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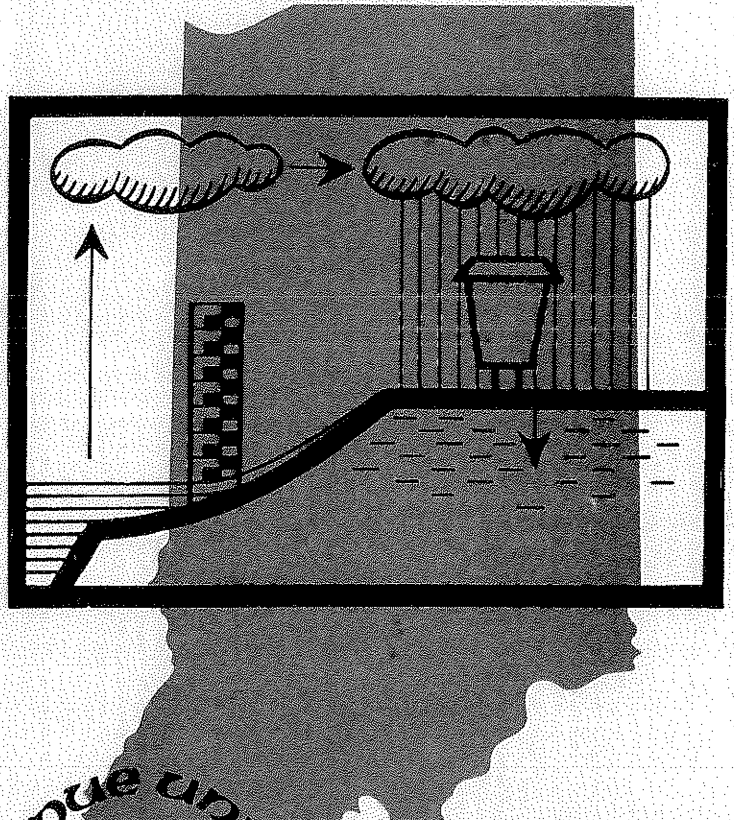
TECHNICAL REPORT NO. 52

DRAINAGE BASIN RESPONSE: DOCUMENTED HISTORICAL CHANGE AND THEORETICAL CONSIDERATIONS

Studies in Fluvial Geomorphology No. 3



by

Dorland E. Edgar
Wilton N. Melhorn

DECEMBER 1974

PURDUE UNIVERSITY
WATER RESOURCES RESEARCH CENTER
WEST LAFAYETTE, INDIANA

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This is a partial completion report for OWRR Project No. A-022-IND (Agreement No. 14-31-0001-4014) entitled "The Effects of Human Activity on Drainage Network Stability and Growth"

Purdue University

Department of Geosciences

West Lafayette, Indiana

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ABSTRACT

Archival materials dating from 1838 were examined in an attempt to document the historical development of small drainage basins representative of central Indiana. Owing to limitations in the available data sources, the study was confined to a comparison of five drainage basins in the Indian Creek Watershed, located approximately six miles west of West Lafayette, as mapped from 1938 and 1968 aerial photography. By using the Strahler ordering system in combination with other, more recently proposed classification schemes and quantitative parameters, morphometric adjustments in the study basins were determined. In general, fourth-order basins experienced small losses in the number of stream segments and decreased in textural complexity while maintaining approximately the same total length of channels within the basins. Fifth-order basins underwent significant increases in the number of segments and textural complexity, and a small average increase in total channel length. All basins showed only minor changes in length, bifurcation, and division ratios with most of the drainage adjustments occurring in the "lost" or nonintegrated portions of the networks.

The observations made were used to test certain salient features of recently proposed theoretical techniques of watershed analysis. Mixed results were obtained. However, it was determined that all those approaches to network development and stability which were examined were of some utility, particularly when two or more were analyzed in conjunction.

Observed drainage changes were tentatively interpreted as resulting from fluctuations of climatic input, threshold conditions, areal distribution of soil type, and human activity through land use changes. Although all of these factors in combination produced the observed drainage adjustments, it is probable that the entire effect of recent human activity was not expressed by 1968. Subsequent basin response to urbanization in the Indian Creek watershed may reflect the full disruptive potential of man's activity on natural fluvial systems.

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SYMBOLS

Symbol	Definition	Units
A	Drainage Basin Area.	acres, mi^2
C	Constant of Channel Maintenance. $C = (1/Dd) \times 5280$	ft^2/ft
Dd	Drainage Denisty. $Dd = L_T/A$	mi/mi^2
F	Channel Segment Frequency. $F = N_T/A$	mi^{-2}
F_ℓ	Link Frequency. $F_\ell = n_t/A$	mi^{-2}
H_u	Number of Horton Streams of Order u.	
HN_u	Number of Channel Segments of Strahler Order u Within the Horton Net.	
HN_T	Total Number of Channel Segments Within the Horton Net.	
L	Maximum Basin Length Measured Approximately Parallel to Mainstream Direction.	ft, mi
L_m	Mainstream Length.	ft, mi
L_o	Length of Overland Flow. $L_o = (1/2\ Dd) \times 5280$	ft
L_T	Total Length of Channel Segments Within the Network.	ft, mi
L_u	Total Length of Channel Segments of Strahler Order u.	ft
$\bar{L}_u$	Mean Length of Channel Segments of Strahler Order u. $\bar{L}_u = L_u/N_u$	ft

Symbol	Definition	Units
$\bar{\ell}$	Mean Length of Shreve Links Within the Network.	ft
ℓ_e	Mean Length of Exterior Shreve Links (equivalent to $\bar{L}_1$).	ft
ℓ_i	Mean Length of Interior Shreve Links.	ft
$\bar{\ell}_u$	Mean Length of Shreve Links Comprising Channel Segments of Strahler Order u. $\bar{\ell}_u = L_u/n_u$	ft
M	Shreve Link Magnitude.	
N_T	Total Number of Channel Segments Within the Network.	
N_u	Number of Channel Segments of Strahler Order u.	
n_t	Total Number of Shreve Links Within the Network.	
n_u	Number of Shreve Links Comprising Channel Segments of Strahler Order u.	
P	Drainage Basin Perimeter.	ft, mi
R_A	Area Ratio Basin Upon Hexagonal Packing.	
R_B	Bifurcation Ratio. $R_B = N_u/N_{u+1}$	
R_C	Circularity Ratio. A/Area of Circle With Circumference Equal to P	
R_D	Division Ratio. $R_D = HN_u/HN_{u+1}$	
R_E	Elongation Ratio. R_E = Diameter of Circle With Same Area as Basin/L	
R_F	Fineness Ratio. $R_F = L_T/P$	

Symbol	Definition	Units
R_L	Length Ratio. $R_L = \bar{L}_u/\bar{L}_{u-1}$	
$R_{\ell t}$	Link-Texture Ratio. $R_{\ell t} = n_t/P$	ft^{-1}
R_t	Texture Ratio. $R_t = N_T/P$	ft^{-1}
u	Strahler Order.	
U_A	Absolute Stream Order.	
U_C	Consistent Stream Order.	
U_P	Proportional Stream Order.	
W	Maximum Basin Width Measured Approximately Perpendicular to Mainstream Direction.	ft, mi
WSF	Watershed Shape Factor. WSF = L_m/ Diameter of Circle With Same Area as Basin.	
Ω	Strahler Order of Largest Stream Segment of the Network = Basin Order.	

PREFACE AND ACKNOWLEDGMENTS

This report is the third in a numbered series of Studies in Fluvial Geomorphology. However, two Technical Reports of the Purdue WRRC, numbers 16 and 22 preceded the current numbered series. The present report describes attempts to document historical development and change in small drainage basins, and assesses the question of how or if human activity disturbs natural processes and leads to dislocations in the fluvial regime of these basins. This study would not have been possible without input of results obtained in the earlier studies.

Helpful suggestions, criticisms, and data have come from a number of sources. We are especially grateful to Dr. R.A. Rao, for assistance in obtaining hydrologic information and for discussion of hydrologic facets of the problem; to Prof. R.D. Miles, who provided time sequential aerial photography of the study basins; and to Mr. Leroy G. Davis, U.S. Geological Survey, for input on data analysis techniques and discussion of geomorphic influences in hydrology. Personnel of the agricultural meteorology staff, Purdue University Department of Agronomy provided precipitation and other climatic data for the study area. Staff of the Tippecanoe County Office of the Soil Conservation Service were exceedingly helpful in discussion of past and present soil conservation and management practices in the basins studied.

CHAPTER 1

INTRODUCTION

General Statement

The most important single trend in geomorphology in the past 30 years is the development of objective, quantitative methods of studying landforms and the processes which initiate and alter them. This trend represents a shift from the historical and purely descriptive approach to landscape development exemplified in the classic work of W.M. Davis and his followers. Quantification of geomorphic attributes has been especially useful and most often applied to the study of fluvial landforms and, in particular, to drainage basins using the techniques proposed by Horton (1945) and those subsequently developed by A.N. Strahler and his many students.

Since the 1950's, numerous examples of morphometric analysis of drainage basins have been reported and have added considerably to an understanding of drainage network development and composition. Using such studies as a foundation, several theoretical models of stream network evolution (see Shreve, 1966, 1967, 1969; Smart, 1969; Woldenberg, 1969) and computer simulation and random walk techniques (see Leopold and Langbein, 1962; Smart, *et*.*al*., 1967; Seginer, 1969; Howard, 1971) have been proposed. Currently, even though numerous studies have been concluded with a presentation of new parameters and developmental hypotheses, the fundamental processes governing growth and adjustment of river basin morphology are still largely unknown.

Purpose of Research

Partly because previous studies have been theoretical, and partly because of the great difficulty involved in examining a time-dependent natural phenomenon, no serious testing of new parameters and evolutionary theories has been undertaken on real river networks. There is currently no precise way to predict conditions of, or changes toward stream network equilibrium. Therefore, it is unrealistic to expect that we can begin to control or even subtly influence the growth and stability of individual channels or small drainage basins. Human activity is so markedly influencing natural river regime and fluvial processes may be so significantly altered as to accentuate detrimental river activity and natural erosive processes. Corrective measures applied within a basin may provide an impetus for a new generation of network instability that produces a series of new and unforeseen problems.

During the present study, an attempt was made to apply some recent theoretical concepts to real drainage networks as a test of their applicability and to gain an understanding of growth and stability in natural stream networks. Furthermore, because man's activity is constantly influencing drainage networks through encroachment, varied land use, or actual physical alteration, an attempt was made to identify the results of human activity on network growth and stability. The objectives of this study are therefore as follows:

1. Map and analyze observable physical changes within selected drainage basins for which historical records

of sufficient detail and accuracy are available.

2. Test existing methods and theoretical models for determining network stability on real stream networks over a period of time sufficient to allow measurable network change.
3. Evaluate various effects of human activity on stream network development and stability.
4. Evaluate the effects of natural variability of controlling independent variables on the physical characteristics of a fluvial system.

It is therefore hoped that this study, aside from simply adding to the existing body of data on drainage network parameters, will be useful in anticipating possible morphologic adjustments to altered land use practices, and provide a test for some of the recently proposed and essentially untried, theoretical models of stream networks.

CHAPTER 2

RESEARCH METHODOLOGY AND DATA COLLECTION

Introduction

Owing to the length of time involved and consequent financial considerations, detailed studies of the historical development of geomorphic features based upon sequential field measurements and observations are quite rare. The period of time necessary for observable and measurable changes to occur is variable in nature from place to place and depends upon the magnitude and frequency of the causative geomorphic forces. In some instances, rapid alterations may be noted, particularly where man's influence has disturbed the natural condition. More commonly, when viewed in the undisturbed state, evolutionary change of the landscape may appear quite slow, taking many years for the operative processes to produce a discernable change.

To overcome this problem, researchers have attempted to study the evolution of landscape units by several different approaches. By selecting areas where conditions are optimum for rapid network growth--for example badland areas where vegetation is scant or absent, artificial land-fill sites, or areas of concentrated urbanization--rapid morphological changes can occur in a shorter period of time (see Schumm, 1956; Leopold, 1973). A second approach involves substitution of space for time by assuming that a sampling of attributes at a given time represents various stages of development owing to variability of local conditions (for example see Hack, 1960). Although this is a common technique, its validity has been questioned by some researchers. Thirdly, experimental studies, which have the advantage of greatly condensing the time element of the model compared to the prototype, have been employed with considerable success (see Parker and Schumm, 1971; Mosley, 1972). A fourth methodology used in recent years is the use of conceptual models and computer simulative procedures (see Woldenberg, 1966; Howard, 1971). Finally, data can be collected on selected drainage basins from historical records and archival materials, enabling quantitative comparisons of parameters over a known interval of time. This latter methodology is used for the present study.

Data Sources

In an attempt to obtain drainage information over a maximum possible interval of time, a thorough search of historical documents was conducted. It was originally hoped that 19th century planimetric maps, though crude, would contain sufficient detail and accuracy to trace drainage basin evolution over a minimum of 100 years. The following data sources were obtained for this program:

1. Map of the State of Indiana, compiled by S.D. King and published by J.H. Colton, 1838.
2. Illustrated Historical Atlas of the State of Indiana, published by Baskin, Forster, and Company, 1876.
3. U.S. Geological Survey 15' topographic maps, partial coverage of southwestern Indiana, period 1900 to 1905.
4. Aerial photographs, a complete coverage of the state obtained at various times from 1938 to 1968, and

5. U.S. Geological Survey 7½' topographic maps of the same areas of southwestern Indiana, surveyed since 1950.

In assessing these historical sources, several difficulties soon were encountered which necessitated the reduction of the proposed time interval of study. The King map of 1838 (Figure 1) contains remarkable detail for the date of compilation and is potentially useful for various types of historical and geographical studies. Considerable information on geographic and natural features and their influence on, and alteration by, cultural development in the state is obtainable. However, the scale of the map (1 inch = 5 miles) permitted the recording of only the largest streams. Furthermore, detail contained on the map is quite variable, with areas surrounding the larger cultural centers of that era possessing the greatest amount of drainage information.

The Baskin and Forster Atlas of 1879 contains individual county maps (Figure 2) and additional historical and biographical information. Although the maps are presented at a larger scale (variable from 0.5 to 0.75 inch = 1 mile) only the larger trunk streams are shown and, as with the King map, detail varies from county to county. Insufficient data are present to permit a detailed morphometric analysis representative of that time period.

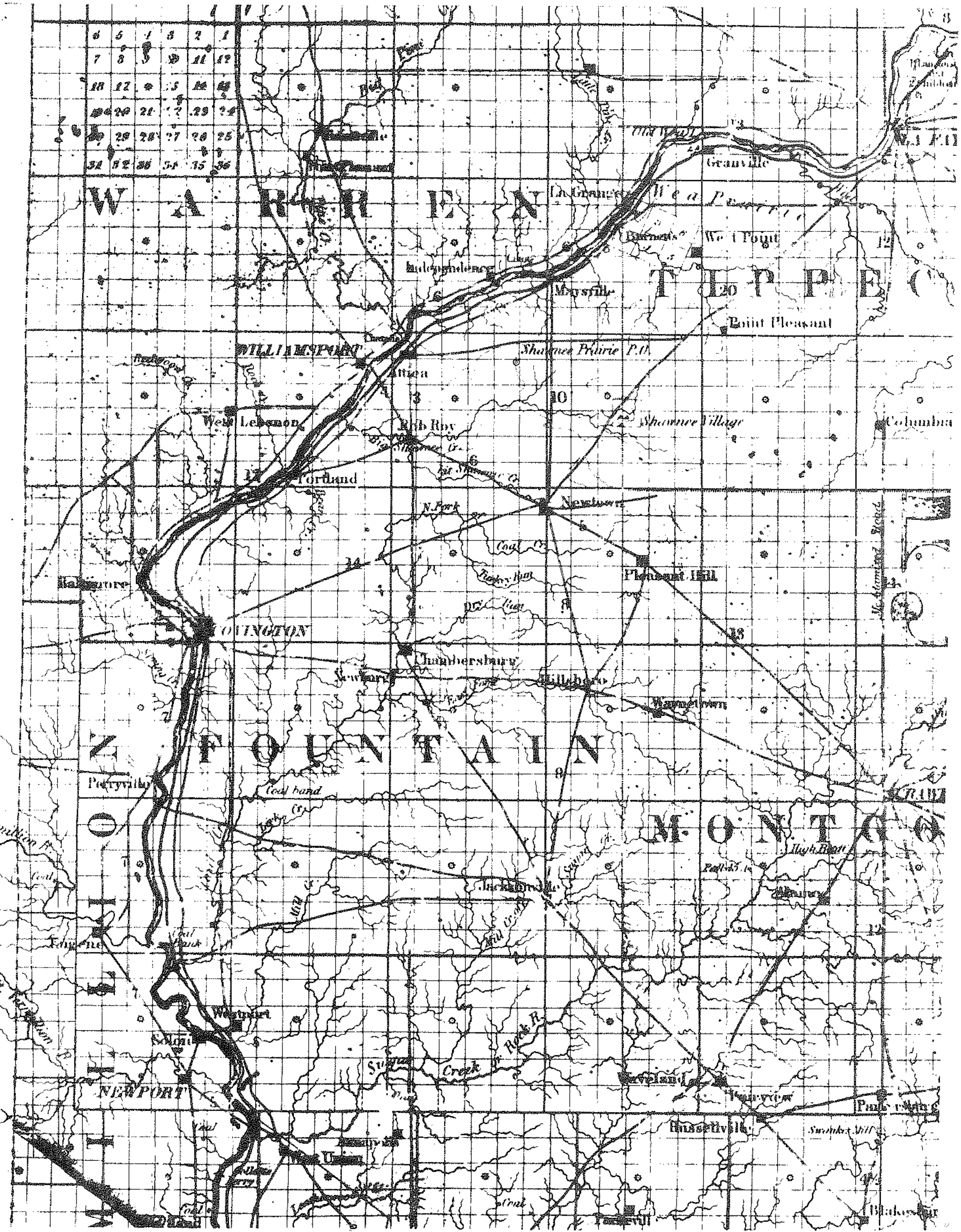
Nine contiguous 15' topographic maps are available covering an area of approximately 1500 square miles in extreme southwestern Indiana. These quadrangles were examined: Boonville (1902), Degonia Springs (1902), Haubstadt (1903), New Harmony (1903), Owensboro (1901), Petersburg (1903), Princeton (1901), St. Meinrad (1903), and Velpen (1903).

These maps give an accurate representation of the area as it appeared at the turn of the century, and maps of this scale have been used by investigators for basin analyses. However, the problem of map scale presents certain difficulties which will be discussed subsequently.

For time comparison, the same area covered by the 15' quadrangles is also available on 7½' quadrangles published by the U.S. Geological Survey since 1950. Unfortunately, an extensive program of channelization, channel straightening, and realignment was conducted in the area between 1910 and 1950. This disrupted surface drainage to such an extent that no comparison of morphometry between the two sets of maps is feasible.

Aside from the difficulties cited, certain innate errors would be introduced by utilizing these data sources of such diverse scale. Obviously, the values of morphometric variables obtained from maps is highly dependent upon the original map scale. Morisawa (1959) concluded that U.S.G.S. topographic maps at a scale of 1:62,500 (15') are unreliable for measuring all drainage characteristics except basin area, and that numbers of stream segments and length data show greater variation when obtained from maps. Coates (1958) found that 1:24,000 scale quadrangles (7½') rarely showed any first- or second-order streams, and that most segments interpreted as first-order were at least third-order. Finally, a detailed study by Coffman et. al. (1972), resulted in the conclusion that, owing to these information losses, topographic maps do not generally show channel networks which are porportional to the real network. Coffman, et. al. (1971) recommended aerial photographs as the best source of planimetric information for

Figure 1. A portion of the map of Indiana compiled in 1838 by S.D. King and shown at the original scale of one inch equal to approximately five miles.


W A R R E N
T I P P E C
F O U N T A I N
M O N T G O
Granville
La Grange
Wea Prairie
West Point
Independence
Maysville
Point Pleasant
WILLIAMSPORT
Attica
Shawnee Prairie P.O.
Shawnee Village
Rob Roy
Columbia
West Lebanon
Portland
Newtown
N. Fork
Coal Cr.
Pleasant Hill
Baltimore
COVINGTON
Chambersburg
Newburg
Hillsboro
Wayne town
Perrysville
Coal band
Jacksonville
High Point
Eugene
Westport
Sugar Creek
Rock R.
Cleveland
NEWPORT
Russellville
Parkersburg
Smokes Mill
Blakesburg
Clinton Ferry
Vermilion R.
Lit. Vermilion R.
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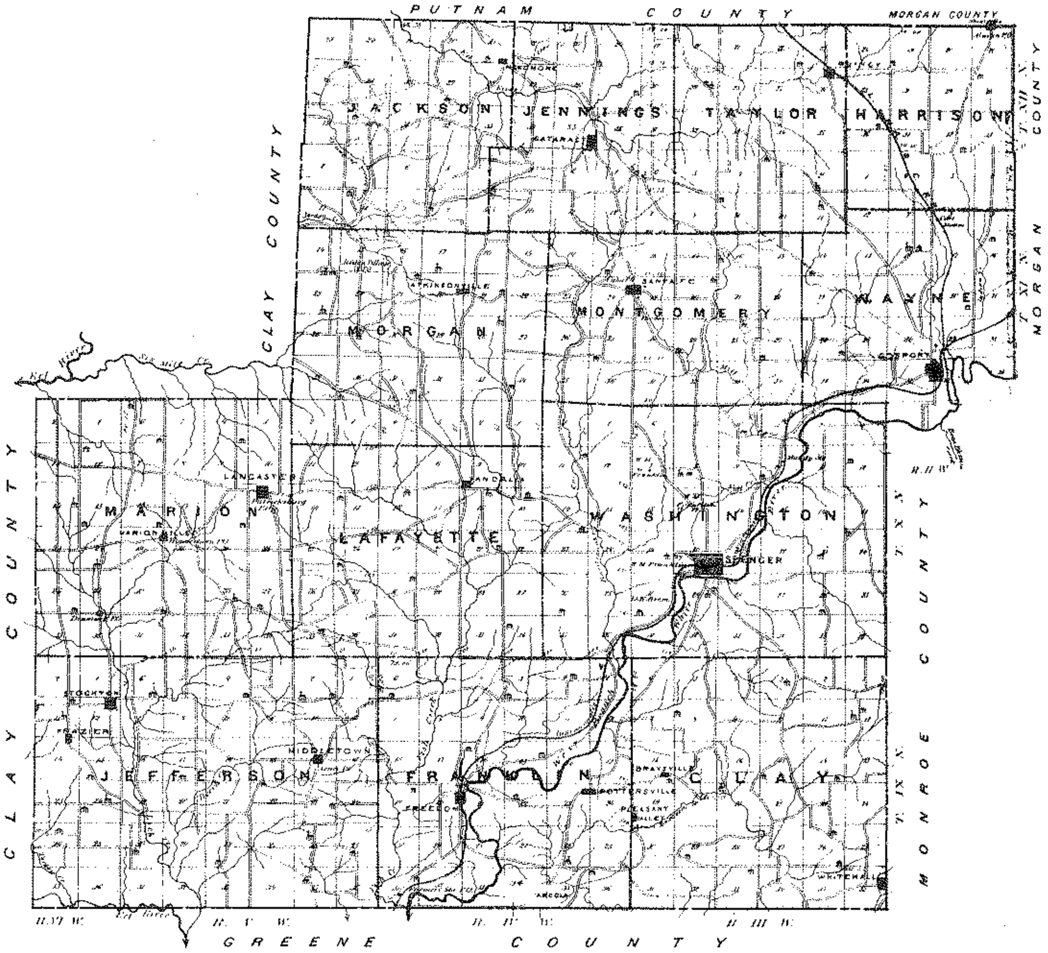


Figure 2. Map of Owen County at an approximate scale of 0.23 inches = 1 mile (from Baskin and Forster Atlas, 1879).

drainage system studies.

Complete aerial photographic coverage of Indiana, obtained at several intervals since 1938, is available. Much of this coverage was obtained for the U.S. Department of Agriculture for crop inventory and was flown during the summer months. Additionally, any single area coverage may involve several months time for completion. Because the ability to accurately delineate the drainage network depends upon the lack of foliage in wooded areas, photographs obtained during the summer growing season are of limited value. These requirements resulted in a severe limitation in the scope of the study. Owing to all the aforelisted limitations in basic data sources, the study was confined to a comparison of drainage basins found on photography obtained under optimum conditions during 1938 and 1968.

Data Collection

Five small drainage basins in western Tippecanoe County ultimately were selected for study. This was one of the few areas examined where the time of photography was optimum for ease of drainage delineation for the maximum time interval. Unfortunately, the 1938 photography was obtained at a 1:20,000 scale whereas the 1968 scale is 1:3,600. However, subsequent analysis results indicate this variance appears to have had minimal effects on the study.

Stream networks and basin perimeters were carefully delineated stereoscopically from small-scale, uncontrolled mosaics. Data were collected from the 1938 photography under 4X magnification whereas

2X magnification was used on the 1968 photography. Where more than one photograph was necessary to map a given basin, care was taken to carefully match and use only the central portion of each print to minimize the effect of aircraft tip and tilt. Undoubtedly, some horizontal displacement and error in length measurements exist, but for several reasons photogrammetric techniques and equipment were not used. As a result, only planimetric data was collected.

After the initial maps were compiled, each was enlarged or reduced to a common scale of 1:7,920 (1 inch = 660 ft.) to facilitate comparisons. These maps then served as work sheets from which appropriate measurements were taken. From these basic data, all morphometric variables analyzed in the study were calculated. A discussion of these variables is found in Chapter 4.

CHAPTER 3

RIVER NETWORK CLASSIFICATION SCHEMES

Introduction

The historical development of river basin and network classification techniques has been discussed in depth by other authors (see Coffman, *et. al.*, 1971, Chapter 2). A historical treatment of the development of geomorphic thought and methodology is not the primary objective of this report but a synoptic review of the origin of techniques and parameters used during the course of this study is warranted, especially for the benefit of readers unfamiliar with geomorphic literature. Therefore a short review of available classification procedures and discussion of the variables used in this analysis is given in the sections immediately following.

Classification Procedures

As already noted, quantification of geomorphic elements and of stream networks in particular is a rather recent development. One of the last network classifications based solely on descriptive terminology was attempted by Zernitz (1932) wherein commonly used but poorly defined stream pattern terms such as radial, annular, trellis, and dendritic were collected together and described. Owing to the vague and subjective nature of such descriptions, a more flexible and utilitarian system was desired. Thus, a transition to quantitative studies was first provided by Horton in 1945.

Horton Stream Order

Although the concept of ordering branches in a river network did not originate with Horton, he restructured the contemporary European concept (see Horton, 1945, p. 281) into the form used today. In Horton's system, all unbranched fingertip tributaries are always designated order 1, whereas streams of order 2 receive tributaries of only the first-order. Third-order streams may receive only first- and second-order tributaries, etc., until the trunk stream of the system is encountered and receives the highest order. One difficulty in applying this ordering system is the need to make a subjective decision at each stream junction, in order to differentiate between the main stream and its tributary so that the main stream can be traced back to its origin (Figure 3). Although Horton gave rules for the determination (Horton, 1945, p. 281-282), it is possible for different investigators to produce differently ordered maps of the same stream network.

The primary contribution of Horton's effort is the introduction of quantitative measures of a drainage basin resulting from his ordering system. He showed graphically the relationships of several stream properties with order and formulated the empirical "Laws of Drainage Composition".

Strahler Stream Order

In contrast with the Horton viewpoint of a trunk stream and branches, Strahler (1952) considered the drainage net to be composed of basic units which he termed channel segments. He defined a given order by the junction, as one end point, of two segments of the next lower order and

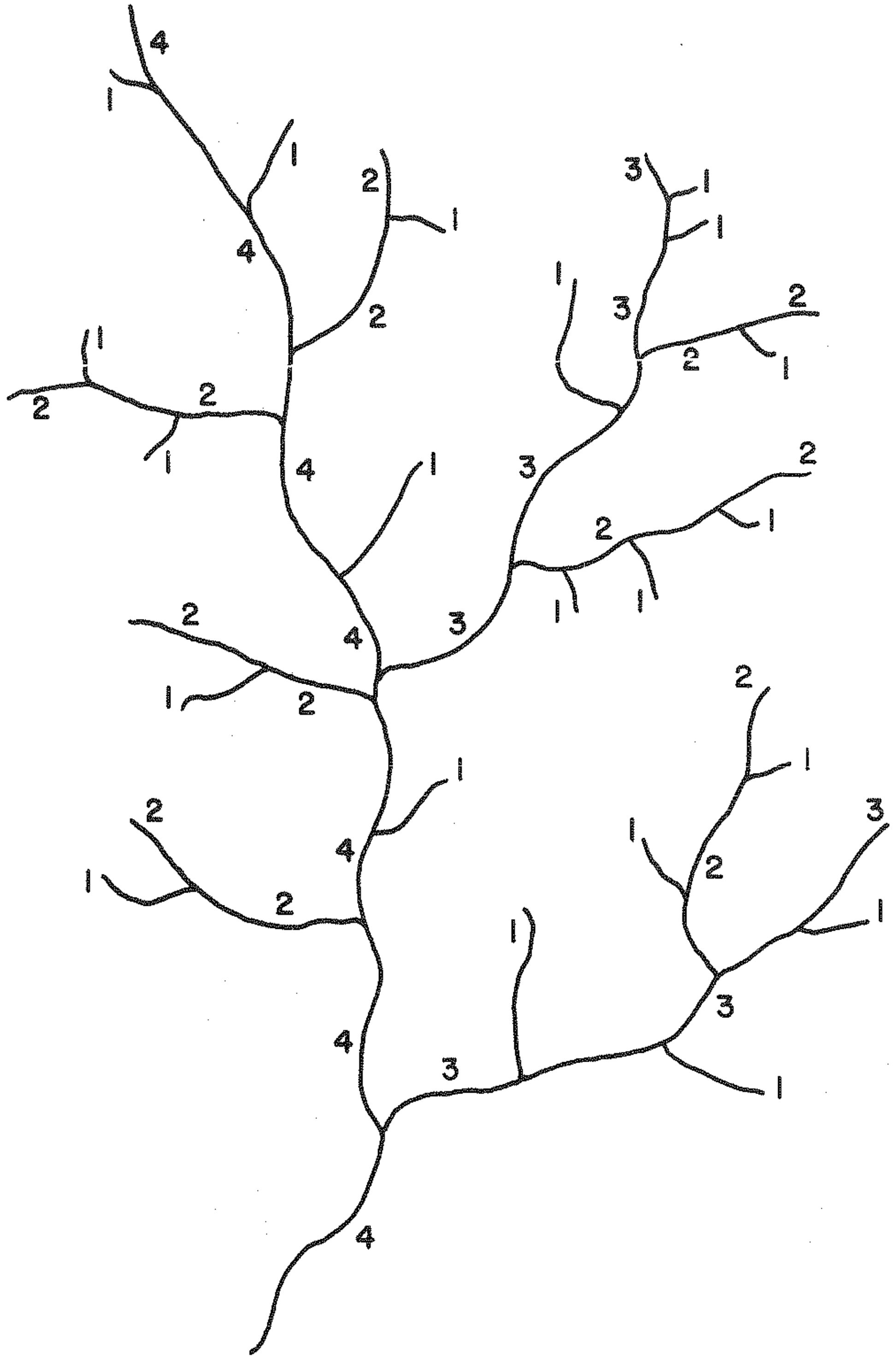


Figure 3. Hypothetical stream network ordered by the Horton method.

terminus in a merger with segments of equal or higher order as the other end point. Consequently, the subjectivity of choosing the main stream in the Horton system was replaced by a single, objective rule which defined the ordering process. Figure 4 depicts a drainage network ordered by the Strahler method. If compared with Figure 3, the difference in results of the two ordering methods becomes apparent.

Consistent Stream Order

The principal criticism of both the Horton and Strahler ordering systems is that neither incorporates the direct contribution to the drainage system of lower order tributaries that directly join higher order streams. No change in order results from the addition of a tributary of order u-1 or smaller to a stream of order u. These lower order tributaries were called "adventitious streams" by Horton (1945, p. 342) and later "lost stream segments" by Scheidegger (1966, p. 788).

Elaborating upon previous work pertaining to this problem, Scheidegger (1965) proposed a Consistent System of Stream Order in which he assumed that order can be raised by two types of junctions rather than by only one. He algebraically derived the following expressions of this system:

$$2^X = 2^N + 2^M$$

or

$$M * N = X = \frac{\log (2^N + 2^M)}{\log 2} = \log_2 (2^N + 2^M)$$

where the asterisk (*) denotes the combination of streams of order M and N to produce a stream of consistent order X. This classification

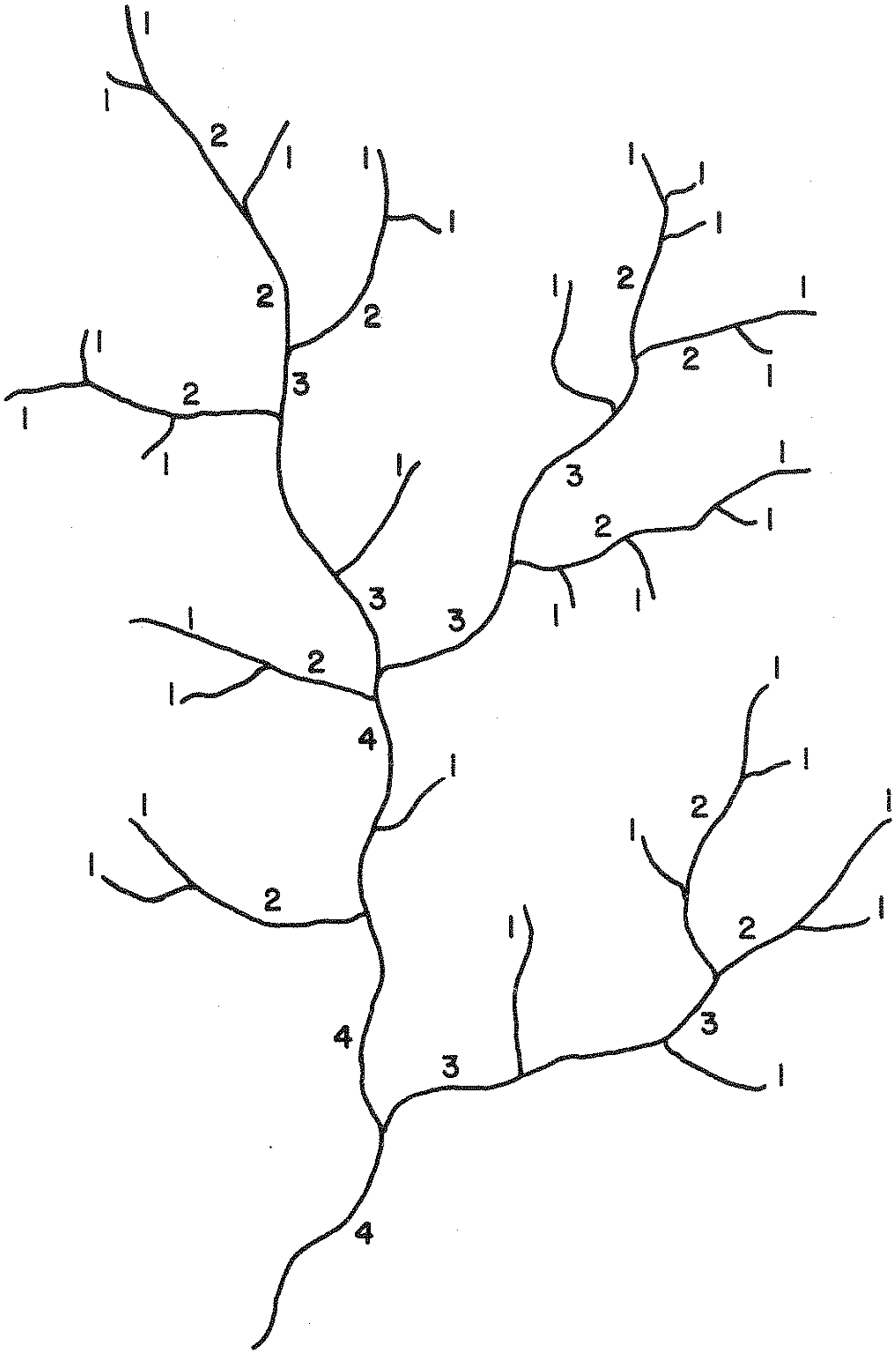


Figure 4. Hypothetical stream network ordered by the Strahler method.

technique has not been widely utilized, possibly owing to its apparent complexity.

Stream Magnitude

The concept of stream magnitude, as proposed by Shreve (1967), represents another effort to incorporate all elements of a channel network by allowing a more realistic representation of the influence of lower order tributaries upon larger channels. This scheme considers the link as the primary unit of the network. Shreve defines a link as "a section of channel reaching without intervening forks from either a fork or a source at its upstream end to either a fork or the outlet at its downstream end" (1966, p. 20). The points farthest upstream in a network are sources whereas the point of confluence of two channels is termed a fork. All sources and forks are also called nodes. Shreve distinguishes two general types of links: exterior links and interior links, which terminate at their upstream ends in sources and forks, respectively (Shreve, 1967, p. 178). All exterior links, which are equivalent to Strahler first-order stream segments, carry a magnitude of one. All link junctions are considered additive; therefore, the magnitude of a link below a confluence is assigned a magnitude equal to the numerical sum of the two joining links. Figure 5 is an example of the Shreve magnitude classification.

