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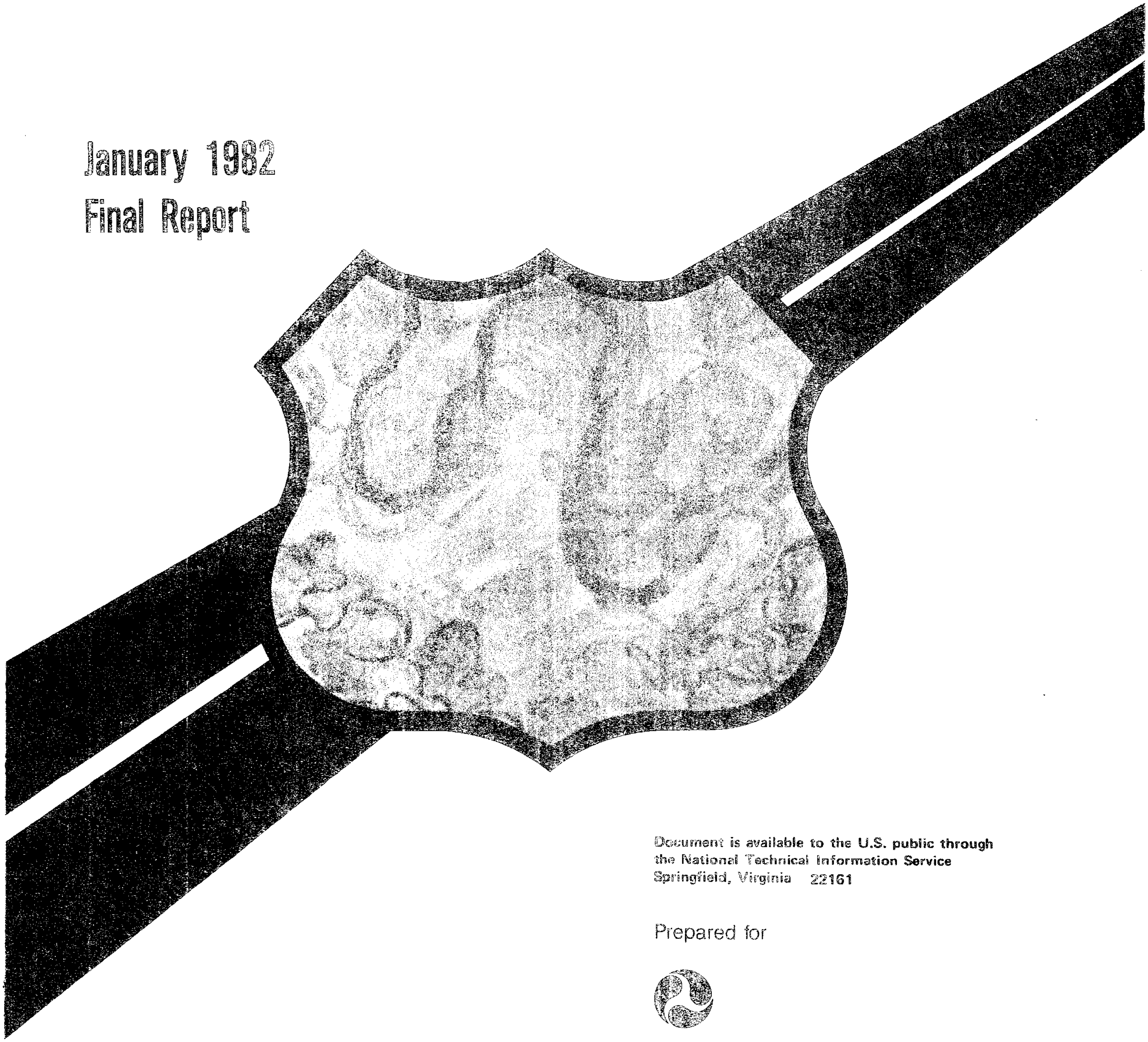
STREAM CHANNEL STABILITY ASSESSMENT

January 1982

Final Report



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Prepared for

U.S. Department of Transportation

Federal Highway Administration

Offices of Research & Development
Environmental Division
Washington, D.C. 20590

FOREWORD

This report provides a simple method for determining relative stability of streams based on stream type. Four stream types are distinguished based on variability of width and presence of bars. These characteristics are readily observed on aerial photographs, supplemented with field investigations. The study is an outgrowth of previous research contracts "Countermeasures for Hydraulic Problems at Bridges" (Research Report Number: FHWA/RD-78/162) and "Stability of Relocated Stream Channels" (Research Report Number: FHWA/RD-80/158). An understanding of the potential for stream instability hazards at a particular crossing is necessary for proper design and maintenance.

Research in highway drainage and stream crossing design is included in the Federal Coordinated Program of Highway Research and Development in Project 5H "Protection of the Highway System from Hazards Attributed to Flooding." Roy E. Trent is the Project Manager and Stephen A. Gilje is the Task Manager and the Contracting Officers' Technical Representative for this efffort.

Sufficient copies of the report are being distributed to provide a minimum of one copy to each FHWA regional office, division office, and State highway agency. Direct distribution is being made to the division offices.

Stanley Byington
for Charles F. Scheffey
Director, Office of Research

NOTICE

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16. Abstract

Channel instability is manifested as lateral bank erosion, progressive degradation of the streambed, or natural scour and fill of the streambed. Lateral stability is related to stream type, and four major stream types having different stability characteristics are distinguished: equiwidth, wide-bend point bar, braided point-bar, and braided. Measurements of bank erosion on a study group of 36 streams indicate that equiwidth streams have the lowest lateral erosion rates and braided point-bar streams the highest. Also, erosion rates increase with stream size. Significant degradation of the streambed can usually be detected from indirect field evidence. The sites of greatest potential scour along a channel can be identified from channel configuration.

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ii

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NOTICE

CONTENTS

ILLUSTRATIONS

TABLES

INTRODUCTION

The objective of this report is to summarize geomorphic methods of stream channel stability assessment for the use of bridge and highway engineers. To provide an indication of the rate and magnitude of lateral erosion that may be expected for streams of different types and sizes, the results of measurement on a selected group of 36 streams are given. In addition, some representative values for channel degradation and for scour are tabulated.

The need for channel stability assessment in the planning of bridges, countermeasures, and channel relocations has been documented in the reports of two previous FHWA projects (Brice and Blodgett, 1978; Brice, 1980). This report is based partly on data collected for these projects. In addition, use was made of a collection of time-sequential airphotos and hydrologic data for 200 stream reaches in the United States, assembled during the period 1970-74 under a grant from the U.S. Army Research Office. The literature has been searched for relevant information and lateral migration rates have been measured for a group of 36 streams in the United States, selected to represent a wide variety of stream types and sizes.

Ideally, a stable channel is one that does not change in size, form, or position through time. All alluvial channels change to some degree and therefore have some degree of instability. For engineering purposes, an unstable channel is one whose rate or magnitude of change is great enough to be a significant factor in the planning or maintenance of a bridge, highway, or other structure. The kinds of change considered here are (1) lateral bank erosion, (2) degradation or aggradation of the streambed that continues progressively over a period of years, and (3) natural short-term fluctions of streambed elevation that are usually associated with the passage of a flood (scour and fill).

In the engineering literature (for example, in Henderson, 1961) no apparent distinction is drawn between the stability of a channel and its attainment of equilibrium or regime; but stability and equilibrium are not identical concepts. Most natural alluvial channels have probably approached a state of equilibrium, as indicated by the reasonably consistent relations of channel width, depth, and slope to discharge (Leopold, Wolman, and Miller, 1964). Nevertheless, natural alluvial channels migrate laterally, at rates ranging from very slow to rapid. A stream that has attained equilibrium is not necessarily stable in the practical engineering sense. It may migrate laterally, at a rate hazardous to engineering structures or other property, while maintaining its equilibrium slope and cross section. Also a stream in equilibrium may have fluctuating changes in bed elevation, of such magnitude as to require special consideration in the design of bridge piers.

In the assessment of scour at bridge waterways, most engineers have relied on engineering judgment rather than on computational methods (Highway Research Board, 1970, p. 9), and this must surely apply to the assessment of channel stability in general. Engineering judgment is evidently based on prior experience with the behavior of streams, on hydrologic analysis of floods, on subsurface investigations, and on hydraulic analysis. Stability assessment from investigation of a stream in the field and the comparison of time-sequential airphotos is a logical extension of this approach. It provides additional documentation and information for the exercise of engineering judgment, and it has already been adopted by several highway agencies. The application of empirical and theoretical equations to the assessment of channel stability has been well summarized elsewhere and will not be discussed here (for example, see Highway Research Board, 1970; Neill, 1964, 1973a; Vanoni, 1975; Simons and Senturk, 1977).

The application of channel stability assessment to the planning of bridges and countermeasures is well described in the following quotation from Klingeman (1973, p. 2180):

> "Whereas designers often consider such changes (in bed configuration and channel flow alinement) as a function of stage, it may be more important to recognize the changes that might occur with time. The constancy of channel alinement and the permanence of stream bed configuration can best be studied from a series of aerial photographs spanning several years. * * * This assists in interpreting the stability of change in locations of banks, bars, riffles, and pools or deep zones. * * * By tracing and overlaying a succession of photographs and accounting for differences in discharge, the progression of any changes can be detected. This will provide the designer with some idea of the rate of change, the direction of change, the location of stable features or "hard points", and the general "feel" for the dynamic character of the particular river reach under study. * * * From this assessment of channel stability the designer can expect to make sounder recommendations regarding the best location of the axis of the bridge, the locations of the piers in the channel, the appropriate stream bed elevation to use in design scour calculations, the elevation for any protective riprap near the piers, and the likelihood for channel changes and potential maintenance problems during the life of the bridge."

The importance of assessing channel stability is demonstrated by a recent study of 224 bridge sites where hydraulic problems had occurred

(Brice and Blodgett, 1978). At 105 sites, lateral instability contributed to hydraulic problems such as erosion at abutments and exposure of pier foundations. At some sites, lateral channel migration overtook piers placed originally outside the channel, and the depth of pier foundations proved to be inadequate. Problems involving vertical stability (degradation, local scour, general scour) occurred at a similar number of sites; however, vertical stability is more difficult to assess than is lateral stability, and the comparison of time-sequential airphotos provides information only on visible changes in the channel bed.

The projects on countermeasures and stability of relocated stream channels, of which this project is an outgrowth, were initiated by Stephen A. Gilje of the Office of Research, Federal Highway Administration. Mr. Gilje has served as contract manager for all three projects and has actively participated in the collection of data and the presentation of results. Much of the information relating to hydraulic problems at specific sites has been obtained through the generous cooperation of engineers in state highway agencies.

AIRPHOTO INTERPRETATION OF CHANNEL PROPERTIES

MAJOR CHANNEL PROPERTIES

Major properties of stream channels are illustrated in figure 1. A satisfactory (if lengthy) description of a particular channel can be obtained by choosing the category that best applies to it from each of the 14 properties. Each of the properties has some relation to channel stability but attention will be given here to the most significant properties of alluvial channels that can be interpreted from airphotos. For preliminary purposes, a stream bordered by a flood plain or low terraces is regarded as alluvial. Non-alluvial and semi-alluvial streams are commonly bordered by rock outcrops and outcrops in the channel are either visible or else are expressed indirectly by waterfalls or rapids. Stability is rarely a problem with non-alluvial channels.

