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CORPS OF ENGINEERS SEDIMENT STUDIES PROGRAM
FOR MISSOURI RIVER BASIN

U. S. ARMY ENGINEER DIVISION, MISSOURI RIVER

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OMAHA

KANSAS CITY

The Corps of Engineers Missouri River Basin sediment studies program was established for the development of practical sediment engineering for rational evaluation, regulation, and utilization of fluvial sediment phenomena. It was implemented as a comprehensive, basin-wide program for coordination of studies of sediment problems in the overall basin program for flood control and allied purposes as well as for continuity and perspective in the planning and design of individual projects. The program includes both investigations for the development of sediment transport theory and observations of existent and occurring phenomena for the purpose of developing the applications of theory to practical problems, developing empirical relationships, and providing aids to judgment.

The program has been conducted during the tenures of and supported by the following Division Engineers:

Lieutenant General Lewis A. Pick
Major General Samuel Sturgis
Brigadier General Don G. Shingler
Brigadier General W. E. Potter
Major General G. E. Galloway
Major General K. R. Barney

Mr. F. B. Slichter was Chief of the Engineering Division from the inception of the program until April 1949. Mr. W. E. Johnson has been Chief of the Engineering Division since that time. The program was formulated and organized by Mr. R. J. Pafford, Jr., Chief, Planning and Reports Branch. Planning and execution is under the immediate direction of D. C. Bondurant with technical advice and assistance provided by an Advisory Board consisting of:

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INTRODUCTION

For many centuries man has been concerned with the action of rivers. In most cases, the highest forms of the earliest civilizations developed in the fertile river valleys, such as the Nile, Euphrates and Indus, and the life of the people was greatly influenced by the action of these streams. The importance of streams in the life of the human race has remained a major factor down to the present. In the past few centuries rivers have been studied and to a minor extent controlled, but in the past half century the idea of developing the total resources of our streams has evolved, which will result in material change in the conditions under which the streams flow. Considerable development work has already been completed, and important changes are becoming evident in the forms of some of the controlled streams, which were largely unanticipated when the works were first planned. Interest in the total development of the streams has spread to the less developed countries, and if the present rate of progress is continued, the next half century will see the streams largely developed in the more fortunate countries, and a very large degree of progress in development reached in many of the less fortunate ones. As a result in the near future the number of cases of changed stream forms will be greatly increased. Moreover, there is ample reason to believe that the magnitude of these effects will increase with time, so that they will be even more important in the future. Some of these changes will be beneficial and some, detrimental. It is very important that, so far as possible, in planning future water resource development projects, these changes be anticipated and advantage be taken of the favorable changes, and the unfavorable ones, so far as possible, be guarded against. For best results this must be done during the period when the works are designed, so that the necessary steps can be made during the original construction, when they usually can be built most economically. These changes may be of the nature of a raising or lowering of the stream bed, or may be a change of stream width. They may also involve a change in the stream alignment, in a straightening of the stream or a change in the direction of more crooked alignment. Considerable study has been given to the changes involving raising or lowering of the stream bed, (1,2) and some study to changes in river width (3) but except for studies of meandering streams, little attention has been paid to changes in alignment. This is probably because the latter changes go on more slowly, and the effects of past construction has not yet become evident. It is therefore not practicable to predict the nature of the future changes from a study of changes that have occurred in the past. The only approach available therefore seems to be a study of the forms of natural streams and of the conditions which give rise to these forms. The changes which will occur can then be inferred from the nature of the changes in conditions that have been or will be made by the engineering works.

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(1) E. W. Lane. 1955. The Importance of Fluvial Morphology in Hydraulic Engineering. A.S.C.E. Proceedings Separate 745.

(2) Retrogression of Levels in Riverbeds below Dams. Engineering News-Record Vol. 112, June 28, 1934, pp 836-838.

(3) Leopold, L. B. and Maddock, Thomas Jr. 1953. The Hydraulic Geometry of Stream Channels and Some Physiographic Implications - U. S. Geological Survey Professional Paper 252.

As is so often the case when an advance is made in knowledge in a given field, the new information is useful in ways which were not anticipated when the study leading to the advance was made. Therefore, in the case of this study, it is believed that the increased knowledge of streams will be beneficial in ways that cannot now be foreseen, in a number of fields. One of these is in geology, where the study of morphology or physiography is an important subject. The forms of streams is an important part of this field of knowledge, and it is hoped that this study will be useful in that field also.

Scope of the Study

Because of the great variety of conditions affecting stream forms, to have a study of reasonable extent, it was necessary to limit considerably the scope of this investigation. In investigating any complex phenomenon, it is necessary to start first with the simpler aspects, for until one can understand these, there is no hope of understanding the more complex cases. The work will therefore be confined largely to the forms which streams carve for themselves in erodible material. In order that the ideas developed may be useful to a wide range of persons, it will be presented in as simple terms as possible, with the mathematics reduced to a minimum, since so many engineers and geologists have lost, through disuse, their ability to handle readily explanations in mathematical terms.

The channel of a stream may be considered to be an irregular, three dimensional solid. It can be adequately represented by a topographic map, but few maps giving the configuration of the stream bottom are available. The material usually available consists of maps, cross sections, and profiles. In this study, generally only the plans and profiles have been used, as the form of cross section has been given considerable study by Messrs. L. B. Leopold and Thomas Maddock, Jr.(3) and it was believed that further study of that subject would be less productive. However, since the width is an important factor in stream form, this study must eventually be considered. Width is also involved in the quantitative relations which it is hoped later to develop, although it has not been included in the analysis in the stage developed in this paper. However, the method of approach used in this investigation is so different from that used by Leopold and Maddock that it is believed that no appreciable duplication of their work will result.

In general this study will consist principally of:

1. A discussion of the principal factors influencing stream channel form.
2. A selection of the principal factors involved.
3. A determination of quantitative relations involving the principal factors concerning meandering sand streams and braided sand streams.
4. A preliminary analysis for streams involving coarser material.
5. A discussion of the nature of a number of other types of streams as disclosed by the foregoing analysis.
6. An attempt on the basis of the results obtained by this method of analysis to develop a better system of classifying types of streams in erodible material including new definitions of meandering and braided streams.
7. A suggested method of quantitatively defining the shape of stream channels.
8. A statement of further studies to carry this investigation more nearly to completion.

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(3) Leopold, L. B. and Maddock, Thomas Jr. 1953. The Hydraulic Geometry of Stream Channels and Some Physiographic Implications - U. S. Geological Survey Professional Paper 252.

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The studies described in this report were carried out largely with the support of the Missouri River Division of the U. S. Army Engineers, as a part of their investigations of sediment problems under Mr. R. J. Pafford, Jr., and Mr. D. C. Bondurant. They were started by the writer about 1948 as a part of his studies of sediment phenomena under the U. S. Bureau of Reclamation. The information used has been collected over the period since that time from a great number of sources, as shown by the numerous references included herein. The writer has been assisted in preparing various phases of the report by K. S. Li, C. M. Umar, R. J. Garde, P. K. Mohanty, K. Davar, and my wife, Margaret S. Lane. The writer wishes to express his deep appreciation to all these organizations and individuals. Without their assistance this report could not have been carried out. The views expressed herein are those of the author, and in some cases may not agree with those of the U. S. Army Engineers or the U. S. Bureau of Reclamation.

GENERAL ASPECTS OF STREAM FORMS

There is a nearly infinite variety in stream forms, if considered in detail. No stream is exactly like any other stream and no part of any stream is exactly like any other part of the same stream. This is because stream forms are the result of a great many factors, and the same combination of these factors is never exactly repeated. However, stream forms are the results of physical laws and if the conditions controlling the shape of any part of a stream were exactly reproduced, the same form of a stream would result. One set of conditions produces one form, and another set gives rise to another form. However, certain factors influencing stream forms are more effective than others, and when similar combinations of these major factors occur, roughly similar streams are produced. In this study an attempt will be made to study the principal types of stream resulting from the most common of these combinations of conditions.

Stream forms is a subject which falls into the field of both the geologist and the engineer, and both have made valuable contributions to the development of the science dealing with them. The geologist encounters the form of streams in his study of the effect of flowing water on the form of the earth's surface. This study, which was formerly known as physiography, is now more frequently called morphology, or the science of the form of the earth's surface. Since this paper is concerned only with the effect of flowing water, the field of this paper may be classed as fluvial morphology.

A knowledge of geology is very important in studying stream forms, for the form which streams now have is largely the result of the geological conditions which have existed in the past, as well as those which exist at the present time. The conditions which existed during and since the time of the Wisconsin glacier (the last portion of the Pleistocene Epoch) or the great ice age, are particularly important. The study of these conditions is a part of what is called historical geology.

The engineer encounters the problem of the form of rivers in his attempts to develop the resources of streams for navigation, flood control, irrigation, water power and other uses. Literature throwing light on the subject is available from a wide variety of sources, and covers a long period of time.

In general, the geologist is interested in much longer periods of time than the engineer. Geologists are commonly interested in millions of years, but in fluvial morphology they study also much shorter periods. The engineer normally considers a century as a long time, but in dealing with water resources, evidence is rapidly accumulating to show that his viewpoint in the past has not covered a sufficient period, and for best results a longer view is necessary. The very short time view of the geologist and the long time view of the engineer are much the same, and a knowledge of both should be mutually beneficial.

Streams have been classified in many ways. One way that is useful for the purposes of this study is to divide them into three groups: (1) streams in which the form is determined predominantly by the relatively inerodible rocks forming the earth's crust in the region through which they flow, (2) streams whose form is determined predominantly by the action of the water of the stream itself and (3) an intermediate class where the stream form is partly determined by the rock of the earth's crust and partly by the stream itself.

There are, of course, no exact boundaries between these classes. The form of relatively few streams of considerable size is determined entirely by the rocks of the earth's crust in the region through which it flows, for the hardest rocks are worn away by flowing water, and over a long period of time great changes result from this action. Similarly, while many streams are called alluvial streams because their form has been predominantly determined by the scour, transportation and deposit of the material through which they flow, in many of these streams there are rock ledges or short sections of rock on the banks which largely influence their nature.

This study, in the stage covered by this report, will be concerned with the second class, where the form is determined predominantly by the water itself. It will include alluvial streams as mentioned above, where the surrounding solid material has been deposited by the flowing water, and those flowing in any other material which can be scoured by the action of the flowing water with sufficient rapidity to produce changes during the time interval with which the engineer is ordinarily concerned. This study does not include a study of rills or gulleys, which are of such importance in soil erosion, nor does it deal with tidal streams, or the steep streams called torrents, the control of which is so important in parts of Europe. So far the study has not covered intermittent streams, nor the arroya type of stream so common in the western part of this country. It is hoped that this study can eventually be extended to cover these forms and the previously mentioned third class of rivers also.

Factors Affecting Stream Channel Forms

A great many factors affect stream channel forms. Some affect the form directly, and others affect it because of their influence on the directly affecting variables. The most important variables are (1) stream discharge, (2) longitudinal slope, (3) sediment load, (4) resistance of banks and bed to movement by flowing water, (5) vegetation, (6) temperature, (7) geology and, (8) works of man. There are no doubt other factors involved, but these eight are believed to be the major ones. In the following paragraphs, the influence of these factors will be discussed in some detail. These factors are not all independent ones, as many depend, to a greater or less extent on the others. The interrelation between longitudinal slope, sediment load and resistance of the banks and bed to movement is particularly close and complex.

Effect of Stream Discharge

Everyone interested in the form of stream channels is aware that some stream channels are large and others are small, and that, in general, the large stream channels carry large quantities of water and in the little ones the flows are small. It may be said that the stream discharge is the most obvious factor in determining stream form. A stream channel form, however, is the integrated effect of all of the factors influencing it, and since the discharge of any natural stream is constantly changing, as far as the influence of discharge is concerned, the channel form of a stream is the integrated effect of all of these discharges. It is well known that in the forms of stream investigated in this study, the change of the banks and bed goes on more rapidly with large flows than with small ones, and large flows therefore have a greater influence on the form of streams than the small ones. Recently there has been a tendency to analyse stream action on the assumption that this action is largely due to a certain discharge or small range of discharges, called the "dominant discharge" and for some purposes this is a useful concept There is no doubt that usually a narrow range of discharge exercises the predominating influence of discharge on stream form and this may be considered to be the dominant discharge. However, it is not possible to account for all the actions of a stream by a consideration of a single discharge or a narrow range of discharges. A determination of the dominant discharge requires an intimate knowledge of the characteristics of the stream, and in this study, where so many streams are compared, it was not practicable to study them all in the detail required to determine their dominant discharges. In the United States, however, the discharge of very many streams has been determined and their average flows is easily obtained by consulting the publications of the U. S. Geological Survey, which collects these data. The average discharge has therefore been used in this study as the measure of the discharge factor, since it is for the purposes of this study, the only flow factor readily available.

The consistency of the results obtained indicate that, while not ideal, it is a reasonably good parameter.

The discharge of a stream influences its form not only because of the magnitude of the discharge, but also because of the fluctuations of the flow. For example, the banks of the Lower Mississippi River are scoured more on a falling stage following a flow of bank full or higher magnitude, than at any other time. Therefore the change of form resulting from this caving depends to some extent on the number of times the stage rises and falls from bank full to a considerably lower value. This same action is known to occur in a similar manner in many other streams.

The part of the flow that occurs in the main channel as compared with that which flows over the banks in floods, also influences the channel shape, and therefore the form of the stream. The water that flows out of the main channel usually has a low velocity and does not greatly influence the stream form, while that which flows in the main channel flows with high velocity and therefore is capable of cutting the banks more rapidly. Other things being equal, the stream in which the greatest portion of the discharge flowed in the main channel would therefore scour its banks the most rapidly.

In an increasing number of cases the works of man have changed the flow of streams, in either the rate of discharge or the variability of flow, and frequently in both. By means of the study reported in this paper it is hoped that more reliable predictions can be made of the effect of these changes of discharge on the stream forms.

The Effect of the Longitudinal Slope

Because the magnitude of the longitudinal slope of a stream flowing in erodible material cannot ordinarily be determined by a visual observation, the effect of slope on stream channel form is not readily observed. It can only be demonstrated from a comparison of the forms of streams having a wide range of slopes. Since data on the slopes of streams are not easy to collect, little work on the effect of slope on stream form has been carried on, and the subject has been rarely discussed. These studies however have progressed far enough to demonstrate that stream slope has a major effect on stream channel form; that it is, in fact, one of the major factors influencing the form of stream channels.

The slope of a stream is generally expressed as a ratio of the drop in elevation along the stream to the length of the stream channel. This can be expressed as the drop per unit of length, such as feet per mile, or preferably as a dimensionless ratio, such as the feet drop per foot of length, or the length for a foot drop.

The longitudinal slope of a stream is set largely by the topography of the country through which it flows. Flat plains usually give rise to rivers of low slope, areas of moderate slope usually produce streams of intermediate slope and mountainous country or areas of high hills usually are drained by streams of high slopes. In an increasing number of cases the works of man have changed stream slope, but in most cases the effect of these changes on the form of streams has not been determined. As previously mentioned, one of the major purposes of this study is to enable reliable predictions to be made of the effect of man-made changes on stream slope on the form of streams.

The Effect of Sediment Load

There can be little doubt that in most streams in erodible material the amount and character of the particles composing the sediment load carried by the stream exercise an important effect on the shape of its channel. This is particularly true of alluvial streams, whose bed and banks are formed by sediment transported by them. The amount and composition of the sediment load carried by a stream is affected by a great number of variables, but this subject lies outside of the scope of this paper.

Although the character of the sediment load is usually set predominantly by the hydrology, geology and vegetal cover of the watershed, sediment may also exercise an important effect on the slope, particularly in those sections of streams affected by the works of man. The nature of the sediment load also strongly influences the resistance of the banks and bed of the stream to scour. When the sediment carried is coarse and/or cohesive, the banks and bed are strongly resistant to scour, but when they are composed of fine, non-cohesive material, the resistance is small. The fine cohesive material carried by a stream usually has little effect on the form of natural streams, unless it has an opportunity to settle and consolidate, but when this occurs, the effect may be considerable. The extent to which this is true is as yet not well worked out. The shape of the lower Mississippi is materially influenced by the large beds of highly consolidated clay deposits which were formed by the filling of the lakes resulting from cutting off of the bends of the river in times past.

The Effect of Resistance of the Banks and Bed to Scour

As previously stated, the resistance to scour of the banks and bed of alluvial streams is usually related to the character of the sediment moved by the streams. In some cases considered in this study the stream flows in erodible material which was not placed by the stream itself, but was deposited by other agents in another geological period. The size, shape, specific gravity and cohesive tendency of the particles composing the banks and bed of the stream is very important as they control the susceptibility of the banks and bed to scour. Of these factors size and cohesive tendency are the most important.

For example, a stream flowing in material which is highly resistant to scour will tend to be much narrower and deeper than one which flows through easily eroded material. This is because the stream widens out until the tractive force on the sides is no longer sufficient to produce scour. When the material is very resistant to scour, it will stand a deeper flow and hence higher tractive force in the stream without scouring, than will less resistant material. The meaning of the term tractive force, as used here, is discussed in an appendix to this paper. Engineers are finding that tractive force is a more accurate index of scouring ability than velocity.

Effect of Vegetation on Stream Forms

The effect of a vegetative cover on the banks and bed of small streams in protecting it from scour has been so amply demonstrated that it needs no discussion here, but vegetation also affects the shape of streams of medium size and even large ones. Even in major streams like the Mississippi and Missouri, the vegetation may have an important effect. Towl* has stated that in 1804 the length of the Missouri between the mouths of the Big Sioux and Platte Rivers was about 250 miles and in 1935 it was about 150 miles. He concludes that the changed length was due to the removal of heavy timber.

Probably the outstanding case of the effect of vegetation on the rivers in this country is that of the "rafts" on the Red and Atchafalaya Rivers in Louisiana. The Red River* was so choked by rafts of floating logs and other

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* Roy N. Towl. The Behavior History of the Big Muddy. Engineering News-Record Vol. 115 August 22, 1935, p. 262-264.

* Physiography of the Eastern United States. Fenneman p. 116-117.

vegetation that it completely changed part of its course and caused numerous lakes to form where tributaries entered it, probably because of the rise in its bottom and water surface which accompanied the choking. Since the raft has been removed, the river has materially lowered both its bed and water surface. The Atchafalaya River in Louisiana was also completely choked by a raft, and on its removal, it materially deepened and widened its channel.

Another famous case where vegetation has affected the form of a major river is in the famous sudd region of the Nile River in Africa, where for many miles the river is so choked by vegetation that it spreads out in a great swamp through which travel is very difficult.

Even in the case of the mighty Mississippi River, it is believed that its form is to some extent influenced by the heavy growth of vegetation which develops on its banks and overflow areas. This river is very meandering, and forms great loops, the ends of which are a short distance apart in a straight line, but many miles distant measured along the course of the river. When this straight line distance becomes small, during high floods much of the water flows along the straight line path, and when the river scours its banks in such a way as to make this path short enough, the water flows with sufficient velocity to scour the earth along the short path severely enough to form a channel, which gradually enlarges sufficiently to carry the entire flow of the river, thus causing what is called a "cutoff". The length of the short path at which scour will occur to a sufficient extent to form a cutoff, would be much less if the ground over which the short path passed was not grown up with the dense vegetation which is found there. Without vegetation the shape of the river could therefore never attain the degree of sinuousity which occurs under existing vegetative conditions. For example, the famous bends which formerly existed near the town of Greenville, Mississippi could, under natural conditions never have had the narrow necks which they did, without the heavy vegetation that existed on these bends.

According to G. H. Matthes, the form of the stream channel of the Mississippi is also influenced by the willow growths which form on the bars. As these growths start they cause sediment to deposit on them, and thus build the bars higher. As the willows become larger they become less easily washed out and also more effective in causing deposit. The deposits often continue until an island is formed, which materially changes the shape of the stream channel from that which existed before the growth started.

In a section of the Kissimmee River in Florida, the channel alignment is very tortuous. In recent years there has been a great growth of water hyacinth, a plant introduced from a foreign country. This plant has grown so profusely in this river that at a number of places it has so choked the channel that the water spread overbank, and flowed across the necks of bends with sufficient velocity to cause cutoffs, which produced major changes in stream alignment. As this plant grows only in warm climates this change, to a certain extent, may be considered a temperature effect as well as a vegetative one, since it would not occur in a cold climate.

In fact temperature is an important factor in all vegetative effects, since the vegetation which affects the stream pattern in any case depends on the growth which can take place with the temperature which exists there. For example, one would not expect vegetation to have much effect on stream patterns in a region where the temperature was so low that only a tundra growth occurred. As an actual case it may be mentioned that the density of vegetation along the streams in the warm state of Florida is very much greater than along the streams in the cold state of Montana, and therefore changes in the stream patterns will usually occur less frequently, or more slowly, other conditions than temperature being the same, in Florida than in Montana.

It is probable that the differences of density of vegetation in Florida and Montana is partly a result of the higher rainfall in the former. This adds another factor to those previously discussed as influencing stream forms. Rainfall also has an important effect on stream discharge, which, as previously mentioned, is a major factor in stream patterns. Since in both cases the effect of rainfall is indirect, its influence will not be considered further, but this mention of it does serve to indicate the complexity of the subject of stream forms, and of the interrelation of the influencing factors involved.

The Effect of Temperature

Temperature effects stream forms in various ways (in addition to its effect on vegetation previously mentioned). These may be classified under four heads as follows:

1) Effect of temperature on resistance of banks and bed to scour.

2) Ice effects.

3) Glacier effects.

4) Effect of temperature on transporting power of flowing water.

These will be discussed in more detail in the following paragraphs.

Temperature in some cases affects the resistance of the banks and bed of a stream to being scoured or worn away by the flowing water in addition to its effect on vegetation. A change of resistance is brought about by the freezing of the banks, which occurs in winter in northern rivers, such as the Yukon River in Alaska. In some areas the ground is permanently frozen, except that a thin layer on the surface thaws out in summer. Unless the banks are thawed out, they would be much less subject to scour than when in their unfrozen conditions.

In northern regions glaciers frequently form in the valleys which affects the stream discharge and sediment load. The stream has its maximum flow when the temperature is high enough to melt the ice. The flow may cease entirely during the winter and at night during the summer. Most of the runoff occurs during a short part of the time and therefore produces high peak discharge rates, which are able to produce greater transportation of sediment than if the flow was more uniform. Also the glaciers usually bring down great quantities of sediment, which they supply to the streams, causing overloaded streams and streams with braided or interlacing pattern.

An examination of detailed topographic maps in Alaska shows a large number of very crooked streams. The cause of this stream pattern is not evident. There is a possibility that it is due to the high resistance of the bank material to scour, since there is some evidence that highly resistant bank material tends to produce crooked streams. The high resistance in this case would be because of frozen bank material.

In northern regions the streams frequently freeze completely to the bottom in winter. In the spring they thaw out and the ice flows down with a great rush, causing jams which naturally raise the water level and cause cut-offs, and seriously scour the banks and bed.

That streams tend to carry more sediment in suspension in winter than in summer has been observed on the lower Colorado River*, the Loup River in Nebraska, Niobrara River in Nebraska and the Missouri River. The effect of

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* E. W. Lane, E. J. Carlson and O. Hanson. 1949. Low Temperature Increases Sediment in the Colorado River. Civil Engineering, Vol. 19, No. 9, September 1949. pp. 619-620.

temperature on suspension has also been demonstrated in artificially created turbulence. The effect of temperature on the movement of the coarser particles on the stream bed has been investigated but there is not complete agreement regarding the reliability of the conclusions drawn. It is believed however that the evidence shows that under some conditions at least, such effects exist, but the nature and magnitude of them is in doubt.

Although the effect of temperature on the transportation of sediment can be demonstrated, it is difficult to show just how this effect influences the form of streams. However, since the form of streams is so much influenced by the sediment carried by them, as shown in a previous section of this report, it seems reasonable that anything which would materially effect the transportation of sediment in streams would also have some effect on their form.

Effect of Geology of Watershed and Stream Channel

The importance of geology in stream channel forms has already been briefly mentioned. Geology is perhaps the most important factor in stream forms because of its effect not only on the form of the stream directly in many ways, but also indirectly in its influence on many of the other variables which directly affect stream form.

For example, the geology influences both the amount and the variability of stream flow. It gives rise to mountain ranges, which increase the rainfall in certain areas and decrease it in others, thus increasing or decreasing the stream flow. It also affects the flow variability by producing lakes or swamps which tend to equalize the stream flow, or porous rocks or earth, which have a similar effect. The slopes of the streams are largely set by geological action, as previously explained, and the slopes of alluvial rivers are sometimes controlled by rock ledges which cross them at intervals. Geology also materially influences the sediment load by providing easily eroded material which produces heavy sediment loads, or resistant material which produces light loads. It also tends to cause high or low sediment loads by producing high or low stream slopes. It further affects the stream form by providing easily eroded or resistant material in the stream bed or banks.

This study has shown that the geological history of many streams in the past is an important factor in the form of many streams in erodible material. The influence of the glaciers which covered most of northern North America in recent geological times, particularly the last great advance of the glaciers in what is called the Wisconsin glacial stage of the Pleistocene epoch, and the recession as the ice masses melted away, and largely disappeared, is still materially influencing the form of many streams, although this glacier reached its greatest advance at least 5-10,000 years ago. Among the streams studied in which this glacier still largely influences the form are the Upper Mississippi, Wabash, Illinois, Minnesota, Red River of the North and the Milk River (Montana). Although geology is no doubt the most important factor influencing stream forms, it will not be discussed at length herein, since within the limited scope of this report it is usually not directly a major factor, and the geology of most alluvial valleys is, for the purposes of this study, very nearly the same. In some cases, however, the past geological history of the stream gives rise to streams of unusual form, which come within the scope of this paper and in these cases the geological aspects must be treated, in order that the forms may be understood.

The Works of Man

The works of man have materially changed the forms of channels in numerous large and small rivers. The Lower Mississippi has been materially straightened, shortened and steepened by cutting off numerous bends. Many miles of the Missouri have been narrowed and straightened by contraction works. Numerous small rivers in Iowa, Illinois, Oklahoma and Missouri have been straightened by cutoff and auxiliary channels. Dams have been constructed forming large reservoirs. Most of these works have been so recently completed that their permanent effect on river forms is unknown, but it is believed that as time goes on, these effects will become more evident and their importance will be greater than is now the case.

Common Classification of Stream Forms

There are a number of forms of streams that are so frequently encountered that they have been given names by persons dealing with rivers. The names most commonly mentioned are meandering, braided, incised or entrenched meanders, and misfit or underfit streams. It is probable that most readers of this report will have at least a general idea of what is meant by meandering and braided streams. Because there is no generally accepted exact definition of either, they are discussed at length in later sections of this report, and what is believed to be better definitions are proposed. Those who are not familiar with the general meaning of these terms should read these definitions first. The definition on meandering streams is on page 52, and that on braided streams is on page 89.

An incised or entrenched meandering stream is formed by a meandering stream cutting downward into rock or other material usually highly resistant to scour, so that while it maintains its meandering form it no longer scours its banks or shifts its horizontal position rapidly. A misfit stream is one that occupies a valley formed by a stream of considerably larger or smaller discharge, so that it has a different channel size and probably different plan form than the channel had which formed the valley. An underfit river is one which occupies a valley which was formed by a stream of much larger discharge than the present one.

Misfit and Underfit Streams

As previously stated, a misfit stream is one that occupies a valley formed by a stream of materially different discharge. The valley forming discharge could be either smaller or larger than the present discharge. An underfit stream occupies a valley formed by a stream of greater discharge. A misfit stream can therefore be either an underfit stream or an overfit stream, but a natural stream which occupies a valley formed by a stream of much smaller discharge i.e., an overfit stream, would usually soon remove all signs of the former smaller stream channel and widen its valley to conform to its present discharge. Therefore overfit streams are rarely found.

Since the term underfit is more definite and accurately descriptive than the term misfit, it is believed that it would be better to drop the use of the designation misfit, and use only the term underfit for the streams of the underfit type. If one of the opposite type is encountered, it may be called an overfit stream. Streams of the underfit type covered in this study are the Milk River of Montana, which flows in a former course of the Missouri River and the Minnesota River, which was the outlet of Lake Agassiz. In one sense, the Middle Mississippi from St. Paul to St. Louis and the lower Illinois, which was the former course of the no longer existing Teays River, may be considered to be underfit streams since the present discharge is much less than that which flowed in them during one stage of Pleistocene time. However, in the case of these two streams it is doubtful if this high flow continued long enough to form a valley commensurate with the larger discharge. The writer therefore prefers to consider these streams as refilling streams. The Minnesota valley may also not have been enlarged to a size commensurate with its high flows, but its valley seems much larger in comparison to its present discharge than do the valleys of the Middle Mississippi and the lower Illinois.

QUANTITATIVE STUDY OF STREAM FORMS

The Formulation of Plan for Attacking the Stream Form Problem

Although a number of attempts have been made to develop a science explaining the formation of meandering streams, an extensive search of the literature in the field of stream forms has disclosed very few articles attempting to develop a science covering other than meandering forms. As the subject is obviously very complex, it has seemed to the writer that the best line of attack would be to find out from measurements on existing natural streams the conditions under which the various forms developed. A study of the relations of the principal variables should give clues to the reasons for the various forms, and if a general fundamental relation could not be developed, at least empirical relations could be developed in various areas which would be very useful in many of the problems which arise in stream engineering.