There is no method to convert between the popular Strahler ordering system and Shreve magnitudes. There is, however, a relationship between the numbers of stream segments and links (Coffman, et.al., 1972). Furthermore, Shreve (1967, p. 179) demonstrated that link magnitude (M) is simply related to Scheidegger's. Consistent Order (U_c) by the relation:

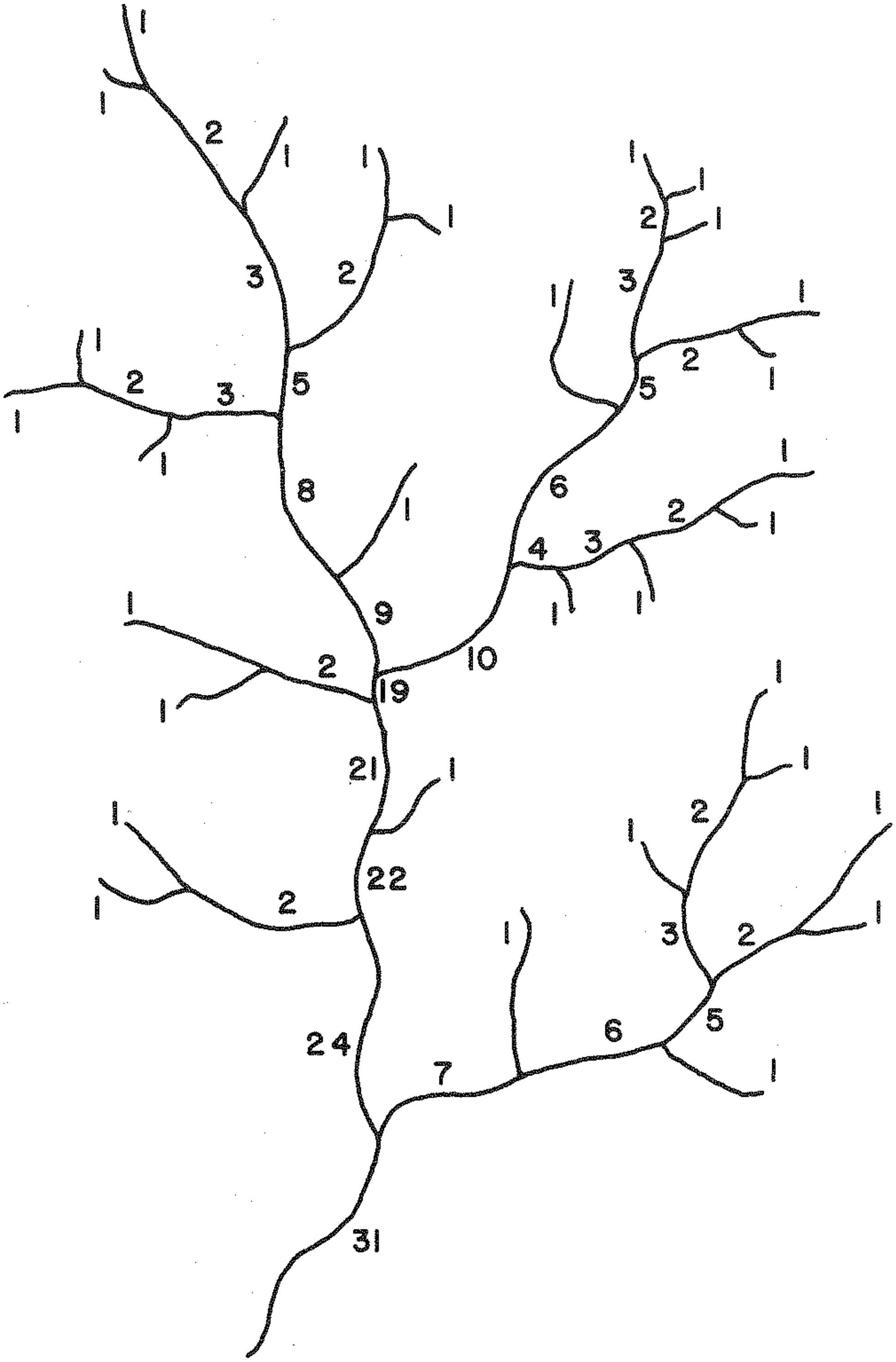


Figure 5. Hypothetical stream network classified according to Shreve magnitude.

$$U_c = \log_2 2M .$$

The primary disadvantage of using Shreve magnitude is shown by Smart (1968) to be the necessity of increased bookkeeping. As an example, a basin with 31 sources require 31 numbers to characterize the network by the Shreve method, whereas only four are required by the Strahler method. However, some investigators think that the link should be considered the basic unit of network composition (Smart, 1968, p. 1004).

Absolute Stream Order

Investigations of geomorphic features and formative processes have often been conducted under a systems approach with considerations of equilibrium conditions. Chorley (1962) and Howard (1965) have defended the utility of an open system approach in geomorphic studies of interactions between form and process. In 1966, Woldenberg demonstrated that if two parts within an open system are related allometrically to the whole system, they are related to each other by a power function in the form $y = a\,x^b$, and consequently form a straight line if plotted on double logarithmic paper. By assuming that streams are in steady state or allometrically growing systems, Woldenberg (1966, p. 433) deduced that Strahler stream order is probably itself a logarithm. On this basis, he proposed an absolute stream order (U_A) related to Strahler order (u) in the form

$$U_A = B^{u-1}$$

where the base B equals the bifurcation ratio or some other appropriate ratio of increase.

Proportional Stream Order

Another attempt to account for the influence of "lost" streams in the Horton and Strahler ordering systems resulted in the Proportional System of Stream Order proposed by Stall and Fok (1968). Their proposed ordering parameter is given by the equation:

$$U_p = u + u_x$$

where U_p is the proportional order, u is the order of any link of a Strahler segment, and u_x is a number less than one relating to the development of first-order segments above the link in question. This scheme thus includes both integer and fractional or decimal numbers.

Ambilateral Classification

Elaborating upon the work of Shreve (1966), Smart (1969) developed the ambilateral classification method. This system evolved from an attempt to obtain a coding scheme yielding more information than Strahler's, but which would be less detailed and cumbersome than an exact description of all junctions and sources. The basis of this scheme is that two topologically distinct channel networks can be placed in the same class if one can be converted into the other by reversal of the right-left order at one or more junctions. It was Smart's contention (1969, p. 1759) that the ambilateral classification is more closely correlated with geomorphic and hydrologic properties than the common stream number classification.

Other Descriptive Systems

Other much more complicated and detailed means of network description have been proposed. Although exactness in detail is possible when these systems are computer processed, they are much too complex for manual calculation. The interested reader is referred to the original publications for the operational procedures. Four of these descriptive systems are: 1) Milton-Ollier Coding (1965), 2) the Storet System of labeling, developed by Green, *et.al*. (1966), 3) Binary String methods proposed by Scheidegger (1967), Shreve (1967), Smart (1970), and others and 4) the WATER System, detailed in Coffman, *et.al*. (1971).

Laws of Drainage Composition

Initially, Horton (1945) presented three "laws" of drainage composition, which he derived empirically through the application of his ordering technique. The Law of Stream Numbers states that "The numbers of streams of different orders in a given drainage basin tend closely to approximate an inverse geometric series in which the first term is unity and the ratio is the bifurcation ratio" (Horton, 1945, p. 291). The second "law" is the Law of Stream Lengths which states "the average lengths of streams of each of the different orders in a drainage basin tend closely to approximate a direct geometric series in which the first term is the average length of streams of the first order" (Horton, 1945, p. 291). Horton also outlined a similar relationship for stream slopes in noting a "fairly definite relationship between slope of the streams and stream order, which can be expressed by an inverse geometric-series law" (1945, p. 295).

Because of the different ordering methodology adapted by Strahler, it was reasonable to question the validity of any drainage composition relationship derived from this new classification scheme. As a consequence, several investigators examined this problem and all concluded that the Law of Stream Numbers was not affected by Strahler ordering (Strahler, 1957; Melton, 1959; Shreve, 1963, 1964). Shreve (1966, p. 23) demonstrated that Horton and Strahler numbers are uniquely related by the statement

$$N_u = \sum_{i=u}^{\Omega} H_i \ , \ u = 1, 2, \ldots \Omega$$

and conversely,

$$H_u = N_u - N_{u+1}, \ u = 1, 2, \ldots, \Omega - 1, \ H_\Omega = 1$$

where N_u = number of Strahler segments of order u,

H_u = number of Horton streams of order u, and

Ω = order of the largest stream in the basin.

Similarly, the other composition "laws" have been examined; the general conclusion is that by one or more slight mathematical restatements, the relationships are valid with the Strahler ordering system.

Subsequent study led to development of several additional empirical relationships. In the original 1945 paper, Horton (p. 294) alluded to a geometrical relation between basin area and order. However, not until 1956 did Schumm (p. 606) formulate the Law of Stream Areas by stating that "the mean drainage-basin areas of streams of each order tend to approximate closely a direct geometric series in which the first term is the mean area of the first-order basins." Maxwell (1960, p. 23) proposed the Law of Basin Relief (the mean relief of basins of each order in a watershed tend closely to approximate a direct geometric series in which the first term is the mean relief of the first-order basins) and the Law of Basin Diameters, stated in similar terminology. Neither of these two proposed relationships have been sufficiently examined to allow expression in a simple mathematical statement as is the case with those formulated earlier in time.

CHAPTER 4

VARIABLES USED FOR MORPHOMETRIC ANALYSIS

Introduction

Since the introduction of Horton's quantitative approach techniques to study of drainage networks, various researchers have proposed numerous parameters which describe the physical properties of drainage basins and reflect their complex interactions. For example, in a 1958 publication Strahler lists 36 properties for use in basin analysis. Many others have been proposed during the following 16 years. Quite obviously not all postulated parameters can be incorporated into a study such as the present one. Many variables are highly intercorrelated whereas certain others have been demonstrated to be of more general value and applicability. In the subsequent discussion, those variables most commonly used, as well as some thought to be of particular utility by the authors, are presented along with their derivation and value.

Linear Aspects of Drainage Basins

Strahler Stream Order

The first step in the basin analyses was the designation of stream orders (u) using the Strahler method. Drainage basin order (Ω) is equivalent to the order of the largest (trunk) stream segment. Order number is dimensionless and provides a basis of comparison between basins of diverse size and physical characteristics. The utility of the ordering system is based on the premise that "on the average, if a sufficiently large sample is treated, order number is directly proportional to relative watershed dimensions, channel size, and stream discharge at that place in the system" (Strahler, 1957, p. 914).

Number of Strahler Stream Segments and Bifurcation Ratio

After the network has been ordered, the number of segments of each order is determined. Horton's (1945) first law of drainage composition is given by the relation:

$$N_u = R_B^{\Omega - u}$$

where N_u is the number of streams of order u, Ω is the basin order, and R_B is a constant called the bifurcation ratio.

As already mentioned, it has been demonstrated that this relation is valid when Strahler order is used. In fact Shreve (1964, p. 50) found that this method gave a better fit to the law than the original Horton ordering.

The bifurcation ratio supposedly measures the tendency of stream segments to divide. However, in most cases, this ratio is not constant between consecutive stream orders owing to the influence of "lost" segments. Individual bifurcation ratios for consecutive orders is obtained by:

$$R_B = N_u/N_{u + 1}$$

whereas the average value for the entire basin is obtained from the slope of the least squares regression line for the plot of log number of segments against order (Figure 6). Bifurcation ratios characteristically range between 3.0 and 5.0 for watersheds developed in the absence of strong structural control (Strahler, 1964).

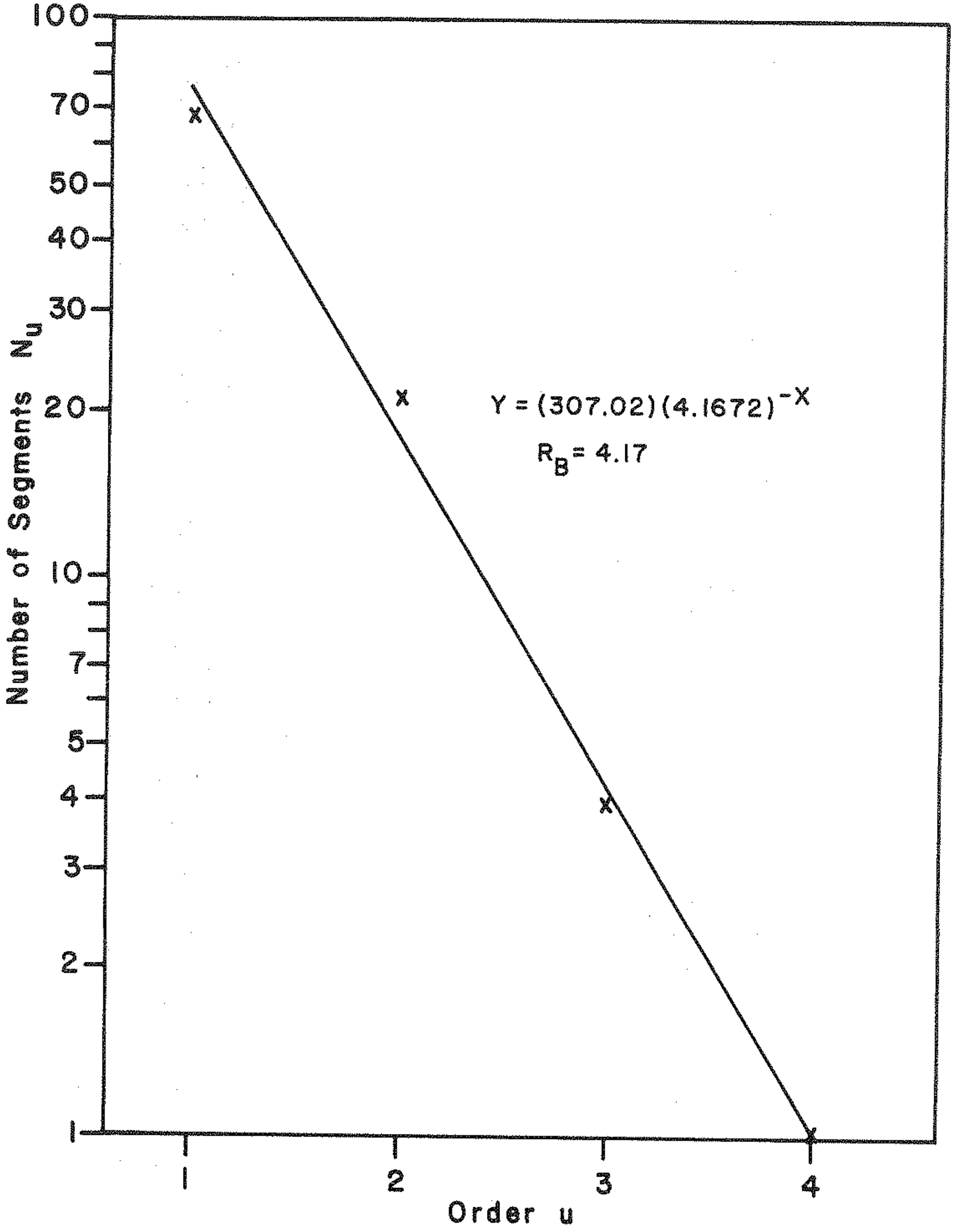


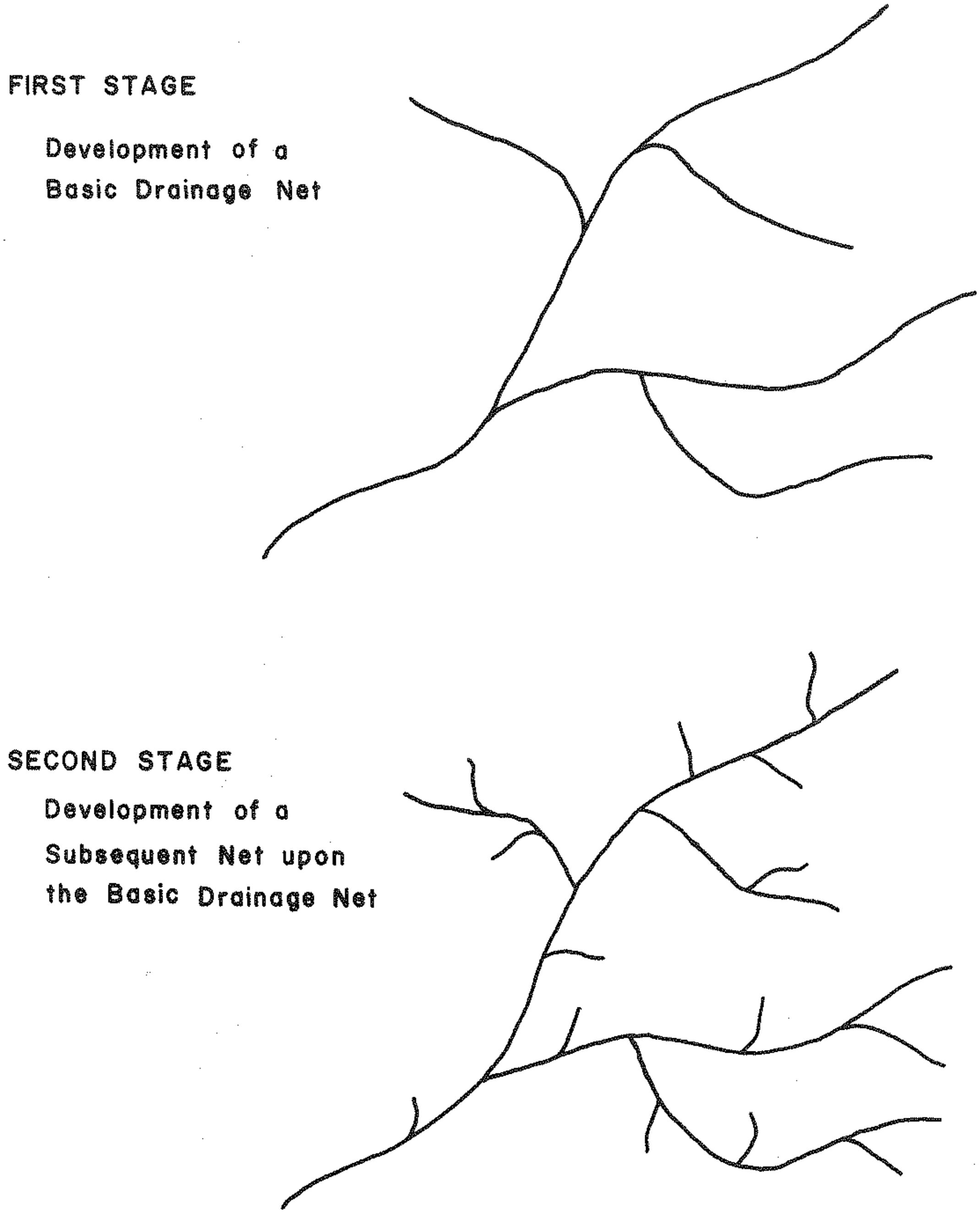
Figure 6. Regression method of determining the bifurcation ratio representative of the entire network.

Division Ratio

As noted, bifurcation ratio of a network was proposed to measure the tendency of stream segments of order u to divide into segments of order u - 1. In actuality it does not do this accurately, because it incorporates the number of segments which unite to form the next highest order and also all "lost" segments of the network of order u which are tributary to segments of order u + 2 or greater and do not add to the ordering process.

When Horton (1945) originally proposed his classification scheme and drainage development model, he recognized that natural, accidental variations of drainage area shape, surface slope, infiltration capacity, and resistance to erosion could produce these types of streams which he called "adventitious." He estimated that "adventitious streams do not in general develop simultaneously with larger streams in the basin but are developed later as the development of the stream system approaches maturity" (1945, p. 342). Elaborating on this point, Bunik and Turner (1972, p. 17) reason that a drainage system can be considered to have two parts - a primary or consequent drainage system developed primarily in response to such constraints as parent materials, initial topography, and climate, and a secondary or subsequent series of channels which consists primarily of the "lost" segments and forms as a function of topography developed by the primary drainage system (Figure 7).

Coffman and Melhorn (1970) reduced natural networks to their Horton Nets by removing all "lost" segments. This resulted in a network in which only segments of order u - 1 joined segments of order u, which



FIRST STAGE

Development of a
Basic Drainage Net

SECOND STAGE

Development of a
Subsequent Net upon
the Basic Drainage Net

Figure 7. Stages in the development of a drainage net (after Bunik and Turner, 1972).

in turn were the only segments tributary to streams of order u + 1, etc. (Figure 8). The number of segments in each order remaining in this reduced network was then counted and plotted on semi-log paper (Figure 9). The slope of the line was called the Division Ratio (R_D). This parameter is therefore comparable to bifurcation ratio, except that it is determined from the Horton Net instead of from the entire drainage network.

Certain applications and ramifications of the use of this measure presented by Coffman et.al. (1972) indicate that this parameter is potentially applicable to the determination of network equilibrium and stability.

Length of Strahler Segments and Length Ratio

The length of all segments of each order was measured, and the mean segment length for each order calculated by dividing the total length of segments by the number of segments of that order. Thus the mean length $\bar{L}_u$ of a channel segment of order u is a dimensional property relating the characteristic size of network components. Generally, $\bar{L}_{u-1} < \bar{L}_u < \bar{L}_{u+1}$.

In mathematical form, Horton's Law of Stream Length is:

$$L_u = \bar{L}_1 \, R_L^{u-1}$$

where $\bar{L}_1$ is the mean length of first-order streams, L_u is the mean length of streams of order u, and R_L is the stream length ratio. Strahler (1957) obtained good fits to a straight line by plotting log of total stream length of each order against log of order. This suggests a relationship described by a power function rather than an exponential one as indicated above. Maxwell (1960) and Melton (1957) found that

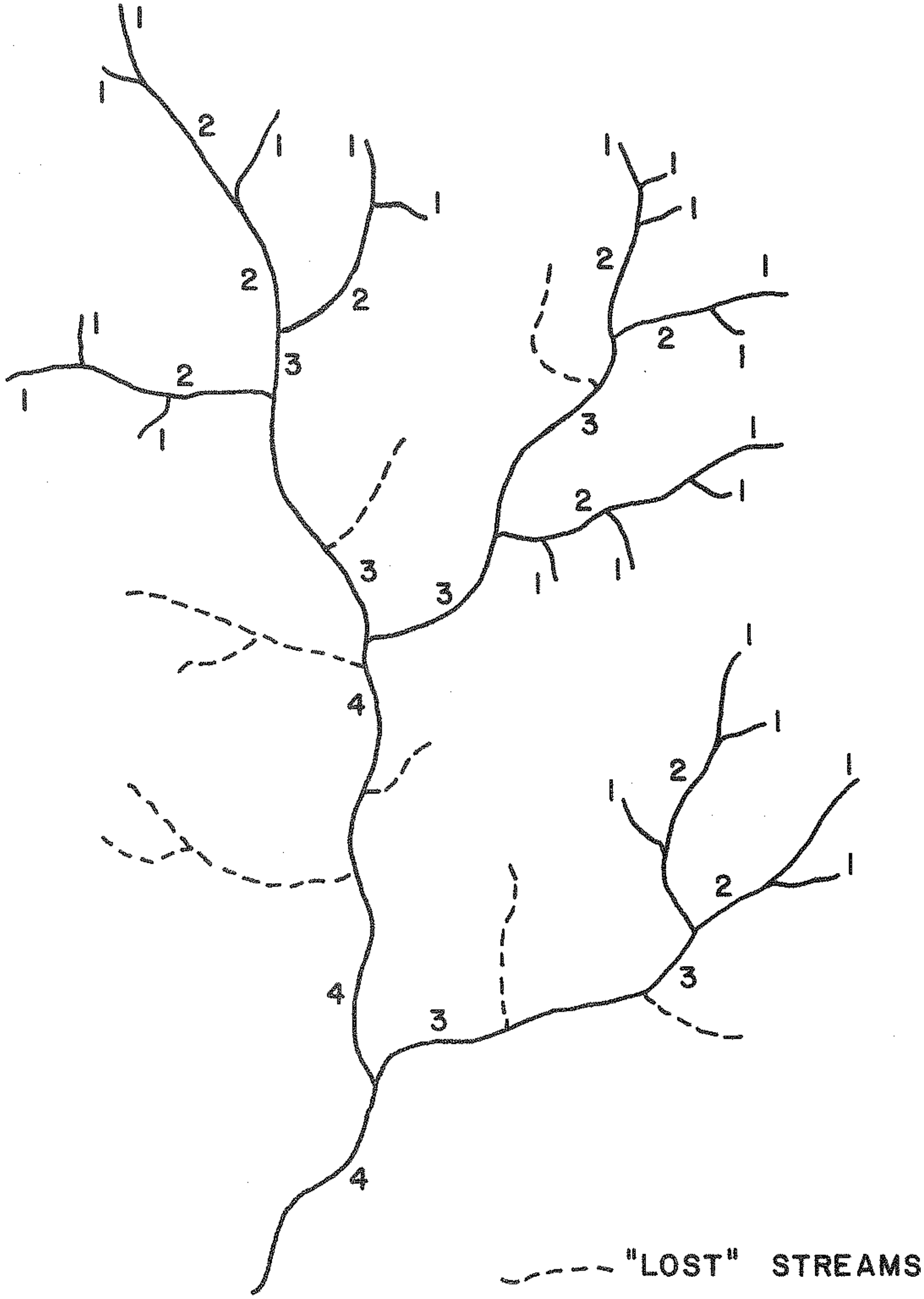


Figure 8. A Horton net indicating lost segments that do not contribute to the ordering process.

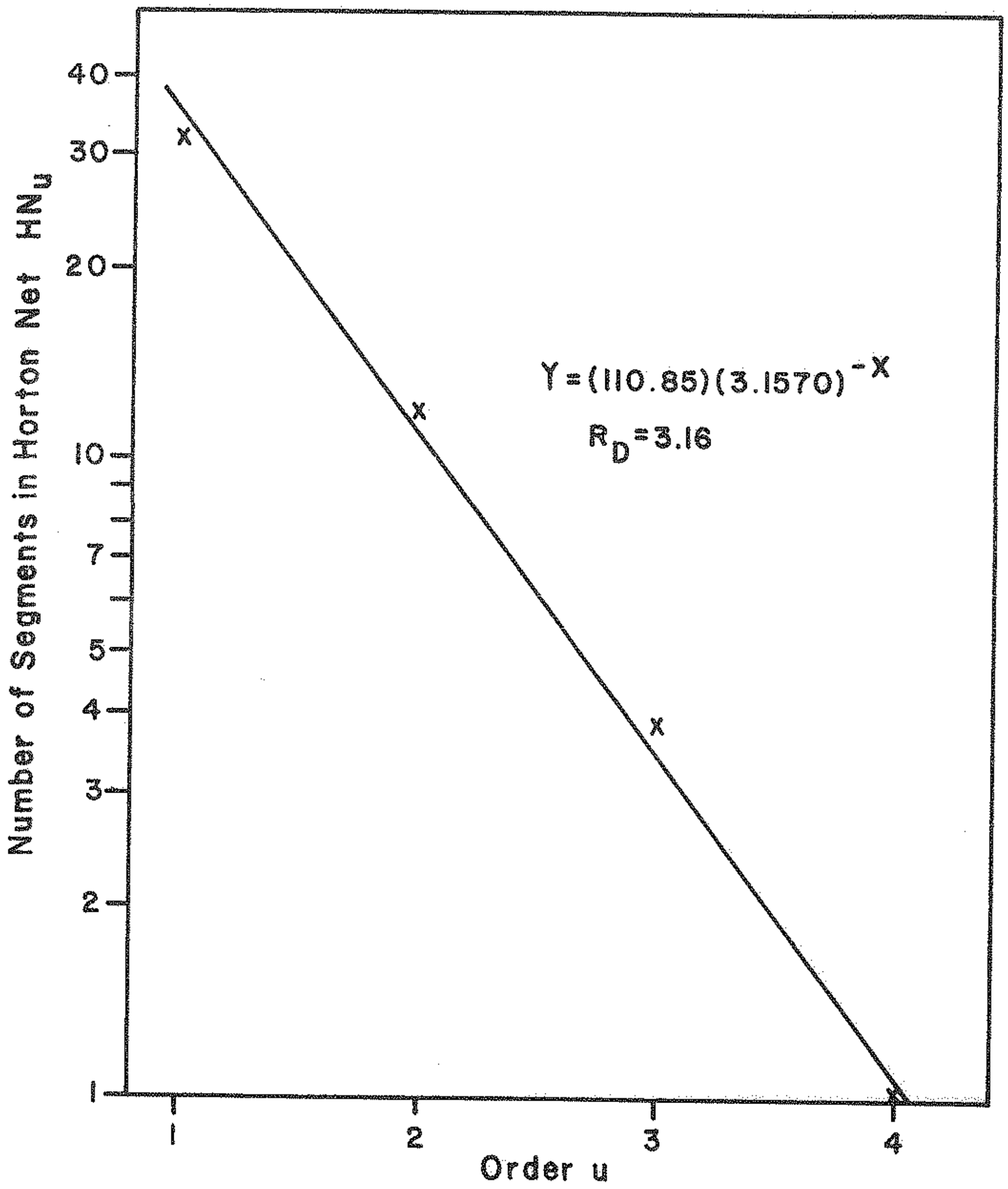


Figure 9. Regression method of determining the division ratio representative of the entire network.

segment length data form a direct geometric series only by chance.

Broscoe (1959) determined that by using cumulative mean length (L'_u) instead of average length, a geometric series was obtained. This result was substantiated by Bowden and Wallis (1964) and also by the present study. Therefore, the length ratio reported herein is the slope of the regression line obtained for the plot of log cumulative mean segment length against stream order (Figure 10).

Total length of channels within the basin is obtained by summing the total length of channels for all orders. This value can then be used in estimation of textural properties of the network related to degree of dissection. Additionally, total channel length (L_T) is related to channel storage, and consequently influences the hydrologic response of the drainage basin.

Mainstream length was measured as prescribed by Horton (1945), by tracing the length of the segment of highest order from the basin mouth back to its source. This measure is closely related to other basin parameters, such as basin size and shape. For example, Hack (1957) found that mainstream length (L_m) was related to basin area (A) by the empirical relation $L_m = CA^n$, where $C = 1.4$ and $n = 0.6$ for basins in Maryland and Virginia. Although mainstream length can be affected by sinuosity adjustments (see Smart and Surkan, 1967) it is commonly an important consideration in hydrologic studies, and in particular in the development of synthetic hydrographs (for example see Snyder, 1938).

Shreve Link Magnitude

The Shreve classification system, introduced in 1967, uses the stream link as the fundamental compositional unit. As already mentioned, all junctions are additive; therefore, there are no "lost" streams as in

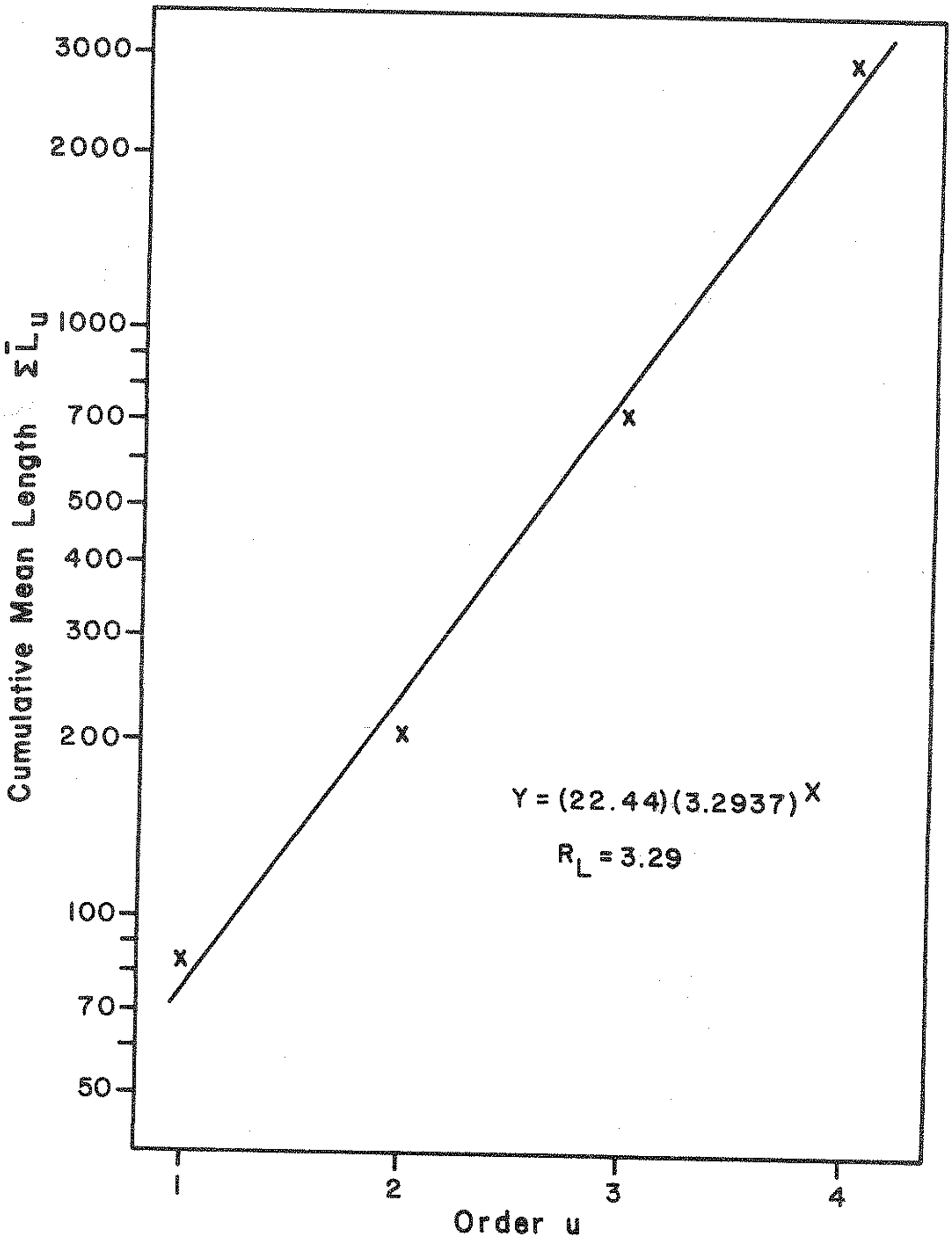


Figure 10. Regression method of determining the length ratio representative of the entire network.

Strahler's method. Smart (1969) suggested that, for topological and hydrological studies, the magnitude approach is more promising than one based upon order. Although this technique was not employed in its entirety during the present study, certain data on link numbers and length were analyzed. By combining link and segment data, information on the internal network adjustments with time can be inferred.

Number and Length of Shreve Links

Refinements and ramifications of the Shreve methodology have not been completely resolved as has been done in the Strahler system. To date, no relationships between link magnitude and number has been determined if, in fact, one exists. Furthermore, studies of link magnitudes and lengths have yielded conflicting results (Shreve, 1969; Smart, 1969). However, link length and number data were obtained by the authors in an attempt to determine the pattern of adjustment in the basins examined. The number and mean length of links was determined for each Strahler segment order and for the entire basin. By examining this link data, information may be obtained about specific locations within the network structure experiencing both growth and decay as well as the net overall changes.

Basin Perimeter

The basin perimeter was an important measure related to the network texture as envisioned by Smith (1950). It may also be related to hypothetical areal and energy conservation considerations such as those discussed by Woldenberg (1969). In our study, the basin outline was delineated stereoscopically directly from the aerial photography and measured from the working copies of the basin maps.

Basin Dimensions

Schumm (1956, p. 612) defined basin length as the longest dimension of a basin parallel to the principal drainage line. This convention was followed in the present study in order to determine the maximum basin length. Maximum basin width was then measured in an approximately orthogonal direction to the length measurement. Although these measures are not of primary importance in basin analysis, they depict the size of the landscape unit and can be used to obtain a measure of basin shape (L/W).

Texture Ratio

This parameter was originally defined by Smith (1950) as the ratio between the maximum number of crenulations along a contour line within the basin and the length of the basin perimeter. For data derived from aerial photography or field surveys, a ratio can be calculated on the basis of total number of Strahler stream segments divided by the basin perimeter (Coffman, *et.al.*, 1971).

The Texture Ratio (R_t) provides a measure of the degree of dissection within a drainage basin, and consequently the relative "coarseness" or "fineness" of the stream network.

Link-Texture Ratio

The Link-Texture Ratio ($R_{\ell t}$) was defined by Coffman *et.al.* (1971) as the ratio between the total number of stream links and the length of the basin perimeter. It was proposed as a potentially more consistent measure of the density of stream length units within a basin, in the belief that the demonstrated consistency of link lengths improves the utility of the textural measure. It was also suggested that this parameter should be very useful in detecting whether an increase in drainage density results from channel lengthening or the addition of new stream segments.

Fineness Ratio

Melton (1957) proposed the Fineness Ratio (R_F) as the ratio of channel lengths to the length of the basin perimeter. It should be noted that this measure is quite similar to the Texture Ratio just described and Stream Frequency as discussed in the following section. This parameter is an additional measure of textural characteristics of a drainage network.

Areal Aspects of Drainage Basins

Drainage Area

The areas of the drainage basins of the present study were obtained from the final working maps by means of a compensating polar planimeter. This parameter, in addition to being the most useful measurement of basin size, was used in the calculation of other morphometric parameters.

The Law of Stream Areas (Schumm, 1956) stated in mathematical form is:

$$A_u = A_1 R_A^{u-1}$$

where A_u is the area of a stream of order u, A_1 is the average drainage area of first-order streams, and R_A is a constant called the stream area ratio. In our study, subareas of the basin were not delineated; therefore, it was not possible to determine area ratio values.

Intuititively, one can deduce that catchment area is one of the major determinants of the discharge leaving a basin. Empirical equations of the general form

$$Q = jA^m$$

where Q is some discharge measure, A is basin area, and j and m are regression constants have been derived from studies in diverse geographical settings. The value of the exponent m is generally somewhat less than 1.0. Owing to the deterministic role of discharge in considering the values of other morphologic and hydraulic variables, catchment area therefore should exert a major influence upon the nature of the enclosed drainage network.

Drainage Density

Drainage Density Dd, which is a measure of the closeness of channel spacing, was proposed by Horton in 1945. This parameter is simply the ratio of total channel length within a basin to the basin area. Thus $Dd = L_T/A$ and is usually expressed in units of miles per square mile.

Because of its considerable variation among real basins, drainage density is of primary importance in landform scale analysis. It is considered to be largely a function of climate, lithology, and stage of development and, in turn, it exerts a strong influence upon sediment yield and runoff response of a basin. Numerical values from as little as 3.0 to 4.0 miles/sq mi (Smith, 1950) to a maximum of about 1,100 to 1,300 miles/sq mi (Schumm, 1956) have been reported for Dd.

Constant of Channel Maintenance

Schumm (1956) defined the Constant of Channel Maintenance (C) as the ratio between the drainage basin area and the total length of channels in the network. Because it is expressed in units of square feet per foot, it therefore is equivalent to the reciprocal of the drainage density multiplied by 5280.

This constant, which in reality is not constant, relates the number of square feet of watershed surface required to maintain one linear foot of stream channel. As a result, it is a quantiative measure of the minimum limiting area required for the development of a length of channel under the prevailing conditions.

Length of Overland Flow

Length of Overland Flow (L_o) was used by Horton (1945) to describe the length of flow of water over the ground before it became concentrated in definite stream channels. This was an important consideration in Horton's conceptual model of network growth and development, which relied heavily upon the idea that some critical overland flow length is required to attain erosive forces necessary to instigate channel formation. As the average length of overland flow is in most cases approximately half of the average distance between the stream channels, Horton (1945, p. 284) recommended using half the reciprocal of drainage density as a mean value for overland flow length for the entire basin, or

$$L_o = 1/2Dd.$$

Stream or Channel Segment Frequency

Horton (1945) introduced Stream Frequency (F) as the number of stream segments per unit area, or the ratio of the total number of segments to the basin area. Channel segment frequency is yet another measure of the texture of the channel network which may influence the hydrologic response of a basin by determining, in part, the length of overland flow and, therefore, the time of flow concentration.

