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Form And Fluvial Processes In Alluvial Stream Channels, Studies In Fluvial Geomorphology No. 2

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TECHNICAL REPORT NO. 47

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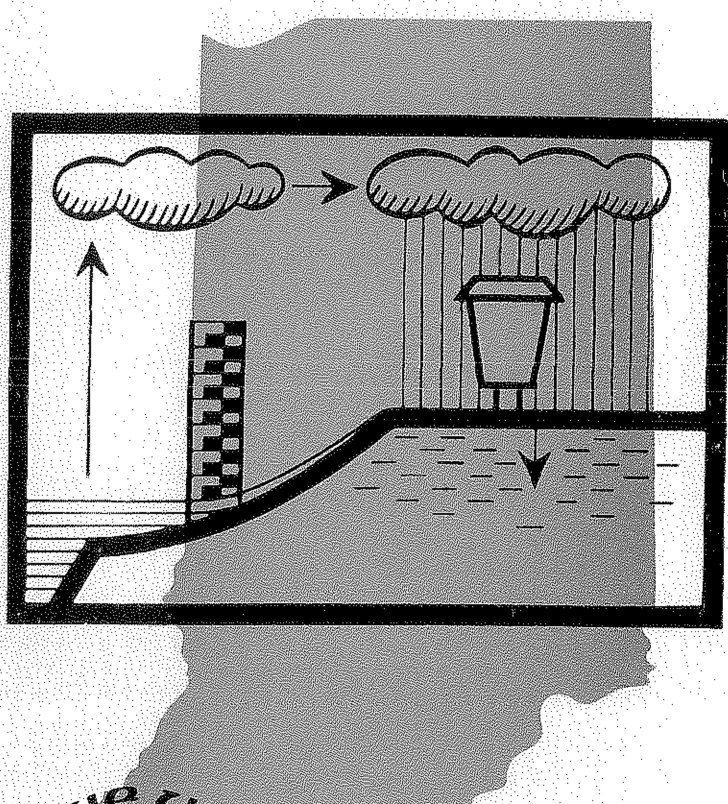

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DECEMBER 1974

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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PREFACE

This report is based on work performed by Dr. Keller in conjunction with a Ph.D. program. Helpful suggestions and constructive criticism have come from Dr. D.M. Coffman, Dr. R.L. Frederking, Dr. R.E. Aten, Mr. R.L. Powell, and Professor R.D. Miles of Purdue University; and from Dr. Marie Morisawa, SUNY-Binghamton and Dr. James Brice, Washington University, St. Louis, Missouri. Discussion of mathematical aspects with Mr. John Bobbitt was fruitful. Field assistance was provided by Mr. R.A. McBane and Mr. G.C. Kukal. Financial support was provided in part by the Water Resources Research Center, Purdue University, OWRR Project A-022-IND.

The report is the second in a numbered series of Studies in Fluvial Geomorphology. However, two Technical Reports of the Purdue WRRC, Technical Reports 16 and 22 are predecessors of the current numbered series of reports. The present report was assisted greatly by the use of results obtained in completing Technical Reports 16 and 22.

Research results presented herein, which led to a better understanding of fundamental natural fluvial processes, were necessarily achieved prior to investigating the ways in which human activity disturbs natural processes and leads to dislocations of the fluvial regime. These latter problems are described in another report now in process of completion and publication as Technical Report 52.

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ABSTRACT

This report attempts to define quantitatively and qualitatively, for alluvial channels, selected aspects of form and fluvial processes which contribute to the development of fluvial systems.

A fluvial system includes three parts: 1) the drainage network, 2) the geology (alluvium and/or rock), and 3) the hydrology (liquid). As a drainage basin evolves or changes, all three parts mutually adjust and each exerts a partial control on the other.

The relationship between the number of links and segments of natural drainage networks is restricted to a narrow envelope. Theoretically, within this envelope a family of curves with the general form $y - 2x - (2^n - 1)$ is defined, wherein y is the number of links, x is the number of segments, and n is the Strahler stream order defined for $n = 2,3,4,5$. Comparison with more than 100 natural drainage networks indicates that these curves delineate threshold and boundary conditions, and may be used to predict stream order.

As drainage networks develop from simple to complex, the range of bifurcation ratios fluctuates until a nearly constant value is reached. However, for any network of given order, bifurcation ratio

increases to an improbable value, whereupon continued development increases the network's order and decreases its bifurcation ratio.

The processes of convergent and divergent flow, which create the tendency for pools and riffles to form, are present in nearly all alluvial channels. The same mechanism may produce meandering channels. Hypothetically, there appears to be a balance of the time rate of energy expenditure through the pool-riffle sequence, which allows channel length to increase until a minimum value of energy expenditure is reached.

Pools, riffles, and point bars are common bed forms in straight and meandering channels. Inflections in meandering channels correspond to riffles in straight channels. Both forms are shoals that are symmetrical across the channel for a short distance. Pool-riffle spacing appears to be independent of channel pattern, and as straight reaches merge with meandering reaches no change occurs in the spacing, form, or symmetry of the pools and riffles. Meandering processes, which increase channel length, may result in the addition of new pools to keep pool-riffle spacing constant. A five-stage model is proposed to explain the development of alluvial channels. The model is based upon channel morphology, channel morphometry, and qualitative conclusions based on numerous field observations.

The purpose of classifying bed forms is to arrange the forms in a way tenable with known ideas, concepts, and processes which define and control alluvial stream channels. Such a classification must be "born from the river", for it is natural fluvial processes which produce the forms.

A generic classification is suggested, which permits hierarchical ranking of common bed forms in straight, sinuous, and meandering alluvial channels. Two major subdivisions: channel-forming and channel-altering bed forms are proposed. First- and second-order, channel-forming bed forms control the formation of the channel pattern, whereas third- and fourth-order channel-altering bed forms do not control channel pattern and are usually superposed on channel-forming bed forms. The proposed classification is tentative. However, the basic components and their relationship to each other appear valid.

CHAPTER 1

INTRODUCTION

General Statement

Man's adaption to the environment is intimately associated with the waters of oceans, lakes and rivers. Early man, like most other mammals, needed water daily, and it is not surprising that he lived, hunted, and died near the lakes and rivers on which he depended for his existence. In recorded history, man has used river systems as avenues for transportation, communication, food supply, disposal of waste, and source of power. Man has built massive dams to dissipate the disastrous effects of floods and drought, and even though we can sometimes control a river we still know little about the processes which form and maintain river systems. Only in relatively recent times have we realized that rivers are natural resources that must be conserved and properly managed if man is to continue a meaningful existence. Therefore, it is extremely important to gain a thorough understanding of the geologic, hydrologic, and topologic processes which control the development of fluvial systems.

Research in fluvial systems has commonly taken two different approaches (Leliavsky, 1966, p. 1-2): 1) the "frontal attack", which attempts to discover the forces and other mechanical factors that control channel shape, slope, sediment transport, and other characteristics of a fluvial system, and 2) the empirical solution, which involves experiment and observation without specific theory. Although the first approach may eventually supply the critical answers, it is the second which has so far proved most valuable.

The evidence we need to understand the evolution of a fluvial system can be found in the field. Theoretical considerations should now await field verification, and the emphasis of fluvial research must migrate from the office and flume to natural streams. An understanding of what streams are really doing will only be realized after thorough field observations and experiments, utilizing both qualitative and quantitative methods.

Purpose and Scope

The purpose of this report is to further an understanding of the processes which control the development of a fluvial system. New theoretical models are introduced only where there is a lack of acceptable theory in the literature. Emphasis is placed on empirical results obtained from qualitative and quantitative analysis of field observations and measurements.

The scope of this study is to: 1) Discuss the concept of a fluvial system, 2) Introduce a new topological relation to facilitate understanding of the development of drainage networks, 3) Introduce a new model to explain the development of alluvial stream channels, 4) Discuss the origin and significance of pools and riffles, and 5) Introduce a tentative generic classification of bed forms for alluvial stream channels.

Previous Publications

Portions of this report are refinements or extension of work previously published. Chapter 3 expands the abstract of a paper presented at the 1971 annual national meeting of the Geological Society of America (Keller, Coffman, and Melhorn, 1971) and a paper published in Water Resources Research (Coffman, Keller, and Melhorn, 1972). Parts of Chapter 4 come from published studies on the development of alluvial stream channels (Keller, 1972b), and on channel morphology-hydrology (Keller, 1971a, 1971b, and 1972a).

CHAPTER 2

CONCEPT OF A FLUVIAL SYSTEM

General Statement

A system may be considered as any part of the universe that is isolated in thought or in fact for the purpose of studying or observing changes that take place under various imposed conditions (Ehlers, 1968). Thus a system may be a planet, a cooling pluton, a landscape, or a drainage basin. I define a fluvial system to include three parts: 1) the drainage network, 2) the geology (alluvium and/or rock), and 3) the hydrology (liquid). As a drainage basin evolves or changes, all three parts mutually adjust and each exerts a partial control on the others. John Playfair (1802) may have been the first to recognize that streams in a fluvial system are delicately adjusted to each other in a non-random way. In Illustrations of the Huttonian Theory, Playfair stated:

> "... Every river appears to consist of a main trunk, fed from a variety of branches, each running in a valley proportioned to its size, and all of them together forming a system of valleys, communicating with one another, and having such a nice adjustment of their declivities, that none of them joins the principal valley, either on too high or too low a level; a circumstance which would be infinitely improbable, if each of these valleys were not the work of the stream that flows in it." (Playfair, 1802, p. 102)

The communication between the various parts in a fluvial system includes a multitude of interactions which tend to maintain the delicate balance or equilibrium in the system. The equilibrium that develops in most streams is the quasi-equilibrium described by Leopold and Maddock (1953, p. 41), or dynamic equilibrium discussed by Hack (1960, p. 85).

General Systems Theory

Two major types of systems recognized by Von Bertalanffy (1950) are 1) the closed system with clearly defined boundaries across which energy but not material may pass, and 2) the open system, in which there are no boundaries for either energy or material. The simplest way to look at a fluvial system is to consider it as a closed system in which potential energy is emplaced at a certain elevation, and as the water moves down slope in the drainage network the potential energy is converted into kinetic energy which is lost by turbulence and friction. This idealized picture is over-simplified as very few fluvial systems, with the exception of flash floods in closed basins of semi-arid regions, can be considered a closed system. In most natural fluvial systems energy and material are constantly being added to or subtracted from the system, and thus must be considered open systems. The advantages and importance of viewing streams as open systems has been discussed by Strahler (1952a) and Chorley (1962). The main advantage of an open system is that a steady state can be achieved, in which form remains constant but energy and material still move through the system. Thus, a time-independent steady state in a stream reach may develop quickly, and the forms produced will remain unchanged as long as the amount of energy and material through the reach remains constant. However, the forms must change if the energy or material levels change. A graded stream, as defined by Mackin (1948), is an example of an open system which has reached a steady state. If discharge or bed-load is increased or decreased, the stream will change its slope to adjust to a new steady state. Thus, the open system is a self-regulating mechanism (Strahler, 1952a, p. 935).

Concept of Entropy in Fluvial Systems

Leopold and Langbein (1962) suggested that the distribution of energy in a fluvial system tends toward the most probable state and, furthermore, that a fluvial system in dynamic equilibrium can be compared to a classical closed system in thermodynamics. The analogy comes from the second law of thermodynamics, which states that there is an increase in entropy in every natural process provided the entire system taking part in the process is considered. However, there are significant differences between a closed thermodynamic system, in which heat energy is referenced to absolute temperature as a base, and an open fluvial system. Justification by Leopold (1962, p. 533) for using the concept of entropy in fluvial systems was: 1) Fluvial systems have a base datum with regard to distribution of energy as do thermodynamic systems. This base datum is base level, which in most cases is mean sea level; 2) Fluvial systems, although they are not closed systems as in the classical treatment of entropy in thermodynamics, do reach a steady state or dynamic equilibrium; and 3) It is the statistical or probability concept of entropy which seems to have application to fluvial systems. Leopold and Langbein (1962) defined entropy as a measure of the energy which is not available to do external work and, therefore, an increase in entropy is a measure of the decrease in availability of energy. The important point is that the entropy of a system is a function of the distribution of energy rather than the total energy. The conclusion drawn from the application of the entropy concept to fluvial systems is that the most probable distribution of energy is one in which energy is as uniformly distributed as geologic constraints allow, and the downstream rate of production of entropy is constant. The concept of entropy in fluvial systems appears to be one of the major breakthroughs in understanding energy relationships in streams, and has recently been used by Yang (1971a) to explain why some streams must meander.

CHAPTER 3

DEVELOPMENT OF DRAINAGE NETWORKS

General Statement

Topology, as defined for geomorphic channel network analysis, is concerned with the way in which various channels are connected to produce a branching network. In a classic paper on the erosional development of streams, Robert E. Horton (1945) presented quantitative measures to define the topological characteristics of stream channel networks. The Law of Stream Numbers which he introduced to relate the number of stream segments of various orders to stream order itself has since been exhaustively studied, and shown to be valid even when Strahler's modification of Horton's order is used (Strahler, 1957). However, as demonstrated by Shreve (1966), the variance of stream numbers from this geometric series law is inherently restricted by the definition of the Horton-Strahler system of ordering. The most probable networks, as predicted by Shreve, show a systematic deviation from Horton's law of stream numbers such that the bifurcation ratios decrease as order increases for a given set of stream numbers.

The topological development of drainage networks has been the objective of a number of other studies. Schumm (1954) investigated the evolution of drainage systems on badland topography. Morisawa

(1964) studied the growth of a drainage network on a newly exposed lake bed, and found that drainage networks tend to obtain a steady state relatively quickly and that subsequent changes in topologic properties are constrained. Model studies by Parker and Schumm (1971) suggest that fluctuations in bifurcation ratios occur as drainage networks evolve until a stable intermediate value is reached. Therefore, it is likely that as channel networks develop, a series of changes occur when threshold values of topologic parameters are repeatedly exceeded.

The authors suggest that a relationship between the number of links and segments in a stream channel network is valuable in explaining changes in both Strahler stream order and bifurcation ratio as a stream network evolves. Theoretically, this relationship delineates a family of curves which represent threshold boundaries for stream order.

Basic Concepts

Quantitative analysis of drainage networks is expected to become a valuable tool to both geomorphologists and hydrologists. Although geomorphologists are primarily interested in the pattern and form of the channels, whereas hydrologists are concerned with the liquid phase, both groups use as the basic unit for study the set of all channels above a given point in a network. A diagram consisting of the channels, idealized as single lines, is called a drainage network, also called channel network, network or net (Smart, 1971a, p. 1).

Topologic elements useful in describing a drainage network are: 1) nodes; 2) links; 3) segments; and 4) outlet (Fig. 1). Nodes

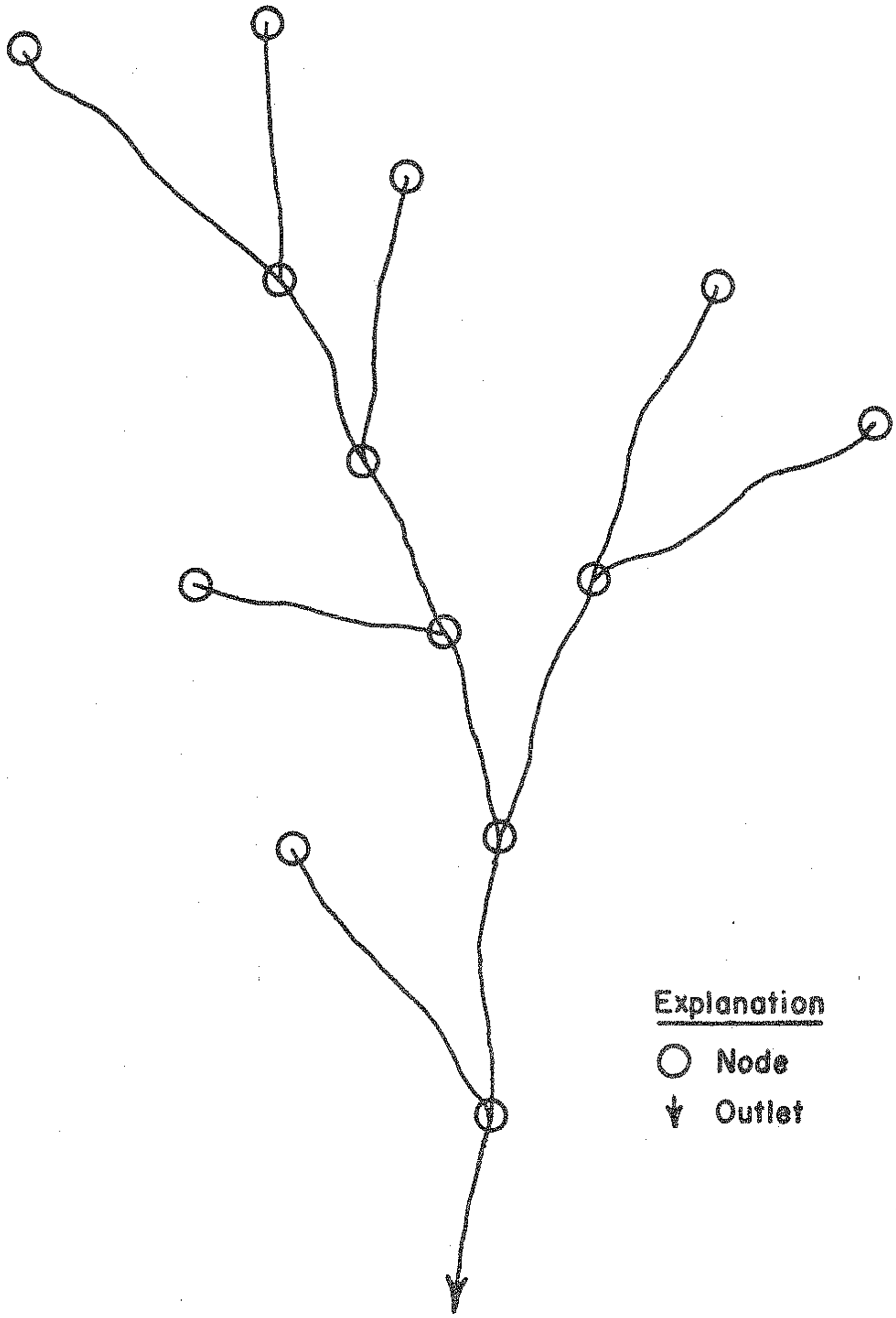


Figure 1. Idealized diagram of a drainage network.

denote sources and junctions. It is assumed that multiple junctions do not occur in nature, and apparent exceptions are resolved by more detailed mapping. A link is the stream channel between any two consecutive nodes in the channel network, and a set of uniquely defined, consecutive links of equal order is designated a segment. The outlet is the farthest point downstream in the network.

The most common classification of drainage networks is the Horton-Strahler method (Strahler, 1957). The ordering procedure (Fig. 2) is: 1) channels that originate at a source are designated first-order streams, 2) when two streams of order "n" join, a stream of order n + 1 is obtained; 3) if streams of different order join the segment downstream from the junction, it is then given the higher order of the two; and 4) the order of the entire drainage net is the highest order of any segment in the network.

For small networks, a classification by magnitude (Shreve, 1967, p. 179) may be more valuable than by order. This results because two drainage networks, each with 25 sources, are probably more similar hydrologically than two fourth-order networks, one with 25 sources and the other with 50 (Smart, 1969). The magnitude of any link in a drainage network (Fig. 3), wherein every source stream is assigned magnitude 1, is equal to the number of sources upstream from that link. Therefore, the magnitude of a network is equal to the number of sources above the outlet. Magnitude is related to the number of links in a network by the relationship $n = 2m-1$, where n is the number of links and m the magnitude.

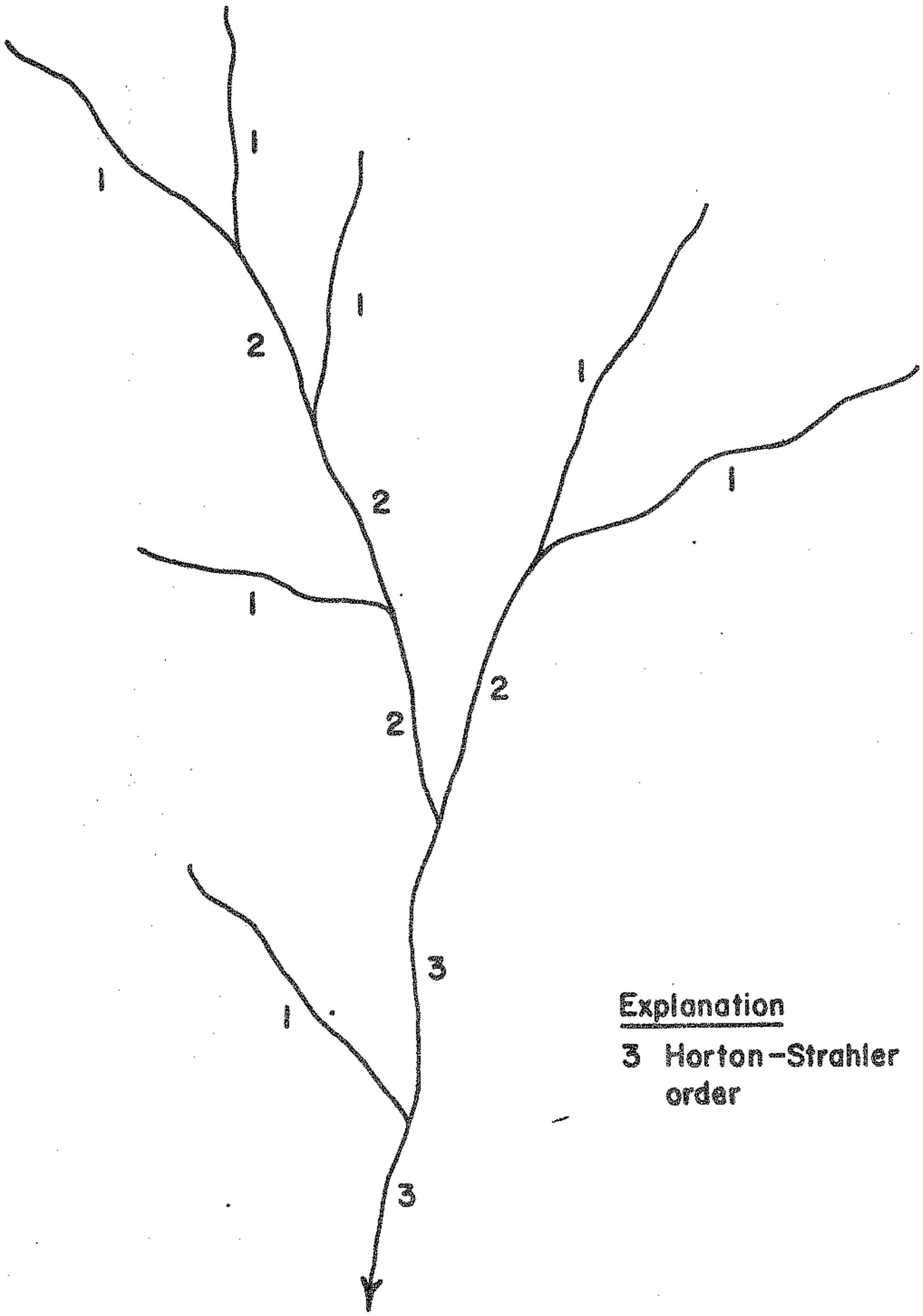


Figure 2. Idealized diagram showing the Horton-Strahler ordering system.

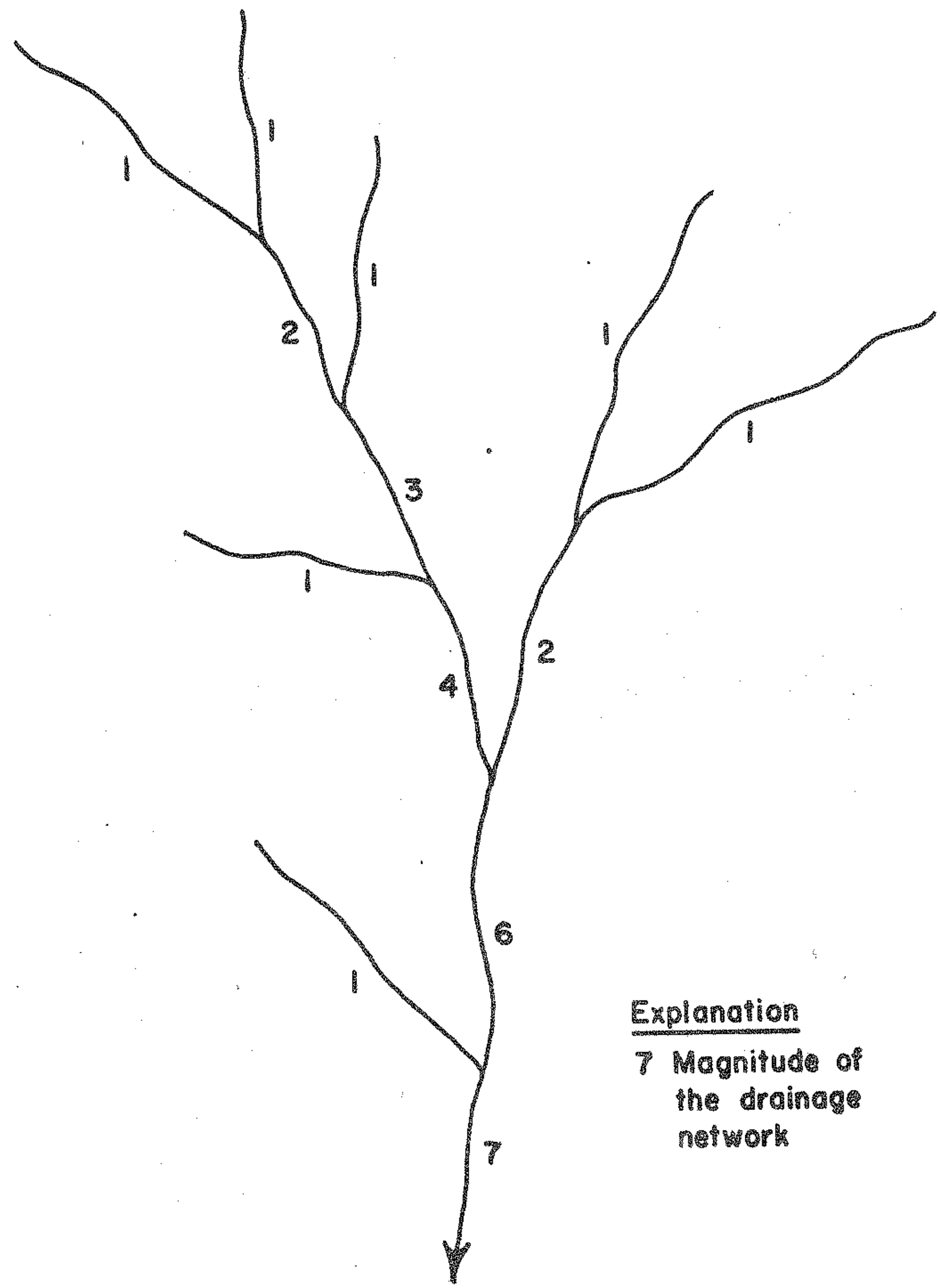


Figure 3. Idealized diagram showing the Shreve magnitude concept.

Data Accuracy and Collection

Considerable effort has been devoted to determining the accuracy and validity of drainage maps used for stream network analysis. Studies by Morisawa (1959) and Coates (1958) suggest that networks obtained from blue lines of U.S.G.S. topographic maps with scales of 1:62,500 or 1:24,000 are generally unreliable. Strahler's (1952b) "Method of V's" decreases the number of otherwise overlooked segments obtained from such maps, but introduces uncertainty about the actual order of the smallest segments. Figures 4 and 5 (Coffman and others, 1971) show stream orders interpreted from 1:24,000 topographic maps using "blue line networks" and "Method of V's" as compared to true stream orders obtained from field-checked aerial photographs. Although the accuracy of drainage maps varies with the total relief of each 7 1/2' quadrangle, it is concluded that topographic maps do not generally show channel networks which are proportional to the real network. The importance of using accurate channel networks when studying topological parameters is thus emphasized, because if stream segments are randomly deleted from a non-random network, then an apparent random network may be obtained (Smart, 1971b). It is not the intent of this paper to dwell on the random, non-random dichotomy, but caution must be exercised to insure that randomness of network parameters such as numbers and lengths of links is not the result of data collection procedures.

Theoretical Considerations

For networks with only binary junctions, the possible combinations of links and segments are restricted by two boundaries as shown in

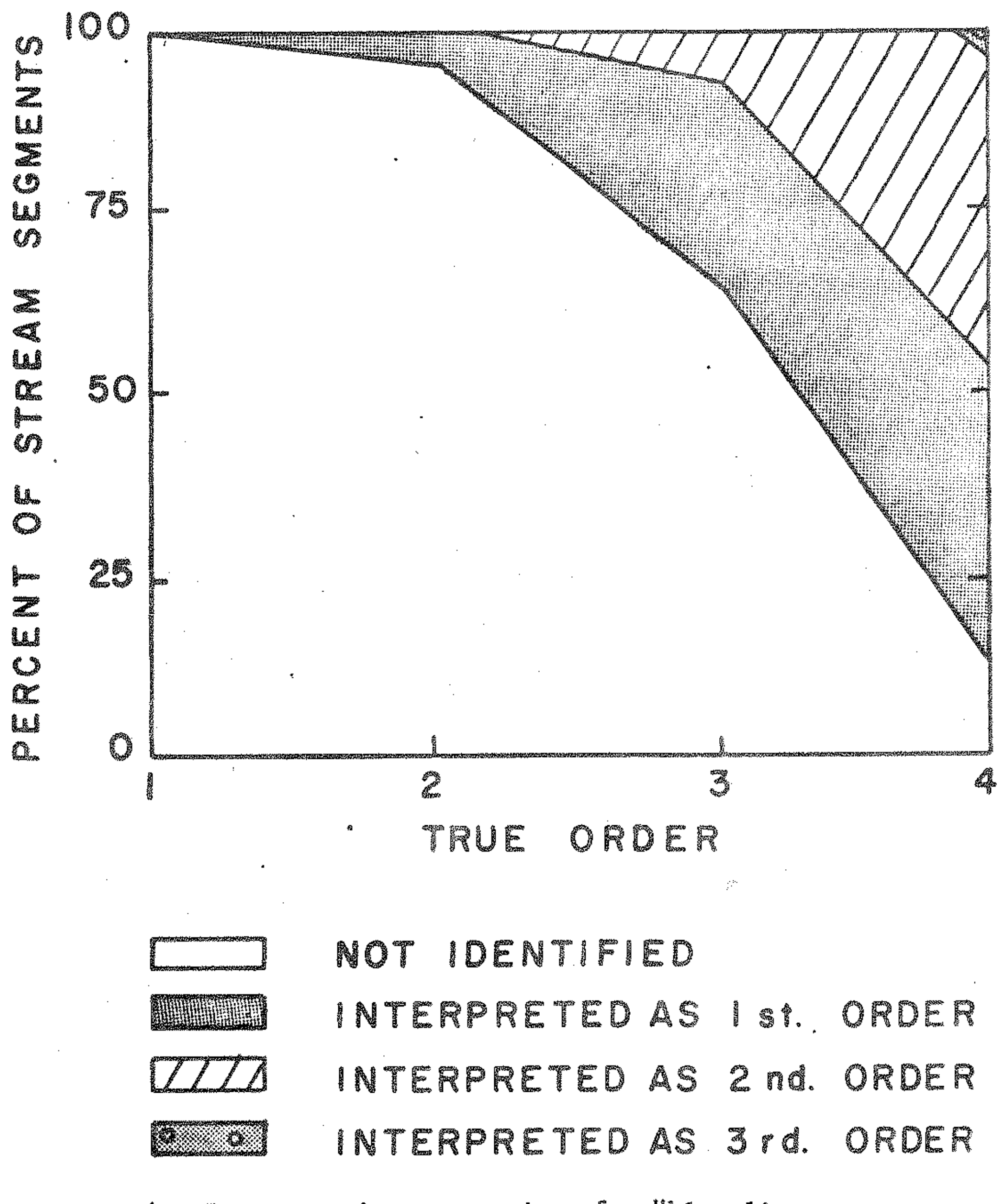


Figure 4. Interpreted stream orders for "blue-line networks", compared to true stream orders (after Coffman and others, 1971).