To carry out such a plan requires a determination of the principal factors involved in the formation of stream channels, and data on these factors for a considerable number of streams covering a wide range of conditions.

Selection of the Principal Factors Influencing the Form of Stream Channels Flowing in Erodible Material

In the foregoing sections of this report it has been pointed out that there were eight major factors which influenced the form of streams flowing in erodible material, and that each of them, in some streams, exercised a major effect on the channel form. With so many variables it was not practicable to appraise separately the effect of each factor, and analyze their interrelation, by treating all of the factors at the same time since some of the factors are interrelated. The best procedure in a case of this kind is to select what appears to be the most important variables and to try to establish the relation between these. If such relations can be established, it is then usually possible to proceed to determine, to some extent at least, the effects of some of the other variables.

Other points which had to be considered in selecting a plan of attack for appraising the effect of the various variables and their interrelations are (1) the possibility of expressing the magnitude of these variables quantitatively and (2) the availability of data on the magnitude or extent of them on a large number of streams. It can readily be seen that the vegetational conditions, the effect of the works of man and the geological conditions cannot be directly expressed in quantitative terms, nor is there extensive data readily available on them. The temperature of the water can be expressed quantitatively, but very few data on it are available. The sediment load transported by the stream can also be measured, and expressed quantitatively, but data on it also are comparatively meagre. The nature of the bank and bed material can, to some extent be expressed quantitatively, especially if it is non-cohesive, but data on it are widely available only in general terms, such as sand, gravel, and clay. The slope and discharge of streams however can be readily expressed quantitatively, the slope used being the longitudinal slope along the channel of the stream, and the discharge can best be expressed as the average discharge over a long period. The plan form of streams can be expressed in quantitative terms, as will be shown later, but this is laborious, and no data on stream forms of this type are available. The tortuosity ratio of a stream (the ratio of the stream length to the valley length) which in some cases can be used as an index of stream pattern can be expressed quantitatively, but a determination of it is time consuming and requires detailed maps of the stream.

In studying quantitatively the form of a large number of streams, we are, therefore, at present limited to expressing the form in general terms, such as meandering and braided, and comparing this with the variables; slope and mean discharge, the bed-bank material, the latter expressed in general terms such as sand, gravel and clay. If more time and funds for the study were available, it would be possible to extend the relations for a number of streams to include tortuosity ratio and other quantitative expressions of plan form and quantitative size of non-cohesive bank and bed material.

As will be shown later, a comparison of stream plan forms when using only the factors of slope, discharge, and bed-bank material, gives very consistent results, with comparatively little scatter of observed points when presented in graphical form. This consistency strongly indicates that the slope, discharge and bed-bank material are the most important factors influencing stream form. This is particularly fortunate, since it is these that are the factors on which data are most readily available. This shows that the best plan of attack to the problem of analyzing stream forms is along the line of a quantitative comparison of these variables, as far as it is possible to do so.

Because of the importance which the sediment load transported has in determining the shape of artificial channels for conveying water, such as irrigation canals*, it may seem surprising that comparatively consistent

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* Lane, E. W. 1955. Sediment Load Charge as a Factor in Stable Irrigation Canals. Journal, Central Board of Irrigation and Power (of India) Vol.XII No. 2, pp 1-8, April 1955.

results are obtained when ignoring this variable. That the sediment load transported is an important factor in shaping the form of streams cannot be denied. That comparatively consistent results can be obtained in analyzing data based on a large number of natural streams without considering this factor arises from the fact that this factor is largely the product of the other factors treated, and in natural streams may be considered as a dependent variable. In a stream in regime or equilibrium (also sometimes called a graded or poised stream) the stream form is very largely dictated by the load of coarse material transported, but this load is the result of the factors: discharge, slope and bed-bank material. Since most of the natural streams on which data were secured for use in this study are probably approximately in regime, the coarse sediment load is the result of factors: slope, discharge, and bed-bank material, and therefore does not have to be treated as an independent variable. In artificial channels, the coarse load is not a result of the slope, discharge and bank-bed material, but is imposed on the channel by being introduced into it from the stream from which the channel draws its water supply. In studying the sediment problems of these artificial channels the sediment load must be considered as an independent variable.

Obtaining Data from Many Streams on the Principal Factors Controlling Stream Channel Form

Having selected discharge, slope and bank-bed material as the three principal variables controlling stream form, it is necessary to find the magnitude of these three factors, together with the channel form produced by them in the case of a large number of natural streams. Since no compilation of these data was available, it was necessary to collect it from any source where it could be found.

The data on the mean discharge of the stream was usually comparatively easily obtained from the very complete records of the U. S. Geological Survey and published in their Water Supply Papers. Nearly all of the mean discharge values for the streams used in this study were obtained from this source.

The slopes of the streams were largely determined from profiles, published in the reports on engineering studies of the streams made in connection with their development for various purposes, such as flood control, irrigation, navigation, and water power. Published reports of the U. S. Army Engineers, U. S. Bureau of Reclamation, and Miami Conservancy District were extensively used. A series of theses of the State University of Iowa, developed under the supervision of Professor C. J. Posey contained valuable data on slope and other characteristics of streams.

Data on the bank-bed material was also largely drawn from these reports and from the writer's knowledge of numerous streams scattered over the country gained in engineering studies dealing with them over a period of more than forty years.

The stream channel form developed was also determined from maps in the various engineering reports, from the quadrangle sheets of the U. S. Geological Survey and from the writer's personal observations.

The data used in the study is tabulated on pages 103 thru 106. More detailed data covering some of the individual streams is given in Appendix I.

Determination of Quantitative Relations Between the Principal Factors Controlling Stream Plan Form in Meandering Sand Streams

The principal factors controlling stream plan form are believed, as previously stated, to be discharge, slope, and bed-bank material. To determine the relation between form, discharge, slope and bed-bank material, involves four variables. To determine their interrelation for a considerable range of all of these variables with a single solution is difficult, since no theory is available to guide the trial analysis, and all that is available is widely scattered data giving the values of these four variables for a large number of streams only part of which data is in a quantitative form. By selecting data, however, it is possible to reduce the variables to two. This can be done by selecting only streams having one pattern and one material size. By choosing only data from streams which have a meandering pattern and a bank-bed material of sand, a plot can be made showing the relation between the slope and the discharge for this type of stream. Figure 1 shows such a plot using the available data, plotted on logarithmic co-ordinates.

The stream of this type having the greatest discharge is the Lower Mississippi, the two main sections of which have mean discharges of about 500,000 cfs. The smallest stream of this type for which data was found is the model of the Lower Mississippi River constructed at the Waterways Experiment Station at Vicksburg, Mississippi. This model had a discharge of 0.10 - 0.15 cfs and was constructed with banks and bed of Mississippi River sand. If one draws a straight line through the points (1,2)* representing the model and averaging those representing the two sections (3,4) of the Lower Mississippi River, the line will be found to have an equation $S = \frac{0.0017}{\sqrt[4]{Q}}$. Since this form of equation was found to fit approximately a large amount of the data on meandering sand streams, as will be shown later, it can be expressed in general terms $S = \frac{K}{\sqrt[4]{Q}}$ and for this line the value of K is 0.0017.

Other tortuous streams with sand beds have been plotted on this diagram. These are Rapid (5), Clear (6) and Old Man Creeks (7) and Maquoketa (8), Raccoon (9), Iowa (10), Cedar (11) and Des Moines (12) Rivers, all in Iowa,

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* These numbers refer to the item numbers for these streams in Table I and point numbers on Figure I.

the Milk River (13) in Montana, Big Black River (14,15) in Mississippi, the Minnesota River (16) in Minnesota, Missouri River near Ft. Peck (17), Montana, the lower part of the Wabash River (18) in Indiana and Illinois, and the Middle Mississippi in Illinois and Missouri (19,20) the Verdigris River (22) in Oklahoma and the Assiniboine River (23) in Manitoba, Canada, Big Blue, Kansas (137), and the Smoky Hill, Kansas (135,136). Also included is the Buyuk Menderes River (24) in South-eastern Turkey, which is the stream from which the term meander was derived. For all of these streams the points showing the relation of slope to discharge falls near the line indicated by the Lower Mississippi River and its model. In other words, in all of these rivers the relation of the slope to discharge is approximately represented by the equation $S = \frac{0.0017}{\sqrt[4]{Q}}$ as they all have K values reasonably close to 0.0017.

However, all of the points do not lie exactly on this line, or have K value of exactly 0.0017, but this is not to be expected. One reason is that the streams are not likely to be all of the same degree of sinuosity, as will be explained later in this report. Another reason is that the size of the sand is not the same in all cases. The sediment sizes for the Lower Mississippi River Model (1,2) and the Lower Mississippi (3,4) should be close to the same size, as Mississippi River sand was used in constructing the model. The sizes of sand in most of the other streams probably differs from that of the Lower Mississippi. For example, the Iowa River (10) material is known to contain some small gravel, and that in the Des Moines (12) and Raccoon (9) probably does also. The same is true of the Missouri (17) near Ft. Peck. The Milk River (13) and the Minnesota River (16) are both "underfit rivers" since they occupy valleys which were formed by a larger discharge than now exists, the Milk (13) occupying a former bed of the Missouri River and the

Minnesota (16) formerly being the outlet of the great Lake Agassiz which drained a very large area and carried off the water of the melting glaciers. These two streams are very tortuous, and appear to have a more crooked alignment than the Lower Mississippi (3,4). There is a slight possibility that these rivers are still refilling the valleys left by their larger flows, and are hence not in equilibrium. These rivers are unusually sinuous, but so also is the Assinboine (23), which is not known to be a refilling river. As will be shown later, the sinuosity of these sand streams tend to increase with the decreasing slope. It is, therefore, probable that the explanation of the highly sinuous pattern of these three streams, i.e., the Milk (13), the Minnesota (16) and the Assiniboine (23), is their low slope, since this would explain all three cases. There is one meandering stream, the Red River of the North (140,141) which does not agree, even approximately, with the other streams. As will be explained later, this is a special case.

Although the plotted points for meandering sand streams do not all fall close to the line representing $S = \frac{0.0017}{\sqrt[4]{Q}}$ for the following four reasons, it is believed that this line very accurately represents the relation between discharge and slope for all meandering streams under equilibrium conditions, with sediment of the size and tortuosity ratio present in the Lower Mississippi.

(1) The fact that this line is based on points having a wide range of discharges has already been mentioned, in fact, they include the smallest and the next to largest discharges used in this study, the next to largest being over a million times the smallest. The great range of the data used tends to make the slope of the line very accurate.. There is a possibility that the model experiments may not represent a condition of exact equilibrium, but a

very thorough study* of the Lower Mississippi River (perhaps the most thorough geological study ever made of any river) led to the conclusion that this stream had been in equilibrium for about 2000 years. Because of the great range of discharges, the magnitude of any correction of the observed slope in the model, which it is reasonable to expect might be necessary to obtain in it the correct equilibrium slope, is not sufficiently large to change appreciably the slope or position of this line.

(2) The fact that the material used in the model was Mississippi River sand, indicating, as previously mentioned, that both model and prototype used the same sand size.

(3) Accurate discharge and slope data on both model and prototype were available.

(4) The foregoing points deal with the position of the line at its ends. The reliability of the position of it between the ends is indicated by its general agreement with the data on other meandering sand streams, the position of the line in nearly all cases deviating from the positions of the points representing other meandering streams in a systematic and logical manner, in the direction that would be expected from the deviations of these streams from the material size, tortuosity and slope of the Mississippi River model and prototype.

Although most of the meandering sand streams agree approximately with the equation $S = \frac{0.0017}{\sqrt[4]{Q}}$, the Red River of the North (140-141) has a much lower slope than this relation gives. This indicates that there is more than

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* H. N. Fisk, 1952 Mississippi River Valley Geology in Relation to River Regime. Trans. A.S.C.E. Vol. 117, pp 667-689.

H. N. Fisk, 1944 Geological Investigation of the Alluvial Valley of the Lower Mississippi - Mississippi River Commission, Vicksburg, Miss.

one type of meandering stream. Although the banks are of cohesive material, the bed contains sand. This is also the case of the Verdigris River (22) which conforms reasonably well with the other sand streams. The explanation of the unusual characteristics of this stream and of the U-shaped bends which are typical of it, no doubt lies in its past geological history. As is discussed in detail in Appendix I, this river is a very young one, having been formed in the bed of an immense lake, formed by the Wisconsin glacier, as the lake drained out when the glacier retreated northward. The reason for the U-shaped bends is not known.

As previously shown, some very tortuous meandering sand streams have the very low slopes and values of K, and it appears probable that high tortuosity generally accompanies low slope. As will be pointed out later in the discussion of braided streams, for braided sand streams the lower the slope the more tortuous the streams become. It appears that this tendency of braided streams continues into the range of meandering sand streams and that there is a gradual transition through both braided and meandering streams with decreasing braiding tendencies and increasing tortuosities as the slope decreases. There is some evidence, however, that there is a lower limit to this situation since a number of streams of very low slope tend to be relatively straight. Examples of this are the Yangtze River in China (66,67) and the St. Clair in Michigan and Canada (143), and the Lower Nile (115). All three of these streams have considerable cohesive material in their channels, but in the case of the Verdigris River (22) cohesive materials seem to have little effect on the meander pattern.

An interesting conclusion follows, if this gradual reduction of tortuosity with increase of slope exists through most of the range of meandering streams: namely, that there is probably no simple relation of meander belt width of meandering streams to stream width, which makes meander belt width a function of stream width only, as Jefferson*, Bates** and others have suggested. For a given stream width, the meander belt width tends to be a function of the degree of sinuosity or the tortuosity ratio of the stream since the more tortuous a stream is, the wider the meander belt will tend to be. Since tortuosity seems to vary with the stream slope the width of meander belt probably also is a function of stream slope. The data showing the relations of meander belt, to stream width as shown in the work of Jefferson and Bates scatter widely, but all give meander belt widths much wider than the stream widths. This results because only highly tortuous rivers are included in the data, as they are the only ones which are considered to be meandering streams. If the less sinuous rivers were included the fallacy of the simple relation of meander belt width to stream width would be demonstrated.

It is well known, that by making the slope of a straight artificial channel low enough, it can be made to maintain a straight course, but it will also maintain a crooked course if originally given that alignment. A smaller slope, however, is necessary to maintain a stable crooked artificial channel than a straight one. The determination of the dimensions of such stable channels from the standpoint of this investigation would probably lead to valuable insights on the patterns of low slope streams. A preliminary investigation of this point, made in connection with this study indicates that the slopes used in irrigation canals are considerably less than is usually found in meandering rivers.

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* National Geographic Magazine, October 1902, pp 373-384.

** Bulletin of the Geological Society of America, Vol. 50, 1939, pp 819-880

The relation $S = \frac{K}{\sqrt[4]{Q}}$, showing that the slope varies inversely as the fourth root of the discharge, is quite different from the results obtained for regime channels by Lacey, which was that S varies inversely as the sixth root of Q. For meandering sand streams, this fourth root relation seems well established, and Lacey's relation does not fit the data available. As will be shown later for other stream patterns and other sizes of material the data available were not sufficient to indicate unquestionably that the fourth root relation holds for them. Further study is needed to settle this point.

Determination of Quantitative Relations for Braided Streams of High Slope and Sand Beds.

As will be shown later, braiding may be caused by the stream having a steep slope or because it is overloaded with sediment. By using only the data from sand streams having steep slopes it is possible to make a quantitative comparison of the slope-discharge relations for this type of stream. The stream most frequently referred to in this country as a braided stream is the Platte River in Nebraska. This stream is steep and is highly braided. At the present time the water of this river, except near the lower end, is so nearly completely used for irrigation, that its discharge is very different from the natural flow which produced the braided condition, which originally existed in this stream*. From Colorado State governmental authorities concerned with water control the best estimate they could give of the original flow of the Platte river (25), has been obtained and plotted on Figure 2. Other sand bed rivers which are highly braided are the Niobrara (26,27 and 28) the lower ends of the North Platte (29)** and South Platte (30)** in Nebraska, and Cherry Creek (31) in Colorado. Other streams which are believed to be of less

* U. S. Engineer Department, 1934 Platte River, Colorado, Wyoming, and Nebraska, 73rd Congress Session, House Document No. 197, p 377.

** The original discharge was also used for these streams.

highly braided form than the Platte River are the main Loup River (39) and its branches, North Loup (40) and Middle Loup (41), all in Nebraska.

A model of the Lower Colorado River (32-38) constructed with sand coarser than that in the Lower Colorado, to study the intake at the Imperial Dam, also had highly braided channels. The discharge-slope relations of these streams can be approximately represented by a line having an equation $S = \frac{0.01}{\sqrt[4]{Q}}$, i.e., ($K = 0.01$). This represents a slope about six times as steep as that representing the meandering sand streams. In this case, the $\sqrt[4]{Q}$ relation is not as well established as for meandering streams, since it is more difficult to estimate the degree of braiding by visual means than it is to determine the degree of meandering. It may not become possible to determine the degree of braiding with sufficient accuracy to establish this slope relation until the quantitative measures for determining stream form are worked out, as discussed later in this paper. Until more precise determinations are available, the K value of 0.01 can be taken as representing approximately a highly braided form of stream in sand.

It seems likely that theoretically there is no upper limit to the slope of braided river, until the limitation is reached of the concentration of sediment that can flow as a fluid. If the slope becomes too steep, the concentration of sediment necessary to provide the water with sufficient load to maintain the slope may become so great that it ceases to be a water flow and becomes a mud flow. Time is not available at present to speculate on the probable result of this situation, and its limitations, where the concentration becomes so high that movement nearly ceases.

However, there are streams which have interlacing channels and are said to be braided, but do not have steep slopes, as is shown on Fig. 2. One section of the Upper Mississippi River (120-121) which is said to be braided has a relatively low slope, much less than the other braided rivers of similar discharge. A map of this section of this stream is shown on Figure 12. Another stream which may have some braided sections is the Lower Illinois River (142). As will be shown later, these two streams are formed under entirely different conditions than are the steep-slope braided streams of the Platte River type.

For purposes of comparison of braided and meandering streams represented by the equation, $S = \frac{0.0017}{\sqrt[4]{Q}}$ is also drawn on Figure 2.

<u>Sand Streams Between Highly Braided and Meandering</u>

There are a number of sand streams which have K values between those which are discussed as meandering and those which are discussed as being highly braided and of the steep slope type. The slope-discharge relations for these streams are shown on Figure 3. In order to show their general relation to meandering and highly braided sand streams shown on Figures 1 and 2 the lines representing K = 0.0017 and 0.01 are also placed on this Figure. Among these are the Republican (42,43), Red River of the South (44), South Canadian (45), Lower Arkansas at four points (46 to 49 incl.), Kansas (139), Lower Colorado (50,51), and most of the Missouri River (54 to 65 incl.). Many of these streams have meandering as well as braided tendencies, and although no quantitative study of the degree of braiding and meandering has been made of these rivers there appears to be a strong tendency for the braiding to be less pronounced and the meandering tendency to become more pronounced as the K value decreases.

Except for the Upper Mississippi and Illinois Rivers there is thus a gradual transition from braided to meandering sand streams and from slightly meandering to highly meandering sand streams. In general the steeper the slope the more braided the stream becomes and the flatter the gradient the more tortuous it becomes extending down through the meandering streams, possibly down to a certain limit below which the streams may become more straight.

Some Conclusions Regarding High Slope Braided and Meandering Streams

Considering streams in erodible material as a whole, the steepest streams, other conditions being the same, tend to adopt a braided form, which is relatively straight and those of smaller slope tend to be more sinuous in alignment, even into the typically meandering streams. This fact presents strong evidence to disprove the view widely held by engineers that a river meanders because its valley has too much slope and has lengthened its channel to reduce the slope to a value which produced a stable channel. If this view is sound, how can it be that for the same discharge and material size streams in non-cohesive material tend to be more nearly straight when they are steeper than the meandering streams. Why do these steeper streams not lengthen out by meandering to the slope of the typically meandering stream, as the above mentioned common belief contends.

In this argument it should be recognized that, to be entirely sound, the comparison of streams should be made on the basis of valley slopes rather than stream channel slopes, since the valley slope would represent more nearly the original slope if the stream had not lengthened itself as this common hypothesis assumes. Since high-slope braided streams are relatively straight, their valley slopes are more nearly equal to the stream slope than is the case of the meandering river in which the stream channel slope may be much less than the valley slope. The valley slopes of the steep-slope braided streams are, therefore, not as much greater than the valley slopes of the meandering ones, as a comparison of their stream channel slopes (which are the values used in this study) would indicate. It is unfortunate that sufficient time has not been available to compare the two types of stream on the basis of their valley slopes, but it appears to be certain that the length of even very tortuous streams is not enough different from the valley length to invalidate the conclusion drawn in the above argument. For example, it is doubtful if any stream is so tortuous that its stream length is six times the valley length, as would have to be the case if a meandering stream with K = 0.00017 like the Lower Mississippi has a valley slope equal to a steep-slope braided river like the Platte with a K = 0.01. If these valley slopes were equal, it would invalidate the argument presented above that meandering streams are not formed because the valley is too steep and that the river lengthens out to reduce the stream slope to a value which will produce a relatively stable channel. There is no doubt that if a study of the relation of valley slopes of alluvial streams to discharge was made, similar to that made in this study, it would show that steeper valley slopes tend to produce straighter channels, as do the steeper stream slopes. The value of the constants comparable to K developed from this new study, however, would differ less for the two types of streams than do the values of K obtained in the study reported herein. It is hoped that a study of this kind will be made in the future.

As previously mentioned in general in non-cohesive material, as the slope flattens, the braided streams become less braided and more meandering until the typical meandering pattern is reached. There is some evidence that as the slopes become still flatter, the streams tend to become more tortuous, and abandon the regular bend pattern of the typically meandering shape and adopt a tortuous alignment in which there is little similarity in the bends. But in any event a few streams of very low slope studied such as the Yangtze

(66,67) and the upstream section of the St. Clair (143) (Figure 3) tend to have comparatively straight alignment, indicating that there may be a minimum slope for meandering streams and that still lower slopes tend to produce straight streams. In other words, there are indications that the slope of meandering streams is intermediate between the straighter steep slope braided streams and some very low slope relatively straight streams.

Determination of Quantitative Relations for Gravel and Cobble Streams

The data found for streams with bed-bank material of gravel and cobbles are not extensive. Considerable data for discharge, slope and material size are available but only in a few cases were there data on the stream pattern. All the available data on these streams are plotted on Figure 4.

One of the streams on which detailed data are available is a meandering section of Fall River (68-69) in Rocky Mountain National Park, which was surveyed under the direction of Professor C. J. Posey. This is a small, highly meandering stream in gravel. The mean flow from a five year record is 38.7 sec. ft. The slope varies from about 0.0030 at the upper end to 0.00081 at the lower end. The over-all average bed material size was about 25 mm, and the average size of the largest bed particles varied from about 160 mm at the upper end to 18 mm at the lower end. In most of the stretch the average size of the largest particles was not far from 26 mm. Most of the data are from a thesis entitled "A Study of Stream Meanders" written at the University of Iowa in 1944 by D. E. Escobar under the direction of Professor C. J. Posey.

Another stream in coarse material on which considerable data were obtained was the Nooksack River (70-76) in northwestern Washington. This stream covers a considerable range of material and stream pattern. The lower end is comparatively straight, and formed in fine material. It also appears to be of considerable depth, as it approaches the sea. As this part is also subject to tidal influence, it is probably too complicated a condition to analyse at the present time. Above this the stream is moderately tortuous and flows in sand. Still further up it has a meandering pattern and flows in sand and gravel; above which is a stretch which is slightly braided in sand and gravel and another which is moderately braided also in sand and gravel. The uppermost section classified was highly braided in sand, gravel and cobbles up to about 6 inches in size. It is not unlikely that this stream may be somewhat overloaded, as it has shifted its location for the lower 30 miles of its length in the not too remote past.

Another stream on which data were available is the Willamette River (77,78) in Oregon. The material through which this stream flows is medium to coarse gravel. From a detailed map of this stream in USGS Water Supply Paper No. 890 the channel seems to have a meandering pattern. It also seems to have a relatively low slope. It is probable that this is an overloaded stream. In his Physiography of the Western States, 1913, Fenneman states (p. 450) "Above (south of) Oregon City, the Willamette River is a sluggish stream with an intricate series of meanders. Apparently a fault crosses the stream at this place, the block on the south side being uplifted at the edge and tilted south, thus helping to stagnate the stream higher up. ---- By reason of insufficient fall and ample load of sediment from the adjacent mountains, it is an overloaded stream".

The Miami River (85-88) runs in a bed of sand and medium size gravel. Most of the stream is relatively straight but at the city of Dayton there is a well formed meander bend, which gives data on the conditions in a meandering stream in gravel.

The lower end of the Tennessee River (91) runs in a bed of sand and gravel, but the banks seem to be straight and quite stable. The upper Colorado River for about 27 miles below Grand Junction (92) Colorado runs in a bed of sand, gravel and small cobbles, and shows a tendency to form a braided pattern.

Data on the discharge, slope and material size of a considerable number of other gravel streams were obtained, but the data on the stream pattern were not sufficiently well defined to be used. The data is listed in the table however, and shown on Figure 4. It is hoped that it will be possible to get data for classifying these streams later.

The Ohio River (93-97) from Pittsburg to Louisville has a bed which is believed to be predominantly sand and gravel, the banks are relatively stable and the slopes of this part of the river are about that for a meandering sand river of equal discharge. This is a low slope for a gravel river. It is not unlikely that the low slope was established when the Wisconsin glacier was retreating, with its face a considerable distance north of the Ohio, the Ohio being the only outlet for the melted ice from a long face of the glacier extending from central Illinois to middle Pennsylvania. Under these circumstances the flow would be large, and a low slope was produced by this large flow. Under the present condition this stream may receive more sediment from its tributaries than it is capable of transporting and the Ohio may also be somewhat of a refilling stream.

The Yellowstone River (98-99) in Montana for the length near Billings and at Buffalo Rapids is a meandering stream in sand, gravel and cobbles.

<u>General Equations for Comparing Streams</u>

As previously pointed out, the relation of $S = \frac{0.0017}{\sqrt[4]{Q}}$ is well established for comparing meandering sand streams, and $S = \frac{0.01}{\sqrt[4]{Q}}$ is less well established for highly braided sand streams of the steep slope type. For streams of larger bed-bank material size, relations of this type have not yet been well established, but the data available indicate that an equation of this type may be applicable. To carry this study farther, it is desirable to get more data for gravel and cobble rivers to see how closely they follow this general form.

Perhaps the best approach for the present is to express the formula in general terms, as $S = \frac{K}{\sqrt[4]{Q}}$, where K is roughly 0.0017 for meandering sand streams, and roughly 0.01 for high slope braided sand streams. If it is found that this form of equation also approximately holds for streams in material coarser than sand, perhaps K can be expressed as a function of the particle size, in such a way that all meandering rivers of the same pattern would have the same value of this function regardless of material size, (as long as the material was non-cohesive).

By determining the degree of sinuosity of a large number of the streams in terms of their tortuosity ratios (i.e., the ratio of the stream length to the valley length), it is believed that an equation can be derived relating slope, discharge, material size and stream pattern as represented by this ratio at least for the streams of considerable sinuosity.

For the present stage of development of the stream forms it will be convenient to compare streams in terms of their K values, and this value has therefore been computed for each of the streams studied, and is given in pages 103 thru 106.

As previously mentioned, the relation for meandering sand stream forms, which seems well established by the data available, does not agree with the Lacey relations, which indicate that for regime channels the slope varies as the sixth root of the discharge. The slope also plainly varies with the stream pattern and the material size as well as Q. Lacey's relations indicate that it varies directly as f, his "silt factor" as well as $\sqrt[6]{Q}$, but Lacey related f only to material size. This indicates that for natural streams the stream pattern is a factor which Lacey omitted.

Of course Lacey's relations were primarily intended for use in the design of stable irrigation canals, but since he compares them with the dimensions of natural streams, such as the Mississippi, he obviously expected that they would be used for such streams. They have been extensively used by others in dealing with river control problems.

In this study to date the principal effort has been expended in getting the data and in drawing the more plainly evident conclusions. No time has been available to compare extensively the results obtained with the results obtained by other authorities, especially Lacey, Blench, Leopold and Maddock. In extending this study further, the relation of the data it develops to the relations of these other authorities should be investigated.

A STUDY OF THE TERMINOLOGY OF MEANDERING STREAMS

In addition to the quantitative studies previously described, considerable thought was given to improving the terminology of meandering streams. The most common word used in classifying crooked streams is the term "meandering". This word comes from the name of a very crooked river in south-eastern Turkey, which name has had a variety of spellings but is now known as the Buyuk Menderes River, regarding which more data is given in Appendix I. The crookedness of this stream has been proverbial since ancient times and has come into the English language as the words meander and meandering, which are used in a variety of ways, and are not confined to descriptions of rivers. The word came into the English language from the Greek via the Latin. It is also found in the German, French, Dutch and Spanish languages, where it no doubt had the same origin, and is probably found in the Italian also.

In Webster's New International Dictionary the noun meander is defined as "(1) a turn or winding, as of a stream; hence, a winding path or course; a labyrinth. (2) A tortuous or intricate movement or journeying. (3) A Greek fret or key pattern ---." The intransitive verb meander is defined "(1) To wind, turn or twist; to make flexious; also to entangle, as in a labyrinth. (2) To follow by meandering." In surveying there is the well known term, meander line, which is defined as "A surveyed line, usually irregular, not a boundary line, especially one following the outline of a stream, lake or swamp."

