulty of tracing and dating paleochannels, research of this nature is somewhat tenuous--but could provide a very useful adjunct to paleoclimatic studies of other kinds.

Changes in valley gradient achieved through tectonic activity undoubtedly has had some impact upon channel pattern changes discernible in the recent past. However, these changes are too widespread for this factor to have exerted any major influence, though it may be important in either enhancing the affect of climatic change or weakening it in localized areas.

Man has also had a large hand in promoting channel pattern changes. Abstractions and diversions for irrigation and navigation, the construction of dams and reservoirs, and the management of catchment areas have greatly affected the variability of flow and the nature of sediment load over almost every part of the United States. In most cases, as man's influence has been very recent, river channel patterns in their gross form as they appear on a map show little reflection of man's interference. In rare cases, however, where resistance to change

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[4] H. N. Fisk, Fine Grained Alluvial Deposits and their Effects on the Mississippi River Activity (Vicksburg, Miss.: Waterway Experiment Station, 1947).

is not great, channel patterns have been drastically altered by man's activity. Gregory described how a stream in Exeter, England changed its pattern from a meandering one to a braided one as the result of the construction of a fly-over in its catchment.[5] Grant reported that depletion of vegetational cover on hillslopes caused an influx of coarse sediment into the channels of some New Zealand rivers, resulting in a change from a narrow meandering channel to a wide straight one.[6] The South Platte River near Boule, Nebraska has changed from a markedly braided river in 1897 to a sinuous one in 1960 due to regularization of flow by man.[7] However, here again channel pattern change is too widespread and too uniform in its trend to be entirely attributable to man's activity.

Theory of Evolution of River Channel Pattern Adjustment in Response to Increasing Aridity

Increasing aridity results not only in increased variability of discharge, but also in a decrease in vegetation cover, further promoting variability in runoff and also increasing sediment yield up to a point.[8] The increasing effectiveness of mechanical weathering over chemical

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[5] K. J. Gregory. Paper delivered to the Hendon College of Technology (London University) symposium on physical geography (June, 1972).

[6] A. P. Grant, "Soil Conservation in New Zealand," Proceedings of the New Zealand Institute of Engineers, XXXVI (1950).

[7] S. A. Schumm, "Geomorphic Implications of Climatic Change," in Water, Earth and Man.

[8] W. B. Langbein and S. A. Schumm, "Yield of Sediment in Relation to Mean Annual Precipitation," Transactions of the American Geophysical Union, XXXIX (1958).

weathering under these conditions results in a larger fraction of the sediment load, as a whole, being of a coarser caliber. Channel pattern response to these stimuli is, first, a decrease in sinuosity and, second, an increase in anastomosity. However, the relationship between the two varies from case to case, depending upon the degree of resistance to change in the form of channel banks or valley sides. The relatively low degree of spatial relationship of hydraulic sinuosity to annual variability of discharge compared to that of anastomostiy, evident from the results of the present research, is largely due to the existence of a differential time lag between the two in response to climatic change. Resistance to climatic change is most strongly felt with regard to changes in sinuosity rather than to changes in anastomosity, because the former requires proportionately greater lateral erosion of the banks. The formation of channel islands does not require a great deal of channel bank modification. As a result of this, anastomosity and sinuosity have a far from perfect inverse relationship. Consequently, highly sinuous streams may be observed to possess channel islands (Fig. 8) which appears incongruous with the generally held view that "the channel course of a braided river is very much less sinuous than a meandering river of comparable size."[9]

Fig. 9 illustrates the evolution of a hypothetical river from a high degree of sinuosity to a high degree of anastomosity under three differing conditions. In the first case, where channel bank resistance is minimal, the river reduces its sinuosity by gradual lateral planation.

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[9] Leopold, Wolman, and Miller, Fluvial Processes in Geomorphology, p. 292.