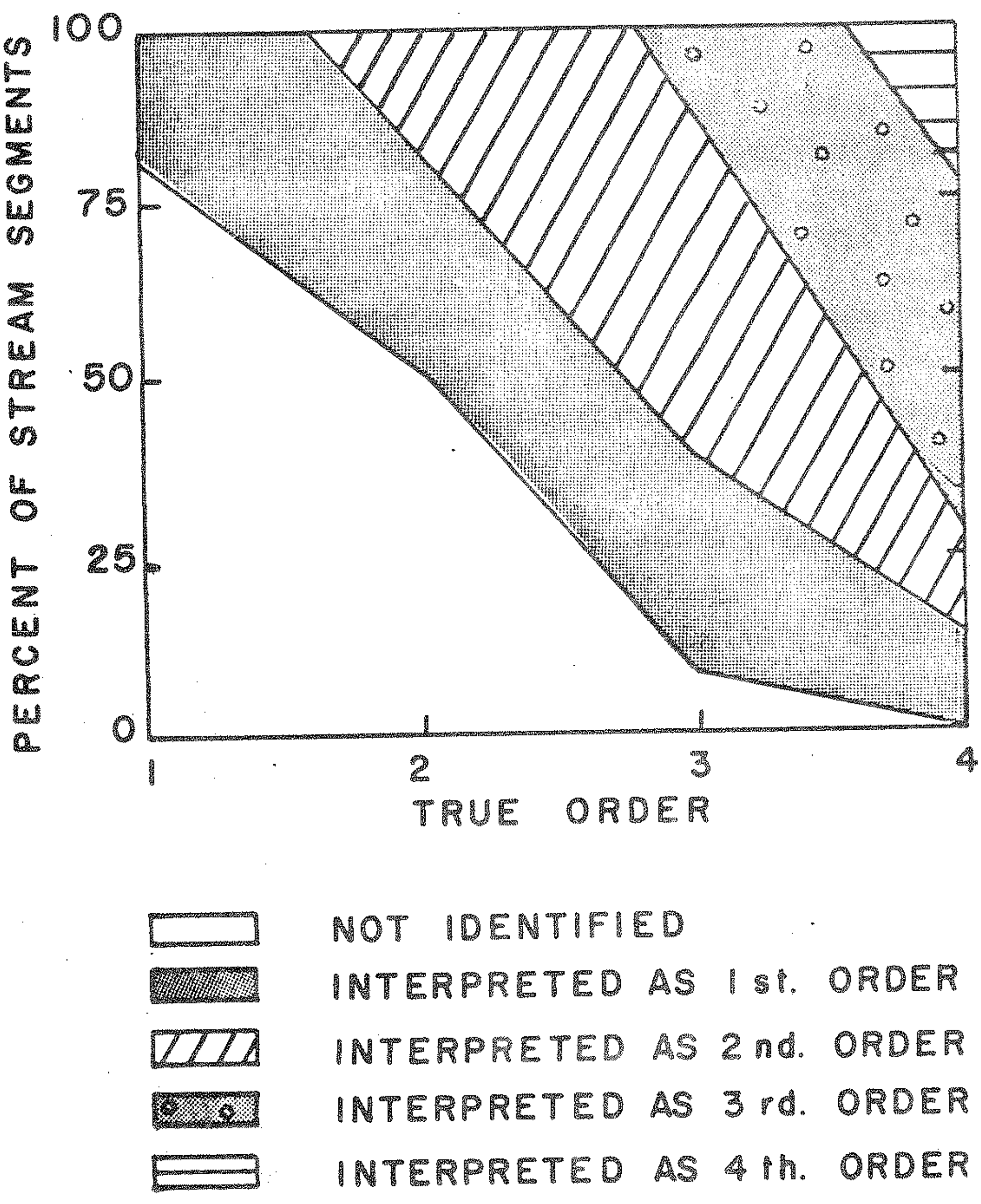


Figure 5. Interpreted stream orders after applying "Method of V's", compared to true stream orders (after Coffman and others, 1971).

Figure 6. The lower boundary, y = x, where y is the number of links and x is the number of segments, minimizes the number of links for a given number of segments. This boundary defines a perfect binary network in which only segments of equal order combine. It is characteristic of this line that the bifurcation ratio is a constant two and that stream order increases with the number of segments.

The upper boundary y = 2x - 3 maximizes the number of links for a given number of segments. This boundary is obtained by holding the stream order constant at two and continually adding first order tributaries, thus increasing bifurcation ratio along the line. All possible combinations of links and segments which can compose a channel network must plot on or in the envelope defined by these boundary lines. Therefore, this envelope is a visual illustration of restrictions to the link-segment relationship as produced by the Horton-Strahler ordering procedure.

Topologically, there is no general threshold condition, dependent only on the number of links and segments, at which the Strahler stream order of a network must increase. For most combinations of links and segments, numerous networks may be derived which have different Strahler stream orders. Exceptions to this statement occur on the lower boundary of the link-segment envelope. Along this line (y = x, Fig. 7), for binary networks, order must change predictably with the number of links and segments. For example, the x,y coordinates 3,3 have an order two, 7,7 an order three, and 15,15 an order four.

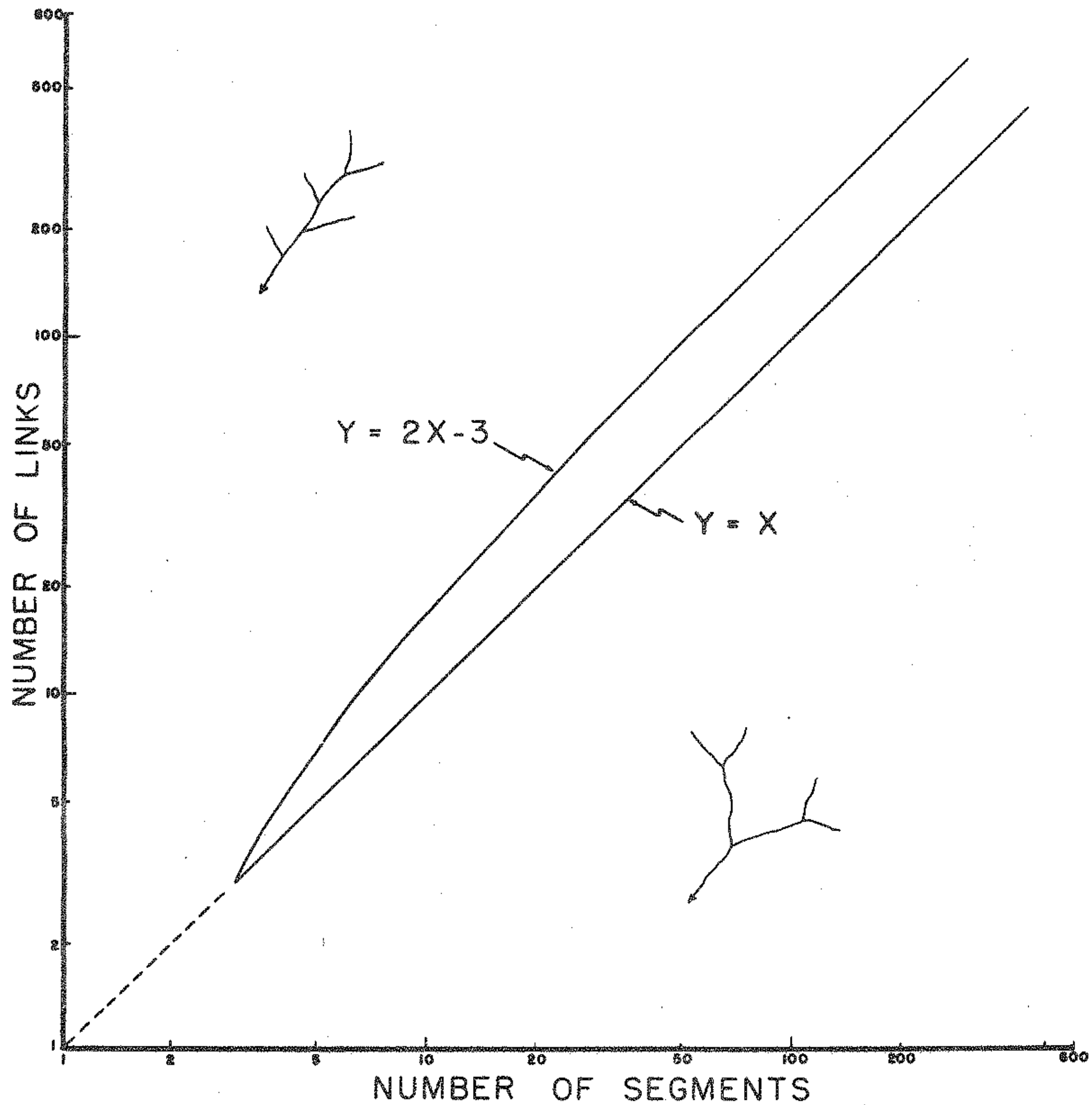


Figure 6. **Upper and lower boundary for all possible combinations of links and segments that produce channel networks.** The lower boundary, y = x connects perfect binary networks of different order, whereas the upper boundary, y = 2 x - 3, connects all possible second order networks.

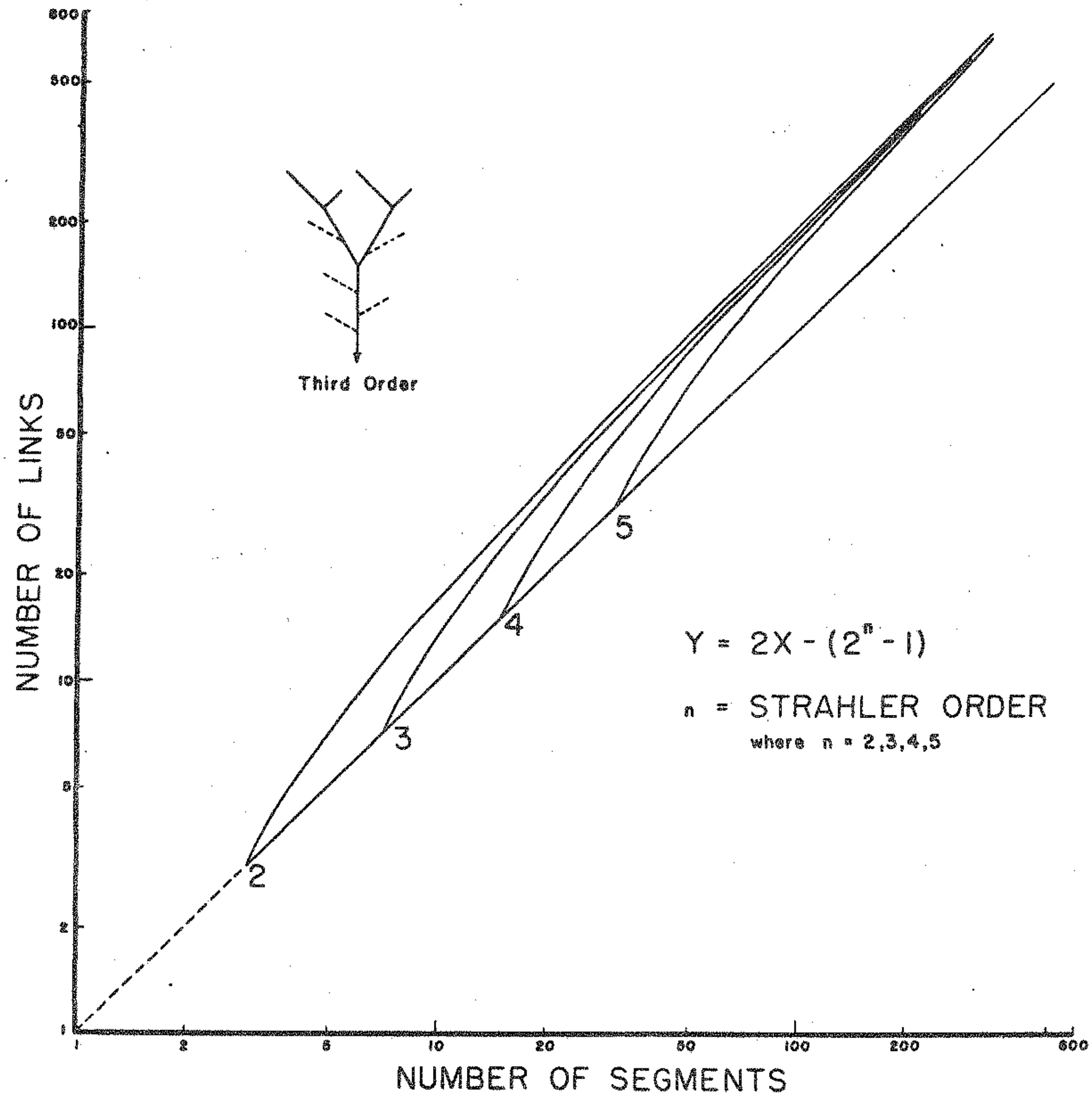


Figure 7. Theoretical threshold boundaries between networks with different Strahler stream order.

The upper boundary line represents a threshold condition for combinations of links and segments which will produce a network with an order of two. It is assumed that threshold lines for other Strahler orders can be generated by adding only first-order segments to the perfect binary networks on the lower boundary line. The general equation for these lines is $y = 2x - (2^n - 1)$, where y is the number of links, x is the number of segments, and n is the Horton-Strahler order. This family of curves (Fig. 7) represents theoretical threshold boundaries between different Strahler orders. The fields between these thresholds represent areas where networks of a given order should plot. Networks not plotting in their proper order field may be unstable, and subsequent growth will tend to move such networks into more probable order fields.

A second family of curves representing constant bifurcation ratios can also be plotted within the link-segment envelope (Fig. 8). These lines were obtained by building networks with given bifurcation ratios between all orders and plotting the numbers of links and segments.

Comparison of Theoretical and Natural Channel Networks

To test theoretical conclusions derived from the interrelationship between numbers of links and segments in channel networks, 106 natural channel networks were selected from detailed surface drainage maps for analysis (Fig. 9). These maps were prepared by the staff of the Airphoto Interpretation Laboratory of the Joint Highway Research Project at Purdue University and are of the highest quality

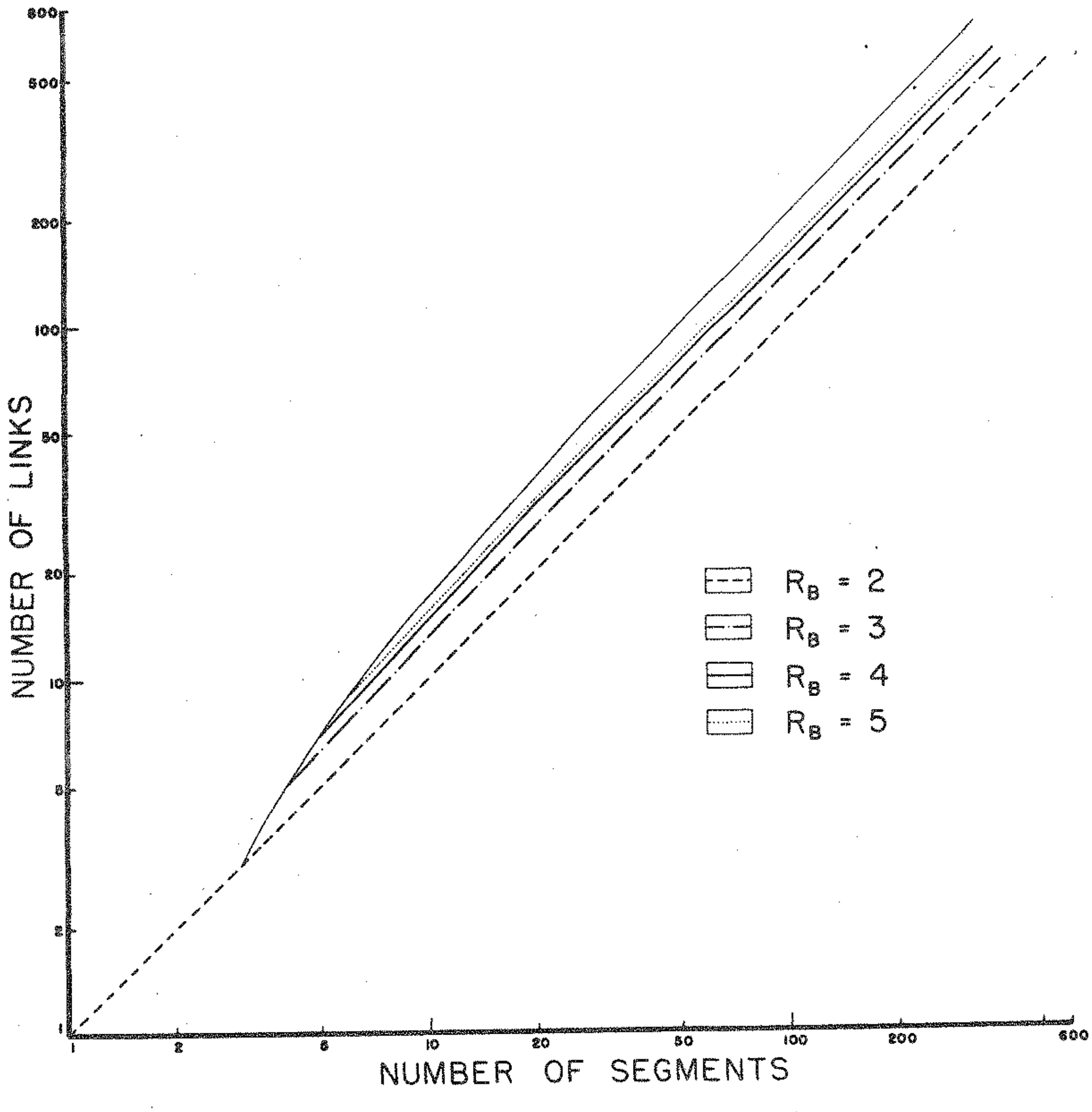
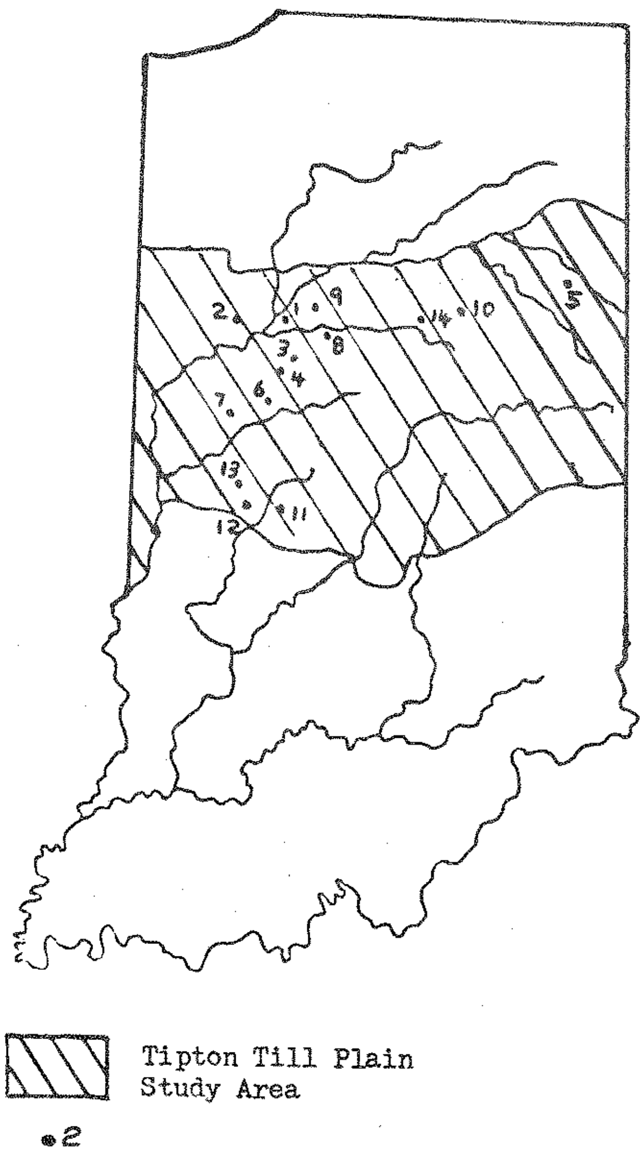


Figure 8. Relationship between links, segments, and bifurcation ratios.



1. Sugar Creek Basins, Tippecanoe County
2. Indian Creek Basins, Tippecanoe County
3. North Fork Wildcat Creek Basins, Tippecanoe County
4. South Fork Wildcat Creek Basins, Tippecanoe County
5. Scuffle Creek Basins, Wells County
6. Sugar Creek Basins, Montgomery County
7. Coal Creek Basins, Montgomery County
8. Middle Fork Wildcat Creek Basins, Carroll County
9. Bridge Creek Basins, Carroll County
10. Stony Creek Basins, Grant County
11. Deer Creek Basins, Putnam County
12. Walnut Creek Basins, Putnam County
13. Ramp Creek Basins, Putnam County
14. Wildcat Creek Basins, Howard County

Note - All size networks were taken from the above basins.

Figure 9. Approximate location of study areas.

and accuracy. All sampled channel networks are located in Indiana, north of the Wisconsinan glacial terminus. The surface material type is predominantly glacial till characterized by erosional development in a dendritic drainage pattern. The networks were not selected randomly. Adequate sampling required at least twenty networks of each Strahler order, 2 through 5, and this necessitated stream ordering prior to final selection. Although the data appears log-normal (Fig. 10), I have not been able to demonstrate this statistically. This possibly results from the non-random data collection method. Cognizant of this limitation, a logarithmic transformation is used in the regression model.

A plot of numbers of links (y) versus numbers of segments (x) is, in general, a forced relationship (Fig. 11). As the number of segments increases, the number of links must also increase. This accounts for high correlation between the variables.

A plot of data showing Strahler order (Fig. 12) suggests that the theoretical boundaries derived for order (Fig. 7) are accurate for the lower orders (2,3,4, & 5). All second-order networks and nearly all third- and fourth-order networks fall within their respective fields. Furthermore, all fifth-order networks are beyond the threshold boundary between fourth- and fifth-order networks. However, for higher orders the general equation defining threshold lines does not hold. Hypothetically, this suggests that for an order greater than four, the threshold conditions which control change in order are different than for lower orders. This may result from the inability

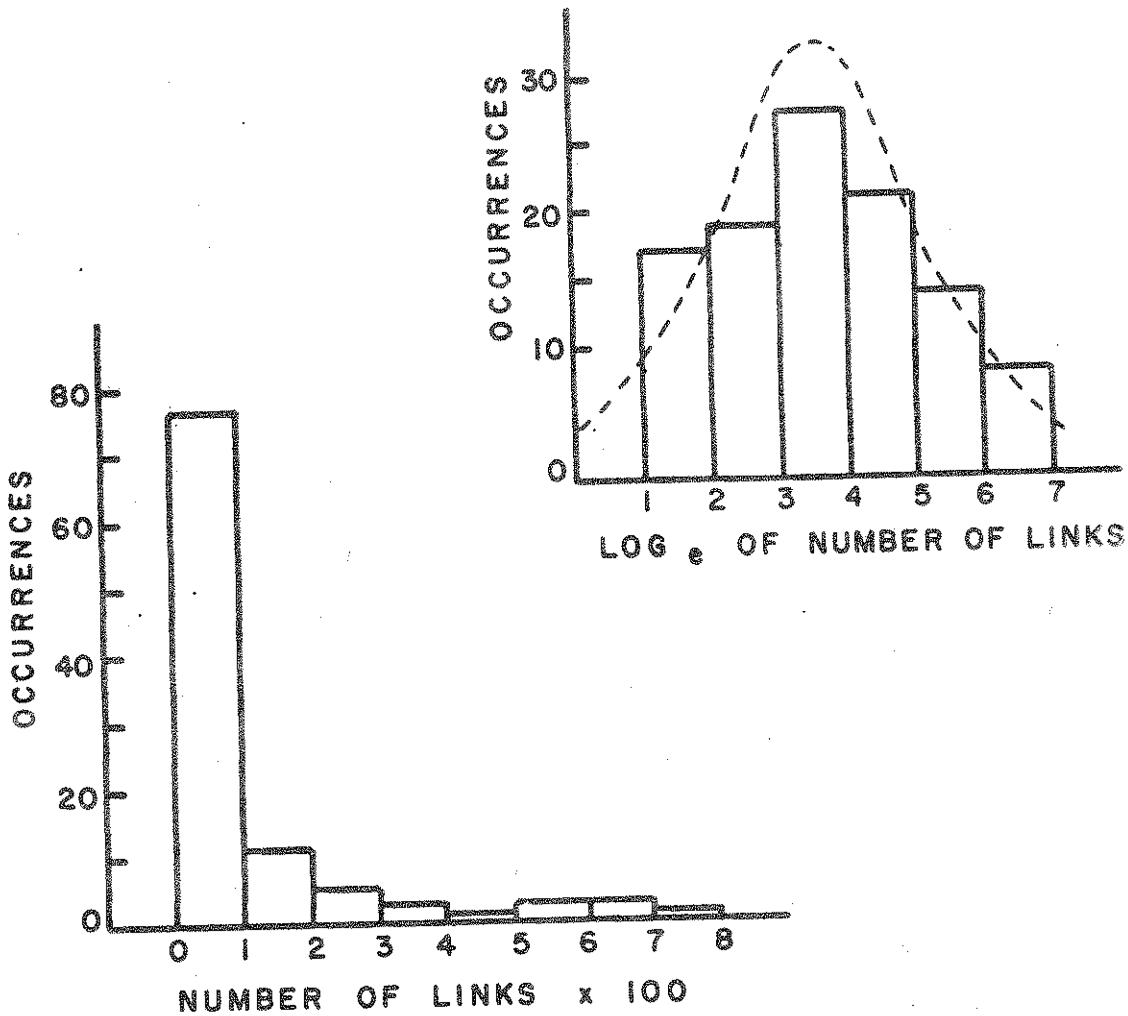


Figure 10. Frequency distributions for the dependent variable (number of links).

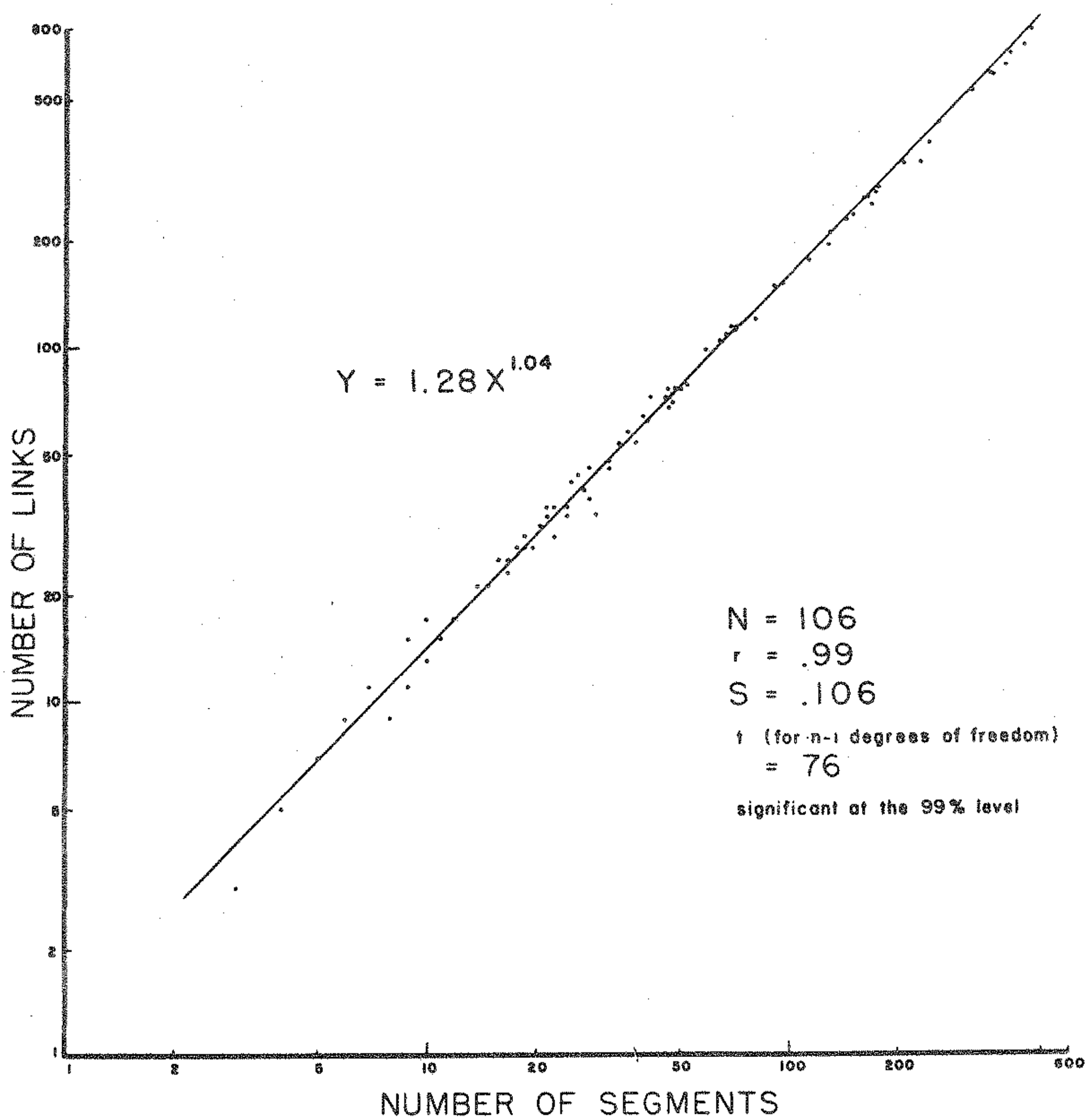


Figure 11. Number of links versus number of segments for natural channel networks.

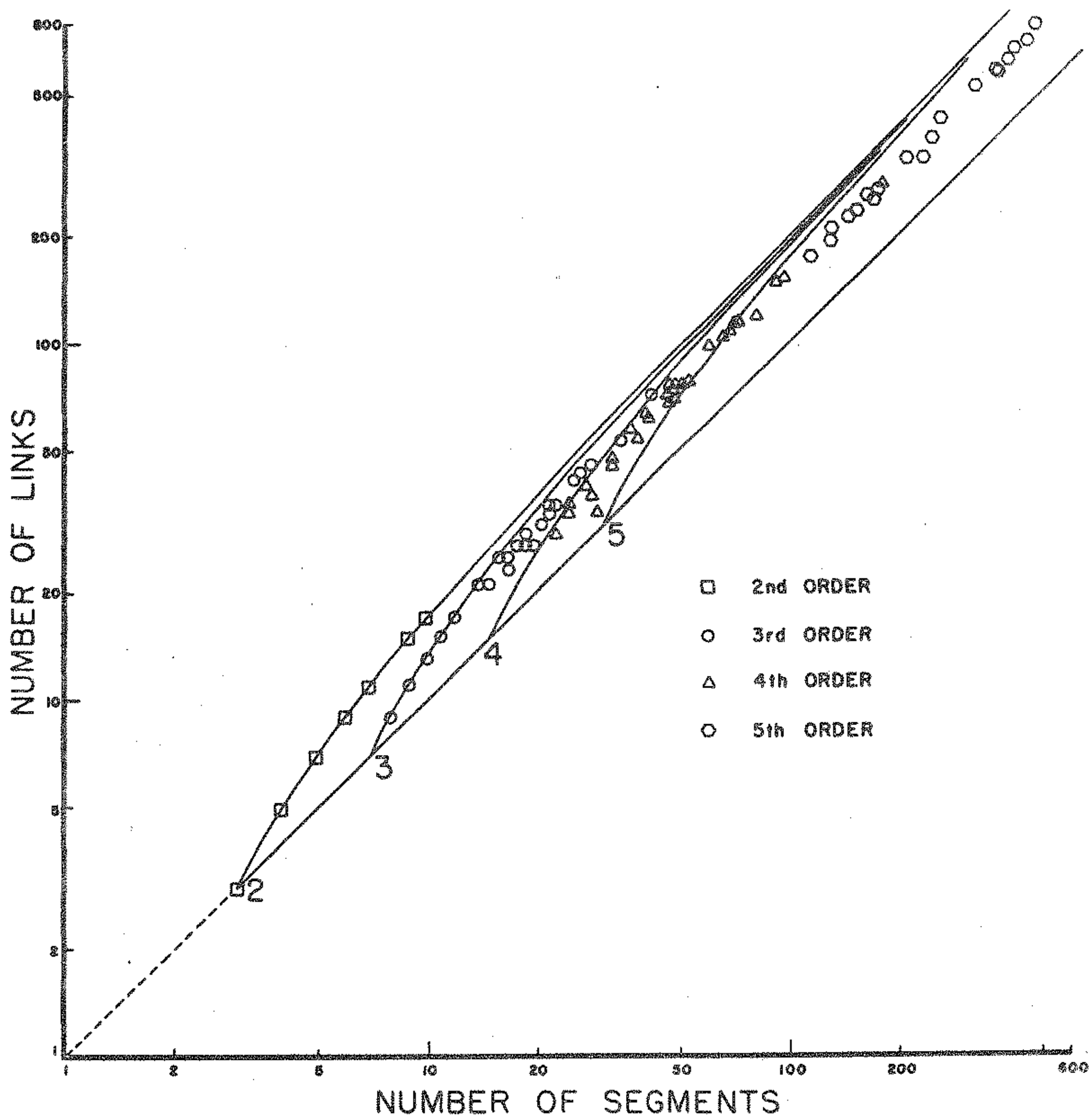


Figure 12. Number of links versus number of segments for natural channel networks ,superposed over the theoretical threshold boundaries for Strahler stream order.

of the equation, stated only in terms of numbers or segments, to reflect the initial premise that only first-order tributaries are being added. However, it may also result from the fact that the threshold lines are minimum, not maximum parameters. In other words, no network of order n can plot to the left of the threshold line $y = 2x - (2^n - 1)$ but, topologically, networks of order n can lie to the right of the boundary line $y = 2x - (2^{n+1} - 1)$.