It will be seen that this word usually means a non-systematic motion or direction, although in the Greek fret the direction is systematic. From Figure 5, a map of a typical part of the river from which the name was derived, (kindly supplied to the writer by the engineering firm Knappen, Tippetts, Abbett and McCarthy) it can be seen that, while there is a tendency toward systematic (i.e., alternate right and left) bends, this tendency is much less than in a large number of streams, and in many parts the alignment of this stream is quite unsystematic. The form of the bends also is not uniform, in fact, there does not seem to be any one typical form of bend.

As applied to streams in the past, the terms meander and meandering have come to be used to designate almost any crooked river, but usually one whose pattern is formed by the action of the stream itself on readily erodible material. It has been widely used to designate both streams which have no systematic pattern and those whose pattern is partly or even distinctly systematic. When one considers the origin of the term meander and its survival through centuries largely devoid of scientific viewpoint, it is obvious that in its common use it could not mean anything very definite, and that any attempt to give it an exact or narrow use would be a restriction of the common use.

Previous Efforts to Improve Terminology of Meandering Streams

Advance in any field of science is necessarily accompanied by the development of the more exact terminology which is required to express the various ideas which this advance develops. In conformity with this general pattern, efforts have previously been made to give a more definite meaning to the term meander, as applied to streams, than could be obtained from the application of the widely varying concepts in general use which have developed as the meaning of the term meander.

In India, the problem of control of its great rivers led to a major advance in the science of stream control which required a more exact terminology than was then in use. In July 1939, the Research Committee of the Central Board (Annual Report, Technical, 1938-39 p. 49 and 1939-40 p. 98) resolved that: Meandering is defined as the adoption of a continually varying sinuous path by the deep water channel (thalweg) of an alluvial river, not imposed by external "restraint", and at its meeting in November 1939, the Central Board of Irrigation tentatively accepted this definition. At its meeting in November 1940, however, the Board adopted a revised recommendation of the Research Committee by resolving that "A meandering river follows a sinuous path due to natural physical causes not imposed by external restraint, and occurs where varying discharges and silt charges lead to curved flow and erosion of its banks". (Ann. Rept. Technical, 1939-40 p. 115). This meaning of the term meander seems to have been widely adopted in India about that time.

In a paper published by the American Geophysical Union, Mr. G. H. Matthes Hon. MASCE*, a noted river engineer in the United States, states that, "The term meander is here applied to any letter S channel pattern, fashioned in alluvial materials, which is free to shift its location and adjust its shape as part of a migratory movement of the channel as a whole down the valley." He also states the term is held "to be strictly appropriate only when the channel migration affects both bends and intervening straight reaches, and is in the nature of a fairly consistent and more or less continuous process in which banks are torn down and others are built up through a transfer of materials. Mere tortuosity, or crooked channel alignments, are not classified as meanders. When the materials composing the alluvium are fairly uniform as to grain size and erodibility, migratory processes of the meander-type produce definite sinuous patterns and are noteworthy for the consistency with which the channel-dimensions are reproduced."

A. Schoklitsch** states that when the length of a bend becomes greater than $\frac{D}{2}\pi$, (where D is the distance from the beginning to the end of the bend), the bend is called a meander. Where less than this length, it is serpentining.

Although ordinary dictionaries define the term meandering, they do not define the term meandering river. The geologist also has felt the need of more exact terminology. In "A Glossary of the Mining and Mineral Industry"***

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* Matthes, G. H. Basic aspects of Stream-Meanders, Transactions American Geophysical Union, 1941, p. 632-636.

** Scholklitsch, A. Hydraulic Structures, Vol. I. p. 149, translated by S. Shulits, 1937, American Society of Mechanical Engineers, New York.

*** U. S. Bureau of Mines Bulletin 95 (1920); also in Dictionary of Geological Terms, C. M. Rice.

A. H. Fay gives the following definition of a meander as ascribed to L. La Forge: "One of a series of somewhat regular and looplike bends in the course of a stream, developed, when the stream is flowing at grade, through lateral shifting of its course toward the convex sides of the original curves." This definition is also given by Rice* and is ascribed to Fay. C. A. Cotton** states, "The development of curvature in the stream channel tends eventually toward the production of regular flowing curves, (termed meanders)---"

Disadvantages of the Suggested Definitions

Although these suggestions for improvement of the terminology are the results of a great deal of study by able and experienced engineers and geologists, and have added to the knowledge of the subject and thus have resulted in a further advance of the science, the writer believes they do not completely meet the needs of the science of rivers. The writer is well aware of the difficulties of trying to improve on them, but believes that scientific advance is possible only by means of constructive criticism of the existing status. He will therefore present what he hopes are constructive criticisms of these definitions, and then present what he believes are improvements thereon.

It will be noticed that all of these definitions somewhat arbitrarily narrow the field which has previously been covered by the term meandering stream. There are a number of disadvantages in the attempt to improve the terminology of rivers by restricting the use of the widely and loosely used term meander to a much narrower class of streams than it has covered in its common usage. One disadvantage is that the more extended use is so general that the restricted use will not be adopted, except by a few persons or where

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* Rice, C. M. 1945. Dictionary of Geological Terms. p. 240.

** Cotton, C. A. 1945. Geomorphology, p. 100. John Wiley and Sons, Co.

the new use is required by some strong organizational authority. At best it could only come into use slowly, over a considerable period of time. Outside of the scope of such an authority, even when it is used in the restricted sense, one cannot be sure that it is being used in this sense, and therefore a good deal of the advantage of the use is lost. Even if its restricted sense came into use by authority or general acceptance, in reading the literature on the subject one would have to know when the change took place, to know whether or not the article in which it was used was written before or after the restriction came into effect.

Another objection to restricting a certain term to a narrower meaning is that, if one wishes to have a terminology covering the whole range of stream forms, it is then necessary to invent new terms to cover the cases which have been excluded by the restriction. Such a complete terminology will be necessary if we are ever to have an adequate science in this field.

Considering now the individual definitions, and first, the final definition of the Central Board of Irrigation given on page 44, the writer feels that the words "follows a sinuous path due to natural physical causes not imposed by external restraint," is somewhat vague. This author presumes that it means that the sinuous path is due to natural physical causes, but that the sinuosity is not caused by the restraint of the path of the flowing water by relatively inerodible natural material or the works of men.

Another objection is the statement, "... and occurs where varying discharges and silt charges lead to curved flow..." Model tests show that meanders can be formed by uniform flow; in fact, many if not most of the model experiments on meanders have been performed with such flow. In many cases in models the meandering has been formed with a constant flow and constant sediment charge, and often with the use of a constant flow of water without an initial sediment load. There is no reason to believe that meanders could not form in streams of very uniform flow. The meanders at the lower end of the St. Clair River in Michigan and Canada is one case and the outlet to Lake Maxinkukee is another case. Both of these streams are described in Appendix I.

Still another objection to this definition is that, with it, until one has established that in a certain stream bank erosion and its curved flow were "due to varying discharges and silt charges," he has not proved that the stream is a meandering one. Since the writer does not know of any case where he is sure these conditions exist, he is not sure that he knows of a single stream that is "meandering" as thus defined. It would seem that an extensive study of any stream would have to be made to prove that it was a "meandering" one according to this definition, as the author understands it.

Still another objection to this definition is that it probably places the engineers in the anomalous position of deciding that the Buyuk Menderes River, from which the term meander originated, is not known to be a meandering stream, since probably no one knows that the varying flow and silt charges on it lead to its curved flow.

The objections to Mr. Matthes' definition is that it limits meandering streams to those having S-shaped bends, thus eliminating many streams previously considered to be meandering. This definition also brings in difficulties when one wishes to designate what is commonly called an incised or entrenched meander. With the restriction to streams in which the bends bodily move downstream, there are few entrenched meanders, since usually the bends cease to move downstream when they become entrenched.

A disadvantage of limiting meandering streams to those whose bends migrate downstream is that the existence of this action can only be established by observing the river over a long period, preferably with a series of maps showing the position of the river at different dates. For practical purposes therefore, meandering streams would be limited to those for which there is a long record of behavior, rather than those physical characteristics or actions, which could be readily determined. Both the migrating bend and the S-shaped bend requirements would definitely eliminate the Buyuk Menderes as a meandering stream. The limiting of meandering to alluvial streams would eliminate those streams in rock, which form the 71 meander cutoffs described by Macar*, and many other cases of entrenched or incised meanders. It would not appear that this definition would be acceptable to geologists.

The principal objection to the definition of L. La Forge is that it is necessary to establish that the stream is flowing at grade, to classify the stream as meandering. This would often be very difficult to do, especially in view of the widely different opinions among geologists of what constitutes a graded stream.

The writer's objections to the statement of Cotton is that the development of curvature in the stream channel does not always tend toward the production of regular, flowing curves. It does only where the conditions are favorable. The development of curvature where conditions favored braiding would tend toward straightening of the channel rather than the formation of more bends. Cotton's definition also limits meanders to curves which are regular and flowing which has the disadvantages previously mentioned of eliminating some of the forms which have in the past been considered by some as meandering. The meaning of a "flowing curve" is very indefinite, but probably means the same as the S-shaped bends discussed later.

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* Macar, P. F. 1934. Effect of Cut-off Meanders on Longitudinal Profile of Rivers. Journal of Geology, Vol. 42, p. 523-536.

Proposed New Definition of Meandering Streams

In the studies leading to this report, including the examination of a large number of maps, in the streams encountered in his past forty-odd years of hydraulic engineering experiences, from the reading of numerous books and articles, and from observations of the country traversed on a considerable number of airplane trips, the writer has come in contact with a very large number of streams. Based on this experience, he believes that there are so many variables involved in meandering streams that the number of combinations of these variables, in what might be considered as meandering streams alone, makes it evident to him that a very extensive classification will be necessary, including the invention of a number of new terms, if the whole range of cases is to be covered by classes of limited range in a systematic and logical classification. To devise a classification of this type, which would be unquestionably sound with the present state of knowledge, may not, in the writer's opinion, be possible. Until the causes of meandering are completely understood, there is always danger in adopting a definition. However, the writer believes that sufficient knowledge is available to take a forward step in this direction, and that such a step would represent progress and therefore should be taken.

After considerable study the writer has concluded that it is possible to attain the above mentioned desirable end for the present by adopting a comprehensive definition of meandering which will not seriously conflict with the widely different uses of the past, and then list a series of qualifying terms, the appropriate ones of which could be applied to each individual stream. This would serve to accurately describe that stream's important attributes, and thus serve to classify it.

Before proposing a definition of the term "meandering stream" it is desirable that one give some thought to the qualities which, to the extent that this is possible, it would be very desirable that the definition possess. The writer believes that the following are the qualities which would be very desirable in a definition of a meandering stream: (1) that it depart as little as feasible from past usage, (2) that it cover as wide a range of streams as feasible and thus reduce the number of primary classifications of streams, (3) that it enable a classification to be made with a minimum of investigation, and (4) that it be acceptable to geologists as well as engineers.

As previously pointed out, there is a serious objection to a definition of meandering which departs materially from that used in the past, as this is sure to lead to confusion. Also any definition adopted should, as far as can be foreseen, be a rational part of a classification which will cover the whole range of streams. It is evident from the extensive literature dealing with meandering streams that they form a large section of streams as a whole and therefore a definition of this term should cover the whole of this section, thus avoiding the necessity of inventing new classifications of the streams which might be placed outside the previous classifications, in addition to the difficulties of securing the acceptance of this new addition. Unless a classification can be made with a minimum of investigation it will be of limited usefulness, because time and effort required to secure the data required to make the classification will, in most instances, prevent the classification from being carried out. Since the subject of stream forms is a field where the interest of geologists and engineers overlap, and where the mutual exchange of information would be of great benefit to both, it is highly desirable that they both use the same terminology, and therefore that any new classifications introduced be acceptable to both groups.

There are two general aspects of the term meandering which may be used when one wishes to define the term meandering stream. One describes the path or course, with its many changes of direction, which the flowing water takes in passing down the stream, the pattern of which is often quite unsystematic and apparently haphazard. The other one describes the shifting which takes place in the channel in which the water flows, due to scour, transport and deposit of sediment by the flowing water. The first emphasizes the direction of the alignment of the channel, and the second, the shifting of the position of location of the channel. The second of these has been advocated by R. F. Griggs*.

The first of these aspects is much broader, and covers a much greater range of cases (including the one covered by the second classification). It can include practically the whole range covered by past usage of the term meander. The scope of the second aspect can be included in the first by the use of a qualifying term, but the first cannot similarly be included in the second. The use of the second aspect in classifying streams as meandering limits such streams to those which are known to be actively shifting their channels and eliminates those which are not, thus necessitating another classification for the non-shifting ones. In view of these objections to the second approach, the writer believes that the first of these alternatives is much more satisfactory and should therefore be used in the definition.

After a great deal of study and many trials, the writer has arrived at the following definition:

"A meandering stream is one whose channel alignment consists principally of pronounced bends, the shapes of which have not been determined predominantly by the varying nature of the terrain through which the channel passes."

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* Griggs, R. F. The Buffalo River, An Interesting Meandering Stream. Bulletin, American Geological Society, Vol. 38, 1906. pp. 168-177.

It is believed that this definition meets the four requirements previously discussed, in that (1) it departs as little as feasible from past usage, since it appears to cover practically all cases of streams that have been referred to as meandering streams in the past, (2) that it covers a wide range of streams, which will enable it to include a large proportion of them into one of the primary classifications of streams as a whole, (3) that streams can be determined to belong to this classification with a high degree of certainty and comparative ease, and (4) that this definition will be acceptable to most geologists as well as engineers, since it is believed to cover the class of streams which they have referred to in the past as meandering streams.

To classify a stream as meandering, it is only necessary to know two things. (1) That its alignment consists principally of pronounced bends. This can be determined from any map or a photograph or view from an airplane or other high point. (2) That the channel shapes have not been determined predominantly by the varying nature of the terrain through which the channel passes.

It is believed that using this definition a stream can be determined to be a meandering stream by a reconnaissance trip down the stream in a boat (except during floods) or by the examination of aerial photographs covering the stream taken when the stream is not in flood.

Classification can also be made with a high degree of accuracy from a geological-topographic map since such a map would show the pronounced bends and probably indicate any variations of terrain which could predominantly influence the bend shape. A topographic map without geological formations would usually serve the purpose, and, for one experienced in this field, a plain map without geology or topography would often be sufficient.

In an earlier draft of this definition of a meandering stream, the writer included the statement that the form of the curves was determined predominantly by the action of the flowing water. While the writer believes that it is true that in meandering streams the shape of the bends is predominantly due to the action of the flowing water, it would be more difficult to prove than that their form was not predominantly due to a variable terrain. Geologists and engineers commonly (and the writer believes correctly) assume that the form of many streams is due to the action of the flowing water, with little or no proof beyond the fact that the pattern of the curves is that commonly observed to be caused by flowing water. The accuracy of this judgment is so high that the writer believes that no good purpose is served in requiring proof that each individual case is so caused, which would be the case if the statement were included in the definition.

One of the advantages of the definition proposed is that it includes incised meanders which usually are located in solid rock. These bends can be inactive, that is, not shifting their location, as, for example, the famous "goosenecks" of the San Juan River in Utah and also those that are slowly shifting, such as the bends treated by Macar* previously mentioned. Incidentally a sign of shifting meanders is the formation of natural bridges in incised streams.

<u>Improvements in the Terminology Associated with Meandering Streams</u>

The adoption of the foregoing broad definition of a meandering stream is only a part of the development of an adequate nomenclature for the science of meandering streams, and the producing of the nomenclature which is a necessary accompaniment of this science. This broad class of meandering streams covers

* Macar, P. F. Effect of Cut-off Meanders on Longitudinal Profile of Rivers - Journal of Geology Vol. 42, pp. 523-536.

a wide range of conditions and a nomenclature must be worked out to classify the various forms which these conditions produce.

It was hoped that a study of the words which had meanings similar to meandering would be useful in making such a classification. A search was therefore made in the dictionaries for such words, and the following were found: crooked, circuitous, tortuous, wandering, winding, twisting, serpentine, snaky, sinuous, sinusoidal, divagating, undulating, flexious and flexuose, roaming. Of these words only crooked tortuous, winding and serpentine are frequently used in descriptions of stream forms.

It was hoped that certain of the words would indicate systematic patterns and others would indicate unsystematic patterns, and that these names could be given to streams having patterns of these types. To a certain extent this was found to be the case. For example, sinusoidal and undulating do indicate a definite back and forth pattern which may be thought of as systematic. Serpentine, snaky and sinuous are probably more commonly used to indicate the back and forth pattern but are not limited to such a meaning. However, many, if not all, of the others can indicate either systematic or non-systematic courses. None of them seemed to indicate exclusively non-systematic courses. Since no word was found which would serve to definitely indicate only a non-systematic pattern, this approach to a better classification of streams proved unfruitful. Another disadvantage of this type of nomenclature would be that it would restrict certain terms to a narrower meaning than is now in use, and would thus have the same drawbacks as those mentioned later in discussing a restricted use of the term meandering.

A Search of Previous Literature and Nomenclature of Meandering Streams

A great deal of study has been given to meandering streams in the past by very able engineers and geologists, and much information on this subject is available in their writings. Many helpful suggestions on classification and nomenclature for meandering streams are given in this literature. Some of the nomenclature developed therein has been widely used and should be adopted in any attempt to improve the present state of the science. In the following paragraphs the most important of the existing literature in this field, from the standpoint of the scope of this report, is discussed and the nomenclature developed therein is pointed out.

One of the earliest papers dealing with meandering was a paper on river terraces published in 1902 by the great American geologist W. M. Davis*. In this paper Davis treats meanders at considerable length, as an aid to understanding the formation of river terraces. This paper includes the following statements: "The space inclosed between tangents drawn outside of the curves or meanders of the stream is the meander belt". "The progressive movement of the meanders down the valley will be called sweeping". "The lateral movement of the meander belt from one side of the valley floor to the other will be referred to as swinging". "The compound movement of sweeping meanders in a swinging meander belt will be called wandering".

In the same year, 1902, as the Davis paper appeared, one by Professor Mark Jefferson was published on "The Limiting Width of Meander Belts".** The

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* River Terraces in New England, W. M. Davis. Bulletin of Museum of Comparative Zoology, 1902, XXXIII, pp. 281-346. Republished in 1909 in a collection of Davis's essays, portions of which were recently republished in Geographical Essays - W. M. Davis, 1954, pp. 514-586, by Dover Publications, Inc.

** National Geographic Magazine, October 1902, pp. 373-384.

writer has not succeeded in examining a copy of this article, but it gives the results of a study measuring the widths of meander belts on maps of 23 non-incised meandering rivers and 30 incised meandering rivers, in the United States. This represents one of the earliest attempts to deal quantitatively with meandering rivers. He deals principally with the relation between the width of the meander belt, finding the average non-incised meander belts to average 17.6 times as wide as the river, but for incised meandering streams the ratio averaged 30.6.

In 1904 an article was published by W. S. Tower* in which he introduces the term "migration" to describe the movement of bends downstream. He also defines incised or entrenched meanders, meander belt, meandering and a meander. He also states that steep sloped rivers tend to have smaller meander widths and the bends migrate more rapidly downstream.

In 1938 the Central Board of Irrigation of India sent out a questionnaire on meandering to a large number of persons and organizations whom they thought might supply some information on this subject. The replies to this questionnaire were summarized by Sir Claude Inglis.** In July 1940 the Board's Research Committee recommended certain definitions concerning meandering streams, and in November 1940 the Board adopted these resolutions with a number of modifications and eliminations. The definitions adopted by the Board are as follows:

A "meander" consists of two consecutive loops, one flowing clockwise, the other anti-clockwise.

A "meandering river" follows a sinuous path due to natural physical

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* Tower, W. S. 1904. The Development of Cutoff Meanders. American Geographical Society Bulletin - Vo. 36. October 1904. p. 590.

** Annual, Reports Technical, Central Board of Irrigation, India. 1938-39, p. 49, 1939-40, pp. 100-116.

causes not imposed by external restraint, and occurs where varying discharges and silt charges lead to curved flow and erosion of the banks.

A "warp" is a bend in a river imposed by external restraint.

"Meander length" is the tangential distance between corresponding points at extreme limits of fully developed meanders.

"Meander belt" is the distance between lines drawn tangential to the extreme points of successive fully developed meanders.

"Meander width" is the amplitude of swing of a fully developed meander from midstream to midstream.

"Meander ratio" is the ratio "meander width" to "meander length".

"Limits of oscillation" is the width within which a river has ranged during historic times.

A "sub-meander" is a small meander contained within the banks of a perennial river channel. These are caused by relatively low discharges after the flood has subsided.

An "incised river" is one which has cut its channel through the bed of the valley floor, as opposed to one flowing on a flood plain.

Some of these definitions can best be illustrated by Fig. 6 (CBI 1939-40, p. 116). They also adopted a definition of meander ratio as the ratio of meander width to meander length.

In 1939 R. A. Bates wrote a paper* which included a study he made bringing up-to-date the study of Jefferson previously mentioned. Bates derived a ratio of meander belt width to stream width of 14 for non-incised rivers and 30.8 for incised rivers, as compared with 17.6 and 30.6 obtained by

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* Geomorphic History of the Kickapoo Region, Wisconsin. Bulletin of Geological Society of America. Vol. 50, 1939, pp. 819-880.

Jefferson. He also attempted to develop a mathematical analysis of the cause of meanders.

In 1941 a paper on "Basic Aspects of Stream Meanders"* was published by G. H. Matthes, Hon. M.A.S.C.E., in which he defines a meandering stream as previously discussed. He also gives other valuable definitions and ideas, many of which are indicated graphically on Fig. 7, which is taken from his report.

Another valuable paper on meanders was published entitled "Factors Affecting Meanders of Channels" by Sir Claude Inglis in 1942** dealing largely with model tests on meanders.

An extensive study of meandering by Capt. J. F. Friedkin was published by the U. S. Waterways Experiment Station at Vicksburg, Mississippi, in 1945 entitled "A Laboratory Study of the Meandering of Alluvial Rivers". This reported on the results of a very thorough investigation made in their laboratory.

Two valuable papers dealing with meanders by Sir Claude Inglis appeared in 1947 and 1949. The first of these is a list of definitions and a chapter on "Meandering of Rivers in a two volume report on "The Behavior and Control of Rivers and Canals***. The second was a paper on "Meanders and Their Bearing on River Training****.

In these papers Sir Claude Inglis uses the definitions adopted by the Central Board of Irrigation except that he defines meander ratio as "the ratio of meander belt to meander length" instead of the ratio "meander width

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* Matthes, G. H. Basic Aspects of Stream Meanders. American Geophysical Union. 1941, pp. 632-635.

** Central Research and Hydrodynamic Station. 1942-43. pp. 51-55.

*** Research Station, Poona, India. Part I, pp. 1-5 and 143-166.

**** Institution of Civil Engineers, Maritime & Waterways Engineering Division Paper No. 7, Session 1945-47.

to meander length" as adopted by the Central Board of Irrigation. He also adopts the term tortuosity, which he defines as "the ratio of the length of the river channel to the axial length of the river". This definition is practically the same as the definition of tortuosity recommended in 1940 by the Research Committee of the Central Board of Irrigation of India, but which was not adopted by the Board.

Two interesting papers containing valuable material on meandering streams, written by A. P. Grant are entitled "Channel Improvements in Alluvial Streams, 1948* and "Soil Conservations" in New Zealand, 1950**, and another valuable one by M. S. Quraishy giving a detailed description of the formation of meanders in a laboratory channel was published in 1944.***

After the text of this part of his study was completed, the writer received from the authors a copy of a paper by them entitled "River Channel Patterns; Braided, Meandering and Straight" - L. B. Leopold and M. G. Wolman. (U. S. Geological Survey Professional Paper 282-B 1957). This paper covers the same general field as the author's paper and contains a great deal of valuable analysis, material and data. The author regrets that the urgency of completing his paper promptly prevented him from treating it at length in his paper. Those who wish to make a thorough study of the field covered by the author's paper should include this paper in their study.

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* Proceedings New Zealand Institution of Engineers, Vol. XXXIV, 1948, pp. 230-304.

** Proceedings New Zealand Institution of Engineers, Vol. XXXVI, 1950, pp. 269-313.

*** The Origin of Curves in Rivers - Current Science. February 1944, pp. 13, 36-39.

Author's Recommendations for Nomenclature of Meandering Streams

The foregoing listed literature contains a great many valuable definitions for use in developing the science of meandering streams, but they cannot be adopted bodily from this literature, since the meaning of the same term is not the same in all the papers. A careful selection of definitions should be made to remove these conflicts. As the result of his studies, the author believes that a number of other terms are necessary in the development of this science. In the following section of this report he has attempted to select from the previous literature a series of definitions which are consistent and he has added to these a number of new definitions which he believes are needed for an adequate development of the science. These latter definitions will generally be accompanied by a discussion of the reasons why they were selected. In order to have the list complete, it will start with the definition of meandering stream previously discussed.

A Meandering Stream is one whose channel alignment consists principally of pronounced bends, the shapes of which have not been determined predominantly by the varying nature of the terrain through which the channel passes.

A Meander consists of two consecutive loops, in one of which the water is flowing in a clockwise direction and in the other anti-clockwise. This is practically the same as the definition adopted by the Central Board of Irrigation of India (page 13) and as used in Inglis' papers. It also agrees with Matthes' use as indicated in Fig. 7.

Meander Length is the tangential distance between corresponding points at the extreme limits of fully developed meanders. This is the same as the definition of the Central Board of Irrigation of India (Fig. 6) and agrees with the usage of Inglis and Matthes.

Meander Width is the amplitude of swing of fully developed meanders, from midstream to midstream. This is the same as adopted by the Central Board of Irrigation of India. Inglis does not use the term and Matthes uses this term to designate the distance from outside to outside of bends rather than from midstream to midstream, as shown on Fig. 7. The distance used by Matthes is the meander belt width, as defined later.

A Meander Belt is the space inclosed between tangents drawn outside of the curves or meanders of the stream. This is the definition given by Davis*. The Central Board of Irrigation and Inglis define meander belt as the width of this space or strip, in other words, the width of the space rather than the space itself. The later usage makes the word "belt" have a significance which it never has in ordinary usage, and therefore the writer believes should be avoided, especially since this can easily be done by adopting the term meander belt width for the width of this strip. Matthes (Fig. 7) uses meander belt to cover the width over which the stream has wandered in the past time, as shown by the position of present meanders and past meanders, as indicated by oxbow lakes. Since none of the other authorities use the term meander belt as the name of this wide zone, it is believed to be undesirable to adopt such a major change of terminology, and instead (if there is sufficient use for such a term) to give this wide belt a new name which will not conflict with past usage.

Meander Belt Width is the width of the space previously defined as "meander belt". This is the same dimension which is defined as "meander belt" by the Central Board of Irrigation. Inglis also calls this dimension meander belt in the text of his papers and in his lists of definitions, but in his graphs showing the relation of the width of this strip to the width of the river

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* Geographical Essays. W. M. Davis. 1954, p. 537.

channel he calls it "width of meander belt", the same as the usage which the author has recommended above in this paragraph.

The author has not included the term meander ratio in his list of suggested definitions, since it does not appear to have much use and has been used with different meanings. The Central Board of Irrigation defines meander ratio as the ratio of meander width, to meander length (as shown on Fig. 6) and Inglis defines it as the ratio of meander belt width (using the terminology recommended by the author above) to meander length. As the meander width differs from the meander belt width by the width of the river, the author suggests that to avoid confusion, if one wishes to use the ratio recommended by the Central Board of Irrigation, he call it the "meander width-meander length ratio", and if he wishes to use the ratio used by Inglis he call it the "meander belt width-meander length ratio".

Tortuosity Ratio is the ratio of the length of the stream channel to the length of the stream measured along the axis of the valley. This has the same meaning as the term tortuosity which was recommended by the Research Committee of the Central Board of Irrigation in 1940 but which was not adopted by the Board. It was, however, used by Inglis in his papers. The author believes that this is an important definition in the development of the science of stream pattern, as it gives an easily measured quantitative value for the crookedness or tortuosity of the stream. Over a long section of the river the slope of the river multiplied by this ratio gives the slope of the valley. This value then is also the ratio of the valley slope to the river channel slope and should be extensively studied in future research in the field of river pattern.

The author prefers the term tortuosity ratio to the term tortuosity alone, since the former indicates directly that this term denotes a quantitative rather than a qualitative value; that it is the ratio of two other quantities, and that it is a dimensionless number, the same in all systems of units.

Migration. Grant* states "By migration of meanders is meant the tendency of the whole pattern of meanders to travel bodily downstream without much change in pattern". This term was probably first introduced by Tower**. Davis (page 537) uses the term "sweeping" to designate this action, and in a later paper Grant*** uses the term "meander creep" instead of migration of meanders which he used in his earlier paper, but he gives no reason for his change of terminology. The author believes that the term migration better describes this action than the term sweeping used by Davis and meander creep later adopted by Grant. The author therefore believes that Grant's first definition, as given above, is an adequate definition for this phenomenon.

Deformed Meanders. This term was probably introduced by Matthes****, who states, "Major departures from the meander pattern (Fig. 7) are usually attributable to interference with the methodical transfer of the bank materials, causing the river to change its mode of migration by seeking a path of less resistance. Large-scale interference results primarily from three natural causes: (a) accelerated erosion of the banks composed of soft or highly erodible alluvium, (b) resistance to bank caving due to the presence of lenses of compacted silts or clays, and (c) contacts with non-alluvial

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* Channel Improvement in Alluvial Streams, p. 244.