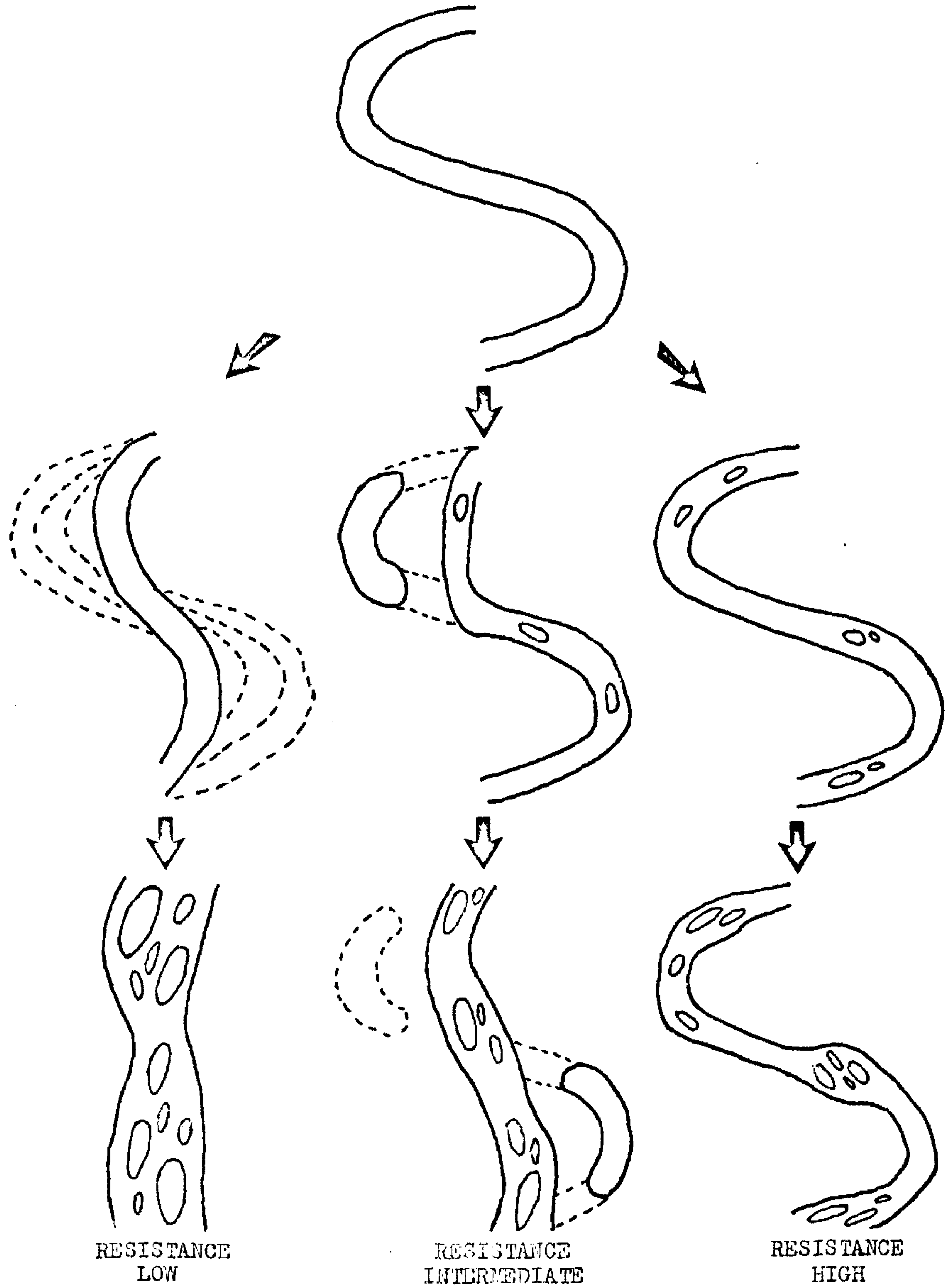

Fig. 9.--The channel pattern evolution of a hypothetical stream, in response to climatic change, under varying degrees of resistance to lateral channel migration as a result of bank resistance or topographic control.

Anastomosity does not occur until a relatively late stage in the evolution. Where bank resistance is more marked, as in the second case, anastomosity occurs relatively early in the evolution in preference to reduced sinuosity. Reductions in sinuosity tend to occur by avulsion during times of peak discharge, producing cutoffs, rather than by a gradual process of lateral shifting. In most cases where topographic control is not oppressive, channel pattern evolution is probably a combination of these first two situations; whichever one being the more dominant depending upon the degree of channel bank resistance. Where bank resistance is strong, avulsion is the dominant process; where bank resistance is small, lateral shifting dominates.