The properties that require field measurement (flow, bed material size, bank material size) are essential for an understanding of stream behavior. However, a preliminary assessment of lateral stability, having a fair degree of reliability, can be made from interpretation of properties visible on an airphoto made at or near "normal" stream stage. For representing a stream on a topographic map, the Topographic Division of the Geological Survey uses, in so far as possible, the so-called "normal" stage, or the stage prevailing during the greater part of the year. They find that the "normal" stage for a perennial river usually corresponds to the water level filling the channel to the line of permanent vegetation along its banks. Stability is inferred mainly from the nature of point bars, the presence or absence of cut banks, and the variability of stream width.

On a laterally unstable channel, or at actively migrating bends on an otherwise stable channel, the point bars are usually wide and unvegetated and the bank opposite a point bar is cut and often scalloped by erosion (fig. 2). The crescentic scars of slumping may be visible from place to place along the bankline. The presence of a cut bank opposite a point bar is evidence of instability, even if the point bar is vegetated. Sand or gravel on the bar appears as a light tone on airphotos. The unvegetated condition of the point bar is attributed to a rate of outbuilding that is too rapid for vegetation to become established. However, the establishment of vegetation on a point bar is dependent on other factors besides rate of growth, such as climate and the timing of floods. If the width of an unvegetated point bar is considered as part of the channel width, the channel tends to be wider at bends. Streams whose width at bends is about twice or more the width at straight reaches, are here called <u>wide-bend streams</u>.

Along an unstable channel, bank erosion tends to be localized at bends, and straight reaches tend to be relatively stable. However, meandering of the thalweg in a straight reach is likely to be a precursor of instability. Bars that occur alternately from one side to the other of a straight reach are somewhat analogous to point bars and are indicative of a meandering thalweg.

Oxbow lakes are formed by the cutoff of meander loops, which occurs either by gradual closure of the neck (neck cutoffs) or by a chute that cuts across the neck (chute cutoffs). Neck cutoffs are associated with relatively stable channels, and chute cutoffs with relatively unstable channels. Recently formed oxbow lakes along a channel are evidence of recent lateral migration. A recently formed lake is usually immediately adjacent to the channel and it transmits flow at high river stages (fig. 2). Commonly, a new meander loop soon forms at the point of cutoff and grows in the same direction as the previous meander. Cutoffs tend to induce rapid bank erosion at adjacent meander loops. The presence of abundant oxbow lakes on a flood plain does not necessarily indicate a rapid channel migration rate, because an oxbow lake may persist for hundreds of years.

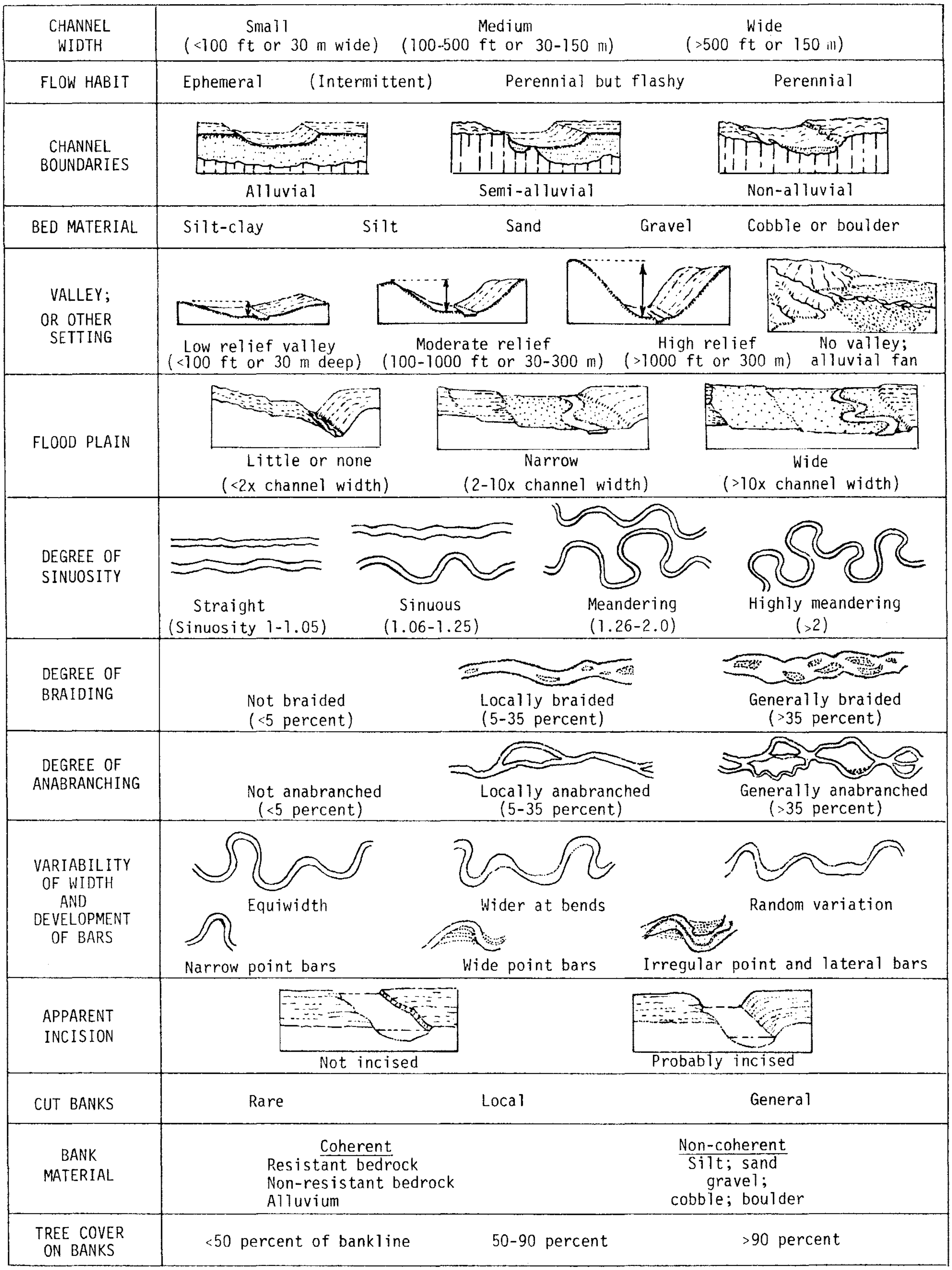

Figure 1. Major properties of alluvial channels.

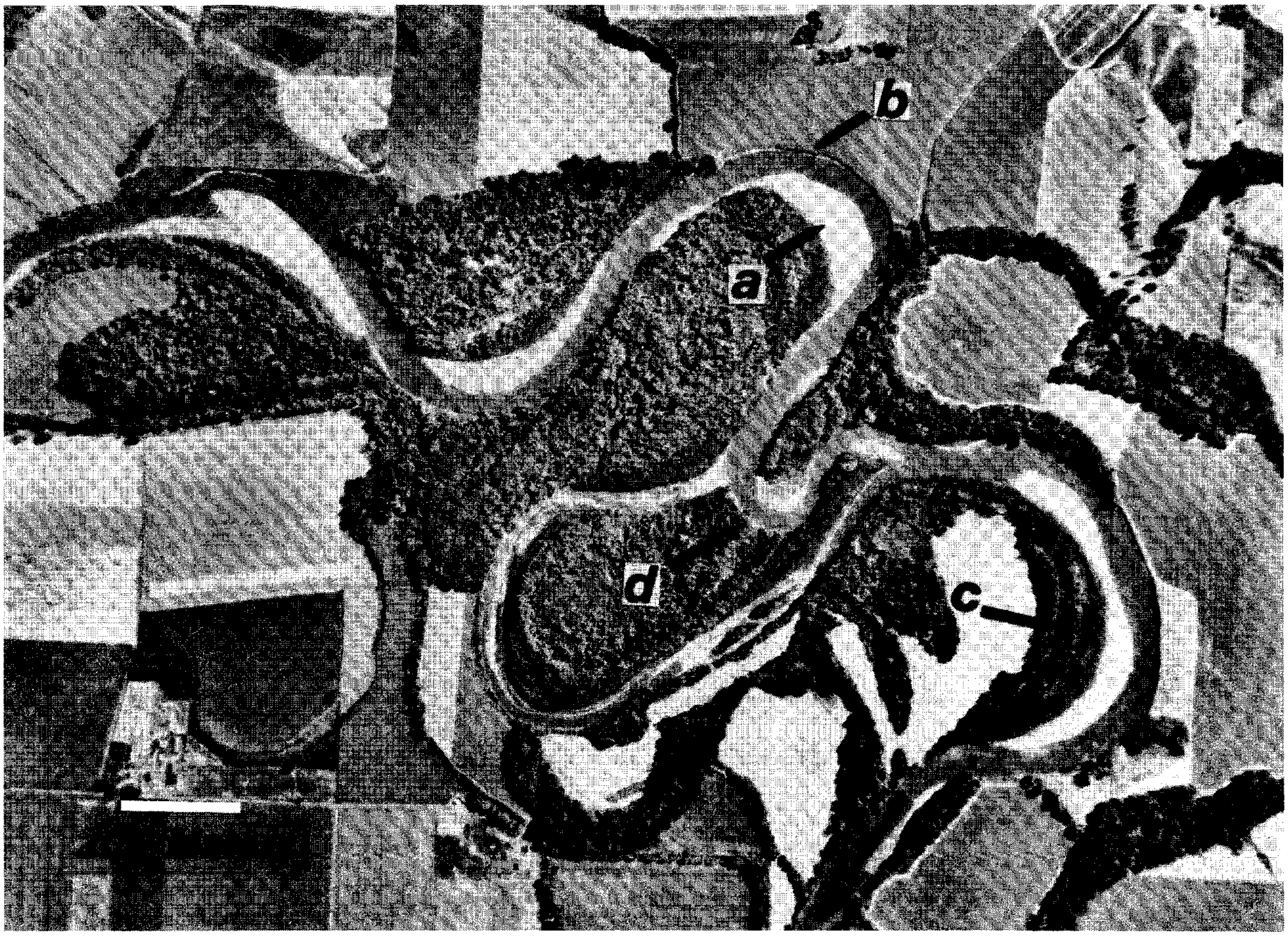

Figure 2. Airphoto showing typical features of a laterally unstable stream (White River near Newberry, Indiana). The stream is at low stage (discharge of 13 m^3/s as compared with average discharge of 128 m^3/s). The outer parts of point bars (a) appear as broad crescents of white sand. Banks (b) opposite the point bars are cut and locally scalloped by lateral erosion. The inner parts of point bars (c) are marked by concentric low ridges and shallow swales (meander scrolls), which represent increments of outward growth. A meander cutoff has occurred recently at (d) about 6 years before the photograph was taken. The rate of lateral erosion by the stream has probably increased greatly since clearing of the forested flood plain in the late 1800's. The median bank erosion rate for the period 1937-66 was 1.7 meters per year (0.02 channel widths per year). (U.S. Dept. of Agriculture photograph, 1966)

On a laterally stable channel, the point bars appear either as narrow crescents or else entirely covered with trees or other permanent vegetation (fig. 3). The bank opposite the point bar is not cut or slumped. The stream width tends to be constant; or if variable, the wider parts are not necessarily at bends but have an apparently random distribution. Streams whose width varies from one place to another by a factor less than two are called <u>equiwidth</u> streams in this report. The association of lateral stability with uniform channel width and narrow point bars has been noted for Canadian rivers (Mollard, 1973, p. 360; Kellerhals, Neill, and Bray, 1972, p. 34).