** Tower, W. S. 1904. The Development of Cutoff Meanders. American Geographical Society Bulletin. Vol. 36, October 1904, p. 590.

*** Soil Conservation in New Zealand, p. 279.

**** Basic Aspects of Stream Meanders, p. 635.

formations..." The alluvium laid down by a river, if not homogeneous in character, wields a marked influence in promoting distortions of the meander pattern. This term has much the same meaning as the term warp, adopted by the Central Board of Irrigation, as previously mentioned. The author believes that "deformed meanders" is a very useful term in studying the science of stream forms. It can be defined as follows:

> A Deformed Meander is one, the pattern of which differs materially from that which the stream would form in a homogeneous deposit of the prevailing material, and is due to encountering material of non-uniform composition. This definition considers the change of pattern due to encountering materials both more and less erodible than the prevailing material, or in other words, due to encountering both more or less external restraint than usual.

Channel Shifting. The definition of a meandering stream proposed by the author, and also those proposed by the Central Board of Irrigation, Matthes and La Forge, as well as the meaning of this term used by Inglis and Grant in their papers, all consider meander or meandering in terms of the shape of the pattern of the stream channel. None of them define or use these terms as meaning the shifting of the channel due to scour and deposit of sediment, which latter procedure was recommended by Griggs*. Frequently in the literature on meandering streams a movement of the position of the channel of the stream, due to scour or deposit of sediment, has in the past been referred to as meandering. For example, if a section of a stream that has experienced little change suddenly begins to change its position due to scour, it is frequently said that the stream suddenly started to meander. For one who

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* Griggs. The Buffalo River, An Interesting Meandering Stream.

accepts any of the above mentioned definitions of a meandering stream or a meander, this use of the term meandering also to denote a changing of position of the stream is not permissible, since it is using the same term with two conflicting meanings. To avoid this undesirable situation, the term "shifting" should be used in these cases of change of channel position due to scour or deposit, rather than to use the term meandering. Another permissible course is to state that the channel "became active", as will be explained later in this report.

Suggested Additional Terms for Use in the Science of Meandering Streams

The author believes that there are a number of terms which can be used in describing stream patterns which have been used little or not at all in the past. Those which will be found most useful are: regular, systematic or repetitive meander pattern, S-shaped meanders, U-shaped meanders, active and inactive meanders, confined meanders and restrained meanders.

In no stream is the pattern at one place exactly the same as at any other, but in some streams there may be found a long series of meanders which are very similar. In others there are many meanders which are somewhat similar to the others, and still other streams in which the bends are highly irregular and few, if any of the bends are of the same shape. All of these streams may be meandering streams under the definition recommended by the author, or have been so classified under the common usage found in most of the literature in the past. All three of the terms, regular, systematic, and repetitive, have much the same meaning, but the last two seem to the author to be somewhat more definitive than the first, as the term regular has so many meanings. At present it appears that the last two can be used interchangeably. A meandering stream can be said to be very systematic, or repetitive in its pattern, or only slightly systematic, or repetitive, or one may be described as being unsystematic, or non-repetitive. For example, the Red River of the North (Fig. 8*) has a very systematic and repetitive pattern; the Lower Mississippi (Fig. 9) has a moderately systematic or repetitive pattern; the original Meander River has an unsystematic and non-repetitive pattern, and the Souris River (Fig. 10*) of North Dakota has a very non-systematic and very non-repetitive pattern. In the present state of the science of stream patterns, it is not possible to establish the boundary lines between these classifications, but it is probable that when the quantitative measures of stream pattern recommended elsewhere in this report have been developed, it will be possible to establish such limits.

Another set of terms is necessary to describe the shape of the bends. Most meandering streams of systematic pattern and moderate to high tortuosity ratios have bends with a shape somewhat like the letter S as shown on Fig. 9, which is a map of the famous Greenville Bends on the Mississippi River. The necks of these bends frequently come so close together that a cutoff results. On the Red River of the North, however, (Fig. 8), the bends take the form of the letter U, and except near the lower end of this stream there is little if any tendency to form cutoffs. As mentioned elsewhere in this report, this stream was formed in the bed of an immense lake that became empty and the reason why it developed its system of highly systematic U-shaped meanders is

* Figure 8 is taken from the map of the Drayton Quadrangle North Dakota and Minnesota of the U. S. Geological Survey and Figure 10 is from their Voltaire Quadrangle North Dakota.

not known. There seems to be no question, however, that this is a distinctly different form of bend than the common S-shaped ones.

The meanders of some streams appear to change their positions rapidly, and some shift their positions little, if any. It is believed that these two classes could be distinguished from each other by calling the former an actively shifting stream, and the latter an inactive one. For example, the Lower Mississippi is a relatively actively shifting stream, and the Red River of the North is an inactive one. It might be argued that it would be better to call the Lower Mississippi River a relatively actively migrating stream and the Red River of the North a non-migrating one. This classification of these rivers is also a sound one, but in the case of the Mississippi we have a detailed record of its positions over a long enough period to establish that it is a migrating stream, and in the case of the Red River of the North the topography shows quite conclusively that it has not migrated. In most cases it is difficult to establish that a river is migrating, but to determine whether it is active it is necessary only to prove that it is eroding its banks, which ordinarily can be easily established.

Streams are not infrequently found which run through a valley, the bottom of which is filled with alluvium, and the sides of which are formed by relatively parallel walls of rock or other relatively inerodible material. Many but not all of these are rivers in the stage of early maturity and have been formed in conformity with the classical Davis* morphological scheme. In some the conditions of discharge, slope and sediment size are such that an actively meandering stream is formed, the channel of which frequently crosses

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* Davis, W. M. Geographical Essays. p. 249-295.

from side to side of the valley and impinges on the rock walls. An outstanding case of such a stream is the Klaralfvens River in Sweden described in great detail by DeGreer*. In this case the rock walls are close together, their distance apart being less than the width of the meander belt which the river would form if the walls did not exist. As a result the river impinges strongly on the rock bluffs at intervals, first on one side and then on the other, as shown in Fig. 11, the impingements on the same side occurring roughlv at distances of a meander length apart. In this section of the stream all of the meanders are deformed. (Incidentally, this river is a migrating one, and the period during which it migrates a distance of one meander length is said to be 2000 years.) The Missouri River for much of its length runs between roughly parallel rock walls, the distance apart of which in some cases is less than its natural meander belt width. In other parts of the stream the valley width is greater, and the stream impinges irregularly on the wall on one side or the other at intervals averaging more than one meander length apart. At the points of impingement of the stream and rock walls deformed meanders result.

It is suggested that in such streams where the walls are less than a meander width apart, the stream be referred to as a confined meandering stream, and where the width is greater than the meander belt width but narrow enough to form impingements at frequent intervals, it be referred to as a restrained meandering stream. The upper limit of valley width of restrained streams is at present indefinite, but a reasonable basis for its determination

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* Klaralfvens Serpentinlopp och flod plan. Sveriges Geologiska Undersokning Ser. C N:O 236, Arsbok 4(1910) No 8.

might be worked out by further study. Of course nearly all streams are interfered with somewhat, for example, the Lower Mississippi swings back and forth across its valley, which averages 75 miles in width, the river channel itself being about a mile wide. In the author's opinion, such a stream should not be considered as being restrained.

A FURTHER STUDY OF BRAIDED AND SIMILAR STREAMS

Grant* has given a definition of a braided stream, which is as follows: "By a braided river is meant the typically wide, steep and shallow course of an alluvial river consisting of a number of channels with islands between, meeting and dividing again, and presenting from the air the intertwining effect of braid". Friedkin** states as follows: "Rivers are described as braided when the channel is extremely wide and shallow, and the flow passes through a number of small, interlaced channels separated by bars. The channel as a whole does not meander although local meandering in minor channels generally occur".

Authorities differ on the cause of braiding but most of them*** contend that braiding is due to deposits in the river resulting from the fact that

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* Grant, A. P. 1948, Proceedings, New Zealand Institute of Engineers, p. 231. Channel Improvements in Alluvial Streams.

** Friedkin, J. F. 1945. A Laboratory Study of the Meandering of Alluvial Streams. U. S. Waterways Experiment Station, pp. 16-17.

*** Thornberry, W. D. 1954. Principles of Geomorphology, p. 126. John Wiley and Sons.
Hinds, N.E.A. 1943. Geomorphology pp. 492, 495, 496, 546, 548. Prentice-Hall, Inc.
Cotton, C. A. 1954. Geomogphology pp. 193, 194, 196. John Wiley and Sons.
von Engeln, O. D. 1942. Geomorphology pp. 234, 252. The MacMillan Co.
Worcester, P. G. 1948. A Textbook of Geomorphology. pp. 66. D. Van Nostrand Co., Inc.
Lobeck, A. K. 1939. Geomorphology. pp. 213-214. McGraw-Hill Book Co.
Grabau, A. W. 1920. A Textbook of Geology: Part I, General Geology.

the stream is supplied with more material than it can transport.

An overloading of a stream may be caused in any of many ways. Thornberry (P 164) gives a long list of possible causes of stream deposition any of which could be the cause of overloading which would produce braiding.

The Platte River in Nebraska has often been mentioned as a typical braided stream. Hinds mentions the Upper Mississippi River in the vicinity of Waukon, Iowa as being braided, see Fig. 12 which is taken from the Waukon, Iowa and Illinois USGS quadrangle map. The question whether or not the Mississippi at this point should be considered a braided river was raised by Nemenyi*(626), but he gives no reason, merely stating that the Mississippi "is probably dynamically different" from other braided streams. Since both rivers, however, have the interlacing channels with many islands which, from their resemblance to braid, give rise to the term braided even though there may be dynamical differences as Nemenyi contends, the writer believes that the Mississippi at this point should be considered to be a braided stream.

The data for these rivers are in Table I and Figure 2 and show that while the Platte River is quite steep, the Mississippi has a much flatter slope, the slope of the Platte being about twenty times as steep as the Upper Mississippi. In fact, the Mississippi at this point is, in comparison with other rivers of comparable discharge, a stream of quite low slope while the Platte has a relatively high slope. If both the Platte and the Mississippi at Waukon are considered to be braided streams, it follows that braided streams are not necessarily steep, but may have either flat or steep slopes.

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* Nemenyi, P. F. 1952. Annotated and Illustrated Bibliographic Material on the Morphology of Rivers, Bulletin of the Geological Society of America. Vol. 63, June 1952, pp. 596-644.

Two Causes of Braided Channels

As a result of the studies discussed in this report and his studies on the design of stable channels in irrigation canals, the author**,*** has concluded that there are two primary causes of braided streams, not just the one, i.e., overloading. Either one of these two causes alone may be responsible for the braided pattern, or they may both be acting to cause it. These causes are (1) overloading, i.e., the stream may be supplied with more sediment that it can carry and part of it may be deposited, and (2) steep slopes causing a wide, shallow channel, in which bars and islands readily form. This second cause has been largely overlooked by those engaged in this field, but the writer believes that it may be as frequently a cause of braiding as overloading.

All steep slope type braided channels, have many characteristics in common, in addition to that of multiple channels. These are as follows: (1) relatively straight course of the main channel, (2) steep longitudinal slopes, (3) wide channel, (4) shallow depth, (5) flat bottom, (6) sand or coarser bed material, and (7) usually relatively high sediment load. Rivers having these characteristics may be overloaded, but all overloaded rivers do not necessarily have this braided form, nor are all braided rivers necessarily overloaded. For example, a part of Sunshine Creek, near Cody, Wyoming, (Fig. 13) has a braided form, with steep slope, but is a degrading stream, due to the addition to it of water from another stream.

Since the cause which is most important in giving the distinctive form to this most common type of braided stream is the steep slope, this type is

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** Lane, E. W. 1937. Stable Channels in Erodible Material, Trans. ASCE, Vol. 102, pp. 123-194.

*** Lane, E. W. 1955. Design of Stable Channels, Trans. ASCE Vol. 120 pp. 1234-1279.

designated as the steep-slope type. From this cause usually result the relatively straight course and the wide, shallow, flat-bottomed channel with coarse bed material. In general the slope of a river is determined by the formation of the land through which the stream flows and the form is usually determined in a large measure by geological causes, such as general land slope, land uplift and glacier action, which are independent of the river action. The form of the land may be modified by flowing water, but the effect of this on the slope of long lengths of the river is usually secondary to other causes. In certain relatively short lengths of a stream, however, and particularly where the works of man have interfered with the natural river, the slope may be principally determined by the interaction of the water flow and sediment load.

A stream with a steep slope tends to have a wide, shallow cross section because with this shape of cross section the shear or tractive force exerted by the water on the sides of the channel is below the value which they can stand without scouring away more material than tends to deposit along the sides of the channel during low flows. The ability of flowing water to scour banks of a stream depends on the shearing or tractive force which the water exerts on them. In the past it has been common to think of the velocity of the flowing stream as the factor which causes scour, but recently engineers concerned with sediment motion have shifted their viewpoint and now consider the shearing force as a much better criterion. The concept of shear or tractive force is a simple but important one. However, as it requires considerable space to explain, it is preferable not to divert the reader's attention by explaining it at this point in the report, but rather to cover this in Appendix II.

If a large steady flow of water is turned into a small, steep channel, the channel will be made wider by scour of the banks until the shear on the banks is reduced to a magnitude equal to that which the material composing them can resist. In the case of variable flows, such as occurs in natural streams, stream width becomes stable when the shear is great enough during times of high flow to scour the banks enough to remove an amount of material equal to that which is deposited along the banks during the periods of low flow. In other words, when high flow scour and low flow deposit on the banks balance each other.

Since for a given slope of stream the shear is proportional to the depth of flow, a wide, steep stream produces less shear on the sides than a deep one of equal slope, and the banks of the wide, shallow, steep streams can, therefore, resist scour better than deep ones of the same slope. Consequently, when a natural stream with steep slope is formed in erodible material, it tends to adopt this wide, shallow shape. If the shape at any point is such that the shear value on the banks is too high, bank scour occurs and the channel widens until the shear is reduced to a value which does not produce too severe bank scour.

A given value of shear in a stream will scour the banks more severely than the bed because the force of gravity acting on the material on the banks assists the scouring by the moving water, but in a stream cross section the maximum value of the side shear is less than the bed shear and the effect of gravity is thus offset. The more easily eroded the bank material is, the wider will be the channel formed. This is probably the origin of Friedkin's view that braided channels result when the banks are extremely easily eroded.

The writer believes that the relatively flat bottom of steep-slope braided streams can be explained as follows: In flowing streams most of the sediment of sand and larger sizes is transported on or near the stream bottom. Much of it may be rolled along the bottom. If one part of the bottom tends to become scoured deeper than another a greater slope is set up in the streams between the scoured part and the remainder of the stream bed which is greater than the general slope of the stream. Hence there is a tendency for more of the moving material to roll down toward this low spot, since in this direction it has, not only the force of the flowing water to move it, but also the force of gravity tending to roll the particles down the slope. Depressions in the bottom thus tend to be filled and the deeper the depression the greater the tendency. Stream beds tend to have coarse material on the bed because such streams produce high turbulence in the flowing water and any fine material which comes into them is kept up in the water in suspension and flows down the stream without depositing on the bottom. As previously pointed out, the wide, shallow, flat-bottomed channel of the steep, common type of a braided stream is caused largely by its steep slope. The multiple channels can be formed by deposits of a small part of the heavy load being carried in certain places forming bars which often cause small islands at low flows, and thus multiple channels. In times of low flow the bars themselves form the multiple channels, although they are usually rapidly changing. On some of these bars vegetation grows, which causes still more deposit, and islands form which persist for some time, even with high water flows. These deposits are the result of local overloading at the points where they are formed, but the river as a whole may be transporting downstream as much sediment as is being brought to it, the bars and islands at some places being formed and enlarged by a rate of deposit equal to the rate of scouring with which bars and islands at other points are being removed.

It is thus possible to have a balance of scour and deposit which forms a river which is in equilibrium and which has been designated as, graded, in regime, in quasi-equilibrium, or poised, by various authorities. A braided stream is therefore not necessarily overloaded. In fact, there is no reason why it is not possible to have a braided river which is underloaded, and is therefore degrading its bed rather than filling it up, since the predominant factor in forming this common type of a braided stream is the steep slope. A stream of this degraded braided type is Sunshine Creek in Wyoming, part of which is shown on Figure 13.

The writer has not found in the literature any explanation of why the general course of this type of braided channel usually tends to be relatively straight. It is easy to see, why an extremely meandering alighment, in which the stream at the two ends of a bend come close together, is less likely to occur in steep streams than in ones of flatter gradient. When a stream is steep the differences of elevation of the water surface at the two ends of the bend is much greater for a given length of bend than when the gradient is small. Flows across the neck between the ends of the bend, in times of flood, with sufficient slope to produce scouring velocities which will cause a channel to form and cause a cutoff. Such cutoffs will take place when the ends of the bend are much farther apart for a steep stream than for a flat gradient one. Cutoffs will therefore occur in a steep stream of less tortuosity than in one of flat gradient and the steep streams will therefore tend to be straighter. It is the writer's belief that a similar action takes place in the multiple channels of a braided stream, the straighter ones of the many channels, which all flow in the general direction of the valley slope, have steeper slopes than the other multiple channels and therefore tend to scour out and carry the most water. Channels which depart widely from this direct path have much lower velocities, and with the heavy sediment loads usually found in braided channels, have a strong tendency to fill with sediment. There is therefore a strong tendency for the steep streams with the multiple channels characteristic of the steep-slope braided stream to flow in straight courses.

Steep-Slope Braided Streams and the Lacey Wetted Perimeter-Discharge Relation

If the foregoing analysis of the cause of the steep-slope braided streams is sound, since it indicates that the stream width is a function of the stream slope as well as the discharge, it follows that the Lacey relation $P = 2.67Q$ cannot apply generally to natural streams. Since the wetted perimeter P of most natural streams, particularly of wide ones, differs relatively very little from the stream width, if the wetted perimeter is a function of the discharge alone, the channel width must be also very closely a function of the discharge alone. This conflicts with the conclusion drawn in this report that steep slope streams of the same discharge tend to be wider and shallower than streams of the same discharge and of low slope, in other words that the width is at least partly a function of the stream slope, and not of the discharge alone.

Conditions Resulting in Braiding in the Upper Mississippi River

As previously stated, the conditions producing braiding in the upper Mississippi River are unusual. The braiding there is of the overloading type and is indirectly due to glaciers, but in a totally different way from that which usually exists in braided streams near glaciers previously described.

The Upper Mississippi may not be unique, in this respect, however, as similar conditions may exist in the lower part of the Illinois River, from the same causes. To understand the conditions in these streams it is necessary to consider the recent geological history of them.

Both of these streams were greatly affected by the glaciers which covered much of their drainage basins during the Pleistocene time. The glaciers advanced southward over all of Canada and the northern part of the United States, and then melted away, the front of the glacier moving gradually back toward the north, leaving in North America only small remnants of this great glacier in mountainous regions of the West. When the front of the retreating glacier moved northward past the divide between the Mississippi River watersheds and those of the St. Lawrence River and streams leading into Hudson Bay, the melt water could not flow down the St. Lawrence nor reach the Hudson Bay because these stream channels were still blocked by the glacier. Water was then ponded between the front of the glacier and the crest of the divide, forming immense lakes. The levels of these lakes was at a height such that the melting water could flow over low places in the divide into the Mississippi River watershed, down which it flowed to the Gulf. Some of these lakes occupied areas partly covered by the present Great Lakes and water reached the Mississippi from them, by flowing down the channels of the Wabash, Illinois, Rock, Wisconsin, Chippewa, and St. Croix Rivers. West of the present Great Lakes, a very large lake called Lake Agassiz was formed in Minnesota, North Dakota, and Canada, which was larger in area than all of the present lakes combined. This immense lake discharged into the Mississippi River through the channel now occupied by the Minnesota River. The water from this lake combined with the runoff from the drainage basin of Upper Mississippi River and the large lakes formed in the St. Lawrence basin south of the front of the retreating glacier to produce a much larger flow in the Mississippi than would result from the normal watershed of this stream.

Because most of this water came from large lakes, and only a small part from watersheds which could produce sediment, it carried very little sediment. This large flow of relatively clear water from the lakes increased the velocity and shear in the Mississippi over that which resulted from the runoff of its normal drainage area. This greater shear carried away a large quantity of sediment from the stream bed, lowering its level, except at places where there were rock ledges of very resistant material. Upstream from each of these ledges the river was excavated deeper and with a flatter slope than it had before the glacier advanced.

Another important factor in the lowering of the gradient of the Mississippi and Illinois Rivers was the degrading effect of the clear water from the lakes, which existed at their upper ends. The clear water from the lake, starting to flow down the river, within a short distance continuously picked up largely from the stream bottom, as great a load of sediment as the stream was capable of carrying, and transported it on down the stream. That this effect is of great importance is shown by the rapid lowering of the bed of the Colorado River, caused by the release of clear water from Lake Mead, which is formed by the dam. Similar action due to the release of clear water, has caused extensive lowering below many other dams. It is not unlikely that the effect of the discharge of clear water down the Upper Mississippi and Illinois Rivers has caused even more lowering of their beds than was caused by the increased flow in them due to the blocking by the glaciers of the streams which formerly eventually discharged into the ocean through the St. Lawrence and Hudson Bay.

As the glaciers continued to melt and retreated northward however, they finally uncovered the entire channel of the St. Lawrence and the rivers leading to Hudson Bay and the water from the lakes escaped to the sea through them, ceasing to flow down the Mississippi. The channel which was excavated by the great flow of water from these glacial lakes, plus the normal runoff of the river watershed however, was on too flat a slope to transport all the sediment brought in from the Mississippi watershed with the smaller flow which was produced by normal runoff from the Upper Mississippi watershed without the glacial water. A great filling of the stream valley then began, which is still going on. In this filling braided channel with a multiplicity of interlacing channels, islands have been formed as shown in Figure 12 which was taken from the Waukon, Iowa and Wisconsin Quadrangle of the U. S. Geological Survey. The slope of the Mississippi River is still too flat to move all of the sediment brought to it, and filling will continue until the slope is steep enough; probably about that which the river had before the glaciers arrived. A similar condition exists in the lower end of the Illinois River, where much the same action occurred.

The aggrading of this valley goes on very slowly, as it has to fill the entire width of the valley and the annual sediment discharge of the tributaries is small. The most of the sediment deposit probably takes place in the ponds, lakes, and secondary channels, where the conditions are very favorable for deposition, rather than in the main stream. In fact, the main channel may even tend to enlarge, since the tendency is to fill up the side channels and thus force the entire flow into the main channel. When the aggradation has progressed to the stage where the river can carry the entire sediment load brought to it by its tributaries, it seems probable that there will be a main channel largely free from islands, sloughs, lakes, ponds and secondary channels.

From his study of the lower end of the Illinois River, Rubey concluded that this stream was in equilibrium. This may be true of the main channel itself, but, considering the river as a whole, including all of the area in the valley, the author is convinced that the lower Illinois and the middle Mississippi are both aggrading streams.

The condition of interlacing stream channels formed in the Mississippi near Waukon, Iowa which the writer believes should be considered to be braided is not confined to the part of the Mississippi appearing on the Waukon USGS quadrangle. There are other areas however along the Mississippi River between St. Paul, Minn. and St. Louis, Missouri in which stream forms are such that some persons will probably not consider them to resemble braid closely enough to justify calling them braided. In some sections there are larger lakes and fewer channels than are present in the Waukon region. In the lower Illinois River are sections which do not appear to the writer to be sufficiently like braid for it to be considered a braided river. Unfortunately, time was not available to study the Upper Mississippi and Lower Illinois Rivers in detail and it is hoped that further studies of this situation can be made later. It is the writer's view, however, that both of these streams are low slope, aggrading streams of the refilling type, since they are refilling their beds back to their normal pre-glacial levels, and are, of course, overloaded. They may also be classified as "underfit", as these valleys are now occupied by a smaller stream than that which formed their present shapes. From the geological history of these streams it is believed that the refilling process has

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* W. W. Rubey, Geology and Mineral Resources of Hardin and Brussels Quadrangle (in Illinois) U. S. Geological Survey Professional Paper 218, pp.129.

gone on longer in the Illinois River than in the Upper Mississippi, and that the Illinois has approached more nearly to a condition of equilibrium than the Upper Mississippi. It is believed that the upper end of the Wabash River represents a later stage of the same action that now exists in the Mississippi and Illinois since the Wabash was the outlet of a large lake at the site of the west end of the present Lake Erie, and the geological history shows that this drained out through the St. Lawrence at an earlier date than the lakes which temporarily discharged through the Illinois and Upper Mississippi Rivers returned to their original outlets. The present Wabash River (described in Appendix I) therefore, represents a later stage of the progress through which the other two streams are likely to pass in the future.

It is probable that this braided type of refilling river will be formed only under special conditions. One of these is that the valley is relatively narrow. This condition exists in both the portions of the Upper Mississippi and Illinois under consideration. These streams are cut down in the surrounding terrain in a relatively narrow gorge, but wide enough that the river in its present condition does not cover the entire bottom of the gorge. If the valley is very wide with respect to the size of the river, it may be that this form of river will not result. Another requirement probably is that considerable sediment is brought into the valley by small tributaries along the stream. In this way the valley is filled up, although the major stream can transport comparatively little sediment, and is responsible only for part of the filling of the valley.

Another requirement probably is a low slope. A medium or high slope probably would not form the deep, narrow channels characteristic of the Middle Mississippi and Illinois.

In this study the braided rivers investigated were either of relatively steep or of relatively flat slope. Are there braided rivers of moderate slope also? The writer believes that a severely overloaded river of moderate slope would also adopt a braided pattern, at least in some cases, but none of the rivers on which the writer obtained adequate data appear to be of this class. It is probable that parts of the Washita River in Oklahoma and the Cimarron River in Kansas* are of this type, but sufficient time has not been available to establish this.

Classification of Braided Streams

In the foregoing discussion it has been shown that the braided form of a stream may be due to the steep slope of the stream, or due to aggradation resulting from the overloading of the stream with sediment, or to a combination of these two causes. Braided streams may therefore be classified according to these two causes into two main divisions, (1) braiding due to steep slopes, and (2) braiding due to aggradation. These two main divisions may be subdivided, to include combinations of these two causes, as shwon in the following classification:

Braided Streams
- I. Braiding due to steep slope
  - 1. Braiding due to steep slope with degradation
  - 2. Braiding due to steep slope with approximate equilibrium
  - 3. Braiding due to steep slope with aggradation
- II. Braiding due to aggradation
  - 3. Braiding due to steep slope with aggradation
  - 4. Braiding due to moderate slope with aggradation
  - 5. Braiding due to low slope with aggradation

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* Accelerated Channel Erosion in the Cimarron Valley in Southwestern Kansas. T. G. McLaughlin, 1947. Journal of Geology, Vol. LV No. 2, March 1947.

In this classification the first three secondary subdivisions are types of steep-slope streams, and the last three are types of aggrading streams, the two groups overlapping to include the type which is both steep-sloped and aggrading. An example of a Class 1 stream is Sunshine Creek in Wyoming, shown on Figure 13. It is probable that there are many such streams, particularly in a region of considerable relief where active channel erosion is in progress. Class 2 probably includes a large number of the steep slope braided streams where conditions are not changing appreciably. Class 3 is typified by many streams carrying an overload of glacial debris.

It is well known that glaciers move like rivers of ice, and carry down to their ends large quantities of sediment on their surface and imbedded in the ice. Also large quantities of rock debris are moved along the under surface of the ice, by the ice and by streams of water under the ice. Much of this sediment is produced by the very severe abrasive action of the moving glacier ice with its imbedded rocks on its bed and banks. Therefore a glacier can ordinarily transport much larger quantities of sediment than can be moved by the stream of water which is produced by the melting ice, that flows away from the glacier. Unless the stream flowing away from the melting ice is very steep, therefore, the water coming from the melting front of a glacier is overloaded. It continually drops part of its load in its channels, filling the channels, forming bars and islands and raising the level of its bed. As channels fill they build up higher than adjacent areas and the water breaks out into these lower areas and forms a new channel. Such channels are therefore not only braided, but are rapidly shifting. The channels from glaciers are usually also relatively steep, so that braiding in them is partly due to the steep slope.

Many streams of this type are found in the watershed of the North Saskatchewan River and other streams in the Rocky Mountain Parks region of Alberta, Canada. As previously stated, Class 4 probably includes relatively few streams. Class 5 is probably also relatively infrequent, and is typified by parts of the Upper Mississippi between St. Louis, Missouri and St. Paul, Minnesota.

As previously stated, in the steep-slope type of braided stream, where not influenced by non-erodible material, the channel as a whole is relatively straight, steep, wide and shallow, and carries a heavy sediment load. The bottom is relatively flat and composed of sand or coarser material. The interlacing channels frequently shift rapidly and the banks are relatively unstable. Frequently these channels are overloaded with sediment. The interlacing channels are not necessarily separated by islands, but may exist only at low flows, and be in the form of bars of small height which rapidly shift their position and are entirely covered during high flows.

Class 5, the flat-slope, aggrading type of braided stream consists of interlacing channels, with many ponds, sloughs and lakes. The banks are relatively stable and the interlacing channels do not shift rapidly and tend to be deeper and narrower than in the steep-slope types. The smaller channels of this type are likely to be formed of fine sediments, such as silts and clays. As previously mentioned, parts of the Upper Mississippi and possibly of the Lower Illinois Rivers are examples of this class.