Link Frequency

Link Frequency (F_ℓ) was proposed by Coffman, et.al. (1971) in the belief that the link is a more consistent and fundamental unit of a network than the Strahler segment. This measure is defined as the number of Shreve links per unit area. It was hoped by these investigators that the measure of link frequency might be more sensitive to variations in other factors which influence network composition, such as surficial material type.

Basin Outline Form

Several variables have been proposed for the purpose of quantifying drainage basin shape in a meaningful way. Miller (1954) introduced Circularity Ratio (R_C) as the ratio of basin area to the area of a circle having a circumference equal to the basin perimeter. As the shape of the basin approaches a circle, the value of this parameter approaches unity. It was Miller's contention that in homogeneous material R_C remained constant and expressed an equilibrium form. Schumm (1956) suggested that the shape of a basin should be described in the same fashion as the shape of a mineral grain by using the Wadell sphericity ratio. He therefore defined the Elongation Ratio (R_E) of a basin as the ratio between the diameter of a circle having the same area as the basin and the basin length. As with the Circularity Ratio, the value of R_E approaches unity as the basin shape approaches that of a circle.

More recently Wu, et.al. (1964), in an attempt to relate physical characteristics of a watershed to the basin hydrograph, developed the Watershed Shape Factor (WSF). This was defined as the ratio of the mainstream length to the diameter of a circle having the same area as the watershed. A more simple measure of basin shape is simply the ratio of basin length to basin width. This value was determined in the present study by using the maximum basin dimensions.

Although other shape factors have been proposed (for example see Horton, 1932, p. 351; and Chorley, et.al., 1957), those already enumerated were considered by the present authors. This choice was based on a desire to check the utility of the last two measures cited and the findings of Morisawa (1958) which indicated that circularity and elongation ratios were both significantly related to runoff measurements.

Relief Aspects of Drainage Basins

Several parameters and analytical techniques are available which incorporate relief or gradient information. However, because of the type of data sources available and the method of data collection employed in this study, no elevation or relief data were obtained. By using current topographic maps, elevation values can be interpolated to within 20 feet, or twice the contour interval. Considerations of several factors resulted in the decision to incorporate only planimetric measurements in the analysis. Because relief obviously exerts considerable control over fluvial processes and resulting form, this represents an unavoidable minor shortcoming of our research. However, owing to the known tectonic stability of the study area and base level constancy of the Wabash River during the time interval considered, the magnitude of change of this control is negligible.

Summary

The preceding sections are devoted to description of the various morphometric parameters of drainage basins and their probable applicability to this study. Quite obviously, some are more utilitarian than others, and some redundancy exists among them (for example Drainage Density, Constant of Channel Maintenance and Length of Overland Flow) through high correlation of these proposed parameters. However, certain parameters may be more valuable to investigators than others, depending upon particular research objectives. Therefore, in an effort to add to the amount of basic data available for possible subsequent analysis, the value of all parameters will be reported herein even though not all were actively considered in the interpretations to follow.

An additional statement is in order regarding the use of certain "traditional" measures, in consideration of recent conceptual developments in quantitative fluvial geomorphology. Extensive topological examination with rigorous statistical and mathematical treatment of network data have led to some doubt about the possible value of some of the "laws" of drainage composition and their associated parameters. Work by Scheidegger, Shreve, Smart and others indicates that many observed relationships, previously considered to result from deterministic cause and effect interactions, may be the result of purely random operations reproducible by probability considerations alone. This has prompted a reexamination of the concepts basic to operational research (see Mann, 1970).

It is not the intent of this report to consider this philosophical problem in depth or detail. Aspects of both approach methods have been used to derive a reasonable interpretation of observed data. From a pragmatic viewpoint, those variables open to question should be retained because their descriptive function and interpretative value has been widely verified. The authors concur with a statement of Bowden and Wallis (1964), *i.e.* the fact that some of the stated laws are statistical relationships does not detract from their utility in indicating the physical properties of the drainage net.

CHAPTER 5

OBSERVED DRAINAGE BASIN CHANGES WITH TIME

Introduction

Three different types of changes within drainage basins can occur over time. These types are: 1) Changes resulting from modifications of inputs to the basin, 2) changes resulting from transformation of the effects of these inputs on the basin, and 3) changes represented by alterations of basin characteristics. In general, input changes result directly from climatic change, but indirectly an apparent change in input can be manifested in various ways. Basin changes can be achieved by earth movements, and changes of basin characteristics can be either a response to these natural factors or to the activity of man (Gregory and Walling, 1973).

Analysis of systems which incorporate time considerations present special problems of interpretation of cause and effect relationships. This complexity was considered by Schumm and Lichty (1965). They reasoned that the distinction between cause and effect is a function of both time and space, because factors that determine the character of landforms can be either dependent or independent variables as the limits of time and space change. As a result, they recommend that geomorphic studies should be considered under three different time frames, which influence any subsequent interpretation of observed changes (Table 1). This table shows that during a brief span of present (steady, in Table 1) time, an apparent reversal of cause and effect is possible owing to feedback to the independent variables.

Because of the limited scope of the present study, obviously we are

Table 1

The status of drainage basin variables during time spans of decreasing duration (from Schumm and Lichty, 1965).

Drainage basin variables	Status of variables during designated time spans Cyclic	 Graded	 Steady
1. Time	Independent	Not relevant	Not relevant
2. Initial relief	Independent	Not relevant	Not relevant
3. Geology (lithology, structure)	Independent	Independent	Independent
4. Climate	Independent	Independent	Independent
5. Vegetation (type and density)	Dependent	Independent	Independent
6. Relief or volume of system above base level	Dependent	Independent	Independent
7. Hydrology (runoff and sediment yield per unit area within system)	Dependent	Independent	Independent
8. Drainage network morphology	Dependent	Dependent	Independent
9. Hillslope morphology	Dependent	Dependent	Independent
10. Hydrology (discharge of water and sediment from system)	Dependent	Dependent	Dependent

not concerned with all of the changes of system input possible over an extended time period. We are looking at relatively minor changes occurring in the short term. Changes described in subsequent sections are, however, worthy of consideration as they are representative of an immediate type of possible response to changing environmental factors. These adjustments, in turn, may be indicative of long term response necessary to reinstate a balance between input and system characteristics.

Study Location

The five drainage basins selected for study are located within a nine square-mile area approximately seven miles west of West Lafayette, Indiana (Figure 11). The study area includes sections 17, 18, 19, and 20, T.23N., R.5W. and portions of sections 12, 13, and 24, T.23N., R.6W., as well as small portions of adjacent areas. Basins 1, 2, and 4 are tributary to Indian Creek below the confluence of Goose Creek whereas basins 3 and 5 are immediately to the east and are directly tributary to Wabash River.

The study area is within the Tipton Till Plain physiographic subprovince and is immediately north of the bluffs of the Wabash Valley. There is approximately 190 feet of relief between the till upland and Wabash River. The study basins occur on the relatively steep slopes which connect the gently rolling till plain with the areas adjacent to the master drainage.

Data Limitations

As discussed in Chapter 2, the data represent the physical condition

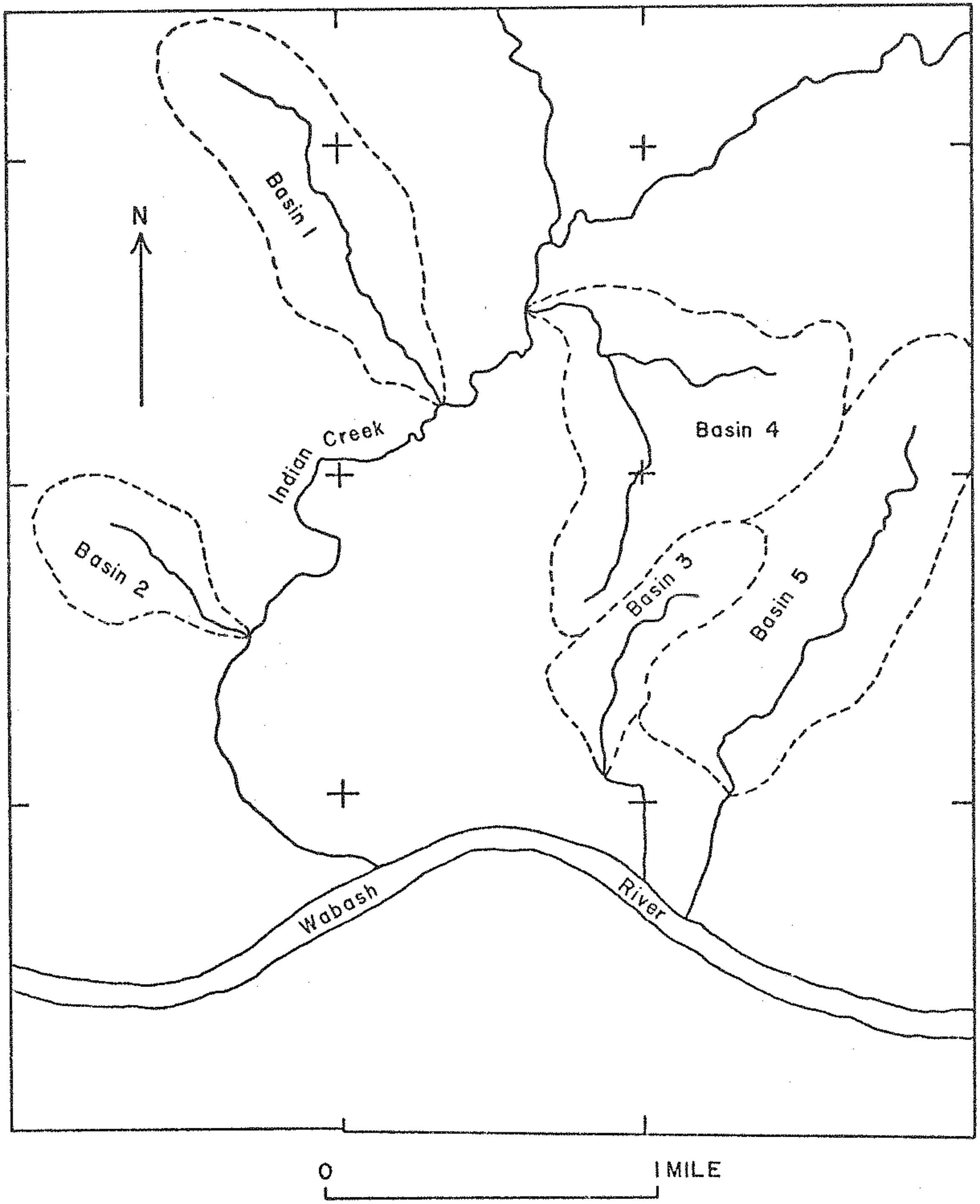


Figure 11. Location map showing the relationship between the study basins and the principal drainage of the area (from Otterbein, Indiana 7½' Quadrangle).

of the sampled basins at two instants in time. All observations consequently are limited to net changes that occurred during a known time interval. Stated differently, the result of going from time A to time C can be observed but the process of achieving this latter position cannot be determined nor can any intermediate phase be accurately inferred. A basin may show a net decrease in the number of stream segments from 100 to 75, for example. Because of the dynamic nature of the system, it cannot be simply assumed that 25 segments were lost; perhaps 50 were eliminated and 25 added elsewhere in the basin. Therefore, unless data are repeatedly collected periodically, no conclusions can be drawn as to real changes in magnitude of individual elements or averages.

To offset the described limitation, the authors have included many variables which, when analyzed in conjunction with others, give more insight about gross morphological adjustments. For example, by using both segment and link data, we can infer where, within the heirarchy of the network, growth or abstraction has occurred. Although this is not a complete solution to the problem, it is an improvement within the confines of the experimental methodology.

Observed Physical Changes

Basin 1

Basin 1, named Southworth Branch on the Otterbein, Indiana quadrangle, enters Indian Creek approximately 2.4 channel miles upstream from confluence with the Wabash. Figures 12 and 13 depict this fourth-order basin as it appeared in 1938 and 1968, whereas Table 2 lists the values of parameters used to describe physical properties of the basin and the numerical and percentage change over the 30-year time span. It should be noted that the percent change values in Tables 2-8 were based in each case upon the initial 1938 value and computed according to the following:

$$\text{Percent Change} = (X_{68} - X_{38}) / X_{38}.$$

Owing to this method of calculation some variables such as Dd and C, which are inversely related to each other ($C = 1/Dd \times 5280$), show different absolute values of percent change. Furthermore, most original measurements and calculations were done in units of feet and acres, and subsequently converted to miles and square miles. As a result of rounding error, slight differences in value of calculations using different units will be noted if compared to some of the original tabled values. These factors should be noted in considering the data tables.

Stream Numbers and Lengths: The number of segments and the total length of first-order drainage decreased, but the mean length of these segments remained the same because of relative equality of the amounts of decrease. A net loss of two second-order segments associated with a large decrease in total second-order length resulted in a substantial decrease in $\bar{L}_2$. The loss of exterior links was such that several segments of order 2 were converted to order 1; but this real decrease was compensated somewhat by the growth of new, but shorter, first- and second-order segments, resulting in a net decrease of only 2 second-order segments. The length of the trunk stream increased owing to an increase in sinuosity throughout its length. Conversely to the losses just described, the Horton Net underwent increases in the number of first- and second-order segments, perhaps in response to some impetus for growth. Therefore,

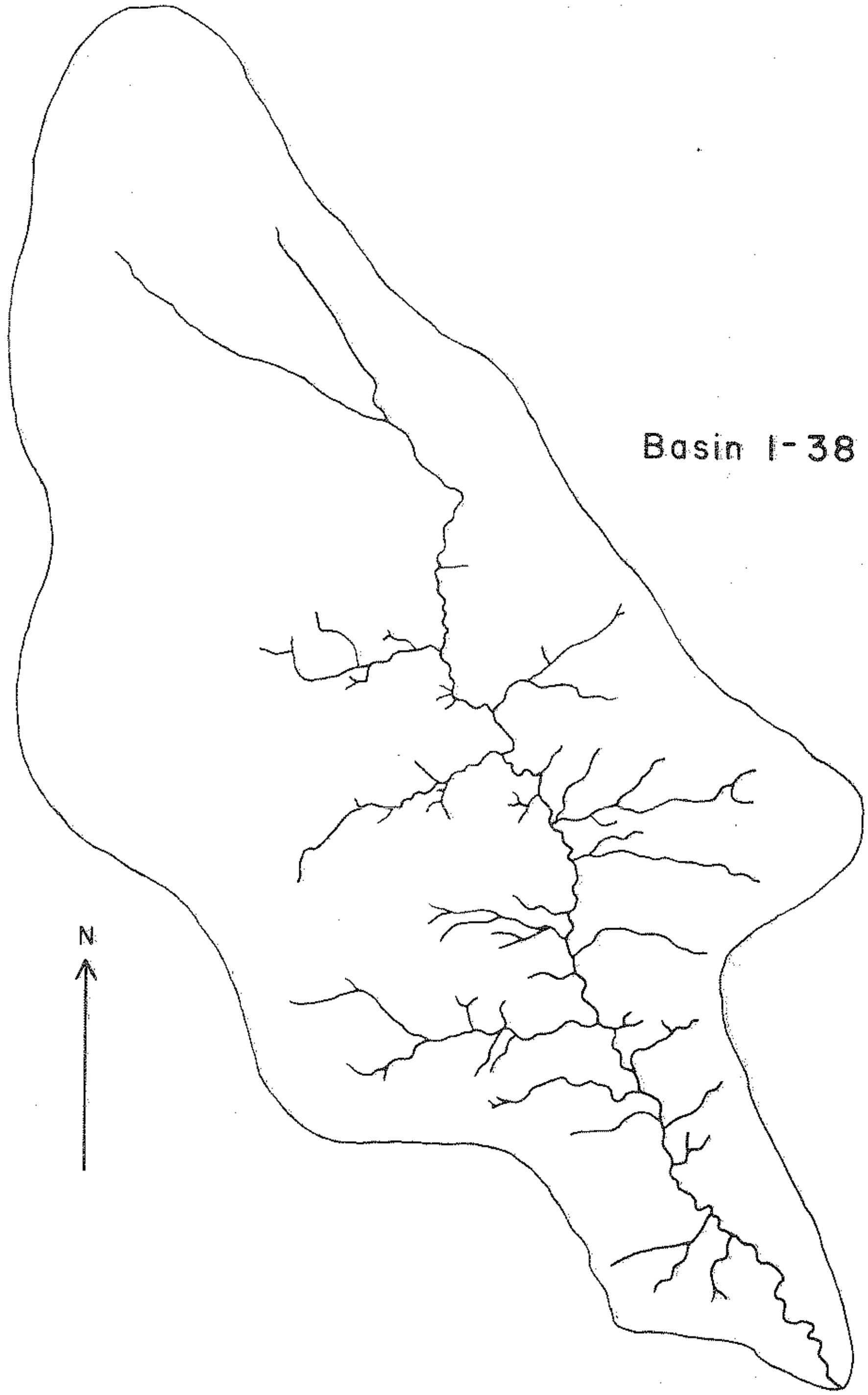


Figure 12. Drainage map of study basin 1 as of 1938.

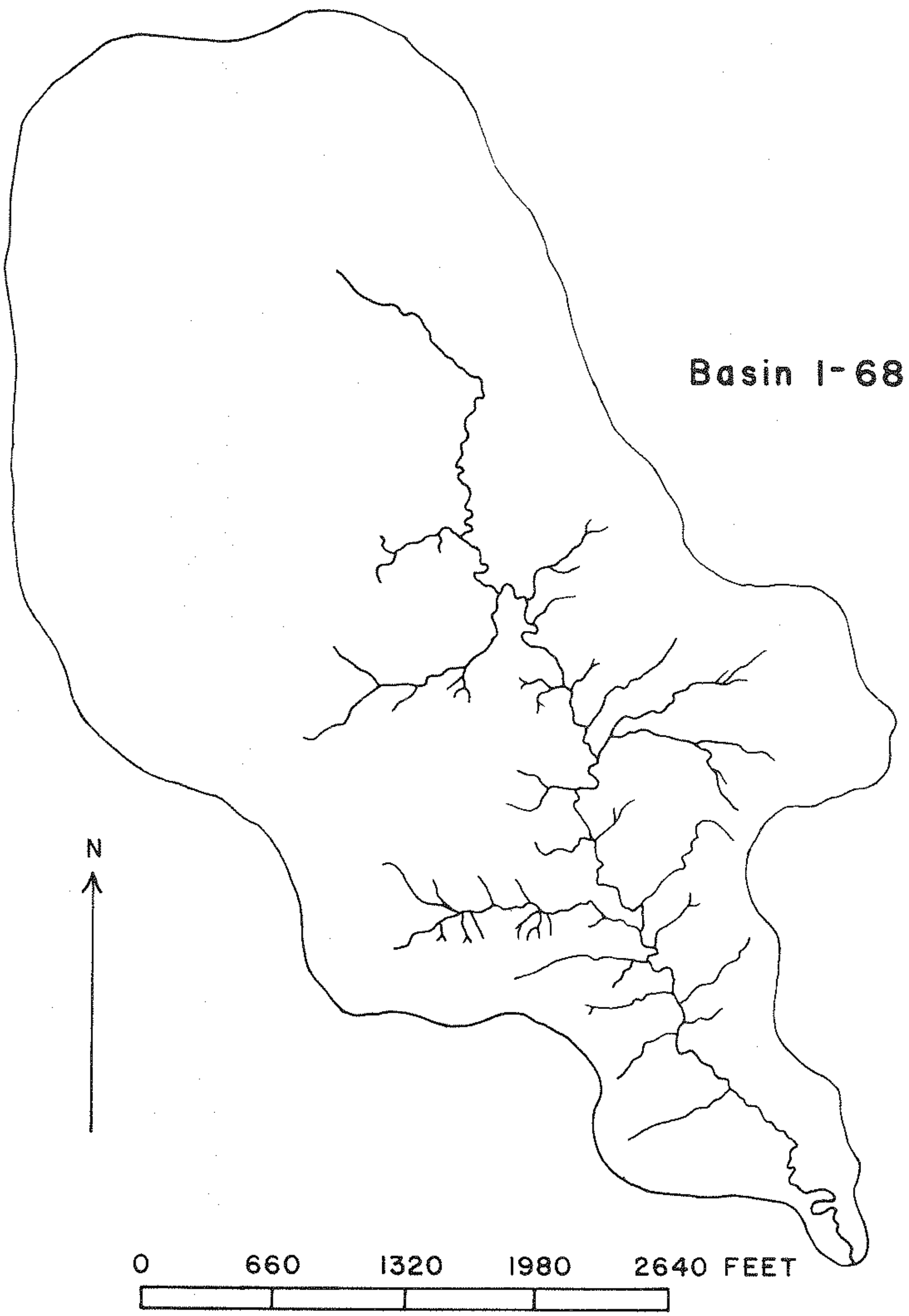


Figure 13. Drainage map of study basin 1 as of 1968.

Table 2. Morphometric Data for Basin 1.

Variable	1938	1968	Observed Change	Percent Change
Segment Numbers				
N_1	67	59	-8	-11.9
N_2	21	19	-2	-9.5
N_3	4	4	0	0
N_4	1	1	0	0
N_T	93	83	-10	-10.8
Segment Length (ft)				
L_1	14,949	13,250	-1699	-11.4
L_2	7,557	5,181	-2376	-31.4
L_3	2,690	2,640	-50	-1.9
L_4	4,422	4,719	+297	+6.7
L_T(ft)	29,618	25,790	-3828	-12.9
L_T(mi)	5.61	4.88	-0.73	-12.9
Mainstream Length				
L_m(ft)	8,283	8,184	-99	-1.2
L_m(ft)	1.57	1.55	-0.02	-1.2
Mean Segment Length (ft)				
$\bar{L}_1$	223	225	+2	+0.9
$\bar{L}_2$	360	273	-87	-24.2
$\bar{L}_3$	672	660	-12	-1.8
$\bar{L}_4$	4,422	4,719	+297	+6.7
Horton Net				
HN_1	32	34	+2	+6.3
HN_2	12	13	+1	+8.3
HN_3	4	4	0	0
HN_4	1	1	0	0
HN_T	49	52	+3	+6.1

Table 2 Cont.

Variable	1938	1968	Observed Change	Percent Change
Link Numbers				
n_1	67	59	-8	-11.9
n_2	33	27	-6	-18.2
n_3	14	13	-1	-7.1
n_4	18	15	-3	-16.7
n_t	132	114	-18	-13.6
Mean Link Length (ft)				
$\bar{\ell}_1$	223	225	+2	+0.9
$\bar{\ell}_2$	229	192	-37	-16.2
$\bar{\ell}_3$	192	189	-3	-1.6
$\bar{\ell}_4$	246	315	+69	+28.0
Mean Link Length (ft)				
$\bar{\ell}$	224	225	+1	+0.4
Interior Link Length (ft)				
ℓ_i	226	224	-2	-0.9
Exterior Link Length (ft)				
ℓ_e	223	225	+2	+0.9
Bifurcation Ratio				
R_B 1/2	3.19	3.11	-0.08	-2.5
R_B 2/3	5.25	4/75	-0.05	-9.5
R_B 3/4	4.00	4.00	0	0
R_B	4.17	3.97	-0.20	-4.8
Division Ratio				
R_D 1/2	2.67	2.62	-0.05	-1.9
R_D 2/3	3.00	3.25	+0.25	+8.3
R_D 3/4	4.00	4.00	0	0
R_D	3.16	3.21	+0.05	+1.6

Table 2 Cont.

Variable	1938	1968	Observed Change	Percent Change
Length Ratio				
R_L 2/1	1.16	1.21	-0.40	-24.8
R_L 3/2	1.87	2.42	+0.55	+29.4
R_L 4/3	6.58	7.15	+0.57	+8.7
R_L	2.85	2.90	+0.05	+1.8
Basin Area				
A (acres)	346	362	+16	+4.6
A (sq mi)	0.54	0.57	+0.03	+4.6
Basin Perimeter				
P (ft)	18,480	18,856	+376	+2.0
P (mi.)	3.50	3.57	+0.07	+2.0
Basin Length				
L (ft)	7,656	7,194	-462	-6.1
L (mi)	1.45	1.36	-0.09	-6.1
Basin Width				
W (ft)	4,224	3,234	-990	-23.4
W (mi)	0.80	0.61	-0.19	-23.4
Texture Ratio (no./mi)				
R_t	26.57	23.24	-3.33	-12.5
Link-Texture Ratio (no./mi)				
$R_{\ell t}$	37.71	31.92	-5.79	-15.4
Fineness Ratio				
R_F	1.60	1.37	-0.23	-14.4
Drainage Density				
Dd(mi/sq mi)	10.39	8.64	-1.75	-16.8
Constant Channel Maintenance				
C(sq ft/ft)	508.2	611.3	+103.1	+20.3
Length Overland Flow				
L_o (ft)	254.1	305.7	+101.6	+20.3

Table 2 Cont.

Variable	1938	1968	Observed Change	Percent Change
Channel Segment Frequency				
F (no/sq mi)	172.2	146.9	-25.3	-14.7
Link Frequency				
F_ℓ (no/sq mi)	244.4	201.8	-42.6	-17.4
Circularity Ratio				
R_C	0.554	0.557	+0.003	+0.5
Elonzation Ratio				
R_E	0.572	0.623	+0.051	+8.9
Watershed Shape Factor				
WSF	1.893	1.827	-0.066	-3.5
Area/Perimeter				
A/P	0.154	0.158	+0.004	+2.6
Length/Width				
L/W	1.813	2.224	+0.411	+22.7

the channel losses in the basin were related to the "lost" or subsequent portions of the network. Link data indicate losses throughout all segment orders with no particular level of concentration. All internal adjustments, reflected in the individual values of R_C, R_D, and R_B, resulted in a net decrease in the total length of channels within the basin.

Basin Dimensions: The size of the catchment area remained essentially constant, with area increasing by only 16 acres (5%) and the perimeter by 376 feet (2%). Both are within the realm of possible measurement error. Maximum basin length and width both decreased.

Basin Shape: Basin shape remained essentially unchanged. R_C and R_E values indicate an elongate form with a slight adjustment toward circularity; Watershed Shape Factor indicates the same trend. However, length/width ratio indicates an increase in inequality between the two measures.

Drainage Texture: All parameters measuring textural features indicate a decrease in drainage complexity or an increase in "coarseness" of the texture. There was a trend toward fewer drainage lines per unit area, shorter length of channels per unit area, and an increase in average distance between drainage lines.

Summary: Thinning of the drainage net was accomplished through adjustments in the length and numbers of first- and second-order streams. The greatest adjustments within the network appear to have occurred in the "lost" portion of the network, which shows the largest amount of drainage termination and abstraction.

Basin 2

Basin 2, a fourth-order watershed, enters Indian Creek in the SE¼ SW¼ Ne¼ sec. 24, T.23N., R.6W., approximately one mile upstream from the junction of Indian Creek and Wabash River. Figures 14 and 15 contain the maps of Basin 2 for 1938 and 1968, and Table 3 contains the representative data for each year.

Stream Numbers and Lengths: The first-order segments show a frequency decrease and a total length extension which increased the mean length of first-order segments. Similarly, N_2 decreased as did L_2, but $\bar{L}_2$ increased because N_2 decreased proportionately more than L_2 (28% compared to 18%). One third-order segment was lost, whereas L_3 remained constant and therefore $\bar{L}_3$ increased. Also, L_4 increased slightly owing to adjustments at the basin mouth and a slight extension resulting from network reorganization. The number of links decreased throughout the network except in order 3 segments, whereas the Horton Net decreases in the first 3 orders. It appears that observed changes resulted from termination of several short, first- and second-order segments. Furthermore, a few fingertip tributaries were lost from order 2 drainage which converted these longer segments into order 1. This factor, combined with exterior link extension, produced the changes observed in the first-order drainage. The loss of the third-order segment, as well as the maintenance of the length of order 3 drainage is the result of restructuring of the network by fingertip growth and decay. Most losses were experienced by the "lost" components, but the Horton Net also was abstracted indicating an attempt of the

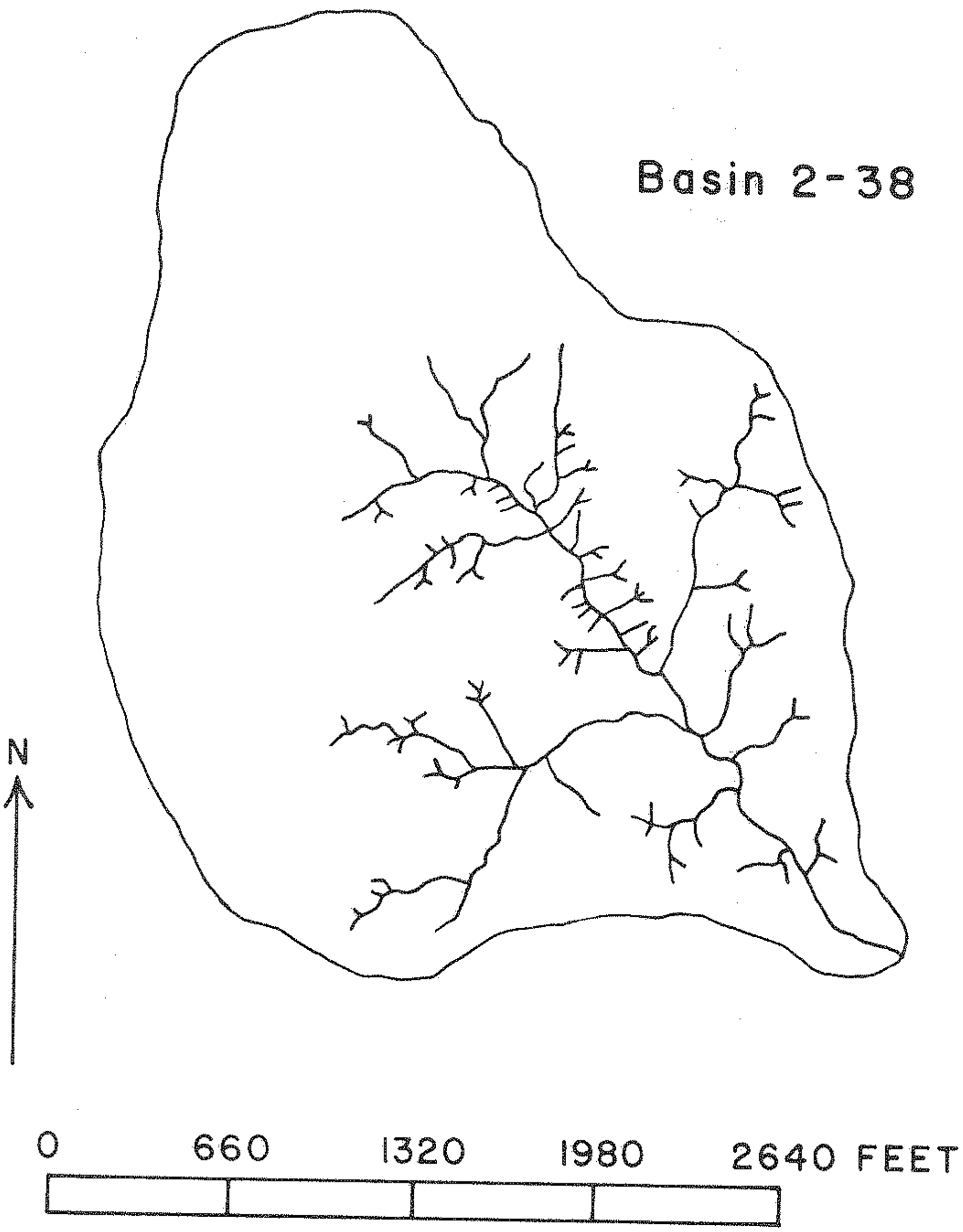


Figure 14. Drainage map of study basin 2 as of 1938.

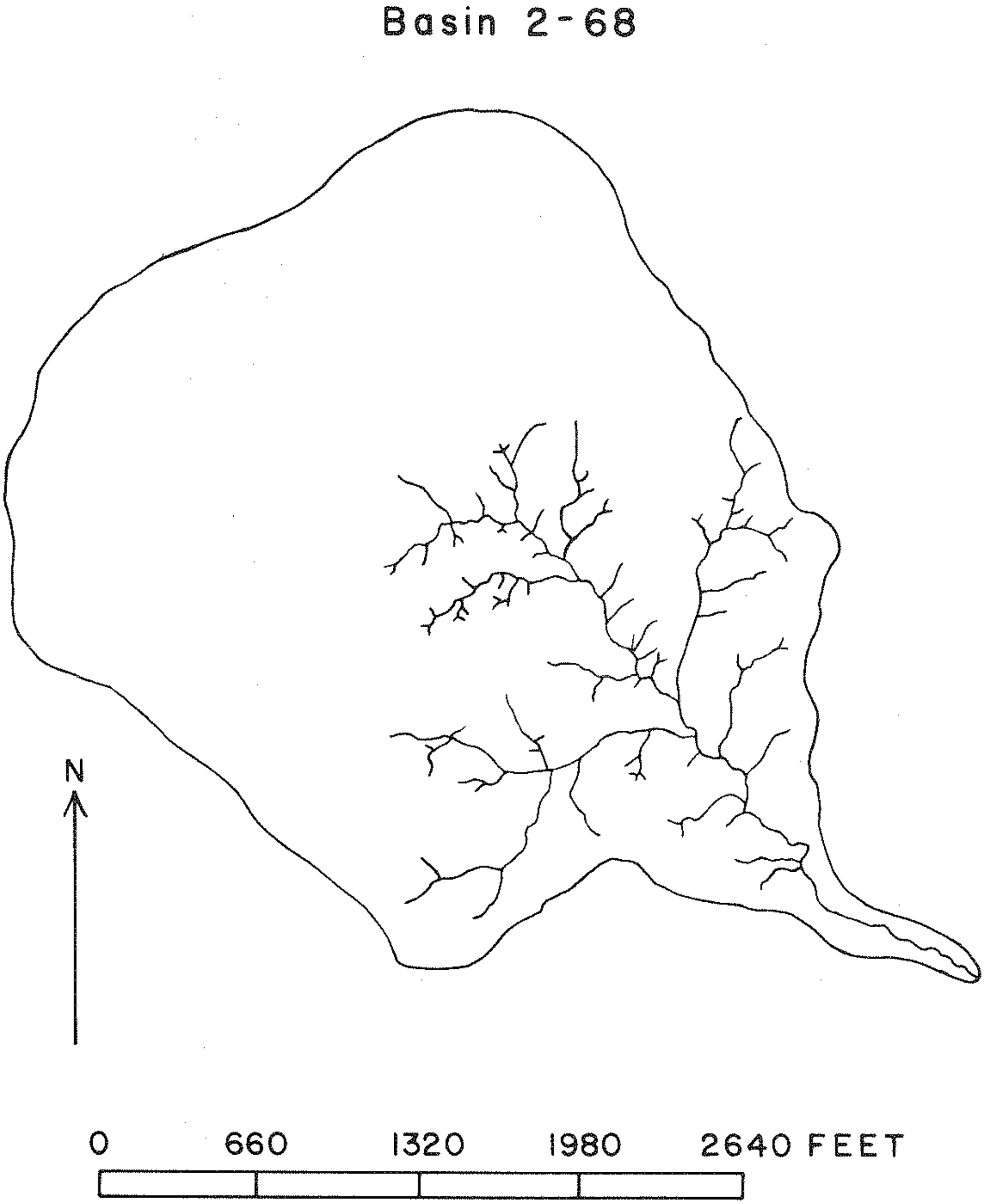


Figure 15. Drainage map of study basin 2 as of 1968.

Table 3. Morphometric data for Basin 2.

Variable	1938	1968	Observed Change	Percent Change
N_1	92	82	-10	-10.9
N_2	29	21	-8	-27.6
N_3	6	5	-1	-16.7
N_Y	1	1	0	0
N_T	128	109	-19	-14.8
L_1	7,854	8,267	+413	+ 5.3
L_2	5,792	4,769	-1,023	-17.7
L_3	3,119	3,119	0	0
L_4	2,244	2,845	+601	+26.8
L_T(ft)	19,009	19,000	9	+0.05
L_T(mi)	3.60	3.60	0	0
L_m(ft)	3,069	3,802	+733	+23.9
L_m(mi)	0.58	0.72	+0.14	+23.9
$\bar{L}_1$	85	101	+16	+18.8
$\bar{L}_2$	120	227	+107	+89.2
$\bar{L}_3$	520	624	+104	+20.0
$\bar{L}_4$	2,244	2,845	+601	+26.8
HN_1	56	52	-4	-7.1
HN_2	19	17	-2	-10.5
HN_3	6	5	-1	-16.7
HN_4	1	1	0	0
HN_T	82	75	-7	-8.5
n_1	92	82	-10	-10.9
n_2	48	37	-11	-22.9
n_3	19	21	+2	+10.5
n_4	19	18	-1	-5.3
n_t	178	158	-20	-11.2

Table 3 Cont.

Variable	1938	1968	Observed Change	Percent Change
$\bar{\ell}_1$	85	101	+16	+18.8
$\bar{\ell}_2$	121	129	+8	+6.6
$\bar{\ell}_3$	164	149	-15	-9.1
$\bar{\ell}_4$	118	158	+40	+33.9
$\bar{\ell}$	107	120	+13	+12.1
ℓ_i	130	141	+11	+8.5
ℓ_e	85	101	+16	+18.8
R_B 1/2	3.17	3.91	+0.74	+23.3
R_B 2/3	4.83	4.20	-0.63	-13.0
R_B 3/4	6.00	5.00	-1.00	-16.7
R_B	4.55	4.33	-0.22	-4.8
R_D 1/2	2.95	3.06	+0.11	+3.7
R_D 2/3	3.17	3.40	+0.23	+7.3
R_D 3/4	6.00	5.00	1.00	-16.7
R_D	3.75	3.70	-0.05	-1.3
R_L 2/1	1.40	2.25	+0.85	+60.7
R_L 3/2	4.34	2.75	-1.59	-36.7
R_L 4/3	4.32	4.56	+0.24	+5.6
R_L	3.29	3.54	+0.25	+7.6
A (acres)	161	192	+31	+19.3
A (sq mi)	0.25	0.30	+0.05	+19.3
P (ft)	10,857	12,797	+1,940	+17.9
P (mi)	2.06	2.42	+0.36	+17.9

Table 3 Cont.