In those instances where topographic control approaches 100 per cent or where bank resistance is extreme, sinuosity will change very little, the evolution being characterized largely by increasing anastomosity. In some localities where topographic control is extreme, even anastomosity may be prevented; and the channel pattern may show no response whatsoever to climatic change.

As can be seen, the three end results differ considerably in terms of sinuosity and anastomosity. This is due to the phenomenon of succession discussed earlier. Where resistance to change is at all appreciable, then a stream is imprisoned, to a greater or lesser extent, by a channel or valley formed under differing climatic controls. Hence, the resulting form is polygenetic.

CHAPTER VI

CONCLUSIONS

The purpose of this study was as much to illustrate the value of a geographic approach in geomorphic research and to highlight the importance of climatic geomorphology as it was to specifically investigate the hypothesis that the spatial variation of channel patterns is related to climate. In the view of this author, the methodology of the present study is as important as the result. The geographic approach employed involving a quantitative spatial analysis has been shown capable of highlighting factors which otherwise remain unnoticed. Furthermore, insofar as all natural phenomena vary spatially to a greater or lesser degree, a spatial analysis enables the establishment of general principles regarding the interaction of these phenomena that have a universal application, rather than being restricted to specific geographic environments. Consequently, conflicts of opinion that have arisen due to research concerning the same topic being carried out in dissimilar geographic settings can be reconciled and a more coherent overview obtained. Conflicts have arisen also due to the failure of many researchers to recognize the relationship between the variables they deal with and their relative degree of dependency upon one another. In the view of this author, it is the major scope of geography as it pertains to geomorphology to study the pattern of spatial variation of independent variables and then to trace the effect of this upon the spatial variation of semi-dependent and dependent variables. This study has looked at the affect of one of these independent variables, climate, upon channel patterns through the medium of variability of discharge.

The effects of climate in controlling the distribution of gross geomorphic agents, such as wind and ice, is relatively clear. However, the role of climate in controlling the distribution of landforms is not so clear and is evident only by careful observation and detailed analysis. The relationship between climate and landform is made obscure by the phenomena of succession and interference. This obscurity has led to the misconception that climate is unimportant in determining landforms in relation to other more potent factors. However, the obscurity of the relationship in no way discredits the ability of climate to control the processes which act now, and have acted in the past, to fashion the present landforms. Spatial analyses of the relationship between climate and discharge variability and between discharge variability and channel pattern have, in fact, revealed that non-anastomosing and highly sinuous streams are preferentially located in humid marine type climates where low annual discharge variability regimes prevail, and anastomosing and low sinuosity streams are more commonly associated with high annual discharge variability regimes which are characteristic of continental and arid type climates. When one considers the degree of climatic control upon weathering and vegetation which also affect channel pattern in addition to discharge variability, the link between climate and channel pattern is strengthened. As well as spatial correlation between climate and channel pattern, there is abundant evidence in the literature to suggest that there is also some degree of temporal correlation between the two.

However, the overall relationship between channel pattern and climate is somewhat complicated by succession and interference. The complexity of the relationship goes beyond a progressive variation of one variable with another. Consequently, without first cancelling out the effects of succession and interference, it proved impossible in this study to define precisely the nature of the relationship between climate and channel pattern in mathematical terms by the use of regression analysis.

This study aspires to be nothing more than a preliminary investigation to illustrate the merits of the methodology employed and its possible application to related problems in geomorphology. The results of the research into the climatic base of river channel patterns performed in connection with this study is neither conclusive nor exhaustive, but it does indicate that this problem is worthy of more intensive research.

A great deal more work needs to be done in certain important aspects of this problem that were only lightly touched upon in the present study. Attempts to measure the effects of succession and interference upon discharge variability and channel pattern at individual sites, although fraught with difficulty, would be of immense value and would result in beneficial repercussions upon climatic geomorphology as a whole. The strength and nature of the relationship between climate and landform cannot be realistically evaluated without fixing the relative importance of the other factors involved, most effectively by the kind of analysis employed in this study.