Bars within the channel have no consistent relation to bank stability. Bars visible at normal stage indicate that bedload, either sand or gravel, is a prominent part of the stream's total load. If a stream is transporting little silt and clay in suspension, the banks may be easily erodible and hence unstable. The degree of braiding of a channel increases with the frequency of midchannel bars. Because of the shifting of these bars and of the braids between

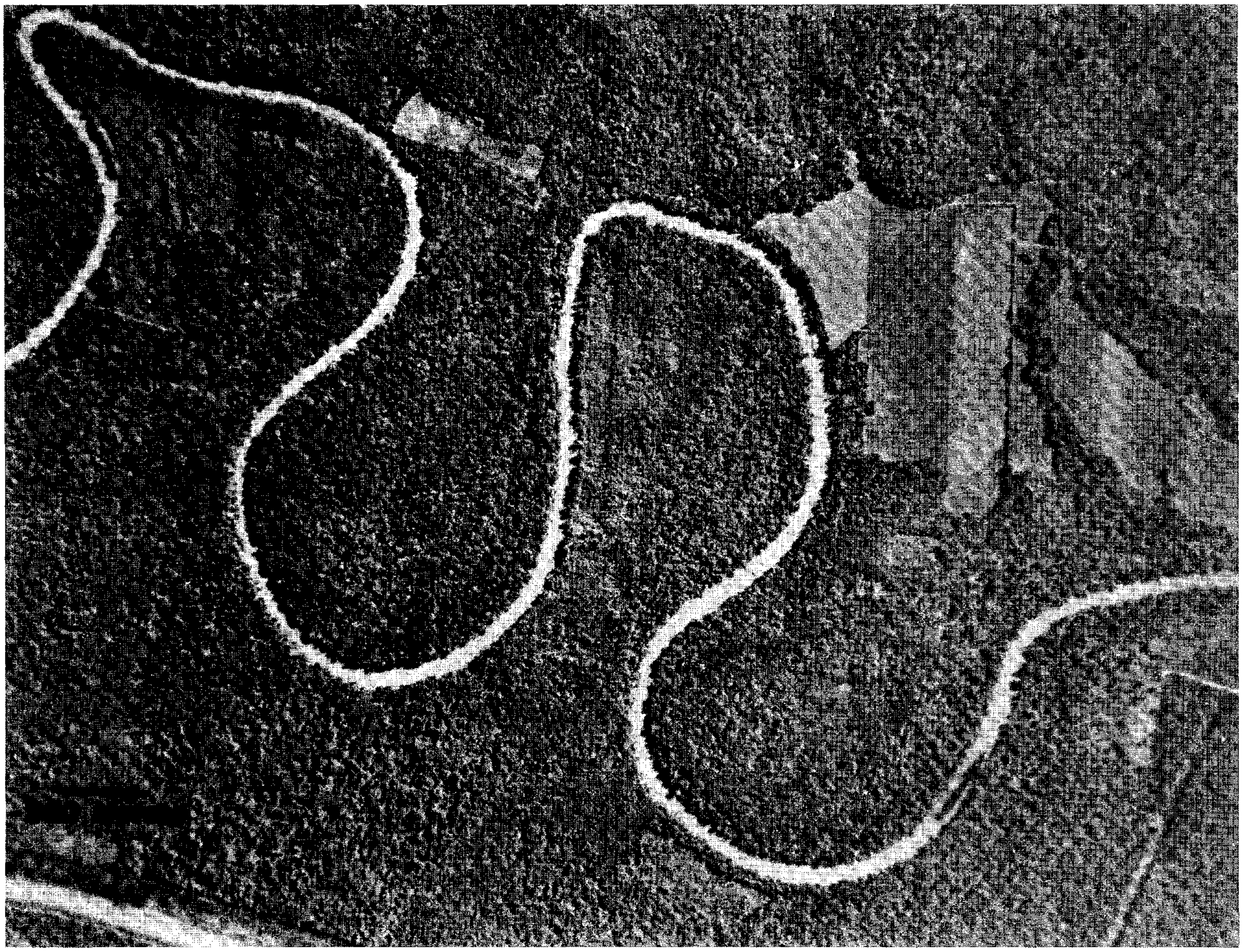

Figure 3. Airphoto showing typical features of a laterally stable stream (Big Muddy River near Grand Tower, Ill.). The river width is nearly constant, and no active point bars are discernible at bends. No bank erosion could be measured for the period 1938-65 by comparison of airphotos at a scale of 1:6,500. (U.S. Dept. of Agriculture photograph, 1965)

them, a braided stream has an unstable bed, but the banks are not necessarily unstable.

An anabranched stream differs from a braided stream in that the flow is divided by islands rather than bars, and the islands are large in relation to channel width. The anabranches, or individual channels, are more widely and distinctly separated and more fixed in position than the braids of a braided stream. An anabranch does not necessarily transmit flow at normal stage, but is an active and well-defined channel, not blocked by vegetation.

ALLUVIAL STREAM TYPES

The channel properties illustrated in figure 1 are combined in various ways for individual streams, no two of which are identical. However, certain associations of properties tend to recur and those associations that recur most often represent a stream type. Four major alluvial stream types are distinguished mainly on the basis of variability of width, nature of point bars, and degree of braiding (fig. 4). Any of these stream types may be anabranched, locally or generally.

The classification applies to a stream reach that is sufficiently long to be representative (usually greater than about 50 channel widths in length) and reasonably homogeneous in its properties. A stream is unlikely to be of the same type throughout its length. Most streams change in a downstream direction, and some change from place to place along their courses. Any meandering stream reach is likely to include some local straight or nearly straight segments, but it is not feasible to classify these separately, because they vary in length from a few channel widths to perhaps 10 or 20 channel widths. Reaches of the four major stream types that are considered to be reasonably homogeneous, together with their characteristic properties and information on their lateral stability, are illustrated in figures 5-19.

The properties of each stream type, as arranged in figure 4, change gradually from one to the next, and some properties have a definite trend. For a stream of a particular size, as measured by bankfull discharge or the mean annual flood, channel width tends to increase from equiwidth to braided streams, and sinuosity tends to decrease. Available evidence indicates that the percentage of bedload (sand or gravel) in the total sediment load tends to increase from equiwidth to braided. The absence of bars in many equiwidth streams suggests a minor transport of bedload, whereas the abundance of bars in braided streams suggests a major transport of bedload. Lateral stability tends to decrease from equiwidth streams to braided point-bar streams but to increase again for braided streams without point bars. However, lateral stability has not been measured for many braided streams and some may be unstable.

Because channel properties are gradational from one stream type to the next, a particular stream may fall at the boundary between two types. For example, it may be difficult to decide whether a stream is of the equiwidth or wide-bend type if channel width is greater at some bends than at others, or if the width at bends does not clearly exceed the width at straight reaches by a factor of two. A borderline stream is probably gradational in stability characteristics between two categories.

A stream may change in type with time, and works of man--such as clearing of a flood plain forest or closure of a dam--may bring rapid changes in stream type and behavior. For this reason, proposed or probable projects along a stream may be considered in assessing its future behavior. The works of man do not necessarily lead to a decrease in stability. For example, on the Sacramento River the closure of Shasta Dam has evidently reduced the rate of bank erosion (Brice, 1977, p. 47).

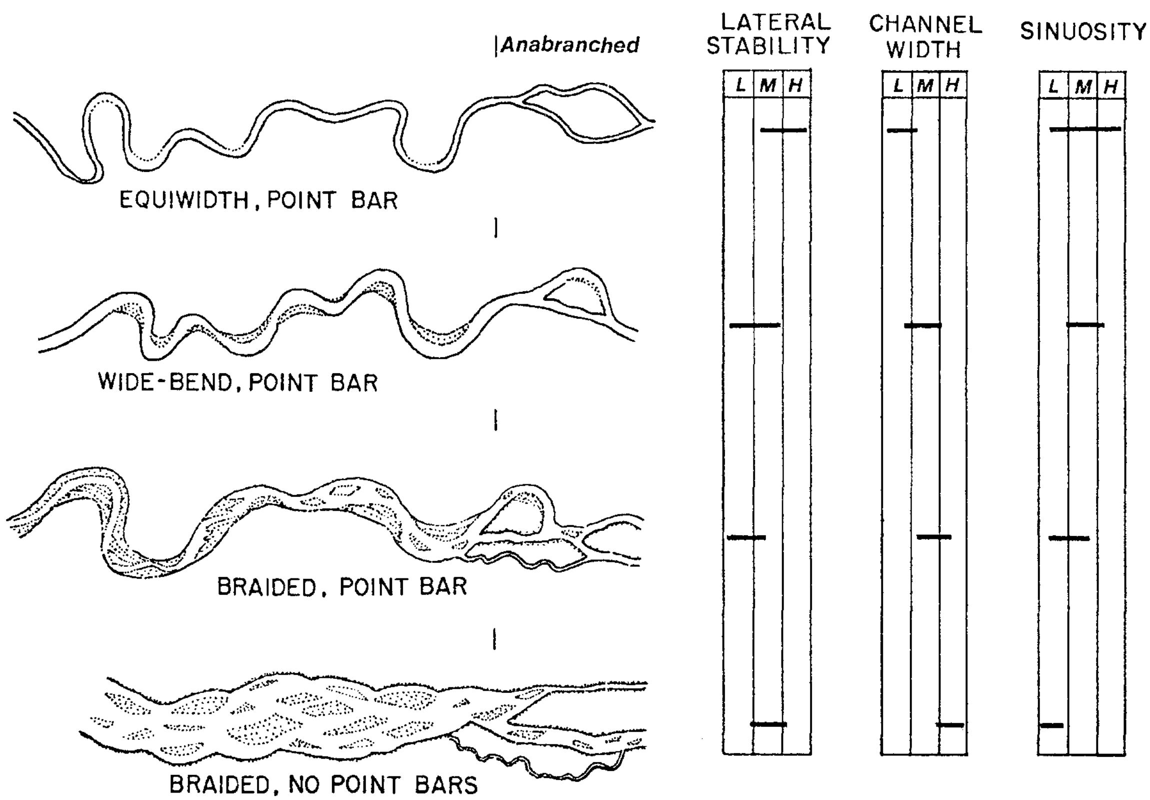

Figure 4. Alluvial stream types.