Variable	1938	1968	Observed Change	Percent Change
L (ft)	4,125	4,620	+495	+12.0
L (mi)	0.78	0.88	+0.10	+12.0
W (ft)	2,772	3,564	+792	+28.6
W (mi)	0.53	0.68	+0.15	+28.6
R_t	62.26	44.97	-17.29	-27.8
$R_{\ell t}$	86.58	65.18	-21.40	-24.7
R_F	1.75	1.48	-0.27	-15.4
D_d	14.29	12.00	-2.29	-16.0
C	369.5	440.0	+70.5	+19.1
L_o	184.7	220.0	+35.3	+19.1
F	508.1	362.9	-145.2	-28.6
F_ℓ	706.6	526.1	-180.5	-25.5
R_C	0.749	0.642	-0.107	-14.3
R_E	0.725	0.706	-0.019	-2.6
WSF	1.026	1.165	+0.139	+13.5
A/P	0.123	0.124	+0.001	+0.8
L/W	1.488	1.296	-0.192	-12.9

integrated network to compensate for an overdeveloped condition under new external conditions. Overall, however, the total length of channels remained constant.

Basin Dimensions: Watershed area and perimeter both increased because of adjustments in an adjacent basin. As a result, both length and width of the basin increased. Figure 15 clearly shows that the network fills less of the basin as a result of these changes. This could result in an extension of the existing network in the future.

Basin Shape: Although the basin outline appears somewhat more circular in 1968 than in 1938, the shape factors indicate an opposite trend. This is basically the result of elongation adjacent to the mouth of the basin. The length-width ratio indicates that these two measures approached equality; however, this is purely a function of the computational formula.

Drainage Texture: All parameters describing the textural properties of the network show a value decrease for the 30-year interval. This trend may be interpreted as indicating that distance between drainage lines increased commensurate with fewer and shorter channels per unit catchment area. These responses can be related to the increase of basin dimensions while the total channel length remained constant, coupled with decrease in the number of network components.

Summary: Net adjustments of Basin 2 are quite similar to those of Basin 1. In general, the network tended toward abstraction and simplification of structure by the loss of first- and second-order streams but drainage line extension was also present as well as the addition of some new exterior links in the "lost" portion of the network.

Basin 3

The third basin chosen for study is directly tributary to Wabash River, and enters it about 0.4 miles upstream from the junction with Indian Creek. It should be noted that the downstream portion of the trunk stream is controlled as it flows from the Wabash River valley wall across the floodplain (see Figure 11). Therefore, only that portion of the network above this section was studied. Below this point there are no tributaries to the main stream. Table 4 and Figures 16 and 17 respectively contain the observed parameter values and watershed maps for this third-order basin.

Stream Numbers and Lengths: N_1 increased very slightly but L_1 decreased, resulting in a decrease in $\bar{L}_1$. The number of second-order segments increased by 1, and the total length of order 2 drainage increased by 27 percent, producing an 18 percent increase in the mean length. No change is seen in the frequency of orders 3 and 4 drainage, but L_3 decreased and L_4 increased with obvious results on $\bar{L}_3$ and $\bar{L}_4$. The total length of drainage lines within the basin remained essentially constant. The Horton Net showed just the opposite, with the number of segments of orders 1 and 2 decreasing by 3 and 1 respectively. The number of links contined in each segment order increased for each order except order 4, with the biggest increase in order 2. From the observed changes it can be reasoned that more exterior links were added than eliminated but, because those added are younger or shorter, the total length of order 1 drainage was less. All additions were confined to the "lost" subnet, because the Horton Net shows a decrease in number of segments. The increase in L_2 resulted primarily from extension of established drainage without an order increase. New second-order channels were established, but

Table 4. Morphometric data for Basin 3.

Variable	1938	1968	Observed Change	Percent Change
N_1	58	61	+3	+5.2
N_2	13	14	+1	+7.7
N_3	2	2	0	0
N_4	1	1	0	0
N_T	74	78	+4	+5.4
L_1	10,379	9,471	-908	-8.7
L_2	4,571	5,792	+1,221	+26.7
L_3	1,353	1,271	-82	-6.1
L_4	3,317	3,201	-116	-3.5
L_T(ft)	19,619	19,734	+115	+0.6
L_T(mi)	3.72	3.74	+0.02	+0.6
L_m(ft)	5,561	6,419	+858	+15.4
L_m(mi)	1.05	1.22	+0.17	+15.4
$\bar{L}_1$	179	155	-24	-13.4
$\bar{L}_2$	352	414	+62	+17.6
$\bar{L}_3$	677	635	-42	-6.2
$\bar{L}_4$	3,317	3,201	-116	-3.4
HN_1	22	19	-3	-13.6
HN_2	6	5	-1	-16.7
HN_3	2	2	0	0
HN_4	1	1	0	0
HN_T	31	27	-4	12.9
n_1	58	61	+3	+5.2
n_2	24	31	+7	+29.2
n_3	5	8	+3	+60.0
n_4	20	17	-3	-15.0
n_t	107	117	+10	+9.3

Table 4 Cont.

Variable	1938	1968	Observed Change	Percent Change
$\bar{\ell}_1$	179	155	-24	-13.4
$\bar{\ell}_2$	190	187	-3	-1.6
$\bar{\ell}_3$	271	159	-112	-41.3
$\bar{\ell}_4$	166	188	+22	+13.3
$\bar{\ell}$	183	169	-14	-7.7
ℓ_i	189	183	-6	-3.2
ℓ_e	179	155	-24	-13.4
R_B 1/2	4.46	4.36	-0.10	-2.2
R_B 2/3	6.50	7.00	+0.50	+7.7
R_B 3/4	2.00	2.00	0	0
R_B	4.08	4.17	+0.09	+2.2
R_D 1/2	3.67	3.80	+0.13	+3.5
R_D 2/3	3.00	2.50	-0.50	-16.7
R_D 3/4	2.00	2.00	0	0
R_D	2.82	2.65	-0.17	-6.0
R_L 2/1	1.96	2.66	+0.7	+35.7
R_L 3/2	1.92	1.54	-0.38	-19.8
R_L 4/3	4.90	5.04	+0.14	+2.9
R_L	2.86	2.94	+0.08	+2.8
A (acres)	147	156	+9	+6.1
A (sq mi)	0.23	0.24	+0.01	+6.1
P (ft)	14,497	14,798	+301	+2.1
P (mi)	2.75	2.80	+0.05	+2.1

Table 4 Cont.

Variable	1938	1968	Observed Change	Percent Change
L (ft)	5,841	5,280	-561	-9.6
L (mi)	1.11	1.00	0.11	-9.6
W (ft)	1,914	1,815	-99	-5.2
W (mi)	0.36	0.34	-0.02	-5.2
R_t	26.96	27.86	+0.90	+3.3
$R_{\ell t}$	38.98	41.79	+2.81	+7.2
R_F	1.35	1.33	-0.02	-1.5
D_d	16.20	15.38	-0.82	-5.1
C	325.8	343.2	+17.4	+5.3
L_o	163.0	171.7	+8.7	+5.3
F	322.6	321.0	-1.6	-0.5
F_ℓ	466.4	481.5	+15.1	+3.2
R_C	0.383	0.390	+0.007	+1.8
R_E	0.456	0.556	+0.100	+21.9
WSF	1.949	2.187	+0.238	+12.2
A/P	0.084	0.087	+0.003	+3.6
L/W	3.052	2.909	-0.143	-4.7

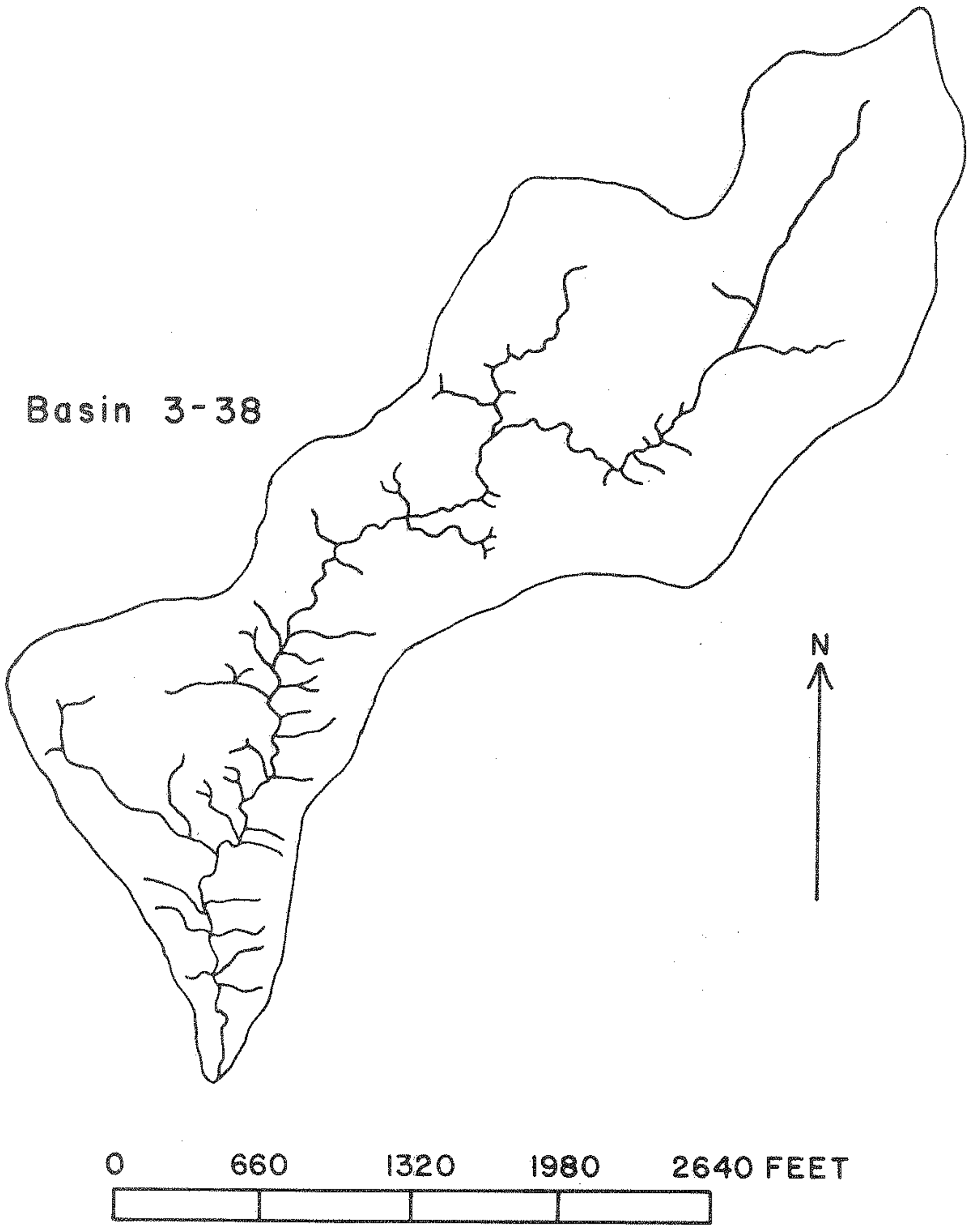


Figure 16. Drainage map of study basin 3 as of 1938.

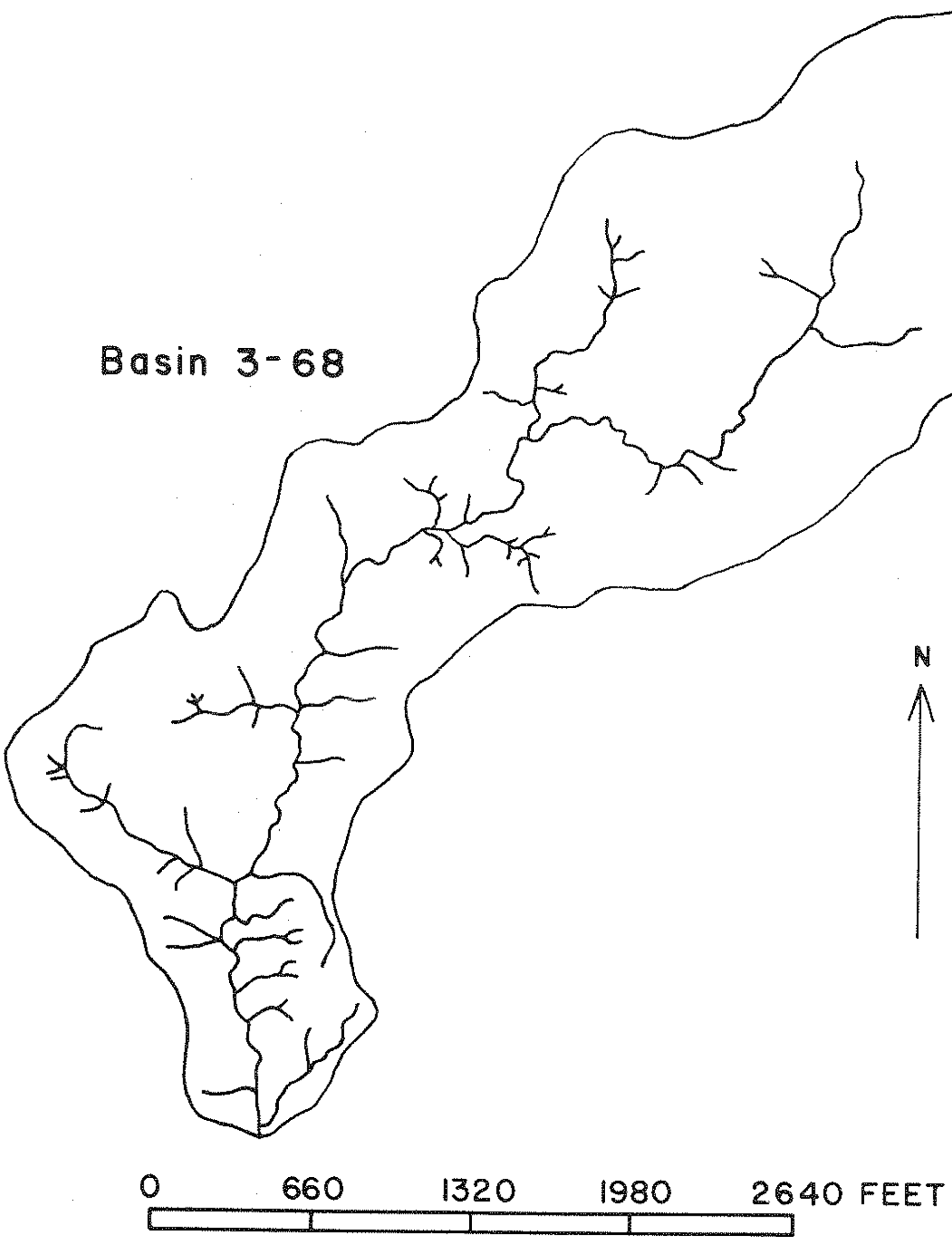


Figure 17. Drainage map of study basin 3 as of 1968.

this was balanced by abstraction. It appears that most of the new channels formed are tributary to the second-order drainage, whereas more "lost" segments were terminated than added to the mainstream. The mainstream decrease in length was accomplished by a slight straightening of its course or a decrease in sinuosity.

Basin Dimensions: Area and perimeter of the basin remained constant despite some captures of small areas by network extension. Similarly, maximum basin length and width show only minor changes.

Basin Shape: Because of the nominal adjustments experienced in the basin dimensions, no major change in the basin outline is noted. Circularity Ratio, Elongation Ratio, and L/W indicate slight adjustments toward circularity, but all values reflect the highly elongate nature of the basin. The Watershed Shape Factor indicated a reverse trend, however, owing to increased mainstream length; meanwhile the area remained unchanged.

Drainage Texture: Upon first examination, somewhat contradictory trends are indicated by the various textural measures. Texture Ratio and Link-Texture Ratio indicate a slight increase in the number of segments and links per unit distance around the basin perimeter. However, Drainage Density, Fineness Ratio, and Link Frequency increased slightly and Channel Segment Frequency also decreased. The magnitude of change in each case is very small, and can be reconciled in terms of the comparative rates of change among the measures used to compute the textural parameters. Figures 16 and 17 and the lack of any dominant trend in the above cited parameters reflect the stability of the drainage texture.

Summary: Compared to the other four basins of the study, only minor changes are observed in Basin 3. The entire network experienced a slight increase in the number of segments and links, but was confined to the "lost" streams. Most length increase within the network structure was accomplished by extension of second-order streams, while the entire network maintained about the same length. Almost no change occurred in the size or shape of the basin or in the drainage texture and degree of basin dissection.

Basin 4

Basin 4 is a fifth-order watershed that is tributary to Indian Creek about 0.55 miles upstream from the junction of Basin 1, and approximately 3.0 channel miles upstream from the mouth of Indian Creek. Topologically, this is the most complex basin of the study group. The maps and data for Basin 4 can be found in Figures 18 and 19 and Table 5.

Stream Numbers and Lengths: The maps and data indicate Basin 4 experienced a phenomenal rate of network growth and expansion during the time interval studied. The number of segments of all orders except order 5 increased, and the total length of segments of drainage orders 1, 2, 3, and 5 increased and order 4 decreased. Consequently, $\bar{L}_1$, $\bar{L}_2$, and $\bar{L}_4$ decreased, but $\bar{L}_3$ and $\bar{L}_5$ increased. The magnitude of change is quite small for L_2 and $\bar{L}_3$. Likewise, the number of segments comprising the Horton Net increased throughout except for the trunk stream, whereas the number of links in the network increased significantly except for order 4 segments which lost 4 links. The total length of channels in the basin increased by about one mile (9%). Change in the first-order

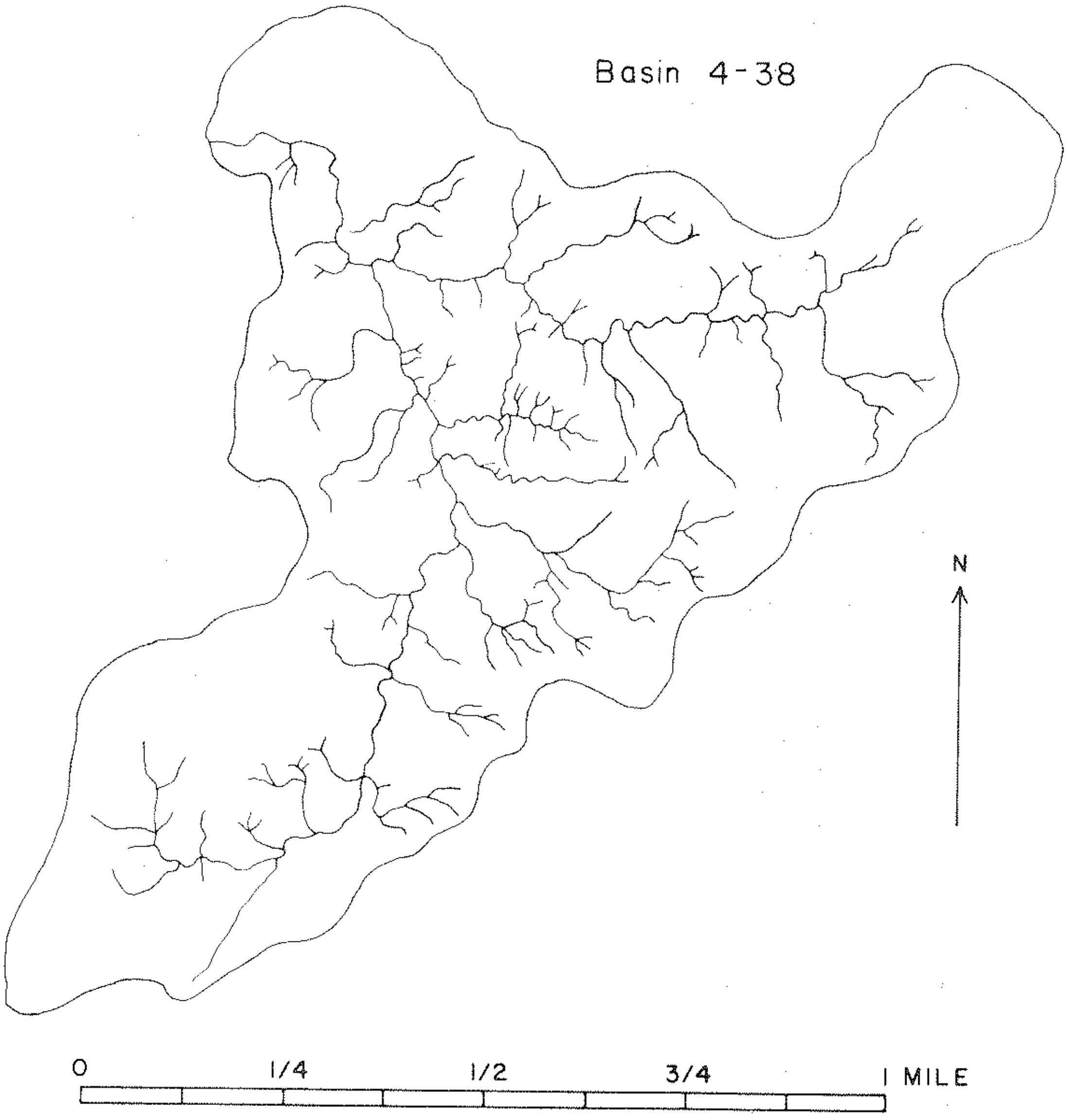


Figure 18. Drainage map of study basin 4 as of 1938.

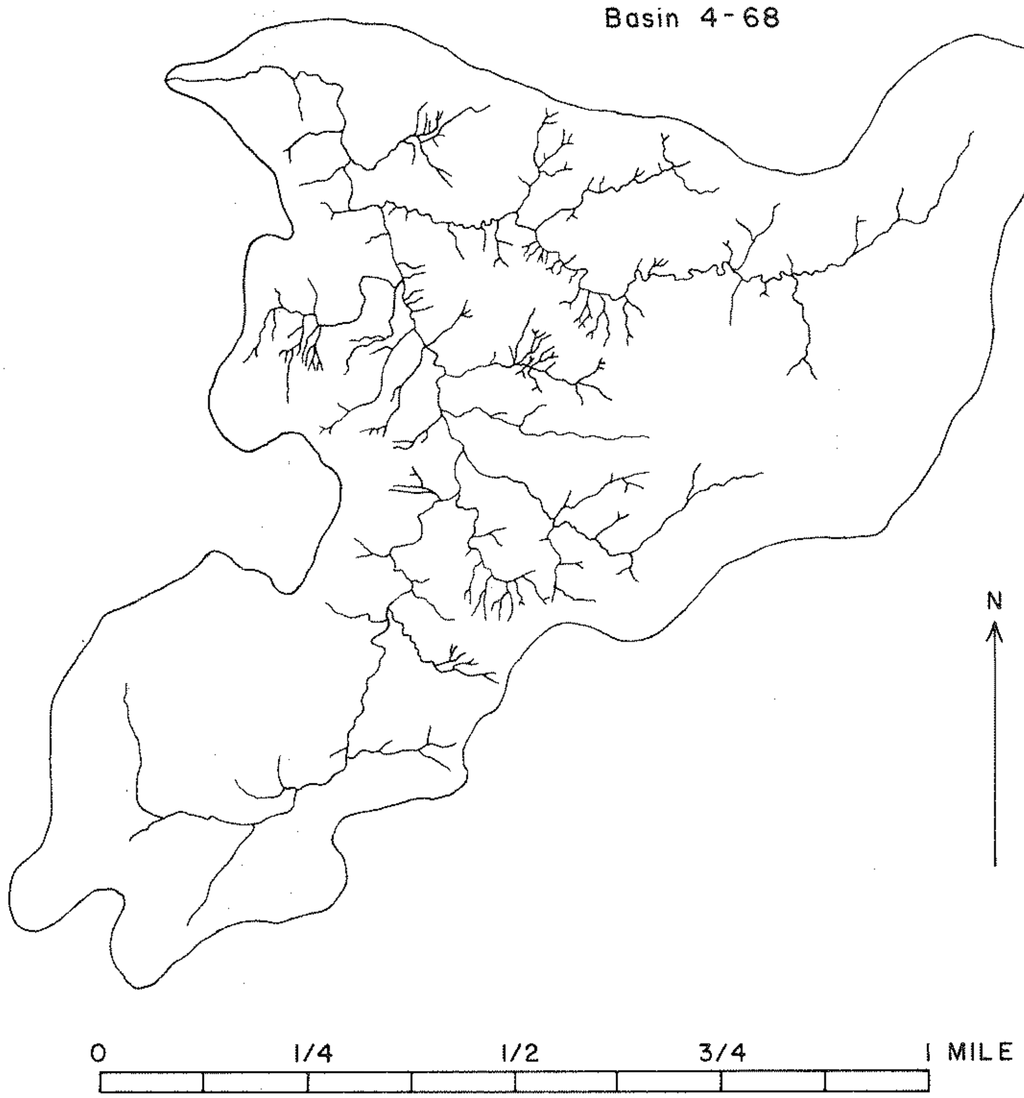


Figure 19. Drainage map of study basin 4 as of 1968.

Table 5. Morphometric data for Basin 4.

Variable	1938	1968	Observed Change	Percent Change
N_1	132	209	+77	+58.3
N_2	39	64	+25	+64.1
N_3	7	13	+6	+85.7
N_4	2	4	+2	+100.0
N_5	1	1	0	0
N_T	181	291	+110	+60.8
L_1	26,631	28,133	+1502	+5.6
L_2	16,038	16,104	+66	+0.4
L_3	4,983	9,422	+4439	+89.1
L_4	8,399	5,280	-3119	-37.1
L_5	1.848	4,208	+2360	+127.7
L_T(ft)	57,899	63,146	+5247	+9.1
L_T(mi)	10.97	11.96	+0.99	+9.1
L_m(ft)	8,448	9,323	+875	+10.4
L_m(mi)	1.60	1.77	+0.17	+10.4
$\bar{L}_1$	202	135	-67	-33.2
$\bar{L}_2$	411	252	-159	-38.7
$\bar{L}_3$	712	724	+12	+1.7
$\bar{L}_4$	4,199	1,320	-2879	-68.6
$\bar{L}_5$	1,848	4,208	+2360	-127.7
HN_1	53	97	+44	+83.0
HN_2	18	38	+20	+111.1
HN_3	7	11	+4	+57.1
HN_4	2	4	+2	+100.0
HN_5	1	1	0	0
HN_T	81	151	+70	+86.4

Table 5 Cont.

Variable	1938	1968	Observed Change	Percent Change
n_1	132	209	+77	+58.3
n_2	68	110	+42	+61.8
n_3	18	49	+31	+172.2
n_4	32	26	-6	-18.8
n_5	5	18	+13	+260.0
n_t	255	412	+157	+61.6
$\bar{\ell}_1$	202	135	-67	-33.2
$\bar{\ell}_2$	236	146	-90	-38.1
$\bar{\ell}_3$	277	192	-85	-30.7
$\bar{\ell}_4$	263	203	-60	-22.8
$\bar{\ell}_5$	370	234	-136	-36.8
$\bar{\ell}$	227	153	-74	-32.6
ℓ_i	254	173	-81	-31.9
ℓ_e	202	135	-67	-33.2
R_B 1/2	3.39	3.27	-0.12	-3.5
R_B 2/3	5.57	4.92	-0.65	-11.7
R_B 3/4	3.50	3.25	-0.25	-7.1
R_B 4/5	2.00	4.00	+2.00	+100.0
R_B	3.57	3.84	+0.27	+7.6
R_D 1/2	2.94	2.55	-0.39	-13.3
R_D 2/3	2.57	3.46	+0.89	+34.6
R_D 3/4	3.50	2.75	-0.75	-21.4
R_D 4/5	2.00	4.00	+2.00	+100.0
R_D	2.76	3.06	+0.30	+10.9

Table 5 Cont.

Variable	1938	1968	Observed Change	Percent Change
R_L 2/1	2.04	1.87	-0.17	-8.3
R_L 3/2	1.73	2.88	+1.15	+66.5
R_L 4/3	5.90	1.82	-4.08	-69.2
R_L 5/4	0.44	3.19	+2.75	+625.0
R_L	2.56	2.62	+0.06	+2.3
A (acres)	475	463	-12	-2.5
A (sq mi)	0.74	0.72	-0.02	-2.5
P (ft)	25,509	26,024	+515	+2.0
P (mi)	4.83	4.93	+0.10	+2.0
L (ft)	5,016	4,752	-264	-5.3
L (mi)	0.95	0.90	-0.05	-5.3
W (ft)	8,844	8,580	-264	-3.0
W (mi)	1.68	1.63	-0.05	-3.0
R_t	37.47	59.04	+21.57	+57.6
$R_{\ell t}$	52.80	83.59	+30.79	+58.3
R_F	2.27	2.43	+0.16	+7.0
Dd	14.78	16.53	+1.75	+11.8
C	357.2	319.4	-37.8	-10.6
L_o	178.7	159.7	-19.0	-10.6

Table 5 Cont.

Variable	1938	1968	Observed Change	Percent Change
F	243.9	402.3	+158.4	+64.9
F_{ℓ}	343.6	569.5	+225.9	+65.7
R_C	0.400	0.374	-0.026	-6.5
R_E	1.023	1.066	+0.043	+4.2
WSF	1.646	1.840	+0.194	+11.8
A/P	0.154	0.147	-0.007	-4.5
L/W	0.567	0.554	-0.013	-2.3

was attained primarily by the formation of new segments which have not had time to lengthen, and secondarily by the extension of previously existing segments. Some exterior links were abstracted, but the dominant pattern is the addition of many new segments. Link data indicate that probably most of these additions were tributary to the second- and third-order segments, with a few "adventitious" segments added to the trunk stream. The total length of second-order drainage remained essentially constant but with an increase in frequency, and indicates that abstraction of existing drainage was active as well as new growth. The large growth in order 3 drainage was undoubtedly accomplished by the addition of exterior links in such a fashion as to increase the order of some of the established segments from 2 to 3. This is in accord with our observations. Similarly, addition of first- and second-order segments increased the order to such an extent that two new fourth-order segments were formed. Meanwhile, L_4 decreased. Abstraction decreased the order of a single, lengthy fourth-order stream, which also contributed to the length increase in order 3. Growth also produced other short third-order segments. The increase in L_5 resulted from formation of new fourth-order drainage further upstream within the network. Much of the growth was again within the "lost" portion of the network, but many of the new segments were incorporated into the integrated network as evidenced by the 86% increase in the number of Horton Net segments.

Basin Dimensions: Size of the catchment was stable over the 30-year interval. Although the perimeter increased slightly (2%) and area, length, and width showed slight decreases (maximum of 5%), magnitude of change in all measures is very small and may reflect possible measurement error.

Basin Shape: Basin 4 is the only watershed in the sample whose shape is not basically elongate, and therefore the length-width ratio is less than unity. Because of the nominal changes involved in basin dimensions, only minor adjustments in basin shape were indicated. R_C decreased slightly (7%) whereas R_E increased by 4%, indicating increase in both elongation and circularity. The Watershed Shape Factor increased, primarily from the increase in the mainstream length. Figures 18 and 19 and the lack of any definite adjustment trend suggest a constancy of basin shape.

Drainage Texture: Obviously, drainage texture underwent significant increases, owing to marked network growth. All textural parameters increased, ranging from 7% to 66%. The range in magnitude of increase comes from relative adjustments in the variables used to obtain the textural parameters. Because of the stability of catchment area and perimeter, the degree of basin dissection increased toward a "finer" drainage texture as a result of internal adjustments.

Summary: Collectively, Basin 4 underwent an episode of major network alteration between 1938 and 1968, which resulted in a sharp increase in the degree of dissection of the watershed and a much finer drainage texture. The dynamic nature of the adjustments is indicated by an increase in the number of segments of 61% while the total length of channels increased only 9%. Evidence for drainage loss commensurate with an extension of established channels and formation of new drainage elements is found on the maps and indicated by the parameters. Growth was experienced in the entire network, that is in both the integrated and "adventitious" portions, with major changes occurring throughout all levels and in all orders of the network.

Basin 5

This fifth-order basin lies immediately west of Basin 3, and is likewise tributary to Wabash River (see Figure 11). Similar to Basin 3, the downstream section of the trunk stream is very straight. It receives no tributaries as it flows across the Wabash floodplain in what appears to be an artificial ditch. Therefore, only that portion of the network upstream from the ditched section was analyzed. The respective data values and watershed maps for Basin 5 can be found in Table 6 and Figures 20 and 21.

Stream Numbers and Lengths: Basin 5, like Basin 4, has undergone significant modifications in structure and complexity of the drainage network. The number of segments increased in all orders except order 5. However, length of segments of order 1 and 3 decreased, whereas orders 2 and 5 increased and order 4 remained essentially unchanged. As a consequence, $\bar{L}_1$, $\bar{L}_2$, $\bar{L}_3$, and $\bar{L}_4$ decreased but $\bar{L}_5$ increased. This is meaningless as only one segment is involved. The Horton Net experienced minor growth throughout with the exception of second- and fifth-order segments. These changes were minor as the increase within the Net was only 3%. The number of links increased through all orders, resulting in an increase of 44% for the entire network. Changes observed in the first-order streams resulted principally from the abstraction of several large segments, combined with addition of many small segments which decreased both L_1 and $\bar{L}_1$. This growth of exterior links increased the order of many segments; therefore, increase in the number of second-order channels resulted from a combination of order conversion and new growth. Order 3 drainage had a gain of 4 segments but a loss of over 3,600 feet of drainage. Because of addition of first-order segments, reordering produced new segments of third-order which were very short compared to the older, more established segments of this order. Simultaneously, a significant loss of third-order length of greater magnitude resulted from termination of exterior links in the headwaters of the basin. Similar adjustments are seen in the fourth-order drainage. The increase in order 5 drainage length came from the formation of a fourth-order segment farther upstream. Most of the fluctuations in number and location of exterior links probably were confined to the "lost" portions of the network, as the Horton Net increased by only 3%.

Basin Dimensions: During the 30-year time interval, size of the catchment decreased significantly because of the transfer of some drainage area to an adjacent basin to the north. The drainage area and basin perimeter were respectively 39% and 25% less in 1968 than in 1938. Accordingly, maximum length and width of the basin also decreased. This decrease in area and perimeter appears, on the basis of photographic comparisons, to result from drainage diversion and artificial drainage establishment in the headwater portion of the catchment.

Table 6. Morphometric data for Basin 5.

Variable	1938	1968	Observed Change	Percent Change
N_1	127	186	+59	+46.5
N_2	35	47	+12	+34.3
N_3	9	13	+4	+44.4
N_4	2	3	1	+50.0
N_5	1	1	0	0
N_T	174	250	+76	+43.7
L_1	26,268	22,737	-3,531	-13.4
L_2	12,458	14,718	+2,260	+18.1
L_3	11,055	7,409	-3,646	-33.0
L_4	6,336	6,303	-33	-0.5
L_5	990	2,459	+1,469	+148.4
L_T(ft)	57,107	53,626	-3,481	-6.1
L_T(mi)	10.82	10.16	-0.66	-6.1
L_m(ft)	12,293	9,884	-2.409	-19.6
L_m(mi)	2.33	1.87	-0.46	-19.6
$\bar{L}_1$	207	122	-85	-41.1
$\bar{L}_2$	356	313	-43	-12.1
$\bar{L}_3$	1,228	570	-658	-53.6
$\bar{L}_4$	3,168	2,101	-1,067	-33.7
$\bar{L}_5$	990	2,459	+1,469	+148.4
HN_1	82	87	+5	+6.1
HN_2	30	27	-3	-10.0
HN_3	9	10	+1	+11.1
HN_4	2	3	+1	+50.0
HN_5	1	1	0	0
HN_T	124	128	+4	+3.2

Table 6 Cont.

Variable	1938	1968	Observed Change	Percent Change
n_1	127	186	+59	+46.5
n_2	61	102	+41	+67.2
n_3	35	42	+7	+20.0
n_4	11	26	+15	+136.4
n_5	1	10	+9	+900.0
n_t	235	366	+131	+55.7
$\bar{\ell}_1$	207	122	-85	-41.1
$\bar{\ell}_2$	204	144	-60	-29.4
$\bar{\ell}_3$	316	176	-140	-44.3
$\bar{\ell}_4$	576	242	-334	-60.0
$\bar{\ell}_5$	990	246	-744	-75.2
$\bar{\ell}$	243	147	-96	-39.5
ℓ_i	286	172	-114	-39.9
ℓ_e	207	122	-85	-41.1
R_B 1/2	3.63	3.96	+0.33	+9.1
R_B 2/3	3.89	3.62	-0.27	-6.9
R_B 3/4	4.50	4.33	-0.17	-3.8
R_B 4/5	2.00	3.00	+1.00	+50.0
R_B	3.51	3.74	-0.23	+6.6
R_D 1/2	2.73	3.22	+0.49	+17.9
R_D 2/3	3.33	2.70	-0.63	-18.9
R_D 3/4	4.50	3.33	-1.17	-26.0
R_D 4/5	2.00	3.00	+1.00	+50.0
R_D	3.17	3.04	-0.13	-4.1

Table 6 Cont.

Variable	1938	1968	Observed Change	Percent Change
R_L 2/1	1.72	2.56	+0.84	+48.8
R_L 3/2	3.45	1.82	-1.63	-47.2
R_L 4/3	2.58	3.69	+1.11	+43.0
R_L 5/4	0.31	1.17	+0.86	+277.4
R_L	2.43	2.61	+0.18	+7.4
A (acres)	613	374	-239	-39.0
A (sq mi)	0.96	0.58	-0.38	-39.0
P (ft)	27,469	20,638	-6,831	-24.9
P (mi)	5.20	3.91	-1.29	-24.9
L (ft)	9,966	7,326	-2,640	-26.5
L (mi)	1.89	1.39	-0.50	-26.5
W (ft)	4,125	2,460	-1,665	-40.4
W (mi)	0.78	0.50	-0.28	-40.4
R_t	33.44	63.96	-30.52	+91.3
$R_{\ell t}$	45.17	93.63	48.46	+107.3
R_F	2.08	2.60	+0.52	+25.0
Dd	11.30	17.39	+6.09	+53.9
C	467.3	303.7	-163.6	-35.0
L_o	233.6	151.8	-81.8	-35.0

Table 6 Cont.