Probability data from Shreve (1966), plotted in terms of links and segments (Fig. 13), show that the most probable channel network with 53 links, is fourth-order. This network plots in the fourth-order field of figure 13, almost directly on the regression line. Other channel networks of known order, taken from Shreve's work, generally plot within the expected fields. This suggests that order can be predicted from the number of links and segments. Furthermore, for a given number of links with variable number of segments, or a given number of segments with variable number of links, the most probable channel networks will plot close to the regression line of figure 11.

Discussion

Parker and Schumm (1971) have demonstrated that, during the evolution of a drainage network, the bifurcation ratio fluctuates until a stable value is reached. Figure 14 shows the bifurcation ratio for a network increasing until an improbably high value is reached, at which time tributaries are added in such a manner that order is

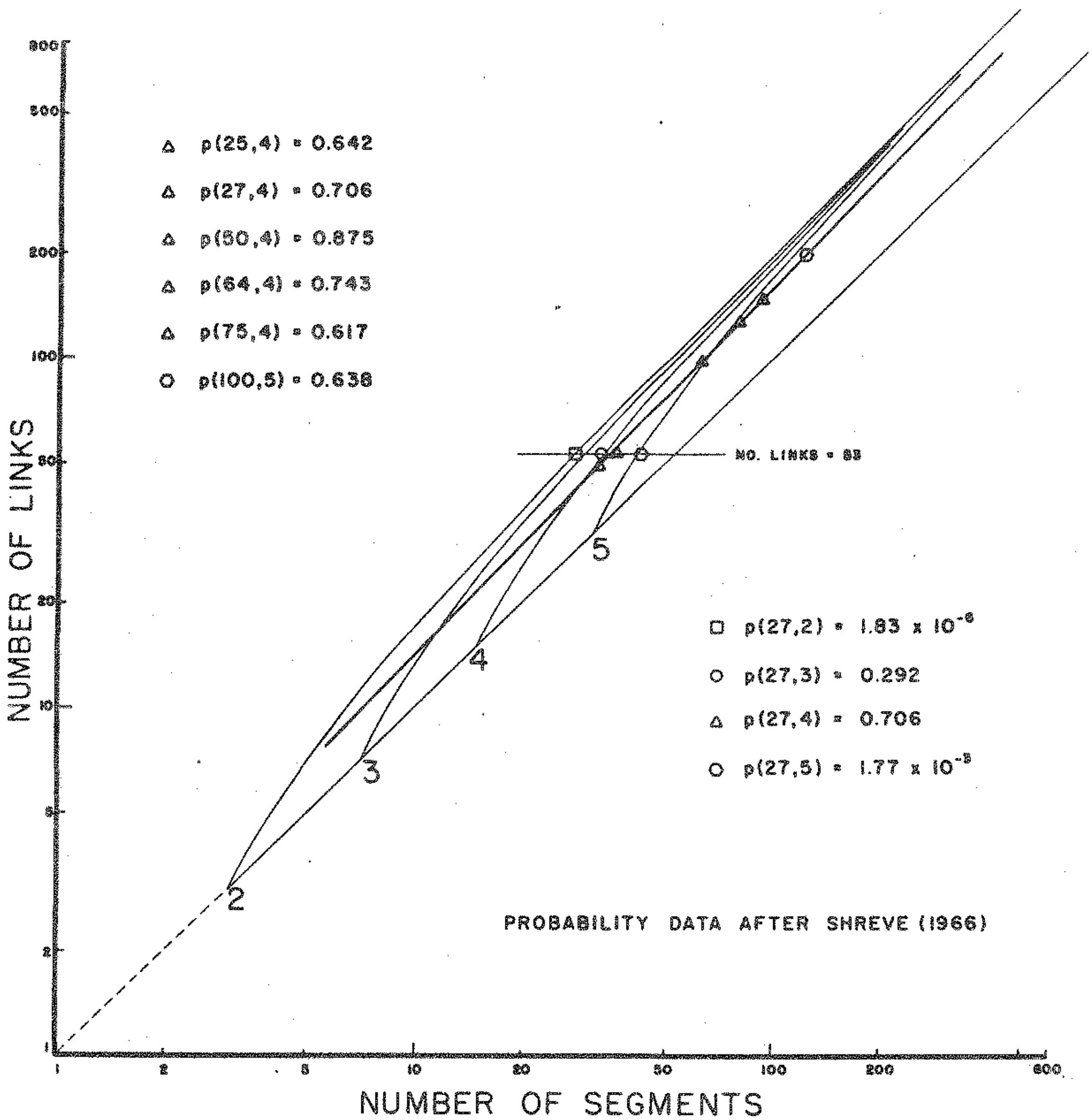


Figure 13. Comparison of Shreve's (1966) probability data with theoretical boundary conditions for Strahler stream order.

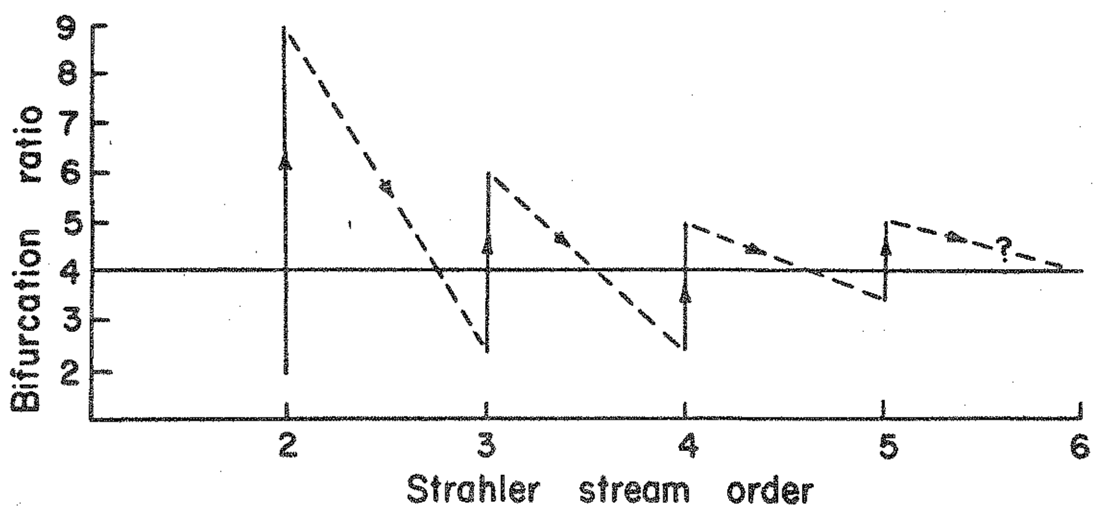


Figure 14. Idealized decrease in the range of the bifurcation ratio with increasing Strahler stream order.

increased and the bifurcation ratio reduced. Hypothetically, the range of bifurcation ratio fluctuations decreases to a constant value in the form of an absolute convergent series. Although the 106 basins used in this paper may not account for maximum variability of bifurcation ratios with order, the data in figure 12 suggest that the trend is probably correct.

The fluctuations in bifurcation ratios during an idealized evolution of a stream net may be understood by examination of figure 15. A small stream begins to grow through the addition of first-order links. The second-order segment continues to develop until its bifurcation ratio becomes improbably large. A segment is then added in such a manner that the stream orderis increased to three, resulting in a decrease of the bifurcation ratio between first- and second-order segments ($N_1/N_2 = R_{B2}$). First-order segments are again added until the bifurcation ratio becomes improbable. Addition of the next tributary reduces R_{B2} to 4.3, and addition of a second tributary increases the order of the network to four, meanwhile decreasing R_{B2} to 3.5. This process continues, with the bifurcation ratios between each consecutive set of orders (R_{B2}, R_{B3}, R_{B4}, etc.) approaching four in a staggered manner. This model of growth patterns appears similar to the one proposed by Schumm (1954, Fig. 24) from his study of the Perth Amboy badlands. Figure 16 shows the path of the idealized growing network plotted on the link-segment envelope. A major constraint controlling stream development is that order cannot increase until a threshold number of links and segments is realized. It is emphasized that this is an idealized growth model (Figs. 15 and 16) and may not completely depict natural network

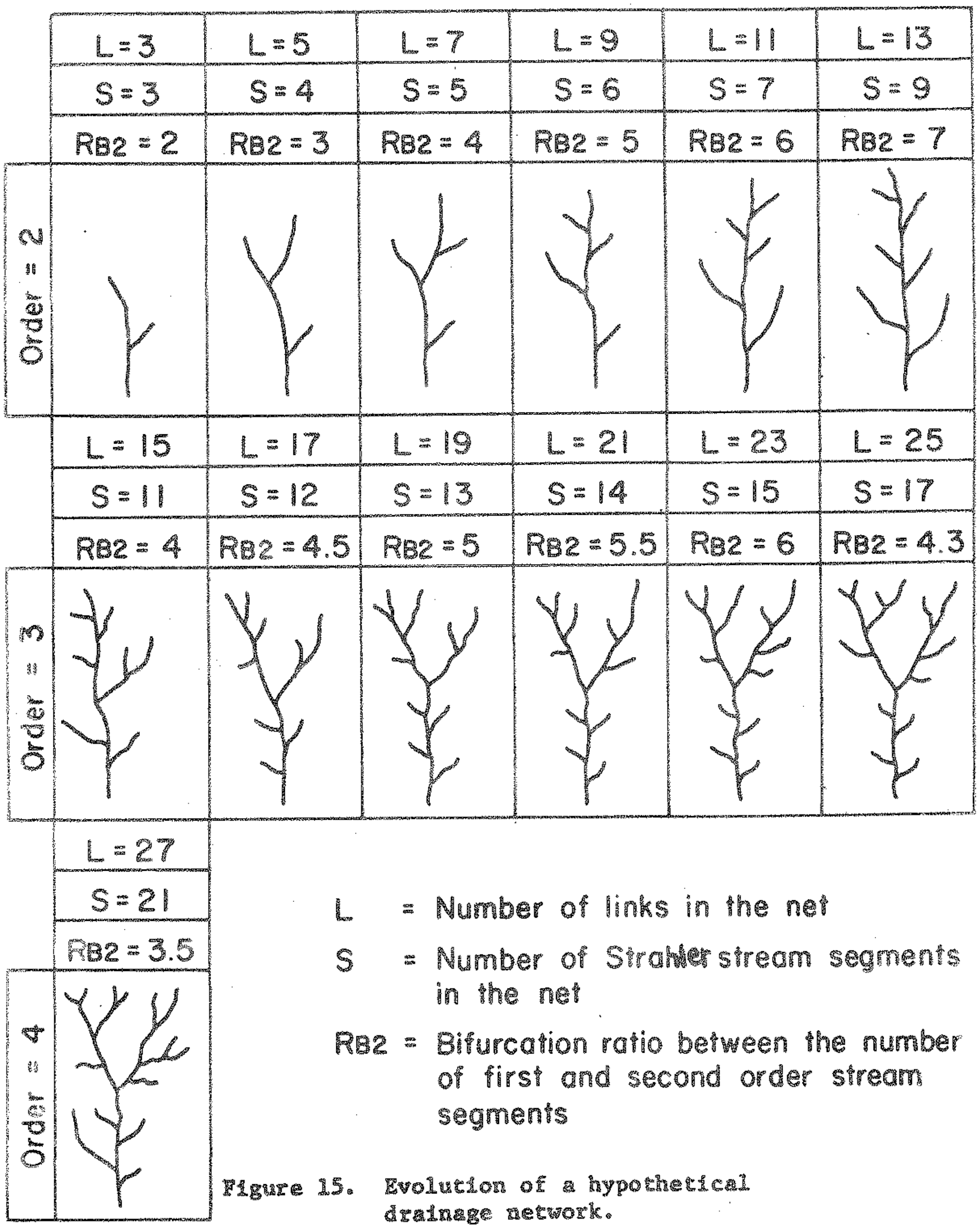


Figure 15. Evolution of a hypothetical drainage network.

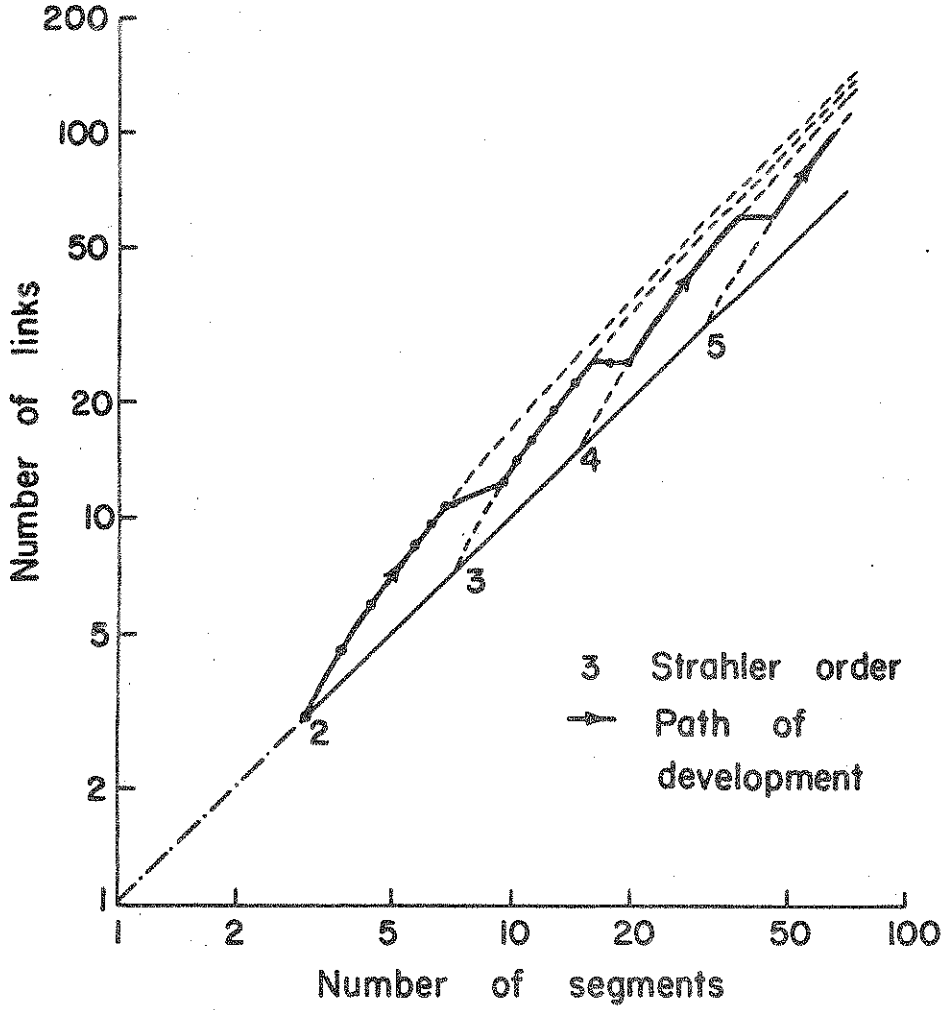


Figure 16. Possible development of a drainage network showing an increase in bifurcation ratio, followed by an increase in order and decrease in bifurcation ratio.

evolution, which may be considerably more complex. However, the basic idea of fluctuating bifurcation ratios appears essentially correct.

The relation between links and segments (Fig. 13) is valuable as an indicator of network development in plan view (Fig. 15 and Fig. 16). However, the concepts of energy distribution discussed in CHAPTER 2 include the vertical dimension. Therefore, theoretical consideration must be given to combining the entire dimension of a drainage basin. Yang's (1971c) work appears best suited to accomplish this. His law of average stream fall, derived from the concept of entropy, states that given dynamic equilibrium conditions in the system, the ratio of average fall between any two different Strahler-order streams in the same network (drainage basin) is equal to one. Therefore, by combining Yang's work with this report, it can be stated that as a drainage network evolves from simple to complex, order will increase after bifurcation ratios become improbably large and a critical decrease in elevation has occurred.

CHAPTER 4

ALLUVIAL STREAM CHANNELS

General Statement

Alluvial stream channels are defined, for all conditions below bankfull discharge, as natural channels with predominantly unconsolidated bed and bank material. Furthermore, alluvial channels seldom scour to bed rock and are formed and maintained by bankfull flows with a recurrence interval (defined as the average number of years within which a given flow will be equaled or exceeded) of one to two years (Dury, 1969). Lokhtine (1909) concluded that there are two fundamental classes of channels: stable and unstable. Stable channels are characterized by a succession of shallows and pools, and although the bed material is continuously moving through the channel, the location of the shallows and pools remains fixed. This may be considered a particle by particle replacement process in which the form remains unaltered. Unstable channels are characterized by little tendency toward stability or fixation of bars, pools, or shallows. In these channels, forms produced by one flow are usually swept away by the next. Quantitative determination of the degree to which a channel is stable or unstable was attempted by Lokhtine (1909). His "coefficient of fixation", defined as the ratio of average particle diameter to water-surface slope, supposedly reflected the degree of channel fixation. High values suggested stable channels, whereas low values reflected unstable channels. Therefore, channels with steep slopes or fine-grained bed material would tend to be unstable, and a fixed sequence of shallows and pools would not develop. This conclusion generally agrees with numerous field observations by the writer.

The necessity of studying natural alluvial channels, rather than flume or model studies, cannot be emphasized too strongly. Thomas Maddock Jr., one of the leading researchers in fluvial hydrology states:

> "Of all the elements that made up a plan of water resources development, those concerning the movement of water in alluvial channels are the least understood. This is because the bed where most of the stream energy is dissipated, constantly changes form. Thus the flow in these channels is locally unsteady and non-uniform, and the departures from a steady or uniform state may vary widely." (Maddock, 1969, p. 2)

Maddock further stated (p. 49):

> "Much of what has been considered to be functional relations among the hydraulic variables of flow in alluvial channels is simply the operation of different constraints. Too often the constraints have been flume size, discharge and method of operation. The result is that any supposedly functional relation involving slope is suspect, and this includes both velocity and sediment load, unless the applicable constraints are known. Much about the variations of flow in alluvial channels is unstudied and unknown. In fact, it is probably a good guess that a great deal of variation is wholly unobserved. ..."

The significant factor is that flumes are not natural channels, and the variability of natural alluvial channels cannot be studied in flumes.

Alluvial channels are the product of processes produced by interaction between flowing water and moving sediment, and it is assumed that characteristic channel forms reflect the processes that produced them. This assumption is consistent with Thornbury's fourth fundamental concept:

> "Geomorphic processes leave their distinct imprint upon land forms, and each geomorphic process develops its own characteristic assemblage of land forms." (Thornbury, 1969, p. 20)

Therefore, it is the authors' suggestion that an understanding of the morphology, morphometry, and spatial relations of characteristic forms in alluvial channels will facilitate deductions about the nature of the processes which produce the forms.

Source Areas

Four alluvial streams chosen for detailed observation and mapping were: Dry Creek near Winters, California (Keller, 1969); Durkee Run, Lafayette, Indiana; Wea Creek, near Lafayette, Indiana; and South Fork Wildcat Creek, near Dayton, Indiana.

Dry Creek near Winters, California is an entrenched, meandering stream. Stream flow is intermittent, with an average of 29 days of flow a year and mean/annual flood of 785 cfs (Keller, 1969, p. 24-27). The 1.30 mile studied reach is located upstream from the state highway 128 bridge, at the SW corner, Sect. 21, T8N, R1W (Fig. 17). The intermittent flow and classical pool-riffle sequence in Dry Creek combine to make this stream an excellent field laboratory.

Durkee Run, Lafayette, Indiana is a small, ungaged intermittent stream with fairly well developed pool-riffle sequences. The 0.38 mile studied reach is located upstream from where the stream crosses 9th street in Lafayette, E 1/2, Sect. 33, T23N, R4W (Fig. 18). The channel bed and bank material is primarily alluvium with minor flood plain development.

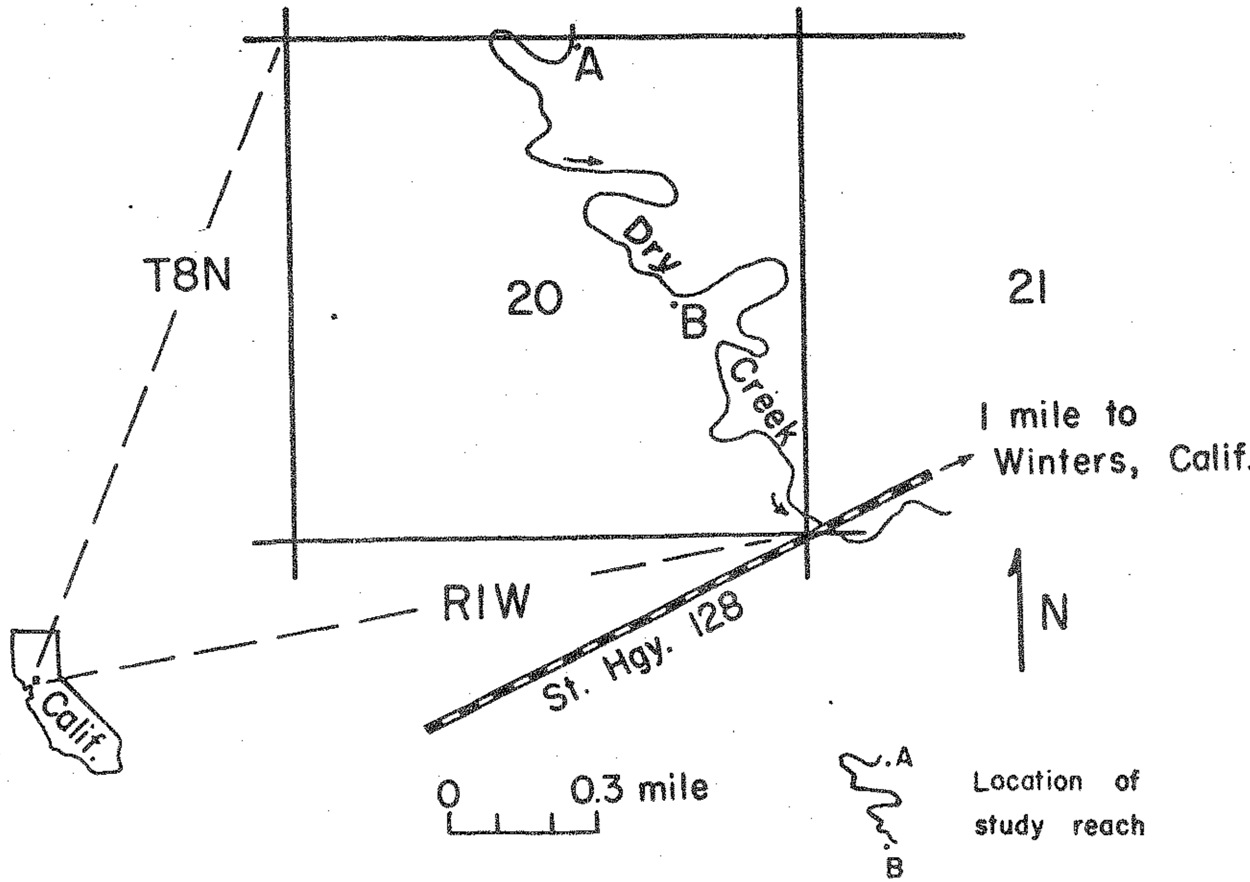


Figure 17. Index map to Dry Creek near Winters California. The study reach is shown in greater detail on Figure 45.

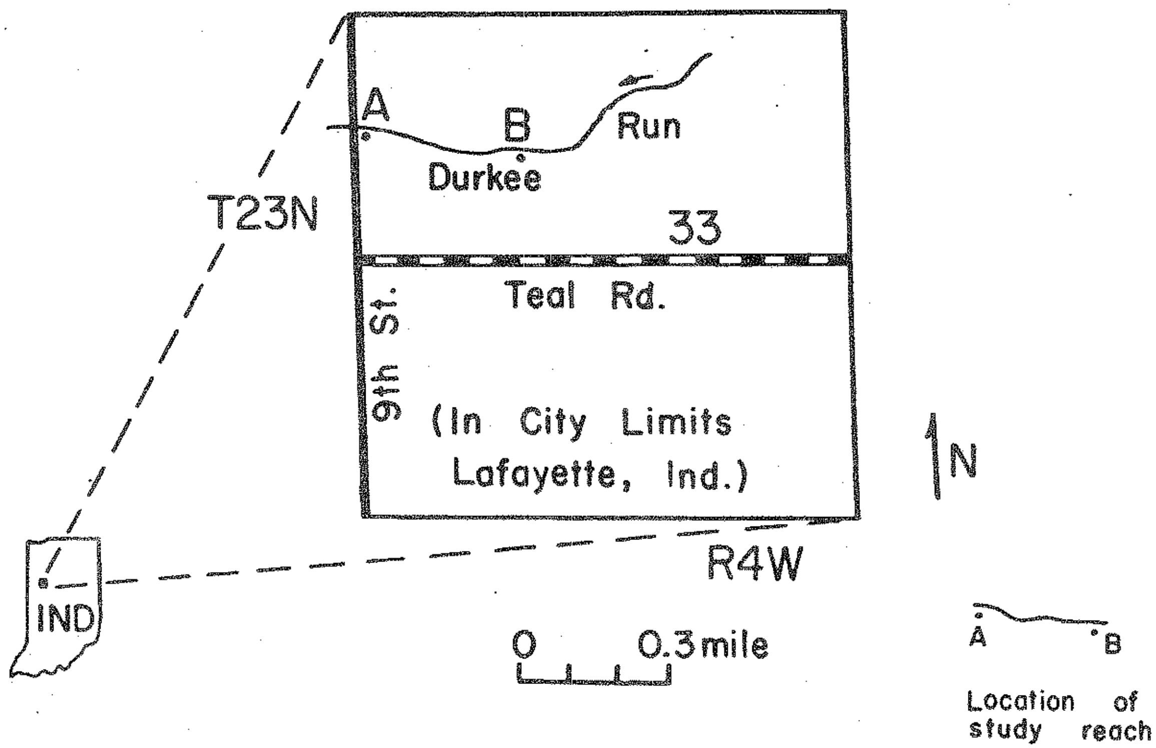


Figure 18. Index map to Durkee Run, Lafayette Indiana. The study reach is shown in greater detail on Figure 45.

Wea Creek, near Lafayette, Indiana is an ungaged perennial stream with well developed pool-riffle sequences. The 1.05 mile study reach is located upstream and downstream from a state highway 25 bridge, in the SW 1/4, Sect. 1, T22N, R5W (Fig. 19). The channel bed and bank material is primarily alluvium, with a fairly well developed flood plain.

South Fork Wildcat Creek, near Dayton, Indiana is a perennial stream with fairly well developed pool-riffle sequences. The 2.80 mile studied reach is located downstream from the bridge over state highway 38, SE corner, Sect. 4, T22N, R3W (Fig. 20). The channel bed and bank material is alluvium with a well developed flood plain. Average discharge over a 26 year period is 227 cfs (Water Resources Data for Indiana, 1969, p. 66).

Channel Pattern

Channel pattern refers to the configuration of a river as it appears in plan view or orthozonal view. The three common channel patterns are straight, meandering, and braided, and all alluvial streams will have one or more of these patterns (Leopold and Wolman, 1957). This concept is significant, because as sinuosity increases channel slope decreases, and this is one of the two ways the potential energy per unit mass of water may be minimized (Yang, 1971a).

Straight channels are those stream reaches with sinuosity, defined as ratio of channel length to valley length, of nearly one. Although straight channels longer than ten times the channel width are rare in nature, they are significant in the development of alluvial

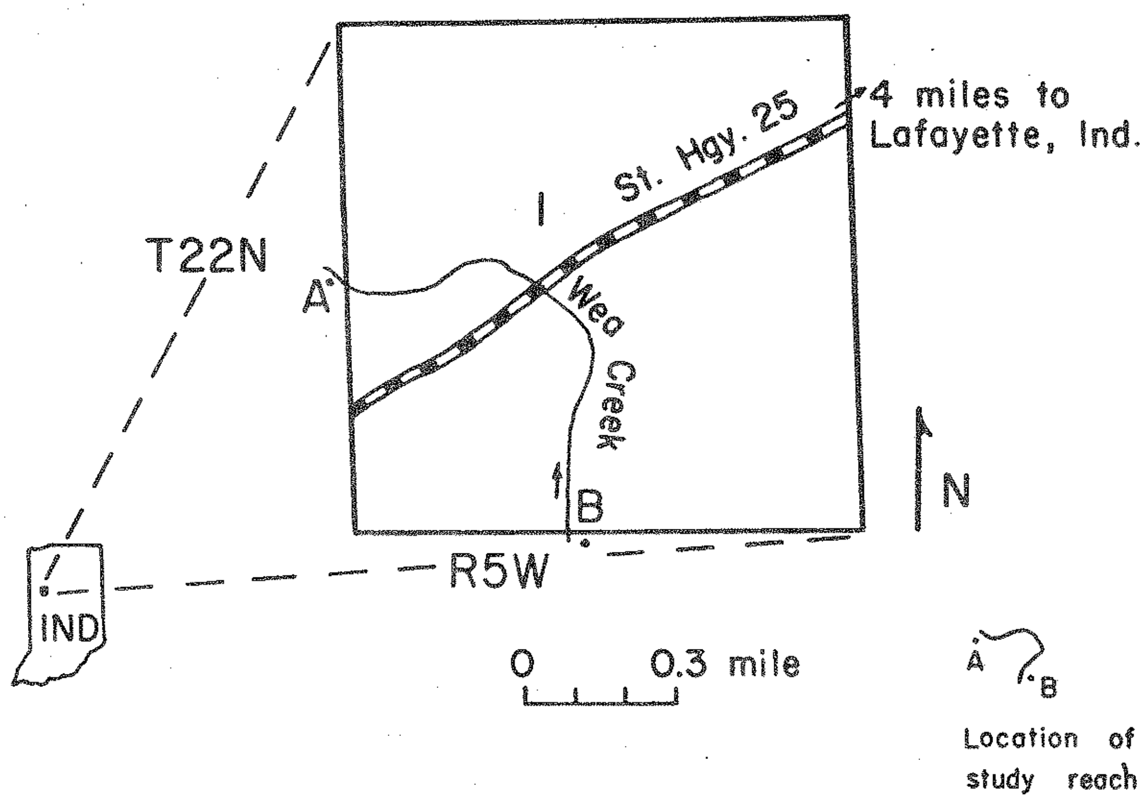


Figure 19. Index map to Wea Creek near Lafayette Indiana. The study reach is shown in greater detail on Figure 45.