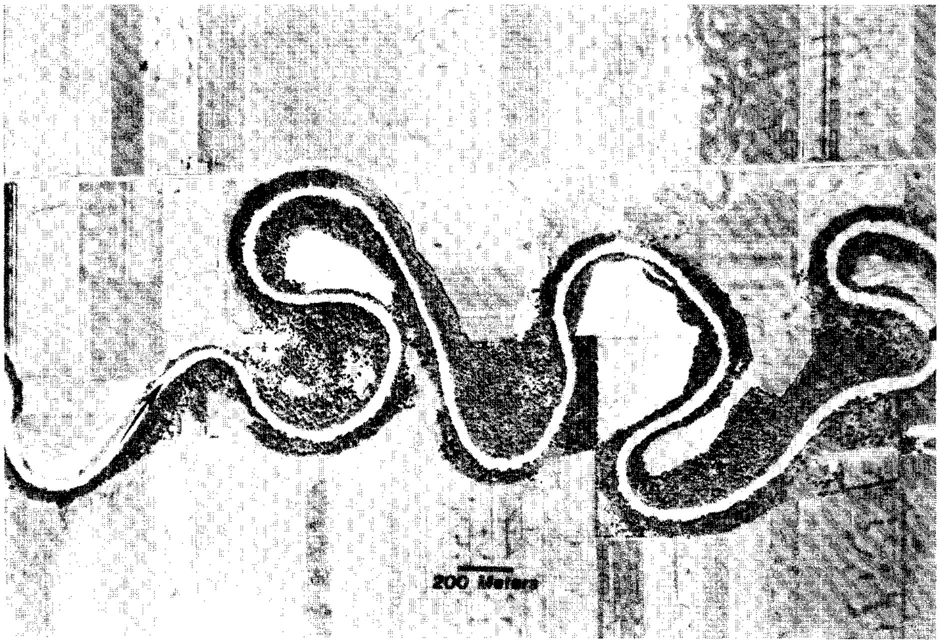

Figure 5. Equiwidth stream incised into cohesive surficial materials (Red River of the North near Perley, Minn.). Channel width is nearly constant. Here, the surficial materials are lake-bed deposits and glacial till. Banks are about 8 meters high, and bank erosion occurs mainly by slumping. The lateral erosion rate is very low. (U.S. Dept. of Agriculture photograph, 1966)

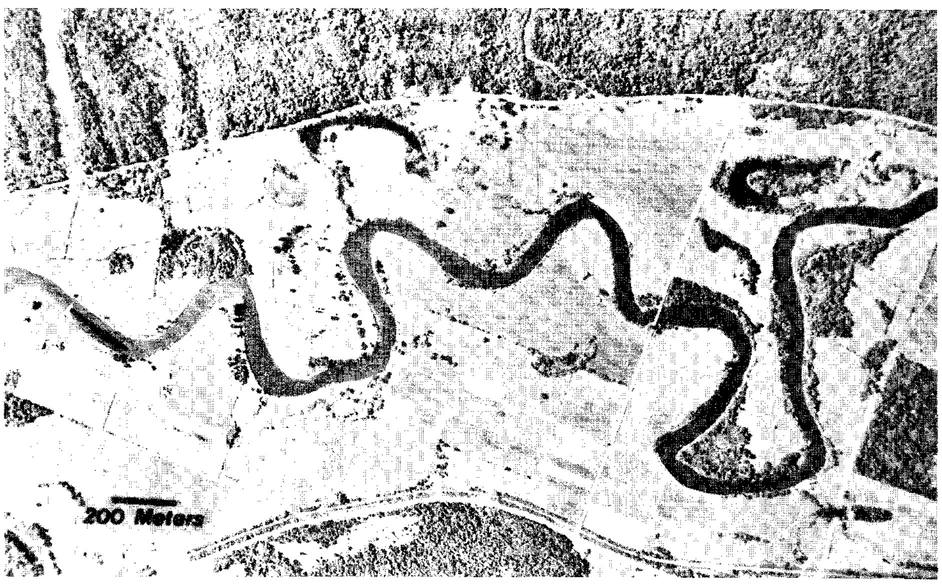

Figure 6. Equiwidth stream moderately incised into alluvium (Snoqualmie River near Carnation, Wash.). Bank height is about 5 meters. Point bars are narrow and steeply sloping toward the stream, and no scrolls are visible at the bars or on the flood plain. Oxbow lakes indicate that lateral migration has occurred, and cut banks are visible at some bends. No lateral erosion could be measured for the period 1952-64, from comparison of airphotos at a scale of 1:4,600. (U.S. Dept. of Agriculture photograph, 1964)

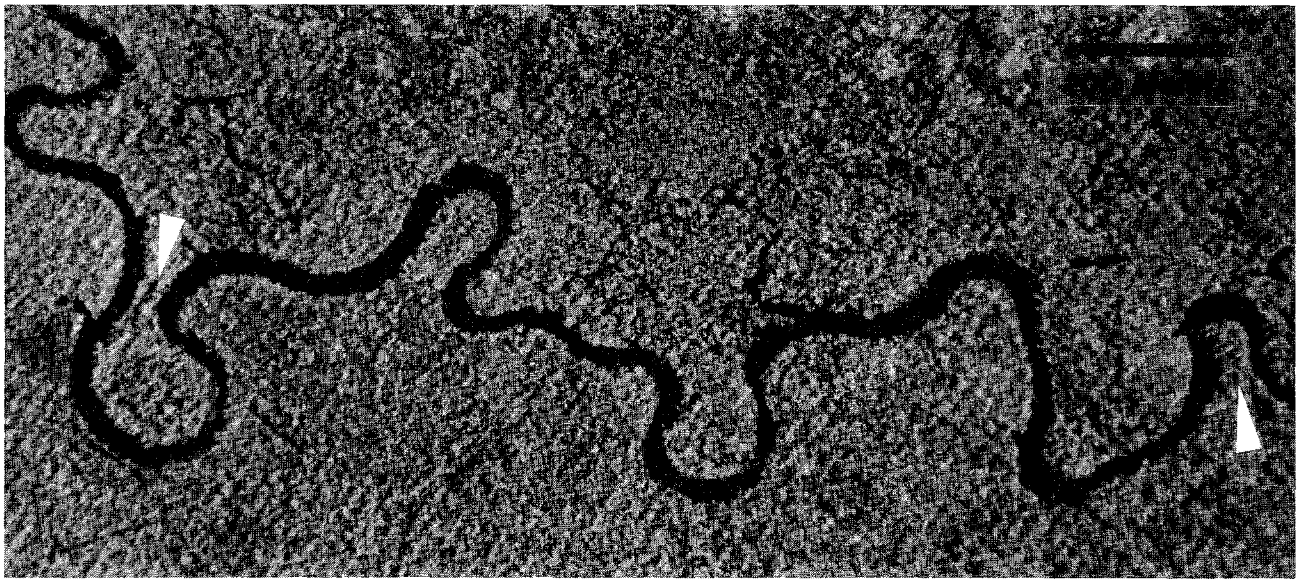

Figure 7. Equiwidth stream on a swampy, densely forested coastal plain (Lumber River near Boardman, N. Car.). Channel width is not constant, but the wider parts (which exceed the narrower in width by a factor of about 1.5) tend to be randomly distributed rather than restricted to the axes of bends. River stage is above normal, and narrow point bars, visible at low stage, are submerged. Two neck cutoffs of meanders (indicated by pointers) that appeared imminent on a 1937 photograph had not occurred by 1966. The lateral erosion rate is very low. (U.S. Dept. of Agriculture photograph, 1966)

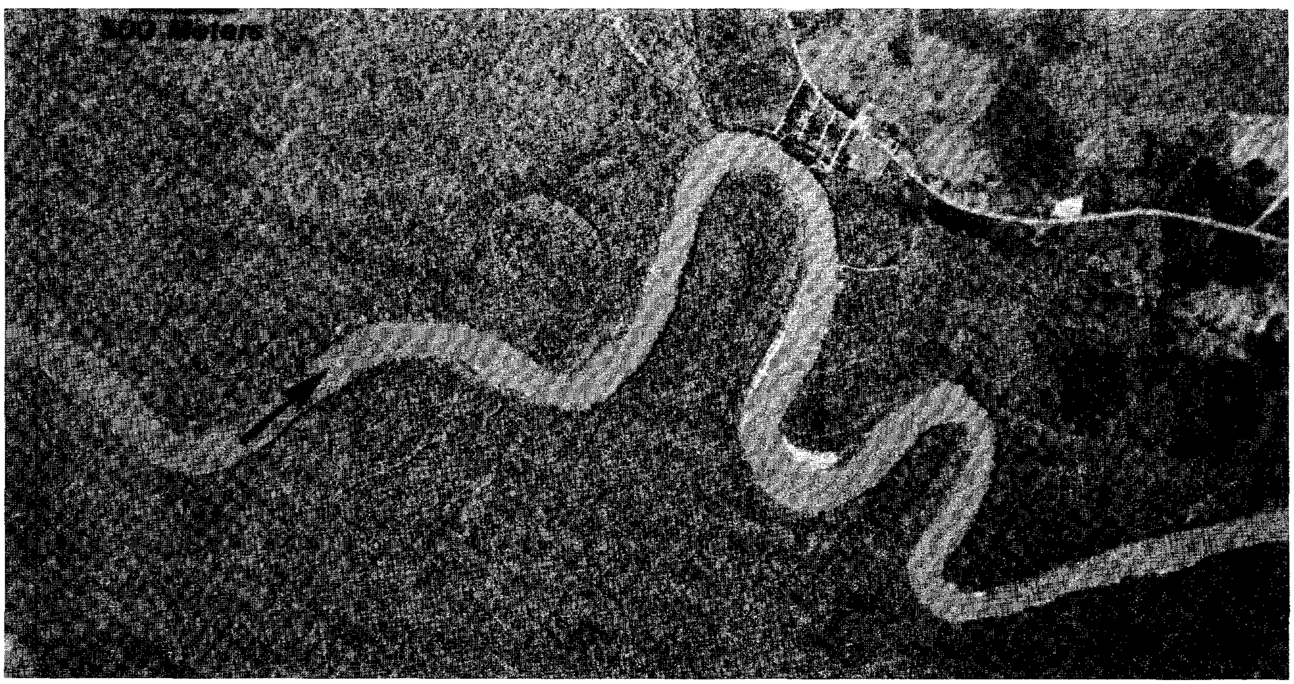

Figure 8. Large equiwidth stream on a densely forested flood plain (Apalachicola River near Bristol, Fla.). Bare point bars are visible at normal stage at some bends. Meander scrolls are present but mostly concealed by vegetation. The median bank erosion rate for this reach is about 1.2 meters per year (0.006 channel widths per year), which is low for streams of this size. (U.S. Dept. of Agriculture photograph, 1972)