Variable	1938	1968	Observed Change	Percent Change
F	181.8	428.0	+246.2	+135.4
F_ℓ	245.5	626.6	+381.1	+155.2
R_C	0.444	0.480	+0.036	+8.1
R_E	0.585	0.622	+0.037	+6.3
WSF	2.109	2.171	+0.062	+2.9
A/P	0.184	0.149	-0.035	-19.0
L/W	2.416	2.775	+0.359	+14.9

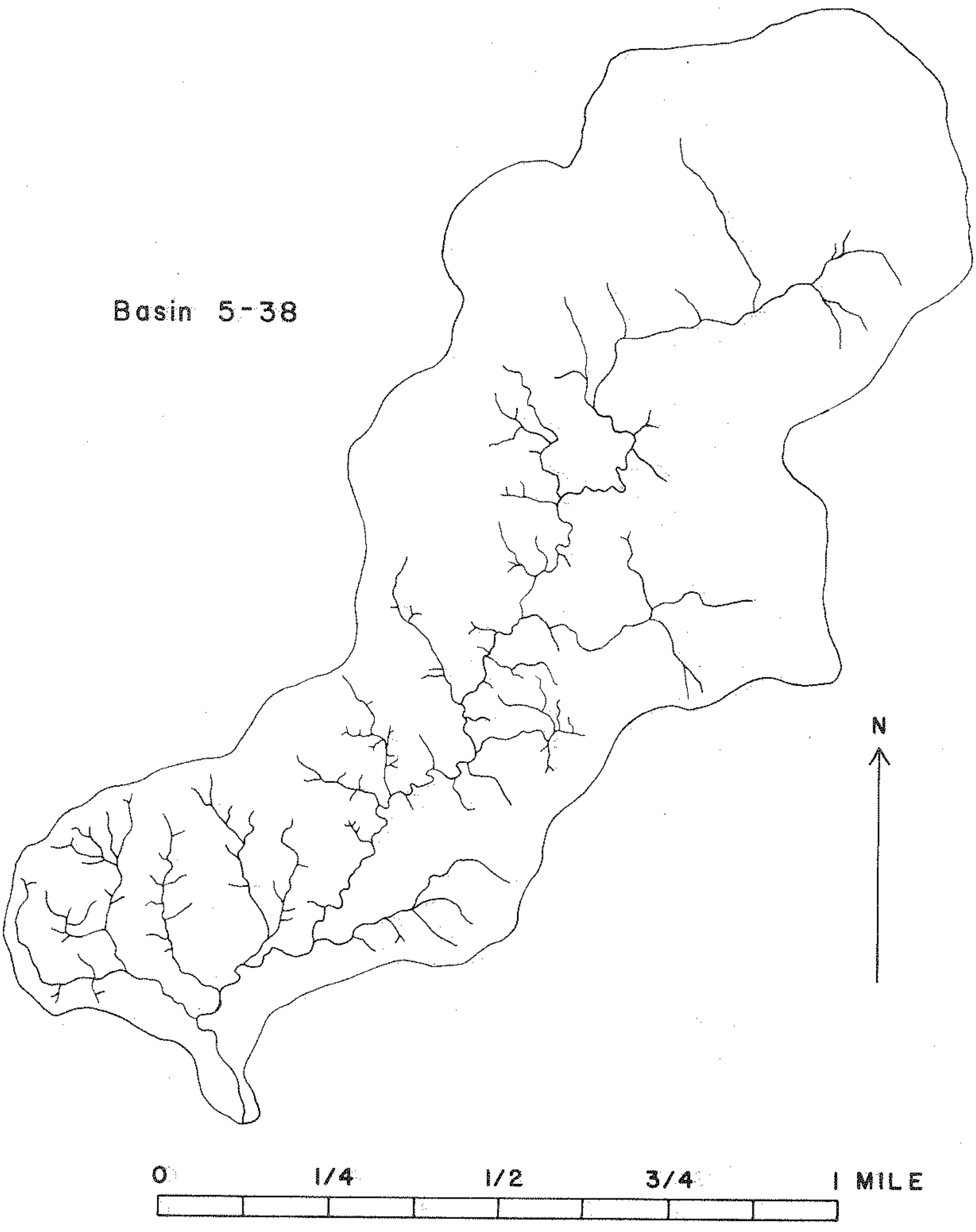


Figure 20. Drainage map of study basin 5 as of 1938.

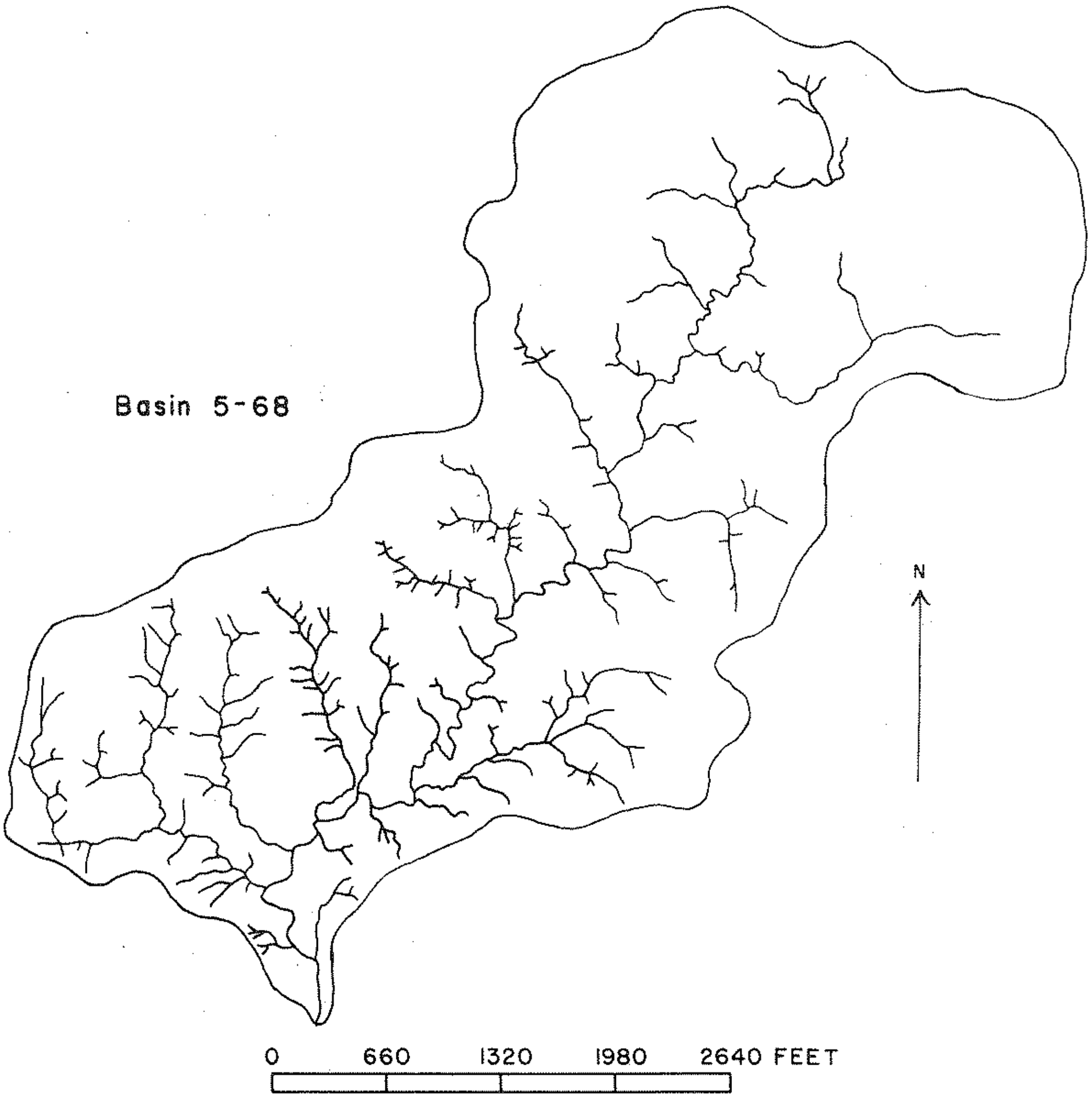


Figure 21. Drainage map of study basin 5 as of 1968.

Basin Shape: Although Basin 5 decreased significantly in size, the shape remained essentially constant as shown in Figure 14 and by the various shape factors. All shape factors indicate a slight decrease in circularity or a trend toward elongation, although the magnitude of change in each case is small.

Drainage Texture: All textural parameters exhibited significant increases in value, ranging from a minimum of 25% to a maximum of 155%. It is obvious from observation of drainage maps in Figures 20 and 21 that textural complexity of the channel network did in fact increase. However, much of the increase shown by the textural variables is the consequence of network adjustments combined with the 39% and 25% decreases in the drainage area and perimeter respectively. Thus, although the total channel length actually decreased by 6%, Fineness Ratio and Drainage Density both increased in value.

Summary: Overall basin adjustments experienced by Basin 4 and 5 are similar. Basin 5 experienced major growth in the number of drainage components, whereas total length of channels in the network decreased slightly. Several new first- and second-order drainage lines were established, which resulted in several internal order and length adjustments and increased the textural complexity of the network. The size of the watershed decreased but the shape was maintained. The degree of basin dissection was increased by the above changes.

Observed Changes Grouped According to Basin Order

Purely by chance, the five study basins may be classed as either fourth- or fifth-order basins. It is rather clear that the changes discussed in describing the fourth-order basins (Basins, 1, 2, and 3) are different from those observed in the two fifth-order basins. Consequently, the sample can be stratified on the basis of basin order and the mean adjustments of each group compared. This is discussed in the following sections.

Fourth-Order Basins

Data contained in Table 7 are the arithmetic mean values of parameters for Basins 1, 2, and 3. They therefore represent average changes observed in the fourth-order basins studied, and are possibly representative of basins of similar size in this geographical area developed under the influence of similar climatic and historical conditions.

Stream Numbers and Lengths: Table 7 indicates a trend toward decreasing numbers of drainage components, although the degree of change is relatively small. Total length of channels in the first three orders decreased, while that of the trunk stream increased. Because of relative rates of change in the foregoing terms, the mean segment length of all orders show a slight increase. Similarly, the Horton Net of the average fourth-order basin lost 4% of its segments, and the entire network showed a comparable loss in the number of links. The greatest percentage of change in the number and length of segments involved second-order streams, but the average change of first-order drainage was slight. However, the number of links has the largest percent change in third- and fourth-order segments. In total, these changes resulted in an average decrease of 6% in the total length of channels in the watersheds.

Basin Dimensions: All fourth-order basins increased in size during

Table 7. Average morphometric data for fourth-order basins.

Variable	1938	1968	Observed Change	Percent Change
N_1	72	67	-5	-6.9
N_2	21	18	-3	-14.3
N_3	4	4	0	0
N_4	1	1	0	0
N_T	98	90	-8	-8.2
L_1	11,061	10,329	-732	-6.6
L_2	5,973	5,247	-726	-12.2
L_3	2,387	2,343	-44	-1.8
L_4	3,328	3,588	+260	+7.8
L_T(ft)	22,749	21,507	-1,242	-5.5
L_T(mi)	4.31	4.07	-0.24	-5.5
L_m(ft)	5,638	6,135	+497	+8.8
L_m(mi)	1.07	1.16	+0.09	+8.8
$\bar{L}_1$	162	160	-2	-1.2
$\bar{L}_2$	277	305	+28	+10.1
$\bar{L}_3$	623	640	+17	+2.7
$\bar{L}_4$	3,328	3,588	+260	+7.8
HN_1	37	35	-2	-5.4
HN_2	12	12	0	0
HN_3	4	4	0	0
HN_4	1	1	0	0
HN_T	54	52	-2	-3.7
n_1	72	67	-5	-6.9
n_2	35	32	-3	-8.6
n_3	13	14	+1	+7.7
n_4	19	17	-2	-10.5
n_t	139	130	-9	-6.9

Table 7 Cont.

Variable	1938	1968	Observed Change	Percent Change
$\bar{\ell}_1$	162	160	-2	-1.2
$\bar{\ell}_2$	180	169	-11	-6.1
$\bar{\ell}_3$	209	166	-43	-20.6
$\bar{\ell}_4$	177	239	+62	+35.0
$\bar{\ell}$	171	174	+3	+1.8
ℓ_i	182	187	+5	+2.7
ℓ_e	162	160	-2	-1.2
R_B 1/2	3.61	3.79	+0.18	+5.0
R_B 2/3	5.23	5.32	+0.09	-1.7
R_B 3/4	4.00	3.67	-0.33	-8.3
R_B	4.27	4.16	-0.11	-2.6
R_D 1/2	3.10	3.16	+0.06	+1.9
R_D 2/3	3.06	3.05	-0.01	-0.3
R_D 3/4	4.00	3.67	-0.33	-8.3
R_D	3.24	3.19	-0.05	-1.5
R_L 2/1	1.66	2.04	+0.38	+22.9
R_L 3/2	2.71	2.24	-0.47	-17.3
R_L 4/3	5.27	5.58	+0.31	+5.9
R_L	3.00	3.13	+0.13	+4.3
A (acres)	218	237	+19	+8.7
A (sq mi)	0.34	0.37	+0.03	+8.7
P (ft)	14,611	15,484	+873	+6.0
P (mi)	2.77	2.93	+0.16	+6.0

Table 7 Cont.

Variable	1938	1968	Observed Change	Percent Change
L (ft)	5,874	5,698	-176	-3.0
L (mi)	1.11	1.08	-0.03	-3.0
W (ft)	2,970	2,871	-99	-3.3
W (mi)	0.56	0.54	-0.02	-3.3
R_t	38.60	32.02	-6.58	-17.0
$R_{\ell t}$	54.42	46.30	-8.12	-14.9
R_F	1.57	1.39	-0.18	-11.5
Dd	13.63	12.21	-1.42	-10.4
C	401.2	457.6	+56.4	+14.1
L_o	200.6	228.8	+28.2	+14.1
F	334.3	276.9	-57.4	-17.2
F_ℓ	472.5	403.1	-69.4	-14.7
R_c	0.562	0.530	-0.032	-5.7
R_E	0.584	0.628	+0.044	+7.5
WSF	1.623	1.828	+0.205	+12.6
A/P	0.120	0.123	+0.003	+2.5
L/W	2.118	2.143	+0.025	+1.2

the 30-year period of interest. On the average, catchment area increased by 9% and basin perimeter by 6%. However, maximum basin length and width each decreased about 3%. This might reflect possible measurement error or slight shape modifications.

Basin Shape: Adjustments of the various shape factors are inconsistent. Circularity Ratio decreased whereas the Elongation Ratio, Watershed Shape Factor, and Length-Width Ratio increased. This yields conflicting information as to average shape alteration; therefore, no obvious trend in shape modification is indicated.

Drainage Texture: Owing to combined effects of elimination of drainage elements and increases of watershed area and perimeter, all textural measures showed a decrease in value. As a result, textural complexity and degree of basin dissection was reduced, on the basis of the parameters examined, by about 15%.

Summary: The most pronouced alteration of fourth-order basins examined was a general elimination or extinction of drainage lines and a loss of channel length. This involved both the integrated and "lost" or subsequent portions of the network. In combination with slight increases in size of the basins, network abstractions resulted in a "coarser" or simplified drainage texture and decreased the degree of basin dissection. As a result, average number and length of channels per unit catchment area decreased and spacing between channels increased, as inferred from the values of textural parameters.

Fifth-Order Basins

Basins 4 and 5, both fifth-order, evidence similar adjustments in several respects. Therefore they were grouped together to obtain averaged measures for fifth-order basins of the sample. Date pertaining to this "average" basin are given in Table 8.

Table 8. Average morphometric data for fifth-order basins.

Variable	1938	1968	Observed Change	Percent Change
N_1	130	198	+68	+52.3
N_2	37	56	+19	+51.4
N_3	8	13	+5	+62.5
N_4	2	4	+2	+100.0
N_5	1	1	0	0
N_T	178	272	+94	+52.8
L_1	26,450	25,435	-1,015	-3.8
L_2	14,248	15,411	+1,163	+8.2
L_3	8,019	8,416	+397	+5.0
L_4	7,368	5,792	-1,576	-21.4
L_5	1,419	3,334	+1,915	+135.0
L_T (ft)	57,504	58,388	+884	+1.5
L_T (mi)	10.89	11.06	+0.17	+1.5
L_m (ft)	10,371	9,604	-767	-7.4
L_m (mi)	1.96	1.82	-0.14	-7.1
$\bar{L}_1$	205	129	-76	-37.1
$\bar{L}_2$	384	283	-101	-26.3
$\bar{L}_3$	970	647	-323	-33.3
$\bar{L}_4$	3,684	1,711	-1,973	-53.6
$\bar{L}_5$	1,419	3,334	+1,915	+135.0
HN_1	68	92	+24	+35.3
HN_2	24	33	+9	+37.5
HN_3	8	11	+3	+37.5
HN_4	2	3	+1	+50.0
HN_5	1	1	0	0
HN_T	103	140	+37	+35.9

Table 8 Cont.

Variable	1938	1968	Observed Change	Percent Change
n_1	130	198	+68	+52.3
n_2	65	106	+41	+63.1
n_3	27	46	+19	+70.4
n_4	22	26	+4	+18.2
n_5	3	14	+11	+366.7
n_t	247	390	+143	+57.9
$\bar{\ell}_1$	205	129	-76	-37.1
$\bar{\ell}_2$	220	145	-75	-34.1
$\bar{\ell}_3$	297	184	-113	-38.0
$\bar{\ell}_4$	420	220	-200	-47.6
$\bar{\ell}_5$	680	240	-440	-64.7
$\bar{\ell}$	235	171	-64	-27.2
ℓ_i	270	183	-87	-32.2
ℓ_e	205	129	-76	-37.1
R_B 1/2	3.51	3.62	+0.11	+3.1
R_B 2/3	4.73	4.27	-0.46	-9.7
R_B 3/4	4.00	3.79	-0.21	-5.3
R_B 4/5	2.00	3.50	+1.5	+75.0
R_B	3.54	3.79	+0.25	+7.1
R_D 1/2	2.84	2.89	+0.05	+1.8
R_D 2/3	2.95	3.08	+0.13	+4.4
R_D 3/4	4.00	3.04	-0.96	-24.0
R_D 4/5	2.00	3.50	+1.5	+75.0
R_D	2.97	3.05	+0.08	+2.7

Table 8 Cont.

Variable	1938	1968	Observed Change	Percent Change
R_L 2/1	1.88	2.22	+0.34	+18.1
R_L 3/2	2.59	2.35	-0.24	-9.3
R_L 4/3	4.24	2.76	-1.48	-34.9
R_L 5/4	0.38	2.18	+1.80	+473.7
R_L	2.50	2.62	+0.12	+4.8
A (acres)	544	419	-125	-23.0
A (sq mi)	0.85	0.65	-0.20	-23.0
P (ft)	26,489	23,331	-3,158	-11.9
P (mi)	5.02	4.42	-0.60	-11.9
L (ft)	7,491	6,039	-1,380	-18.6
L (mi)	1.42	1.14	-0.28	-18.6
W (ft)	6,485	5,520	-965	-14.9
W (mi)	1.23	1.05	-0.18	-14.9
R_t	35.46	61.50	+26.04	+73.4
$R_{\ell t}$	48.99	88.61	+39.62	+80.9
R_F	2.18	2.52	+0.34	+15.6
Dd	13.04	16.96	+3.92	+30.1
C	412.3	311.5	-100.8	-24.4
L_o	206.2	155.8	-50.4	-24.4

Table 8 Cont.

Variable	1938	1968	Observed Change	Percent Change
F	212.8	415.1	+202.3	+95.1
F_{ℓ}	294.5	598.1	+303.6	+103.1
R_C	0.422	0.427	+0.005	+1.2
R_E	0.804	0.844	+0.040	+5.0
WSF	1.878	1.726	-0.152	-8.1
A/P	0.169	0.148	-0.021	-12.4
L/W	1.492	1.665	+0.173	+11.6

Stream Numbers and Lengths: The number of stream segments in the network increased by 53%, with major increases in all orders except order 5. The length of channels in orders 2, 3, and 5 increased, but decreased in orders 1 and 4. Total channel length showed only a 2% increase, because opposite trends were measured in the two original watersheds. Owing to relative rates of change of frequency and length data, the mean segment length decreased for each order except for the trunk segment. The Horton Net showed gains in the number of segments in all orders, and correlative changes in the number of links in the network are indicated. Therefore, the average firth-order basin experienced major growth throughout the system by the addition of exterior links, principally to the integrated network, which caused major order alterations through all levels. Total drainage length remained essentially constant, because abstractions and channel losses were occurring simultaneously with addition of younger and shorter drainage lines.

Basin Dimensions: Average changes in basin size resulted in a decrease in all parameters. The magnitude of the average results primarily from large drainage losses experienced by Basin 5.

Basin Shape: Decrease in basin size was accompanied by a very modest change toward circularity. Although this trend is indicated by all parameters except length-width ratio, the magnitude of change is small as the maximum adjustment reflected in a shape measure was only 8%.

Drainage Texture: Because the number of network components increased and the size of the basin decreased by considerable amounts, textural measures underwent sizable increases. These increases represent the development of a finer and more complexly detailed network on the catchment surface.

Summary: Fifth-order basins in the study showed a significant increase in the number of drainage components, as well as in the degree of textural complexity and basin dissection. Many of these stream segment additions were integrated into the network, which produced order adjustments in some of the higher ordered segments. Although the number of segments and links increased, total length of channels remained essentially constant, indicating drainage termination was also active within the basin.

General Conclusions

The values of variables used in this study indicate that changes experienced in the fourth- and fifth-order basins are in essentially opposite directions. Therefore, if average adjustments are considered for all five basins, resulting mean values would tend to be smaller in magnitude and reflect the trend of larger changes experienced in most of the fifth-order basin values. This is perhaps an additional point for consideration in attempting to decipher the dynamic nature of basin adjustments. It is obvious from the data presented in this chapter that even immediate basin responses to altered system inputs, i.e., those adjustments most closely related to the input transitions, are not simple adjustments involving only one or two aspects of the watershed. For example, the data cited clearly indicate that drainage modifications, such as simple extension of the network through new segment additions and headward growth, did not occur alone but were accompanied by simultaneous losses elsewhere in the basin. Consequently, modifications are complex responses involving many aspects of the basin's physical characteristics with feedback, interplay, and multiple interrelations among the alteration processes.

CHAPTER 6

THEORETICAL CONSIDERATIONS

Introduction

Since quantitative fluvial geomorphology was ushered into existence by Horton in 1945, many investigators have contributed new methodologies, parameters, and hyphotheses. Subsequent to the excellent field study conducted by Schumm in 1956, mechanisms of drainage basin development and evolution have received considerable attention. Concurrently, development of computer technology has allowed researchers the luxury of testing mathematical and conceptual models of network growth rapidly and without exhaustive manual calculations. Consequently, the past 15 years witnessed the introduction of several models of network growth, and techniques for estimating stability and equilibrium conditions within the fluvial system. Additionally, some researchers have taken an essentially topological approach to the study of drainage networks, and have reported results based upon rigorous statistical treatment of observed and computer-generated hypothetical river nets.

It is not feasible to consider in this report all aspects and ramifications of every theoretical study. Additionally, the observations reported herein are based upon such a comparatively small sampling of natural drainage basins that inherent natural variation may mask any evidence that tends to confirm any theory. With these limitations in mind, a few of the more prominent aspects of specific theoretical studies will be discussed and compared with observations as presented in Chapter 5. First, however, a statement about the actual mechanisms of network adjustment is required.

Mechanics of River Network Alteration

Mechanics of Growth

Most studies of network change have involved consideration of growth and expansion related to evolution toward a more complex state. For example, computer simulation techniques involve study of growth of networks based upon certain underlying assumptions of node pattern and location, path length and direction, and combinative possibilities with alternatives chosen by predetermined probability values. Such techniques may involve growth analogous to a low to high order direction, with the net resulting from successive union and joining of paths as in random walk models and the branching theory of Scheidegger (1966), or network simulation may be based upon headward growth and branching (Howard, 1971). A third possibility is a method of simulation which presupposes no method of development where only the final resulting network is of concern (Shreve, 1966, 1967, 1969). Although arguments for both headward growth and coalescing growth are possible, the first of these processes appears more tenable if the master drainage has been established and lower order tributaries are being formed. This occurs in the basins observed in the present study, and the data support the predominance of headward growth and extension, as also in other studies (see Schumm, 1956; Carter and Chorley, 1961).

Mechanics of Drainage Loss

Unlike the growth and extension phase of network change, the processes of abstraction, drainage loss, and channel termination have not been so widely studied. However, this activity was present, in varying degrees, in all of the study basins. Although the influence of such activity has been noted by several investigators (Morisawa, 1964; Howard, 1971) mechanics of channel loss has been considered by only a few researchers. In discussing origin and development of stream systems, Horton relates rill growth and loss to certain stages within the developmental framework. Horton (1945, p. 331) states that:

> "Where a rilled surface develops on a newly exposed slope the usual result is the development of a deep crustal master rill or gully, with more or less parallel, shallower, shoestring rills, decreasing in depth and frequency, on both sides of the master gully. These shoestring rills do not generally survive. The deeper ones close to the master gully are absorbed by the master rill by bank caving or are destroyed by the breaking down of the narrow ridges between them. Those more remote are later obliterated when lateral slope has developed sufficiently to permit cross flow."

Horton (1945, p. 333-34) reasoned that, with time, the system of parallel gullies is transformed into a dendritic net as a direct consequence of overtopping and breakdown of intermediate ridges between gullies by overland flow during heavier storms.

Horton (1945, p. 335) summarized the methods of rill obliteration and their importance in his concept of network development as follows:

> "When a storm occurs exceeding in intensity preceding storms on the newly exposed areas, the divide between two rills may be broken down at its weakest point by (1) caving in of the divide between two rills, diverting the higher into the lower thus diverting the higher rill; (3) overtopping of the divide at the low point by the higher rill, again diverting it into the lower rill. This breaking down of divides between adjacent rill channels and diverting the higher into the lower rills is described as micropiracy. Micropiracy much resembles stream capture by lateral corrasion, but micropiracy results chiefly from water overtopping a low spot in the narrow ridge between two rills. Micropiracy obliterates the original system of rills and their intermediate ridges on a uniform newly exposed surface. The process of erosion, in the course

> of development of a stream system and its accompanying valleys destroys most of the record of their origin. Ultimately the original slope parallel with the stream is replaced on each side of the stream by a new slope deflected toward the stream. This process is described as "cross-grading."

This discussion indicates the emphasis which Horton placed upon overland flow and hydrologic input for network growth and alteration. Similar reasoning was used by Schumm (1956, p. 620-621) in describing the evolution of the Perth Amboy drainage pattern. However, Schumm gave more consideration to the matter of competition for drainage area and consequently more overland flow rather than to reliance upon a single high intensity storm. Schumm states that:

> "A headward developing incised channel is hydrophilic, advancing always toward maximum water supply. The most vigorously developing initial rill channel thus dominated its less effective neighbor and established itself as the axis of a broadening ovate drainage basin. Its permanence was decided initially by a favored position...from which it was supplied with more runoff than its competitors... The added runoff allowed deepening of the drainage channel with corresponding oversteepening and collapse of its valley-side slopes."

Although not specifically so stated, Schumm's discussion appears to imply the same general process of micropiracy, but by competition for drainage area rather than by lateral corrosion as suggested by Horton.

Mass-wasting is a third possible mechanism that contributes to drainage channel and rill termination. Certain mass-wasting phenomena, such as freeze-thaw contribution to downslope movements of soil materials, is seasonally distributed and can have a pronounced effect on slope processes (see Schumm, 1964). In humid temperate climates, the greatest incidence of freeze-thaw activity should occur from late fall to early spring, and therefore generally precedes the times of occurrence of maximum runoff.

If intensity of soil movement is enhanced by abundant freeze-thaw activity, it would be no difficult task to infill and obliterate small, shallow channels and rills which have not been firmly established and integrated into the total network. This would be particularly true if ensuing runoff was small and the processes could be repeated the following year. This concept is supported by Kirkby and Chorley (1967, p. 17) who conclude that "there is a vital balance between fluvial down-cutting and aggradation by slope processes along the valley axis."

Obviously, the cited processes are pertinent in discussion of network changes in small, low-order segments and rills around the periphery of a network and the "lost" portions directly tributary to higher order channels. To envision adjustments in length and numbers of integrated streams located internally within the network, other factors must be considered.

Hydrologic Impetus

Basic to perception of drainage basin formation and evolution is an understanding of the antecedent forces of water acting upon the watershed surface. Considerable attention has been paid to the role of water as an erosive and transportive agent within the confines of a river channel. Consequently, cause and effect relationships can be estimated by using a foundation of hydraulic, geomorphic, and sediment transport theory. However, the role of water in shaping the landscape and in hydrologic estimation, from the time of water impact on the catchment surface to the time it becomes a part of streamflow, is another matter. Although this problem has been previously investigated (Emmett, 1970), the relative importance of the contribution of overland flow versus that of interflow in basin development and hydrograph formation is still unsettled.

Horton (1945) proposed a conception of the origin and development of stream systems. Some aspects of this concept are presented at the beginning of this chapter. Basic to his conceptual model is the importance of overland flow as an erosive agent, indicated by his statement (1945, p. 309) "it is this same unobtrusive and almost imperceptible overland flow which, with greater depths and larger volumes on longer slopes, is largely responsible for carving the landscape of drainage basins into observed forms." Horton proposed that, for any given terrain, some minimum overland flow length is needed to produce runoff volume sufficient to initiate erosion, and this critical distance depends upon slope, funoff intensity, infiltration capacity, and soil resistivity to erosion. On this premise he was able to relate the origin of the observable characteristics of drainage basins. Horton's reasoning has apparently been the basis of many subsequent studies of basin growth (for example, see Schumm, 1956).

More recently, Kirkby and Chorley (1967) presented some valid arguments against the dominance of overland flow in river network growth processes. Based upon earlier, detailed investigations of watershed hydrology, Kirkby and Chorley (1967, p. 7) note that "where there is appreciable soil and vegetation, and especially where there is humus or little cover, little surface runoff seems to occur over much of the basin except in the most extreme storms." Given these conditions, the authors subsequently developed a model that emphasizes both observationally and theoretically, the importance of throughflow in humid vegetated regions. They then demonstrated application of the model to hydrologic and geomorphic investigations.

It should be noted that, except in rare cases, channel initiation and extension cannot take place without overland flow. By combining aspects of the throughflow model with those of the overland flow model, a more useful and realistic approach to the problem is achieved.

The Random Model and Link Theory

The work of several investigators is related to the proposition of random drainage netowrk development. This concept has evolved since the middle 1960's, primarily through the efforts of Scheidegger (1966, 1967, 1968), Shreve (1966, 1967, 1969), Smart (1968, 1969, 1972a, 1972b, 1973), and their associates.

The basis for the random model of drainage basin composition is reviewed by Smart (1973). Evolution of geomorphic features such as channel networks involves many complex and interrelated processes. As a result, many variables are necessary to specify even the smallest systems; the initial states are generally unknown and are often stated as an assumption upon which subsequent reasoning is based. Therefore, it seems that exact predictions of basin developments are not possible. Proponents of the random approach suggest that, instead of trying to predict geomorphic properties precisely, they should be regarded as random variables drawn from specified populations. Consequently, if the population distribution can be defined or estimated, certain predictions may be permitted by statistical inference at a given level of confidence or probability of occurrence. This will also permit testing of hypotheses relating to the equality of theoretical and observed networks.

The keynote for the random approach was given in a paper by Shreve (1966) in which, according to Smart (1972a) he 1) first introduced the concept of a topologically random population of channel networks; 2) gave formulas for the relative probability of different sets of stream numbers in such a population, 3) showed that the most probable networks conform to Horton's law of stream numbers, 4) proposed that in the absence of geological controls a natural population of channel networks will be topologically random, and 5) tested this hypothesis by showing that sets of stream numbers from natural networks can be drawn from a topologically random population. Most subsequent studies on random theory have involved explanation of previously reported phenomena and empirical relationships observed in natural basins, and expansion of various predictive and statistical aspects of this approach by using link data. A good discussion of the development of this approach and its present capabilities is found in Smart (1972a, 1973).

In the present study, various proposed probability distributions were not compared with the observed data, because this correlation in general (Smart, 1972b), and in Indiana in particular (Lee and Delleur, 1972) has already been demonstrated. The possibility exists, however, that the fit of the study basins may be less satisfactory owing to their small size (see Smart, 1973). However, other characteristics seem compatible with the random model and link theory.

Shreve (1966, p. 32) presents, in tabular form, the probability of obtaining a drainage network of order Ω if given various numbers of first-order streams (N_1). This table indicates that, according to the random model, at some value of N_1, between 75 and 100, the order of the most probable network changes from 4 to 5. Data for the present study reflect an identical situation. In the same paper, Shreve also indicates various values of bifurcation ratio expected for given N_1, Ω, and $p(N_1; \Omega)$ values, and concludes that the most probable network order is that which makes the geometric mean R_B closest to 4. These relationships are in relatively close agreement with our observations as summarized in Tables 2-8. Additionally, the mean R_B values for all basins in 1938 and 1968 were 3.98 and 4.01 respectively. These, in turn, are in agreement with the value of 4.008 obtained by Ranalli and Scheidegger (1968) for the Wabash River.

Shreve (1967, p. 182) also states that the probability $s(u)$ of drawing a Strahler stream of order u at random from the streams comprising an infinite topologically random network can be obtained from the following:

$$s(u) = 3/4^u, \qquad u = 1, 2, 3, \ldots..$$

A comparison of these probabilities with the frequencies observed in our study basins is given in Table 9 and shown graphically in Figures 22 and 23. Obviously the agreement is excellent and lends support to the theoretical distribution. Note that in nearly every instance adjustments in drainage composition that occurred between 1938 and 1968 resulted in less discrepancy between the theoretical and the observed values. Perhaps this represents a trend toward a more probable or equilibrium condition.

Table 9. The probability of drawing a stream of order u from the random population of streams and the observed frequency of stream segments in the average fourth- and fifth-order basins of the study sample.

Order	Theoretical Probability	Observed Frequency Fourth-Order Basins		Fifth-Order Basins	
U		1938	1968	1938	1968
1	0.75	0.7347	0.7444	0.7303	0.7306
2	0.1875	0.2143	0.2000	0.2079	0.2066
3	0.0469	0.0408	0.0444	0.0449	0.0480
4	0.0117	0.0102	0.0111	0.0112	0.0148
5	0.0029			0.0056	0.0037

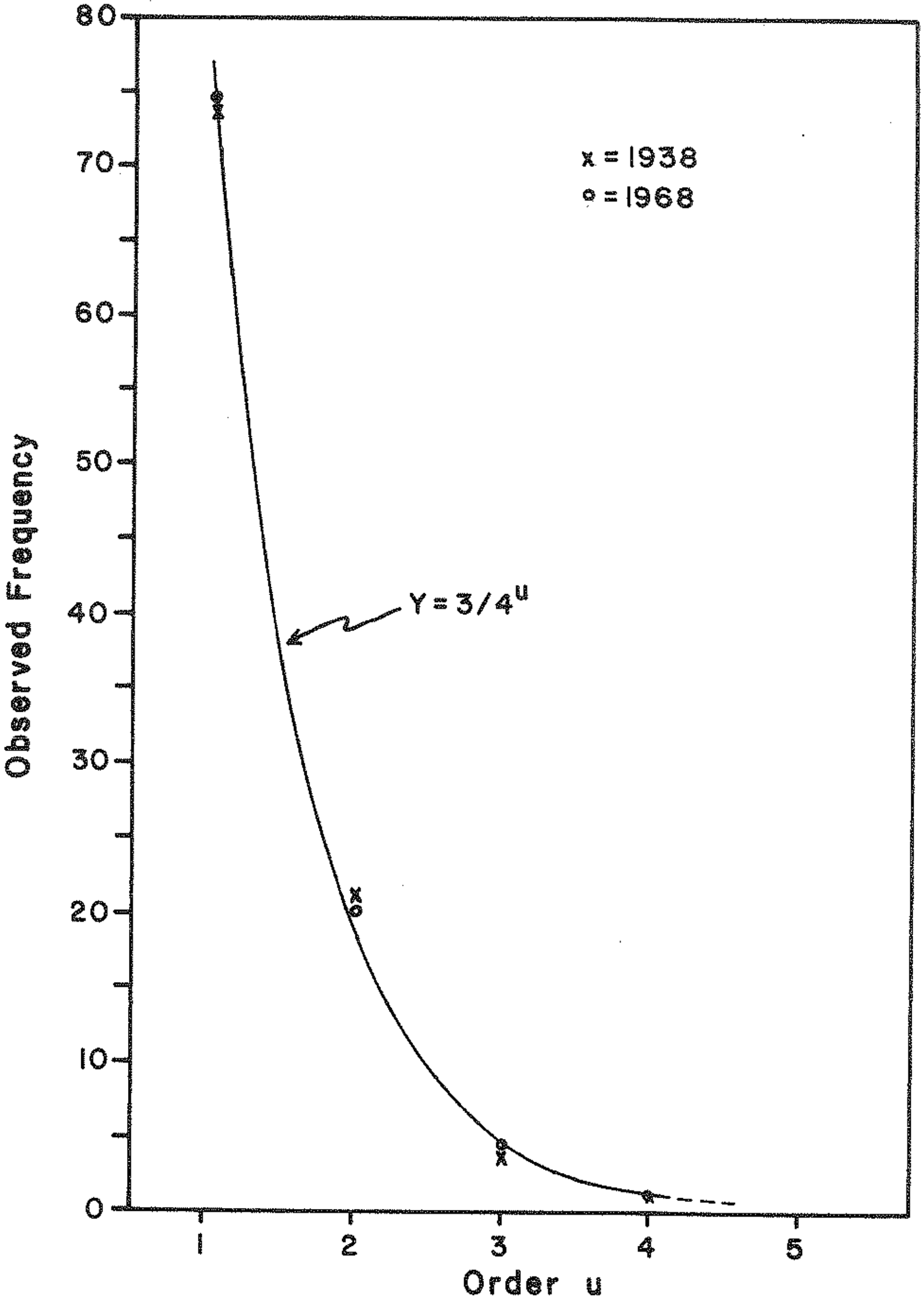


Figure 22. Relationship between observed frequency of stream segments of order u in the average fourth-order basins and the probability ($3/4^u$) of drawing a stream of order u from the random population of streams.