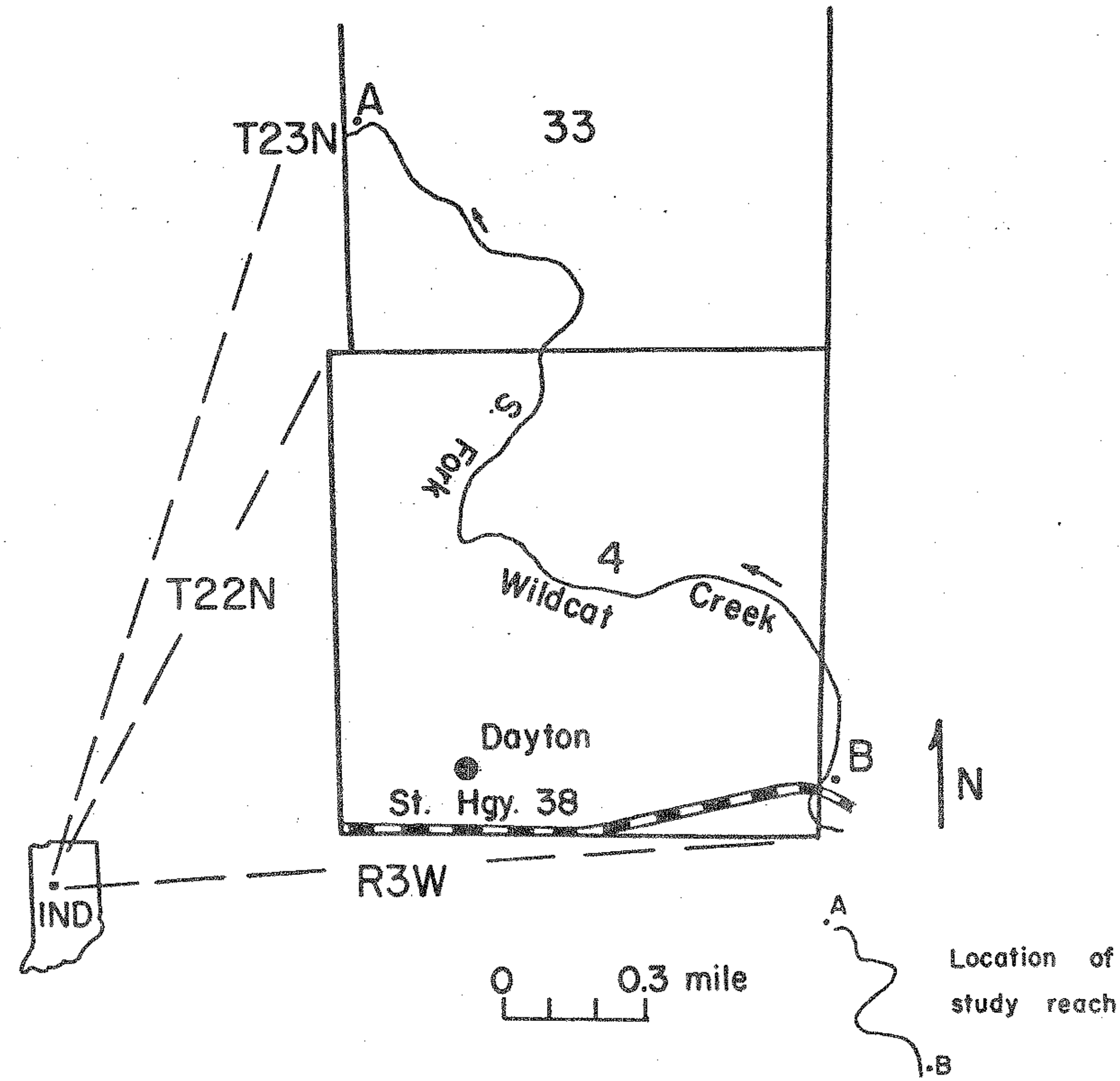

A
T23N
33
S. Fork
4
Wildcat
Creek
T22N
Dayton
St. Hgy. 38
B
N
IND
R3W
0
0.3 mile
A
B
Location of
study reach

Figure 20

channels. Straight reaches are primarily produced in two ways: 1) meander cutoffs; and 2) lateral migration of adjacent meander bends. Furthermore, although a straight channel has straight banks, it implies neither a uniform stream bed nor a straight thalweg (Leopold and Wolman, 1957, p. 55).

Meandering channels are those stream reaches with sinuosity greater than 1.5 (Leopold and others, 1964, p. 281). Although the most probable channel pattern for a stream with a pool-riffle sequence appears to be the meandering pattern (Langbein and Leopold, 1966, p. 1), there are no criteria as to degree of symmetry necessary to designate a channel as meandering.

Braided channels are characterized by an abundance of islands which divide the channel into a number of sub-channels which successively meet and redivide (Leopold and Wolman, 1964, p. 281). Although there is no requirement of sinuosity for braided channels, they appear to be closely related to the meandering pattern (Leopold and others, 1964, p. 292).

It seems desirable to consider adding a fourth channel pattern. With the classification listed above, there is no category for a stream reach with a sinuosity greater than that for a straight stream reach but less than the 1.5 for a meandering reach. Unfortunately, a great many natural channels, one-half of all channels according to Leopold and others (1964, p. 296), have a sinuosity too great to be considered straight and too little to be called meandering. These authors suggested (p. 281) that rivers with sinuosity less than 1.5 be considered either straight or sinuous. However, they did not propose criteria to distinguish straight from sinuous channels. Therefore, for the present discussion, straight channels will be considered as those relatively short stream reaches with sinuosity arbitrarily defined as less than 1.1, whereas longer reaches with higher sinuosity (1.1 to 1.5) will be considered sinuous. With this distinction, Dry Creek, with sinuosity of 2.40, is considered meandering, whereas Durkee Run, Wea Creek, and Wildcat Creek, with sinuosities of 1.13, 1.38, and 1.42 respectively, will be designated sinuous. All of the streams investigated, however, contain short straight reaches, whereas none have braided reaches.

Fluvial Hydraulics

In many alluvial channels, the characteristic forms are produced at relatively high channel-forming flows and are only modified at low flow. Under these conditions, conventional hydraulics apply at low flow when the channel is essentially a rigid container for the liquid phase. However, at high flow when appreciable sediment is being transported by the stream, conventional hydraulics are no longer applicable because many of the variables are not unique (Maddock, 1969, p. 67). Leliavsky (1966, p. 98) also distinguishes fluvial hydraulics from hydraulics in general as a necessity to understanding natural streams.

Three important principles of fluvial hydraulics emphasized by Leliavsky are: 1) In no part of alluvial channels are contiguous stream lines parallel to one another or to the bank of the river, 2) The greater the curvature of the horizontal projections of the stream trajectories, the deeper the channel scours below them, and 3) Perhaps the most significant principle in fluvial hydraulics, validity of de Leliavsky's (1894) convergence-divergence criterion. Leliavsky (1966, p. 162) summarized de Leliavsky's contribution:

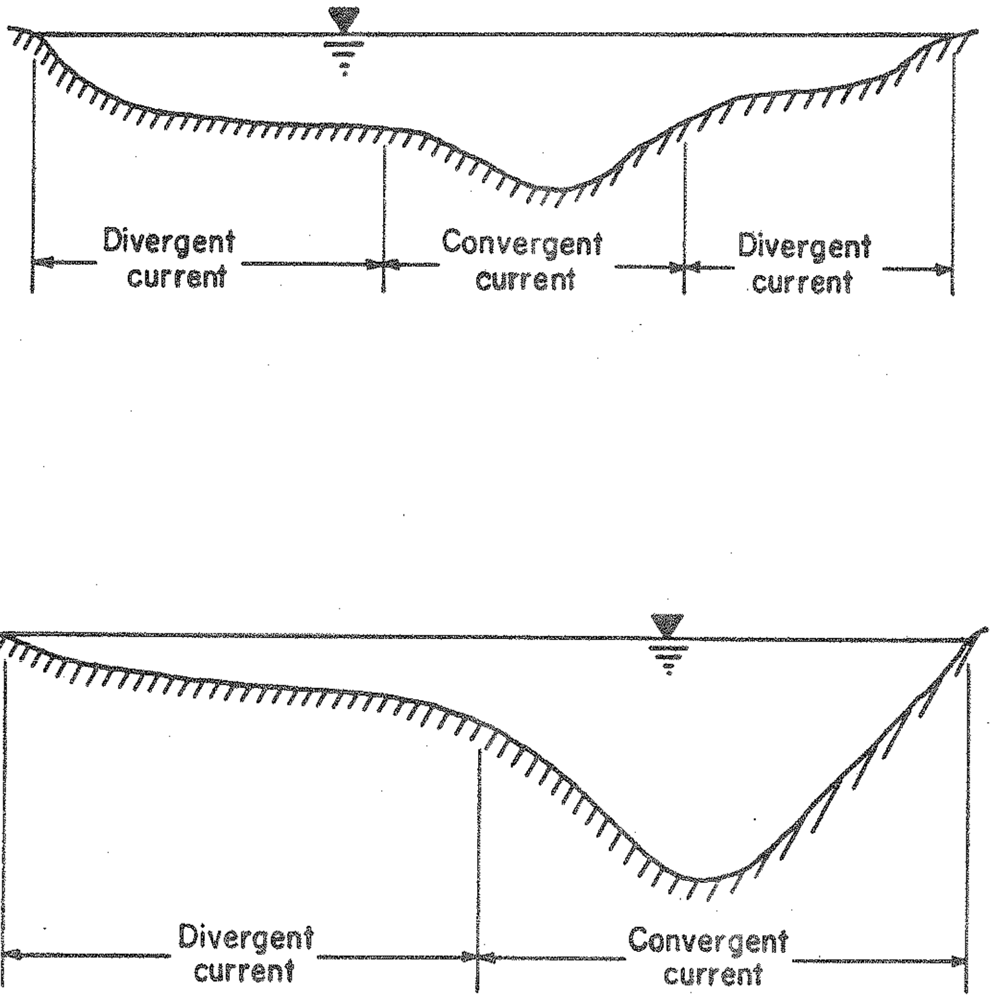
> "... It was an inference, i.e., a general law, drawn from a very large number of individual facts, that is observations, derived from nature and from engineering practice. This aspect of de Leliavsky's criterion is best described by the term "ex flumine nato", i.e., born from the river, for it was the natural structure of the erodible river channel and the distribution of the velocities therein, which suggested its basic idea; namely, that erosion was always correlated with, and due to, convergent flow, while on shoals the flow was always divergent."

Typical river sections explaining Leliavsky's criterion are shown in Figure 21. In general, converging directions of flow are typical of pools, whereas diverging flow produces shallows (Van Ornum, 1914, p. 364).

The verification of de Leliavsky's criterion has been emphasized by its application to design of river-training works (Leliavsky, 1966). However, its full potential for use has not been realized in studying alluvial streams. This results from the fact that at low flow, when most rivers are studied, convergent flow may not be scouring and divergent flow may not be causing deposition. During this stage the normal hydraulics is applicable. However, at high flow, with moving sediment, fluvial hydraulics applies and convergence of flow in pools is probably responsible for the observed scour. Therefore, the constraints at low flow may nullify de Leliavsky's criterion, but is probably valid at high flow when these constraints no longer apply.

River Meanders

Meandering rivers have long interested geologists, hydrologists, and engineers and many theories have been introduced to explain why



After Leliavsky, 1966

Figure 21. de Leliavsky's convergent-divergent criterion. The symbol ∇ indicates the water surface.

a river should meander. Whereas the Coriolis effect, random local obstructions, and bank erosion have been shown inadequate to explain meandering (Yang, 1971a), increased knowledge of energy relationships promises to facilitate an understanding of why a river meanders. Leopold and Langbein (1966) concluded that streams meander because it is this form in which the river does the least work. They further stated that, because the alternation of straight shallow reaches (riffles) with curved deep reaches (pools) most closely results in uniform energy expenditure, meandering is the most probable form a river can take. This was consistent with their earlier (1962) concept of entropy. Yang (1971a) criticized Leopold and Langbein because they attempted to minimize the total energy expenditure, which according to Yang is impossible. However, Yang utilized the concept of entropy in fluvial systems, introduced by Leopold and Langbein (1962), to derive his law of least time rate of energy expenditure which states:

> "... during the evolution toward its equilibrium condition, a natural stream chooses its course of flow in such a manner that the time rate of potential energy expenditure per unit mass of water along its course is a minimum." (Yang, 1971a, p. 235).

The mathematical expression of this law is

$$\frac{\Delta H}{\Delta t} = \frac{kY}{\Delta t} = \Phi(Q, Su, Cs, G\ldots) = \text{a minimum}$$

where $\Delta H/\Delta t$ is the time rate of potential energy expenditure per unit mass of water in a stream reach with fall Y, Δt is the average time required for a unit mass of water to travel through the reach, k is a conversion factor between energy and fall, and Φ is a function of the external constraints applied to the stream including discharge Q, valley slope Su, sediment concentration Cs, geological constraints G, etc. The minimum value therefore depends on the nature and extent of the external constraints applied to the stream.

The law of least time rate of energy expenditure is probably the best approximation of why streams meander, assuming a semicircular channel cross-section. Yang (1971a, p. 238) demonstrated mathematically that in order to minimize $\Delta H/\Delta t$ a stream must decrease its channel slope. Excluding downcutting, this is accomplished by meandering. He also showed that an increase in channel width helps minimize $\Delta H/\Delta t$. Therefore, the overall time rate of potential energy expenditure per unit mass of water should decrease in the downstream direction, causing channel width to increase and channel slope to decrease (Yang, 1971a, p. 250). As the law is derived for a unit mass of water, it is applicable to both large and small streams and alluvial or ice channels.

Leopold and Wolman (1960)were probably the first to recognize that for natural river meander bends the curvature ratio, or ratio of radius of curvature to channel width, tends to be relatively stable between 2 and 3. Bagnold (1960), attempting to explain this observation concluded that the resistance to flow in a channel with uniform cross-section falls to a well defined minimum when the curvature ratio is between 2 and 3. However, he did not attempt to show the same minimum resistance for channels whose cross-section was not uniform, and he was not able to suggest why natural channels should minimize the resistance to flow in curves. Assuming that natural channels do minimize the resistance to flow in channels with a curvature ratio between 2 and 3, the explanation as to "why" is possibly suggested by the law of least time rate of energy expenditure. The minimum flow resistance might suggest a minimum energy expenditure. However, this does not imply that the total energy expenditure has been minimized, and only explains why the curvature ratio is between 2 and 3. If streams must meander to minimize $\Delta H/\Delta t$, then we might expect that most bends would have the form and configuration to allow both meandering processes to continue and to minimize energy loss.

The writers accept Yang's law, with its admittedly shaky assumptions, as essentially correct in explaining why some streams may meander. However, it does not explain two important aspects of meandering in alluvial channels: 1) The fluvial processes which produce the increase in channel length; and 2) The nature of possible constraints imposed by the channel morphology. A natural stream may adjust its slope, geometry and morphology to minimize $\Delta H/\Delta t$; however, the exact nature and extent of these adjustments is still largely unknown. Probably channel morphology is one of the most significant constraints. This is inferred because many apparently stable alluvial channels, although they are sinuous, are not meandering. This suggests that the constraints in the channel minimize $\Delta H/\Delta t$ before sinuosity increases to 1.5.

Channel Morphology and Morphometry

Basic Concepts and Definitions

Excluding the fluid phase, the most obvious forms in an alluvial channel are bed forms. Bed form is a generic term defined as any irregularity produced on the bed of an alluvial channel by the interaction between flowing water and moving sediment (Simons and Richardson, 1966).

Bed forms useful in describing the straight, sinuous, and meandering channel patterns are shoals and pools. There are two basic types of shoals; symmetrical and asymmetrical. The most common symmetrical shoal is the riffle. The symmetry is defined only near the inflection point between pools for about one-tenth of the total wave length (Leopold and Wolman, 1960, p. 777). The writer defines riffle as a topographic high area in an alluvial channel produced by the lobate accumulation of relatively coarse-grained bed material. The inflection point of the thalweg is located on the riffle approximately half-way between successive pools. The cross-profile is generally symmetrical (Keller, 1971b, p. 279). It seems desirable to use the term riffle as just defined because it is applicable to straight, sinuous, and meandering channels. Riffle has also been used to designate asymmetrical shoals that slope alternately first toward one bank, then the other, producing a sinuous water path (Leopold and others, 1964, p. 203). There has been considerable confusion in applying these two definitions and, furthermore, the latter definition requires a change in symmetry in the transformation from an asymmetrical riffle in a straight channel to a symmetrical riffle in a meandering channel. The importance of an invariant transformation from a straight to meandering channel has been well presented by Tinkler (1970). Therefore, it is proposed that asymmetric shoals which seem to initiate meandering be simply referred to as asymmetric shoals, or skew shoals as designated by Quraishy (1944, p. 38).

A pool is a topographic low area in an alluvial channel produced by scour, which generally contains relatively fine-grained bed material. Pools are us ually associated with a point bar, which is an accumulation of bed material on the concave side of the thalweg adjacent to a pool. The point bar and pool together produce an asymmetrical cross-profile (Keller, 1971b, p. 279).

Pools and riffles can also be defined in terms of hydraulic characteristics. At low flow, pools can be recognized by relatively deep, slow water, whereas riffles are areas of relatively fast, shallow water (Leopold and others, 1964, p. 206). Quantitative definitions for pools and riffles have been suggested by Dolling (1968) and Yang (1971b). Dolling used the velocity to depth ratio as a criterion, whereas Yang used energy gradients to distinguish pools from riffles. However, definitions based on hydrology or energy gradient are only valid at low flow, and should not imply that pools and riffles no longer exist when the water slope over the forms is constant (pools and riffles are drowned out).

It is the authors' opinion, based on flume experiments (Friedkin, 1945) and channel morphology studies, (Keller, 1969), that the basic form of the pools and riffles does not change at high flow (bankfull stage). This does not suggest that extremely high flows with a return period of tens of years will not wash out the forms. It is extremely difficult to accurately define the discharge which actually forms the pools and riffles. However, most authors agree that the necessary channel-forming discharge occurs somewhere between the average flow and mean annual flood (Daniel, 1971). Three rather different studies: Daniel (1971), working with traveltime data; Dreyfuss' (1972) theoretical model for the development of pools and riffles; and Keller's (1971a) velocity reversal concept, all concluded that there is a critical discharge or threshold condition which controls the development of pools and riffles. However, the hydrology involved with this condition remains undiscovered. We will therefore predict, based on the cited studies and intuition, that the critical discharge, when discovered, will be some fraction, less than half, of the mean annual flood.

The pool-riffle sequence seems to be intimately related to the evolution of alluvial channels. Pools are often spaced at 5-7 times the channel width, which is approximately one-half the wave length of a meander, measured along the channel. Therefore, in its most ideal state, each meander wavelength along the channel contains two pool-riffle sequences, each spaced at 5-7 channel widths (Leopold and others, 1964, p. 203). The pools are located on the bends, and riffles at the inflection point (Fig. 22A). This idealized meandering pattern is seldom found in natural stream channels for more than a few bends. A more common occurrence is a mixed reach containing both straight and meandering sections. The meandering reaches themselves do not normally fit the idealized pattern, as more than one pool may be found on a bend and pools may be found between bends (Fig. 22B). Pool-riffle spacing investigations on Dry Creek near Winters,

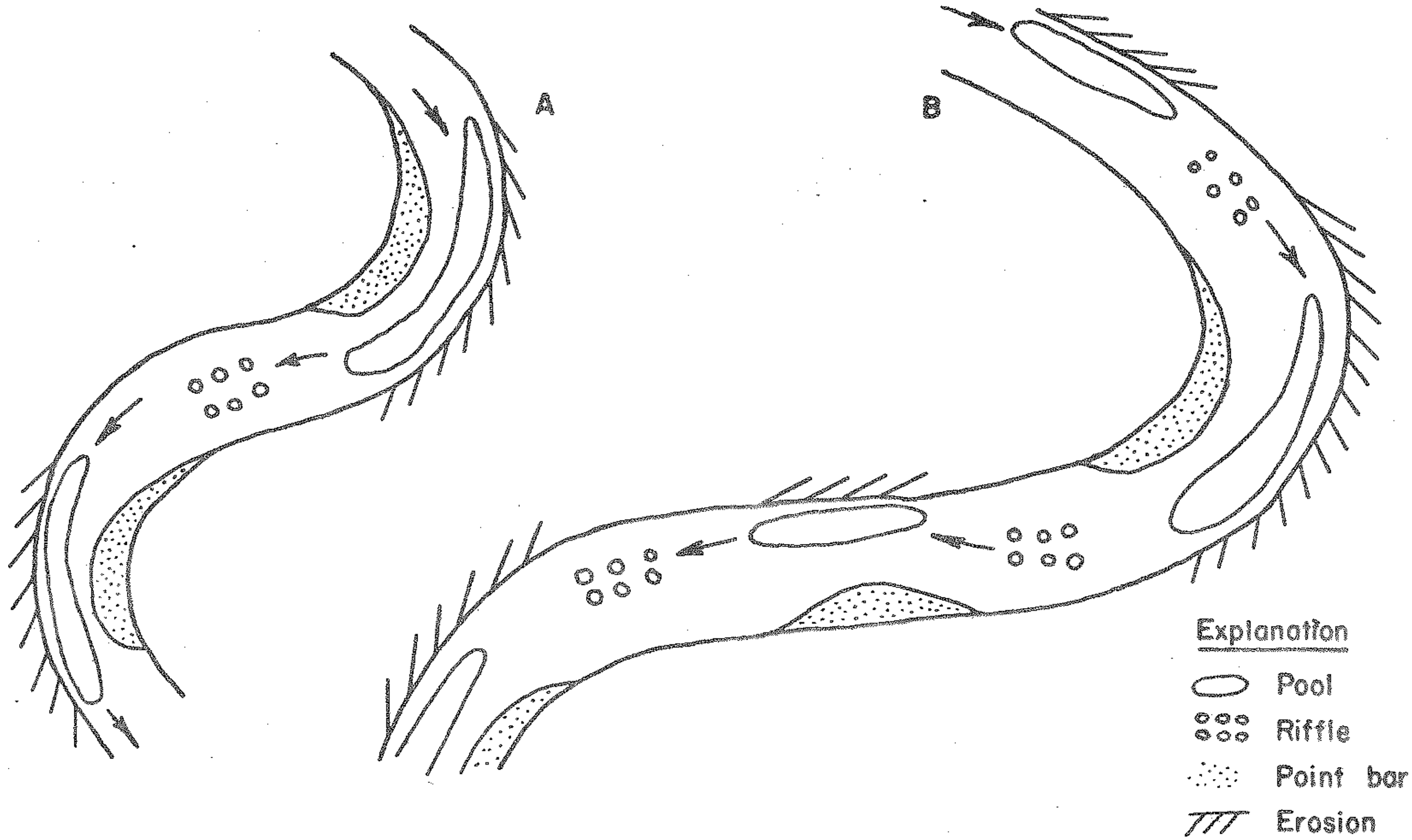


Figure 22. Illustration of pool-riffle sequences for: A, idealized meandering channel; and B, the common field occurrence.

California suggest that spacing is constant in both straight and meandering reaches and, therefore, pool-riffle spacing is independent of channel pattern (Fig. 23). The straight reaches in Dry Creek are all apparently owing to lateral migration of meander bends. Thus new pools are added as channel length increases, to keep the constant spacing (Keller, 1969). Paradoxically, the process of meandering which produces the most probable pattern with minimum variability of energy dissipation (Leopold and Langbein, 1966), also produces straight reaches which must tend to increase the variability of energy dissipation.

Origin of Asymmetrical Shoals

Asymmetric shoals are probably the primary bed form in the evolution of alluvial channels, and it is the contention of the writer that pools, riffles, and point bars all develop from the basic asymmetric shoal. Unfortunately, because asymmetric shoals are often masked by other bed forms, they are seldom seen in their original form in natural streams with an abundance of coarse-grained bed and bank material. However, evidence for the development of asymmetric shoals in stream channels is relatively abundant from flume studies and limited field observation.

Quantitative, mathematical aspects of the origin of asymmetric shoals are not available. However, detailed description of their development in flumes is available. Quraishy (1944) stated that, as soon as the flume experiment started, the topmost grains began to roll and skip over the bed in a jerky but relatively straight path parallel to the channel sides. However, preferential scour areas soon developed on alternating sides of the channel. These appeared, to Quraishy, to

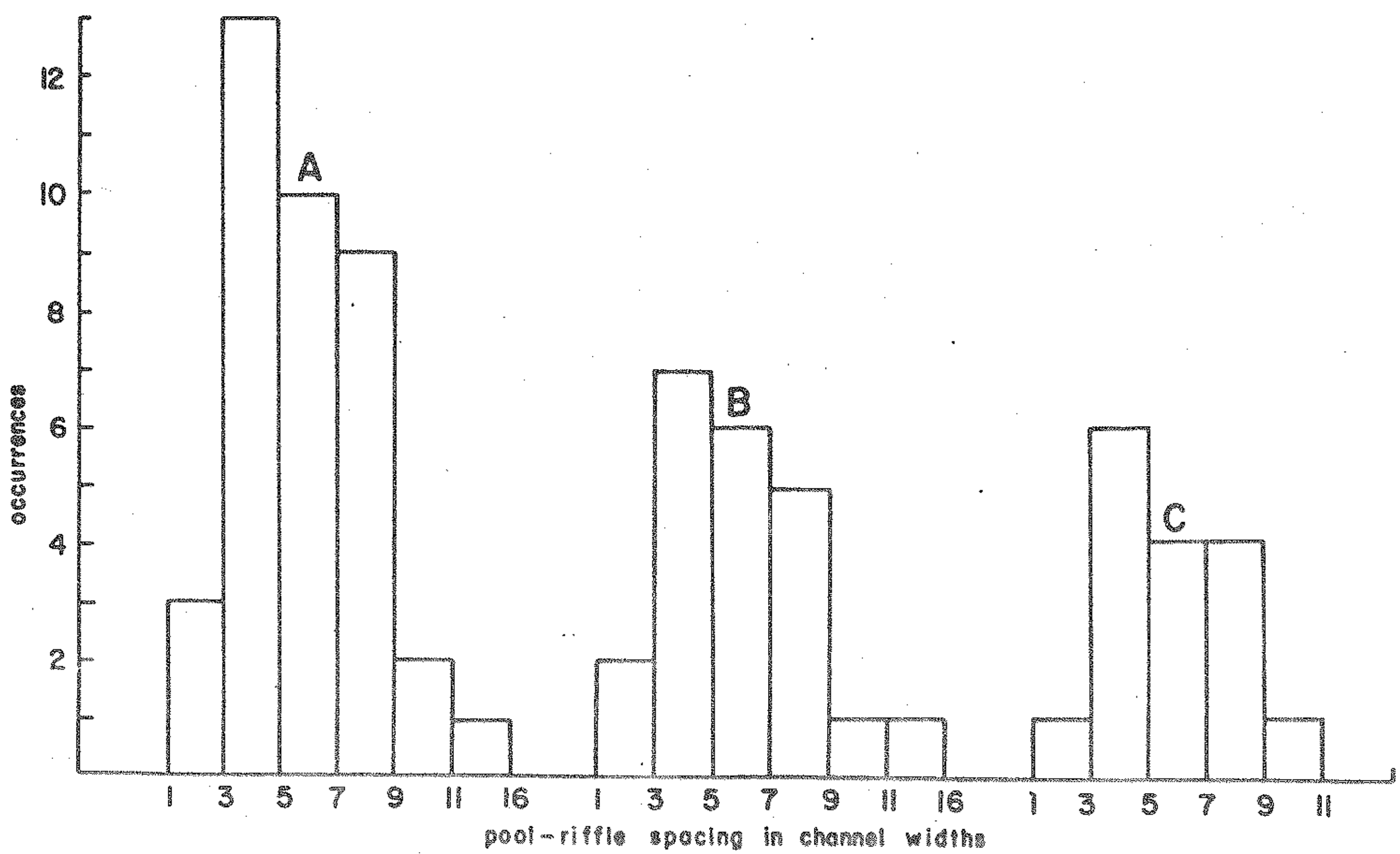


Figure 23. Frequency of pool-riffle spacing for Dry Creek: A, straight and meandering reaches inclusive, B, meandering reaches, and C, straight reaches.

develop as a consequence of the breaking up of the stream at these positions because of a deficiency in energy and momentum. Material appeared to be scoured from the side and deposited in the center in a systematic way. As this process continued, incipient asymmetric shoals developed only a few grains thick with a pitch of 50 to 500 times their thickness. These continued to grow until they began to look like long drawn out dunes which pitched alternately from bank to bank. Flume studies by Simons and Richardson (1966, p. 12) noted that the main current meandered from side to side in the flume, and bars of small amplitude and large area developed in an alternating pattern. It was upon these forms that the ripples, dunes and other bed configurations developed. It seems likely that these alternating bars are analagous to the asymmetric shoals described by Quraishy.

Classical flume experiments by Friedkin (1945) also appear to support the thesis that asymmetric shoals are the primary bed forms in alluvial channels. Figures 24 and 25, from Friedkin's work, show an early development of asymmetric shoals. The uniform and symmetric development of the shoals and curves is probably the result of uniform material and slope. The cross-sections in Figure 24 show the effect of convergence and divergence of flow on bends, producing scour and deposition. Figure 25 summarizes results of an experiment which started with a sinuous channel, and therefore probably more closely resembles natural conditions, in which a stream may have an initially sinuous path owing to constraints caused by heterogeneous bed-and-bank material. Again after a short time asymmetric shoals developed in the channel, and the cross-sections indicate scour and convergent

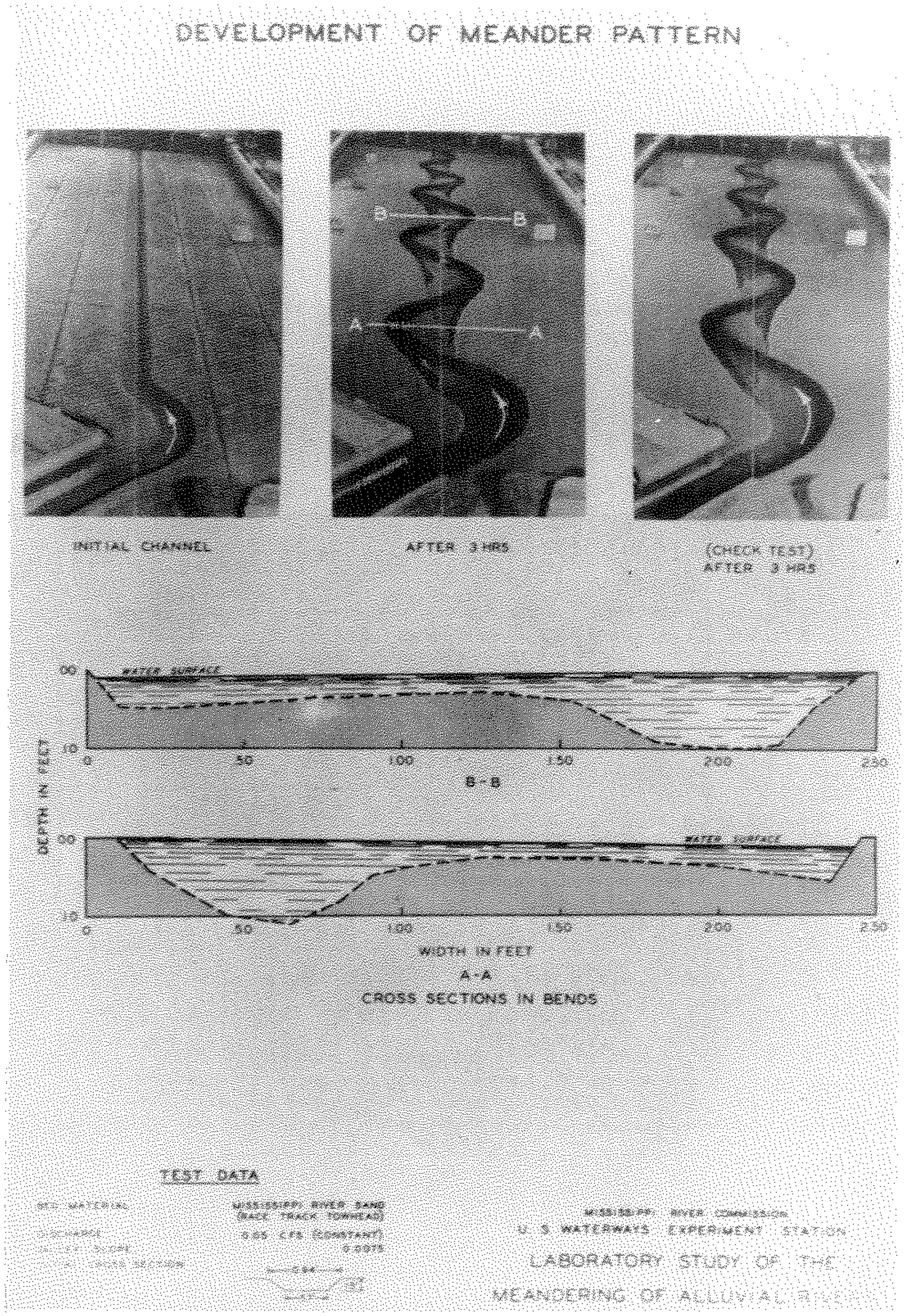


Figure 24. Development of asymmetric shoals in a meandering channel (after Friedkin, 1945).