It will be seen from this classification that braided streams due to overloading can have any slope, but braiding without aggrading can only occur in steep streams. Braiding in a stream in balance, or in a degrading stream is possible only if the slope is great.

The Engineering Significance of High Slope Braided Streams

From the definition of a braided stream as previously given, it will be seen that this type of stream is distinguished by its appearance, due to its interlacing or anastomosing channels, and covers streams in which the other characteristics are quite different. It is the appearance rather than the nature of the stream that distinguishes them, as they have in common only the one characteristic of multiple channels. This characteristic is a very good one for visual classification, but it is one which seems to have very little other practical importance. From an engineering standpoint the branching channels ordinarily have little, important effect on engineering structures, such as dams, bridges or revetments which are constructed on them, and on the overloaded, low-slope type the engineering works ordinarily do not differ much from other streams except that there may be several small bridges rather than one large one. However, the steep-slope form of braided river, from an engineering standpoint, is important, since it gives rise to quite different forms of engineering structures from those on most other streams. This type of stream is characterized, in addition to its multiple channels, by a steep slope, relatively straight alignment, wide, shallow, flat bottomed channel with high velocity flow and usually with relatively coarse bed material and a high sediment load.

These characteristics give rise to very different forms of bridges, dams and revetment and stream training works than are usually found in other types of streams. For smaller braided streams in the United States, long pile supported bridges are commonly used rather than masonry piers supporting longer steel or concrete spans such as are commonly used on other type streams.

In China a pile type bridge has been used on the Yellow River, which is a very large braided stream, to carry the Peking-Hankow Railroad. It has been in use for over forty years, and is supported on screw piles.

The dams on braided rivers are also commonly confined to long, low head structures of the barrage type. They are now usually constructed with piers with gates between, although originally they were built of loose rock, sometimes with some masonry walls and paving. Although the barrage type with piers and gates is frequently used on other types of rivers, in these other rivers dams are not limited to this type. High dams of large storage capacity are not usually built on high slope braided streams because of the wide, shallow valleys in which these streams usually flow makes high dams on them very expensive because of the great length and the deep foundations usually required, and the high sediment content usually present in the water causes them to fill rapidly with sediment.

The form of bank protection on high slope braided rivers is usually quite different from those used on the deeper, less swift streams. In India and Pakistan, extensive use of dikes or groins for steep-slope braided streams has been developed, largely based on model tests. In this country permeable pile dikes have been extensively used. In this country also for smaller streams "Jacks", usually of steel, have been extensively used. These are formed of units consisting of three straight bars of equal length, all connected at their mid points and extending at right angles to each other, as in the children's toy jacks. None of these three types of revetment except the pile dike is commonly used on low slope streams. For low slope, deep streams, revetments in the shape of a mattress of planks, woven willows, asphalt or concrete blocks are widely used, but only infrequently used on braided, steep-slope rivers. All of these differences of engineering structures are almost entirely due to the characteristics of steep-slope braided rivers rather than to the multiple channels.

Suggested Nomenclature for Braided and Similar Streams

The term braided stream has been so extensively used in scientific literature that it is unlikely that it will be dropped in the near future. The selection of the term to identify one type of stream is obviously because of the resemblance of the form of these streams to braid. This resemblance can never be very close since all streams differ considerably from what is commonly designated as a braid. When applied to streams, therefore, it is not a very exact term because its use depends only on a resemblance. A wide difference of opinion can, therefore, exist in many cases between well-qualified persons on how closely a given stream pattern resembles braid. The writer believes, however, that at the rather elementary state of development of the science of stream forms at the present, it is not desirable to try to depart too widely from the past usage of this term, because further study may show that the proposed changes are undesirable.

Many streams exist which have certain properties in common with streams which have as close a resemblance to braid as is possible for a stream, but do not in their appearance resemble braid. It is the writer's opinion, however, that these streams should not be arbitrarily put in a braided classification but that the braided classification should be confined to those resembling braid.

Author's Suggested Definition of a Braided Stream

The only common characteristic of all streams which in the past have been considered to be braided seems to be that they have patterns of dividing and reuniting channels from which the word braid originated. From the foregoing definitions and from the analysis of the data assembled in this study, the following definition and description of a braided stream has been evolved, the definition being a slight modification of that of Grant, previously given. "A braided stream is characterized by having a number of alluvial channels with bars or islands between meeting and dividing again, and presenting from the air the intertwining effect of a braid". This definition differs from that of Grant in omitting the terms steep, wide and shallow since this study has shown that channels which resemble braids do not necessarily have these properties.

Anastomosing Streams

In reading the geological literature dealing with stream forms, one sometimes finds the term "anastomosing". This term is practically unknown to engineers but is occasionally used by geologists in describing stream patterns. It is usually not defined, but is used as if its meaning was practically the same as braided. The word is derived from the word anastomosis, for which the dictionary definitions are as follows:

"The rejoining of different branches which have arisen from a common trunk, so as to form a network".*

"Union or intercommunication of any system or network of lines, branches, streams or the like".*

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* Webster's New International Dictionary, 2nd Edition, Unabridged.

"A union, interlacing or running together as of two or more arteries, veins or other vessels, whereby their canals have become common and freely intercommunicating" *

These meanings of anastomosis do not apply directly and exactly to stream pattern, but with a little adjustment, they can be expanded to cover the case of streams with little violence to the original meaning of the term.

Based largely on the dictionary definitions given above and a knowledge of existing streams, the writer believes that an anastomosing stream can be defined as: "a watercourse consisting of channels, with or without lakes and ponds, which usually arise from a common trunk and divide, intercommunicate and rejoin as the flow moves downstream". Lakes and ponds have been included in the definition to cover the condition in the Upper Mississippi and Illinois Rivers.

This definition is a broader and more exact one than the definition of braiding, as it does not depend on a similarity on which even experts opinions could widely differ. The writer believes that it includes most, if not all, of the braided streams with the five subdivisions previously mentioned. It also includes many sections of the Upper Mississippi and Lower Illinois which do not sufficiently resemble braid to be classified as braided rivers. It would also include such streams as Cooper's Creek** in Australia, the plain

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* New Standard Dictionary - Funk and Wagnall, 1957.

** Discussion by W. H. R. Nimms of Paper on the Importance of Fluvial Morphology in Hydraulic Engineering published in ASCE Journal of the Hydraulics Division No. HYI, February 1956, Paper 881, pp. 38-41.

sections of the Kosi River*** in India and the lower end of the Lower Colorado River in Mexico.****

These last three sections of river are all what may be called land deltas, and are formed where a relatively steep channel reaches a flatter area where the stream has a lesser slope and is unable to continue to carry its load. It drops a part of the load and breaks up into multiple channels forming a sort of delta. It differs from the ordinary form of delta in that the streams do not flow into a lake or other body of quiet water, but the channels rejoin and reform a continuation of the original stream. This land delta form could be a subdivision of non-braiding anastomosing stream.

It is possible that, as the science develops and the term anastomosing stream, as previously defined, becomes more familiar, it would come into general use and to a large extent replace the term braided stream. It also might be adopted as one of the major divisions of the whole field of stream patterns, with braided streams included as one main subdivision and non-braided forms the other main subdivision under it.

Multiple Channel Streams

Because of the fact that the word multiple is more widely used than the word anastomosing, and its meaning is clearer to engineers, since it is in current use among them, the writer believes that a better nomenclature of braided and similar streams would be secured if the streams in that class

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*** C. C. Inglis. Denudation, Erosion and Floods, Central Board of Irrigation India (Technical) 1944, pp. 136-141.
Rapid Westerly Movement of the Kosi River. Central Board of Irrigation India (Technical) 1942 pp. 7, 8.

**** W. Kelly, 1925. The Colorado River Problem. Trans, ASCE Vol. 88, p. 312.

be called Multiple Channel Streams rather than Anastomosing Streams, as discussed in the previous section of this report.

Webster's New International Dictionary, 1935, defines multiple as "containing more than once, or more than one; consisting of more than one, manifold". The term multiple channels could therefore be used in place of both the terms braided and anastomosing as previously discussed.

A multiple channel stream can be defined as "a stream in which the flow, for a considerable part of its length, is divided up between two or more channels or paths". This definition is very broad and includes the various types of braided and anastomosing streams previously discussed. Its scope is shown on Figure 14. It can therefore be used to cover a large class of streams, which constitute an appreciable part of streams as a whole. For example, all streams could be divided into two classes, (1) single channel streams, and (2) multiple channel streams. Multiple channel streams cover the land delta forms previously mentioned and can also cover the channels forming a delta in a body of quiet water. There is considerable doubt whether this ordinary form of delta channels should be included in anastomosing streams since the channels in this case do not rejoin. Isolated cases can be found where this definition would cover streams with many islands which were of non-erodible material such as the Thousand Island section of the St. Lawrence River, but the greater part of this class is probably found in readily erodible alluvial formations.

The writer believes that this classification is the best that has been developed, and should be used until a better one is found.

THE FORM OF AN ALLUVIAL STREAM ENTERING A LAKE OR OCEAN

The writer some years ago was puzzled by the fact that the bottom of the Mississippi River, for over a hundred miles upstream from the point near its mouth where it subdivides into several channels, averages about sixty feet below the level of the water surface of the Gulf of Mexico, into which it discharges. He wondered what the reason for this great depth was. He also wondered why small streams tributary to the Great Lakes, which for most of their length were so shallow that at low water they were scarcely navigable in a canoe, formed at their mouths a harbor of considerable depth, and gave rise to great ports such as Chicago, Cleveland and numerous others.

From time to time the writer thought about this phenomenon and has devised what he believes is a satisfactory explanation. As this condition is a common form of the channel of natural streams flowing in erodible material, it comes within the scope of this report on stream channel forms. As will be pointed out, the action which causes this condition may be of considerable importance in the design of a levied floodway discharging into a lake, and considerable trouble will probably be avoided if this action is adequately considered when such a floodway is designed.

It is believed that a deep channel will always form at the mouth of a stream entering a lake if the following conditions are present: (1) the material in the stream and lake bed is readily erodible, (2) the lake level is comparatively constant, (3) the stream is subject to occasional high flows, and (4) the stream does not carry a high concentration of sediment load. The cause of the action which produces this condition can be easily understood by visualizing what would take place at the end of an artificial channel discharging into a lake under the four conditions named above, if the channel was not constructed with a bottom considerably below lake level where it joined the lake. For example, suppose the artificial channel was built as shown in Fig. 15-A, with its bottom A-B reaching the lake at a depth below lake level equal to the depth of low water flow in the stream. Immediately after completion, at low water the surface profile would occupy the position C-D, but a high water flow would produce a surface such as that at E-F, with a drop down curve in the surface profile adjacent to the lake. Such a condition would produce high velocities that would cause erosion of the sides and bed of the channel near the lake and the lake bed for some distance out from the end of the channel. This scouring of the channel bottom will cause the flood surface profile to be lowered and produce more scour farther and farther upstream. The flood flow will therefore cause a deepening of the channel and lake adjacent to the channel, as represented by the crosshatched area JHK in Fig. 15-B, and would thus provide a deep water "harbor". In Figs. 15-A and 15-B the vertical scale is greatly exaggerated and the deep water extends much further up the stream and into the lake than the figures indicate if the scale exaggeration is ignored. In times of low flow the harbor will tend to fill up with sediment, and on streams carrying heavy sediment load, the harbor may be entirely filled before another flood comes to scour it out. If the lake level should rise rapidly as the flood enters it, the drop down curve might be too small to produce sufficient scour to produce a harbor of considerable size.

Most natural streams in erodible materials tend to approach a condition of equilibrium. Under these conditions the movement of sediment past any cross-section of the stream over any period of a considerable number of years tends to be the same, and equal to the sediment load brought down by the stream from its watershed. If the bottom of the stream was not deepened near the lake, there would be severe scour at that point and more sediment would be moved away than came down, giving rise to a net scour and deepening of the bed. Hence, usually the bed tends to deepen until, over a considerable period of time, the amount of sediment moved at all points in this deepened section will equal the sediment load carried by the stream in this period. This section will tend to fill in times of low water, and the deposited sediment will scour out in times of high water.

In at least one case this action has proved important in the maintenance of a levied floodway leading into a lake. Such floodways are usually constructed by building two roughly parallel levees, to confine the water, by excavating earth from borrow pits adjacent to and between the two levees. The borrow pits are usually placed between the levees rather than outside of them, since in the former procedure the excavated borrow pit provides additional discharge capacity for the floodway with little, if any, added expense. The floodway under discussion followed this procedure, and the scour in the borrow pit near the lake, due to the high velocities produced by the drop down curve as shown in Fig. 15-a, was so great that the channel bottom and sides were scoured to such an extent that the safety of the levee near the lake was seriously threatened. In the design of levied floodways leading into a lake, the possibility of such action should be investigated, and guarded against if necessary. In long floodways the borrow pits could be placed inside the levees, to take advantage of their carrying capacity, down to the point where the too severe scour will eventually reach, as the end of the channel enlarges.

Below this point the levees should be built from outside borrow pits and the inside borrow pits could be connected to a pilot channel, excavated with discontinuous spoil banks, down the middle of the floodway. As these channels enlarged they would draw the water away from the levee and tend to prevent the drop at the end of the channel from endangering the levees. If the floodway is very wide, it may be desirable to construct pilot channels between th levees on each side of the floodway, far enough out from the levees to eliminate the possibility that scour from them would endanger the levee. The possibility should be investigated to determine the probability that natural stream channels or other depressions in the floodway near the lake might cause scour which would progress upstream and endanger the levees. If the floodway is short and has a control structure at its upper end, care should be exercised so that the scour in the borrow pit or pilot channel does not extend far enough upstream to endanger this structure. If such scour will take place the control structure must be designed to be stable in spite of this scour.

QUANTITATIVE REPRESENTATION OF CHANNEL PLAN FORMS

It has been said that no subject has been perfected to the extent where it can be called a science until it can be discussed in quantitative terms. This is probably an overstatement, since some fields do not lend themselves to quantitative measurements. It is true, however, that in any field where quantitative relations are possible, the best results cannot be secured if they are neglected.

An attempt should therefore be made to express the plan form of stream channels in quantitative form, so that the forms of the various streams may be compared on this basis, rather than by the use of loose descriptive terms such as meandering and braided. In the following paragraphs an approach to this problem is suggested.

One of the simplest dimensions of a stream channel form is the width of the channel. Obviously, a natural channel does not have a uniform width, but rather a varying width. The width can therefore be expressed as an average width, found by dividing the plan area of the stretch under consideration by its length. A more accurate description of its width will be given, however, by a frequency diagram of stream widths. This can perhaps best be presented by a curve showing the percent of the stream length in which the width is less (or more) than various values.

Another property of stream channel forms is curvature. Some streams have a great deal of curvature and some very little. One of the dimensions of curvature is the radius of the bends. However, stream bends do not have a constant radius of curvature, but a continually varying one. This variation for any stretch of the river may be expressed by a frequency diagram showing the proportion of the length of the stream which has radii of curvature greater (or less) than various values, or in other words, a frequency curve of the various radii of curvature.

The width of a stream and the radii of curvature are dimensional quantities. For many purposes the channel form of the stream can probably be best expressed in non-dimensional terms. Such a non-dimensional basis would be obtained by dividing the radii of curvature values of the frequency curve of stream curvature radii by the mean or median width of the stream. Perhaps a better way would be to determine the ratio of the radius of curvature to the stream width at a large number of equally spaced points along the stream and construct a frequency curve of these values.

Another factor in a stream channel form is the angle the stream turns in one direction (for example, clockwise) before it reverses direction and flows in the other direction (counter clockwise). A frequency curve in terms of the percentage of the total number of these stretches between reversals for which the angles of deflection were greater (or less) than various values, could be constructed. These angles could be expressed in degrees, or radians, and would be non-dimensional.

It is probable that the length of the stream between points of reversal from clockwise to counter-clockwise and vice versa is a factor in representing the shape of the river, and a frequency curve of these distances could be developed. To make these lengths non-dimensional, they could be divided by the mean or median stream width.

In the studies covered by this report the slope value used is the longitudinal slope of the river or the ratio of the fall in the section of river under consideration to the length of the stream in that section, measured along the main channel or talweg. In the case of meandering streams, the general slope of the valley is considerably steeper than the slope of the stream. As previously discussed, the best index of the tortuosity of the stream appears to be the ratio of the stream length to the length of the valley covered by that length of stream. The ratio of valley slope to the stream slope will be the same as the ratio of the stream length to the valley length. It will probably be found that in describing quantitatively the form of stream, this ratio will be found to be convenient, and study of these relations should therefore be made. Thought should be given to the possibility that other and better methods of expressing channel form than those discussed above might be devised. It seems probable that there are quantitative relations between the factors influencing stream form previously discussed and the values of these ratios, which could be developed. It is believed that when quantitative data on shape of stream channels is developed, it will lead to a much more exact classification of stream types and a much better understanding of their action.

It is probable that the above suggested quantitative representations of stream channel form cannot be applied to braided channels, but if so, the fact that they cannot be used for all forms of stream does not mean that they could not be useful in some cases. If braided streams cannot be handled by the methods previously suggested, further study should be given to the problem to see if some other method could be devised which would handle them. For example, a plot could be made of the variation of the number of channels in cross sections at any place along the stream by plotting the number of channels in the cross section against the distance along the stream from some initial point. Another way might be a plot of the ratio of the total width of the bars and islands to the total channel width at the various points along the channel.

SUGGESTED FURTHER STUDIES

This report may be regarded as a progress report, as it does not represent a completed study. The following studies are suggested in this field which seem most likely to increase our knowledge of the plan forms of stream channels. Many of these have been previously suggested in this paper, but to make this statement complete, are repeated herein.

Additional data should be collected on the slope, discharge and material size of natural streams, particularly those with banks and beds of gravel and coarser material, in order that the relations between the factors affecting the form for these material sizes can be more closely determined. Data of a quantitative nature on material sizes should be collected, in order that more accurate quantitative relations involving size may be obtained.

These data should be analyzed in an attempt to find a general equation for streams in erodible material which would have one constant for a given stream pattern regardless of the size of sedimentary material involved, and a general equation including slope, discharge, material size and stream form all expressed quantitatively.

Data should be collected on the relation of valley slope to stream slope or the tortuosity ratios of meandering and other streams in order that their form may be expressed in quantitative terms. The other methods of quantitatively expressing the form of rivers, as discussed previously in this paper, should be studied, in order that the best methods may be determined, and that the laws governing the form may be developed in the best quantitative terms. An attempt should then be made to relate these quantitative expressions of shape to the other variables such as slope, discharge and material size. Since tortuosity ratio is the easiest method of expressing stream pattern in quantitative terms, at least for the relatively sinuous streams, perhaps one of the first studies should be the relation of this ratio to the discharge, slope and material size for meandering streams.

A comparison of discharge to valley slope of meandering streams should be made, similar to the one made herein comparing discharge and stream channel slope, to prove or disprove the author's contention previously mentioned that the streams do not lengthen their channels to reduce their slope to a value which will produce relatively stable channels.

A study should be made of the various attempts* to develop quantitatively the causes of meandering streams, as given in the literature on the subject, and to see to what extent they agree with the relations developed so far in this study. Since this study does not disclose any satisfactory relations or rational reason for the formation of meanders, an attempt should be made to develop one.

A comparison should be made of the relations developed by Lacey, Blench, and Leopold and Maddock, to explore the interrelation of the data, ideas and conclusions given in their reports to those developed by the method of approach used herein.

Data should be collected on the properties of stable channels used for irrigation and other purposes, to study the relation of such channels to the patterns of natural channels, as developed in this study.

This study should be extended to some of the more unusual types of streams, such as the arroyo type so common in the western portion of this country. Other types of streams which should be studied are misfit or underfit streams, deltas, tidal streams, alluvial cones, and the effect of confinement by non-erodible material in the valley walls of a meandering stream. Estuaries should also be included. An attempt should be made to develop a systematic classification of all streams. A detailed study should be made of the Red River of the North and its tributaries to see if an explanation of the form of this unusual stream can be found. As many of the tributaries of this stream

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* Uber die Urschen der Maanderbildung der Flusse und des Baer'schen Geselze Albert Einstein (the Senior Einstein) - Die Naturwissenschaften Vol. 14 1926 pp. 223-225 (abstracted by Nemenyi Bull. Geological Society of America June 1952 pp. 613-614) Republished in Ideas and Opinions - Albert Einstein 1954 or 1955 Crown Publishers Inc.,
Geomorphic History of the Kickapoo Region, Wisconsin R. E. Bates 1939. Bull. Geological Society of America Vol. 50. pp. 844-850.
On the Origin of River Meanders, Werner, P. W. 1951 Trans. AGU Vol. 32 No. 6 Dec. 1951 p. 898.

have a form similar to that of the main stream, they should therefore be included in the study. The Souris River of Montana and the Tisza River in Hungary, which are very tortuous and probably were formed in an old lake bed, should also be examined.

A study should be made of the lower end of the Illinois River and the Upper Mississippi to determine the extent of braiding in these two streams and the conditions which result in this braiding. Also the sequence of steps through which they (together with the Wabash River) have passed or may be expected to pass in the future.

Included in this study should be an examination of the effect, if any, on the present form of the Upper Mississippi, Illinois and Wabash Rivers of the earth tilt which is still going on in this region.

DATA ON STREAM CHANNEL FORMS

SLOPE

	Name	Location	Stretch	Ft/Mile	Fall / Length	Length / Fall	Average Discharge in Sec. Ft.	Material	Pattern	Value of K	Remarks
1.	Lower Mississippi Model	Model	Plate 4	14.7	.0028	359.2	0.15	Sand	Meandering	.00174	
2.	" "	"	Plate 15	17.6	.0034	296.6	0.10	"	"	.00192	
3.	Lower Mississippi		Cairo-Arkansas City	0.40	.000076	13,200.0	443,000	"	"	.00194	
4.	"		Arkansas City - Red River Ldg.	0.28	.000053	18,857.6	537,000	"	"	.00141	
5.	Rapid Creek	Iowa	Near Iowa City, Ia.	3.64	.00069	1,450.5	13.0	"	"	.00131	
6.	Clear Creek	"	" " " "	3.75	.00071	1,408.0	70.0	"	"	.00205	
7.	Old Man Creek	"	" " " "	3.01	.00057	1,754.2	105.0	"	"	.00132	
8.	Maquoketa River	"	Just Above Mouth	2.28	.00043	2,315.8	921	"	"	.00237	
9.	Raccoon River	"	Adel Dam - Commerce	2.1	.00040	2,514.3	1,000	"	"	.00225	Contains some small gravel
10.	Iowa River	"	Below Iowa City	1.16	.00033	3,000.0	1,476	"	"	.00205	Contains some small gravel
11.	Cedar River	"	The 20 miles below Moscow, Iowa	1.55	.00029	3,406.5	3,020	"	"	.00215	
12.	Des Moines River	"	Des Moines - Red Rock	1.4	.000265	3,771.4	3,480	"	"	.0020	Contains some small gravel
13.	Milk River	Montana	Havre - Vandalia	1.12	.00021	4,714.3	712	"	"	.00109	
14.	Big Black River	Mississippi	Near Pickens, Miss.	.99	.000188	5,333.3	1,966	"	"	.00125	
15.	" " "	"	Near Bovinda	1.40	.000265	3,771.4	3,677	"	"	.00207	
16.	Minnesota River	Minnesota	68 miles below - Mankato	0.76	.00014	6,947.4	2,160	"	"	.00095	
17.	Missouri River	Montana	Below Ft. Peck Dam	0.925	.000175	5,708.1	7,519	"	"	.000165	Contains some small gravel
18.	Wabash River	Illinois	Near Mt. Carmel	0.76	.00014	6,947.4	25,440	"	"	.00183	
19.	Middle Mississippi	Missouri	St. Louis - Chester	0.52	.000098	10,153.8	171,000	"	"	.00198	
20.	" "	"	Chester - Cape Giradeau	0.57	.000108	9,263.2	172,000	"	"	.00215	
21.	Ohio River	-	Louisville to Evansville	0.28	.000053	18,857.1	111,300	"	"	.00192	
22.	Verdigris River	Oklahoma	Miles 23 to 43 above Mouth	0.73	.000138	7,232.9	4,170	"	"	.001105	Some cohesive material in bed
23.	Assiniboine River	Manitoba, Canada	40 to 75 miles above Mouth	1.05	.00020	5,028.6	1,650	"	"	.00128	
24.	Buyuk Menderes	Turkey	Below Aydin for 80 kilometers	1.05	.00020	5,028.6	3,000	"	"	.00148	
25.	Platte River	Nebraska	85 miles below junction of N & S Platte	6.5	.00123	812.3	4,850	"	Braiding	.0102	
26.	Niobrara	Nebraska	Verdel, Nebraska	6.7	.00127	788.1	1,595	"	"	.008	
27.	"	"	Spencer, Nebraska	7.2	.00136	733.3	1,280	"	"	.00815	
28.	"	"	Meadeville, Nebr.	8.8	.00157	636.1	1,048	"	"	.00999	
29.	North Platte River	"	Just above mouth	6.32	.0012	835.4	2,200	"	"	.0084	
30.	South Platte River	"	" " "	7.68	.00145	687.5	2,620	"	"	.0140	
31.	Cherry Creek	Colorado	3.5 miles above Melvin, Colo.	22.6	.00427	234.6	22.6	"	"	.00935	
32.	Colorado River	-	Model	37.0	.00701	142.7	2.08	"	"	.0084	
33.	" "	-	Model	42.0	.00795	125.7	2.08	"	"	.0095	
34.	" "	-	"	29.0	.00548	182.1	5.94	"	"	.0091	
35.	" "	-	"	26.4	.00518	200.0	2.08	"	"	.0062	
36.	" "	-	"	31.7	.00600	166.6	2.08	"	"	.0072	
37.	" "	-	"	21.5	.00407	245.6	3.96	"	"	.00572	
38.	" "	-	"	21.5	.00407	245.6	1.87	"	"	.00470	
39.	Loup River	Nebraska	Near Columbus, Nebr.	4.00	.00076	1,320.0	295.2	"	"	.0056	
40.	North Loup River	"	Above St. Paul, Nebr.	5.25	.00099	1,005.7	873	"	"	.0054	
41.	Middle Loup River	"	" " " "	5.48	.00104	963.5	1,162	"	Between braided & meandering	.00605	
42.	Republican River	"	Below Bloomington, Nebr.	3.71	.00070	1,423.2	730	"	Between highly braided & meandering	.00364	
43.	" "	Kansas	Below Clay Center, Ks.	2.80	.00053	1,885.7	1,114	"	"	.00307	
44.	Red River	Texas-Okla.	Dennison - Reserve	1.63	.00031	3,239.3	5,462	"	"	.00267	

DATA ON STREAM CHANNEL FORMS

	Name	Location	Stretch	SLOPE Ft/Mile	Fall / Length	Length / Fall	Average Discharge in Sec. Ft.	Material	Pattern	Value of K	Remarks
45.	South Canadian	Oklahoma	Mouth to Mouth of N. Canadian	1.94	.000368	2,721.6	6,452	Sand	Between highly braided & Meandering	.0033	
46.	Arkansas River	Arkansas	Mouth to Little Rock	0.70	.000132	7,542.8	43,700	"	"	.00191	
47.	" "	"	Little Rock to Dardenelle	0.70	.000132	7,542.8	42,880	"	"	.0019	
48.	" "	Arkansas & Oklahoma	Mouth of Grand River - Dardenelle	0.95	.00018	5,557.9	32,000	"	"	.0024	
49.	" "	Oklahoma	Tulsa to Mouth of Grand River	2.07	.00039	2,550.7	7,714	"	"	.04367	
50.	Colorado River	California & Arizona	Palo Verde Valley	1.57	.00030	3,363.1	17,900	"	"	.00347	
51.	Colorado River	California & Arizona	Near Needles	1.67	.00032	3,161.7	17,900	"	"	.0037	
52.	Missouri River	Montana	Ft. Peck to Wolf Pt. Mont.	1.054	0.0002	5,009.5	7,240	"	Meandering	.00184	
53.	" "	Montana & No. Dakota	Wolf Pt., Montana to Williston, N.D.	.860	.000164	6,082.9	13,440	"	"	.00177	
54.	" "	North Dakota	Williston to Bismarck, N. D.	.778	.000147	6,786.6	19,960	"	Between braided & meandering	.00174	
55.	" "	N. & S. Dakota	Bismarck, N.D. to Mobridge, S. D.	.718	.000136	7,353.8	20,980	"	"	.00164	
56.	" "	South Dakota	Mobridge to Pierre, S. D.	.872	.000165	6,046.0	21,915	"	"	.002	
57.	" "	" "	Pierre to Yankton, S.D.	.888	.000168	5,945.9	23,880	"	"	.0021	
58.	" "	S. Dakota & Iowa	S. Dakota & Iowa Yankton to Sioux City	1.023	.000194	5,161.3	27,220	"	"	.00248	
59.	" "	Iowa & Nebraska	Sioux City, Iowa to Omaha, Nebraska	.878	.000166	6,013.7	28,370	"	"	.00216	
60.	" "	Nebraska	Omaha to Nebraska City	1.060	.000205	4,981.1	30,210	"	"	.0027	
61.	" "	Nebraska & Missouri	Nebraska City to St. Joseph, Mo.	.928	.000176	5,689.7	34,440	"	"	.00238	
62.	" "	Missouri	St. Joseph to Kansas City	.915	.000173	5,770.5	40,370	"	"	.00245	
63.	" "	"	KC to Waverly, Mo.	.863	.000163	6,118.2	44,330	"	"	.00236	
64.	" "	"	Waverly to Boonville, Mo.	.802	.000152	6,583.5	50,060	"	"	.00227	
65.	" "	"	Boonville to Herman, Mo.	.860	.000163	6,139.5	63,180	"	"	.00257	
66.	Yangtze River	China	Hankow to Kiukiang	.123	.0000233	42,926.8	900,000	"	Braided	.000718	Some cohesive material
67.	" "	"	Kiukiang to Wuhiu	.105	.00002	50,285.7	900,000	"	"	.000718	" " "
68.	Fall River	Colorado	Meandering Section - Upper End	16.0	.00304	330.0	39	Gravel	Highly Meandering	.00204	
69.	" "	"	Horse Shoe Park - Lower End	4.27	.00081	1,236.5	39	"	"	.00341	
70.	Nooksack River	Washington	From 0 to 6.57 miles	-	-	-	-			-	Subject to tidal influence
71.	" "	"	From 6.57 to 14 "	2.4	.00045	2,200.0	3,300	Fine Material	Comparatively Straight	.00525	
72.	" "	"	From 14 to 15.8	3.9	.00074	1,353.8	3,300	"		.0071	
73.	" "	"	From 15.8 to 18.5	3.7	.00070	1,427.0	3,200	Sand	Moderately Tortuous	.0094	
74.	" "	"	From 18.5 to 20.5	5.0	.00095	1,056.0	3,200	"	"	.0124	
75.	" "	"	From 20.5 to 23.2	6.5	.00123	812.3	3,100	Sand & Gravel	Meandering	.0131	
76.	" "	"	From 23.2 to 35.7	9.3	.00176	567.7	3,100	Gravel & Cobble	Braided	.00418	
77.	Willamette River,	Oregon	Salem (near)	1.8	.000341	2,933.3	22,370	Gravel	Meandering	.00308	
78.	" "	"	Albany (near)	1.5	.000284	3,520.0	13,790	"	"	.001285	
79.	Wabash River	Indiana	Lafayette (near)	0.76	.000145	6,947.4	6,170	Sand	Between braided & meandering	.001287	
80.	" "	Indiana	Covington (near)	"	"	"	6,229	"	"	.001407	
81.	" "	"	Montezuma (near)	"	"	"	8,894	"	"	.001438	
82.	" "	"	Terre Haute (near)	"	"	"	9,723	"	"	.001444	