The several possible mechanisms by which climate exerts its control over channel pattern, some of which were only alluded to in this study, need to be critically analyzed and evaluated. This study has been restricted to the continental United States and to only a relatively small sample size. The spatial relationship between climate and channel pattern needs to be reexamined over a wider study area, one that also includes cold and equatorial climates, and using a larger number of observations. The precise nature of the relationship can then be more thoroughly investigated and possibly some mathematical formulas derived.

In this study, only two indexes of variability were employed; more research needs to be done with several more indexes in order to determine exactly which type of discharge variability affects channel pattern the most. More research is also needed to determine more precisely the nature of the relationship between changes in anastomosity and sinuosity under varying degrees of bank resistance.

When all of these aspects have been researched in more detail, a more comprehensive and accurate model of channel pattern evolution can be attempted from which channel movements and changes in hydraulic geometry can be predicted. In addition to the gradual changes in channel pattern perpetrated by climatic change, man's increasing influence on fluvial processes, both directly and indirectly, is resulting in rather more rapid channel pattern adjustments; and prior knowledge of the nature of these adjustments could prove to be of immense use for planning purposes.

APPENDIX I

SAMPLE SITE NO.	RIVER LOCATION
1	Wynoochee River, near Montesano, Washington
2	Priest River, near Priest River, Idaho
3	Rogue River, at Grant's Pass, Oregon
4	Weiser River, Near Cambridge, Idaho
5	Gros Ventre River, at Kelly, Wyoming
6	Moreau River, at Bixby, South Dakota
7	James River, at Ashton, South Dakota
8	Rib River, at Rib Falls, Wisconsin
9	Souhegan River, at Merrimack, New Hampshire
10	Sacramento River, below Wilkin's Slough, Calif.
11	Duchesne River, Near Randlett, Utah
12	South Platte River, at Julesburg, Colorado
13	Platte River, at North Bend, Nebraska
14	English River, at Kalona, Iowa
15	Blue River, at Shebyville, Indiana
16	Shavers Fork, at Parsons, West Virginia
17	Rio Grande, at Albuquerque, New Mexico
18	North Canadian River, Near Guymon, Oklahoma
19	Cimarron River, near Guthrie, Oklahoma
20	Spring River, at Imboden, Arkansas
21	Harpeth River, at Belleview, Tennessee
22	Little Pee Dee River, near Dillon, S.C.
23	Lampasas River, at Youngsport, Texas
24	Red River, at Alexandria, Louisiana
25	Pigeon Creek, near Thad, Alabama
26	Suwanee River, at White Springs, Florida
27	San Antonio River, at Goliad, Texas
28	Manistee River, near Sherman, Michigan
29	Green River, at Green River Utah
30	Portneuf River, at Pocatello, Idaho

SAMPLE SITE NO.	RIVER	LOCATION
31	Salt River,	near Chrysotile, Arizona
32	South Platte River,	near Hartsel, Colorado
33	Pecos River,	near Acme, New Mexico
34	Clark Fork,	below Missoula, Montana
35	Knife River,	at Hazen, North Dakota
36	White River,	near Oacoma, South Dakota
37	Sweetwater River,	near Alcova, Wyoming
38	Crow Wing River,	at Nimrod, Minnesota
39	Rock River,	at Afton, Wisconsin
40	Des Moines River,	near Boone, Iowa
41	Delaware River,	at Valley Falls, Kansas
42	Little River,	near Wright City, Oklahoma
43	Nueces River,	near Asherton, Texas
44	Brazos River,	at Seymour, Texas
45	Guadalupe River,	at Victoria, Texas
46	Pawnee River,	near Larned, Kansas
47	Saline River,	near Junction, Illinois
48	Bluestone River,	near Pipestem, West Virginia
49	Swift River,	near Roxbury, Maine
50	Musconetcong River,	near Bloomsbury, N.J.
51	Meherrin River,	at Emporia, Virginia
52	Ocmulgee River,	at Macon, Georgia
53	Chiwapa Creek,	at Shannon, Mississippi
54	Deschutes River,	at Moody, near Biggs, Oregon