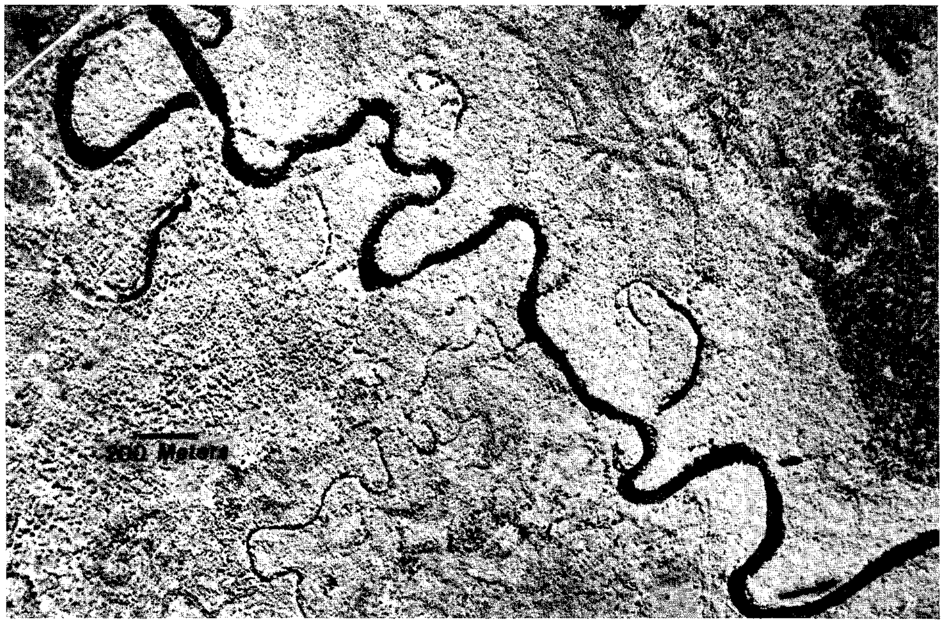

Figure 9. Equiwidth stream on swampy, forested glacial drift plain (Muskegon River near Marion, Mich.). Channel width is not constant, but the wider parts tend to be randomly distributed. The oxbow lake at upper left was formed by artificial cutoff for highway purposes in 1939. The straight relocated channel, constructed to have a greater width than the natural channel, showed little change during the period 1939-79. Note the small equiwidth tributary entering from lower left. (U.S. Dept. of Agriculture photograph, 1952)

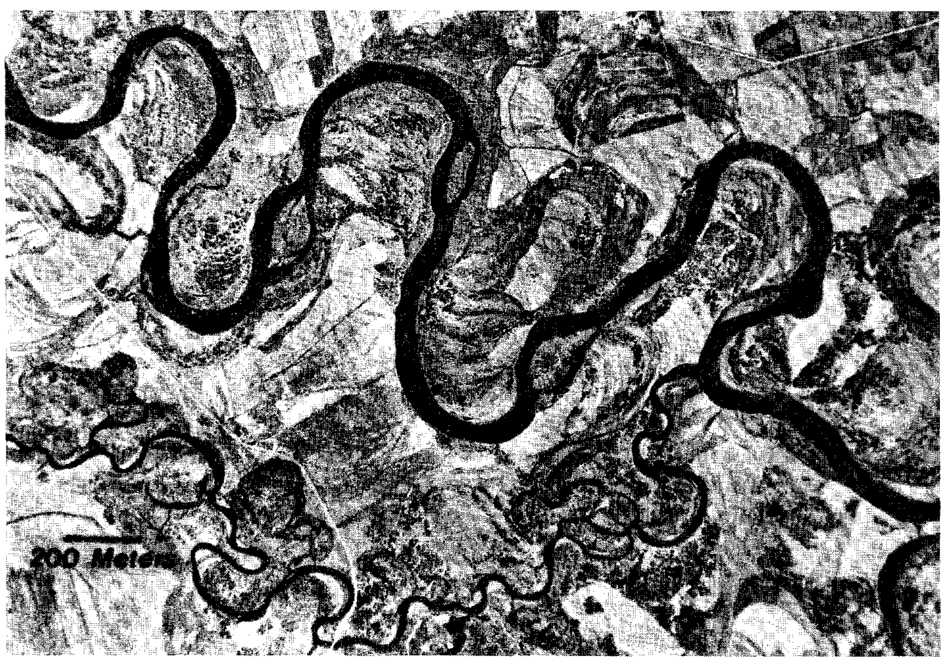

Figure 10. Equiwidth stream, locally anabranched, on a semiarid plain (Henrys Fork near Rexburg, Idaho). The flood plain is marked by many meander scrolls and filled oxbow lakes. The meandering subsidiary channels are anabranches. Point bars are sparsely vegetated, probably because of the dryness of the climate. The stream has an unstable aspect because of the sparse vegetation and the conspicuous meander scrolls, but no lateral erosion could be discerned for the period 1951-66 by comparison of airphotos. (U.S. Dept. of Agriculture photograph, 1951)

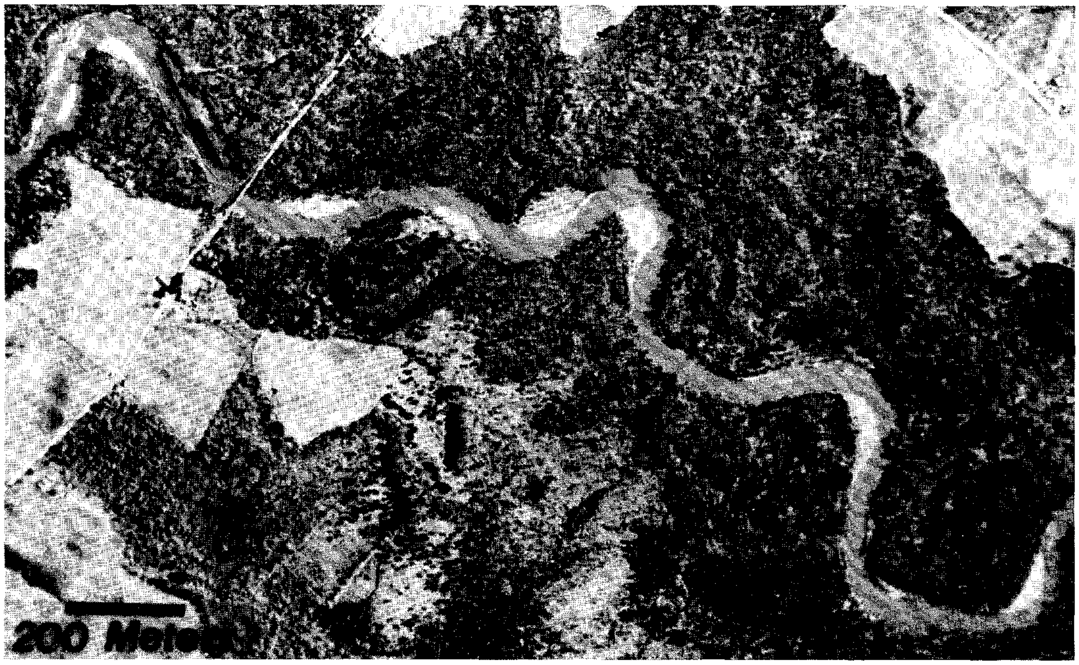

Figure 11. Wide-bend point-bar stream on a flood plain forested with hardwood trees (Tallahala Creek near Runnelstown, Miss.). Wide, bare point bars and cut banks are present at some bends but not at others. Filled oxbow lakes are visible from place to place along the stream course but none appear to be recent. Meander scrolls have apparently been obliterated by vertical accretion of sediments during floods. The median lateral erosion rate for the reach is 0.49 meter per year (0.004 channel width per year) for the period 1942-70. (U.S. Dept. of Agriculture photograph, 1942)

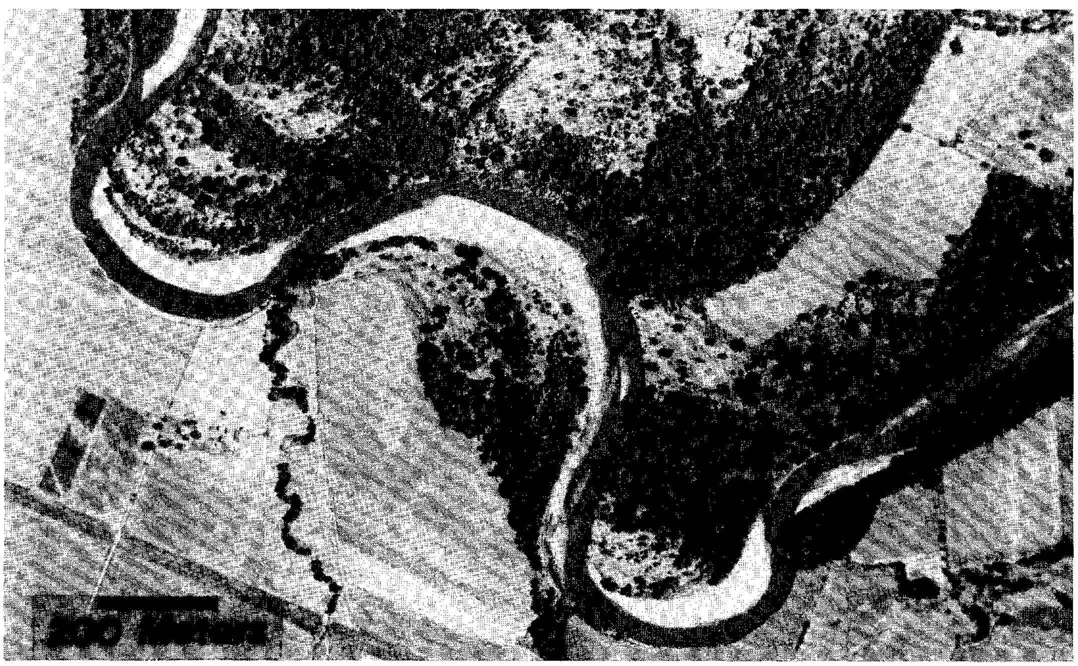

Figure 12. Wide-bend point-bar stream on a deforested flood plain (Iowa River near Iowa City, Iowa). The channel width at bends is about twice the width at straight reaches. The stream is at low stage, and the bare point bars are somewhat wider than at normal stage. Meander scrolls and filled oxbow lakes are visible on the flood plain. The median erosion rate for this reach was 0.8 meter per year (0.011 channel width per year) for the period 1937-70. The most rapid erosion occurred at the bend near center, lowermost in the photograph. (U.S. Dept. of Agriculture photograph, 1937)