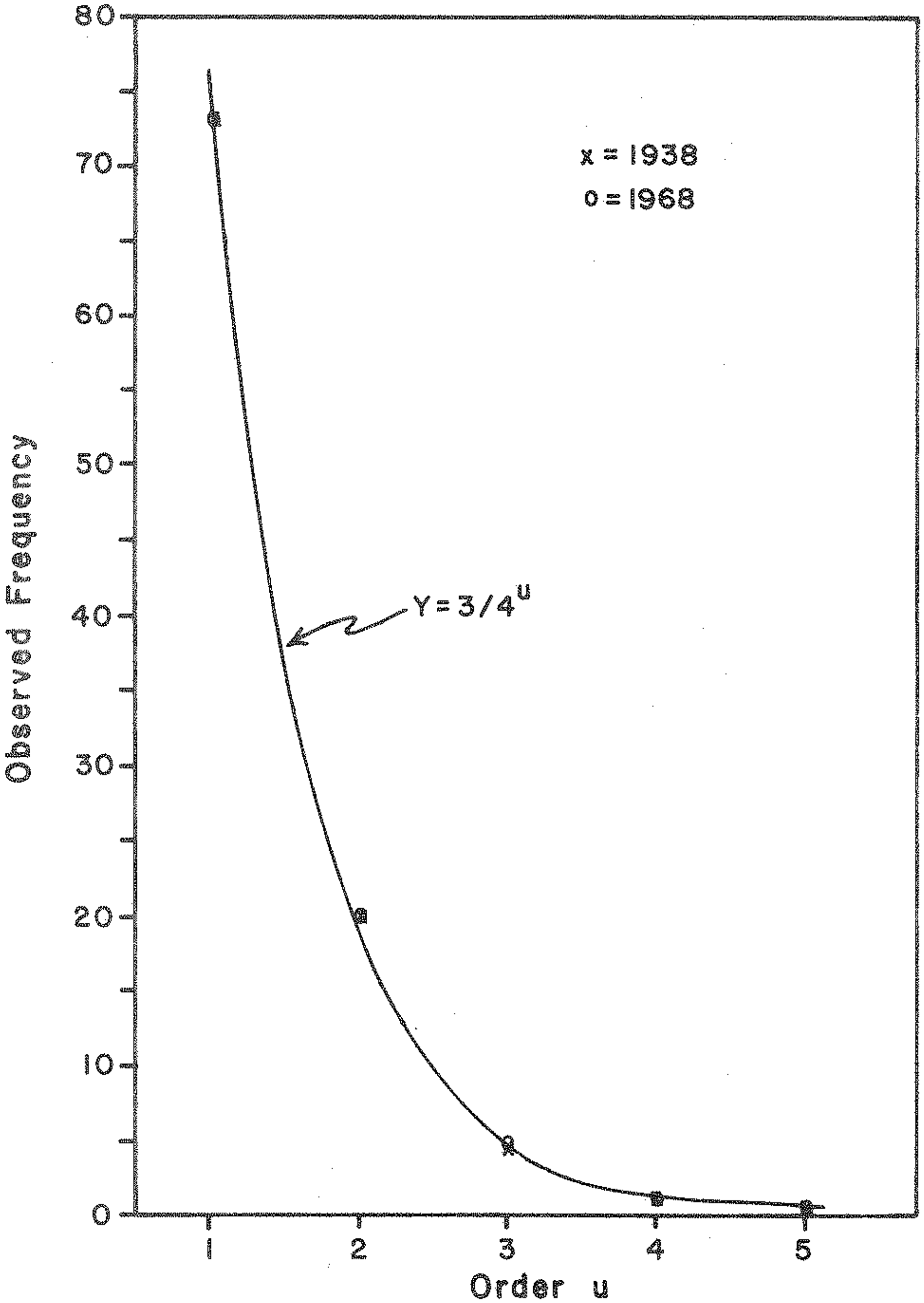


Figure 23. Relationship between observed frequency of stream segments of order u in the average fifth-order basins and the probability ($3/4^u$) of drawing a stream of order u from the random population of streams.

Coffman, et.al. (1972) considered the relationship between the numbers of Shreve links and Strahler stream segments, as well as other topological properties and possible threshold boundaries of channel networks. Applying regression analysis to more than 100 data points, these authors determined that the number of links (Y) is related to the number of segments (X) by the equation

$$Y = 1.28\ X^{1.04}$$

which accounted for 98 percent of the data variability ($r = 0.99$). Table 10 indicates that this relationship was capable of predicting the number of links from the observed number of segments, with a maximum error of 14% and an average error of less than 9%. The predictive ability of the relationship may in actuality be even better than indicated in the application cited.

In development of the topologically random network procedure, Shreve (1967, p. 178) assumed that one, and only one, path exists between any two points, and that at its upstream end each link either connects to two other links or terminates in a source. In other words, no confluence of more than two channels at a single point was permissible. This appears to be generally true in natural networks. Consequently, if more than two links join at a point on a work map, to comply with the original assumption this condition should be rectified by mapping at a larger scale, adjusted by field examination, or eliminated by a judgement by the investigator. In the present study, none of these actions was taken. As a result, the basic acknowledged facts--that every network with x sources will have 2x-1 links, in which x

Table 10. A test of the equation $Y = 1.28 X^{1.04}$ where Y is the number of links and X is the number of segments as proposed by Coffman, et. al., 1972.

Basin	X	Predicted Y	Observed Y	ΔY	% Error
1-38	93	143	132	11	7.6
1-68	83	127	114	13	10.2
2-38	128	199	178	21	10.6
2-68	109	168	158	10	5.9
3-38	74	113	107	6	5.3
3-68	78	119	117	2	1.7
4-38	181	285	255	30	10.5
4-68	291	467	412	55	11.8
5-38	174	274	235	39	14.2
5-68	250	399	366	33	8.3
$\bar{4}$-38	98	151	139	12	7.9
$\bar{4}$-68	90	138	130	8	5.8
$\bar{5}$-38	178	280	245	35	12.5
$\bar{5}$-68	271	434	389	45	10.4

are exterior links and x-1 are interior links--do not apply to the link data of the present study. As a result of the mapped multiple junctions, fewer interior links were recorded than actually exist. This is indicated in Table 10, where the predicted number of links is greater than the observed in every case, a situation which adds further credence to the accuracy of the predictive equation.

All these examples indicate the general applicability of the random model and Shreve link relationships to the drainage basins in question. However, not all aspects of his analytical approach were equally accurate in describing and predicting characteristics in our study. Of particular note is the inability of the model to reproduce the length and area relationships of the study basins. Shreve (1967) reasoned that on the basis of link and segment distributions and assuming that all links have the same length, the stream length ratio is 2 and the cumulative length ratio is 4. The present data indicate that several individual length ratios between successive stream orders are indeed close to 2, but overall are extremely variable within individual basins. Furthermore, cumulative-length ratios obtained for each basin approach an average value of 3.

Smart (1968) also derived a method for determining individual length ratios within a basin, based essentially on the set of stream numbers. This is a very appealing idea, because network length data are more difficult to obtain and generally show more variability than the number of drainage components. Approximations for individual stream length ratios (Smart, 1972a, p. 352) are as follows:

$$\lambda_2 = \left[(N_1 - 1) / (2N_2 - 1)\right] (\ell_i / \ell_e)$$

and

$$N_u = (N_{u-1} - 1)/(2N_u - 1), \qquad u = 3, 4, \ldots, \Omega$$

where λ is the length ratio approximation, N_u is the number of segments of order u, ℓ_i and ℓ_e are the mean length of interior and exterior links, and Ω is the basin order. Smart has reported (1968, 1972a, 1973) a high degree of success with this approximation (Figure 24), but it should be noted that an application to only 2 different basins has been reported. This may lead one to question the scope of its general applicability. The relationship between predicted and observed length ratios was found to be very poor in the present study. However, this must be viewed in reference to the possible data interpretation discussed in Chapter 7.

Basic to the random model is the premise that a sample of basins is random, and therefore is representative of a population of topologically random networks developed in the absence of geologic control. If the sample is not random and sample basins have been influenced by geologic or other controls, such as those by man, then the sample should not be expected to conform precisely to the postulates of the random model. Clearly, the basins discussed herein do not qualify as a totally random sample owing to limitations imposed by the actual data sources. Additionally, several lines of evidence indicate that these same basins may have experienced adjustments directly attributable to human activity (see Chapter 7). Therefore, the lack of exact correspondence between observations and predictions based on the described assumption must not be interpreted as conclusive evidence against this theoretical approach. On the contrary, the demonstrated applications just related may indicate the possibility of a broader utility then originally assumed by the

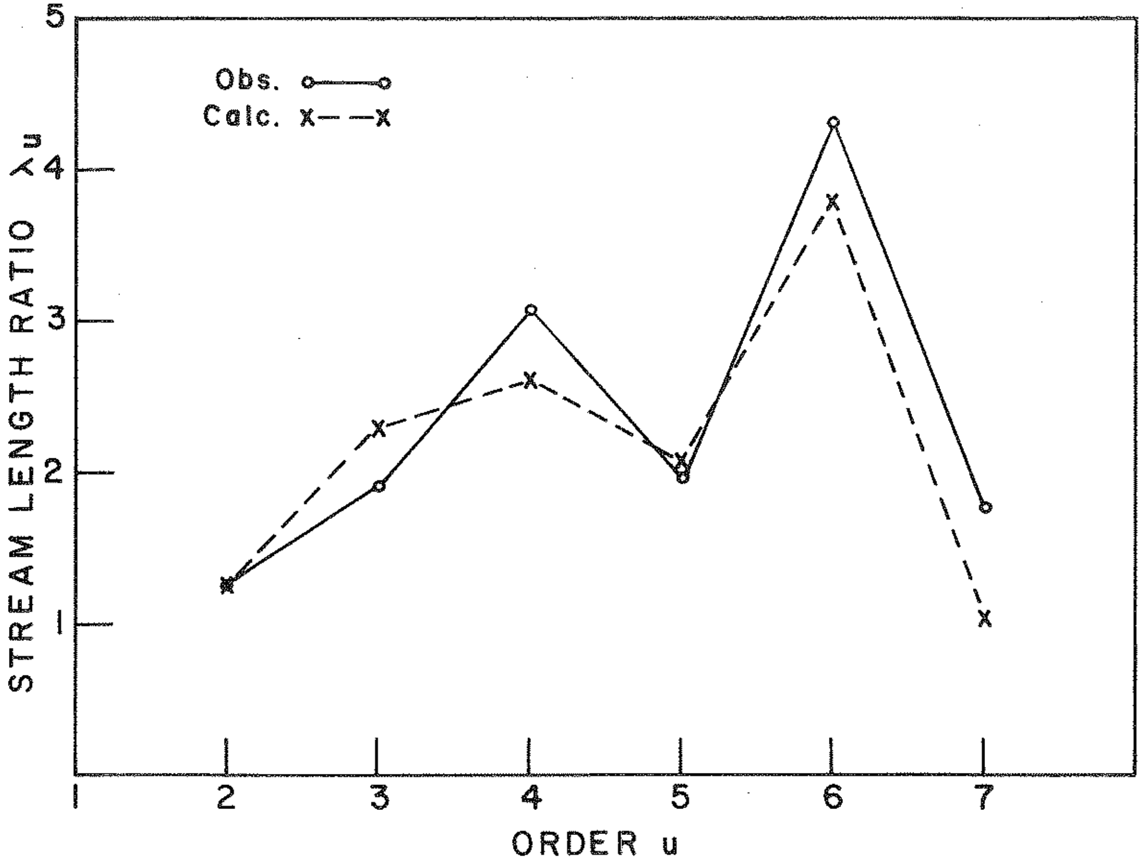


Figure 24. Observed and calculated stream length ratios for Old Man Creek, Iowa (from Smart, 1973).

proponents of this approach.

Mixed Hexagonal Hierarchies

Concepts of allometric growth and mixed hexagonal hierarchies have been proposed and tested in a series of publications by Woldenberg (1966, 1969, 1971). Earlier work of Christaller (1933) showed that both tree-like hierarchies and central place systems appear to follow the same spatial laws, so that a number of streams or a number of towns both form an inverse geometric series with order. Because of this apparent relationship between stream orders and hierarchies of market places and towns, Woldenberg argued that modelling on the basis of a mixed hexagonal hierarchy is more appropriate for stream networks than the stochastic or random model.

The basis for this model is the assumption of nested hierarchies of hexagonal basin areas. Both Christaller (1933) and Losch (1954) recognized that a circle is the most efficient geometric shape in terms of accessibility to the center. Because circles cannot be packed in space without leaving interstices, hexagons are the shapes which permit closest packing, meanwhile maintaining accessibility to the center. Thus, it is reasoned that a minimum work situation can be achieved only where all areas are hexagonal (Woldenberg, 1969, p. 99).

Obviously, natural terrain features do not appear as regularly shaped hexagons. It is argued that a variety of distortions occur, because of heterogeneity of materials and environment and the influence of varying energy expenditures. As a result of these factors, the surface adjusts its shape in response to physical work exerted by erosive forces. Woldenberg (1969, p. 99) then conjectures that the physical surface apparently is a spatial transformation of a "flat" surface, and that the flatness is one in which the work done over each unit area is as constant as possible.

Woldenberg is further able to show that a given hexagonal area may be divided into 3, 4, or 7 smaller hexagonal areas (Figure 25), depending upon nodal configuration. This hierarchical system is analogous to the nesting of stream segments and drainage areas based on order in that every segment or basin of order u is composed of at least 2 segments or basins of order u-1 and so on. Woldenberg (1969, p. 101) points out that, if the area ratio (R_A) is less than 3, the total available space can not be filled with hexagons and R_A can not exceed 7, because streams would eventually join and create higher-order basins. Thus, physical limits of 3 to 7 are established for natural bifurcation ratio, because 3, 4, 5, 6, or 7 hexagonal areas or streams may be present in one area before combination and order increase is dictated.

Based upon previous work involving the central place theory, Woldenberg showed that the geometric series to the bases of 3, 4, and 7, when mixed together in order of increasing magnitude, form an approximate geometric series. Given this array of numbers (Table 11), it is necessary only to know the number of first-order basins (equivalent to the number of first-order stream segments) and the number of orders to deduce the number of basins or segments per order for the rest of the system. This procedure involves grouping consecutive numbers from the array in Table 11 for each order, so that all group geometric means form a geometric

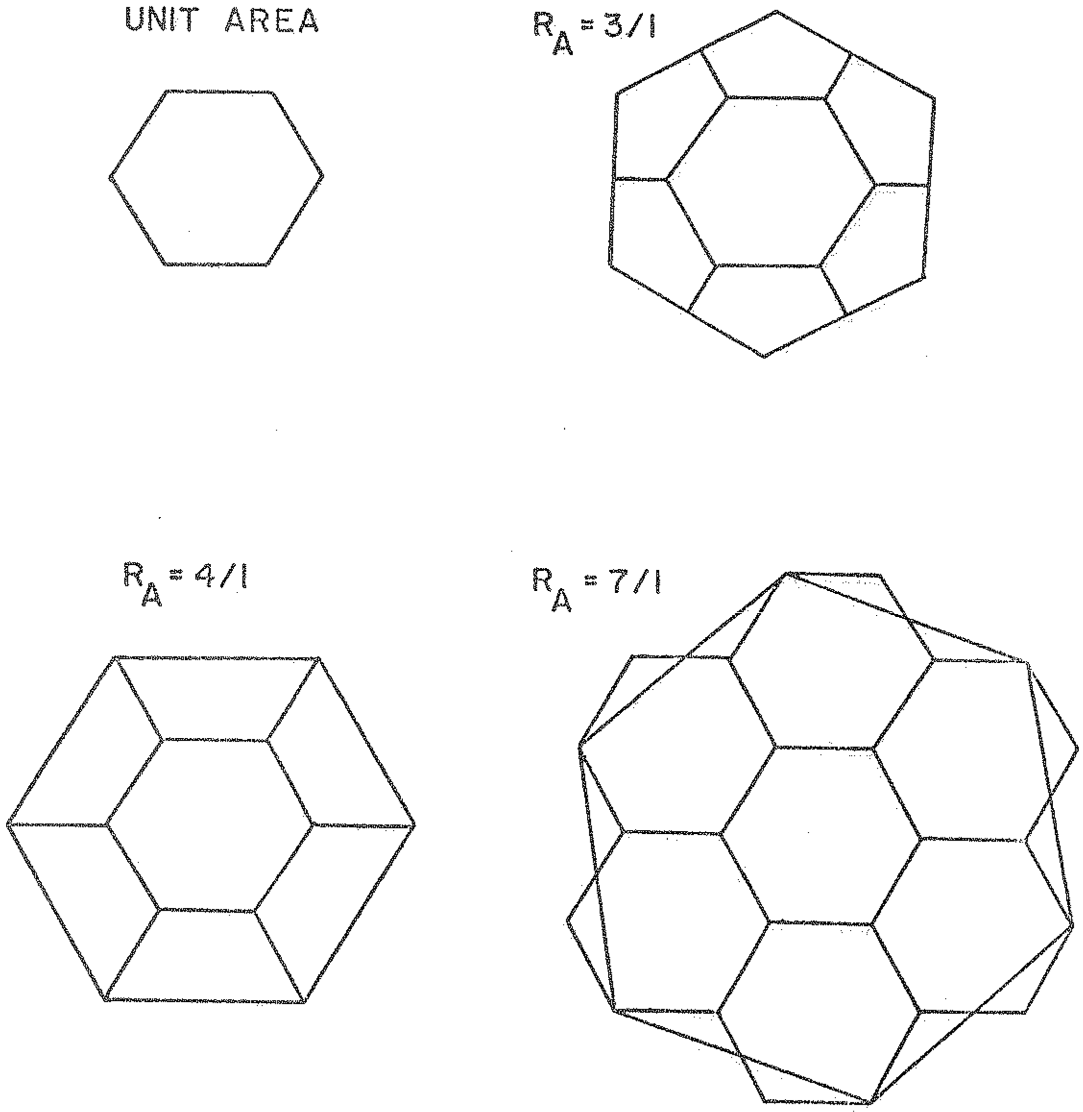


Figure 25. Mixed hexagonal hierarchies with ratios of 3, 4, and 7 unit areas.

Table 11. Geometric progressions to the bases of 3, 4, and 7.

$R_A = 3$	$R_A = 4$	$R_A = 7$
1	1	1
3	4	7
9	16	49
27	64	343
81	256	2401
243	1024	16807
729	4096	etc.
2187	16384	
6561	etc.	
etc.		

progression as closely as possible. After selecting appropriate groups, a convergent mean (point of convergence between the arithmetic and geometric means) for the group is calculated. This convergent mean gives a good fit to the data representing the number of stream basin areas or segments per order. For complete details on the above procedures, the reader is referred to Woldenberg (1969).

To test the applicability of the mixed hexagonal hierarchy theory to the sample of study basins, the procedures outlined by Woldenberg were applied to the average fourth- and fifth-order basins. The degree of correlation between the observed number of segments of each Strahler order and hexagonal theory approximations is shown in Table 12. Agreement between the two sets of values is obviously quite good. This is therefore interpreted as providing additional corroborative evidence for the validity of the hexagonal hierarchy concept.

This concept is very intriguing because of the apparent commonplace occurrence of the hexagon in other areas of geology (mud cracks, columnar jointing, permafrost and periglacial features, crystal structures, etc.). Within the confines of fluvial geomophology, the hexagonal concept has possible interpretative value in relation to energy expenditure and equilibrium considerations. Woldenberg (1969, p. 103) reasons that the arithmetic mean of a group is a large number, and therefore its reciprocal is small. Therefore areas associated with the arithmetic mean are small, and overland work in movement to the channel is minimized. Conversely, the geometric mean of a group is a smaller number and has a larger reciprocal; thus areas and flows within channels associated with the geometric mean are large. This leads to gains in channel

Table 12. Application of convergent mean model to the average fourth- and fitth-order study basins (after Woldenberg, 1969).

Order	No. of segments	Groups	Convergent mean
		Basin $\bar{4}$-38	
4	1	1,1,1	1
3	4	3,4,7	4.52
2	21	9,16,27,49	23.03
1	72	64,81	72.25
		Basin $\bar{4}$-68	
4	1	1,1,1	1
3	4	3,4	3.48
2	18	7,9,16,27	16.53
1	67	49,64,81	64.00
		Basin $\bar{5}$-38	
5	1	1,1	1
4	2	1,3	1.87
3	8	4,7,9,16	8.48
2	37	27,49	37.19
1	130	64,81,243	117.97
		Basin $\bar{5}$-68	
5	1	1,1,1	1
4	4	3,4	3.48
3	13	7,9,16,27	13.76
2	56	49,64	56.25
1	198	81,243,256	183.05

efficiency, because the wetted perimeter increases at a much lower rate than does the volume of flow. In other words, the arithmetic mean economizes overland work but loses economy of scale, whereas the geometric mean accomplishes just the opposite. Woldenberg concludes that the convergent mean is a least work equilibrium condition between these nadirs. This conclusion is closely related to attempts made by other investigators to explain fluvial systems on the basis of energy expenditure (see Langbein and Leopold, 1964; Leopold and Langbein, 1962; Yang, 1971).

If the hexagonal hierarchy hypothesis can be demonstrated as valid in a variety of geologic and geographic settings, very useful predictions will be possible. The present stability state of a drainage basin can be inferred and, as a result, future adjustments predicted as the basin develops toward an equilibrium condition. Results of our study indicate that Woldenberg's concept of watershed composition is valid for at least some streams in Indiana, and that an equilibrium condition is not a prerequisite for selecting the study basin.

Equilibrium and Stability

For several years, geologists and engineers have reasoned that there must exist some condition in rivers in which an equilibrium is attained between the various independent and dependent variables. Engineering studies of regime conditions by Kennedy, Lacey, Inglis, Lane, Blench, and many others have attempted to define this condition in both natural and artificial waterways. Similarly, in geology such concepts as grade (Mackin, 1948), quasi-equilibrium (Langbein and Leopold, 1964), entropy (Leopold and Langbein, 1962), rates of energy expenditure (Langbein and Leopold, 1966; Yang, 1971), and dynamic equilibrium (Hack, 1960) have been presented to define this nebulous condition. To define and predict channel adjustments, a presumed condition of equilibrium is often invoked. Because these concepts involve considerations of time, we are again faced with the problem of crossing temporal boundaries and the complexities alluded to previously (see Table 1).

If the problem of stability is extended to an entire drainage basin, the degree of indeterminancy increases because of the increased number of variables necessary to define the system. Both the random and mixed hexagonal hierarchy models relate to the question. The most probable condition and the attainment of Woldenberg's geometric series in basins are undoubtedly closely associated with equilibrium. Further examination of this problem is given below and tested against the observations of the present study, where possible.

Melton (1958) reported on a study of the geometric properties of more than 150 "mature" drainage basins. The basins were selected on the basis of maturity of dissection, lack of extensive gullying or channel trenching, and absence of features attributable to structural control of channel positions. Quoting Melton (1958, p. 36), a mature drainage basin is one "whose every channel has developed a watershed with smooth slopes extending to the divide." He further states that

> "A formerly mature basin whose channel net has expanded by gullying of old valley-side slopes is no longer mature because there exist channels without watersheds having smooth slopes to the divides. Likewise, a formerly mature basin, many of whose channels have ceased to erode or

> even transport debris, is no longer mature because watersheds with smooth slopes exist where there is no longer need for a channel."

These statements, although implying some sort of stable or equilibrium condition, clearly limit the base of application of his results. In view of network adjustments witnessed in the basins currently under consideration, it seems they would not fit the above definition of a mature basin, and consequently not be expected to rigorously comply with Melton's conclusions. However, two results of his study are of possible interest and were therefore examined.

Realizing that commonly several streams of order u joined streams of order u+1 or greater, Melton noted that these "extra" channels, though necessary to drain the area adequately, are not connected most efficiently to produce higher-ordered channels. In an attempt to account for this condition, Melton (1958, p. 44) defined a "conservative" drainage system as one "having the minimum number of channel segments necessary for the highest order of the system." He proposed as a measure of the conservancy for any order u

$$S_u = \frac{N_u - 2(N_{u+1})}{2(N_{u+1})} = \frac{R_{B\ u:u+1}}{2} - 1$$

where $R_{B\ u:u+1}$ is the bifurcation ratio for channels of order u+1. When $S_u = 0$, a condition of maximum conservancy is indicated. This conclusion appears straightforward, and the equations can easily be derived on the basis that maximum conservancy is approached as bifurcation ratio approaches the minimum value of 2. However, an application of this relationship to the current data indicates that the concept is not infallible.

Table 13 contains conservancy values obtained by the preceding equation, and gives information on numbers of "lost" segments and percentage of the total network in this category for the third- and fourth-order averages. It is logical that if a network, or for that matter a given order level within a network, is more conservative as defined by Melton, it will contain fewer "lost" segments or the "lost" portion of the network will comprise a smaller percentage of the total network than one which is less conservative. Data in Table 13 indicate that, at least in this particular case, these relationships do not hold. It is not clear in the text of Melton's paper if this test can only be applied to basins which adhere to his definition of maturity, although this is probable. If this is the case, then the discrepancy is perhaps due to an application to non-mature basins. Another possiblity lies in the fact that the number of "lost" streams is the number of segments not included in the Horton Net. It should be recalled that the Horton Net does not include segments of order less than u-1 that are directly tributary to segments of order u. However, with this criterion, any number of segments of order u-1 can be included, not just 2 as Melton's definition of maximum conservancy implies. Therefore, although the number of "lost" segments and conservancy as defined by Melton are intimately related, they are not directly analogous. Consequently, the data in Table 13 do not disprove the validity of the conservancy equation, but they do cast some doubt as to its utility in presenting the information for which it was developed.

In addition, Melton (1958, p. 36) demonstrated that channel segment frequency, F, (the number of segments per unit area), and drainage density, Dd, (the total length of channels per unit area) are closely

Table 13. Conservancy and "lost" stream data for the average fourth- and fifth-order study basins.

Order	Conservancy (S_u)		No. "lost" segments		% of the network "lost"	
u	$\bar{4}$-38	$\bar{4}$-68	$\bar{4}$-38	$\bar{4}$-68	$\bar{4}$-38	$\bar{4}$-68
1	0.71	0.86	35	32	48.6	47.8
2	1.63	1.25	9	6	42.9	33.0
3	1.00	1.00	0	0	0	0
4	-	-	0	0	0	0
	Σ = 3.34	3.11	44	38	44.9*	42.2*
	$\bar{5}$-38	$\bar{5}$-68	$\bar{5}$-38	$\bar{5}$-68	$\bar{5}$-38	$\bar{5}$-68
1	0.76	0.77	62	106	47.3	53.3
2	1.31	1.15	13	23	35.1	41.1
3	1.00	0.63	0	2	0	15.4
4	0.00	1.00	0	1	0	25.0
5	-	-	0	0	0	0
	Σ = 3.07	3.55	75	132	41.6*	48.3

*Percent of network lost for entire network = $\frac{\text{Total number of "lost" segments}}{\text{Total number of segments}}$

related (r = 0.97) as defined by the equation

$$F = 0.694\ Dd^2$$

which is dimensionally balanced. Furthermore, this relationship has been observed by other investigators. By application of the random model (see Smart, 1973), the relation

$$F/Dd^2 = 2/3$$

can be derived. This is obviously quite similar but theoretically derived, whereas the former equation is empirical. One may therefore assume that this relationship represents some equilibrium condition between the number and length of channel segments per unit area. Figure 26 shows the line representing the inferred equilibrium relationship, and the trend of adjustments in F and Dd shown by the average fourth- and fifth-order basins from 1938 to 1968. It is interesting that, although the data points are displaced from the regression line, the trend lines are essentially parallel to one another as well as to the line representing the equation. This substantiates Melton's (1968, p. 39) reasoning that the image point of a basin undergoing a drainage density transformation will follow a path "essentially parallel to, and perhaps collinear with" the regression line. This also supports the contentions of Smart and Shreve that a definite and predictable relationship exists between the number and length of streams. On the basis of Figure 26 and other data to be presented, certain predictions, although only first approximations, can be made about the stability of the study basins in 1968 and their potential adjustments thereafter.

Another means of gaining insight into the stability of a drainage

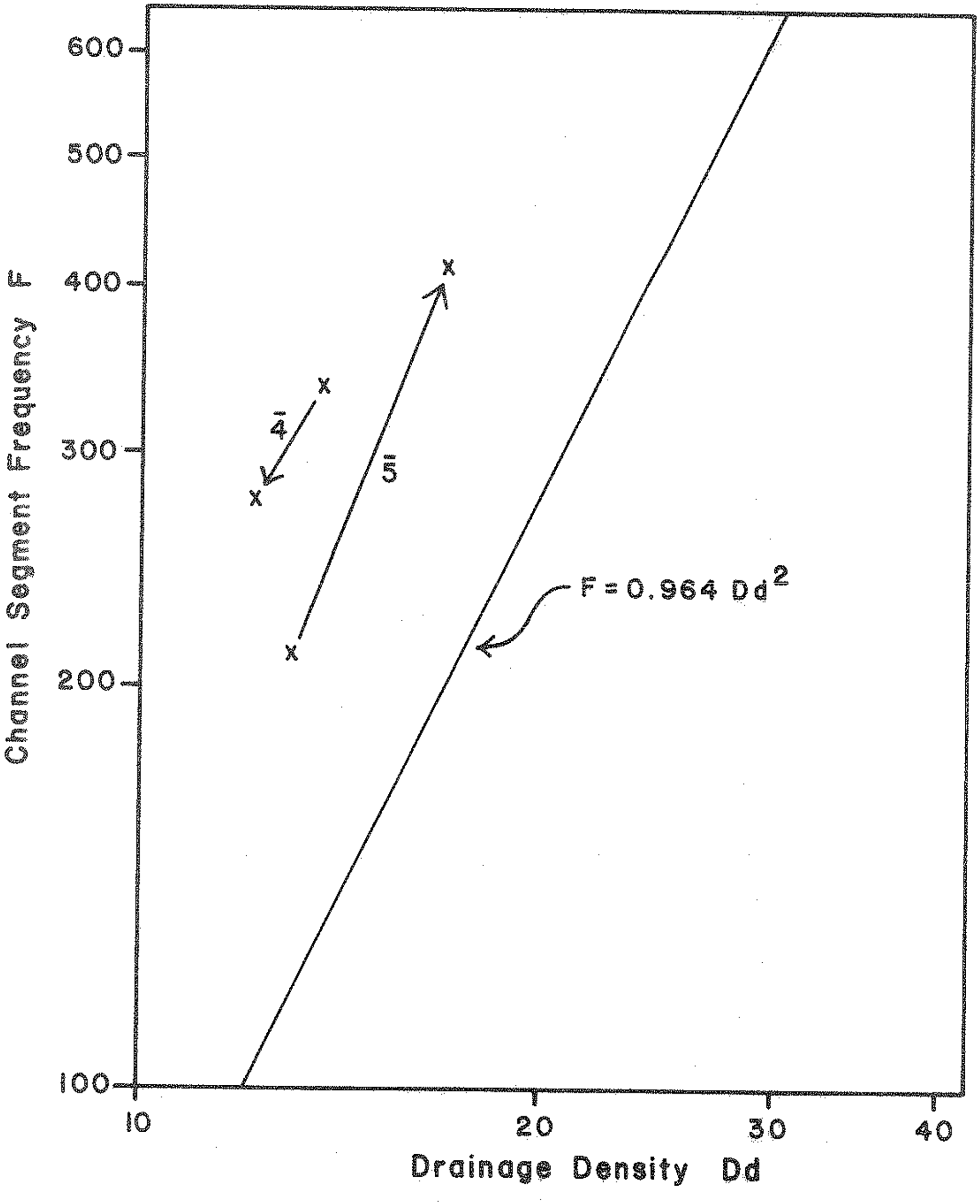


Figure 26. Relationship between channel segment frequency and drainage density as proposed by Melton (1958). Lines between data points indicate direction and magnitude of change in the average fourth- and fifth-order basins studied.

basin has been presented by Coffman (1972). It will be recalled that Coffman and Melhorn (1970), recognizing the weakness of the bifurcation ratio owing to the influence of "lost" stream segments, proposed the division ratio as a substitute measure by utilizing only the Horton Net portion of the channel network. From an examination of the R_D values of several basins formed on the Tipton Till Plain, Coffman (1972, p. 86) concluded that the division ratio remains constant for a given lithology and has a value of 3.0 for basins developed in glacial till. The results of the present study are in agreement with this observation, as the mean value of R_D for all of the study basins was 3.13 for both 1938 and 1968 data.

Expanding upon the concept of absolute stream order suggested by Woldenberg (1966), Coffman (1972, p. 139) determined that streams in northern Indiana developing in glacial till show a consistent correlation between Shreve magnitude (M), which is equivalent to the number of first-order streams, and the Strahler order of the network (Ω). This relationship is described by the equation

$$M = {R_D}^{\Omega-1} = U_A$$

where R_D is the division ratio and U_A is the absolute stream order. Once R_D has been determined, the magnitude of any segment can be compared with the theoretical value of U_A. According to Coffman (1972, p. 142) if U_A is equal to M the segment is in equilibrium, if U_A exceeds M the segment is underdeveloped, and if M exceeds U_A the segment is overdeveloped. From this information, the topological evolution of a segment can be predicted.

> "A segment in equilibrium will be expected to maintain its present topology until lengthening of one or more

> segments exceeds reasonable limits. Underdeveloped segments will be expected to bifurcate in such a way that the magnitude increases without increasing the Strahler order of the segment. Overdeveloped segments will be expected to bifurcate in such a way that the Strahler order is increased thus increasing the calculated value of U_A and restoring equilibrium." (Coffman, 1972, p. 142-43).

The method just described was applied to the basins of this study, the results of which are shown in Table 14. Those changes which represent a change toward a better adjusted or equilibrium condition are starred (*). The data indicate that, on the basis of Coffman's predictive method, 16 of 36 (about 45%) of the possible adjustments toward equilibrium were predicted. The fact that more changes in this direction were not observed does not necessarily represent shortcomings in the method. As a conclusive test of the method's accuracy, it should be applied to basins which are known to have experienced no major changes in the systems input for an adequate period of time. This condition cannot be demonstrated for the basins currently under consideration and, in fact, the opposite situation appears more likely as will be shown in the following chapter. Consequently, it is possible that, owing to various external influences, these basins may be in a state of disequilibrium and have not had the necessary time of response to establish a new and stable condition. This general trend is indicated in Table 14. Additionally, data contained in the table represent the most complete adjustments involving order changes over the 30-year period. These figures do not reflect smaller drainage terminations and additions in the adjustment process which did not produce changes in the order structure. It should be noted that several such cases were observed. With reference to these qualifications, this predictive methodology appears sound.

Table 14. Topologic stability of the study basins as predicted by the method proposed by Coffman (1972).

Order	1-38	1-68	2-38	2-68	3-38	3-68	4-38	4-68	5-38	5-68
1	-	-	-	-	-	-	-	-	-	-
2	6 U	6 U	9 U *	4 U	4 U *	2 U	9 U	24 U	17 U *	12 U
	2 0 *	1 0	5 0 *	4 0	2 0	2 0	2 0	5 0	4 0	8 0
	4 = *	6 =	5 = *	9 =	0 = *	1 =	7 = *	9 =	9 = *	7 =
3	3 U *	2 U	3 U *	1 U	1 U	1 U	4 U	5 U	5 U	5 U
	1 0	2 0	2 0	2 0	1 0	1 0	3 0 *	2 0	4 0	4 0
	0 =	0 =	1 = *	2 =	0 =	0 =	0 = *	4 =	0 = *	1 =
4							1 U	2 U	1 U	2 U
							1 0	2 0	1 0	1 0
							0 =	0 =	0 =	0 =

*Indicate a change within a network toward an equilibrium condition.

U - Underdeveloped 0 - Overdeveloped = - Equilibrium

According to Coffman, the adjustments mentioned represent a determination of the topology of growth. In addition, Coffman (1972, p. 140-42) presented a means to determine the potential for growth based upon the concept of the unit hexagon and hexagonal hierarchies of Woldenberg. If drainage area (A) and total length of channels (L_T) are known, then the existing drainage density (Dd) can be computed by the equation $Dd = L_T/A$. If the area of the unit cell or unit hexagon (a) can be determined for the surface material of the basin, then the maximum length (ML_T) of all channels, representative of complete dissection of the drainage area, can be calculated as follows:

number of unit hexagons in basin = $n = A/a$

maximum channel length = $ML_T = (3)\ (n)\ (R)$

where R = radius of an inscribed circle in a regular hexagon. Therefore, the maximum drainage density possible within the given drainage area can be obtained by

$$Dd_{max} = ML_T/A$$

The degree of dissection which has occurred within the basin is equivalent to the ratio Dd/Dd_{max}. From this relationship, it may be reasoned that the smaller this ratio, the greater is the potential for growth and rapid change.

By application of the Thiessan polygon method and planimeter measurements, Coffman (1972, p. 115) determined that the average size of the unit hexagon was 0.0056 sq mi, and the corresponding radius of an inscribed circle was 0.04 miles. Assuming that these values are accurate and representative of other small basins developing under similar conditions, they can be applied to the study basins. Utilizing this information, the percentage of dissection for the mean fourth- and fifth-order basins was calculated and is presented below.

Table 15

Percentage of dissection for mean fourth- and fifth-order basins

Basin	Dd	Dd_{max}	% Dissection
$\bar{4}$ - 38	13.63	21.43	63.60
$\bar{9}$ - 68	12.21	21.43	56.98
$\bar{5}$ - 38	13.04	21.43	60.85
$\bar{5}$ - 68	16.96	21.43	79.14

These values are in accord with the observations reported in Chapter 5 and appear reasonable on the basis of visual estimation from the watershed maps. However, as in the method for estimating the topology of growth, a certain constancy of basin input, particularly a stable catchment area, is necessary for meaningful results. Because of external influence, a tendency for increased dissection indicated by the low percentage in the fourth-order basins for 1938 was negated by the overall drainage losses, as discussed previously. The utility of these values are also suspect because of the observed changes in drainage area. In other words, based upon the degree of dissection of the fourth-order basins in 1938, it could be speculated that drainage growth and extension, not loss and termination, would predominate in the future. Thus it appears that the two predictive methods presented by Coffman are valid, but should be applied with caution unless one is aware of the status of the external factors influencing basin development.

It should be noted that maximum drainage density is constant for all basins. As the area of a regular hexagon is given by the formula

$a = (6)(R^2)(\tan 30^\circ)$, by substitution into the formula for calculating Dd_{max}, we obtain

$$Dd_{max} = (3)(R)/a = 1/(2)(r)(\tan 30^\circ).$$

It can be seen that Dd_{max} is dependent only upon the size of the unit hexagon because R (radius of inscribed circle) depends upon a. Consequently, after the size of the unit cell is determined, the maximum drainage density is fixed, regardless of the size of the test basin.