APPENDIX II

SAMPLE SITE NO.	TOTAL SINUOSITY	TOPOGRAPHIC CONTROL (%)	INDEX OF ANASTOMOSITY	HYDRAULIC SINUOSITY
1	1.6250	28.00	0.345	1.3830
2	1.7212	31.99	0.413	1.3984
3	1.5500	63.64	0.225	1.1481
4	1.3334	24.99	0	1.2308
5	1.1058	0	3.554	1.1058
6	2.2371	37.40	0.074	1.5282
7	2.6737	0	0	2.6737
8	1.5000	25.00	1.620	1.3334
9	1.6731	21.43	1.420	1.4622
10	1.3000	0	0	1.3000
11	1.4038	0	3.655	1.4038
12	1.1154	0	0.711	1.1154
13	1.0481	0	14.620	1.0481
14	1.5000	0	0	1.5000
15	1.5481	0	1.117	1.5481
16	1.8105	68.83	2.854	1.1622
17	1.0673	0	6.397	1.0673
18	1.4808	9.99	0.969	1.4128
19	1.2308	16.67	3.031	1.1852
20	1.4344	17.45	1.609	1.3334
21	2.0897	12.65	0.609	1.8365
22	2.0116	17.24	0	1.7228
23	2.3077	100.00	0.044	1.0000
24	1.3500	0	0	1.3500
25	1.7297	9.26	0.267	1.6203
26	1.6044	0	0.116	1.6044
27	1.8462	0	0	1.8462
28	2.7000	0	0	2.7000
29	1.2750	0	2.332	1.2750
30	1.2500	10.00	0	1.2195

SAMPLE SITE NO.	TOTAL SINUOSITY	TOPOGRAPHIC CONTROL (%)	INDEX OF ANASTOMOSITY	HYDRAULIC SINUOSITY
31	2.1538	100.00	0.283	1.0000
32	1.6154	0	0.305	1.6154
33	1.2500	0	0.102	1.2500
34	1.3864	0	1.560	1.3864
35	1.5652	0	0.153	1.5652
36	2.4519	56.93	1.445	1.3421
37	1.6667	0	0	1.6667
38	1.6463	0	4.250	1.6463
39	1.4038	66.67	0.240	1.1060
40	1.5481	63.16	0.377	1.1500
41	1.6827	64.79	0.070	1.1667
42	1.0962	100.00	0.278	1.0000
43	1.2500	100.00	0.162	1.0000
44	1.1923	0	0.914	1.1923
45	1.7938	0	1.524	1.7938
46	2.0481	100.00	0.050	1.0000
47	1.0947	0	0	1.0947
48	2.4327	65.77	0.732	1.2525
49	1.3568	29.58	1.200	1.2273
50	1.1269	100.00	0	1.0000
51	1.7308	0	0.102	1.7308
52	1.8250	0	0	1.8250
53	1.0480	0	0	1.0480
54	1.3333	100.00	0.253	1.0000

APPENDIX III

SAMPLE SITE NO.	TOPOGRAPHIC SINUOSITY	RIVER GRADIENT (ft/ft)	VALLEY GRADIENT (ft/ft)
1	1.1750	0.00189	0.00261
2	1.2308	0.00161	0.00225
3	1.3500	0.00115	0.00132
4	1.0833	0.00188	0.00231
5	1.0000	0.00761	0.00757
6	1.4639	0.00065	0.00099
7	1.0000	0.00005	0.00013
8	1.1250	0.00090	0.00119
9	1.1442	0.00126	0.00184
10	1.0000	0.00005	0.00006
11	1.0000	0.00146	0.00204
12	1.0000	0.00148	0.00165
13	1.0000	0.00091	0.00095
14	1.0000	0.00036	0.00054
15	1.0000	0.00074	0.00114
16	1.5579	0.00394	0.00457
17	1.0000	0.00111	0.00118
18	1.0481	0.00182	0.00257
19	1.0385	0.00050	0.00059
20	1.0758	0.00050	0.00066
21	1.1379	0.00049	0.00089
22	1.1744	0.00025	0.00043
23	2.3077	0.00087	0.00087
24	1.0000	0.00001	0.00001
25	1.0676	0.00064	0.00103
26	1.0000	0.00025	0.00040
27	1.0000	0.00032	0.00059
28	1.0000	0.00052	0.00140
29	1.0000	0.00076	0.00096
30	1.0250	0.00103	0.00125