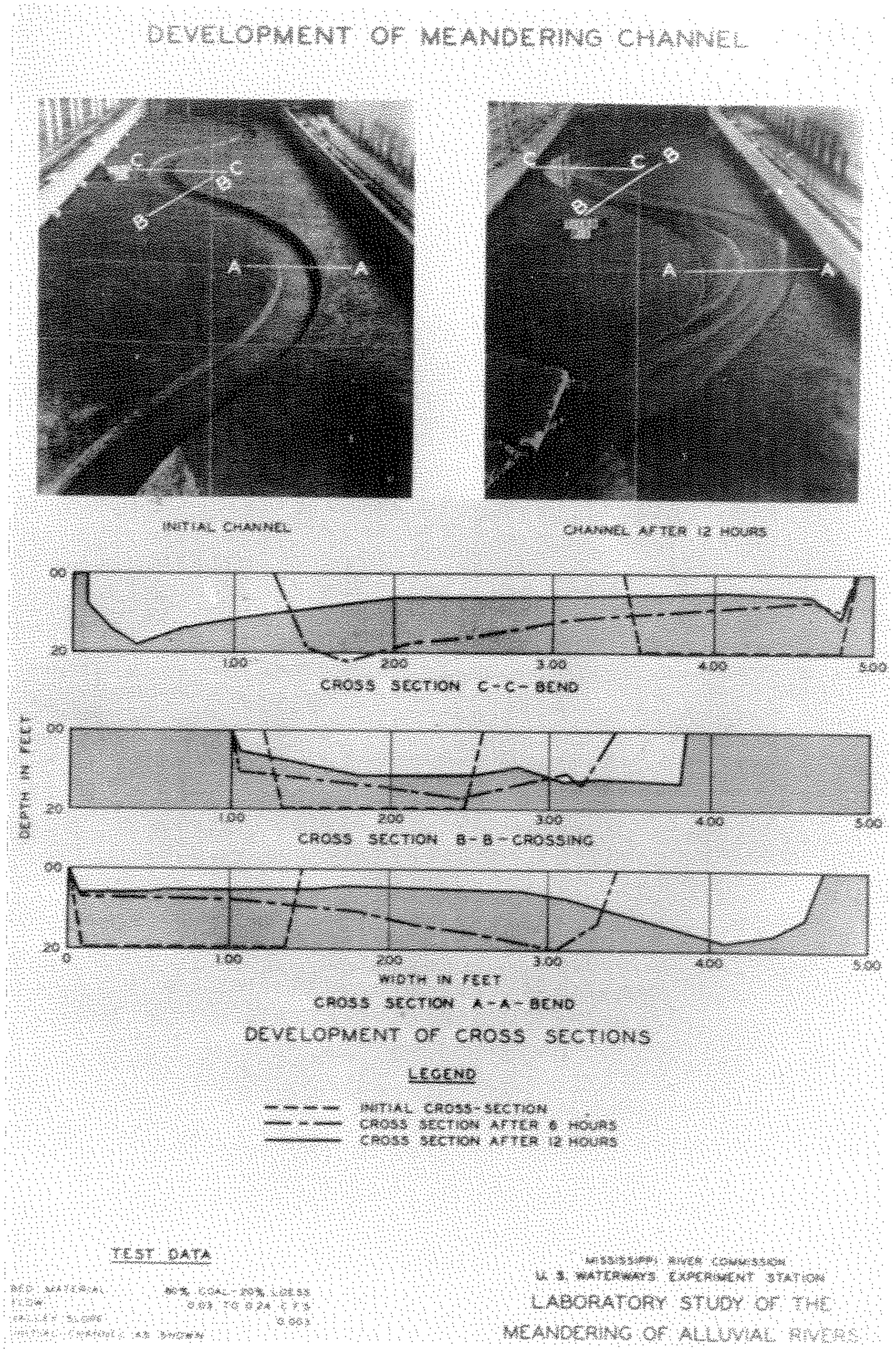


Figure 25. Development of asymmetric shoals in an initially sinuous channel (after Friedkin, 1945).

flow on the outside of bends and deposition and divergent flow on the inside of bends and on crossing. However, it must be realized that whereas these flume studies may give an indication of fluvial processes in natural streams, field conditions are far more complex and the analogy may not be entirely correct.

A cutoff occurring since March, 1968 air photo coverage in Wildcat Creek, Indiana, produced 1,320 feet of new channel, and provided a rare opportunity to study asymmetric shoals in the field. The new channel contains four asymmetric shoals which slope alternately from bank to bank (Figs. 26, 27, and 28). Small incipient pools and riffles (Figs. 29 and 30) have also developed, but are not of sufficient size to mask the asymmetric shoals.

In many streams, relict parts of large asymmetric shoals may remain, and influence the development of inflection points on riffles. It has long been noticed that at low flow the water may flow diagonally across the channel near the inflection point (Leopold and Wolman, 1960, p. 777). This diagonal flow appears to be the result of interaction between two asymmetric shoals. This may happen even if most of the original asymmetric shoals have been replaced by pools and riffles, or have become point bars. Figure 31 shows a field example in Wildcat Creek of an incipient pool developing at the expense of two asymmetric shoals. It is expected, on the basis of what is known about convergent and divergent flow, that eventually the divergent diagonal flow over the partly destroyed asymmetric shoal will become a well-developed riffle.

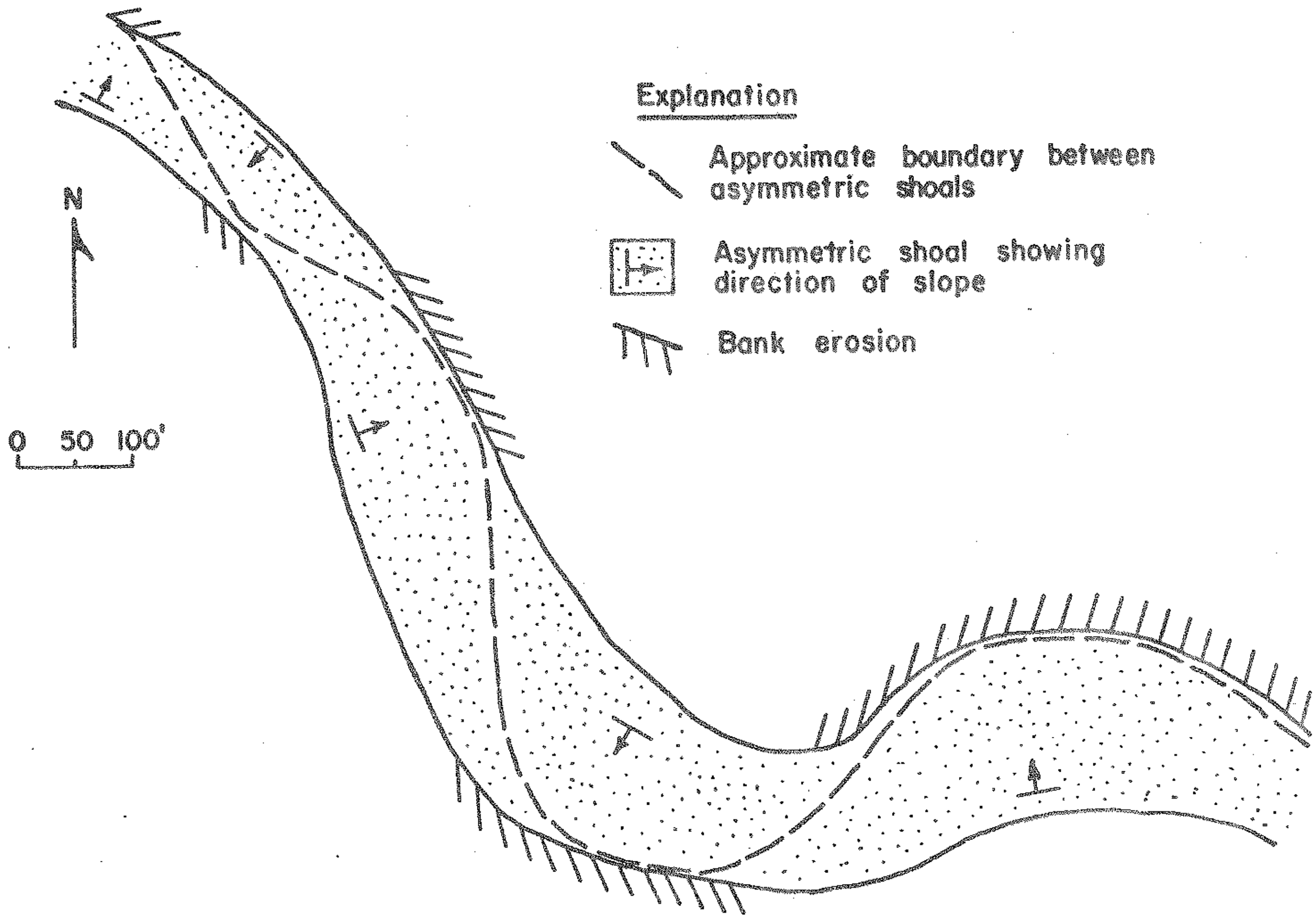


Figure 26. Development of asymmetric shoals in Wildcat Creek. The location of this reach is shown by 3A-4A in Figure 45. The location of the incipient pools is shown on Figure 51.

Figure 27. Downstream view from 3A in Figure 45 of two asymmetric shoals. A large shoal is clearly visible in the center, another sloping toward the opposite bank is seen in the background.

Figure 28. Upstream view from 4A in Figure 45,showing asymmetric shoals.

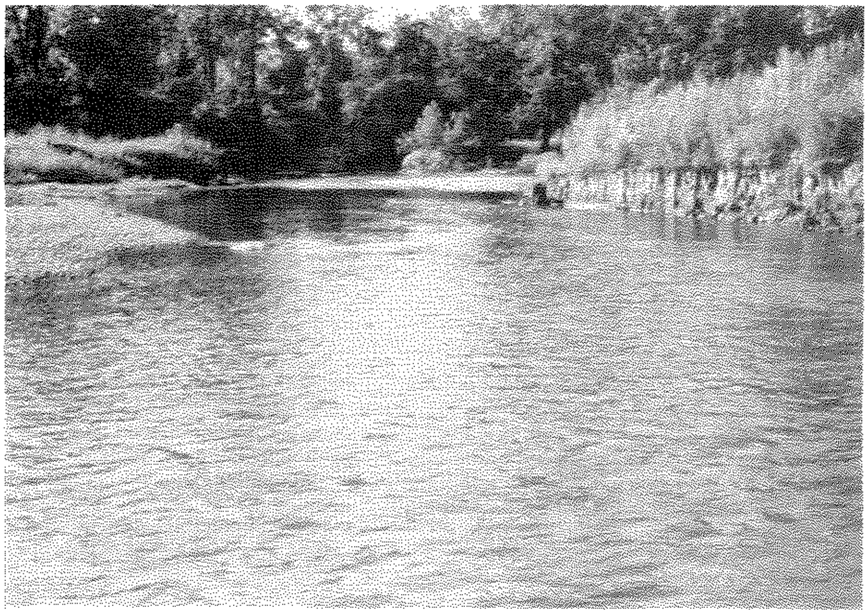


Figure 29. Incipient pool in Wildcat Creek. The location of this pool is in the vicinity of 4A in Figure 45.

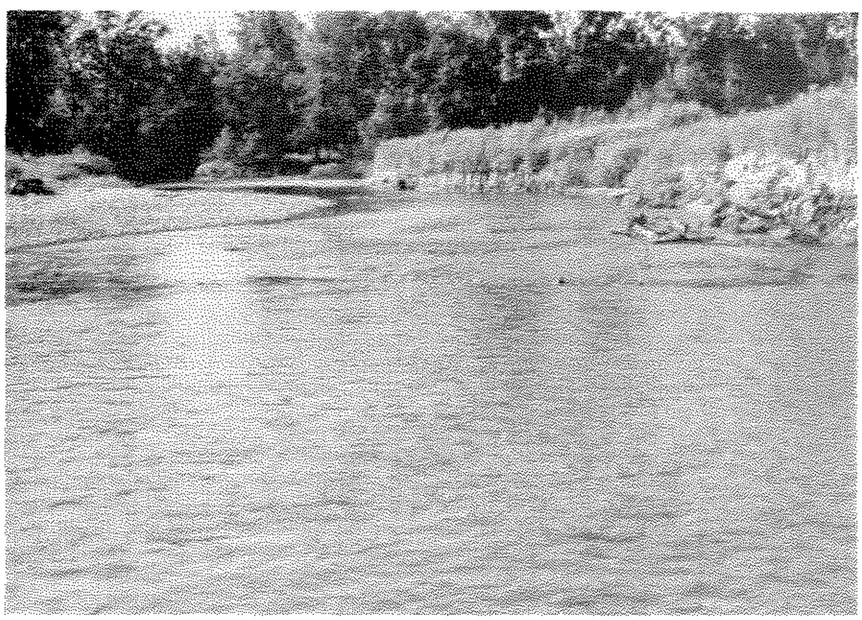


Figure 30. Incipient riffle in Wildcat Creek; directly upstream from the pool in Figure 29.

Figure 31. Upstream view from 3A in Figure 45, showing a large asymmetric shoal (left) being partly destroyed by the development of a small pool (center). The inflection point is at the upstream projection of the asymmetric shoal, which trends diagonally across the channel.

If Yang (1971a) is correct, and streams do want to minimize the time rate of potential energy expenditure per unit mass of water, then development of asymmetric shoals is probably the first step. Thus, asymmetric shoals develop, because they are the most probable bed form that initiates processes which will facilitate slope reduction and thereby minimize potential energy expenditure. This appears consistent with the concept of entropy, which tends to move the energy distribution in a system to a more probable state.

Origin and Significance of Pools and Riffles

The occurrence of shallows and deeps in alluvial channels has been observed and studied for many years. The use of the terms pool and riffle for deeps and shallows has long been used by fishermen, and in particularly good fishing streams the pools and riffles may be given specific names. Although some alluvial streams with fine-grained bed material or steep slopes do not have well developed pools and riffles (Lokhtine, 1909), most alluvial streams do. This very common occurrence of pools and riffles was substantiated by Dearinger and Woolwine's (1971, p. 43) inventory of natural streams. Nearly all of the 58 streams they investigated contained pools and riffles.

Any proposed origin for pools and riffles must explain: 1) Why an alluvial channel deform its bed into regularly spaced pools and riffles; 2) Why pool-riffle spacing is independent of channel pattern; 3) The fluvial processes and fluvial hydrology which produces the pools and riffles; 4) The generally observed areal sorting of bed material, i.e., relatively fine-grained bed material in pools and relatively coarse-grained bed material in riffles; and 5) Why, in streams that occasionally scour to older alluvium or bed rock in pools, there may be no bed load material observed at low flow and no bed load transport in the pools, whereas the adjacent point bar and riffles contain abundant bed material.

Pools are basically areas of scour, whereas riffles are areas of deposition and therefore, according to de Leliavsky's (1894) criterion, must be associated with convergence and divergence of flow. The morphology of a typical pool in Dry Creek is shown in figure 32. Notice the almost complete lack of coarse-grained bed material. Figure 33 is an upstream view of the adjacent riffle to the pool in figure 32. Notice the abundance of coarse-grained bed material. Figures 34 and 35 show a downstream view of a well developed pool and point bar in Wea Creek. The lighter area in the center of the pool is scoured into an underlying basal till unit. Although the point bar and adjacent riffle contain abundant bed load material, the center part of the pool is completely void of bed load material. Other good examples of pool-riffle sequences in Wea Creek are shown in Figures 36 and 37. The pools are recognized by the relatively dull, slow, flat water surface whereas riffles are recognized by the broken water surface and relatively fast water which reflects more light.

At low flow, the water surface over pools is relatively flat compared with that of adjacent riffles. However, with increasing discharge the water surface over the pool increases, whereas it decreases over the adjacent riffle. At bankfull stage the difference in water slope has disappeared, and the pool-riffle sequence is said

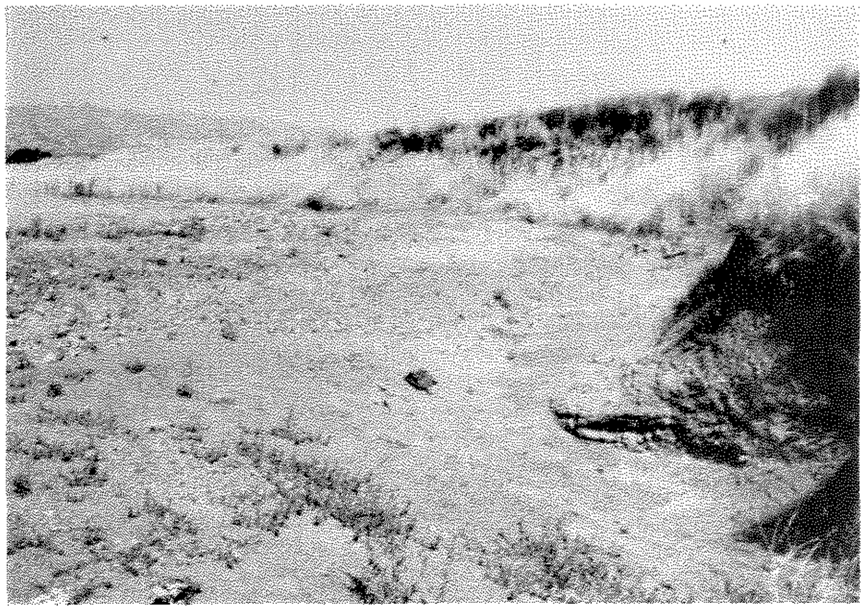


Figure 32. Upstream view from 2B in Figure 45 showing a well developed pool in Dry Creek.

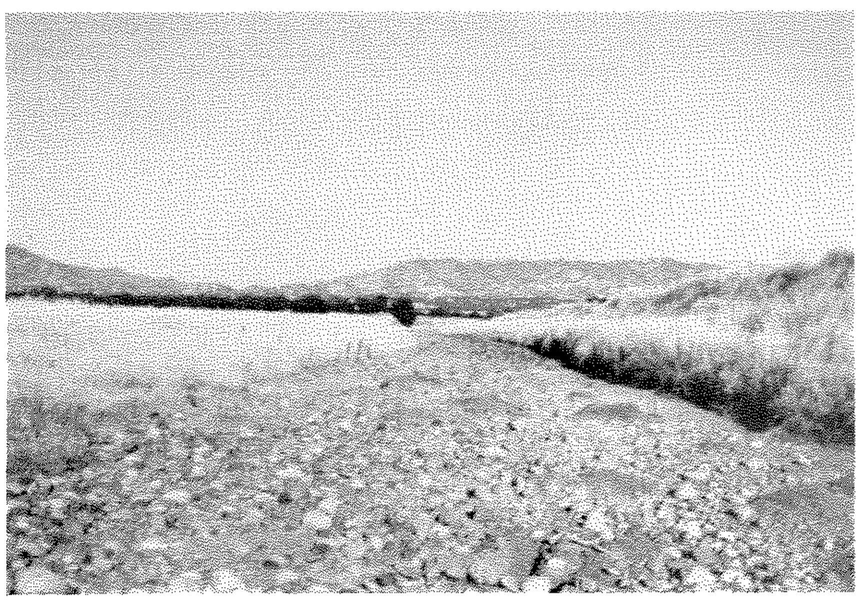


Figure 33. Upstream view of a well developed riffle in Dry Creek. This riffle is directly upstream and adjacent to the pool in Figure 32.

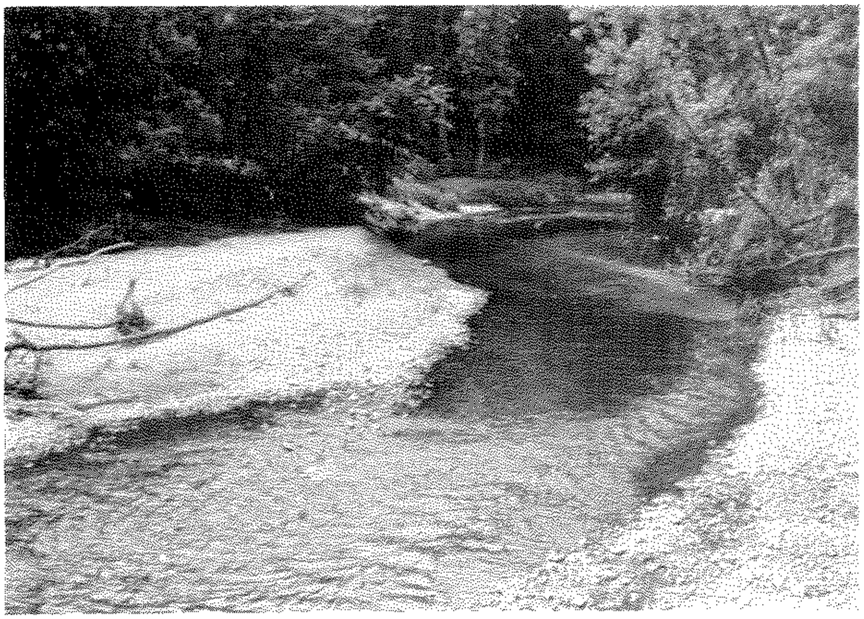


Figure 34. Downstream view from 3C in Figure 45 showing a well developed riffle, pool and point bar in Wea Creek.

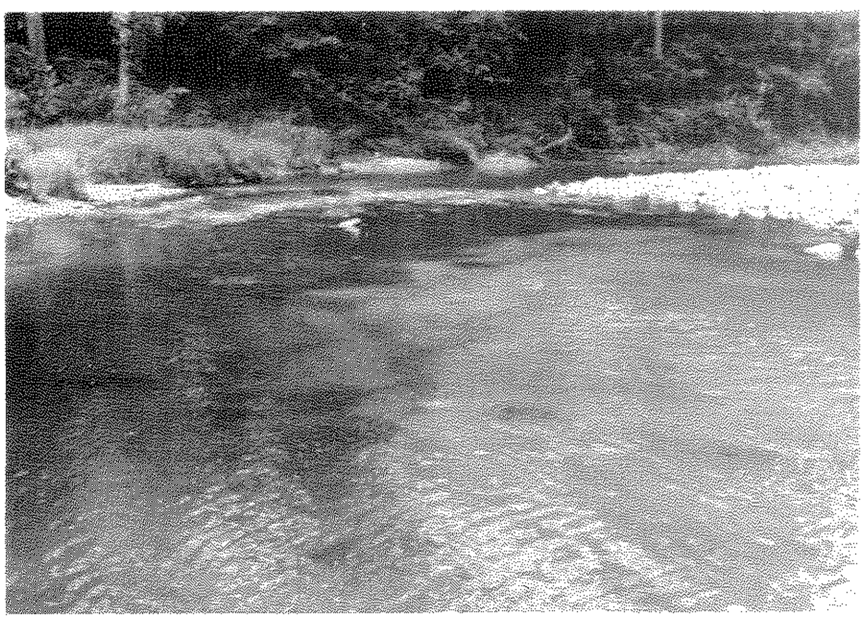


Figure 35. Close up view of the pool in Figure 34. The lighter area in the central part of the pool is a well compacted till. This pool is completely devoid of bed material.

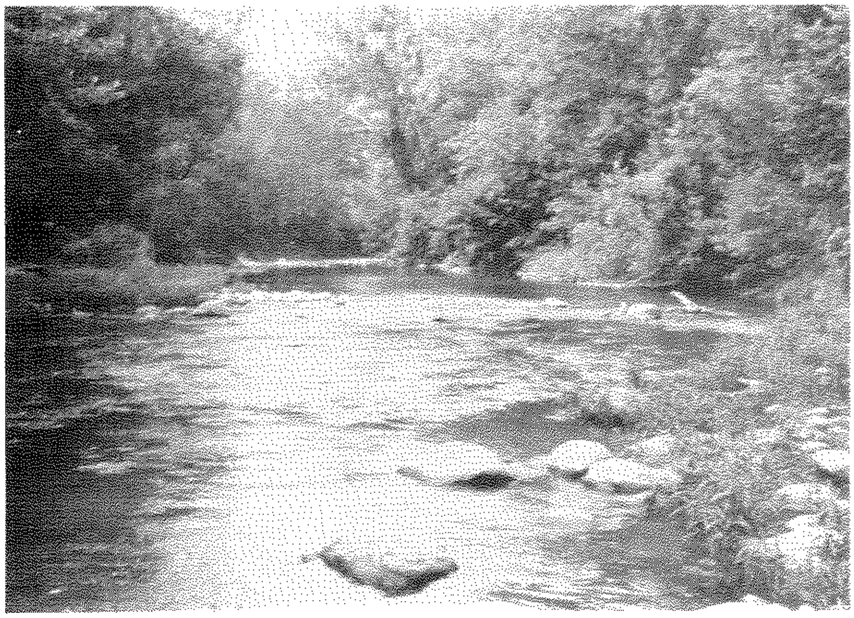


Figure 36. Downstream view from 1C in Figure 45 showing a well developed riffle (center) and pool (background) in Wea Creek.

Figure 37. Downstream view from 2C in Figure 45 showing pool (foreground) riffle (center) and pool (background) in Wea Creek.

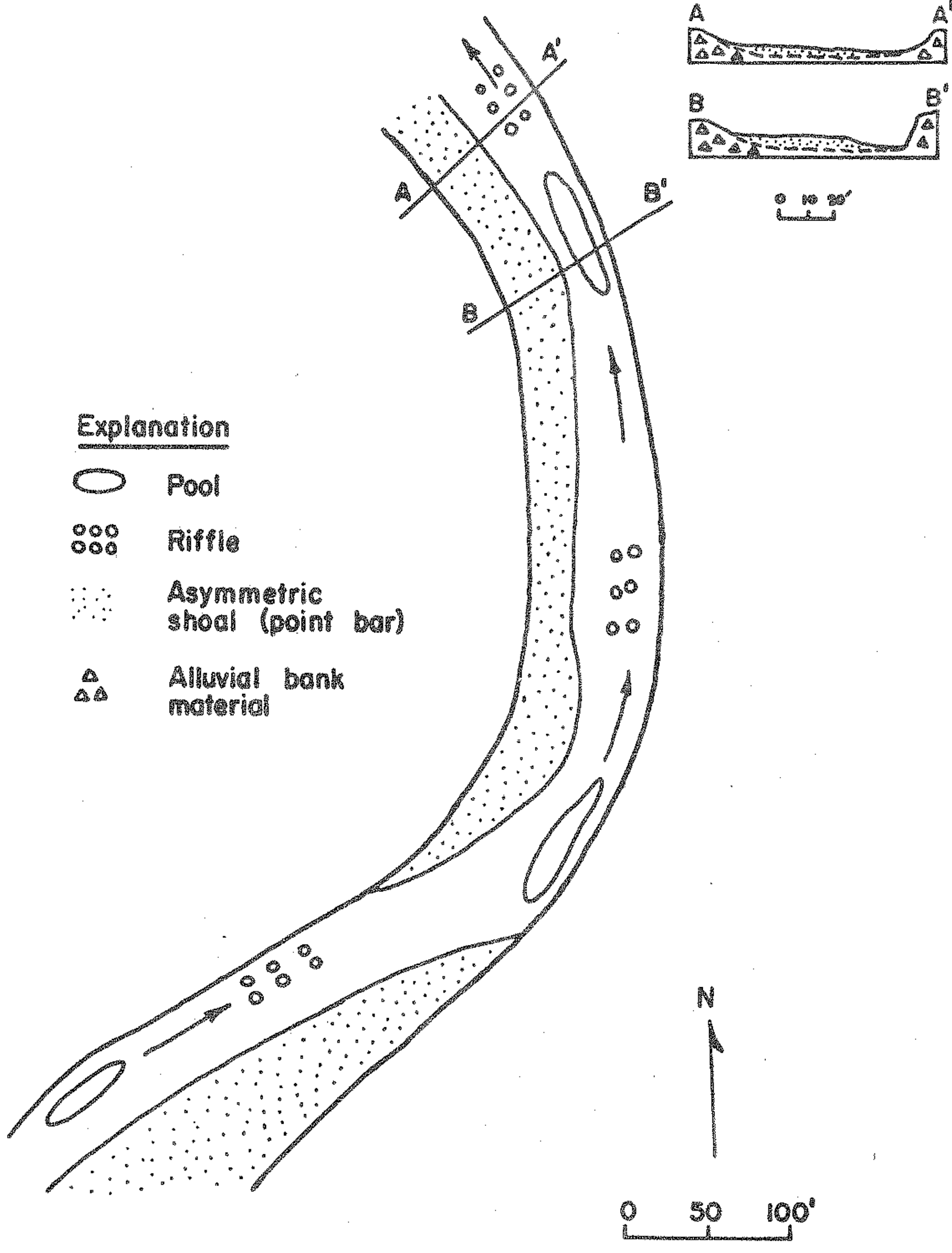


Figure 38. Morphologic map of bed forms along a short reach of Wildcat Creek. The location of this reach is shown by 1A to 2A in Figure 45.

to be "drowned out" (Leopold and others, 1964, p. 206). A detailed morphologic map of bed forms along a short reach of Wildcat Creek (Fig. 38) shows a series of pools on a bend. The pools are poorly developed, but can be recognized from the morphology, thalweg, and water surface at low flow (Fig. 39). The cross-sections in figure 38 are typical for a pool and riffle, and indicate convergent flow for the pool and divergent flow for the riffle. Detailed topographic maps for Dry Creek (Keller, 1969, plate 3) and Seneca Creek (Leopold and others, p. 204-205) also suggest convergent flow for the pools and divergent flow for the riffles. This suggests that pools are produced by convergent flow which causes increased tractive force and scour, whereas riffles are produced by divergent flow and deposition. Essentially this is correct, but the entire process is considerably more complex. What must be considered is why there is periodic scour and deposition, and when the forms are produced.

Flume studies, because of obvious constraints, have not produced well developed pools and riffles. However, the characteristic spacing of shallows and deeps produced by asymmetric shoals has been observed in flumes (Friedkin, 1945), and this is significant because it may reflect the periodic scour and deposition characteristic of pools and riffles. Figure 40 summarizes an experiment in which asymmetric shoals produced alternating deeps and shallows. The thalweg profiles indicate that the basic form of the channel bottom, in a vertical scale, does not change with increasing discharge up to bankfull stage, where the forms are considered drowned-out. Furthermore, lateral changes in the main current with increasing discharge may help explain why pools are nearly

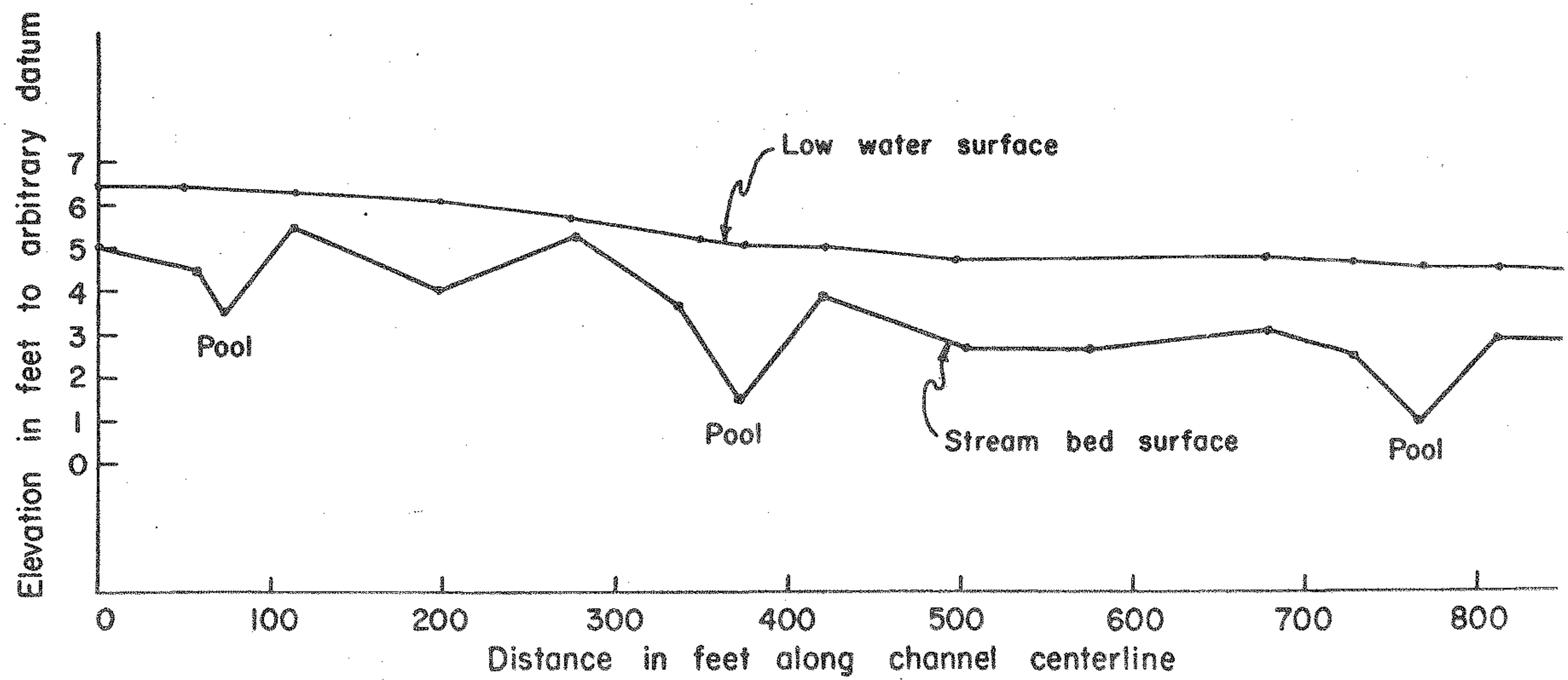


Figure 39. Thalweg profile and low water surface corresponding to the morphologic map of Figure 38.