Momentarily re-examining the relationship between F and Dd developed by Melton (1958), additional information on stability and possible adjustments in the study basins may be obtained. If it is assumed that the regression line represents the most stable condition, then with time the numbers and/or lengths of channel segments should adjust in such a manner that the basin values of F and Dd approach this condition. This of course requires the assumption that no additional disruptive forces are applied to the adjusting system, especially forces directly influencing the catchment area. In this situation, two possible developmental trends are as illustrated in Figure 27. If the basin environment is such that the number of streams present in 1968 is appropriate, then the segments must lengthen, thereby increasing Dd, and the basin image point will move essentially parallel to the abscissa and toward the regression line. Provided the number of streams remains essentially constant, the fourth- and fifth-order basins should develop toward drainage density values of 19.98 and 24.45 mi/sq mi respectively. It is interesting that the predicted value of drainage density based on the unit hexagon method outlined above (see Table 15) is 21.43 for all

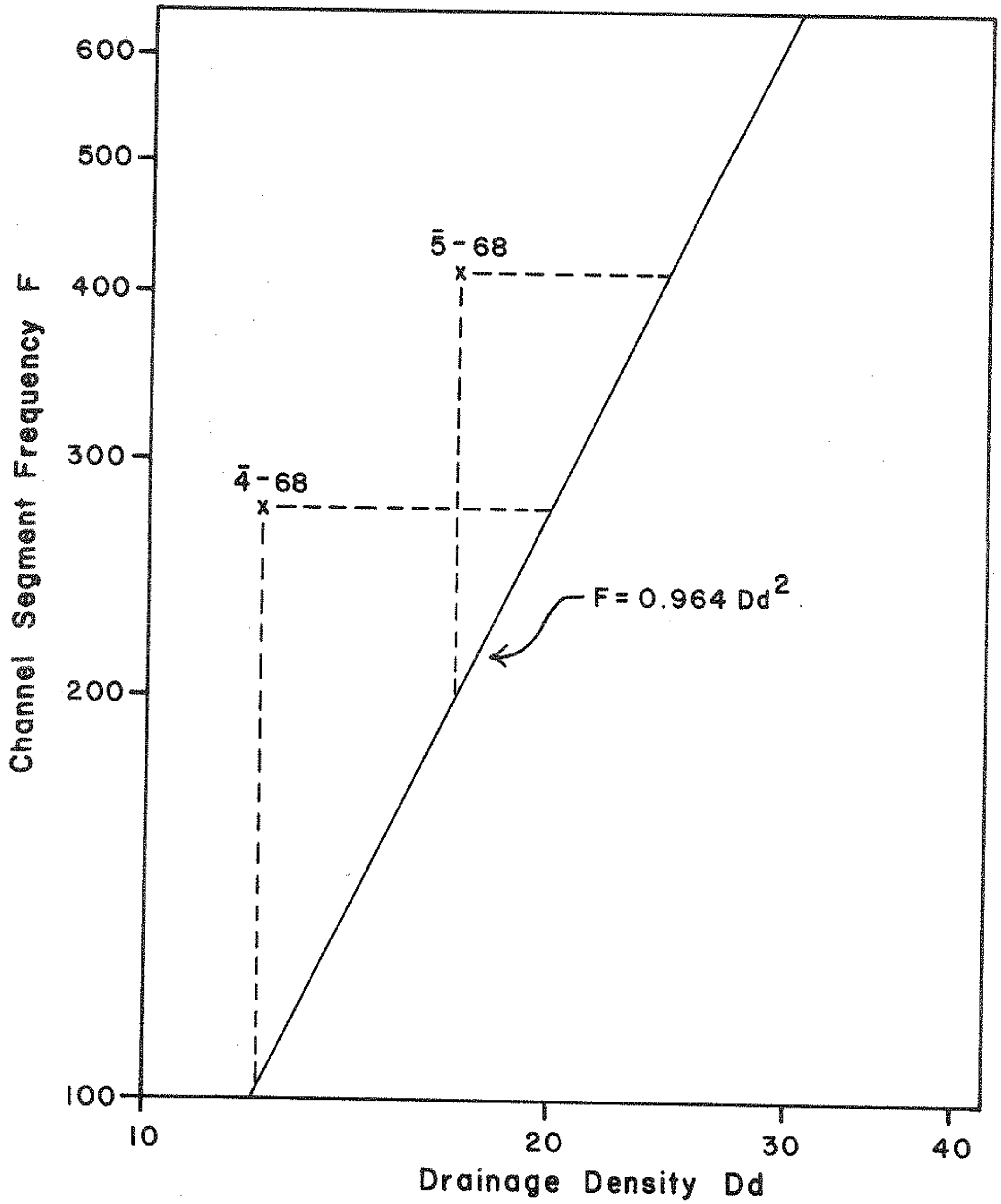


Figure 27. Possible drainage density or channel segment frequency adjustments as basins approach the "Mature" condition.

basins. This observation tends to reinforce both Melton's and Coffman's methods.

On the other hand, if the 1968 values of drainage density are in better adjustment with the basin environment than the segment frequency, then we might expect the values of F to decrease, whereas Dd would remain essentially constant. This requires lengthening of some segments to compensate for the length of channels lost through drainage termination. In this situation, the ultimate values of F would be 103 and 200 per sq mi for the fourth- and fifth-order basins respectively.

Any change in the number of channel segments will affect the length of channels. Furthermore, owing to the limits of channel lengthening imposed by basin boundaries and competition between basins, it is unlikely that significant increases in drainage density can be accomplished without the addition of new segments. Therefore, adjustments toward the hypothetical equilibrium condition would probably be accomplished through simultaneous changes in both F and Dd, and the path would be represented as zig-zag lines in Figure 27 (see Melton, 1958, pp. 38-39).

Summary

This chapter has analyzed some recent theoretical developments in fluvial geomorphology and their possible utility in drainage basin analysis. In addition to briefly relating the major components of these procedures, an effort was made to demonstrate and objectively test their applicability to a small sample of natural basins. Although the results are far from conclusive, they do indicate that all of the methods discussed have some interpretative value, particularly when different approaches are considered conjunctively. It may be inductively reasoned that, if a given hypothesis is applicable to such a small and geographically limited sample, it will also be applicable to larger samples of basins which developed under different conditions. This broader application will permit investigators to place greater confidence on any conclusions drawn from the analysis of a larger sample and to incorporate the influence of additional independent variables.

No conclusions as to the relative merit of one investigator's results over that of another are presented. This task is delegated to the reader. The utility of each approach is in part determined by individual research objectives and the type of information necessary to formulate meaningful conclusions. Upon initial examination the approaches described appear quite diverse; however, the applications in this particular study indicate that all concepts examined are somewhat interrelated and may be used conjunctively to obtain additional information for interpretation.

CHAPTER 7

INTERPRETATIONS OF OBSERVED DRAINAGE CHANGES

Introduction

In Chapter 5 an account was presented of the physical changes which occurred in 30-years time in the study basins. It should be recalled that although many of the measured characteristics remained essentially constant, others underwent significant changes in such a short period of time. In this chapter an attempt will be made to deduce the possible causative influences which provided the impetus for these adjustments. The reader should note that the interpretations that follow are based on inference and are not directly observed because of the method of data collection.

Factors Influencing Temporal Variations of Geomorphic Elements

All physical and biological elements of the natural environment show variability and change from place to place as well as through time. A geomorphologist attempts to determine geomorphic history by considering changes in a given feature through time, or he may make observations of the same type of feature in different areas to ascertain the role of different controlling parameters, with time being of relatively minor significance. The present study involves both time and space considerations because different basins, although geographically restricted, show different adjustments over the observed time interval. Possible causes for such changes may be any one or several of the types discussed in subsequent sections.

Base Level Changes

The concept of base level was lucidly stated by Powell (1875) when he wrote:

> "We may consider the level of the sea to be a grand base level, below which the dry lands cannot be eroded; but we may also have, for local and temporary proposes, other base levels of erosion, which are the levels of the beds of the principal streams which carry away the products of erosion...the base level would, in fact, be an imaginary surface, inclining slightly in all its parts toward the lower end of the principal stream..."

W.M. Davis later used this concept as an integral part of his hypothesized "Cycle of Erosion" as did W. Penck and the proponents of their respective theories of landscape evolution. Although the concept embodies areal lowering of base level as erosion progresses, positive changes may also be accomplished by tectonic activity, isostasy, and sea-level (eustatic) change. Over the years the concept of base level has been used as the causative agent to explain geomorphic response in the evolution of slopes, alluvial fans, pediments, coastal features, and glacial landforms in addition to rivers and drainage basins. In essence, this concept is applicable to the interpretation of practically all geomorphic research.

Climatic Changes

All geomorphic studies that involve considerations of process must include climatic input. As most geomorphic activity is exogenetic, climatic input represents the driving force for weathering, erosional, and depositional agents and processes. As climatic factors change, geomorphic activity changes in rate and/or direction and results in an alteration of landscape elements. Although climatic changes, as well as base level changes, are usually considered long-term transitions, minor fluctuations are capable of eliciting immediate, short-term responses from the geomorphic system. If the scope of the investigation is restricted to a short time period, these minor fluctuations may represent major variation in the independent variables.

As with base level change, it is commonly reasoned that climatic changes are a major influence in controlling the alteration of a variety of landscape elements through time. The role of climate in relation to fluvial systems is discussed by Langbein and Schumm (1958), Schumm (1965, 1968, 1969), and several other geologists and engineers.

Natural Catastrophies

Students of the historical and philosophical development of geology are fully aware of the battles between the two factions of early geologists who advocated either the "catastrophic" approach or the "uniformitarian" approach to geologic inquiry. Most geologists now adhere to the principle of uniformitarianism, meanwhile recognizing the possibility of the occurrence of rare "catastrophic" events which might drastically alter a given portion of the landscape in an extremely brief period of time. In modern terminology we would call these high magnitude, low frequency events and not a catastrophe. However, many people would certainly consider the occurrence of a 1,000-year flood a natural catastrophe, especially those whose lives are markedly disrupted as a direct result.

Wolman and Miller (1960) considered magnitude and frequency of forces in geomorphic processes in terms of the relative amounts of work done on the landscape and in terms of the formation of specific landscape features. Their analyses of sediment transport by various media indicate that a large portion of the "work" is done by events of moderate magnitude, which recur relatively frequently, rather than by rare events of unusually large magnitude. Similarly, they deduce an identical situation in terms of the formation of landscape features. This relationship is supported, but for different reasons, by Dury (1973). In analyzing the 1947 flood on the Ouse River in England, he concluded that it corresponded to the 1,000-year flood. Remarkably, however, no widespread erosion or deposition took place and, as a consequence, no significant geomorphic effects resulted. Conversely, Nixon (1973) reported that geomorphic changes by the 1972 flood on Victoria Creek, Black Hills, South Dakota were quite significant. He observed that the stream valley changed from a small stream meandering on a grass-covered flood plain to a single, straight channel consisting of alternating pools and riffles. This change was accompanied by the removal of 25,000 cubic feet of sediment from the upper channel reaches. Nixon estimated that this event had a recurrence interval of 400 years.

Considering the two extremes described, one is faced with the question, "Why does an extreme event produce dramatic geomorphic effects in one area, whereas in another area an even larger, less frequent event passes through the system and produces essentially no change?" The authors believe that, aside from the influence of different geologic settings, the size and consequently the developmental history of each fluvial system is of primary importance. In the cited examples, the

Ouse River is much larger and consequently has experienced a longer and probably more varied geomorphic history than the much smaller Victoria Creek. This reasoning is based upon the fact that the smaller, fingertip tributaries in a network are less developed and considerably younger than the higher-ordered principal drainage of a system. During development of the larger, older streams, there is opportunity to experience and adjust to severe and rare events, whereas the younger and smaller streams have not had this opportunity. At some time in the past, major disruption may have occurred within these older streams and, through morphologic and dimensional adjustments, they can now transmit an event of equal magnitude without additional adjustment. Obviously other factors such as degree of flood plain development, type and quantity of vegetation, soil development, and sediment properties also relate to the problem. However, all these additional factors are directly or indirectly related to geomorphic evolution of the fluvial system. For example, the basins currently studied are small and relatively young in comparison to the Wabash River. Consequently, they are quite susceptible to major change by rare events. This dilemma may also be examined from the aspect of proximity to threshold conditions.

Threshold Conditions

To explain temporal changes in geomorphic variables, geomorphologists have also turned to the concept of crossing threshold boundaries. The basis of this approach is given by Schumm and Khan (1972, p. 1769) in the statement that:

> "...natural systems may not always respond progressively to altered conditions. Rather, a progressive change may be interrupted by an abrupt and dramatic adjustment as critical erosional and depositional threshold values are exceeded. There are threshold values for sediment movement and for

> the hydraulic characteristics of fluids (Froude and Reynold's numbers) and, therefore, landscape components (streams and hill slopes) should be expected to behave similarly."

The threshold concept has been successfully applied to channel pattern and morphology changes (Leopold and Wolman, 1957; Schumm and Khan, 1972; and Edgar, 1973). Additionally, Schumm (1973) presents strong arguments for the existence of threshold values in reference to discontinuous gullies, cut and fill sequences, terrace levels, and drainage basin evolution in general. In the same paper, Schumm (1973, p. 303) reasons that the proximity of valley slope to a threshold will in part determine the channel response to a major flood event. Noting that major floods have destroyed the flood plain of the Cimarron River (Schumm and Lichty, 1963), whereas equally large events have not significantly altered the Connecticut River (Wolman and Eiler, 1958), Schumm concludes that an explanation of the conflicting evidence requires further consideration of the threshold concept.

Influence of Man

The role of man in disrupting natural states of balance and altering the rates of geomorphic processes has been recognized by a few individuals. For example, Lamplugh (1914) commented that "I am constantly struck with the effect of human culture upon the streams. Hardly in any particular has Man in a settled country set his mark more conspicuously on the physical features of the land." Interest in the effects of man on streams was encouraged by the spread of soil erosion and the simultaneous necessity to develop techniques for soil conservation. More recently, the potential force of man's activities in producing dramatic, short-term changes in drainage basins has become increasingly evident through environmental studies.

Some major ways that man has modified the character and function of the drainage basin are given in Table 16. Most of these examples result from direct process modification by altering the natural distribution of water. However, indirect effects arise from the influences exercised upon drainage basin characteristics. The implication of Table 16 is that the facets of drainage basin stability which man may influence are numerous and complexly interrelated to the entire system economy.

In rural areas, agricultural activities can greatly modify soil and vegetation characteristics and thus change runoff and erosion rates. As an example of the possible magnitudes of change, Leopold (1956) reported that human activity has increased sediment yields by between two and fifty times. Similar great increases are reported by Douglas (1967), in Australia. In fact, Douglas (1967, p. 928) remarked that "...human interference is so extensive and has spread so rapidly that we cannot be sure that observations relate to natural condition."

For the middle Atlantic Piedmont area, Wolman (1967) has proposed a sequence of adjustments which may have occurred through the stages of land use from pre-agriculture to a completely urbanized landscape. His model is presented in Figure 28 and indicates the marked effect upon sediment yield of urban encroachment and construction activity. Similar results were reported by Leopold (1973) from a 20-year study of a small drainage basin in Maryland. He observed that the increased rate of land alteration, primarily in the form of urbanization, caused large amounts of sediment to be deposited in the downstream portion of the basin. As a result, the main channel decreased in cross-sectional area by 20%, and the number of floods exceeding channel capacity increased dramatically.

Table 16. Examples of drainage basin changes effected by man (from Gregory, K.J., and Walling, D.E., 1973).

	Direct changes	Form affected
Drainage network changes:	irrigation networks	n
	drainage schemes	n
	agricultural drains	n
	ditches	n
	road drains	n
	storm water sewers	n
Channel changes:	river regulation	g p
	bank stabilisation, protection	g p
Water and sediment balance:	abstraction of water	g
	return of water	g
	waste disposal	g
	Indirect causes	
Land use:	cropland	n p g
	building construction	p g
	urbanisation	n p g
	afforestation	n p g
	reservoir construction	p g
Soil character:	drainage	n
	ploughing	n p
	fertilisers	

Many of these can instigate changes of stream flow and of sediment and solute production and subsequently result in modifications of channel geometry (g), channel pattern (p), drainage network (n).

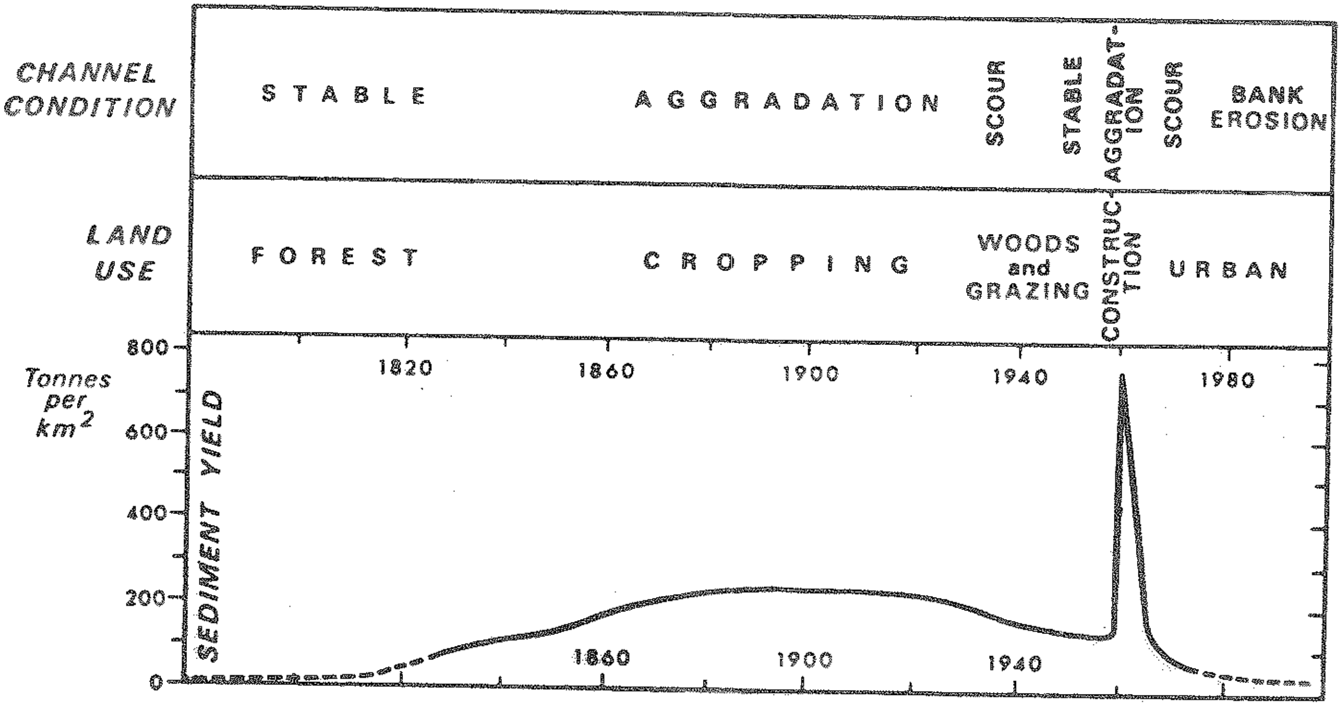


Figure 28. Variation of sediment yield over time as deduced by Wolman (1967). (From Gregory and Walling, 1973.)

Factors Influencing Observed Basin Changes

Base Level Change

Superficially, there appears no reason to expect significant natural changes in the base level conditions within the immediate study area during, or immediately preceding, the 30-year time interval. Obviously the area has not experienced measurable tectonic or isostatic adjustments in this short period of time and, in view of the number of years required for even minor degradation, it is unlikely that the local slope of the Wabash River has experienced major changes. In terms of large-scale, man-induced changes, no major engineering works have been emplaced in the immediate area. Although two dams were installed on the Tippecanoe River near Monticello, Indiana prior to the 1930's, these structures are through-flowing and have exerted no major influence on water levels downstream in the Wabash (L.G. Davis, U.S.G.S., personal communication). More recently the Salamonie, Mississinewa, and Huntington Reservoirs were completed in 1966, 1967, and 1969 respectively (Chang and Toebes, 1972) in the upland portions of the Wabash River basin. These may eventually effect water-surface elevations in the Lafayette area but were completed too recently to have any influence on this particular study.

It is possible to obtain a very general idea of water level and consequently base level fluctuations on the Wabash River by analyzing the rating curves for the period of record of the Lafayette gaging station. Figure 29 contains the rating curves in effect during 1935 and 1965 for this gage, which is located approximately 8.7 miles upstream from the junction with Indian Creek. Because of the proximity of the two points, it is assumed that both experienced similar adjustments,

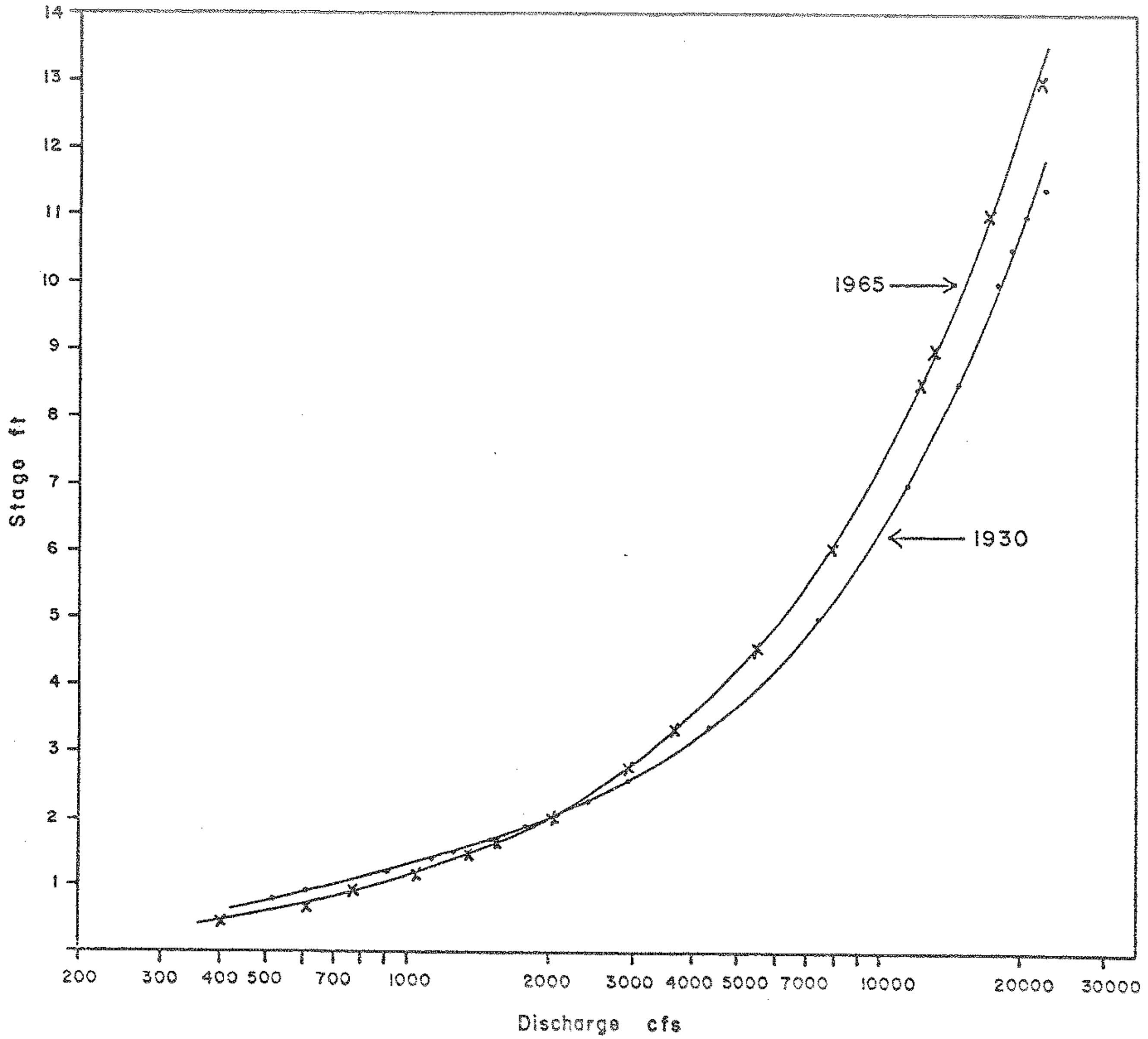


Figure 29. Rating curves for the Wabash River gaging station at Lafayette, Indiana for the 1930 and 1965 water years.

although this may not hold precisely. Figure 29 indicates that from 1935 to 1965 the stage increased slightly for the same value of discharge. Because the water-surface elevation increased, this indicates, in general, that base level for the tributaries of the Wabash raised slightly.

To delineate the intermediate steps of the trend indicated in Figure 29, Table 17 lists the stages representative of various discharges obtained from the historical rating curve data. For 47 years of record (1923-1969) the avarage discharge ($\bar{Q}$) is 6,252 cfs. The discharges listed in Table 17 are therefore approximately 0.25 $\bar{Q}$, 0.50 $\bar{Q}$, 0.75 $\bar{Q}$, 1.00 $\bar{Q}$, 1.50 $\bar{Q}$, and 2.00 $\bar{Q}$. It is obvious that the stages representative of a particular discharge did not progressively increase, but show alternating, short-duration, fluctuations of increase and decrease as might be expected. Therefore, the net increase is somewhat misleading because the trends reversed about every 10 years, and these adjustments probably were not in effect long enough to significantly influence tributary development in response to either a positive or negative base level change. It will also be noted that the net increase in stage from 1935 to 1965 is variable, with a minimum increase of 0.20 ft for 1,500 cfs and a maximum of 1.05 ft for 12,500 cfs. From flow duration analysis it has been determined that commonly many rivers flow at rates less that the average discharge between 60 and 75 percent of the time. This indicates that the smaller values of stage increase observed at the Lafayette gage are representative of a greater duration of time than the larger increase of the larger flow rates. This also diminishes the relative importatce of the indicated base level trend.

Table 17. Stage-discharge values for the Wabash River gaging station at Lafayette, Indiana from 1935 to 1965.

DISCHARGE (cfs)	STAGE (ft)						
	1935	1940	1945	1950	1955	1960	1965
1,500	1.45	1.65	2.0	1.85	1.80	1.80	1.65
3,100	2.50	2.80	3.10	3.10	2.85	3.10	2.85
4,700	3.50	3.80	4.10	3.95	3.75	4.00	4.05
6,250	4.35	4.75	5.30	4.80	4.65	4.90	5.00
9,400	6.10	6.75	7.30	6.70	6.65	6.85	6.95
12,500	7.65	8.50	9.00	8.50	8.15	8.65	8.70

On a smaller, more local scale, the situation is different. In several locations along Indian Creek gravels have been removed from the flood plain areas adjacent to the stream. Depending upon the amount and location of excavation, alteration of channel and flood plain storage could elicit more dramatic and immediate adjustments in the gradient of Indian Creek and significant base level changes for its tributaries. In addition, it was previously noted (see Figure 11) that study basins 3 and 5 drain across the Wabash flood plain in man-made ditches. Any dredging or improvement work on these would have produced base level influences on basin development. Unfortunately, there are no accessible records of these activities. The potential influence of such actions, however, will be discussed in subsequent sections of this report.

Climatic Change

It is customary to consider climatic change as occurring over an extended period of time, and therefore it is important in determining long-term geomorphic response. However, as mentioned already, short term fluctuations of significant magnitude can exert stress upon geomorphic features. Subtle changes and fluctuations of climatic input have in fact been postulated as the initiating cause of arroyo development in the southwestern U.S. in the latter part of the nineteenth century (see Antevs, 1952).

Because of the possible implications of changes in climatic input, precipitation data for Lafayette, collected continuously since 1880, was analyzed. Total precipitation was reasoned to be most closely associated with runoff and network development, although other climatic factors are also of importance. Table 18 contains yearly total precipitation, cumulative precipitation, and the yearly variance from the mean (37.47 in) value; all units are in inches. Cumulative precipitation may be plotted against time to obtain a mass curve. If the precipitation input has remained essentially constant over the period of record, the plot should closely approximate a straight line. Figure 30 does indeed indicate the relative constancy of precipitation input for the 90-year record.

Additional information about input variability may be obtained from a simple precipitation histogram such as that shown in Figure 31. This graph clearly indicates a cyclic tendency or periodicity within the precipitation data. This cyclicity can be accentuated by plotting the variance from the mean for the same five year periods (Table 19). This plot, Figure 32, is interpreted as consisting of three complete cycles (1885-1909, 1910-1929, and 1930-1959), with what appears to be the peak of a yet earlier cycle (1880-1884) and the trough of another cycle beginning in 1960. This of course is a somewhat subjective analysis, and various interpretations are possible, especially for the period of 1935 to 1959. For example, a different interpretation might be that the period between 1930 and 1940 represents one individual cycle of smaller duration and amplitude. If, for the moment, it is assumed that just three complete cycles have occurred, the periodicity or length of time necessary for completion of one cycle increases from about 20 to 25 years for the first two cycles to 30 years for the third. Regardless of the number of cycles present, it is obvious that the recurrence of both above and below average precipitation, as well as the magnitude

Table 18. Precipitation data for West Lafayette, Indiana.

Year	Total Precipitation (in)	Cumulative Precipitation (in)	Variance from mean (in)
1880	44.63	44.6	7.2
1881	46.18	90.8	8.7
1882	46.01	136.8	8.5
1883	42.71	179.5	5.2
1884	37.87	217.4	0.4
1885	38.75	256.2	1.3
1886	34.35	290.5	-3.1
1887	26.82	317.3	-10.7
1888	33.73	351.1	-3.7
1889	34.10	385.2	-3.4
1890	42.45	427.6	5.0
1891	36.71	464.3	-0.8
1892	43.60	507.9	6.1
1893	37.07	545.0	-0.4
1894	35.20	580.2	-2.3
1895	27.07	607.3	-10.4
1896	38.65	645.9	+1.2
1897	33.34	679.2	-4.1
1898	44.38	723.6	+6.9
1899	30.84	754.5	-6.6
1900	42.74	797.2	5.3
1901	32.01	829.2	-5.5
1902	45.94	875.2	8.5
1903	33.67	908.8	-3.8
1904	39.07	947.9	1.6
1905	43.16	991.1	5.7
1906	41.42	1032.5	4.0
1907	45.93	1078.4	8.5
1908	32.41	1110.8	-5.1

Table 18 Cont.

Year	Total Precipitation (in)	Cumulative Precipitation (in)	Variance from mean (in)
1909	55.08	1165.9	17.6
1910	31.72	1197.6	-5.8
1911	33.58	1231.2	-3.9
1912	35.80	1267.0	-1.7
1913	37.96	1305.0	0.5
1914	25.05	1330.0	-12.4
1915	34.77	1364.8	-2.7
1916	39.18	1404.0	1.7
1917	33.98	1437.9	-3.5
1918	39.55	1477.5	2.1
1919	33.65	1511.1	-3.8
1920	32.39	1543.5	-5.1
1921	44.97	1588.5	7.5
1922	32.62	1621.1	-4.9
1923	40.81	1661.9	3.4
1924	44.00	1705.9	6.5
1925	32.31	1738.2	-5.2
1926	47.27	1785.5	9.8
1927	54.91	1840.4	17.4
1928	34.92	1875.3	-2.6
1929	50.41	1925.7	12.9
1930	30.55	1956.3	-6.9
1931	35.55	1991.8	-1.9
1932	36.40	2028.2	-1.1
1933	30.88	2059.1	-6.6
1934	28.82	2087.9	-8.7
1935	39.61	2127.6	2.1
1936	36.83	2164.4	-0.6
1937	40.21	2204.6	2.7
1938	40.64	2245.2	3.2

Table 18 Cont.

Year	Total Precipitation (in)	Cumulative Precipitation (in)	Variance from mean (in)
1939	37.80	2283.0	0.3
1940	28.73	2311.8	-8.7
1941	32.17	2343.9	-5.3
1942	37.96	2381.9	0.5
1943	37.43	2419.3	0.0
1944	28.60	2447.9	-8.9
1945	40.62	2488.5	3.2
1946	38.19	2526.7	0.7
1947	38.56	2565.3	1.1
1948	33.54	2598.8	-3.9
1949	40.71	2639.5	3.2
1950	45.92	2685.5	8.4
1951	37.04	2722.5	-0.4
1952	43.48	2766.0	6.0
1953	33.74	2799.7	-3.7
1954	32.67	2832.4	-4.8
1955	38.06	2870.5	0.6
1956	27.94	2898.4	-9.5
1957	50.45	2948.8	13.0
1958	42.47	2991.3	5.0
1959	41.48	3032.8	4.0
1960	34.07	3066.9	-3.4
1961	36.88	3103.7	-0.6
1962	35.40	3139.1	-2.1
1963	25.47	3164.6	-12.0
1964	28.92	3193.5	-8.6
1965	38.23	3231.8	0.8
1966	31.37	3263.1	-6.1
1967	32.74	3295.9	-4.7
1968	38.39	3334.3	0.9
1969	37.97	3372.2	0.5

Mean Annual Precipitation = 39.47 in.

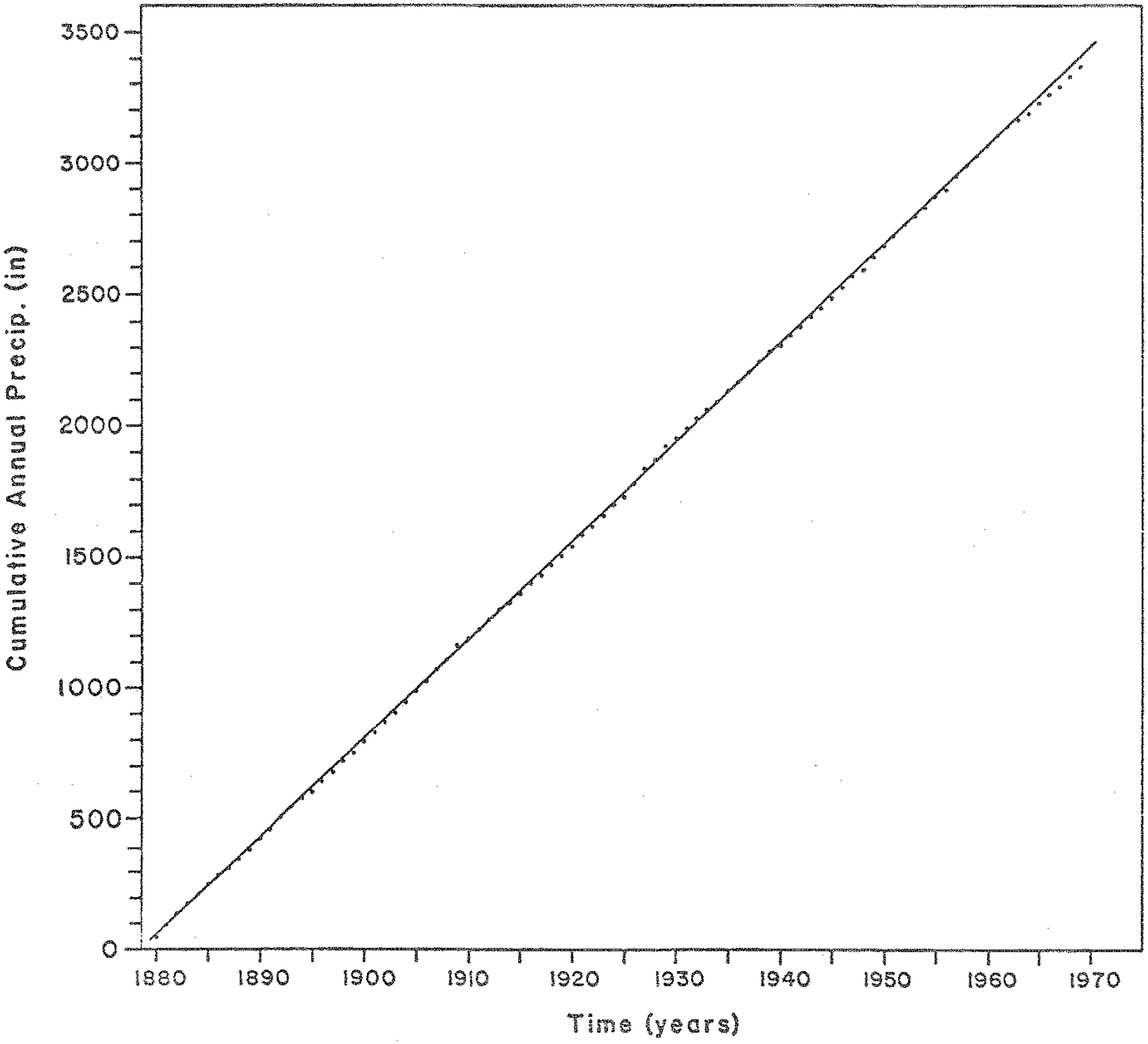


Figure 30. Precipitation mass curve for Lafayette, Indiana.

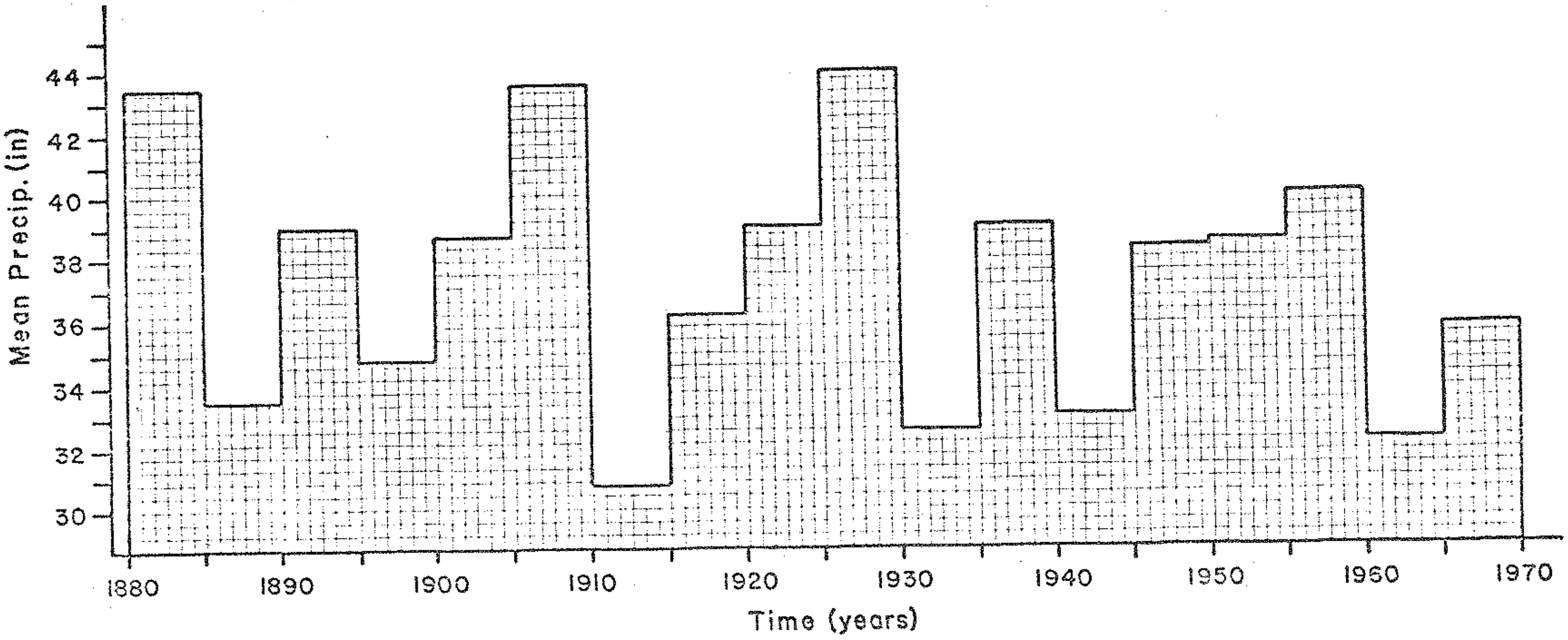


Figure 31. Histogram of annual precipitation plotted on a five-year time base.