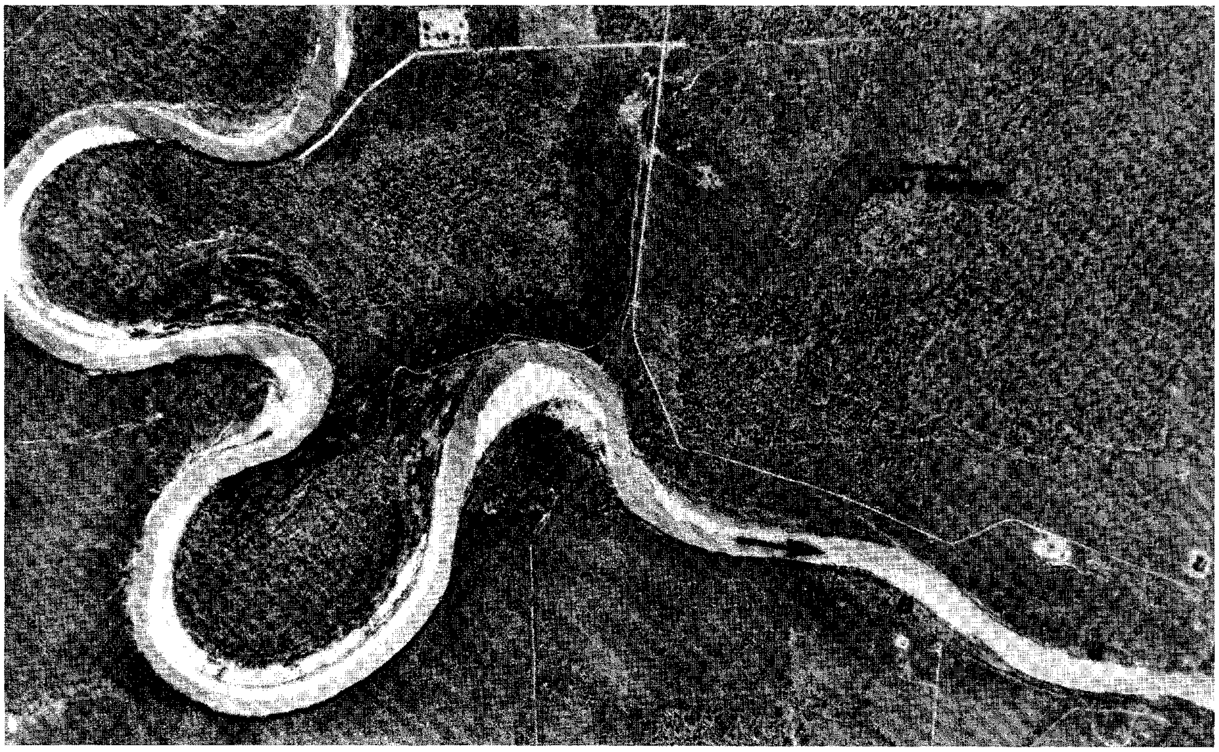

Figure 13. Wide-bend point-bar stream, incised, on a sparsely wooded plain (Brazos River near Richmond, Texas). The bank erosion rate is high, as indicated by the wide point bars and the cut and slumped banks. Meander scrolls are discernible at the point bars but are lacking on the flood plain, as are oxbow lakes. The banks are about 10 meters in height, and overbank flows are uncommon. The median lateral erosion rate for the period 1948-64 was 2.3 meters per year (0.015 channel width per year), but erosion in the straight reaches at right was much less than this value. Alternate bars in the straight reach are indicated by the letter "a". Bank erosion on the Brazos has endangered both bridge and pipeline crossings. (U.S. Dept. of Agriculture photograph, 1957)

Figure 14. Wide-bend point-bar stream, transitional to a braided point-bar stream (Sacramento River near Butte City, Calif.). Meander scrolls are poorly developed on the wide point bars and lack a regular concentric pattern. At high stages, the flow tends to cut across the necks of meander loops; and loops are cut off by chutes rather than by gradual closure of the neck. The median erosion rate for this reach was about 5 meters per year (0.015 channel width per year) for the period 1947-74. Because of the tendency toward chute cutoffs, bank erosion is difficult to control. (U.S. Dept. of Agriculture photograph, 1970)

Figure 15. Wide-bend point-bar stream, anabranched and braided, in a semiarid cold-winter region (Yellowstone River near Billings, Mont.). The main channel, at top, is separated from an anabranch, below, by a large island. Median bank erosion rate for the main channel is about 3 meters per year, but the anabranch migrated laterally at one point by about 300 meters during a 29-year period. On a distinctly anabranched stream, an anabranch may be of a different stream type from the main channel, and it may migrate at a different rate. (U.S. Dept. of Agriculture photograph, 1940)

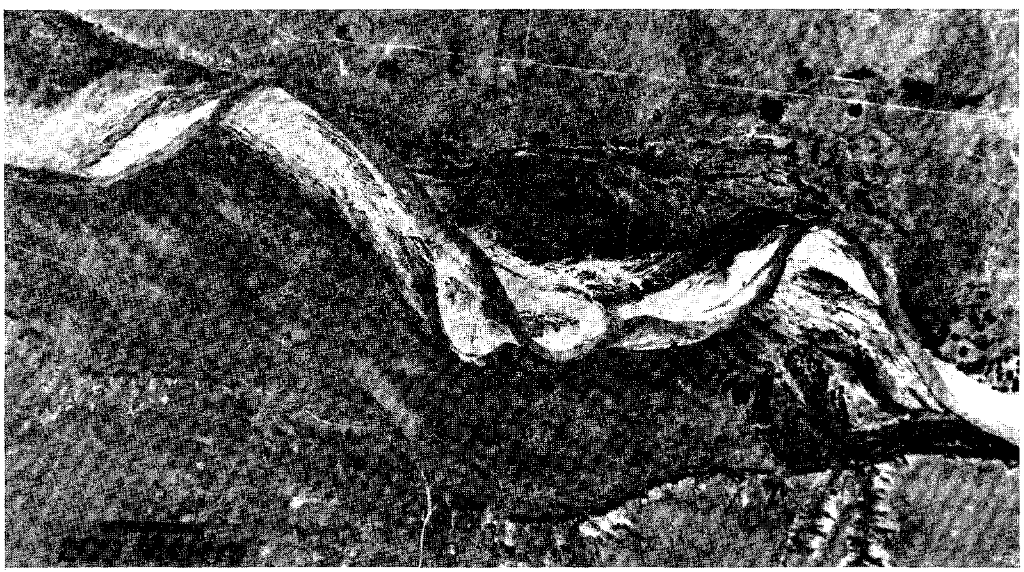

Figure 16. Braided point-bar stream on the semiarid Great Plains (North Canadian River near Guymon, Okla.). The thalweg, which meanders within a wide sandy channel, shifts during floods and tends to erode banks rapidly where it impinges against them. Trees are sparse along the bankline. Point bars are discernible but are marked by a braided pattern rather than by concentric meander scrolls. Oxbow lakes are lacking. For this reach, the median bank erosion rate for the period 1936-66 was 4.5 meters per year (0.064 channel width per year). The lateral erosion of the lowest surface on which vegetation is well established is regarded as bank erosion; in many places the bankline is not marked by a well defined scarp. (U.S. Dept. of Agriculture photograph, 1966)

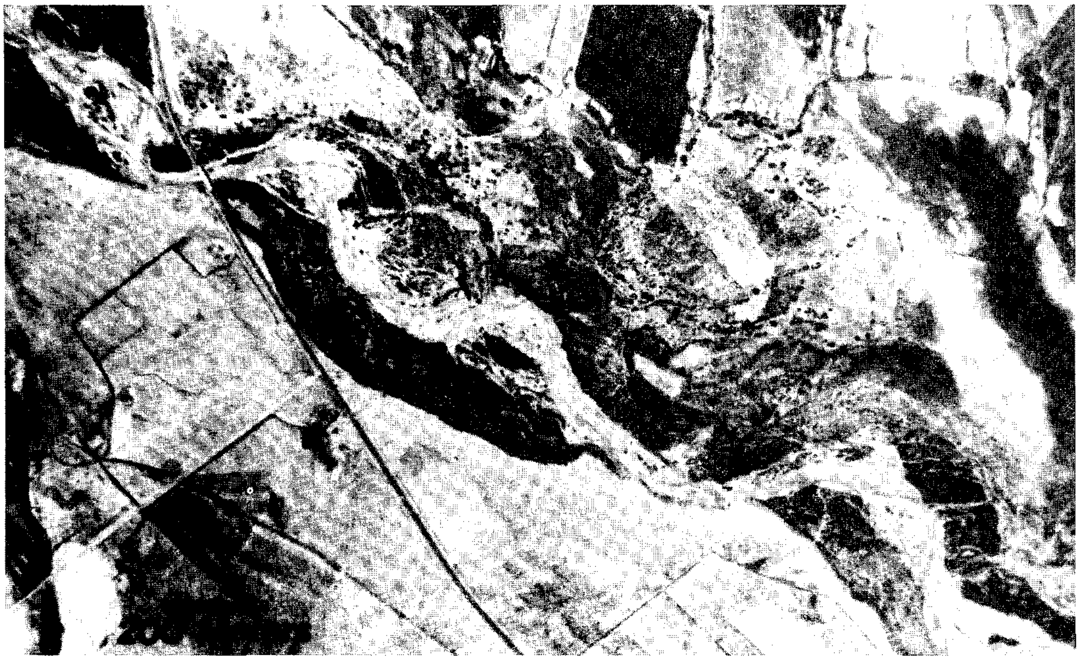

Figure 17. Braided point-bar stream, locally anabranched, in an arid cold-winter climate (Greybull River near Basin, Wyo.). Point bars are marked by a distinctly braided pattern, rather than by concentric scrolls. The meandering thalweg tends to shift during floods and to erode vegetated parts of the flood plain. Anabranches are more transient than for streams in humid regions. During the period 1939-64, the median bank erosion rate was 1.7 meters per year (0.019 channel width per year). (U.S. Dept. of Agriculture photograph, 1939)

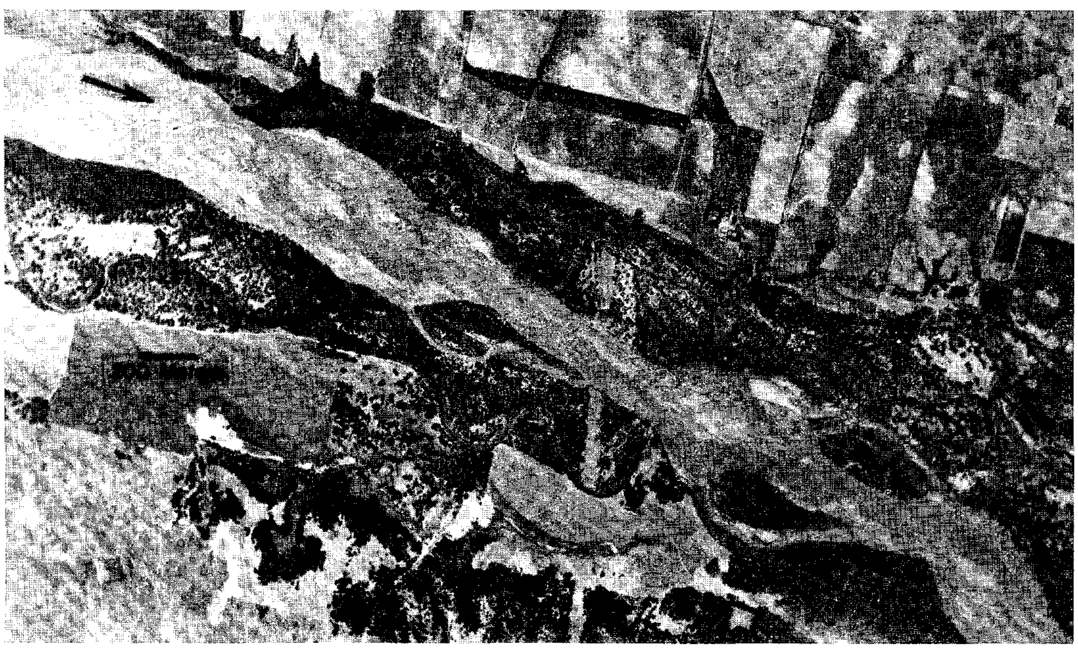

Figure 18. Braided and locally anabranched sandbed stream on the semiarid Great Plains (Niobrara River near Spencer, Nebr.). The flow in the main channel is divided by bars or small islands (vegetated), channel width is variable, and sinuosity is low. Larger islands separate anabranch from the main channel, but an anabranch is usually abandoned after several decades. The bankline is scalloped from place to place, as at upper left, where sinuous braids impinge against it. Although the bed of a braided stream is unstable because of the shift of bars, the bank erosion rate is not necessarily high. For the period 1939-67, the median bank erosion rate for this reach was about 1 meter per year (0.0027 channel width per year). (U.S. Dept. of Agriculture photograph, 1967)