DATA ON STREAM CHANNEL FORMS

SLOPE

	Name	Location	Stretch	Ft/Mile	Fall / Length	Length / Fall	Average Discharge in Sec. Ft.	Material	Pattern	Value of K	Remarks
83.	Wabash River	Indiana	Riverton (near)	0.76	.000145	6,947.4	9,894	Sand	Between braided & meandering	.001451	
84.	Wabash River	"	Near Vincennes	0.76	.000145	6,947.4	10,510	Gravel	Comparatively Straight	.00145	
85.	Miami River	Ohio	Below Sydney	6.50	.00123	812.3	481	Sand & Gravel	"	.00575	
86.	" "	"	Taylorville - Dayton	2.64	.00050	2,000	950	"	"	.002775	
87.	" "	"	From Dayton to Miamisburg	2.64	.00050	2,000	2,202	"	"	.00342	
88.	" "	"	Near Hamilton	3.70	.00070	1,427.0	3,332	"	"	.001682	
89.	Mad River	"	Above Mouth for 99 miles	6.68	.00126	790.4	628	"	"	.0063	
90.	Stillwater River	"	Above Mouth	4.20	.00080	1,257.1	554	"	"	.00368	
91.	Tennessee River	Tennessee	Above Mouth	0.36	.000068	14,666.7	64,000	"	"	.00108	
92.	Colorado River	Colorado	Below Grand Junction	5.9	.00112	894.9	6,900	Sand, Gravel & Cobble	Braided	.00102	
93.	Ohio River	Pennsylvania & West Va.	Pittsburg to Wheeling	0.777	.000147	6,795.4	31,820	Sand & Gravel	Meandering	.00196	
94.	" "	W. Virginia	Wheeling to Huntington	0.587	.000111	8,994.9	54,000	"	"	.00169	
95.	" "	W. Virginia & Kentucky	Huntington to Louisville	0.352	.0000666	15,000.0	95,000	"	"	.001164	
96.	" "	Kentucky & Indiana	Louisville to Evansville	0.266	.0000504	19,849.6	111,300	"	"	.00207	
97.	" "	Indiana	Below Evansville	-	-	-	-			-	
98.	Yellowstone River	Montana	Near Billings	8.2	.00155	643.9	6,496	Sand, Gravel & Cobble	"	.01395	
99.	" "	"	Buffalo Rapids	4.04	.00076	1,306.9	10,700	"	"	.00866	
100.	Gunnison River	Colorado	Below Gunnison	17.1	.00324	308.8	847		Not Known	.0175	
101.	Big Thompson	"	Below Estes Park	35.6	.00675	148.3	131	"	Meandering	.0228	
102.	Susquehanna River	Penn.	Wilkes Barre	1.64	.00031	3,219.5	13,440	Sand & Gravel	Comparatively Straight	.00334	
103.	Twin Creek	Ohio	Above Mouth	6.90	.00130	765.2	265	"	"	.00525	
104.	Miami River	Ohio	Miamisburg - 25 mi. below Hamilton	3.70	.00070	1,427	3,332	"	"	.005376	
105.	Scioto River	"	Above Dublin, Ohio	7.5	.00142	7,040	760		Not Known	.000745	
106.	" "	"	Near Columbus, Ohio	1.65	.000312	3,200	1,330	"	Comparatively Straight	.00189	
107.	" "	"	Near Circleville,"	0.93	.000176	5,677.4	2,168		Not Known	.00122	
108.	" "	"	Near Chillicothe,"	1.90	.000360	2,778.9	3,345		Not Known	.00154	
109.	" "	"	Near Higby, Ohio	1.90	.000360	2,778.9	4,218		" "	.00164	
110.	Cowlitz River	Washington	Above Mossy Rock	15.2	.00286	347.4	5,311		" "	.0137	
111.	Susquehanna River	Pennsylvania	Near Danville, Pa.	1.69	.000321	3,124.3	15,220		" "	.00356	
112.	" "	"	Near Towanda, Pa.	2.70	.000521	1,955.5	10,310		" "	.0052	
113.	Juniata River	"	Near Mouth	2.81	.000532	1,879	4,305		" "	.00431	
114.	Susquehanna River	Pennsylvania	Near Williamsport	2.31	.000438	2,285.7	8,808		" "	.00425	
115.	Nile River	Egypt	Aswan to Roda	0.41	.000078	12,878	90,200	Sand	Braided	.00135	Banks clay, bed sand
116.	Yellow River	China	134 mi below R.R. Ry. Bridge	0.94	.000178	5,617	42,800	Very fine sand	Braided	.00256	
117.	" "	"	84 mi. above Tsinan Shantung	0.58	.000111	9,103.4	55,000	" " "	Not Known	.00170	
118.	Upper Mississippi	Minnesota	St. Paul - Redwing, Minn.	0.379	.000072	13,931.4	11,410	Sand	Braided	.00075	
119.	" "	Minn - Wis.	Winona, Minn - LaCrosse, Wis.	0.459	.000087	11,503.3	25,780	"	"	.00110	
120.	" "	Wis. - Iowa	LaCrosse, Wis - Lansing, Iowa	0.3570	.000068	14,790	25,730	"	"	.00086	
121.	" "	Iowa - Wis.	Lansing, Iowa - Prairie du Chien, Wisconsin	0.257	.000049	20,544.7	31,520	"	"	.00065	

DATA ON STREAM CHANNEL FORMS

	Name	Location	Stretch	SLOPE Ft/Mile	SLOPE Fall / Length	SLOPE Length / Fall	Average Discharge in Sec. Ft.	Material	Pattern	Value of K	Remarks
122.	Upper Mississippi	Wis. - Iowa	Prairie du Chien, Wis.-Dubuque, Ia.	0.346	.000066	15,260.1	40,160	Sand	Braided	.00093	
123.	" "	Iowa	Dubuque, Iowa - Clinton, Iowa	0.293	.000056	18,020.5	56,670	"	"	.000864	
124.	" "	"	Clinton, Iowa - LeClaire, Iowa	0.228	.000043	23,157.9	56,670	"	"	.000663	
125.	" "	"	Davenport to Muscatine, Iowa	0.337	.000064	15,667.7	63,470	"	"	.00101	
126.	" "	Illinois	Warsaw to Quincy, Illinois	0.479	.000091	11,022.9	61,150	"	"	.00143	
127.	" "	Illinois-Mo.	Quincy, Ill - Hannibal, Mo.	0.447	.000085	11,812.1	61,770	"	"	.00134	
128.	" "	Missouri	Hannibal to Louisiana	0.437	.000082	12,082.4	61,770	"	"	.00129	
129.	" "	Mo.-Illinois	Louisiana, Mo. - Grafton, Ill.	0.455	.000086	11,604.4	63,440	"	"	.00136	
130.	South Canadian	New Mexico	Below Conchas Reservoir	6.06	.00115	871.3	276	Sand, gravel & boulders	Canyon Section	.00458	
131.	North Canadian	Oklahoma	Wetumka Mile 185.3 to 141.8	2.54	.000476	2,078.7	222	Sand	Braided	.00255	
132.	Cimarron	Oklahoma	Perkins, Mile 87 to 46	2.03	.000385	2,601.0	1,149	"	"	.00224	
133.	Deep Fork River	"	Beggs, Mile 85.2 to Mile 159	1.87	.000354	2,823.5	966	Not Known	Meandering	.00196	
134.	Papaloapan River	Mexico	Below Coosamaloapan	0.084	.0000159	62,857.1	14,200	" "	"	.00017	
135.	Smoky Hill River	Kansas	Ellsworth to Marquette	3.22	.00061	1,639.8	252	Sand	"	.00243	
136.	" " "	"	Marquette to Salina	2.36	.000447	2,237.3	252	"	"	.00178	
137.	Big Blue River	"	Randolph to Cleburne	1.88	.000355	2,808.5	1,688	"	"	.00228	
138.	Republican River	"	Clay Center to Junction City	2.38	.000452	2,218.5	1,195	Sand bed	Both braided & meandering	.00265	
139.	Kansas River	"	Mouth to Mile 90	1.73	.000328	3,052.0	6,868	Sand	Between braided & meandering	.00299	
140.	Red River of North	Minnesota - North Dakota	Near Fargo, N. D.	0.67	.000127	7,880.6	462	Sand	Highly Meandering	.000588	Banks of cohesive material. Some fine sand in bed.
141.	" " " "	" "	Near Grand Forks, N. D.	0.258	.0000489	20,465.1	2,198	"	"	.000342	" " " "
142.	Illinois River	Illinois	Lower 120 miles	0.172	.0000326	30,697.7	15,000	"	Braided	.000324	
143.	St. Clair River	Michigan	Port Huron - Algonac	0.121	.000023	43,636.4	189,000	"	"	.000480	Some cohesive material
144.	Saline River	Kansas	Downstream from Sylvan Grove	3.20	.000607	1,650.0	156	"	Meandering	.00214	

Appendix I

MORE DETAILED DATA ON CERTAIN RIVERS

In these studies a number of rivers were encountered which were either unusual in some way or had a special significance in regard to stream forms. As their characteristics cannot adequately be given in the brief notes of the tabular data, there are described in the following paragraphs in terms of the facts regarding them which seem to the writer to be most significant from the standpoint of stream forms.

Buyuk Menderes (Meander) River

This stream, which in ancient times was called the Meander, is the stream from which the term "meander" came. It has also been variously spelled Meanderes, Maeander, Maiandros, and Menderez, but is now known as the Buyuk Menderes. It is located in southwestern Turkey and discharges into the Mediterranean Sea about 265 miles southeast of Istanbul (Constantinople). It has a valley about 115 miles long and 6 miles wide. The longitudinal slope is comparatively small, and over much of its length it is very meandering. See Fig. 5.

This stream has recently been studied for the Turkish Government by the engineering firm of Knappen, Tippetts, Abbett, and McCarthy of New York. The following information has been supplied by the late Mr. Charles F. Travis, who was in charge of this study.

"The Menderes is a very sinuous stream. It severely erodes its banks and has formed and still forms many cut-offs. The banks of the stream are erodible but it is believed that the term "silty-sand" would better designate the type of soil rather than "sand"."

"Having been here only from 1949 to date (1955), it is not possible to determine from observation whether or not the bends of Menderes move uniformly downstream. From observation of past occurrences, we do not believe this to be the case. There are many old ox bows and silted up channels which are now under cultivation, but there is no presently visible evidence to indicate that these bends were formed by uniform movement downstream. The evidence is that the river has made cut-offs of considerable length and that these cut-offs eventually attained about the same length as that of the previous channel. For example, there is positive evidence that in the lower valley above the town of Soke, the river made a cut-off of over six kilometers and the present channel is on an average more than two kilometers south of the previous channel. Without actual measurement it is believed that the present channel is about the same length as the previous channel."

"Below Soke the river switched from the north side of the plain to the south side, a distance of about twelve kilometers maximum. The distance from the head of this cut-off or switch-over to the sea is about forty kilometers airline and the length of the present channel, again without actual measurement, is probably about the same as the previous channel."

"From these observations, it would seem to me therefore that there has not been progressive movement of the bends downstream but rather a lateral movement of the channel back and forth across the valley, with the over-all length of channels remaining approximately the same and without any appreciable uniform downstream movement of the bends."

"About the only other characteristic of the Buyuk Menderes River which may be of interest is that while it is a perennial stream, there is a distinct wet and dry season and during the dry season which corresponds to the annual cropping season, the river carries progressively less water downstream, and below the town of Aydin in years of unusually low rainfall, all the water has been removed from the river for irrigation, and the channel is dry."

The slope of the stream, as determined from the report, seems to be about as follows: Yenice to Aydin, 174 km, slope 0.00074. Aydin-Eski Menderes 91 km, slope 0.00020, Eski-Menderes to the sea, 83 km, slope 0.00019. At the time the report was prepared, the stream flow data was meagre, a 15 month record at Aydin indicating giving a mean discharge of very close to 3000 cfs. As shown on Figure 5 the stream alignment is very crooked and the bends do not have any typical shape, radius of curvature, or central angle.

Red River of the North (Nos. 140-141)

The Red River of the North is a very unusual stream from the standpoint of stream forms, since it is very meandering, but has a slope which is very much flatter than most meandering rivers, and the shape of the meanders is somewhat different from the usual form.

This stream, which forms the boundary between the State of Minnesota and North Dakota, is called the Red River of the North, to distinguish it from the Red River of the South which forms the boundary line between the States of Oklahoma and Texas. It is one of the few larger streams in the United States that flows northward, its course leading into Canada, the water eventually reaching Hudson Bay. The stream is formed by the junction of the Bois de Sioux and the Otter Tail Rivers and has a length of 394 miles to the Canadian line and about 140 more to its mouth in Lake Winnipeg. Detailed maps and considerable other information on it was given by P. T. Simons and F. V. King in 1922 in a "Report on Drainage and Prevention of Overflow in the Valley of the Red River of the North" - U. S. Department of Agriculture

Bulletin No. 1017 and much of its course is now covered by U.S.G.S. topographical quadrangle maps.

The material through which the stream flows is clay, clay loam and a very little fine sand. There is some fine sand in the stream bottom. The stream is unusually crooked, the length along the stream being about twice the length of the stream valley. There are very few natural cutoffs and ox-bow lakes. Unlike many meandering streams in which many of the curves are about the same shape, those in this stream are of a wide variety of shapes, varying from bends of very small radius to those having very large ones, but in general the bends tend to be U-shaped rather than S-shaped. A typical section of the river is shown in Figure 8 which is taken from the USGS Drayton Quadrangle Map North Dakota - Minnesota. This river has a very flat slope, for the first 100 miles being about 1 foot per mile and below this to the Canadian border it decreases from 0.6 to 0.3 foot per mile.

In his paper, "The Buffalo River, an Interesting Meandering Stream*" R. F. Griggs describes in the following three paragraphs the lower part of the Buffalo River, which he says is typical of the streams of the Red River Valley, which lie in the old lake bed, since they are all formed in the same material.

"Like all streams of the Red River Valley, it is extremely crooked; but its crooks are relatively stationary, not rapidly shifting. Though bends often approach quite close to each other, cutoffs are of rare occurrence. Frequently the river is actively cutting on both sides of its bed, and deposition, such as is a necessary part of meandering in filling up the cut-offs, is entirely insignificant. There is no flood plain, but the crooks are deeply sunken into the plain over which the river flows. They belong, therefore, to

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* Am. Geog. Soc. Bull. Vol. 38, 1906, pp. 168-177.

the class of entrenched meanders. In the lower portion, though the velocity is lower, lateral wandering goes on only very slowly, even where the stream is not sunk below the level of the country."

"The Buffalo, in portions of its lower course, is cutting both of its banks: and while the cut on the inside bank seems not to be sufficient in this case to result in straightening the stream, it certainly must retard its lateral wandering and tend to keep it in its bed."

"The sticky gumbo clay of the Red River Valley through which the lower reaches flow, is only with difficulty taken up by running water, and is then in a finely-divided state, giving the water the turbid appearance characteristic of the streams of the region. This gumbo, once in suspension, settles out but very slowly, so that there are no deposits in bars and the like along its bed, but its channel is swept deep and clean like a canal."

Most streams that meander are what is known geologically as mature or old streams, but the Red River of the North is a very young stream, since it is probably less than 5000 years old. The history of this stream is quite well known. It has been formed in the bed of an extinct lake, called Lake Agassiz, which was formed by the glaciers in the latter part of the glacial epoch. This lake covered parts of the States of Minnesota and North Dakota and a large area in Canada. It was formed when the glaciers, coming down from the north, formed a dam across the outlet of the valley of this north flowing river; and formed a great shallow lake with an area greater than the combined area of all five of the present Great Lakes. The level of this lake rose until it ran over the divide between its watershed and that of the Minnesota River. The outflow of the lake then flowed down what is now the valley of the Minnesota River to the Mississippi River at St. Paul. Near the end of the glacial epoch the glacier retreated northward sufficiently to allow the water impounded in the lake to escape northward, draining the lake, the bottom of which had been covered with fine sediment brought in and deposited in the lake. As the lake water receded, a stream to carry the runoff of the watershed formed, running down the lowest part of the lake bottom. Just how the bends were formed is not clear, because the lake bed material was very fine but little solidified, the flow, even on the flat slope existing in the stream was sufficient to carry away material from the stream bed. It therefore started to deepen its course, forming what amounts to incised (intrenched or entrenched) meanders in the fine material of the old lake bottom forming a deep groove in a very flat plain. The tributary streams where they flow through the old lake bed are similar to the main stream in having low slopes and very crooked alignment. The current is not strong enough to attack the banks severely, and therefore the stream does not rapidly widen or change its position, causing cutoffs.

The Illinois River (No. 142)

The following paragraphs contain some facts not brought out in the previous discussion of the Illinois River. This stream, like the Upper Mississippi below St. Paul, is composed of many sloughs, lakes and islands, but for most of its length seems to have a fairly well defined main channel. The refilling process here is probably further developed than the Middle Mississippi, since a longer time has probably elapsed since it served as an outlet for water from the glaciers. The main channel is quite straight and stable and there is little if any bank cutting. The slope is very low; in the lower 261 miles of its length it is about 0.172 feet per mile. Another unusual condition on this stream has been reported by Rubey*. Mr. Rubey states, "The current as marked by the main channel on the deepest part of the Illinois River has the almost unique characteristic of flowing, not like most streams against the outside, but close against the inside of the curves in the river's course. The channel of the Illinois River is proportionately much deeper than any of the other rivers of the region." It is believed that the unusual phenomenon of the current following the inside of the bends in this very low slope river may furnish a valuable clue in the search for the explanation of meandering.

A channel in which there is a great thickness of sediment between the river bottom and the bedrock exists at the lower end of the Illinois River. It is probably related to the fact that this section of the Illinois occupies the site of a part of the Teays River**, which was the ancestor of the Ohio River. It started in North Carolina, crossed Virginia, Ohio and Indiana to Central Illinois where it was joined by its principal tributary, the Upper Mississippi, which had a somewhat different location than at present, and flowed into the Gulf of Mexico which then reached to near St. Louis, Missouri. Parts of this stream survive as parts of the New and Kanawha Rivers, a very short section of the Ohio River and the lower end of the Illinois, but all that part of it in Ohio and Indiana has been filled with glacial debris. The channel of this extinct stream has been located principally from the records of borings for water wells, but at Lafayette, Indiana, and perhaps in

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* Geology and Mineral Resources of Hardin and Brussels Quadrangles (in Illinois) W. W. Rubey. U. S. Geological Survey Professional Paper 218, p. 129.

** Janssen, R. E. 1952. The History of a River, Scientific American, Vol. 186, June 1952, pp. 74-80.

other places, it can be traced on airplane photographs.

If a detailed, thorough study of this river is undertaken, an investigation should be made to determine what effect, if any, the earth tilting which is now going on in the Great Lakes region may have had on the slope of the stream. The existence of such a tilt since glacial times is shown by the slope which now exists in the beach lines of the lakes which were in this region during the glacial periods. That such earth movement is now going on is proved by the changing elevation of the zeros of the water level gauges which is taking place, as indicated by the continuous readings of the lake level on these gauges.

The Wabash River (No. 84)

Another gravel stream for which data are available is the Wabash River in Indiana and Illinois. This is an unusual stream in having a very uniform slope over a considerable part of its course. This stream served as an outlet for the glacial lakes which were located at different times at what is now the western end of Lake Erie, but these lakes drained out to the eastward much earlier than the lakes which formed at the lower end of Lake Michigan and drained down the Illinois. The stages the Wabash passed through are thus the same as the Upper Mississippi and the Illinois but the process has gone farther than in the other two streams. In the vicinity of Lafayette, Indiana, the bed of the Wabash (79-84) is formed of sand and gravel and the sides are of a resistant, cohesive material. As a result the channel is very stable except at a few places where islands tend to form. Under the present conditions it may be a refilling stream. Between Terre Haute, Indiana and the mouth of this stream there are a number of bends which are cutting the banks and threatening to cut-off, or have been cut-off artificially. It is believed that the material in the lower end of this stream is sand, and these meandering sections are, therefore, classified with the other meandering sand streams.

Lower Yangtze River, China (No. 67)

The lower Yangtze River, extending from the ocean to Hankow, is an unusual river because of its flat slope and great discharge. It shifts its channel to some extent although its movement is somewhat restrained by numerous rock out-crops. In some places there are bends resembling meanders, but the stream shifts very slowly and it is not a meandering river as is the Lower Mississippi. The bed is of fine sane and the banks are probably largely of silt and clay. The writer believes that the low slope is due to the rising of the sea level and the low sand load of the stream. A large part of the sediment from the Middle Yangtze and three of its four principal tributaries is stopped by Tungting and Pao Yang Lakes, and the remaining sediment load has not been large enough to form deposits in excess of those required to keep up with the rise in sea level, to form a steeper river. It is probable that these two large lakes have been formed because the sediment load of the tributaries in whose valley they were formed was insufficient to fill their valleys as fast as the Yangtze raised its bed, as the sea level rose during the latter part of the last glacial period as a result of the melting of the glaciers.

The St. Clair River (No. 143)

This stream connects Lake Huron with Lake St. Clair, which in turn, connects with Lake Erie through the Detroit River. At its lower end it forms what is probably a delta in Lake St. Clair, depositing here the sand which it brings down from the wearing away of the beaches on the east side of the southern end of Lake Huron, and which is carried into the river at its upper end by littoral currents. The upper end of the stream runs through a dense clay deposit in a very straight channel with almost no shifting. Near the lower end, in the delta section, the river divides and the streams have a meandering pattern. The water is clear and the sediment load is probably far less than the stream would carry if it were supplied with as much as it could carry. Slope data is available only in the upper, straight section. The river is unusual because of its relatively high discharge, low slope, low sediment content and very uniform flow.

The Nile River in Egypt (No. 115)

Another interesting river is the famous Nile in Egypt. This stream also has a low slope and a comparatively straight channel with a deep sandbed and banks of tenaceous clay which fills the valley from bluff to bluff. This stream shifts very little. The clay valley fill is believed to have been deposited by the river as the level of the stream rose, following the rise of the Mediterranean water levels due to the melting of glacial ice since the glacial epoch. The composition of the bed sand is said to be very similar to that in the Missouri River.

The Yellow River in China (116-117)

This stream carries probably the heaviest sediment concentration of any large stream in the world, its annual sediment production being about 2000 million tons. In the plains region there are two sections with somewhat different characteristics. In the upper section the stream has a braided pattern, but the slope is about that which, in the ordinary sand stream, would produce a meandering stream. It carries a very heavy sediment load, at times reaching a concentration of about 50 per cent. The lower section is much narrower and has a lower slope than the upper section. It has a gently sinuous alignment, but does not cut its banks as actively as does the Mississippi. The sediment load in the downstream section is much less than the upstream one, the difference of the two loads being largely deposited overbank, as the stream breaks its levees in large floods. Near the upper end of the lower section during extreme floods the largely clarified water from this overbank flow rejoins the main stream. Both sections of this stream are rapidly building up their beds (which are composed of very fine sand and silt), and are therefore not in equilibrium.

Maxinkuckee Lake Outlet

The outlet of a small lake of unknown name which is just downstream from Lake Maxinkuckee in northern Indiana, is extremely sinuous. The bends are believed to be of the letter S type similar to the former famous Greenville bends on the Lower Mississippi. The inflow into Lake Maxinkuckee is said to be largely due to springs. No data on discharge or slope of this stream is available. The purpose of recording this case is that since the stream is the outlet of a spring fed lake, it has a relatively constant flow and carries very little, if any, sediment load. It therefore indicates that this type of meanders may form in a stream with a practically constant flow of clear water, a fact which may have a bearing in developing the reason for the formation of meanders, since it has been claimed that variable flow and sediment movement are causes of meandering.

Appendix II

THE CONCEPT OF TRACTIVE FORCE OR SHEAR APPLIED TO THE FORM OF STREAM CHANNELS

Hydraulic engineers and geologists have been accustomed to explaining the action of rivers in the terms of the velocity of the flowing water. Although velocity is a useful concept for this purpose, it does not satisfactorily explain many phenomena. In recent years hydraulic engineers have been using more widely the concept of shear or tractive force to explain many phenomena, and have found it to give a clear explanation of them. The concept was first applied to rivers by M. P. du Boys* in 1879, but it has only recently come to be extensively used principally in the field of fluid mechanics, but to some extent in river engineering. It has been found to be particularly valuable in studying the laws of the movement of sediment by flowing water and the writer believes that it offers a means of better insight into the causes of the shapes of many channels. Because this concept of shear or tractive force is unfamiliar to many engineers and geologists, and is used in numerous places in this report, it seems desirable to explain it at some length, in order that this paper may be more clearly understood, and that engineers and geologists who are not acquainted with it may acquire a very useful tool for their work.

When one starts to coast down a hill on a bicycle or in an automobile, his speed gradually increases until (if the slope of the hill is uniform) he reaches a nearly constant speed, beyond which no appreciable change of velocity occurs, no matter how long the hill is. This constant speed is reached when the resistance to the motion of the bicycle or auto from the air or the

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* The Rhone and Streams with movable Beds, Anals des Ponts et Chaussees Tome XVIII, 1879.

ground, or from the friction of the internal moving machinery, becomes equal to the force which causes the bicycle or automobile to move down the hill. This latter force is due to the force of gravity and is equal to the weight of the moving body times the sine of the angle of slope of the hill. If there were no resistance to the movement of the bicycle or automobile, it would continue to speed up indefinitely.

Similarly, when water at rest starts to flow down a channel of uniform slope and cross section, it increases in speed until it reaches a velocity at which the resistance to its motion is equal to the force causing it to move, and after this point is reached, no further increase in velocity of the water occurs as it moves on down the channel. When this condition of uniform motion is reached, both the force causing motion and the resistance to motion of the water down the channel, is equal to the weight of the water times the sine of the angle of slope of the channel. This resistance to the motion of the water is in the form of a force which the air above the channel and the sides and bottom of the channel exert on the moving water. The air resistance force however is so small in comparison to the bed and bank resisting force that the air resistance usually can be ignored. In practically all natural channels therefore, except where the water is speeding up or slowing down, the force that the banks and bed exerts on the water is practically equal to the weight of the water times the sine of the slope of the stream. Unless the slope is very large the sine of the angle of slope is practically equal to the tangent of the slope, which tangent is the gradient of the channel or the fall or drop in elevation of the water surface elevation per foot of horizontal distance of travel along the channel. According to one of Newton's fundamental laws of motion, when the bank and bed exerts a force on the water retarding its motion, the water must exert an equal force on the banks and bed, but in the opposite direction. The banks and bed exert a force on the moving water in the direction opposite to that of its movement, and the water exerts on the banks and bed an equal force in the direction of flow. This force in the case of moving water is called the tractive force, and is also called the shearing force or more frequently is referred to as the shear.