Table 19. Precipitation data grouped into five year intervals.

	Mean Precipitation (in)	Variance from mean (in)
1880 - 1884	43.48	+6.0
1885 - 1889	33.55	-3.9
1890 - 1894	39.01	+1.5
1895 - 1899	34.86	-2.6
1900 - 1904	38.69	+1.2
1905 - 1909	43.60	+6.1
1910 - 1914	30.82	-4.7
1915 - 1919	36.23	-1.2
1920 - 1924	38.96	+1.5
1925 - 1929	43.97	+6.5
1930 - 1934	32.44	-5.0
1935 - 1939	39.02	+1.5
1940 - 1944	32.98	-4.5
1945 - 1949	38.32	+0.9
1950 - 1954	38.57	+1.1
1955 - 1959	40.08	+2.6
1960 - 1964	32.15	-5.3
1965 - 1969	35.74	-1.7

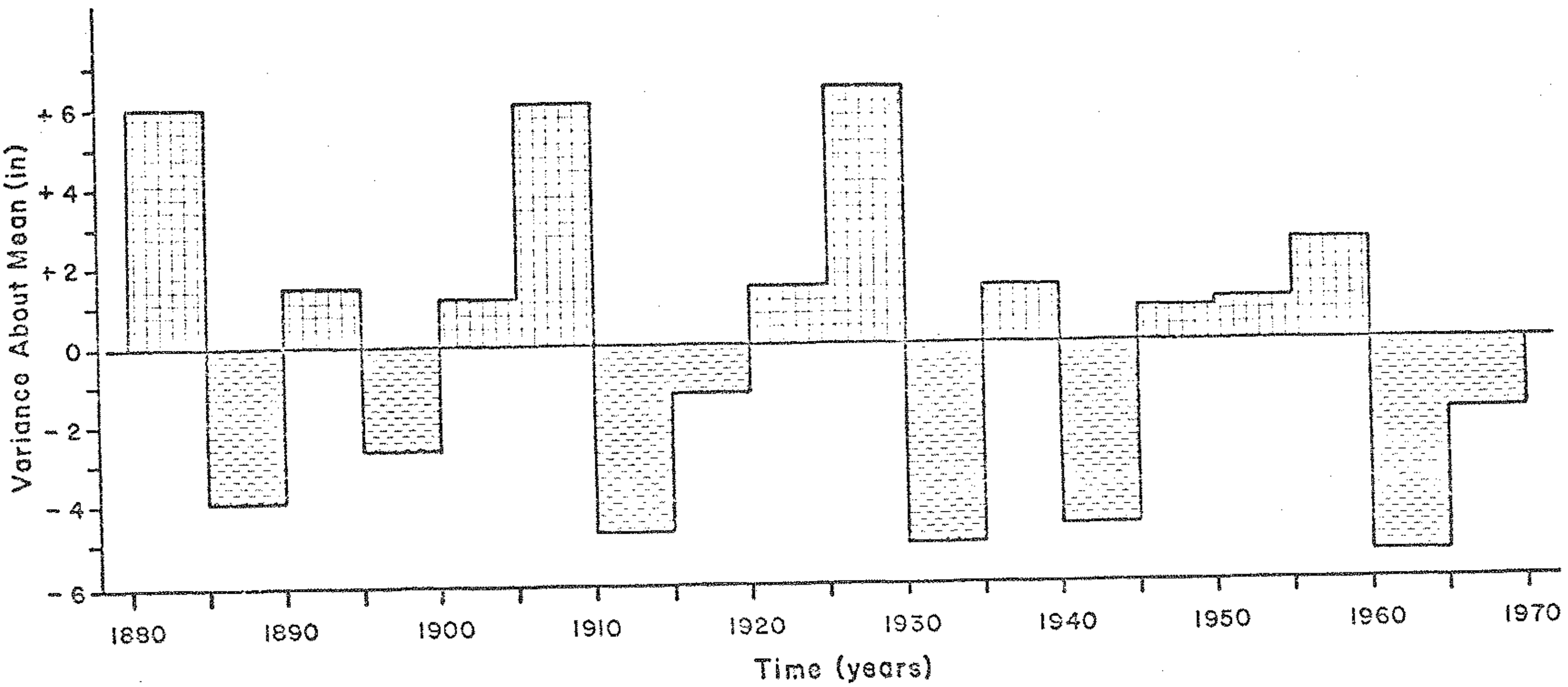


Figure 32. Precipitation variation about the mean for five-year intervals.

of the negative intervals, is comparatively regular. On the other hand, it can be seen that the maximum positive peak of the last cycle is much smaller than in previous cycles. All the above factors of precipitation variability have geomorphic significance, especially the observed peak attenuation.

By multiplying mean precipitation values for the plotting intervals (Table 19, Figure 32) by the number of years in question and summing algebraically, an indication can be obtained of the quantity of precipitation above or below the mean for that period of time. Applying this technique to Figure 32, the first 50 years of record (1880-1929) contains +52 inch-years of precipitation, whereas the period of 1930 to 1969 received a net -52 inch-years of rainfall. This further substantiates the observed unequal distribution of rainfall. As rainfall and runoff are positively correlated, these data indicate that the period from 1880 to 1929 had the greatest potential for inflated runoff, erosion, and sediment yield rates, whereas the period of 1930 to 1969 had small potential for such activities. Carrying the argument a step further, it is logical that the earlier period should have experienced active drainage network extension and growth, whereas the later period may have been characterized by minor growth or perhaps drainage loss, owing to a resultant overdeveloped condition in relation to the decreased precipitation input.

If, for simplicity, it is assumed that drainage expansion and termination are in direct response to rainfall input, and assuming all other factors remained unchanged from 1880 to 1969, the corrsponding drainage network adjustments can be conceptually extrapolated from Figure 32 into the form presented in Figure 33. This simplified diagram indicates that the channel networks in the area may have undergone three major periods and one minor period of network expansion, separated in time by four periods of overall network losses. It is interesting that the manner of adjustment presented in Figure 33 is quite similar to observations of other researchers. For example Glock (1931), on the basis of pattern observations from maps, categorized developing stream networks into stages of extension and integration. The same adjustments were observed by Morisawa (1964), who concluded that developing networks quickly reach an equilibrium and any subsequent variations and fluctuations tend to be conservative. Additionally, Schumm and Lichty (1965, p. 114) state that during graded time:

> "The landforms have reached a dynamic equilibrium with respect to processes acting on them. When viewed from this perspective one sees a continual adjustment between elements of the system.... In other words the progressive change during (a longer) time is seen to be, during a shorter span of time, a series of fluctuations about or approaches to a steady state."

These statements add credence to the hypothetical manner of adjustment depicted in Figure 33.

In relation to the specific drainage basin changes described in Chapter 5, the overall drainage losses of the fourth-order basins agree with those expected on the basis of climatic input alone. According to Figure 33, the nets should have experienced drainage losses during the approximate intervals of 1930-1945 and 1960-1969. The excess drainage lines observed on the 1938 photography may be reasoned to have originated in the extension period of 1920 to 1930, and consequently some overlap and response lag is indicated, as is expected. Conversely,

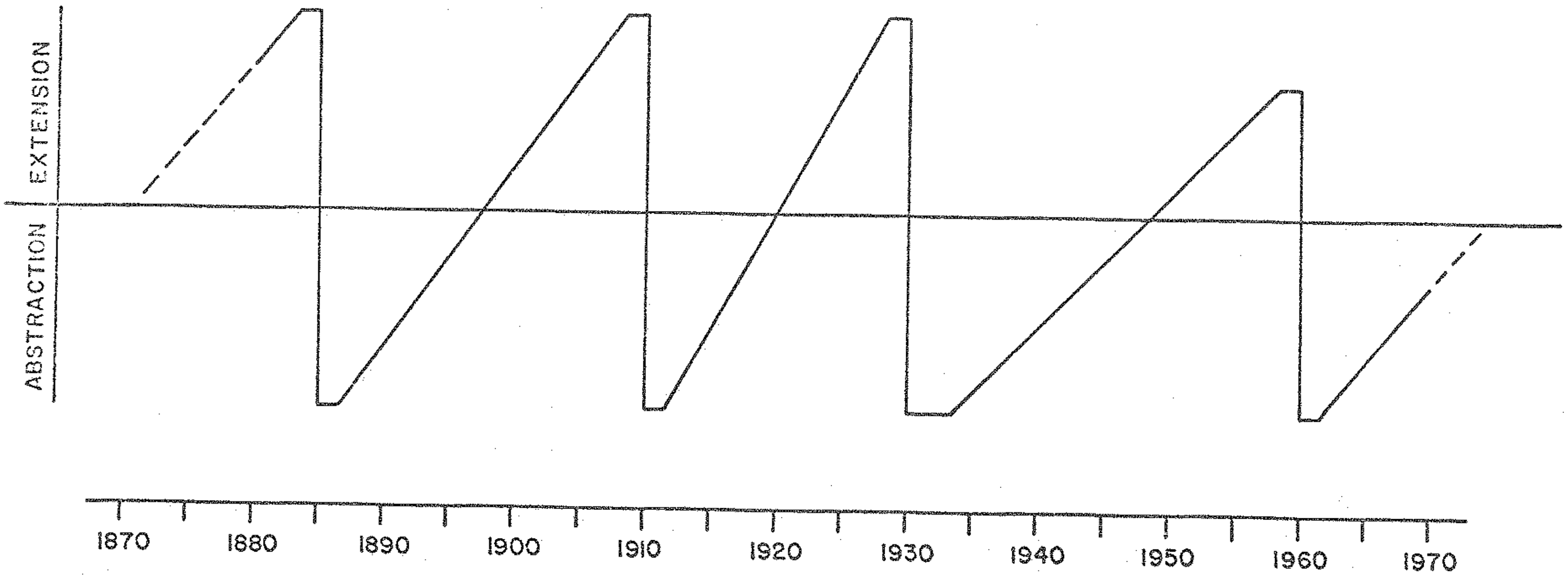


Figure 33. Idealized drainage network response to the climatic fluctuations shown in Figure 32.

the fifth-order basins experienced marked network extension between 1938 and 1968. One might reason that these larger, more complex basins, composed of more network components, would require a longer period of time to adjust to an altered rainfall pattern. To incorporate this time lag into Figure 33, the curve could be translated to the right, resulting in better agreement with the observations.

Obviously, other factors than total precipitation have influenced drainage basin evolution in the study area, and the hypothesized adjustments schematically depicted in Figure 33 are the result of extreme simplification of the problem. However, it is reasoned that such a basic response of geomorphic processes and resultant morphology to climatic fluctuation is inherent, but is complicated by the temporal and spatial variation of other causative factors. The influence of these additional factors are considered in subsequent commentary.

Influence of Man

A consideration of the degree to which man is capable of disrupting a natural fluvial system was undertaken in a previous section of this report. An original objective of this study was to determine the magnitude and type of influence or constraints man has imposed upon natural drainage basin stability and development in the geographic setting of which this study is representative. The following discussion is directed toward this end.

During the past several years, the Indian Creek watershed has experienced several forms of construction and urbanization activities in addition to earlier land use changes related to agricultural practices.

As already mentioned, several small gravel pits are located along the main valley bottom of Indian Creek. These pits evidently served primarily as local sources of aggregate for road construction in the area. The physical effects of these excavations are probably minor, but may locally influence runoff, flood propagation through the principal valley, and possibly base flow and ground water movement. Much more important in terms of potential system disruption is residential development, subdivision construction, and related activities undertaken to accomodate increased housing demands for West Lafayette. Unfortunately, respeated and wide-spread inquiries to city and county authorities and area real estate developers have failed to produce precise information about the time that accelerated construction began. Several additions and subdivisions such as Homewood Addition, Indian Hills, Indian Creek, Big Oak, Lake Villa, Carriage Estates, and Westwood are located within the drainage basin, but these were not constructed at the same time nor rate. Several contain only a few dwellings, whereas others are substantially developed. The available information indicates that major, large-scale construction probably did not begin until the late 1950's or early 1960's (for example, see West and Barr, 1965)

In order to determine the effect of urbanization activity on the drainage system, the study basins tributary to Indian Creek were selected for analysis and comparison with those tributary to the Wabash River (see Figure 11), which were to serve as control basins. However, from the observed basin changes, it appears that no significant differences exist between these two groups. Instead, the adjustments can be categorized on the basis of basin order (see Chapter 5). The possible causes of these observed differences will be discussed in another section to follow.

It is very unlikely that the extensive human activity would produce no observable effects on the Indian Creek drainage system. Because construction activity in located some distance above the study basins, and probably began only 8 to 10 years prior to the date of the last photography which was analyzed, it is probable that the total effect of urbanization had not been propagated downstream and was not reflected in the tributary networks. The apparent constancy of Indian Creek channel morphology, especially in the downstream reaches, as observed on both sets of photography tends to support this conclusion.

However, land use changes associated with agricultural activity occurred much earlier, and the effect on network growth and development is readily determined. In the late 1800's and early 1900's land was increasingly converted into crop production as natural stands of trees and grass were removed. This activity was rather widespread, and very little consideration was exercised as to preservation of original land slope, erosion, or retention of established surface drainage. If slopes were not too steep to prohibit tillage, they were eventually converted into productive crop land. This was particularly common early in this century with the advent of mechanized farming and the commensurate capability to increase productivity. Eventually these soil cover changes, coupled with the periods of above average rainfall already reported, resulted in severe soil erosion, gully development, and drainage network extension because of increased runoff. The result of this drainage extension is quite obvious on the 1938 photography with gullies extending headward across bare ground in all of the basins, especially where steep slopes and silty soils were cultivated and grazed. Therefore, it is reasoned that poor agricultural practices related to cultivation of steep slopes and overgrazing of pastures had a definite influence on drainage stability of the area.

In subsequent years, conservation practices and associated land use changes have begun to reverse or inhibit the previous trend toward network enlargement. In the early 1940's the Soil and Water Conservation District servicing Tippecanoe County was activated. This period therefore represents the advent of supervised planning and implementation of programs to decrease watershed runoff and soil erosion. Shortly thereafter, increased efficiency and yields from modern farming practices led to temporary crop surpluses and permitted removal of steep land areas from crop production. This acreage was converted into grazing land or woodlots for better soil protection by increased vegetative cover. Many gullied and eroded areas were shaped and smoothed by farm and earth-moving equipment, cover was reestablished, and more stable grassed waterways were constructed. Additionally, many fields were tiled to improve internal drainage and some new drainage ditches constructed to increase surface drainage, thereby increasing productivity in the till uplands. On the 1968 photography, many of the severely eroded areas evident on the 1938 photos are either absent or contain fewer, more stable channels. In field plots on the upland areas, the photos show that land is generally being tilled and worked perpendicular to slope. This has greatly inhibited channel extension into these areas, as farmers continually work across drainage line and fill them in. The recent photography also shows that most of the channels are developing on steeper slopes adjacent to the principal drainage lines, but they abruptly terminate at the slope break which coincides with cultivation and grazing boundaries. Where channels do exist on the uplands, they are small, widely spaced, and largely controlled by man.

The cumulative effect of all these human activities has been to inhibit runoff and resultant channel network growth and expansion. This represents a complete reversal of imput from man during the last 100 years. It is believed that network extinctions and terminations noted in the smaller basins of the study sample are directly attributable to the combined activity of man and decreased precipitation input. The net increase in drainage complexity experienced by the fifth-order basins may result from a lag effect, owing to the more complex nature of the network and larger size as mentioned previously. However, there is some evidence to indicate additional complexities may be involved.

Threshold Conditions

As related in a previous section of this chapter, Schumm (1973) and others have presented substantial evidence, based on both laboratory and field observations, for the existence of geomorphic thresholds. This approach to geomorphic inquiry and deduction appears to have value in interpreting the fluvial adjustments observed in the present study and, as a consequence, should be examined.

It should be recalled that original selection of the study basins, aside from considerations of the time of photography, was made to determine the effect of land use change and urbanization upon drainage within the Indian Creek watershed. However, as discussed in the immediately preceding section, observed changes were naturally grouped by basin order and not on the basis of location either within or outside the Indian Creek drainage. In other words, basins of similar order showed similar adjustments, apparently without regard to location. This raises the question of whether some geomorphic threshold of drainage basin development exists between basins of different order, so that basins of order less than this limiting value develop and respond differently than those of greater order, given similar external conditions.

Concepts of threshold attainment and excedence have previously been applied to the evolutionary development of geomorphic features in an attempt to explain some complex response (see Schumm, 1973). One can apply the same concepts in a manner analogous to discriminant function analysis to segregate groups of different characteristics. The analysis of critical slope values in relation to stream channel pattern types (Leopold and Wolman, 1957; Schumm and Khan, 1972; Edgar, 1973) is an example. Therefore, the threshold concept may be used in both temporal and spatial analyses. Threshold boundaries may be crossed, and seemingly anomalous behavior exhibited as basins evolve and increase in order. Therefore, there is no reason to preclude the existence of response or adjustment thresholds between basins of different order and inferred evolutionary stage which are observed simultaneously at varying instants in time.

Whether because of possible threshold conditions, considerations of geometric similarity (Strahler, 1957), or other unspecified criteria, most reported investigations of basin morphometry have been stratified or grouped on the basis of basin order (see Shreve, 1966, p. 32). Furthermore, Bunik and Turner (1972, p. 121-122) conclude that

> ...network patterns are closely related to the stage or geographical location within the basin itself (upstream or downstream) rather than to the absolute amount of time available for pattern development over the entire basin. In other words, the downstream drainage pattern has generally undergone more development and has developed a pattern which is not only distinct from the upstream pattern, but is also more similar to the downstream patterns of other networks of similar material type but of different geologic age."

This conclusion indicates that two factors are particularly important in relation to drainage pattern: material type, considered in the following section, and stage of development. Given similar external conditions, stage of development should be strongly correlated with basin order; therefore, network pattern should be correlated with basin order.

Two additional pieces of information indicate the relevance of basin order considerations and the potential for threshold order values. In a study involving the relationship between numbers of Shreve links, Strahler stream segments and Strahler order, Coffman, et.al.(1972) were able to mathematically define and graphically depict certain threshold boundaries existing between these three variables. They note (p. 150), however, that

> "...for higher orders the general equation defining threshold lines does not hold. Thus for orders of >4 the threshold conditions controlling change in order may be different from those for lower orders."

Furthermore, in testing certain aspects of the random model by application to natural data, Smart (1973) selected stream number data on 38 networks of fifth or higher order. He states (1973, p. 35) that "The comparison was restricted to order greater than or equal to 5 because neither method (Horton's laws or random model) could be expected to work very well for lower orders...." Smart subsequently demonstrates the validity of the random model for predicting the number of first-order segments of a basin. However, it is interesting that the application to basins of order 5 or greater was successful, whereas those pertaining to order less than 5, on the basis of the quotation just given, were apparently unsuccessful.

It will be recalled that the basins of the present study were of either order 4 or order 5, and that individual basins of the same order developed in similar fashion during the 30 years involved. However, these two groups exhibited opposite trends of development. In the discussion immediately preceding, lines of reasoning exist which indicate the possible existence of threshold values of basin order, and two examples were given that specifically relate to anomalies between basins of order >5 and those of order <5. Although these arguments are not conclusive, they do add credence to the contention that a threshold of some sort may exist between basins of order 4 and order 5, and that this condition may influence basin development to a significant and observable degree. If such a threshold exists in the study basins, the resulting influence on watershed development may have been sufficient to suppress any immediate expression of land use change or urbanization effects on the Indian Creek drainage during the study period. Subsequent adjustments may reverse this situation however, particularly if the influence of man is dramatic in relation to system dynamics.

Soil Type

Control exerted on drainage basin development and channel network characteristics by material type (bedrock, unconsolidated deposits, and soil type) is widely recognized. These materials influence the fluvial system through local variations in resistance to erosion, internal drainage characteristics, topographic form, slope magnitude, and other basic properties of the material itself, such as particle size and distribution, texture, internal structure, etc. Although most studies related to the influence of material type have included extensive and diverse geographic areas so that sufficient geologic variability may be observed, the same technique may be applied to a restricted geographical area of essentially uniform parent material but variable soil type.

The Soil Conservation Service of the U.S.D.A. and the Purdue University Agricultural Experiment Station (1959) have mapped in detail the soil types of Tippecanoe County. Units presented on the soil maps of this publication include slope and erodibility characteristics in addition to the distribution of general soil types. Within the confines of the study area, four groups of soil series are present. Genesee and Eel soils are adjacent to the larger drainage channels in the valley bottoms. Hennepin soils are developed on steeply sloping valley walls, and Russell (similar to Miami) soils occur at the upper edge of the valley walls where slope decreases and becomes the transition zone between the steep slopes below and the gently rolling till uplands. On the till uplands, Cope and Brookston soils occur in depressions, whereas Fincastle (similar to Crosby) soils are found on gentle slopes. The engineering properties and other characteristics of these soil types are described by Belcher, et.al. (1943).

Hennepin soils have a brown, friable surface horizon and a shallow profile composed mostly of silt but including clay and sand. They characteristically occur on slopes ranging from 16% to 55%. Because of steepness of the slope and the silty texture, Hennepin soils are highly susceptible to fluvial erosion. A large portion of the drainage networks of the study basins are formed in this soil type, especially the lower-ordered or adventitious segments tributary to the larger channels.

Russell soils occur topographically above the Hennepin, on slopes ranging from 4% to 16%. These also have a silty texture with a slightly plastic silt, clay, and sand subsoil. Parent material (till) is found at about 48 inches depth. As with the Hennepin, location and texture of the Russell soils makes them rather easily erodible. The study networks have generally extended through the Russell zone and terminate near the topographic break between the valley-side slopes and the till uplands. This is partly due to farming practices in the area, as already discussed.

On the till uplands, generally two soil types have developed, and their distribution is determined primarily by local topography. The Cope-Brookston soils are found in depressions and consequently have poor internal and surface drainage. These soils have a deep profile, with a highly organic topsoil and a compact, dense, plastic silty clay subsoil. Because of the topographic location and basic properties of this material, it is difficult to erode and usually contains no natural surface drainage channels. Conversely, the Fincastle-Crosby soils are more susceptible to erosion. These soils possess imperfect internal drainage and are characterized by silty and sandy clay below the commonly silty topsoil. They are normally found on slopes ranging from 0% to 4%. Therefore, on till upland regions of the study area, two basic soil types exist and are characterized by different susceptibilities to erosion and topographic (slope) conditions. It is believed that the distribution and relative areal extent of these two soils have significantly influenced the drainage network adjustments observed during this study.

A detailed examination of the soil map of the study area (Purdue University, 1959, map no. 4) indicates that an extensive area of Brookston-Cope soils is present on the till uplands area immediately west of Indian Creek. This is the upland area into which the drainage of basins 1 and 2 are attempting to extend and become established. Topographically the area is generally characterized by a subtle, elongate depression with slow runoff, and soils which are difficult to erode. It is logical to infer that much of this area has been tiled to increase internal drainage and increase crop productivity. This situation would tend to further decrease surface runoff and erosive capability. In contrast to this situation, upland areas east of Indian Creek contain a much larger proportion of Fincastle soils. Consequently, this area has a more rolling surface with slightly more local relief than the district to the west. This deduction is verified by observations from the aerial photography. Additionally, texture and other properties of the Fincastle soils make them more susceptible to erosion than the depression soils. Some trade-off will exist between increased internal drainage and increased slope relative to runoff values, but it is believed that runoff should be more effective in erosive activity, if not also greater in magnitude, on Fincastle soils than Brookston-Cope soils. This characterizes the upland areas into which the drainage of basins 3, 4, and 5 are developed and extending.

Based on these observations, some of the variability in basin response noted in this study appears attributable to soil type. During the time from 1938 to 1968 basins 1 and 2 did not extend their drainage; rather, they sustained network component losses. This could result in part from topographic and soils conditions in the headwater regions of the watersheds. Conversely, basins 4 and 5 experienced significant increases in the number of low-order stream segments. Comparing the drainage maps (Figures 12-21) with the soil map, it is evident that areas which experienced the most severe erosion are correlated with the more erodible soils found on steeper slopes. These observations are supported by the adjustments which occurred within basin 3. It will be recalled that this basin is of fourth-order, like basins 1 and 2, but it is located adjacent to fifth-order basins 4 and 5 (Figure 11). Observed changes in this basin (Table 4) are transitional between those experienced by the two groups; that is to say basin 3 experienced some of the adjustments common to the fourth-order basins 1 and 2, as well as those of the fifth-order basins 4 and 5. This is ascribed to the combined effects of stage of development (order) and local influences of slope and material type (see Bunik and Turner, 1972, p. 121-123).

Summary

The preceding discussion adequately demonstrates the complex interactions involved in drainage basin response to altered system inputs. Furthermore, it indicates the futility of attempting to describe cause and effect relationships without proper consideration of all possible controls, regardless of their apparent insignificance. In this particular study a minimum of five different groups of controls have been proposed as causative agents in eliciting the observed drainage changes. Only one of these agents, base level change, can be reasonably considered as of minor significance on the basis of the foregoing discussion. Climatic fluctuations, threshold conditions, human activity, and soil type all appear to have exerted some degree of control on development of the study basins, and there may have been other factors. The difficulty in a study of this type, without continuous observations and measurements, is in determining the degree to which each of these factors has been influential and which specific basin characteristics and processes have responded to the individual input variations. However, certain logical interactions, their general physical significance, and the relative direction of change can be deduced or inferred on the basis of previously reported results and the application of known geomorphic principles. This is the approach used by us, hopefully with an acceptable degree of rationality, to explain the observations which are contained in this report.

CHAPTER 8

SUMMARY AND CONCLUSIONS

During the several years following Horton's (1945) presentation of the basic concepts of quantitative watershed analysis, Strahler and his students refined the original techniques and established new descriptive parameters and physical relationships. Numerous studies of watershed morphology and morphometry followed. Many of these researchers proposed additional parameters for consideration, other hypotheses of network evolution and development, or refined previous studies. More recently, a theoretical approach, either mathematical or conceptual, has dominated research within the discipline. Preliminary theoretical results have been tested primarily by statistical techniques and secondarily by application to small samples of previously published natural data. Furthermore, the majority of studies of natural watersheds characteristically involve data collection at one point in time, whereas conclusions obtained from analyses of these data are commonly applied to evolutionary development through time. This data translation is based on the tacit assumption that variations in space are representative of, and analogous to, variations in time. It appears that a failure to note certain areal variations in factors known to exert controls on drainage basin processes and morphology could reduce the credibility of this assumption.

With this in mind, the present study was undertaken to document watershed adjustments through an extended period of time, utilizing historical and archival materials dating from 1838. Unfortunately, several difficulties encountered in assessment of these data sources necessitated a reduction of the time interval of study from 130 years to 30 years. The King map of 1838 contains remarkable detail for the date of compilation, but the scale permitted recording only the largest streams. Individual county maps contained in an 1879 Atlas of Indiana are presented on a larger scale, but detail varies greatly and is insufficient to allow detailed basin analysis anywhere in the state. Additionally, an extensive program of channelization in southwestern Indiana between 1900 and 1950 disrupted surface drainage to the extent that no comparison between topographic maps representative of this time interval is feasible. Owing to these limitations in basic data sources, the study was confined to a comparison of five drainage basins mapped from 1938 and 1968 aerial photography of western Tippecanoe County.

A review of geomorphic literature relates the various schemes for quantification and classification of drainage networks and describes the extensive list of variables which have been proposed for use in basin analysis. Although most potential classification schemes were discussed, only the Strahler ordering system was used in this particular analysis. This decision was based on the demonstrated utility of the method, and the fact that it is more widely used than any other and therefore facilitates comparisons with results of other studies. However, certain selected parameters pertaining to other methods were incorporated on the basis of their particular descriptive and analytical merit. Parameters are available for description of linear, areal, and relief aspects of the drainage basins; but, because of the data sources used, relief aspects were considered only in a very general and cursory fashion. By utilizing parameters developed from different classification schemes, in particular the Horton-Strahler ordering systems and the Shreve magnitude and link method, additional insight into the observed physical adjustments of the basins can be obtained.

For five basins studied, we observed that three fourth-order basins experienced generally similar adjustments, as did two fifth-order basins; but the two groups adjusted in essentially opposite directions. The fourth-order basins generally suffered overall network loss in number of components and length. As a result of these losses, network texture decreased in complexity, became coarser, and the basins were less dissected at the end of the 30-year interval. On the other hand, the fifth-order basins experienced significant network growth with an average increase of 32% in the number of stream segments in the basin, whereas the total length of channels remained essentially constant. This indicates the dynamic nature of basin response in that network expansion and terminations were occurring simultaneously. Because of the increased number of drainage components, these basins experienced significant increases in textural complexity and fineness as measured by most textural paramters. It is interesting that even though the networks showed marked adjustments in drainage composition, all ratio parameters such as bifurcation, length, and division ratios remained essentially constant. This observation, combined with modest variations in total channel length within the basins, intimates that the observed adjustments are relatively minor in terms of long-term geomorphic evolution and are possibly observations of small-scale fluctuations about an established state of adjustment. In view of the short time base of observation, this reasoning appears tenable. Nevertheless, such changes become important when information pertaining to immediate response and adjustment mechanisms is desired for environmental and planning purposes.

Several recently developed theoretical models were discussed in this report and certain salient features of each were compared with observations from the study basins. The first of these considered was the random model, developed primarily by Scheidegger, Shreve, and Smart. Proponents of the random approach suggest that, instead of attempting to predict geomorphic properties precisely, they should be regarded as random variables drawn from specified populations and treated statistically. These workers further reason that entire networks develop in a totally random or stochastic manner in the absence of geologic control. Comparisons of several proposed relationships derived from the random model with the observations reported herein yielded mixed results. Several observations corresponded very closely with predictions based upon maximum probability conditions. Additionally, a comparison between the calculated probability of drawing a Strahler stream of a given order at random from a population of streams comprising an infinite topologically random network and the observed frequency of streams of the same order showed excellent agreement. Similarly, good agreement was demonstrated between observed and predicted relationships of the number of links and segments, as originally proposed by Coffman, et.al. (1972). On the other hand, poor agreement was obtained with other features tested, particularly a proposed method of predicting stream length and length ratios on the basis of stream number data. Most other aspects of this approach to network composition and development which were compared with the present observations showed acceptable levels of agreement.

The concept of mixed hexagonal hierarchies applied to drainage basins was proposed by Woldenberg (1969). By means of astute observation and considerations of energy expenditure, Woldenberg reasoned that basins could be visualized as composed of small hexagonal areas and that the network within the basin would reflect this condition. Excellent agreement was obtained between the observed average fourth- and fifth-order networks and the condition predicted by this model. By analyzing the deviations from this theoretical structure, potential drainage adjustments may be inferred.

Finally, estimates of network stability and equilibrium as proposed by Melton (1958) and Coffman (1972) were examined and tested on the study basins. Melton defined a conservative drainage system as one possessing the minimum number of channel segments necessary for the highest segment order of the system. By comparing calculated values of Melton's proposed measure of conservancy with adjustments in the study basins, it was apparent that good agreement was not always possible with changes in the "lost" or non-integrated portions of the networks. This was due primarily to the proposed method of calculating the degree of conservancy. However, it is reasonable to believe that better agreement should have resulted from the analysis because the lost segments are by definition intimately related to the conservancy concept. The relationship between drainage density and channel segment frequency suggested by Melton and substantiated by Smart (1973) indicates that the study basins contain too many segments for the stable conditions defined by Melton's study. If Melton's results are valid, future basin adjustments in the study area should involve some combination of channel segment losses or increases in segment length.

Coffman (1972) presented a method for determining the potential for network growth, developed around the unit hexagon concept. The results of application of his method are in good agreement with those obtained by other techniques. He also proposed a method of predicting the topology of growth based upon the division ratio. By comparing the magnitude of a given stream segment with the absolute stream order, computed by using the division ratio as a base, Coffman was able to designate the segment in question as overdeveloped, underdeveloped, or in equilibrium. On this basis, predictions of network adjustments could be made. Application of this technique to the study basins indicated that the method is useful for predictions of a general nature.

Essentially all the concepts cited appear to be of some value in understanding watershed growth and response, particularly when results of two or more methods are analyzed conjunctively. However, for meaningful results, the situation to which the methods are applied should not violate the basic assumptions and conditions from which the methods were originally derived.

There are essentially six basic categories of external causality to which temporal and/or spatial variations of drainage basin morphology may be ultimately ascribed. These are base level changes, climatic changes, natural catastrophes, threshold conditions, geologic or material type variability, and human activity. With the possible exception of the 1913 flood, the study area has experienced no event of sufficient magnitude to be considered catastrophic. Furthermore, considering the factors which produced the 1913 flood, it is unlikely that this event had a significant influence on the small basins of the present study. Analysis of past rating curves for the Lafayette gaging site on the Wabash River yielded general information on base level adjustments experienced by the tributary basins from 1935 to 1965. Because of the minor vertical fluctuations for longer duration flows and the lack of an extended increasing or decreasing trend over the period of record, it was concluded that any influences of base level change were minor and could be eliminated from consideration.

To simplify analysis of climatic influence, it was assumed that total annual precipitation was representative of average climatic input into the fluvial systems. The analysis of these data, collected continuously at West Lafayette since 1880, indicated a cyclic trend in input over the period of record. If it is further assumed that precipitation directly correlates with runoff, erosion, and network growth, then alternating periods of network expansion and integration or termination are indicated by the extreme wet and dry intervals in the record. This interpretation seems to correlate very well with observed network adjustments in the sample fourth-order basins. By invoking a lag time for response in the larger, more complex fifth-order basins, reasonable agreement is obtained.

Evidence was also presented which indicated the possible existence of a geomorphic response threshold between basins of order 4 and order 5. Although the evidence is not conclusive, this interpretation seems plausible based upon observations from this study and those reported by other investigators. If such a threshold exists, its influence may have been sufficient to suppress, or at least confuse, the expression of other influences on the development of the basins.

It appears that areal distribution of slope and soil type in this geologically homogeneous area influenced observed network adjustments. Examination of a detailed soils map of the area indicated that topography, soil type and texture, and internal and surface drainage characteristics are different in the vicinity of basins 1 and 2 from basins 3, 4, and 5. These factors in combination indicate that the general potential for soil erosion and concurrent drainage network extension is less in the former area than in the latter area. This helps explain the observation that, when the basins were grouped according to order, basin 3 (order 4) showed adjustments that were more similar to those in basins 4 and 5 than did either basin 1 or basin 2.

Finally, in interpreting observed basin adjustments, the influence of human activity must be considered. In relation to short-term basin response, such as those reported herein, man's influence becomes a major factor in determining basin stability. Increased housing construction and associated urbanization activity began in the late 1950's and early 1960's. However, any influence that this may have had on the Indian Creek drainage was not obvious. It was concluded that this was probably owing to the stronger influence of other factors, and the fact that this larger basin did not have the necessary time to respond to this impetus before the last set of observations were made in 1968. On the other hand, land use change associated with early agricultural practices in the area appear to have instigated a period of accelerated erosion and network extension, the results of which are evident on the 1938 photographs. Subsequently, conservation measures and different agricultural practices appear to have again altered basin runoff conditions and, at least in part, initiated a period of drainage loss in the smaller, less complex study basins.

In view of all this evidence, it is concluded that the observed drainage basin changes resulted primarily from the combined influences of climatic fluctuations, threshold conditions, material type variations, and human activity. It is probable that other more subtle variations and unique situations may have been apparent if the basins were examined in detail on an individual basis. Because of complex interactions and mutual determinism among the basin adjustments and the integrated influence of the proposed causative factors, it is impossible to attribute all observed changes to only one of the four proposed causes. This typifies the complex process-response, cause-effect relationships which are characteristic of all natural geomorphic systems.

In terms of long-term geomorphic activity, the observations of the present study are of minor significance. If viewed over a long period of time, processes undoubtedly exhibit minor fluctuations about some mean value, with commensurate variations in geomorphic form elements. However, these minor fluctuations become very important if basin stability is examined over a more restricted time base. Furthermore, tampering with the fluvial system to decrease the amplitude of such short-term fluctuations, or significant alteration of the natural condition of the system by human activity may create an unstable condition and disrupt the long-term dynamics of the geomorphic processes. In this situation, a system could pass from equilibrium into disequilibrium before adjusting to a new and different condition of stability.

Black (1970, p. 76) presents some interesting points pertinent to the present discussion. In describing stability considerations in relation to watershed planning, he notes that

> "If we array streamflow-affecting factors in order of decreasing magnitude, we find atmospheric-climatic, geologic-geomorphic, vegetation-soil, and channel factors in that order. Man has the greatest access to the latter groups of factors, although he has made small inroads into drainage basin tampering and weather modification. What is more important, is that large-scale factors have less effect on stream flow from small watersheds, where man has the most access. Consequently we infer that man can achieve a greater degree of control over flow from small watersheds through manupilation of local factors."

He further states that

> "Whatever the practice, and insofar as he is active on the land, man is a factor of watershed equilibrium himself, because he can modify one or more of the environmental factors which contribute to equilibrium. He may, of course, increase watershed stability but, more frequently, he is a destructive force rendering the watershed more susceptible to a change or changes in factors which will upset equilibrium."

From Black's statements, one could reason that the land use adjustments discussed in this study may have been the primary factor responsible for observed network adjustments in the small study basins. Regardless of its relative position of importance, the demonstrated influence of human activity on the study basins over the 30-year period and the potential disruptive effect of accelerated intervention alluded to above indicate that additional detailed study of this problem is warranted. The six years elapsed since 1968, combined with continued urbanization of the Indian Creek watershed, may have been sufficient for physical expression of this input. Identification of magnitude and direction of basin response directly attributable to this activity would be quite useful. Therefore, it seems logical to recommend that additional study of this area should follow, using the results in this report as a base line.

The results of this study should be viewed as preliminary. Our conclusions are the result of essentially qualitative analysis of quantitative data. Increasing the number of basins sampled would permit statistical treatment and analysis with a higher degree of confidence than was possible with only five basins. Additionally, several local factors could be considered. For example, information about the history of human influence in basin 1 related to the natural drainage of the upland ponds in the catchment, dredging and maintenance of the ditches connecting basins 3 and 5 with the Wabash River, specific details of conservation and land use practices, and other factors could be obtained from discussions with local residents. These unanswered questions do not negate the conclusions drawn, but they are necessary for a complete understanding of the observations in the study area.

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