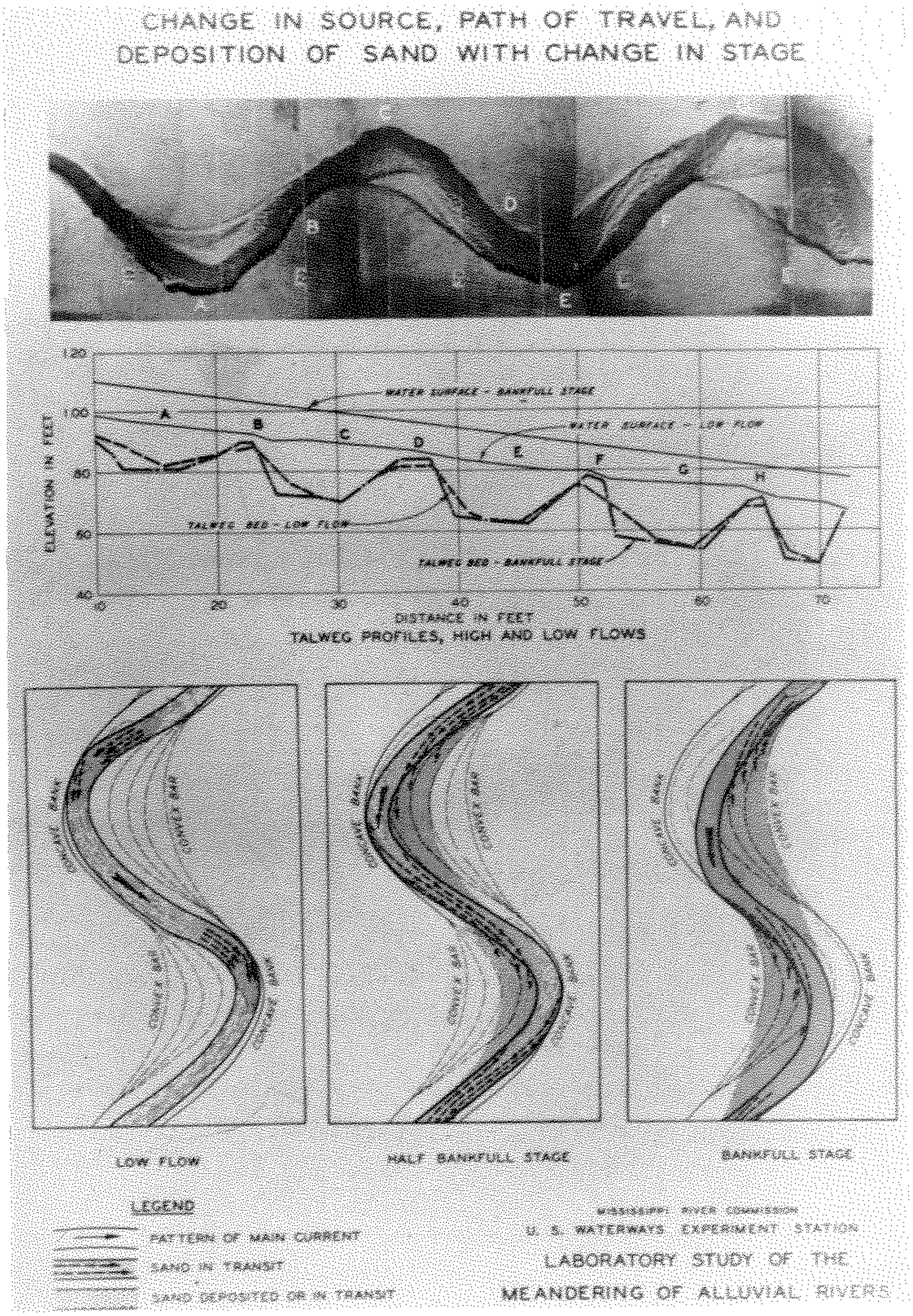


Figure 40. Flume generated series of asymmetric shoals producing deeps and shallows (after Friedkin, 1945).

always located slightly downstream from the point of greatest curvature of asymmetric shoals or point bars.

Another important characteristic of pools and riffles is their apparent stability. Although, bed forms controlled by the flow regime appear and disappear as flow conditions change (Simons and Richardson, 1966), pools and riffles tend to remain in essentially the same spot during a series of flows (Keller, 1972a). Even though small shifts must take place as the stream wanders back and forth across the flood plain, this apparently has nothing to do with the flow regime. This was further substantiated by Langbein and Leopold's (1968) study. They found that in a typical pool-riffle sequence, in which they painted cobbles on the riffle at low flow, after a high flow the painted rocks were gone, but the position and morphology of the riffle unchanged. Even artificial pools and riffles, when spaced at 5-7 channel widths apart, are relatively stable (Stuart, 1953).

The observed areal sorting of bed-load material, that is, relatively large material in riffles and finer material in pools, has been a subject of vigorous debate. Any solution must explain both areal distribution of bed material and the lack of any bed material in some pools. It seems obvious that in many alluvial channels the velocity distribution at low flow, with little or no sediment transport, is such that bottom or bed velocity in pools is significantly less than in adjacent riffles. At this low stage, normal hydraulics apply and de Leliavsky's criterion may not be applicable. The riffles at this stage act as small, downstream, dams to the slower, deeper water in the pools. There may not be sufficient traction to transport the bed-load, and the only moving sediment may be relatively fine-grained material which is winnowed off the riffles and settles in the pools. Therefore, at low flow the steeper slope of the riffle is more significant in producing tractive force than any convergence of flow in the pools. However, it also seems obvious that pools have to scour at some flow, and if not at low flow, then certainly at high flow. Along this line of thinking, Carey and Keller (1952) stated, "It may develop that in effect the bends are scoured out at high stages, and that much of the scoured material is simply moved to the first crossing." They also concluded that slope (in a local sense) is a result rather than a cause, and suggested that bed-load movement in bends (pools) may be completely different from bed-load movement in crossings (riffles). Assuming that the characteristic cross-sections, surveyed at low flow, depict relict forms produced at high flow, then pools converge flow and riffles diverge flow. This implies that at high flow the tractive force in pools exceeds that in riffles. G. K. Gilbert stated in 1914 (p. 221):

> "The deeps at high stage are pools at low stage and have currents too feeble for traction. As the reduced stream passes from pool to pool it crosses the shoal formed at high stage with quickened current. The velocities are still diversified, but the greater and smaller velocities have exchanged places."

Gilbert further concluded (p. 220) that if sediment is being actively transported, and thus areally sorted, bed velocity near the outer bank is much greater than that on the inner bank, and also greater than that on any relatively straight part of the stream. This is consistent with Leliavsky's (1966, p. 164-165) conclusion that accelerated flow is associated with pools, and decelerated flow with riffles. Gilbert suggested that at low flow the velocity of the water in pools is less than for adjacent riffles. However, at high flow conditions are reversed and pools have faster moving water than adjacent riffles. This phenomenon has been observed and measured by Keller (1971a, p. 753). Furthermore, the senior author named this phenomenon "velocity reversal" and used it to explain the areal sorting of bed-load material in pools and riffles. Bed-load movement through a pool-riffle sequence might be as follows:

> "After a storm, discharge increases, but below the velocity reversal only relatively fine material is transported. The bottom velocity of the pool is less than that of the riffle, so the largest material which can be moved through the riffle is trapped in the pool. With increasing discharge a transitional point is reached where the bottom velocity of the pool equals that of the riffle; at this point, material that can be transported through the riffle is also transported through the pool. Above the reversal velocity, the bottom velocity of the pool exceeds that of the riffle. The largest bed material moves only at flood stage, and at this point the pools can transport any bed-load particle that moves into the pool. Therefore, at very high flow the only stable areas for large bed-load material are on bars and riffles, where there is less tractive force. With decrease in discharge following the peak flow, the largest bed-load material is left on bars and riffles. Below the reversal velocity some of the particles moving through a riffle could not be moved through the pool, and if the velocity should fall rapidly there could be an abrupt change from relatively coarse to fine material in some of the pools. The size of the largest bed material in the pools beneath the fines is dependent on the reversal velocity. The higher the reversal velocity, the larger is the material left in the pool with decreasing discharge and velocity," (Keller, 1971a, p. 754).

The result of the sorting process can be seen in Figure 41 and Figure 42. The very coarse-grained material downstream from the pool can only be explained by some process which produces greater tractive force in the pool than in the adjacent riffle. The pool is scoured to

Figure 41. Upstream view from 1A in Figure 45 showing a pool, riffle, and point bar in Dry Creek. The fan-shaped deposit of coarse-grained material was deposited at high flow.

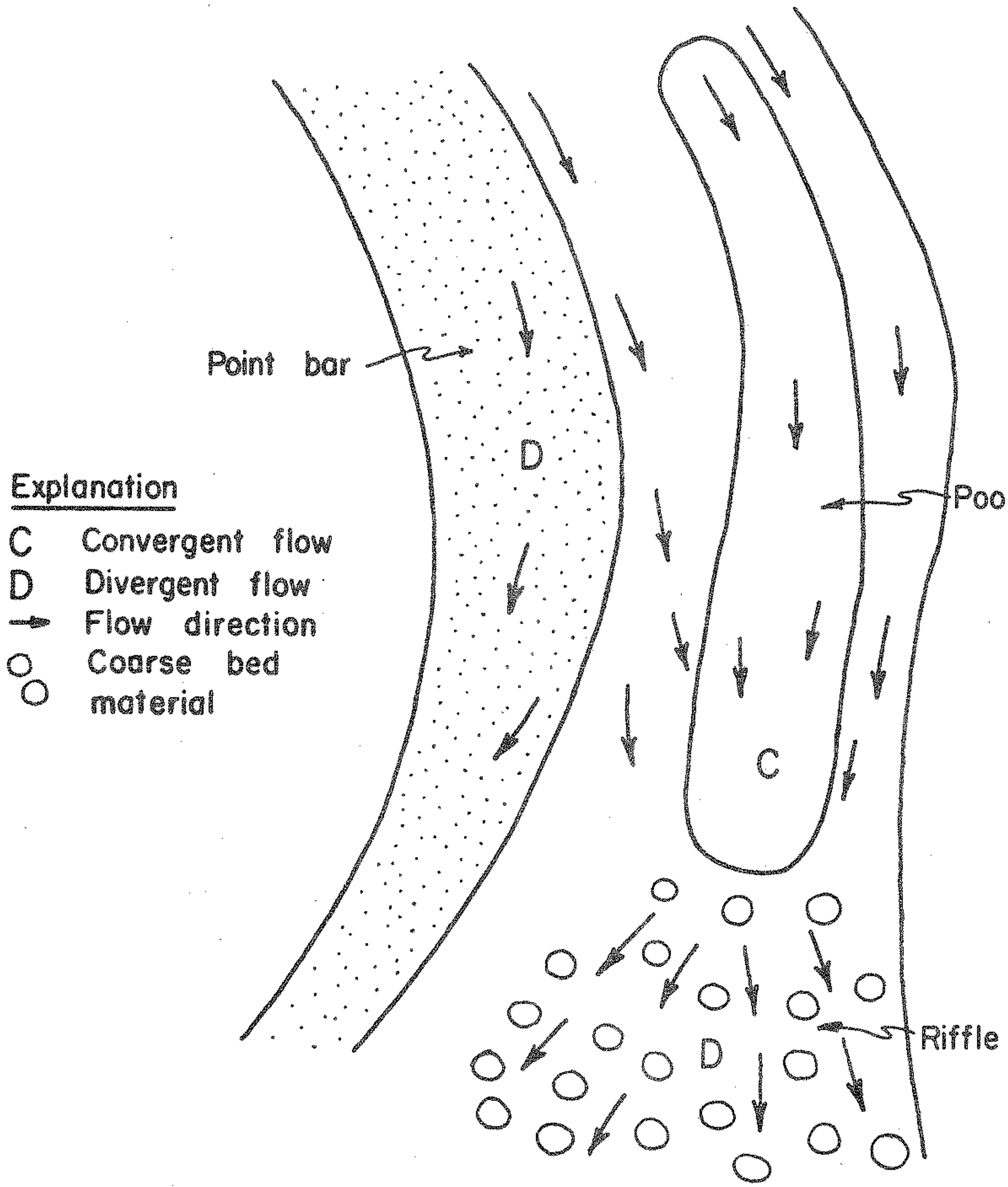


Figure 42. Idealized illustration of the convergent and divergent flow which deposited the coarse-grained material at high stage in Figure 41.

older, partly consolidated alluvium and contains no coarse-grained bed material. It is assumed that the fan-shaped deposit of coarse-grained bed material was deposited at high flow when convergent flow in the pool diverged on the adjacent riffle.

The concept of a velocity reversal has been challenged by Teleki (1972). He argues that the observed areal sorting of bed-load material results from velocities which are greater on riffles than in pools. He further states that the origin of coarse-grained material on riffles is owing to a greater bottom shear stress there. The validity of "drag" or intensity of the tractive force, defined as the product of the water depth by the hydraulic slope and by the specific weight of water, is still being debated (Leliavsky, 1966, p. 40). Furthermore, Maddock's (1969) work questions the validity of a unique or determinate relationship between velocity, depth, slope, and rate of sediment movement. Even assuming that the depth-slope product is a measure of the tractive force, Teleki's explanation appears incorrect. First, it violates de Leliavsky's well-founded and tested criterion, and second, it cannot explain why coarse-grained sediment is not found in pools. Assuming that areal sorting results from faster velocity on riffles, as proposed by Teleki, then one would expect that at some time, when coarse-grained bed material is being transported, material moved off a riffle would become trapped in the pool by the lesser tractive force there. However, studies by Leopold and others (1964, p. 208) and Keller (1971a,p. 753) suggest that this is not the case for alluvial channels. Both authors concluded that at some stage of flow, material must be scoured from pools that cannot be transported through the riffle. Therefore, the principal conclusion remains that at some stage the tractive force in pools is apparently greater than for riffles, and this must produce the areal sorting.

Assuming that the depth-slope product is valid, it does not appear to conflict with the velocity reversal concept. At high flow, when the water-slope over the pool-riffle sequence is constant, the greater depth in the pool should result in greater tractive force there. Even the Manning equation which is used to predict mean velocity is consistent with the velocity reversal. The equation is

$$v = 1.49 \frac{R^{2/3} S^{1/2}}{n}$$ (Leopold and others, 1964, p. 158)

where v is the mean velocity, R the hydraulic radius (mean depth), S the water surface slope, and n the Manning number, which varies from 0.01 for smooth metal surfaces to 0.06 for rough natural channels. From this equation, if the slope is constant, then velocity varies with depth and n. Therefore, at high flow this suggests that the pools, with greater depth and smaller Manning number, should have a higher mean velocity. However, this is speculative because no mean velocity measurements, as were measured for bottom or bed valocity (Keller, 1971a), have been taken over a range of flows in a pool and adjacent riffle and, furthermore, the depth-slope product may not be valid.

If future research proves the velocity reversal invalid, then it must be abandoned as a possible mechanism to produce the known areal sorting of bed material. However, any hypothesis will have to explain the apparently higher tractive force in the pool at high flow, as well as the lack of coarse-grained bed material in some pools and lack of any bed material in other pools which occasionally scour to bed rock. The concept of a velocity reversal is the only published explanation which satisfies both of these criteria.

Two other important processes in pools and riffles are dispersion and partial interaction. In riffles, the largest bed material commonly forms a single layer on the surface (Keller, 1971a, p. 753). Bagnold (1968) explained the tendency for large material to be deposited on the surface of riffles by the dispersive stress. This stress is proportional to the square of the particle size and, therefore, the relatively large particles will drift toward the region of least shear at the upper surface of the bed. Where large particles reach the surface of the bed, hydraulic action concentrates them on the riffles. Yang (1971b, p. 1571) has used the dispersive stress to explain how pools and riffles form. However, even though dispersive stress may facilitate the formation of pools and riffles, it cannot produce them. This results because dispersive stress cannot cause the observed scour in pools. Because riffles are concentrated areas of coarse-grained bed material, particle interaction owing to this concentration may be significant. Langbein and Leopold (1968, p. 19) used this to explain the spacing of riffles:

> "... the kinematics suggest that spacing of riffles is related in part to the thin veneer of gravel set in motion by the flow. The bar represents an interaction between two opposing factors: increasing water velocity, which tends to increase wavelength, and decreasing amplitude, due to erosion, which lends to decrease wavelength. Such a balance results in riffle bars which do not appreciably move downstream."

Although this theory explains why pools and riffles may be relatively stable, it does not explain the origin of the forms. Furthermore, the concentration of coarse-grained bed material appears to be totally a function of fluvial hydraulics.

The fluvial processes which produce a typical pool-riffle sequence can be ideally described by a two-stage transformation. Stage one is characterized by transformation from the original condition to a series of asymmetric shoals which alternately slope, first toward one bank then toward the other. Stage 2 is characterized by transformation from the asymmetric shoals to pools, riffles, and point bars. The development of asymmetric shoals has already been discussed. An idealized diagram showing processes for the second stage is shown in Figure 43. The thalweg is the dashed line, which denotes the boundary between asymmetric shoals. The morphology of the shoals produces an asymmetric profile at the widest part of the shoal, and this tends to converge flow in a restricted area where the water is the deepest. The water, after leaving the area of convergent flow, starts across the channel toward the opposite bank. Here the cross profile is more symmetrical, and divergent flow results. It is emphasized that scour takes place only over a relatively restricted area in the channel. Furthermore, these convergent-divergent relationships may not hold for low flow conditions. This results because secondary scour channels may develop on riffles at high flow, even though the flow is primarily divergent. These are not significant at bankfull stage, but at low flow with a much reduced channel width these channels may actually converge flow. If one of these

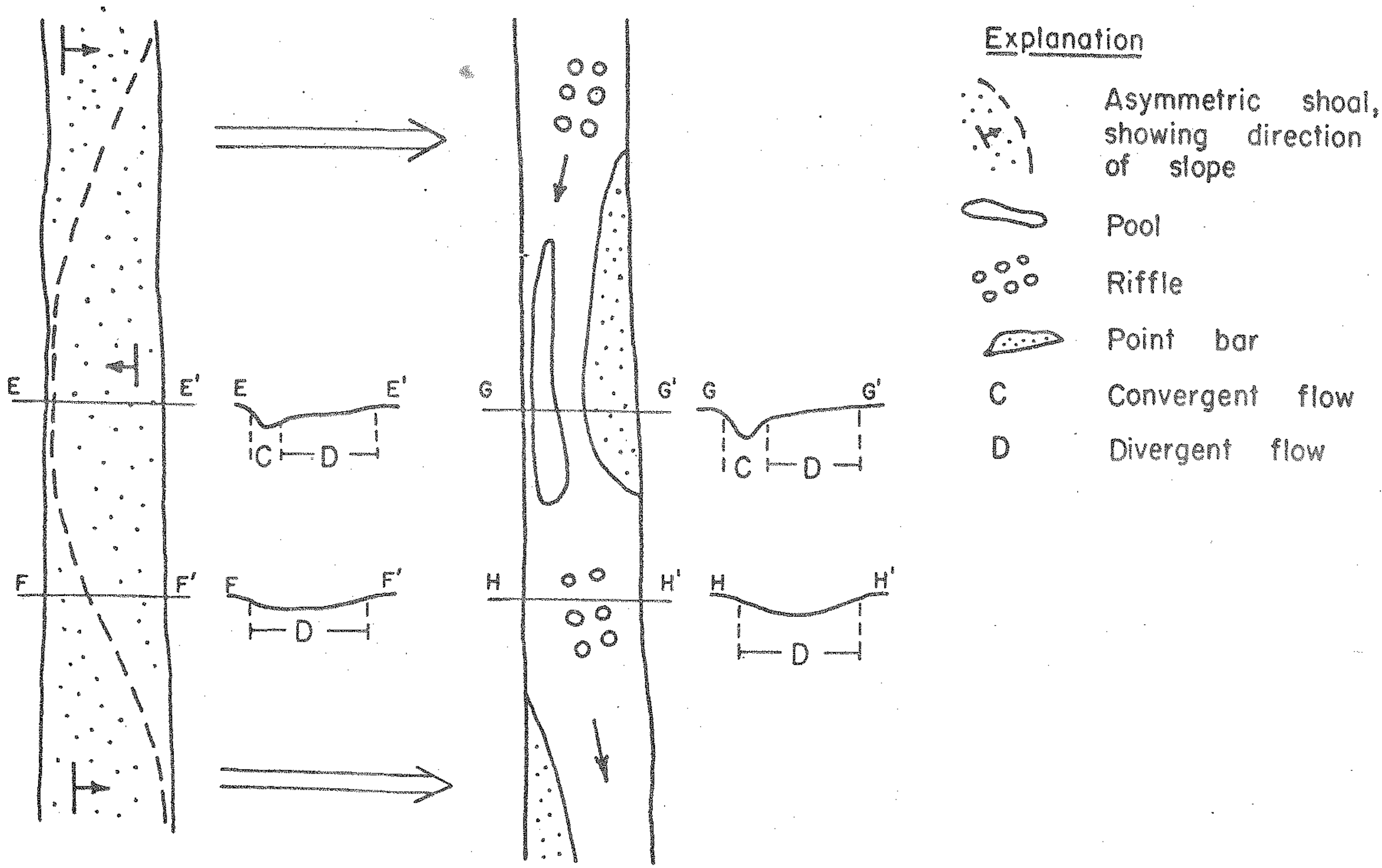


Figure 43. Hypothetical transformation from asymmetrical shoals to pools and riffles.

channels heads into a large scour pool formed at high flow, then the water at low flow will actually diverge over the pool. This is just the opposite of what occurs at high flow. Therefore, the bankfull morphology measured at low flow depicts conditions at high flow, but the water at low water flow may be at the mercy of relatively insignificant constraints which formed at bankfull stage.

The convergence and divergence of flow produces incipient pools and riffles: pools where scour is the greatest, and riffles where deposition is the greatest. As this process continues, the pools and riffles grow at the expense of the asymmetric shoals. The end result is a well developed pool-riffle sequence (Fig. 43). What is left of the asymmetric shoal is referred to as a point bar. This does not imply that point bar formation is primarily an erosional process. As pools scour part of the original shoal, and riffles cover up other parts, flow is still divergent on the upper part of the shoal, and thus deposition of material continues there. If this were not so, the stream channel would become wider but there would be little increase in channel length. This argument is further supported by the fact that meander bends migrate laterally while maintaining a relatively constant width, a condition which would be impossible if there was not a balance between scour on the outside and deposition on the inside of the bend.

The formation of pools and riffles in alluvial streams appears to be a self-adjustment mechanism that minimizes the time rate of potential energy expenditure per unit mass of water (Yang, 1971b, p. 1567). This is consistent with Dolling's (1968) conclusion that the pool-riffle sequence somehow maintains a balance in energy expended by the stream, and therefore is an important element in maintaining a state of quasi-equilibrium. However, neither of these authors were able to completely define conditions that allow the proposed energy relationships to be established in the pool-riffle sequence.

Stream length must increase to minimize the time rate of energy expenditure (Yang, 1971); therefore, the morphology of the channel must facilitate such an energy distribution. Furthermore, the only way a stream can increase its channel length, with the exception of headward erosion or progradation, is by lateral erosion which increases sinuosity. Therefore asymmetric shoals, pools, riffles, and point bars have the most probable morphology to allow lateral migration as the time rate of energy expenditure is minimized. This results because the only way channel length between two points can increase is for the stream to concentrate energy expenditure on one bank or the other. If this is done by converging flow, according to de Leliavsky's criterion, then the cross-section must be asymmetrical. However, this appears to violate Yang's (1971a) law of least time rate of energy expenditure because the convergent flow tends to increase energy expenditure. This would be true if the stream reach was straight or sinuous. However, if the entire pool-riffle sequence is considered, the increase in energy expenditure is probably compensated for by the divergent flow on the riffles. It appears that the riffle with a relatively flat, asymmetrical cross-section is the most probable morphology to cause divergence of flow. Therefore, there appears to be a balance of the time rate of energy expenditure through the pool-riffle sequence that allows channel length to increase until a minimum value of time rate of energy expenditure is reached. The minimum value for any particular stream reach is determined by the external constraints imposed by the geology, discharge, valley slope, etc. The above argument is only valid for high flow conditions when the forms are being produced. It appears likely that the constraints produced by the pool-riffle sequence may best satisfy the two premises of the concept of entropy: uniform distribution of energy, and minimum energy expenditure.

Pool-Riffle Spacing

Pool-riffle spacing was investigated by field measurement of channel width and distance between pools. For the spacing, the distances measured were from center point to center point of consecutive pools. The deepest point in the pool was considered the center point. This helps remove some of the subjectivity of deciding where the pool or riffle starts or stops, and the periodicity is not affected as long as a constant reference point is used. For this report, channel width is considered to be the width of the channel covered by bed material, measured at right angles to the channel banks. Although this distance is normally easy to determine, it is more subjective than the spacing measurements. In general, width measurements were made on riffles where the banks were well defined. The width measured is probably close to the bankfull width of Leopold and others (1964).

Measuring of pool-riffle spacing along the four sampled streams confirmed the conclusion of Leopold and others (1964) that mean spacing is 5-7 channel widths. However, the most frequent spacing may not be 5-7 channel widths, and this appears to have genetic implications (Keller, 1972b). Table 1 and Figures 23 and 44 summarize channel characteristics, and the distribution of pool-riffle spacing for the sampled streams. It has been suggested (Keller, 1971b) that as channel length increases new pools are added to keep the spacing constant. The frequency distribution of pools for Wildcat Creek and Dry Creek (Figs. 23 and 44) show that there are few pools spaced less than 3-5 channel widths, and few greater than 7-9 channel widths. This suggests that spacing of greater than 7-9 channel widths is unstable and breaks up into two pool-riffle sequences, each spaced at 3-5 channel widths. With alluvial material and ideal conditions, the most stable spacing should be 5-7 channel widths. This produces a wave length along the channel of 10-15 channel widths and, if sinuosity exceeds 1.5 with pools on the bends and riffles on inflections, produces the most probable channel pattern in terms of variance of energy expenditure (Leopold and Langbein, 1966). Of the four streams studied, Durkee Run and Wea Creek (Fig. 45C, 45D), with mean and mode spacing of 5-7 channel widths most closely approaches this ideal and most probable state. Wildcat Creek and Dry Creek, however, have a more frequent spacing of 3-5 channel widths. This suggests that these channels are in a state of flux as part of an evolutionary pattern.

TABLE 1. SUMMARY OF CHANNEL CHARACTERISTICS AND POOL-RIFFLE SPACING FOR THE SAMPLED CHANNELS

	Type of Stream	Bank Material	Sinuosity	Channel Length (mi.)	Channel Width (ft.)	N*	Pool Riffle Spacing Mode	Pool Riffle Spacing Mean
Wild Cat Creek near Dayton, Indiana	Perennial	Alluvium	1.42	2.80	82	30	3-5	5-7
Wea Creek, near Lafayette, Indiana	Perennial	Alluvium	1.38	1.05	67	16	5-7	5-7
Durkee Run, Lafayette, Indiana	Intermittent	Alluvium	1.13	0.27	14	18	5-7	5-7
Dry Creek near Winters, California	Intermittent	Alluvial Fan Deposits	2.40	1.30	33	38	3-5	5-7

* N is the number of pool-riffle sequences samples.
Pool-riffle spacing is measured in channel widths.

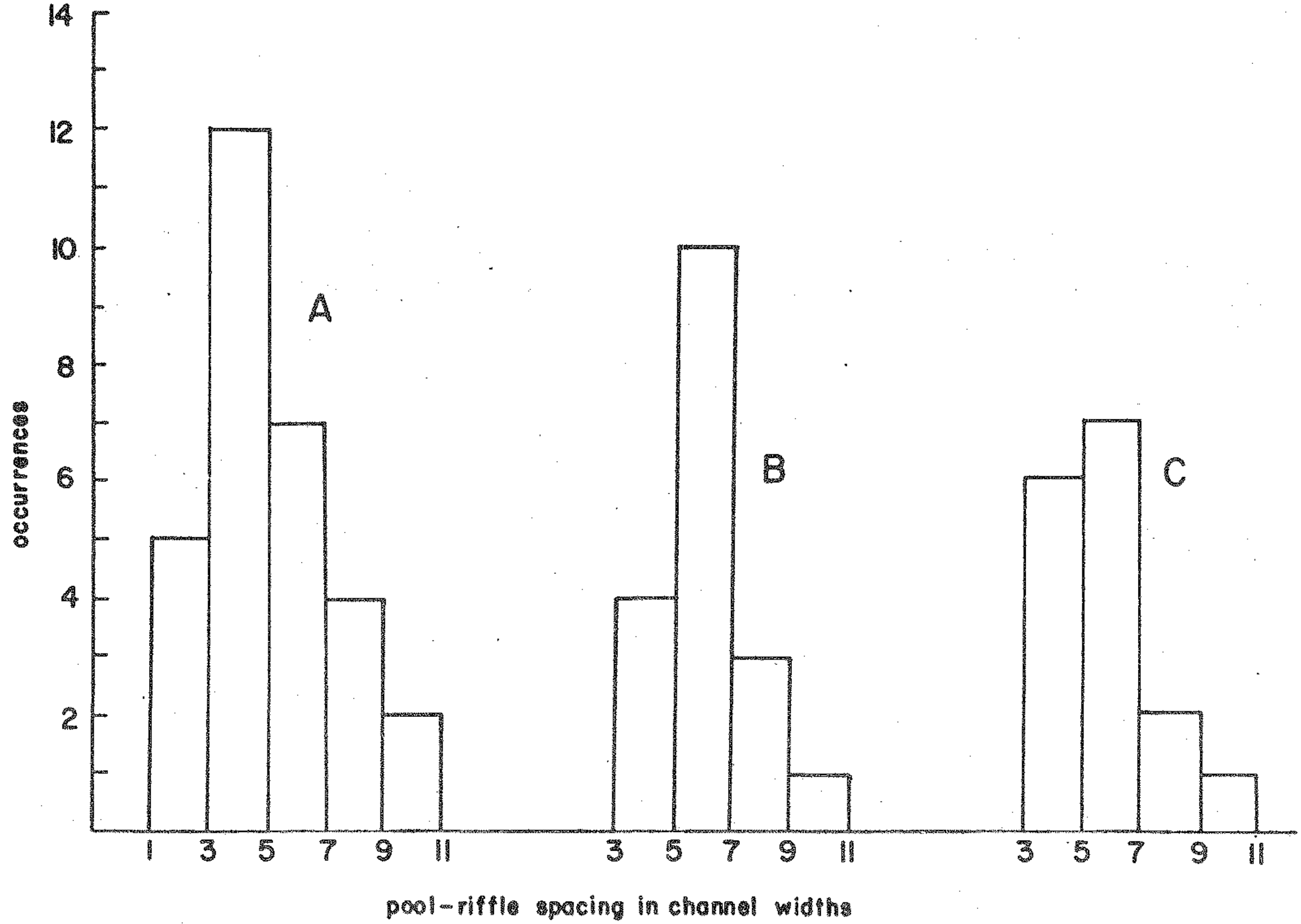


Figure 44. Frequency of pool-riffle spacing for: A, Wildcat Creek; B, Durkee Run; and C, Wea Creek (after Keller, 1972).