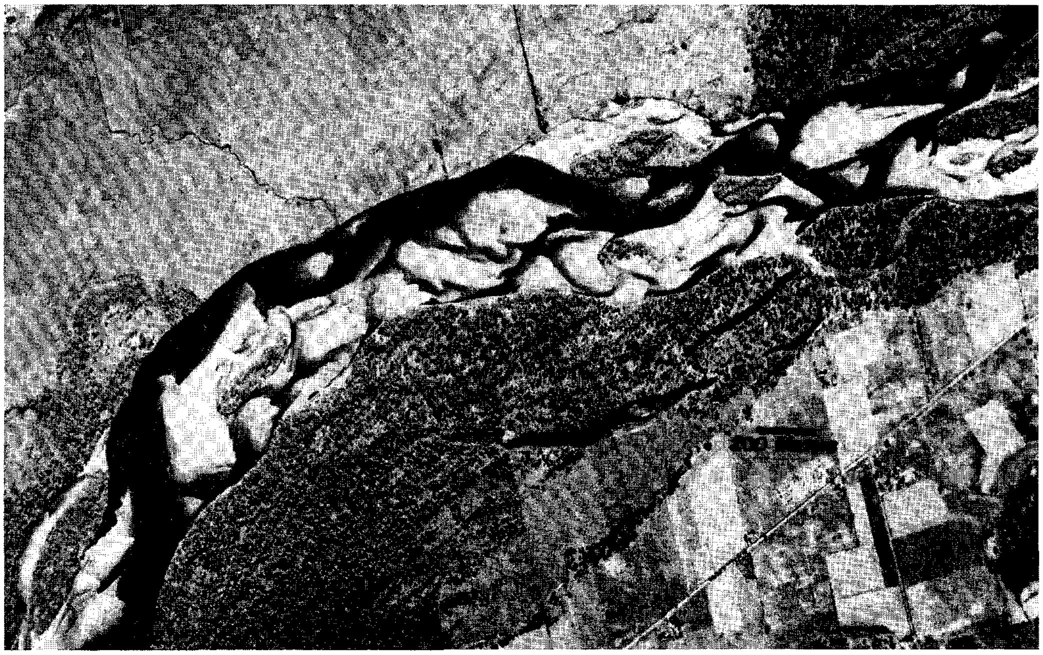

Figure 19. Braided sandbed stream in a humid region (Wisconsin River near Prairie du Sac, Wisc.). Flow within a distinct main channel is divided by sand bars and small vegetated islands. The leaf-like aspect of the bars, as seen on airphotos, is characteristic of sand bars. The bars shift frequently, but the islands (indicated by pointers) showed little change during the period 1940-68. Median bank erosion rate for this period was 0.36 meter per year (0.001 channel width per year). (U.S. Dept. of Agriculture photograph, 1940)

LATERAL STABILITY

FIELD ASSESSMENT

Maps and cross sections of a channel are routinely made for the planning of a bridge or channel alteration, and large-scale airphotos of the site are obtained by most highway agencies. Field assessment of channel stability upstream and downstream from the proposed construction site is a logical and useful extension of this work. This assessment provides insight into the potential lateral channel migration at the bridge site, and thus into the need for countermeasures and the depth to which foundations should be placed for pile bents on the flood plain. For channel relocations, the stability of a relocated channel is related to the prior stability of the natural channel (Brice, 1980). For any construction work involving a stream channel, documentary evidence of channel instability prior to construction would be useful in the event of subsequent litigation. Suggestions are offered here for making a field assessment, and illustrations are provided of banks having different degrees of stability, which has (for most of the examples) been determined for the last 20-30 years by comparison of time-sequential airphotos.

Assessment of bank stability is best made at a stage near or below "normal". At high river stages (at or near bankfull), channel bars are submersed and the banks are not only partly submersed but difficult of access. In most regions of the United States, the most favorable time of year for assessment is the late fall, after the leaves have fallen from deciduous vegetation and before the streambanks become muddy. Along most channels, summer is an unfavorable time for photographs because of concealment of the banks by vegetation. Use of a boat greatly facilitates observations and permits access to steep banks that may be inaccessible from above. Before field observations are made, the reach should be studied carefully by stereoviewing of airphotos. Notes should be made on places to be observed, particularly those that look unstable or are concealed by vegetation. Points of access can also be readily determined from the airphoto. Equipment for the assessment should include a camera, a topographic map, and an enlarged airphoto of the reach.

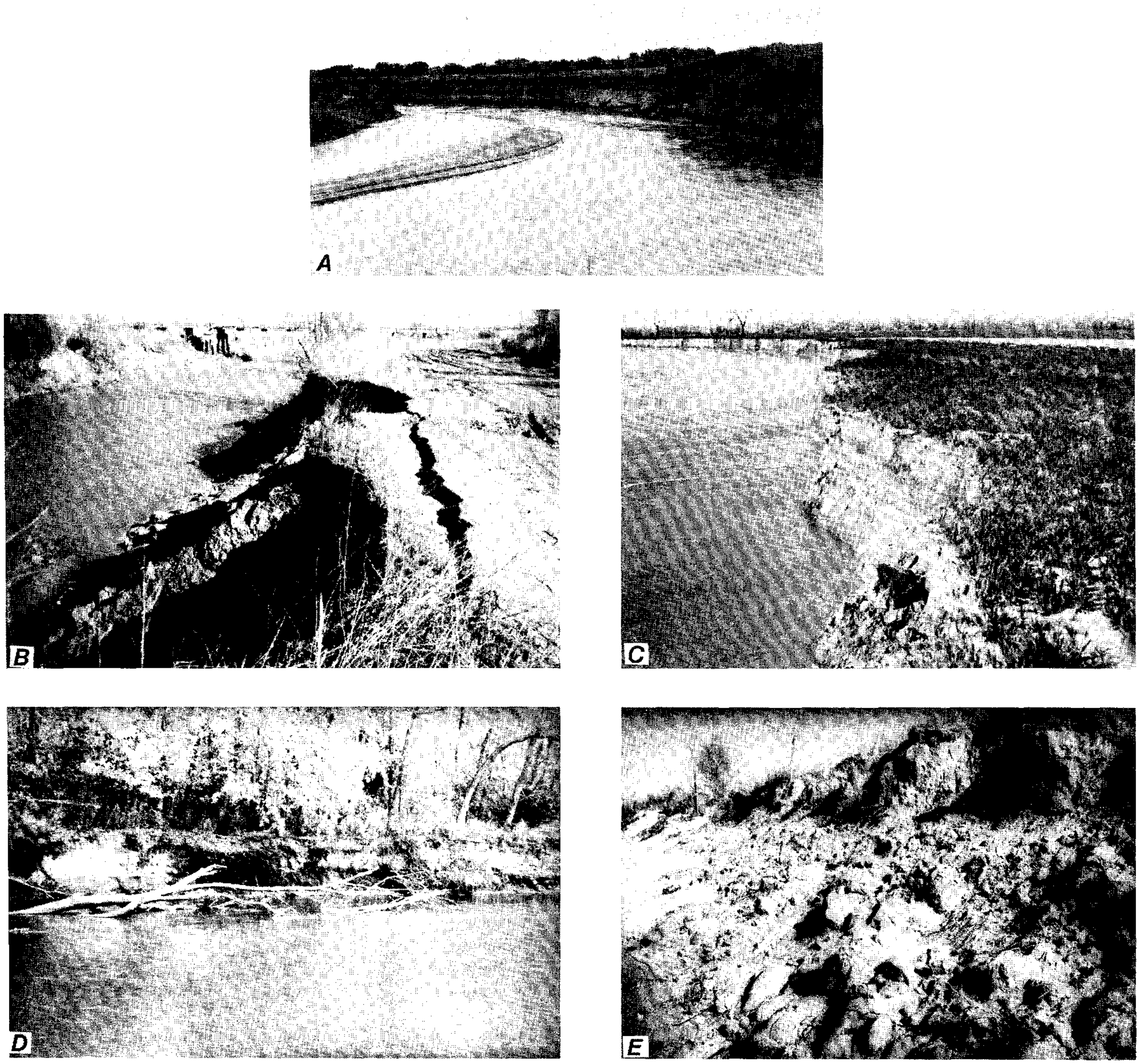

Figure 20. Unstable banks, erosion rate moderate to high. A, South Loup River, Custer Co., Nebr. Cut bank at bend is composed of sand and silt and represents a low terrace. B, Obion River near Union City, Tenn. Banks are steep and ungraded. C, Sacramento River near Chico, Calif. Bank is nearly vertical to water's edge. D, Iowa River near Marengo, Iowa. E, Obion River near Union City, Tenn. Recently slumped soil has accumulated at toe of bank, forming a slope.

Unstable banks, erosion rate moderate to high--Unstable banks are not smoothly graded, the slope angle usually exceeds 30 percent, and a cover of woody vegetation is rarely present (fig. 20). At a bend, the point bar opposite an unstable cut bank is likely to be bare at normal stage (fig. 20A), but it may be covered with annual vegetation and low woody vegetation, especially willows. Where very rapid erosion is occurring, the bankline may have irregular indentations. Fissures, which represent the boundaries of actual or potential slump blocks along the bankline (fig. 20B), indicate the potential for very rapid bank erosion. At the site shown in figure 20B, the steep ungraded banks are a consequence of channel straightening and clearing of the flood plain forest.

Field estimates of the rate at which a bank has been receding are likely to be inaccurate unless the position of the bank at some past time is known. Loss of agricultural land (fig. 20C) may be apparent from the boundaries of fields. Exposed tree roots in a near-vertical bank, and recently undercut trees (fig. 20D), suggest a moderate to rapid erosion rate.