In a section of channel with constant shape and slope in which the water is flowing at a uniform velocity, let us consider the water between two vertical planes at right angles to the direction of the channel and a unit length apart. The weight of the water between the planes is equal to the area of cross section of the water in the channel times the unit weight of the water, and this weight, times the slope of the channel is equal to the force which the banks and bed exert on the flowing water in a direction opposite to that of the flow. It is also equal to the tractive force or shear which the water exerts on the banks and bed in the direction of flow. This tractive force is not equally distributed over the bed and banks but is greater on those parts where the velocity is higher. The average tractive force per unit area which the water exerts on the banks and bed between the two planes, is equal to the total tractive force due to the water between the two planes, divided by the area of the bed and banks between the planes, with which the water is in contact. Since the planes are one unit distance apart, the average tractive force is numerically equal to the total tractive force divided by the length of the strip of unit width on which the water is in contact with the bed and banks. This length is called the wetted perimeter of the cross section of the stream. In a section which is very wide, the wetted perimeter is very close to being the same as the width, and the average tractive force per unit area on the bottom and banks is practically numerically equal to the total tractive force divided by the channel width.

Consider next, the case of uniform flow in an infinitely wide channel of constant slope. The volume of water in a prism between the two vertical planes a unit distance apart across the channel and also between two other vertical planes a unit distance apart, at right angles to the other planes, or in the direction of the channel, forms a vertical rectangular prism one square unit in cross sectional area. Then the tractive force exerted by this water on the bottom will be equal to the weight of the water in this prism times the slope of the channel. Since the prism has a cross section of one unit area, its volume is numerically equal to the depth of the flow, and its weight is numerically equal to this depth multiplied by the weight of water per unit of volume. The tractive force which it exerts on the bottom is therefore the depth of the water, times the unit weight of the water, times the slope of the channel. Since the area of contact of this prism with the bottom is one unit of area, the intensity of this tractive force or shear per unit of area is equal to the product of the depth of water and the unit weight of water and the slope of the channel. Studies to develop the best method for the design of artificial channels through erodible materials have shown that the tractive force is the best criterion for analyzing this problem, and it is believed that it will also be found to be an equally useful tool in the analysis of natural stream channels. The concept of tractive force or shear is widely used in solving many other hydraulic and fluid mechanics problems.

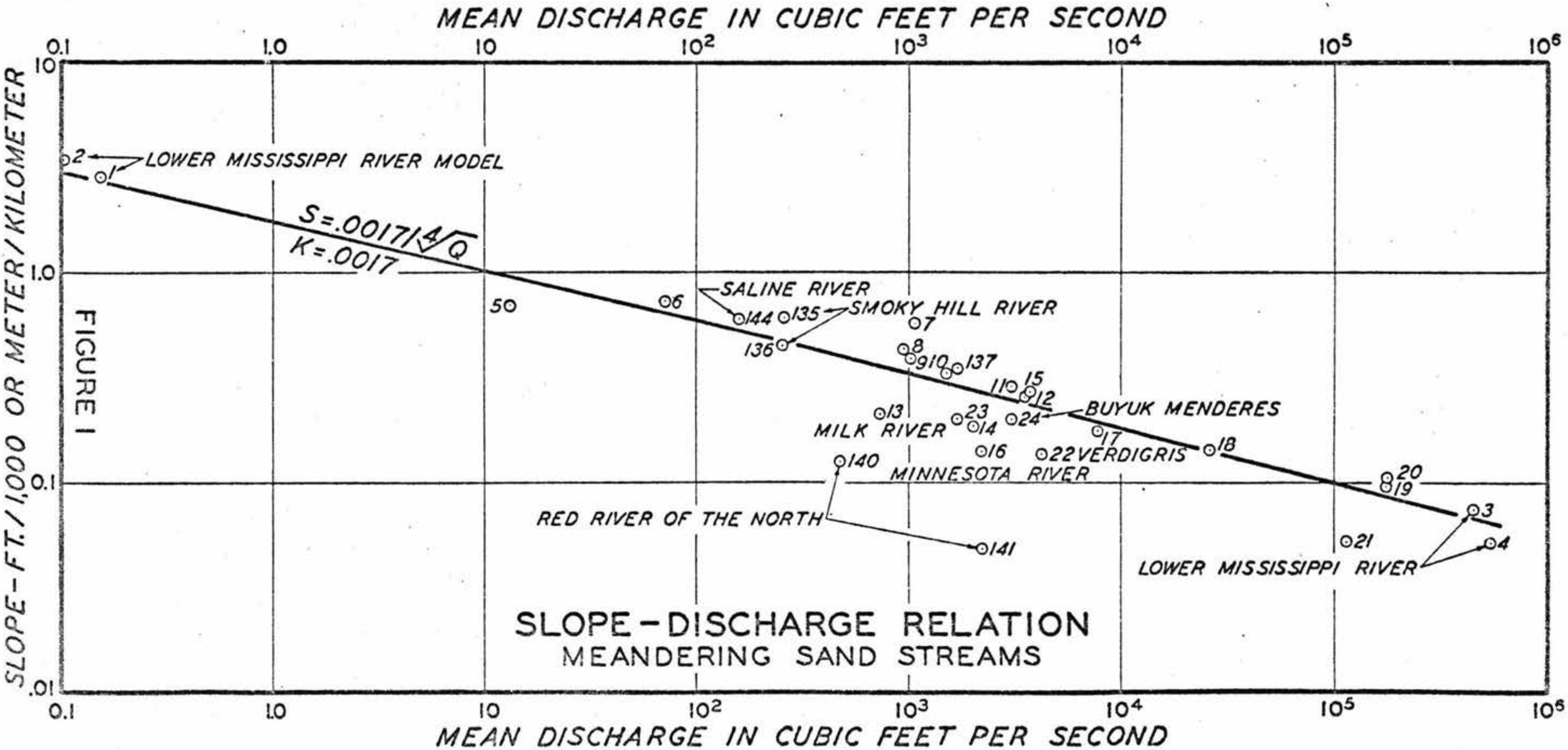

MEAN DISCHARGE IN CUBIC FEET PER SECOND
0.1
1.0
10
10^2
10^3
10^4
10^5
10^6
SLOPE-FT./1,000 OR METER/KILOMETER
10
1.0
0.1
.01
2
1
LOWER MISSISSIPPI RIVER MODEL
$S=.0017/\sqrt[4]{Q}$
K=.0017
50
6
SALINE RIVER
144
135
SMOKY HILL RIVER
136
7
8
9 10
137
11
15
12
13
23
14
24
BUYUK MENDERES
MILK RIVER
17
16
22 VERDIGRIS
18
140
MINNESOTA RIVER
20
19
RED RIVER OF THE NORTH
3
21
141
4
LOWER MISSISSIPPI RIVER
SLOPE-DISCHARGE RELATION
MEANDERING SAND STREAMS

FIGURE I

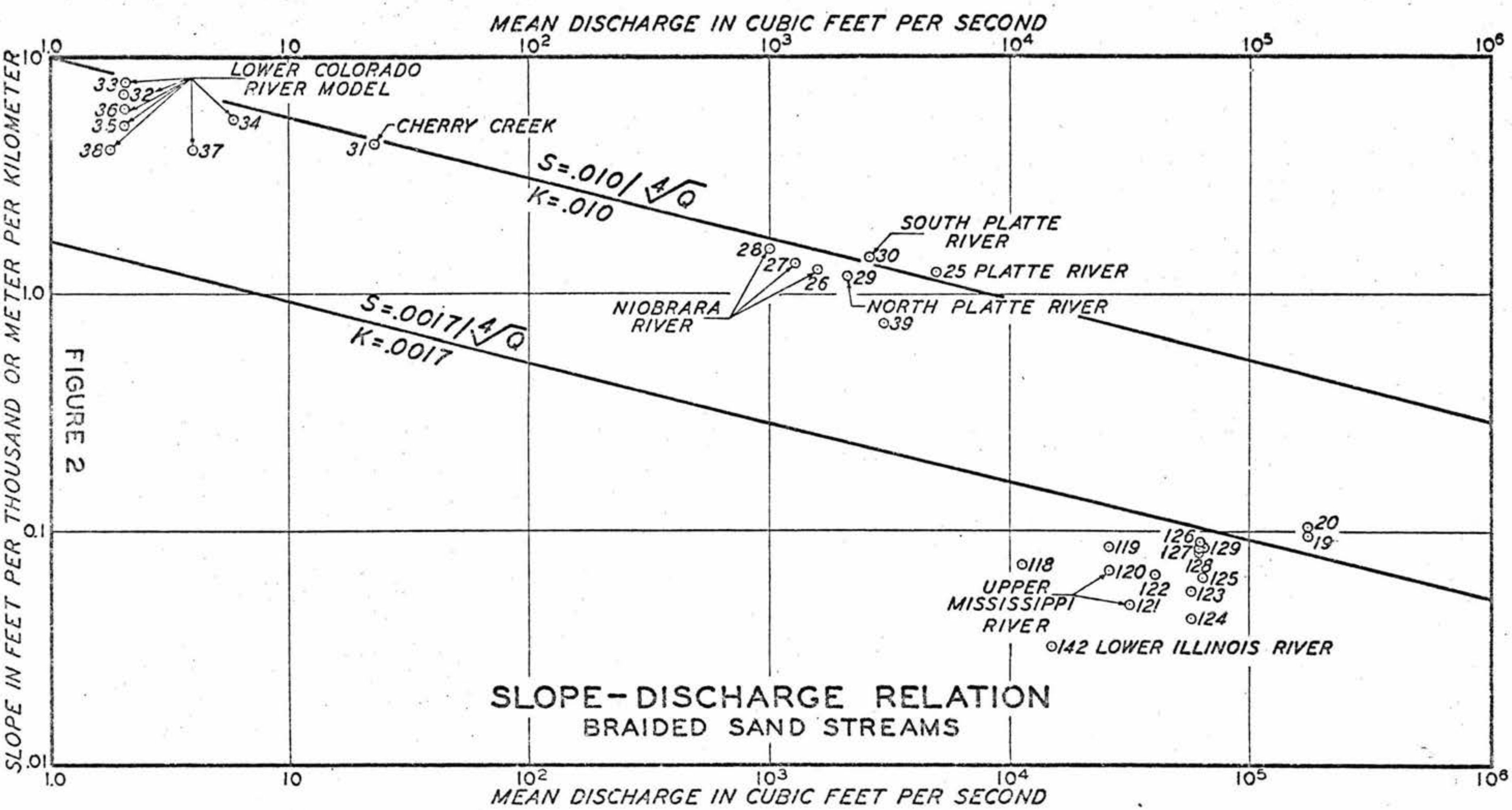

MEAN DISCHARGE IN CUBIC FEET PER SECOND
1.0
10
10²
10³
10⁴
10⁵
10⁶
SLOPE IN FEET PER THOUSAND OR METER PER KILOMETER
10.
1.0
0.1
.01
LOWER COLORADO RIVER MODEL
33
32
36
35
38
34
37
CHERRY CREEK
31
S=.010/∜Q
K=.010
SOUTH PLATTE RIVER
30
28
27
26
29
25 PLATTE RIVER
NIOBRARA RIVER
NORTH PLATTE RIVER
39
S=.0017/∜Q
K=.0017
20
19
126
127
129
128
125
123
124
119
118
120
122
121
UPPER MISSISSIPPI RIVER
142 LOWER ILLINOIS RIVER
SLOPE-DISCHARGE RELATION
BRAIDED SAND STREAMS

FIGURE 2

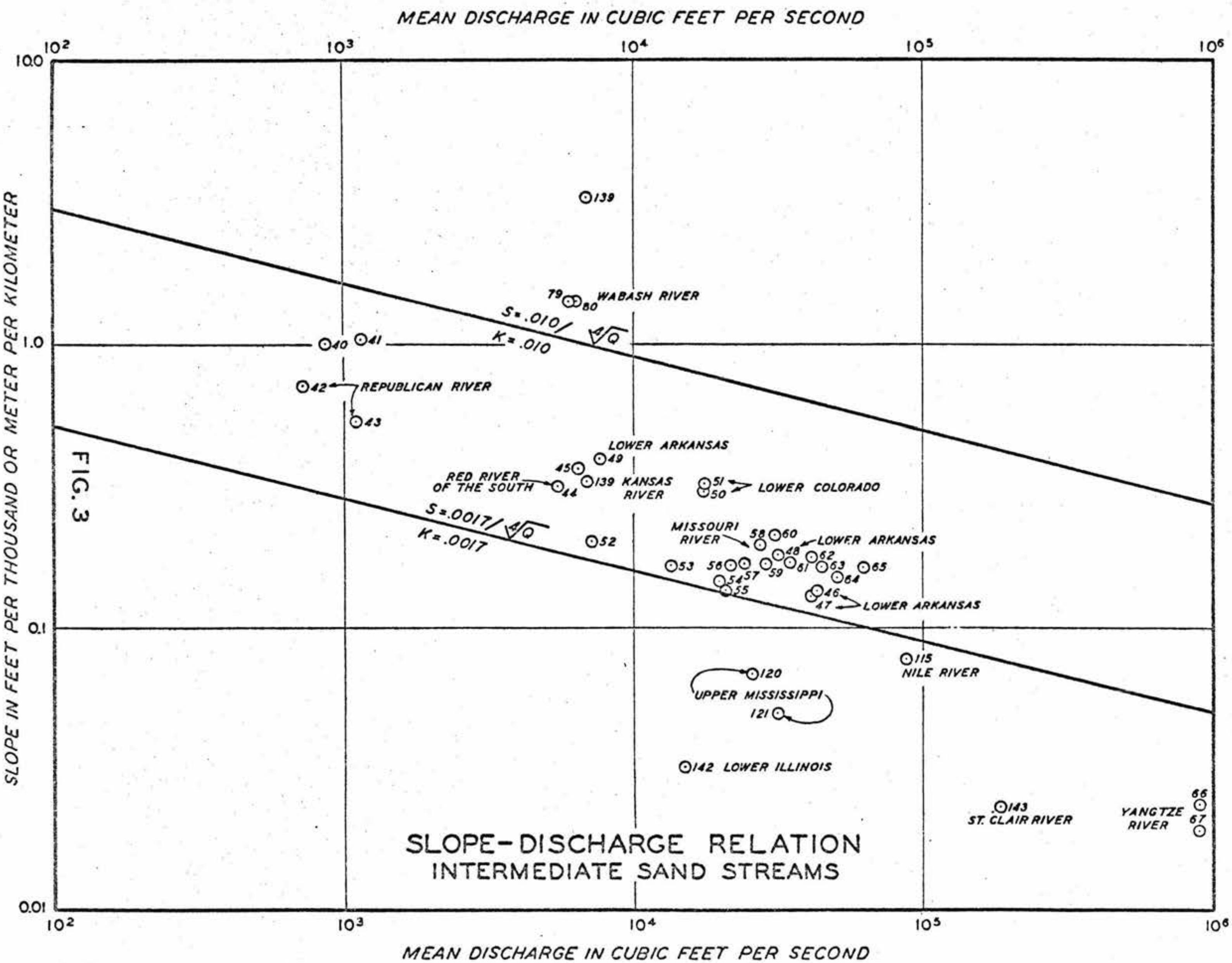


FIG. 3

SLOPE-DISCHARGE RELATION
INTERMEDIATE SAND STREAMS

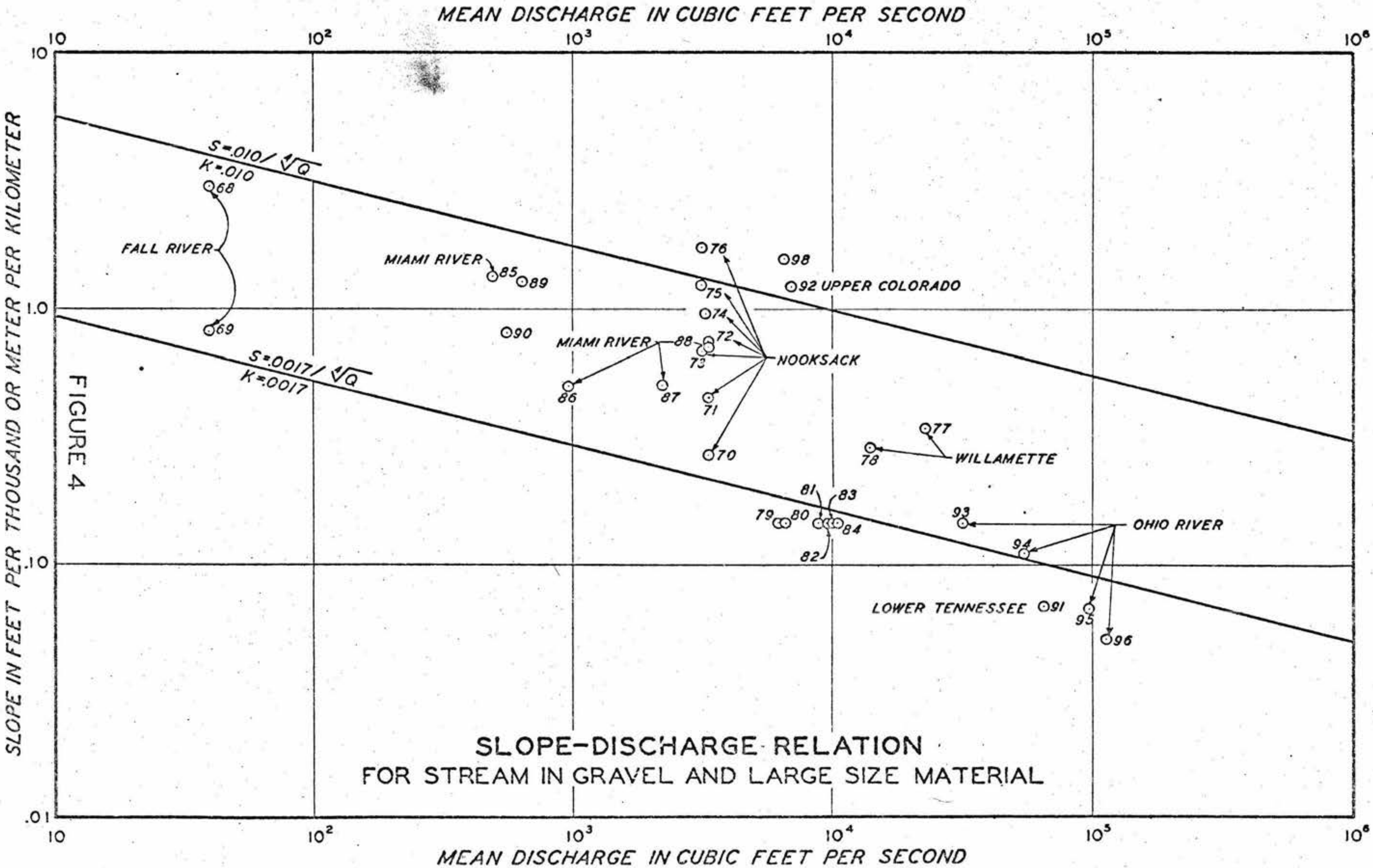
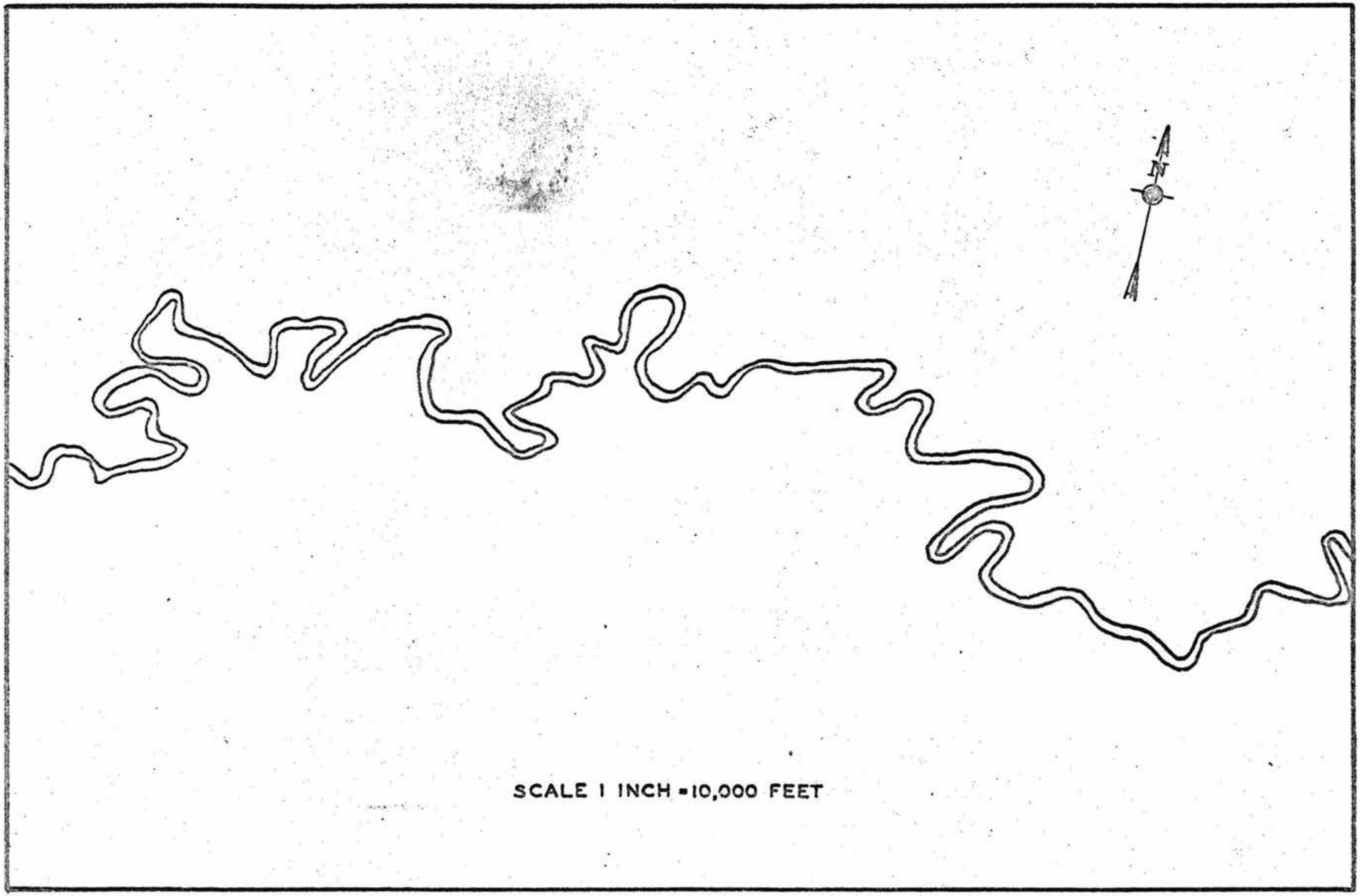


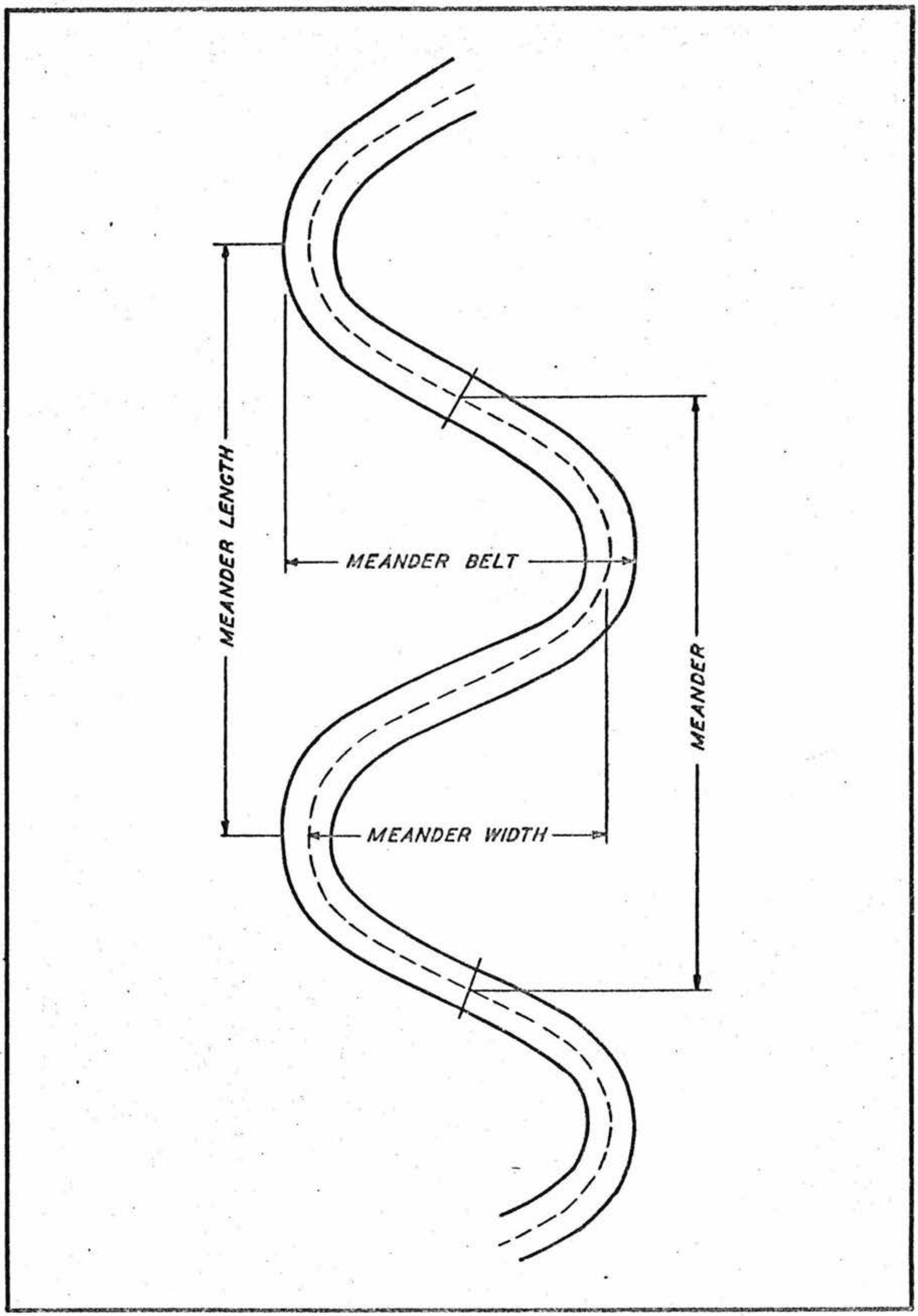
FIGURE 4

SLOPE–DISCHARGE RELATION
FOR STREAM IN GRAVEL AND LARGE SIZE MATERIAL

FIGURE 5



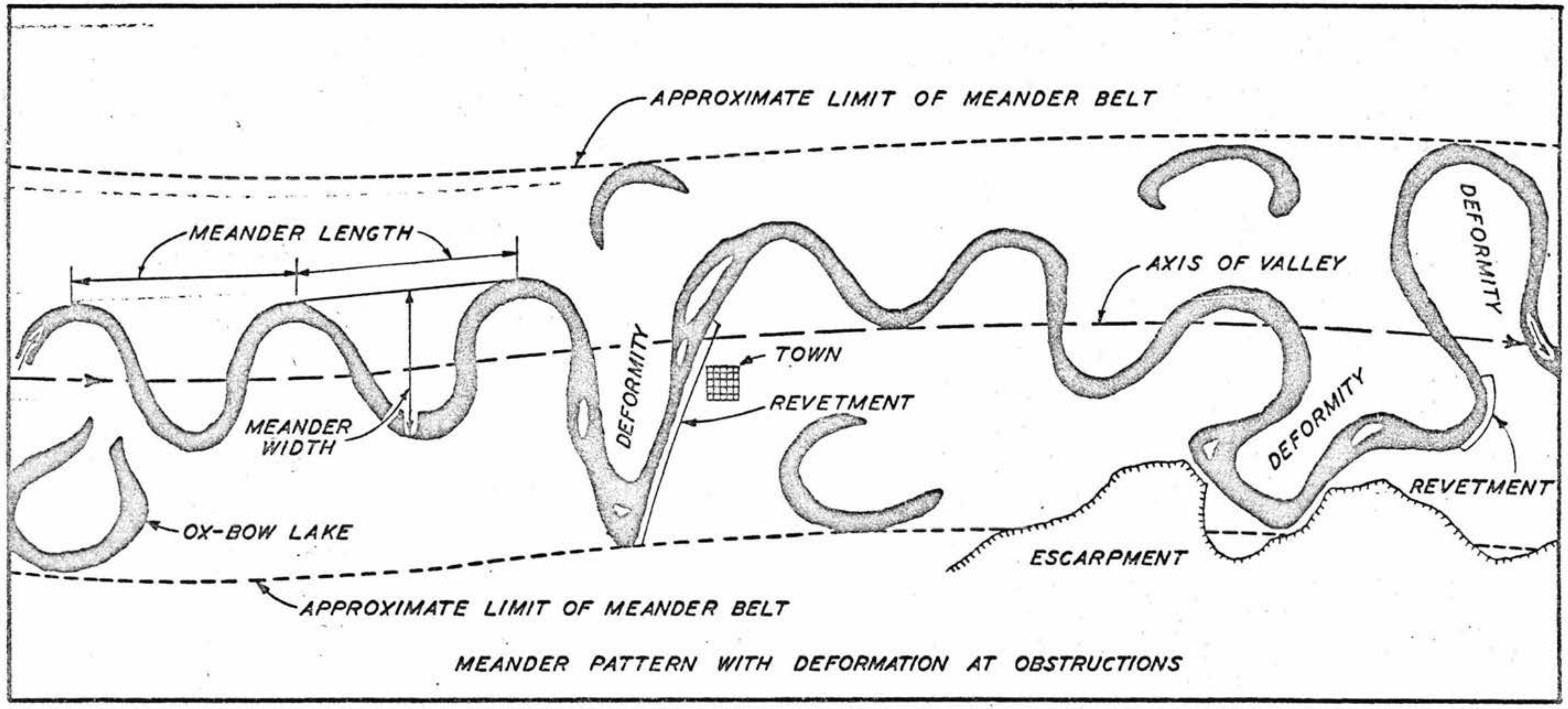
SECTION OF THE BUYUK MENDERES RIVER, TURKEY