SAMPLE SITE NO.	TOPOGRAPHIC SINUOSITY	RIVER GRADIENT (ft/ft)	VALLEY GRADIENT (ft/ft)
31	2.1538	0.00623	0.00623
32	1.0000	0.00244	0.00394
33	1.0000	0.00080	0.00129
34	1.0000	0.00112	0.00155
35	1.0000	0.00045	0.00070
36	1.8269	0.00070	0.00093
37	1.0000	0.00111	0.00184
38	1.0000	0.00060	0.00098
39	1.2692	0.00015	0.00016
40	1.3462	0.00029	0.00033
41	1.4423	0.00038	0.00044
42	1.0962	0.00100	0.00100
43	1.2500	0.00166	0.00166
44	1.0000	0.00060	0.00071
45	1.0000	0.00033	0.00059
46	2.0481	0.00039	0.00039
47	1.0000	0.00005	0.00005
48	1.9423	0.00527	0.00660
49	1.1055	0.00641	0.00786
50	1.1269	0.00197	0.00197
51	1.0000	0.00039	0.00067
52	1.0000	0.00021	0.00038
53	1.0000	0.00085	0.00089
54	1.3333	0.00256	0.00256

APPENDIX IV

SAMPLE SITE NO.	DISCHARGE VARIABILITY		DRAINAGE AREA (□ mls)
	LONG TERM (%)	ANNUAL	
1	7.45	14.813	179
2	13.13	4.046	902
3	60.51	12.535	2459
4	42.99	6.980	605
5	31.78	7.316	622
6	127.93	60.343	1570
7	161.49	6.503	11000
8	47.20	46.573	309
9	34.74	12.588	171
10	6.61	2.542	12940
11	58.81	7.835	3920
12	105.83	6.544	28138
13	88.97	8.277	77800
14	77.81	29.210	573
15	41.09	16.779	425
16	35.96	16.196	214
17	39.05	11.744	17440
18	68.51	516.080	2139
19	94.34	48.566	16892
20	65.16	21.797	1162
21	45.47	25.012	408
22	44.51	4.344	524
23	89.10	413.040	1242
24	42.44	4.537	67500
25	57.94	11.936	296
26	64.33	7.592	1990
27	77.84	20.515	3918
28	16.70	2.535	900
29	38.72	4.980	40600
30	28.84	2.907	1250

SAMPLE	DISCHARGE VARIABILITY		DRAINAGE
SITE NO.	LONG TERM (%)	ANNUAL	AREA (□ mls)
31	27.50	29.052	2849
32	96.75	11.418	880
33	85.20	57.737	11380
34	16.28	5.536	9003
35	84.27	36.277	2350
36	88.96	25.280	10200
37	41.95	6.734	2327
38	32.46	2.550	1010
39	46.54	3.733	3300
40	87.76	12.343	5511
41	114.82	58.060	922
42	31.96	38.559	645
43	89.43	62.562	4082
44	68.96	86.583	14490
45	84.63	16.335	5161
46	86.19	59.604	2148
47	48.74	12.598	1040
48	47.57	17.234	363
49	54.49	33.561	60
50	48.96	8.273	143
51	22.66	14.820	749
52	49.18	10.468	2240
53	39.73	78.439	136
54	36.44	2.425	10500

VARIABILITY OF DISCHARGE VALUES FOR THOSE STOCHASTIC ANCHOR POINTS EXCLUDED FROM THE STUDY

GAUGING STATION		ANNUAL DISCHARGE
RIVER	LOCATION	VARIABILITY
Pecos River	near Girvin, Texas	37.762
Santa Maria River	near Alamo, Arizona	323.668
Baker Creek	near Baker, Nevada	9.608
Martin Creek	near Paradise Valley, Nevada	14.422
Mojave River	at Afton, California	122.721
Musselshell River	at Mosby, Montana	24.251

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