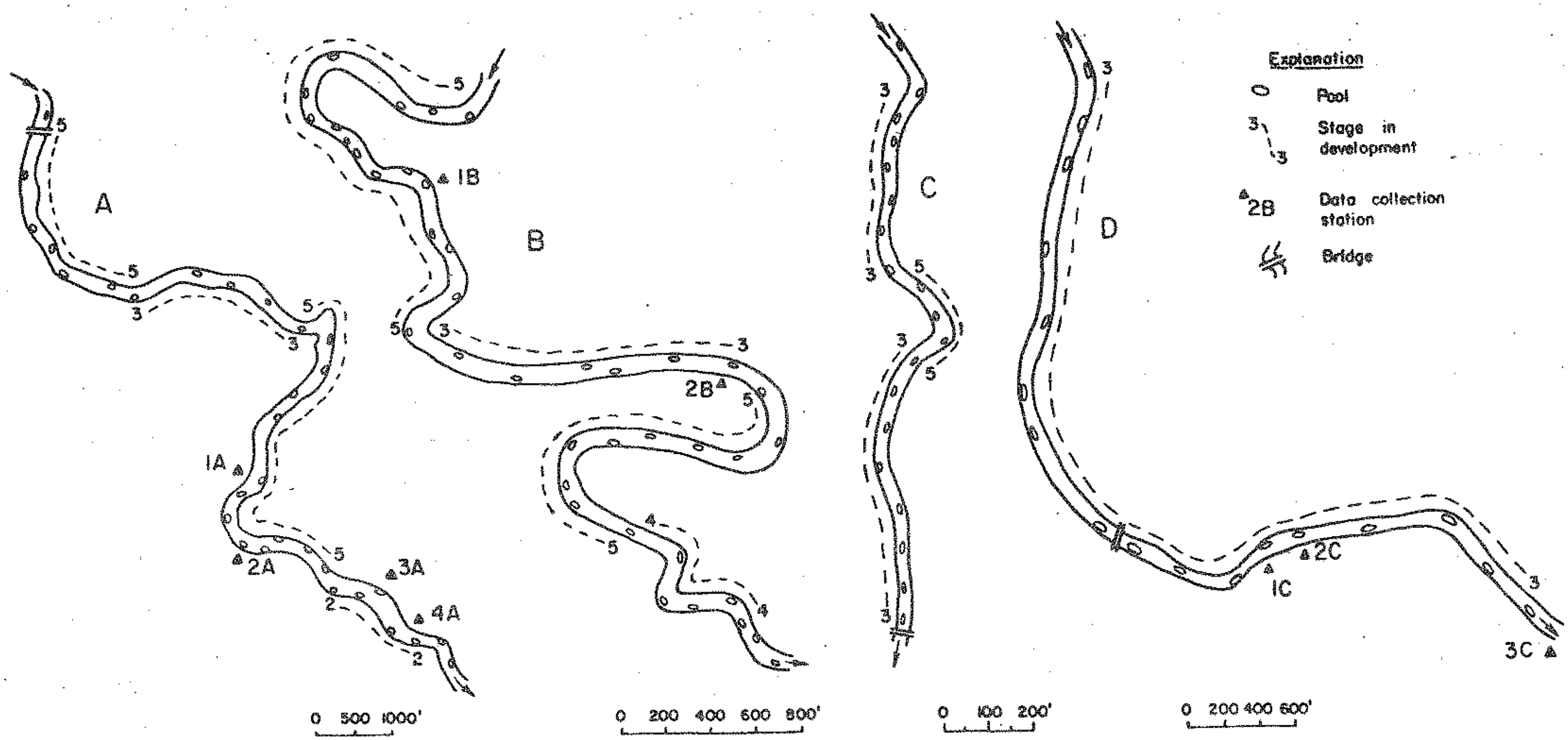


Figure 45. Illustration showing the location of pools, data collection stations and stages of development for: A, Wildcat Creek; B, Dry Creek; C, Durkee Run; and D, Wea Creek. Channel width is exaggerated for illustrative purposes.

Leopold and others (1964, p. 203) stated:

> "The similarity in spacing of the riffles in both straight and meandering channels suggests that the mechanism which creates the tendency for meandering is present even in a straight channel and that this mechanism is associated with some form of wave phenomenon."

This statement suggests that the significant process is the meandering, and this produces pools and riffles. However, the important process appears to be one that produces pools and riffles, and this may lead in turn to meandering. One of the primary things alluvial streams are doing is building pools and riffles. This tends to reduce the time rate of energy expenditure (Yang, 1971b), and may reduce it sufficiently so that a stream must increase sinuosity only a little to minimize the energy relationship. This explains why many apparently stable alluvial streams do not meander. Figure 46 is Leopold's (1964, p. 296) relation between meander length and channel width with pool-riffle data superposed. Although the mathematical function is the same for both, there is less scatter for the pool-riffle data. This suggests that meandering starts with the development of pools and riffles. Because pools are spaced at 5-7 channel widths a constraint is imposed on the meandering so that one-half the wave length of meanders seldom exceeds this value greatly. Therefore, the writers suggest that Leopold's statement be modified to read: the similarity in spacing of the pools, in both straight and meandering channels, suggests that the processes which create the tendency for pools and riffles are present in nearly all alluvial streams, and the mechanism, which is associated with some wave phenomena, may produce meandering channels.

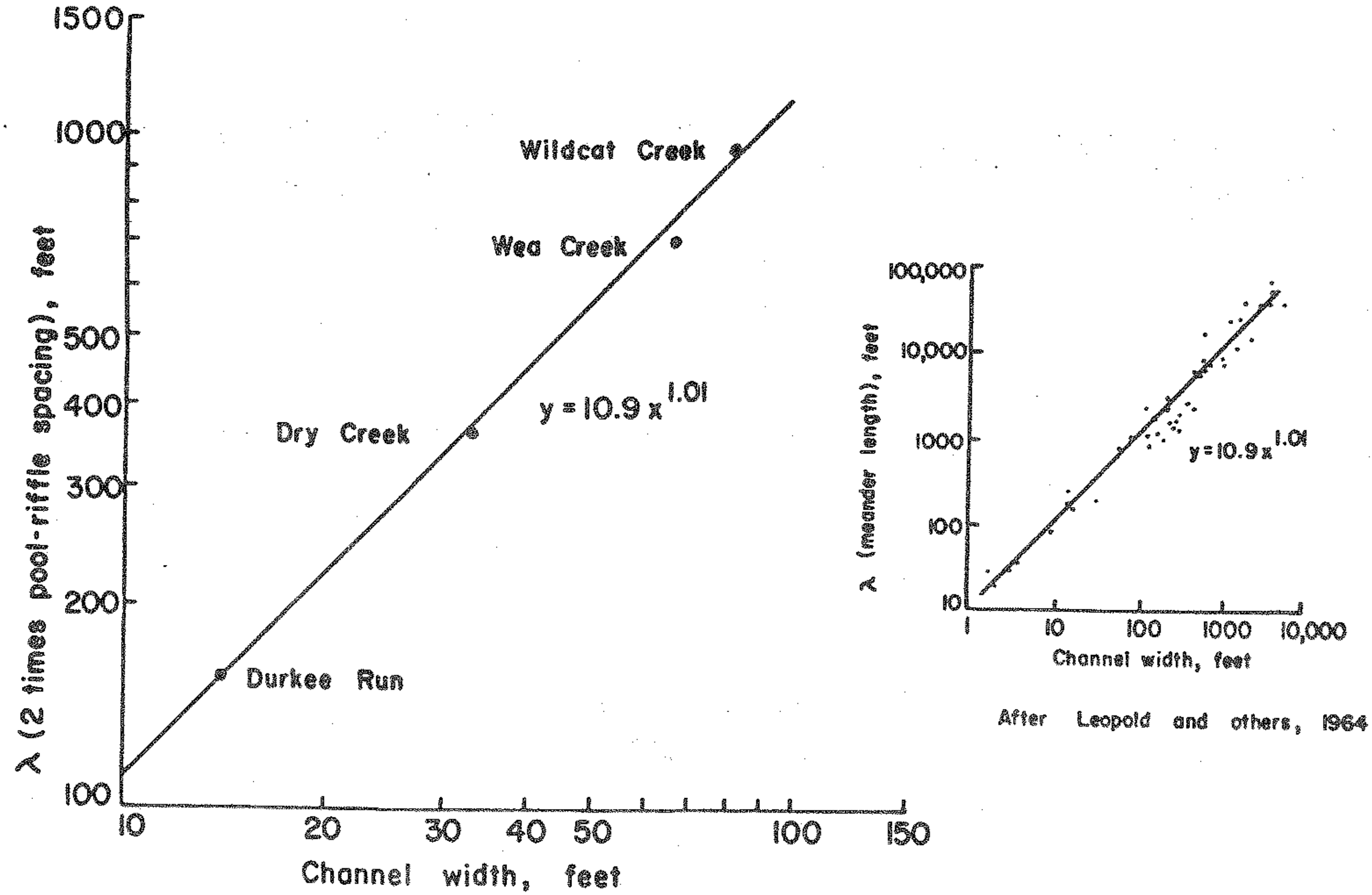


Figure 46. Comparison of the relation between channel width and pool-riffle spacing to the relation between channel width and meander wave length.

Development of Alluvial Stream Channels

General Statement

An alluvial stream is a moving, ever-evolving system, and as the channel wanders back and forth across the flood plain,new meandering, sinuous, and straight reaches are both created and destroyed (Keller, 1972b). The evolution of natural stream channels can be approached from either a qualitative or quantitative standpoint, but any solution is ameliorated when one method complements the other.

This study will demonstrate that a five-stage model is adequate to explain the development of an alluvial stream channel. The model is based on quantitative measurements of pool-riffle spacing frequency and qualitative conclusions from field observations.

Previous Work

Evolution of alluvial stream channels is usually approached from the position that there is a transformation from a straight to meandering channel (Quraishy, 1944, Dury, 1969, and Tinkler, 1970). Quraishy's model (Fig. 47) suggests that meandering is initiated by the development of asymmetric shoals. The writer agrees with Quraishy's inferences as to the initiation of meandering, but development beyond asymmetric shoals must also be considered. Dury (Fig. 48) suggests that transformation from a straight to meandering channel primarily involves an increase in amplitude of the wave form. However, this model is not adequate for two reasons: 1) the end result is a meandering channel with all pools on bends and riffles between

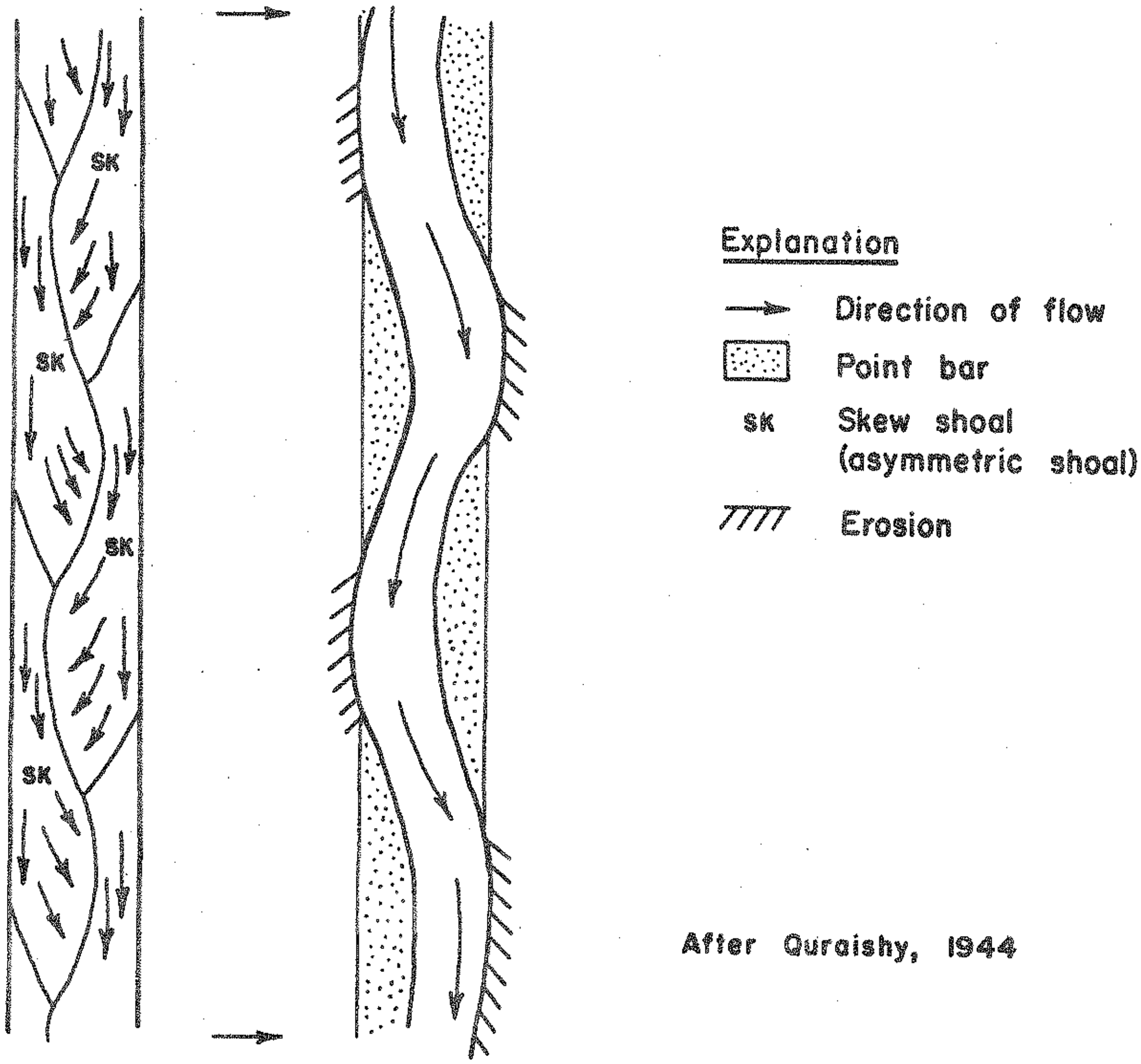


Figure 47. Quraishy's transformation from a straight to meandering channel.

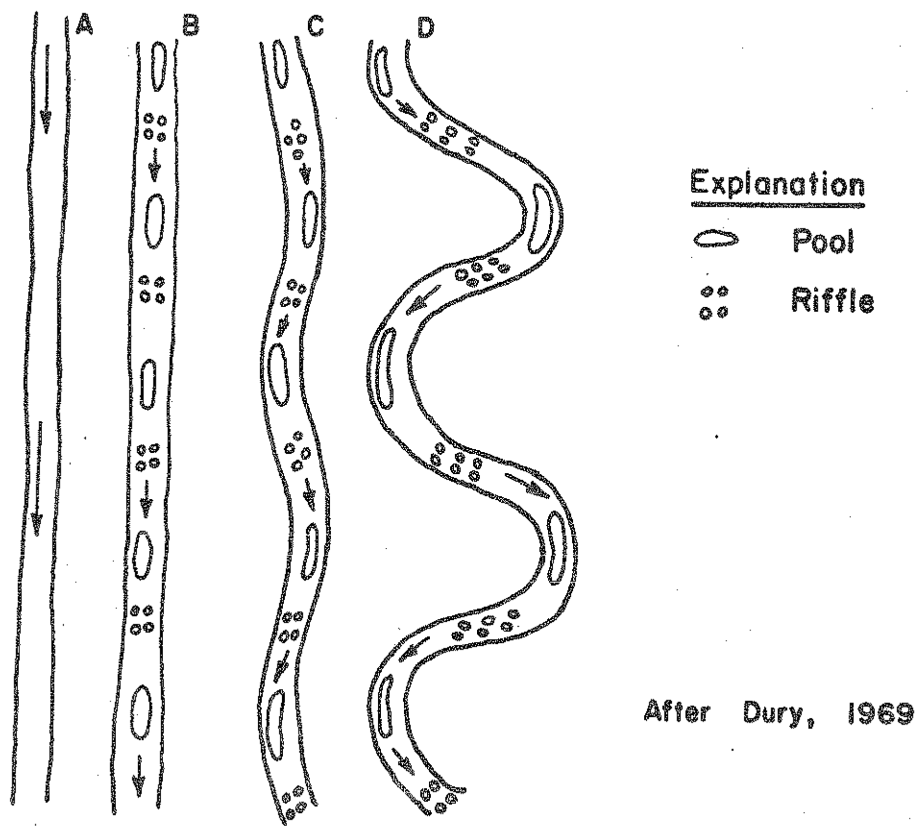


Figure 48. Dury's transformation from a straight to meandering channel.

bends, a condition seldom found in natural streams for more than a bend or so; and 2) the initial channel, with pools in the center of the channel, will have a symmetric cross-section, a condition that will not allow the alternating bank scour which is necessary to increase channel length. Tinkler's transformation (Fig. 49) suggests that riffles and pools in straight channels are transformed into point bars and riffles respectively in meandering channels. However, what Tinkler considers a riffle we have called asymmetric shoal, and what he calls incipient deposition or central channel bar, we consider a riffle. Tinkler (1971) has agreed that the writers' definitions of pool, riffle and point bar remove possible ambiguities which arise when using his model. Therefore, with appropriate changes in terminology, Tinkler's transformation appears consistent with the opinion that asymmetric shoals are transformed to point bars. However, Tinkler's model is not complete because it does not explain the formation of incipient riffles and pools. Furthermore, his model is only applicable to meandering streams wherein all pools are on the bends and all riffles on the inflections, a condition found in few natural streams.

Five Stage Model of Development

A five-stage model (Fig. 50) is proposed to explain the development of alluvial stream channels (Keller, 1972b). The model is based on evidence from quantitative data for pool-riffle spacing (Fig. 23 and 44), interpretation of morphogenetic maps and cross sections (Figs. 26 and 38), longitudinal profiles (Figs. 39 and 53), and field observations. Each stage is recognized by general characteristics (Table 2) that may appear

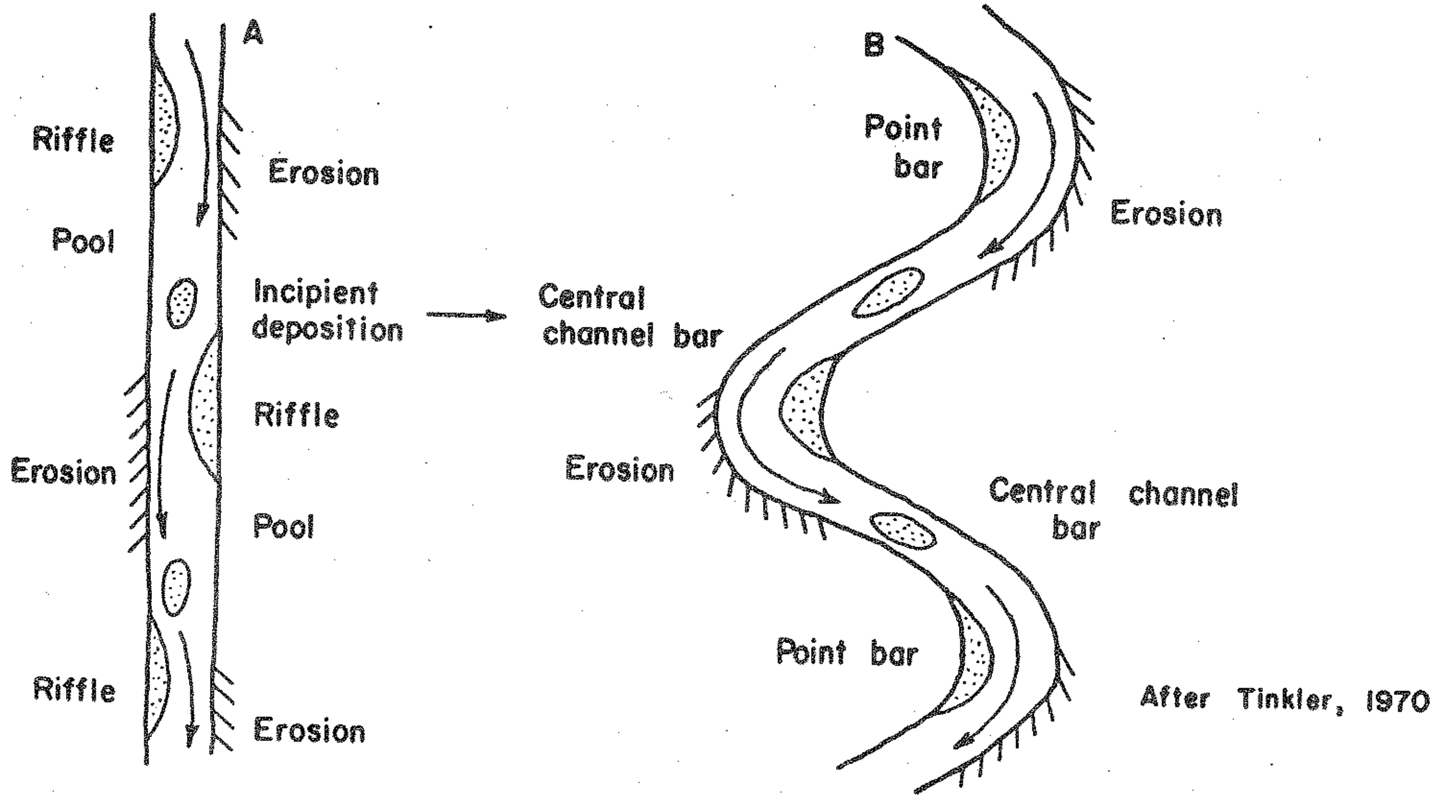


Figure 49. Tinkler's transformation from a straight to meandering channel.

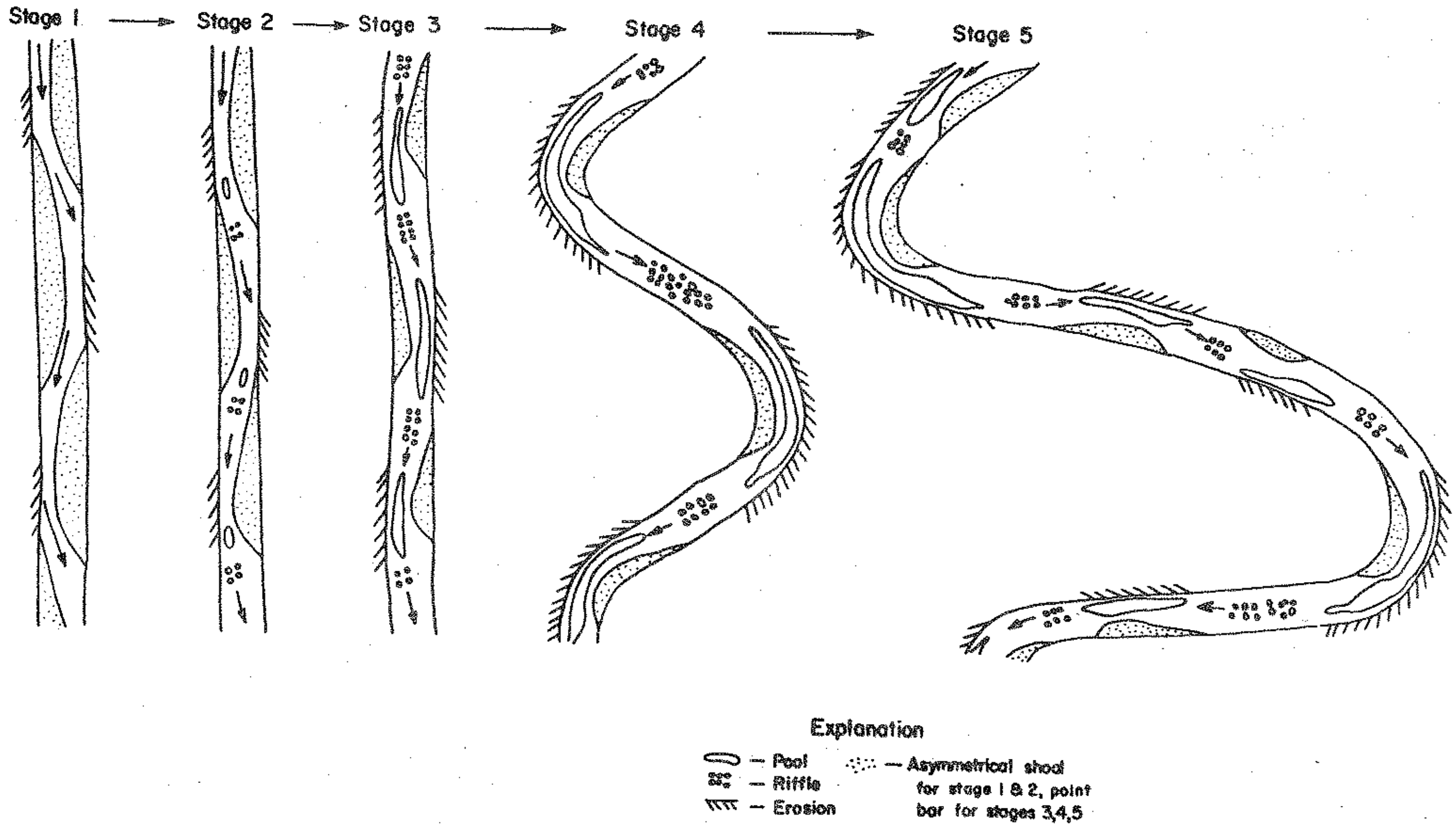


Figure 50. Illustration of the five stage development of alluvial stream channels.

TABLE 2. CHARACTERISTICS OF THE FIVE STAGES IN THE DEVELOPMENT OF ALLUVIAL STREAM CHANNELS

Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
No pools or riffles	Incipient pools and riffles spaced at about 3 to 5 channel widths	Well-developed pools and riffles with mean spacing 5 to 7 channel widths and mode 3 to 7 channel widths	Well-developed pools and riffles with mean spacing 5 to 7 channel widths and mode 5 to 7 channel widths	Mixture of well-developed pools and riffles with incipient pools and riffles--mean spacing is generally 5 to 7 channel widths with a mode of 3 to 7 channel widths
The dominant bed forms are asymmetrical shoals	Dominant bed forms are asymmetrical shoals	Dominant bed forms are pools, riffles, and asymmetrical shoals (mostly point bars)	Dominant bed forms are pools, riffles, and asymmetrical shoals (mostly point bars)	Dominant bed forms are pools, riffles, and asymmetrical shoals
	Pools and riffles are small	Pools are about 1.5 times as long as riffles	Pools are generally greater than 1.5 times as long as riffles	Pools are generally much longer than riffles

as the channel changes from one stage into the next. Furthermore, because different stream reaches evolve at different rates at different times, one stream may have any or all of the stages in different reaches. It is emphasized that for some stream reaches considerable field observation may be necessary to determine what stage the reach is in. Although the idealized diagram (Fig. 50) indicates an increase in sinuosity and decrease in channel slope from stage 1 to stage 5, there are no fixed criteria for either of these variables. The reason is that whereas for a particular reach the development through various stages increases sinuosity and decreases slope, not enough streams have been sampled to determine if threshold limits between stages can be delineated on the basis of slope or sinuosity. Hypothetically, such limits probably do not exist because of the wide variety of constraints imposed upon alluvial channels. Especially important constraints are the nature of the bed and bank material and relief. Flume studies emphasize the need of using caution in trying to use channel slope or sinuosity to determine stage. Experiments by Friedkin (1945, plate 4), and Simons and Richardson (1966, Fig. 17), produced a series of asymmetric shoals, and yet the sinuosity in Friedkin's flume channel is considerably greater than for Simon's. Therefore, two channels may be in the same stage of development and have a quite different sinuosity.

The five stages appear to be the most representative in the continual development of alluvial streams. Although any one of the stages may, under certain conditions, be stable in nature, stages 3 and 5 seem to be most common. Stage 3 is not necessarily a straight channel as ideally illustrated in figure 50, and many sinuous channels in stage 3 appear to be stable. Therefore, stage 3 may be the last stage in the development of some stream reaches. An example of this is indicated on Wea Creek (Fig. 45). Furthermore, it is not necessary that all other stages be developed prior to the appearance of stage 5. For example, stage 3 may be transformed to stage 5 without going through stage 4. The transformation to stage 5 is critical because so many stream reaches fit this stage. It apparently is a logical consequence of meandering processes which lead to an increased channel length. The development is reinitiated whenever a new channel is produced suddenly, as commonly happens when a meander cutoff occurs. A cutoff that has occurred in Wildcat Creek since March, 1968 produced 1,320 feet of new channel. This reach now has four pools and is in stage 2 (Fig. 51). Figure 52 from Friedkin's (1945) model study shows the development of asymmetric shoals. The associated thalweg profile, low water surface, and cross-sections are remarkably similar to those for the section of Wildcat Creek in stage 2 (Fig. 51 and Fig. 53). The analogy of flume studies with stage 2 of the five stage model suggests that for the sandy bed load material usually used in flume studies and the constraints of the flume, stage 2 is stable. However, it may be that flume studies are not continued long enough for well developed pools and riffles characteristic of later stages to appear. Examples of stages 2, 3, 4, and 5 are given in Figure 45. The existence of stage 1 is largely hypothetical and, while its duration is probably very short, it is necessary if stage 2 is to develop.

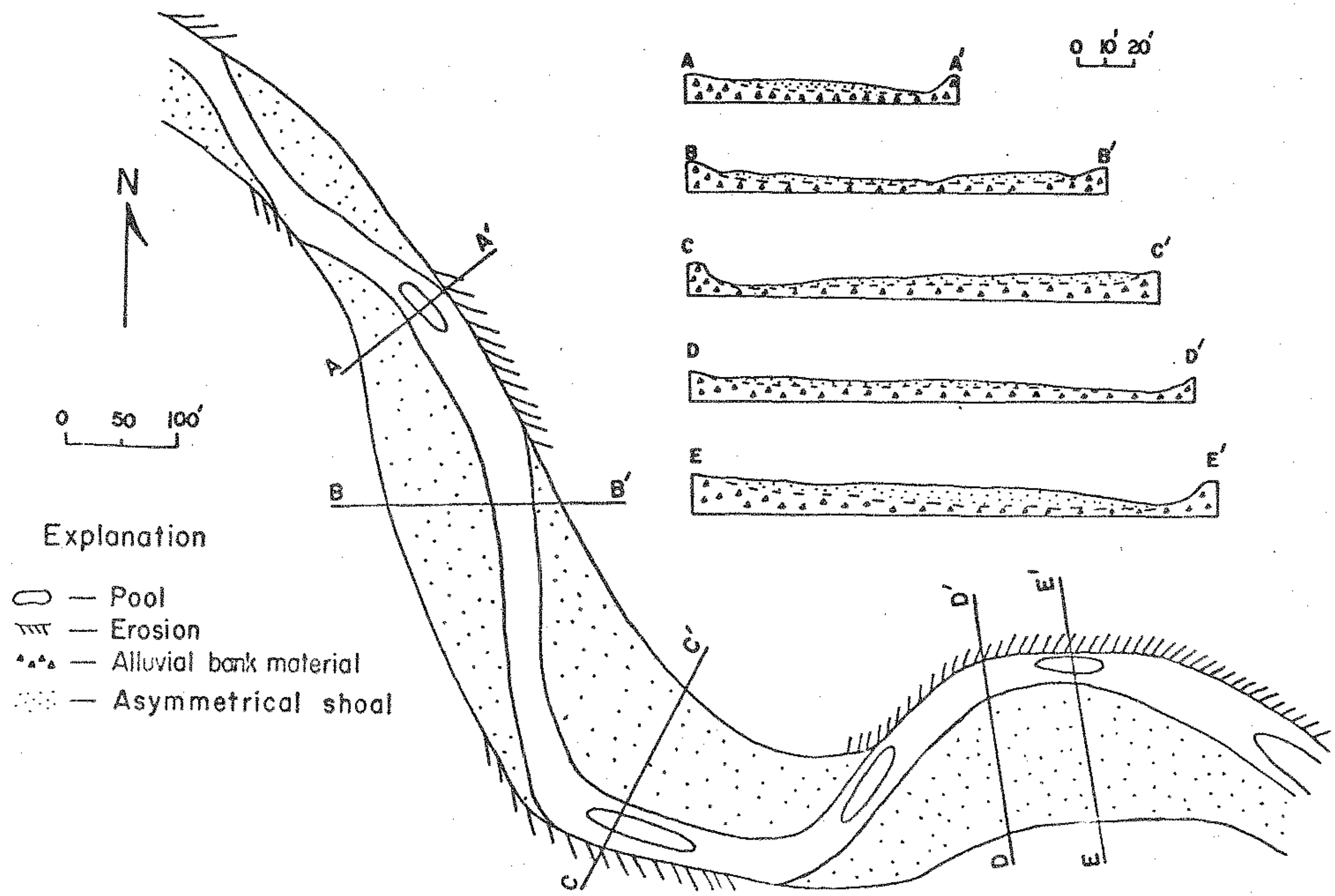


Figure 51. Detailed map showing a reach of Wildcat Creek in stage 2. The location is 3A-4A in Figure 45. The dashed lines in the sections indicate the approximate boundary between the asymmetrical shoals and underlying alluvial material.