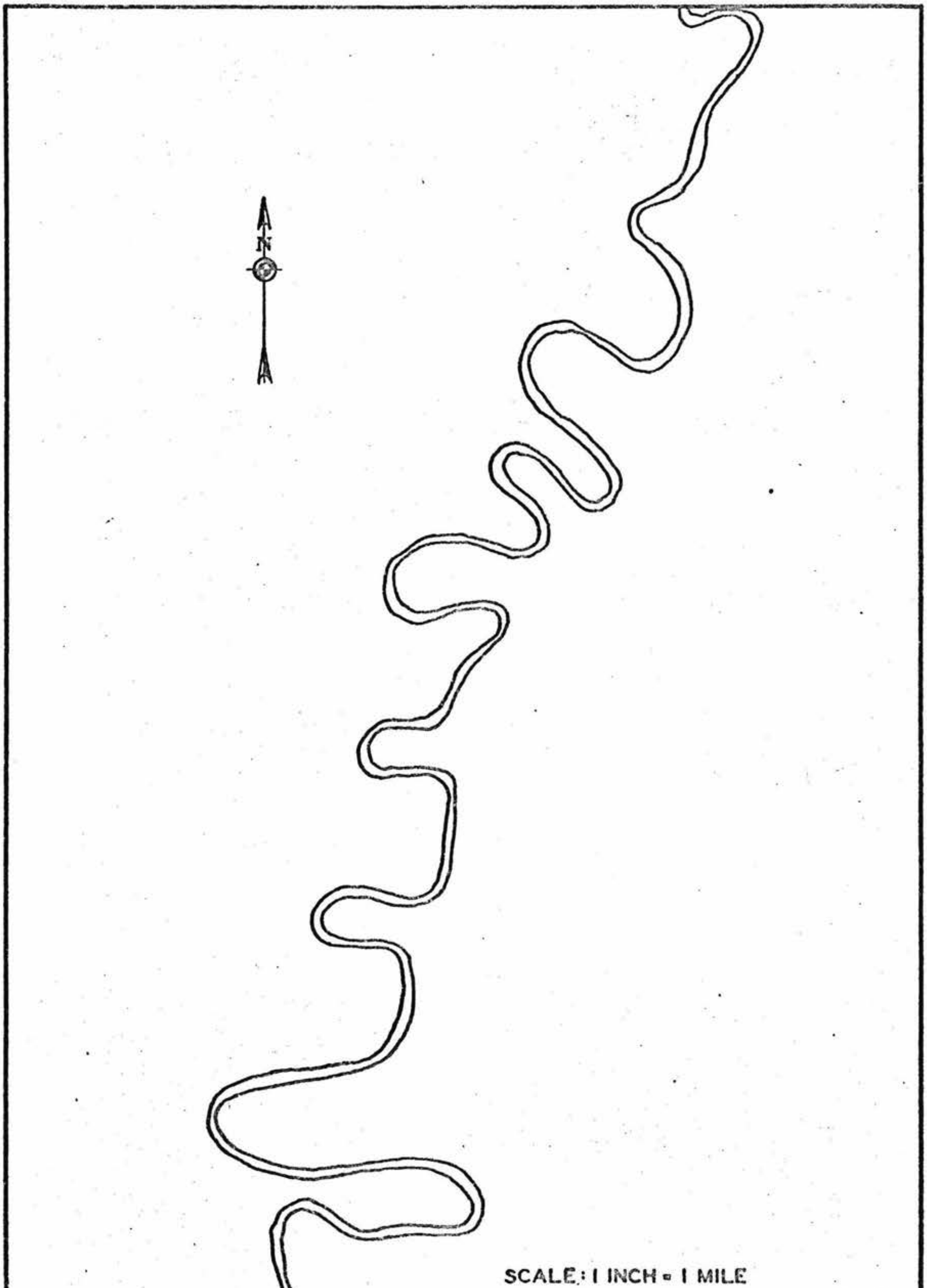
DIMENSIONS OF STREAM MEANDERS RECOMMENDED BY CENTRAL BOARD OF IRRIGATION OF INDIA

FIGURE 6

FIGURE 7



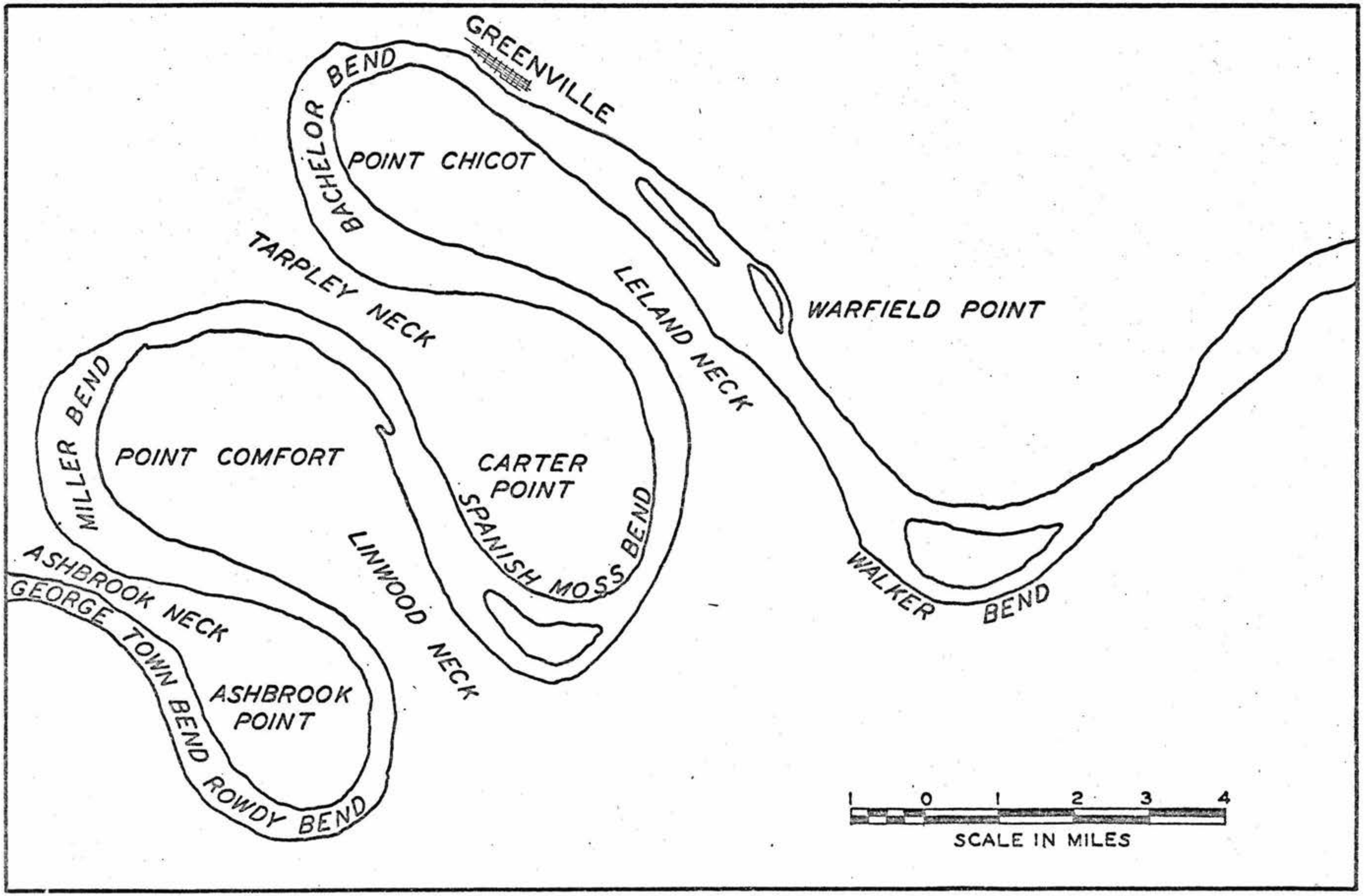
DIMENSIONS OF STREAM MEANDER RECOMMENDED BY G.H. MATTHES



MAP OF A TYPICAL SECTION OF THE RED RIVER OF THE NORTH NEAR DRAYTON, N.D.- SHOWING U-SHAPED BENDS

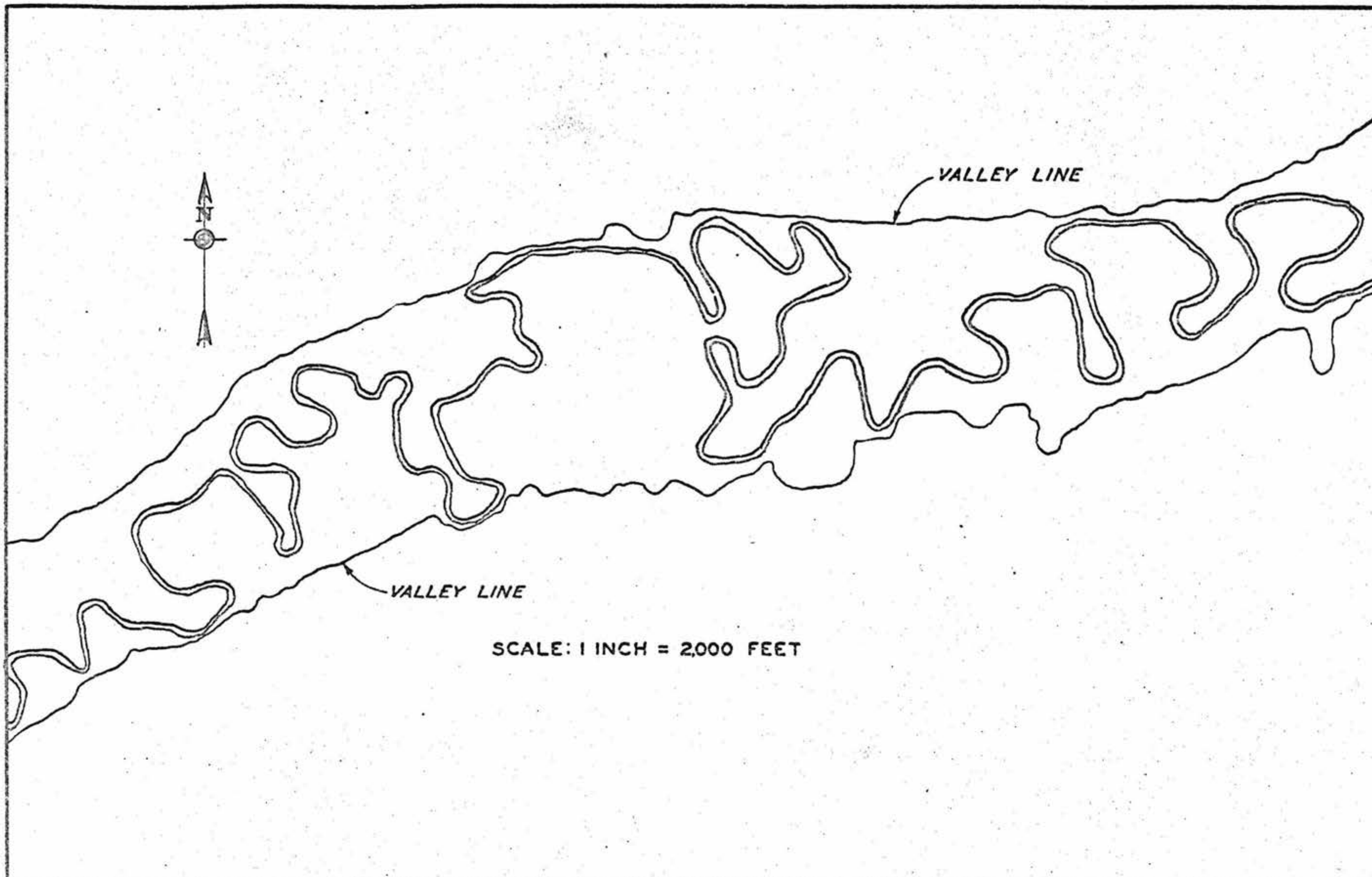
FIGURE 8

FIGURE 9



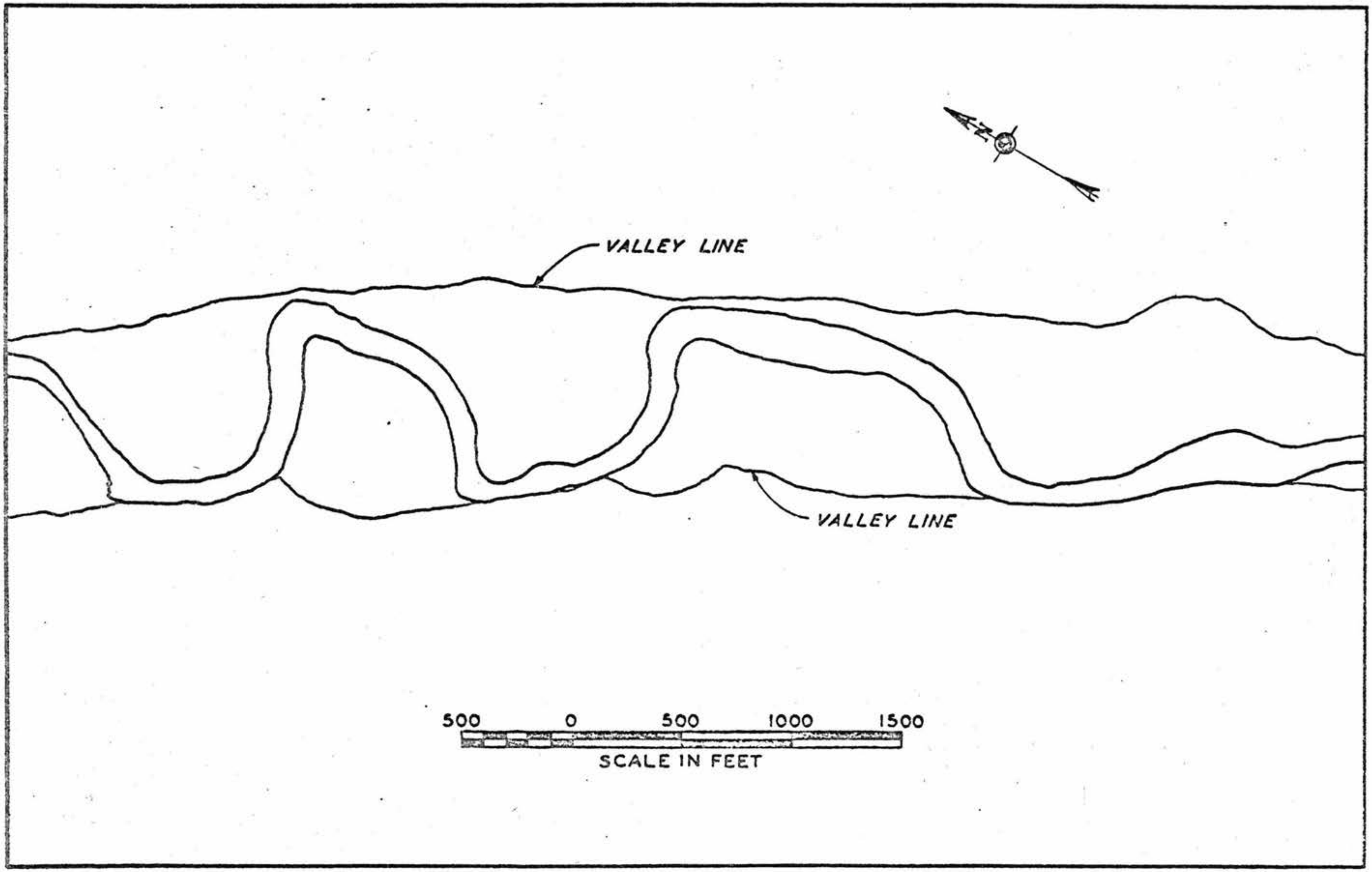
S-SHAPED BENDS IN MISSISSIPPI RIVER NEAR GREENVILLE, MISS.

FIGURE 10

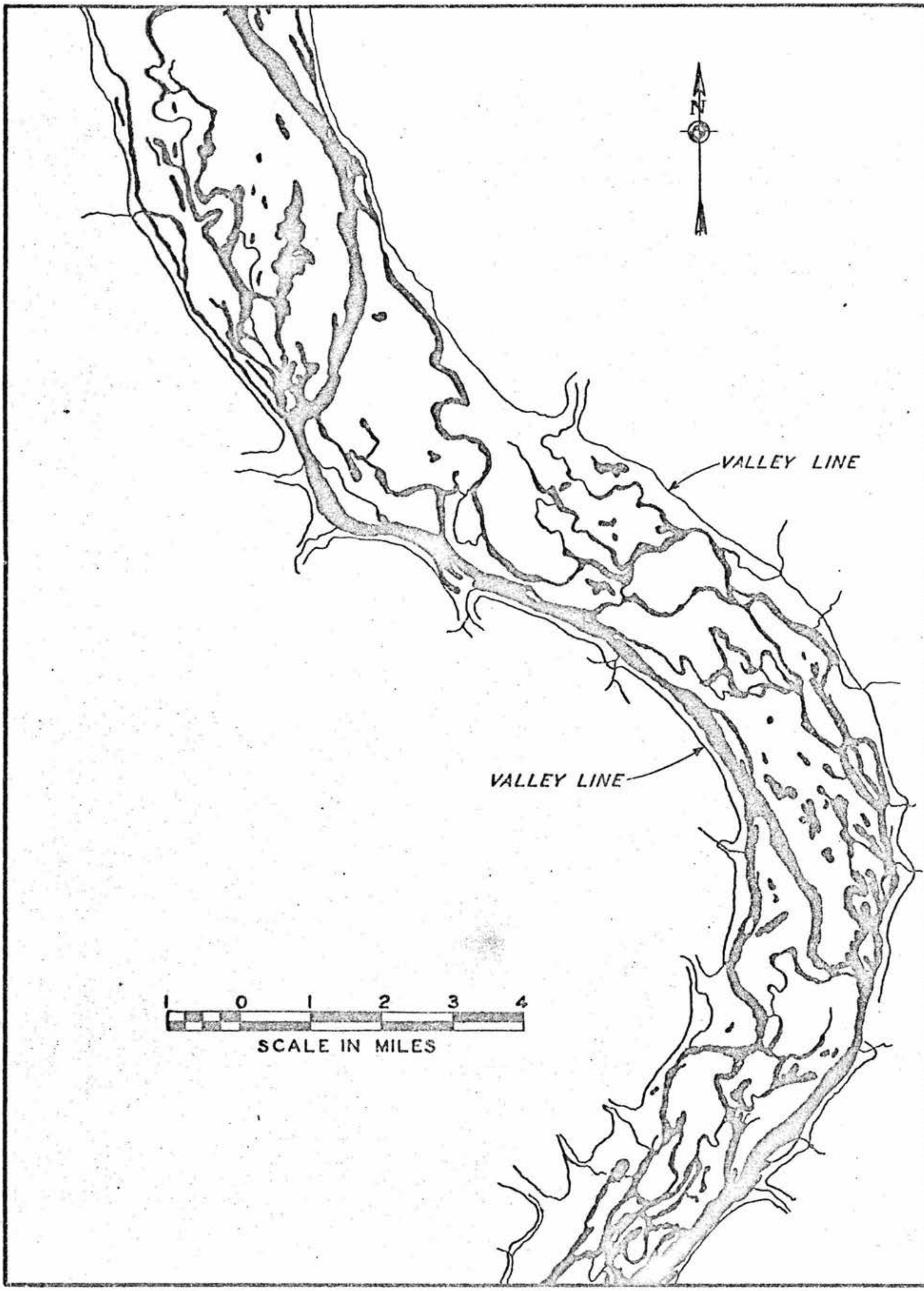


MAP OF A SECTION OF THE SOURIS RIVER NEAR VOLTAIRE, NORTH DAKOTA

FIGURE 11



MAP OF A SECTION OF THE KLARALFVEN RIVER IN SWEDEN
(A CONFINED MEANDERING STREAM)



A LOW-SLOPE BRAIDED SECTION OF THE UPPER MISSISSIPPI RIVER NEAR WAUKON, IOWA
FIGURE 12

SECTION OF SUNSHINE CREEK, WYOMING–A DEGRADED BRAIDED STREAM

FIGURE 13

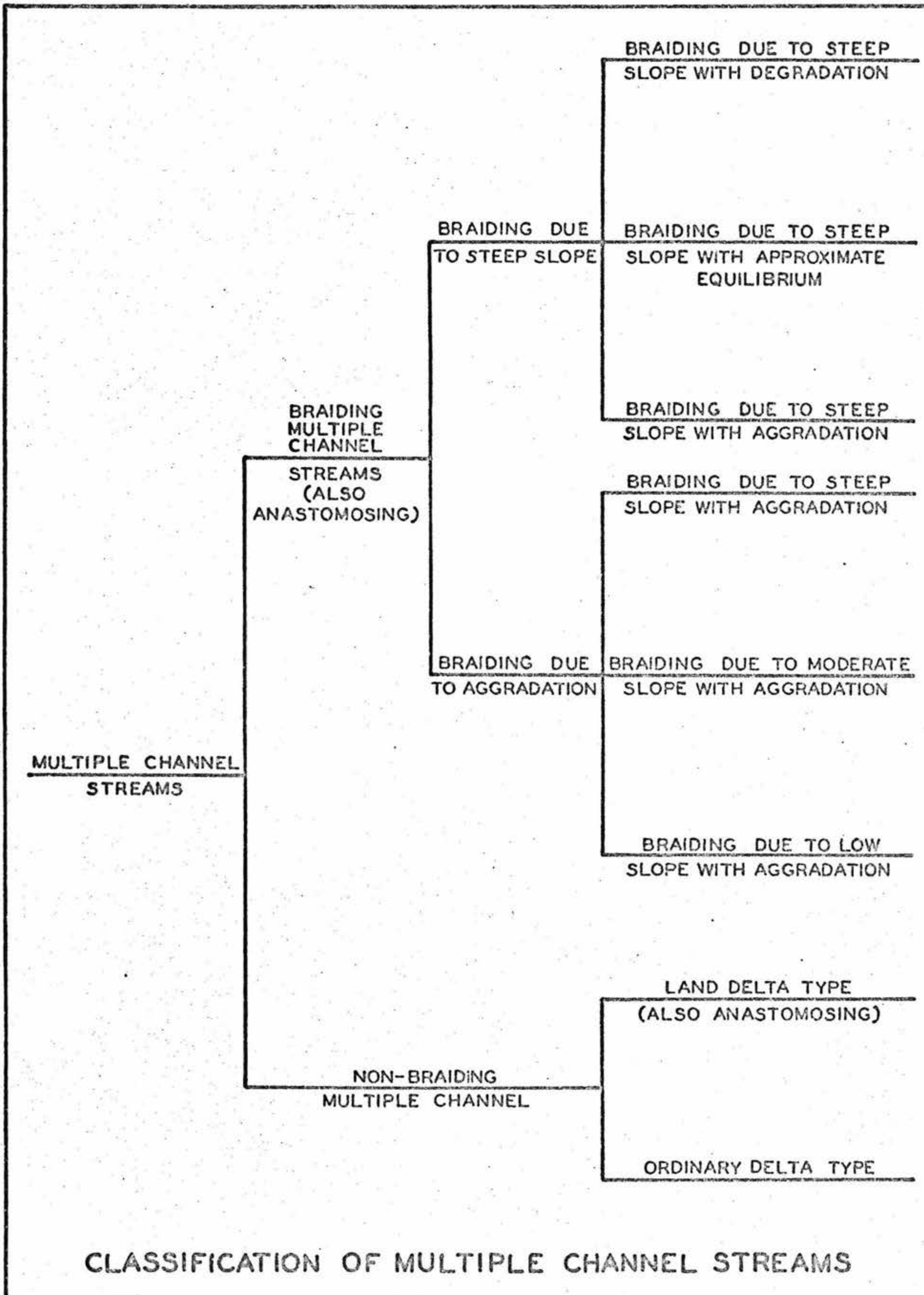
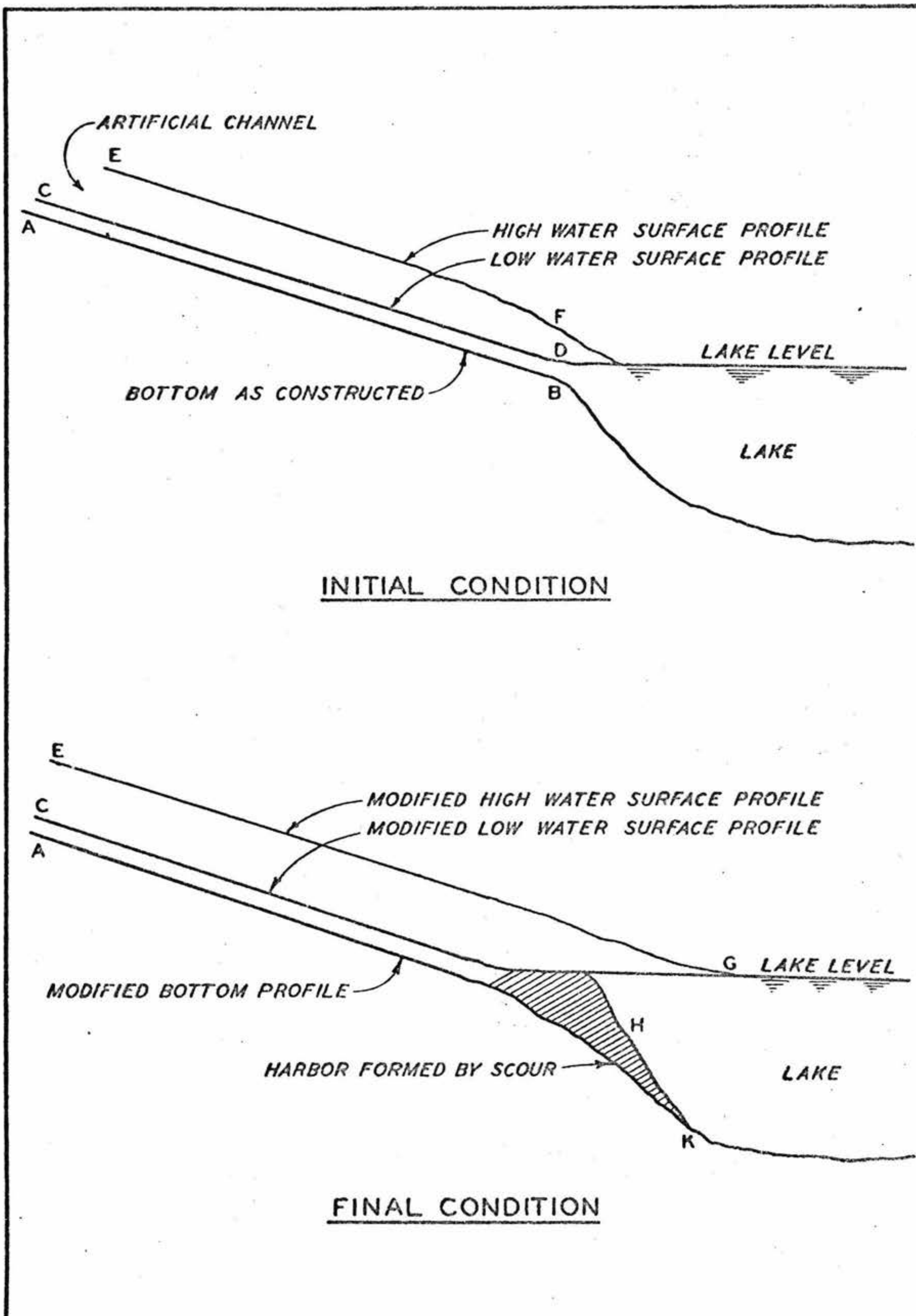

MULTIPLE CHANNEL STREAMS
BRAIDING MULTIPLE CHANNEL STREAMS (ALSO ANASTOMOSING)
NON-BRAIDING MULTIPLE CHANNEL
BRAIDING DUE TO STEEP SLOPE
BRAIDING DUE TO AGGRADATION
BRAIDING DUE TO STEEP SLOPE WITH DEGRADATION
BRAIDING DUE TO STEEP SLOPE WITH APPROXIMATE EQUILIBRIUM
BRAIDING DUE TO STEEP SLOPE WITH AGGRADATION
BRAIDING DUE TO STEEP SLOPE WITH AGGRADATION
BRAIDING DUE TO MODERATE SLOPE WITH AGGRADATION
BRAIDING DUE TO LOW SLOPE WITH AGGRADATION
LAND DELTA TYPE (ALSO ANASTOMOSING)
ORDINARY DELTA TYPE
CLASSIFICATION OF MULTIPLE CHANNEL STREAMS

FIGURE 14



PROFILE OF ARTIFICIAL CHANNEL ENTERING A LAKE

FIGURE 15