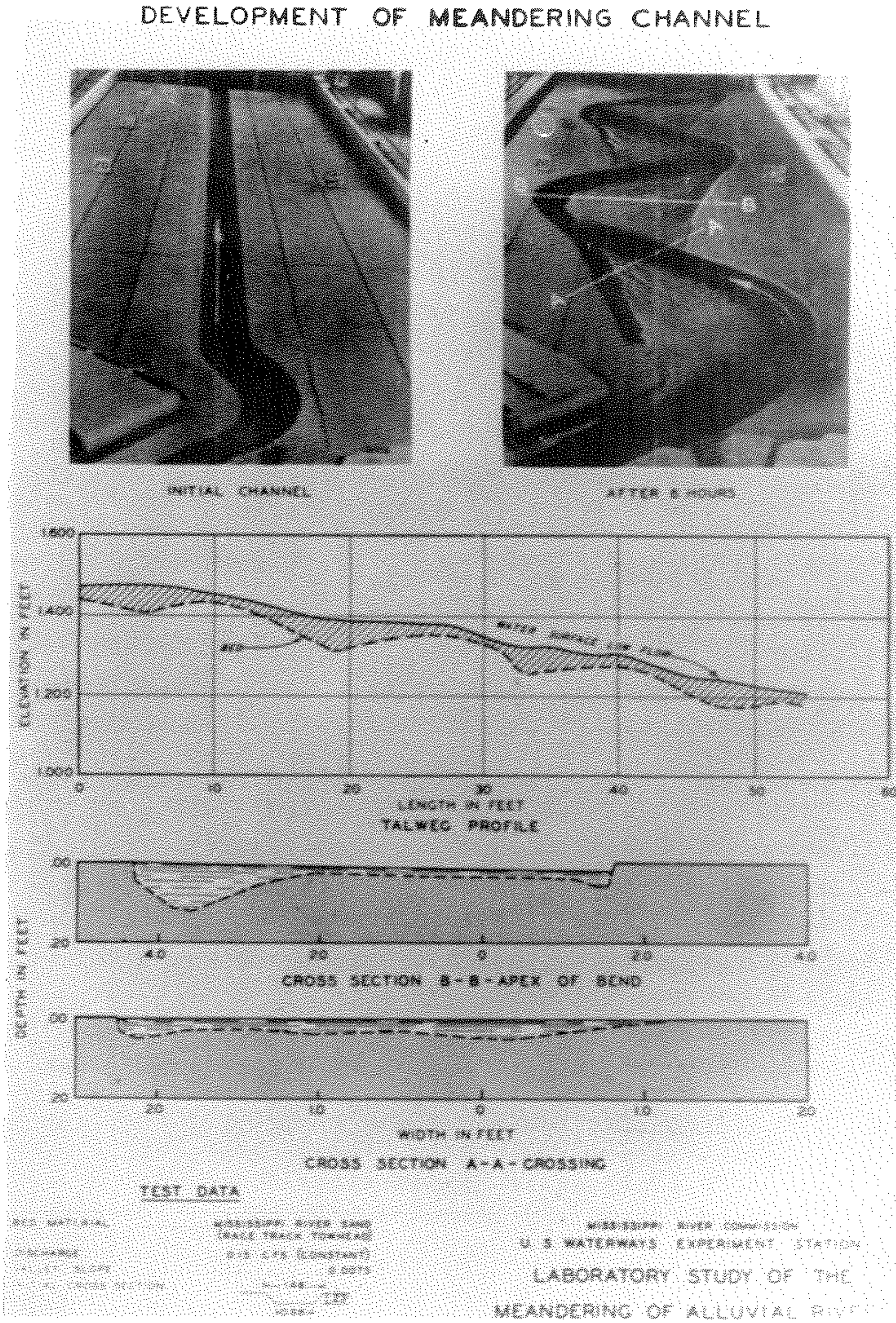


Figure 52. Development of a meandering channel in a flume(after Friedkin, 1945).

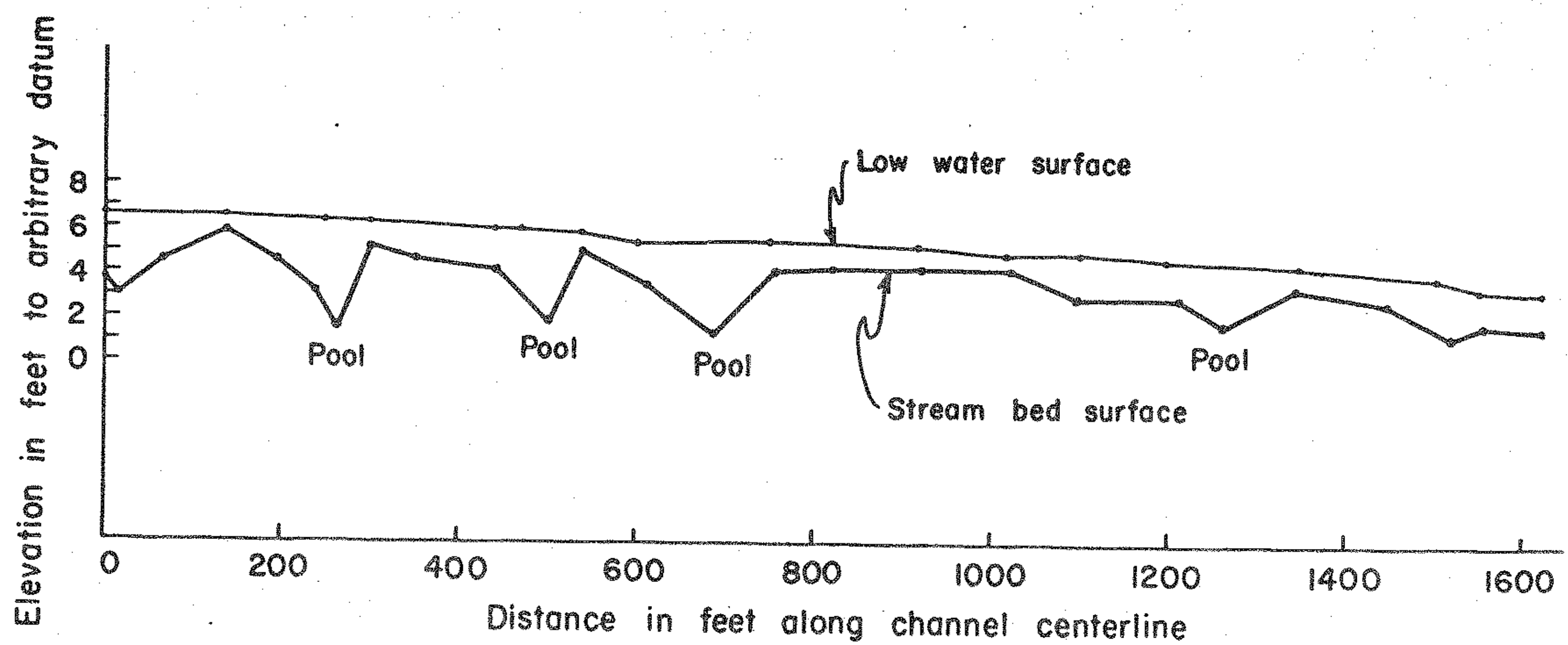


Figure 53. Thalweg profile and low water surface for the stream reach shown in Figure 51.

The five-stage model is more complete than the transformations from a straight to meandering channel proposed by Dury (1969, p. 422) and Tinkler (1970, Fig. 3); furthermore, these transformations appear to be subsets of this five-stage model. Dury's transformations would be the transformation from stage 3 to stage 4, whereas Tinkler's transformation corresponds, with appropriate terminology changes (See Tinkler 1971, p. 281), to transformations from stage 2 to stage 3 to stage 4. The five-stage model has the advantage that it can be applied to nearly all alluvial channels.

Discussion

The five-stage model of alluvial stream channel development provides a genetic basis for labeling, with the possible exception of braided patterns, of most alluvial stream reaches. However, there is a close relationship between meandering and braiding (Leopold and others, 1964, p. 292) and future research may be able to add the braided pattern to a developmental model. Stage 1 is largely hypothetical as I have not found examples of it in natural streams; however, it is a necessary and logical step to precede stage 2, which is more stable and does occur in nature. The asymmetical shoals in stage 1 cause convergence of flow in incipient bends and divergence of flow between the bends. This leads to scour and deposition which forms the incipient pools and riffles of stage 2. During the transformation from stage 2 to stage 3 the pools and riffles increase in size at the expense of the asymmetrical shoals, which become point bars. Stage 3 can be relatively stable, and transformation to stage 4 involves primarily an increase in amplitude, decrease in radius of curvature, and decrease in variability of energy expenditure. The transformation to stage 5 is primarily the result of meandering processes which increase channel length. As pool-riffle spacing is independent of channel pattern, new pools may be added to keep the spacing constant. Whereas this decreases the energy expenditure per foot of channel, it increases the variability of energy expenditure by the addition of short, straight reaches.

Tentative Classification of Bed Forms

General Statement

"Classifications are contrivances derived by men to fulfill certain purposes. Because they are not themselves truths capable of being discovered, the best classification is that which best serves the purpose for which it was derived" (Soil Survey Staff, 1960, p. 6).

The purpose of classifying bed forms in alluvial stream channels is to arrange the forms so that an orderly sequence of ideas, concepts, and processes, which define and control the channel, is produced. Such a classification must be, "born from the river", for it is the natural fluvial processes which produce the forms. This would exclude classification based on flume studies, an idea apparently consistent with Neill's (1969, p. 83) conclusion that excessive study and analysis of bed forms in flumes may result in an over-simplified classification of forms.

Bed forms have been defined or classified on the basis of the flow regime (Simons and Richardson, 1963, 1966), relative size (Neill, 1969), and morphology (Leopold and others, 1964 and Keller, 1971b). Terminology for description of bed forms in alluvial channels is not yet standardized. An attempt to do so by ASCE Task Force (1966) resulted in a fairly good descriptive classification of many common bed forms, but it completely neglected some major forms in stable channels such as pools and riffles. This study suggests that a generic classification, which permits hierarchical ranking of bed forms in alluvial stream channels, may be an improvement on existing classifications. However, it is emphasized that the proposed classification is tentative and subject to change as better understanding of fluvial processes is achieved. Furthermore, the proposed classification is only applicable to straight, sinuous or meandering alluvial channels.

Classification of Bed Forms

The proposed classification of bed forms in alluvial channels includes two major subdivisions: 1) channel-forming bed forms, and 2) channel-altering bed forms (Fig. 54). Channel-forming bed forms are those forms which control the development of the channel pattern, whereas channel-altering bed forms generally do not control the channel pattern and are usually superposed on the channel-forming forms. Channel-forming bed forms are further subdivided into first- and second-order forms and the channel-altering bed forms are subdivided into third- and fourth-order forms.

First-Order Bed Forms are asymmetric shoals which alternately slope first toward one bank, then toward the other (Figs. 26, 27, and 28). These shoals, as already defined, appear to be the primary bed form in the evolution of alluvial channels (Keller, 1972b). Given a stable channel, i.e., a channel which develops pools and riffles, the asymmetric shoals will be transformed to point

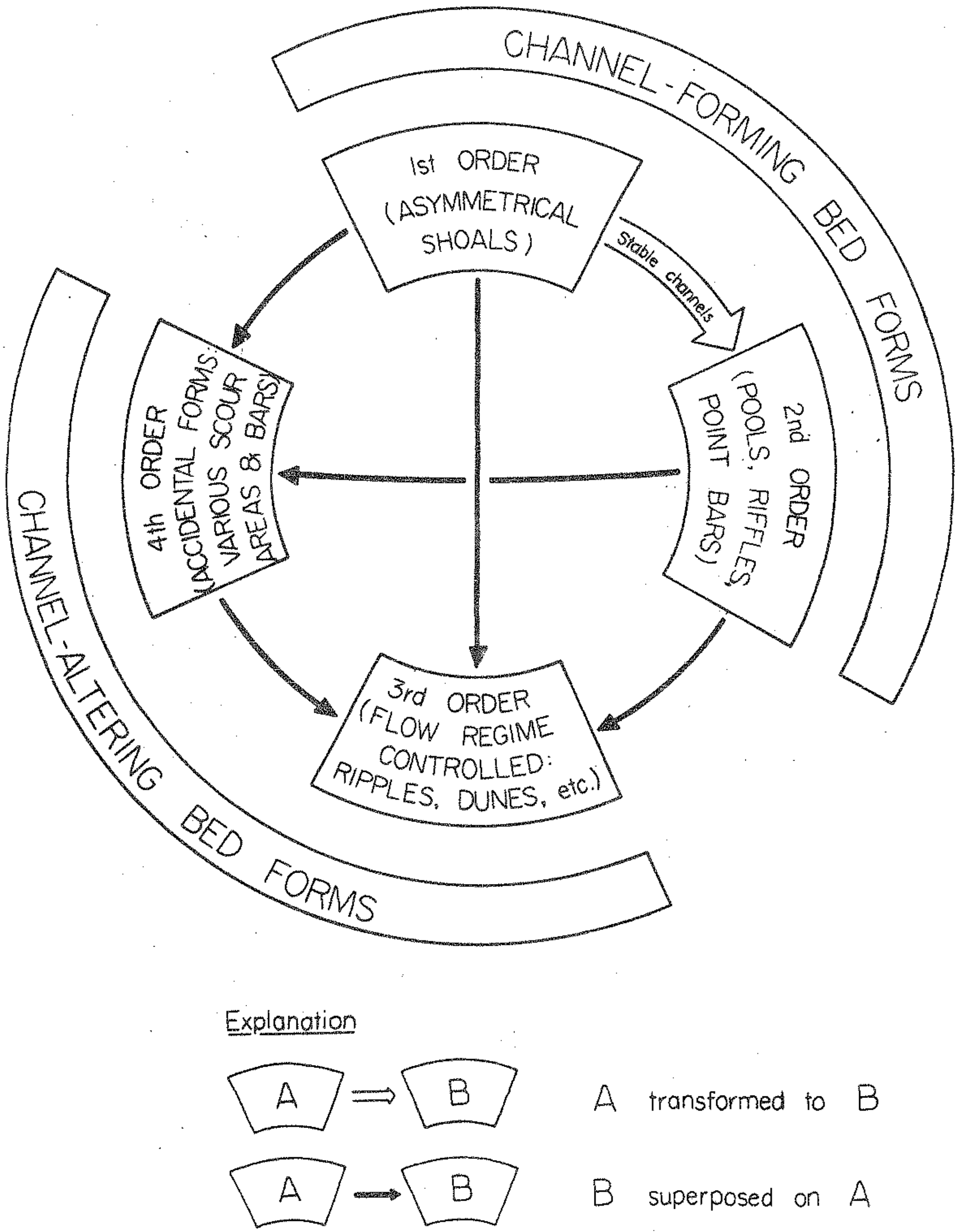


Figure 54. Tentative classification of bed forms for alluvial stream channels.

bars as pools and riffles develop. Given an unstable channel with relatively fine-grained bed material or steep slope, pools and riffles may not develop. In this case, the asymmetric shoals may be masked by the channel-altering bed forms. However, these conditions are not always clearly defined, and an intermediate zone exists for channels that have poorly developed pools and riffles. These channels have some characteristics of both stable and unstable channels.

Second-Order Bed Forms consist of pools, riffles, and point bars. Examples of these forms, defined previously in this dissertation, are shown on Figures 32, 33, 34, and 38 . Pools, riffles, and point bars control the development of many alluvial channels, and therefore are channel-forming forms. However these forms may be altered or partially masked by third- or fourth-order bed forms.

Third-Order Bed Forms are those forms shown to be controlled by the flow regime. Simons and Richardson (1966) defined flow regime as a range of flows characterized by similar bed forms, resistance to flow, and mode of sediment transport. Two flow regimes, upper and lower, separated by a transition zone, are generally recognized in alluvial channels. The bed forms of the lower flow regime are ripples, ripples on dunes, and dunes, whereas the bed forms of the upper flow regime are plane bed, antidunes, and chutes and pools (Fig. 55). These forms are defined as follows:

"Ripples. Small triangular-shaped bed forms that are similar to dunes but have much smaller and more uniform amplitudes and lengths. Wave lengths are less than about 2 feet, and heights are less than about 0.2 foot.

Dunes. Large bed forms having triangular profiles, a gentle upstream slope, and a steep downstream slope. They form in tranquil flow and, thus, are out of phase with any water-surface disturbance that they may produce. They travel slowly downstream as sand is moved across their comparatively gentle, upstream slopes and deposited on their steeper, downstream slopes. The downstream slopes are approximately equal to the angle of repose of the bed material. Dunes are smaller than sand bars but larger than ripples. They generally form at higher velocities and larger sediment discharges than do ripples, but at lower velocities and smaller sediment discharges than do antidunes. However, ripples form on the upstream slopes of dunes at lower velocities.

Plane bed. A bed form in which there are no irregularities larger in amplitude than a few grain diameters.

Antidunes. Bed forms of curved symmetrically shaped sand waves that may move upstream, remain stationary, or move downstream. They occur in trains that are inphase with and strongly interact with gravity water-surface waves. The water-surface waves have larger amplitudes than the coupled sand waves. At large Froude number, the waves generally move upstream and grow until they become unstable and break like surf (breaking antidunes). The agitation accompanying the breaking obliterates the antidunes, and the process of antidune initiation and growth is repeated. At smaller Froude numbers the antidunes generally remain stationary and increase and then decrease in amplitude without breaking (standing waves).

Chutes and pools. The flow phenomenon and bed configuration accompanying flows that occur at steep slopes and large bed-material discharges. The flow occurs at slopes steeper than for antidunes and consists of a series of pools in which the flow is tranquil, connected by steep chutes where the flow is rapid. A hydraulic jump forms at the downstream end of each chute where it enters the pool. The bed configuration consists of triangle-shaped elements with a steep upstream slope, a flat, almost horizontal back, and a gentle downstream slope. The chutes and pools move slowly upstream." (Simons and Richardson, P. V-VI).

These forms are not generally significant in controlling the development of a channel, but they may significantly alter a channel. In channelswith pools and riffles, ripples and ripples on dunes can sometimes be seen superposed on and slowly moving through the larger channel-forming forms at low flow.

<u>Fourth-Order Bed Forms</u> are accidental forms produced by obstruction to flow. They consist of variously shaped scour areas and bars which

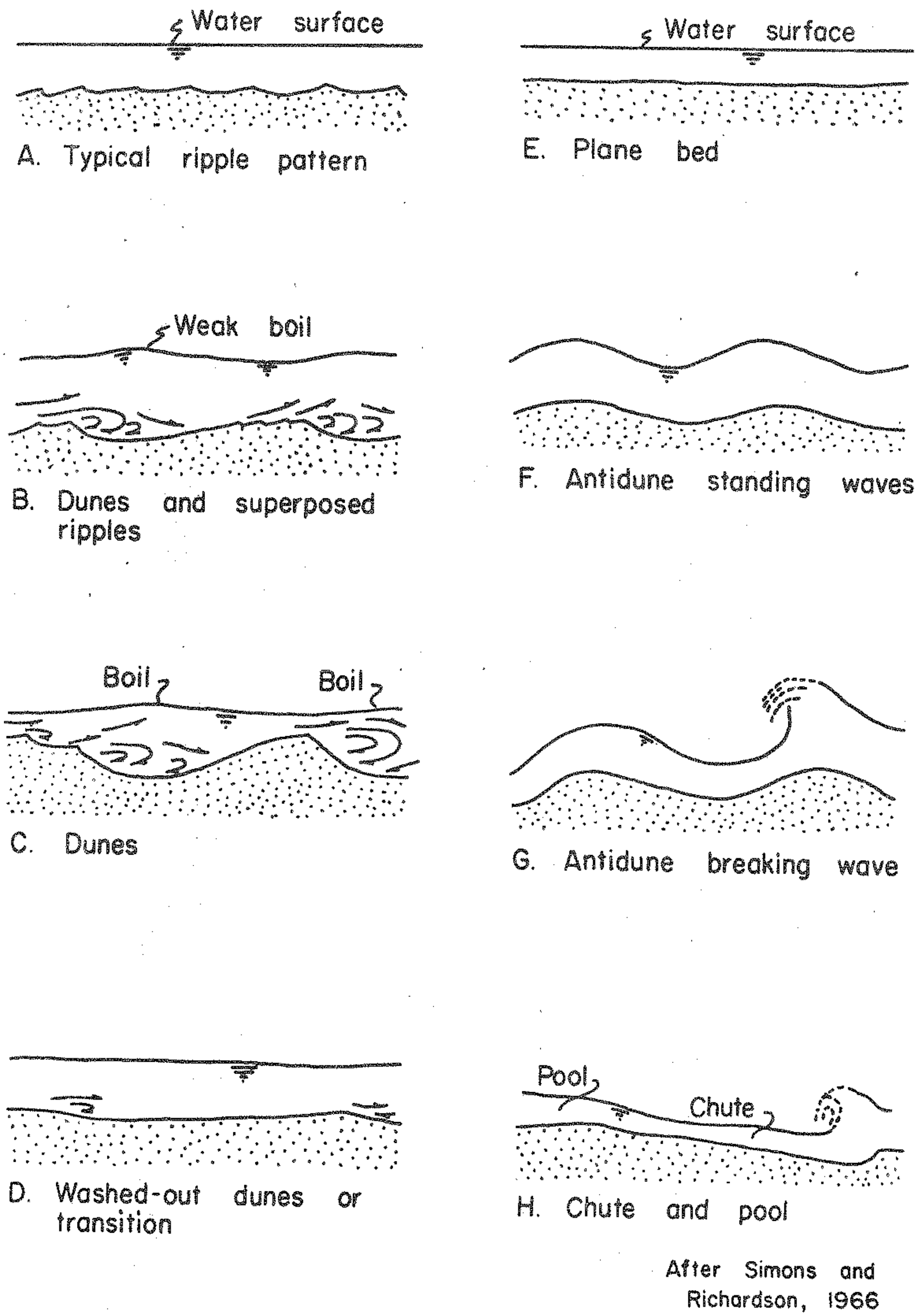


Figure 55. Bed forms for the lower (A–C), transition (D), and upper (E–H) flow regime.

can be quite large. An example of an accidental form is the scour area and bar produced when a large tree falls into a stream and obstructs flow. Scour will take place upstream of the tree and a depositional bar will form downstream of the tree. Fourth-order bed forms are usually observed at low flow conditions and high flow tends to remove obstructions and destroy the bed forms. These forms do not appear to control (except perhaps locally) the development of a channel, but they can significantly alter it. Third-order forms may be superposed on fourth-order forms, but the converse is not generally true because a sudden obstruction would destroy the flow regime, destroying any previous third-order forms.

Discussion

The tentative classification of bed forms presented herein is primarily based on numerous field observations, measurements of bed forms, and available quantitative data from stream and flume studies. The channel-forming bed forms are most likely produced by channel-forming flows (bankfull) with recurrence interval of one to two years. When observed and measured at low flow, they may be partially altered or masked by third- or fourth-order bed forms. Detailed observation at high flow when the channel-forming forms are produced would be extremely valuable. However, owing to hazardous conditions during flood stage when the channel-forming forms are being produced, few observations have been made. The ASCE Task Force on the nomenclature for bed forms in alluvial channels stated:

> "It is often difficult or impossible to obtain data on the flows that generate bed forms in alluvial channels because the features often cannot be measured until the flow has diminished or completely

stopped, and the bed forms then seen are the result of earlier flows, including those that occurred while the discharge was decreasing..." (ASCE Task Force, 1966, p. 52).

These authors further stated:

"... However, quantitative data on bed forms should be obtained whenever possible. No definition or description, no matter how carefully phrased, can substitute for good quantitative data." (ASCE Task Force, 1966, p. 52)

The writers essentially agree with both statements. Qualitative and quantitative methods are complementary, and both are needed for a complete study. Furthermore, a qualitative, generic model of channel development, inferred from and based on limited quantitative information and abundant field observations, seems superior to a descriptive classification based only on quantitative data.

The evidence necessary to understand alluvial streams can be found in the field; a pool with ripples on the stream bed, dunes superposed on an asymmetric shoal at low flow, or a tree obstructing current all suggest that there is order in the genesis and spatial relations of the forms.

The distinction between channel-forming and channel-altering bed forms is significant and should be justified. Channel pattern, whether straight, sinuous, or meandering is primarily a function of the interaction between the moving water and movable bed and bank material. Therefore, channel-forming bed forms are those forms which allow the development of the channel pattern. Asymmetric shoals are probably the primary bed form in the development of alluvial channels (Keller, 1972a). These shoals produce the convergence and divergence of flow necessary to develop pools, riffles, and point bars (Fig. 51).

Furthermore, pools, riffles, and point bars appear to be the forms which help some stream channels minimize the time rate of potential energy expenditure (Yang, 1971b). Therefore, pools, riffles, and point bars are channel-forming forms. Bed forms controlled by the flow regime and accidental bed forms, however, do not appear to control the development of alluvial channels. Locally there are, of course, exceptions to this as exemplified by large obstructions to flow such as debris islands or landslides.

It is expected that, as our understanding of fluvial processes increase, the classification will be modified. However, with the present degree of knowledge, the basic components of the classification and their relationship to each other appear essentially correct.

CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

A system is any part of the universe that is isolated in thought or in fact for the purpose of studying or observing changes that take place under various imposed conditions (Ehlers, 1968). A fluvial system includes three parts: 1) the drainage network, 2) the geology (alluvium and/or rock), and 3) the hydrology (liquid). As a drainage basin evolves or changes, all parts mutually adjust to each other and each exerts a partial control on the other.

As a drainage network develops, the bifurcation ratio fluctuates between a maximum and minimum as stream order increases. This fluctuation appears to have the form of an absolute convergent series which results in a nearly constant bifurcation ratio at high orders. The relationship between the number of links and number of segments in a network is valuable as an indicator of drainage network evolution. An envelope containing all possible combinations of links and segments for drainage networks can be illustrated on a single graph, and theoretical threshold conditions for changes in order as well as boundaries between constant bifurcation ratios can be shown within this envelope. Although a number of possible Strahler orders for a given set of links and segments exist, only one order is likely to be found in nature.

Alluvial stream channels are natural channels in which movable bed and bank material is predominantly unconsolidated to partially consolidated sediment. There are two fundamental classes of channels: stable and unstable. Stable channels are characterized by pools and riffles, whereas unstable channels lack pools and riffles. Asymmetric shoals which slope alternately, first toward one bank and then the other, appear to be the primary bed form in the evolution of alluvial channels. Pools, riffles, and point bars are common bed forms in straight, sinuous, and meandering stable, alluvial channels, and there is no significant change in symmetry of these forms with different channel pattern. Mean spacing of pools and riffles is constant in straight, sinuous, and meandering channels and thus is independent of channel pattern. Furthermore, the most-frequent spacing of pools and riffles is variable and this has genetic significance. Processes which lead to meandering as the most probable channel pattern paradoxically also produce straight reaches by lateral migration of bends or cutoffs, which seem to increase the variability of energy expenditure. As an alluvial channel migrates back and forth across the flood plain, new straight, sinuous, and meandering reaches are constantly being created, maintained, or destroyed. A proposed five-stage model of stream channel development provides a genetic basis for classifying most alluvial stream reaches.

In many alluvial channels, characteristic forms are produced at relatively high, channel forming flows, and are only modified at low flows. Under these conditions, conventional hydraulics apply at low flow when the channel is essentially a rigid container for the liquid phase. However, at high flow with moving sediment, conventional hydraulics no longer are applicable and fluvial hydraulics must be considered. The most significant principle of fluvial hydraulics is de Leliavsky's (1894) convergence-divergence criterion which states that erosion is due to convergent flow, whereas deposition results from divergent flow. This criterion may not be applicable at low flow with little sediment transport, but is probably very significant in forming pools and riffles at high flow. In fact, the distribution of tractive force at low flow may be entirely different than that of high flow. That is, at low flow pools are apparently areas of relatively low tractive force and riffles are areas of relatively high tractive force, whereas during high, channel-forming flow, pools may be areas of high tractive force and riffles of low tractive force. The writers believe that this distribution of tractive force is produced by convergence of flow in pools and divergence of flow in riffles at high flow.

The concept of entropy, as applied to fluvial systems, has been used by Yang (1971a) to show why a stream must increase its path length. Yang's Law of Least Time Rate Energy Expenditure explains why streams meander. It is the authors' hypothesis that the morphology of the pool-riffle sequence is the most probable channel configuration to allow lateral migration of the channel, thus increasing channel length, meanwhile conforming to Yang's Law. Therefore, the similarity in spacing of pools and riffles in straight, sinuous, and meandering channels suggests that the processes which create the tendency to form pools and riffles (convergent and divergent flow) are present in nearly all alluvial streams, and the mechanism, which is associated with some wave phenomena, may produce meandering channels.

The purpose of classifying bed forms is to arrange the forms in a way tenable with known ideas, concepts, and processes which define and control alluvial stream channels. A generic classification is suggested, which permits hierarchical ranking of common bed forms in straight, sinuous, and meandering alluvial channels. Bed forms such as asymmetric shoals (first-order bed forms), and pools, point bars, and riffles (second-order bed forms) are considered as channel-forming bed forms, whereas flow regime controlled forms such as ripples, dunes, and antidunes (third-order bed forms) and accidental forms (fourth-order forms) are considered as channel-altering bed forms. The proposed classification is tentative. However, the basic components and their relationship to each other appear valid.

Conclusions

New models to explain the development of drainage networks and straight, sinuous, or meandering alluvial stream channels have been presented. Based on an investigation concerning the development of drainage networks, it is concluded that:

1) An envelope defined by the lines $y = x$ and $y = 2x - 3$ contains all possible combinations of links and segments for drainage networks (Fig. 6). Theoretical threshold conditions for changes in order (Fig. 7), and bifurcation (Fig. 8) can also be fitted to the envelope.

2) As a drainage network develops from simple to complex, bifurcation ratio fluctuates between indefinite maximum and minimum values as order increases. This fluctuation appears to have the form of a convergent series, resulting in a nearly constant bifurcation ratio at high orders.

3) The relation between links and segments (Fig. 7) can be used to predict order and possible growth of a network.

4) The model presented in this thesis to explain the development of networks can be combined with C. T. Yang's (1971c) work to explain both horizontal and vertical dimensions of network development.

Based upon the investigation concerning the development of alluvial channels, it is concluded that:

1) Asymmetric shoals, which slope alternately first toward one bank and then toward the other, may be the primary bed form in the evolution of alluvial channels.

2) Pools, riffles, and point bars are common bed forms in straight, sinuous, and meandering channels, and there is no significant change in symmetry of these forms with change in channel pattern.

3) Mean spacing of pools and riffles is constant, at six times channel width, in straight, sinuous, and meandering channels and therefore is independent of channel pattern. However, the most frequent spacing of pools and riffles is variable (Figs. 23 and 44). Furthermore, as channel length increases due to lateral migration of meander bends, new pools are added to keep the spacing constant.

4) A five-stage model (Fig. 50) is proposed to explain the development of alluvial stream channels. The model is based, in part, on conclusions 1 - 4 above, and provides a genetic basis for classifying most alluvial stream reaches.

Recommendations

The research presented in this report has contributed to our understanding of some selected aspects of fluvial processes. In addition, new problems have been identified. It is recommended that researchers interested in fluvial morphology consider:

1) Why pools and riffles are spaced at six times the channel width. It is expected that this is related to the distribution of energy expenditure as well as hexagonal packing of the network.

2) Investigate the relations between mid-channel islands and fluvial processes in straight, sinuous, and meandering alluvial channels. It is expected that they are related to central channel-bar deposition characteristic of riffle formation.

3) Development of an improved generic classification of bed forms in alluvial channels.

4) Investigate the significance of bedrock control on stream morphology. It is expected that processes and forms in alluvial and bedrock channels will be similar, but that constraints in bedrock channels will tend to mask both form and process typical of alluvial channels.

5) Apply the knowledge concerning relations between form and process to river-training projects. It is expected that such application might be used to minimize the adverse effects of channelization.

6) Based on known channel morphology, sediment size, and discharge attempt to determine rates of potential energy loss in a pool and adjacent riffle. This should be done for low, average, and high discharge. Such a study may assist in understanding, from a quantitative base, why a channel should form pools and riffles, and how this facilitates meandering processes.

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