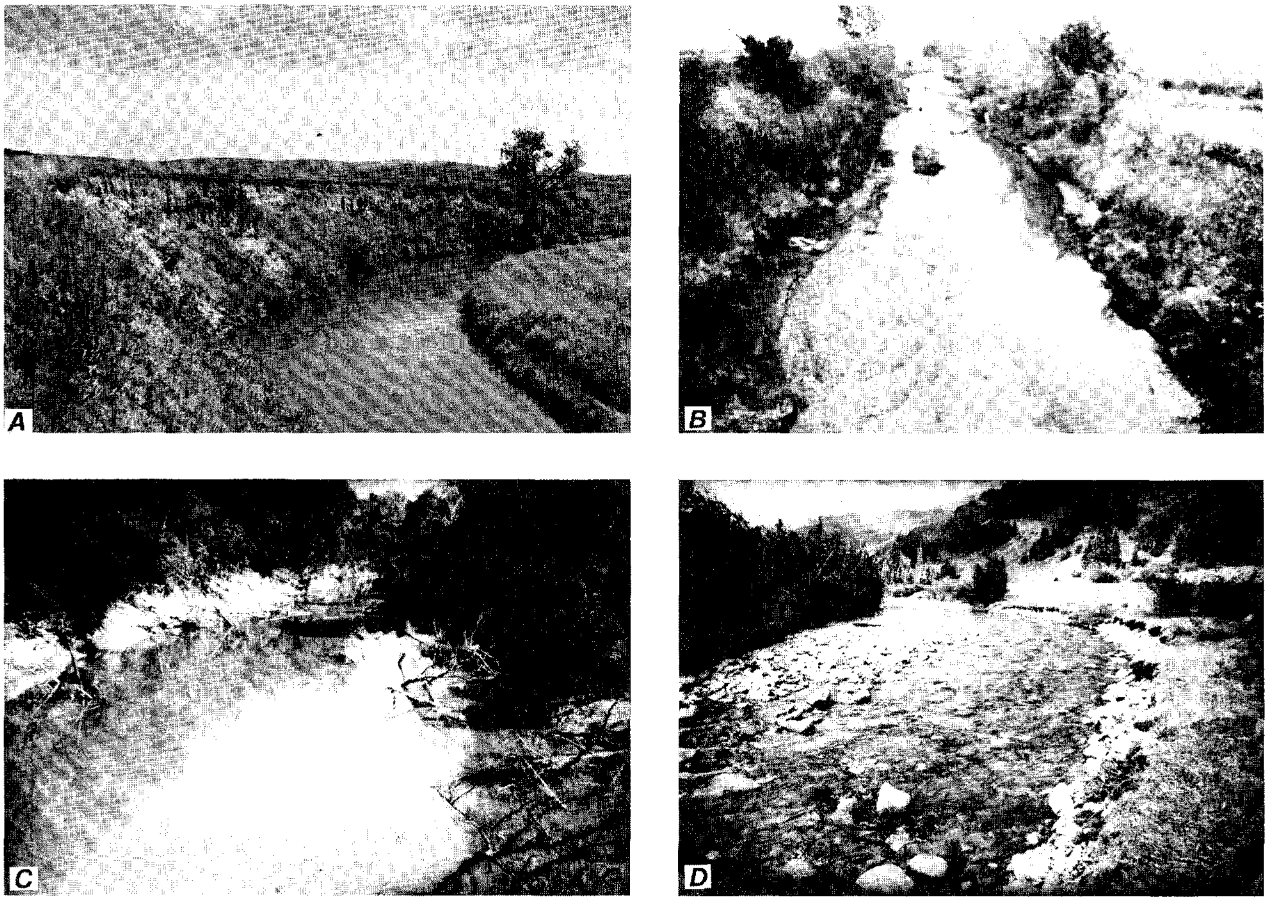

Figure 21. Unstable banks, erosion rate low to moderate. A, South Loup River, Custer Co., Nebr. B, Middle Creek near Lincoln, Nebr. Perennial grasses and small trees on the bank suggest a slow erosion rate, although the bank is steep and not smoothly graded. C, Big Black River near Canton, Miss. D, Dolores River near Lizard Pass, Colo.

Unstable banks, erosion rate slow to moderate-- If a bank is partly graded, the degree of instability is difficult to assess and reliance is placed mainly on vegetation (fig. 21). The grading of a bank typically begins with the accumulation of slumped material at the base (fig. 20E) such that a slope is formed, and progresses by smoothing of the slope and the establishment of vegetation. In figure 21A, the upper bank is locally vertical and the lower graded slope is mostly mantled with grass and weeds. The massive silt in the bank tends to maintain a vertical face and its erosion is probably due more to rainwash than to the stream. The position of the mature cottonwood tree, at far right, and the well vegetated point bar, indicate that the recent erosion rate has been slow. In figure 21B, perennial grasses and small trees on the bank suggest a slow erosion rate, although the bank is steep and not smoothly graded. In figure 21C, the lower bank is bare but partially graded, and the upper bank is densely forested. Bank erosion, and the abundant fallen trees in the channel, are attributed to a recent severe flood, and the bank is likely to be "healed" by regrowth of vegetation. In figure 21D, the low banks consist of boulders and cobbles overlain by a thick sod mat. In view of the shallow depth and roughness of the channel, the size of the bank materials, and the bank protection afforded by draping of the undercut sod mat, the erosion rate is probably slow.

Stable banks, erosion rate very slow-- Stable banks tend to be graded to a smooth slope and the slope angle is usually less than about 30 percent (fig. 22). In most regions of the United States, the upper parts of stable banks are vegetated, but the lower part may be bare at normal stage, depending on bank height and flow regimen of the stream. Where banks are low, dense vegetation may extend to the water's edge at normal stage. Mature trees on a graded bank slope are particularly convincing evidence for bank stability. Where banks are high, occasional slumps may occur on even the most stable graded banks. Shallow mountain streams that transport coarse bed material tend to have stable banks.

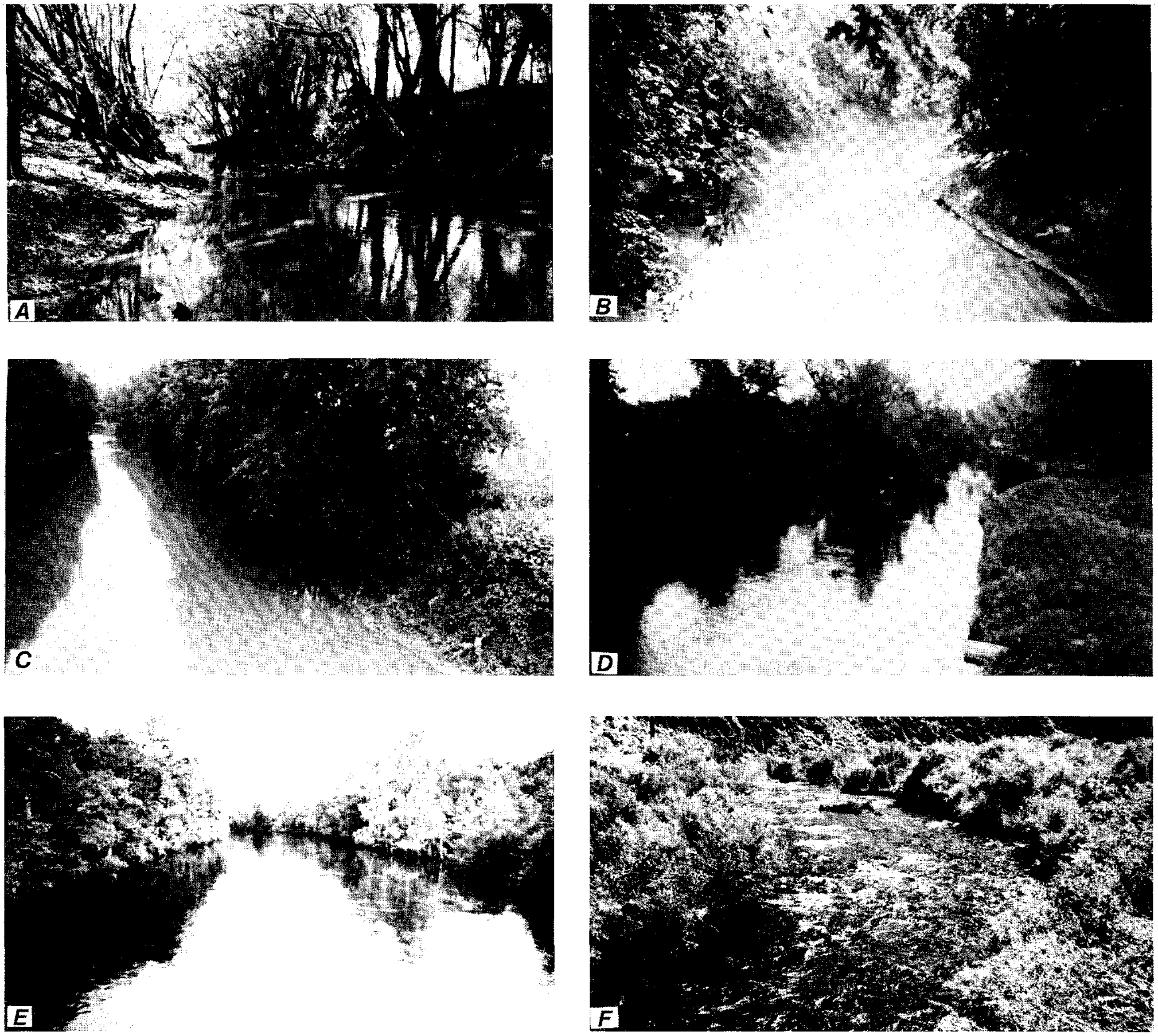

Figure 22. Stable banks, erosion rate very low. A, Rolling Fork near Boston, Ky. Moderately incised channel, mature trees on graded bank. B, Patoka River near Princeton, Ind. Lower bank well graded but unvegetated. C, Blanchard River at Glandorf, Ohio. Lower bank well graded and protected by dense mat of tree roots. D, Fawn River near White Pigeon, Mich. Low banks, densely vegetated. E, Little Pee Dee River at Galivants Ferry, S. Car. F, East Walker River near Bridgeport, Calif. Stream is shallow, high gradient, bed material in the cobble to boulder size range.

In figure 22A, the channel is moderately incised, as indicated by the bank height of about 6 meters. The banks attain a slope angle of about 30 percent, but are generally wooded with mature trees. Bank recession occurs locally by slumping, although no slumps are present at this site. In figure 22B, the stable lower bank is well graded but unvegetated. Bank height is about 3 m, and bank slope in the range of 20 to 30 percent. Banks of this type are typical of humid region channels in cohesive alluvium, as are the banks in figure 22C. The stability of the unvegetated lower bank is increased by a mat of tree roots. The low, well vegetated banks shown in figure 22D are typical of channels in swampy, recently glaciated terrain. On swampy coastal plains, trees tend to grow to the edge of channels (fig. 22E) and the stability of the bankline is indicated by the maturity of the trees. On many mountain streams, as in figure 22F, erosive velocities at the bankline are diminished by the shallow stream depth and the high channel roughness.

REPETITIVE SURVEYS OF CHANNEL CROSS SECTION

Accurate measurement of lateral channel migration, as well as changes in channel size, shape, and bottom elevation, requires repetitive surveys of the channel cross section. This is particularly true of small streams and of streams bordered by dense vegetation. Under some circumstances, it may be advisable to begin such surveys in the early planning stages of a bridge or roadway and to continue them at intervals after construction is completed.

A major difficulty in repetitive surveys is the relocation of end points of a cross section. Experience with regard to this and other aspects of channel surveys has been briefly summarized by Emmett (1974). Emmett recommends that end points be marked by 1.2-m lengths of 10 to 15-mm diameter steel rods driven nearly flush with the ground surface. To insure relocation of the rods, each should be referenced to at least two additional triangulation points, marked by a concrete monument or in some other permanent way. An intersection of two tape measurements from triangulation points may be used to locate the steel rods, and location is most accurate when the angle of intersection is near 90°. Triangulation points are best located where a transit or other surveying instrument can be positioned above them.

MEASUREMENT ON AIRPHOTOS AND MAPS

The lateral stability of a channel is measured from records of its position at two or more different times, and the available records are usually maps or airphotos. Surveyed cross sections, although useful, are rarely available. For most agricultural regions of the United States, airphotos are available for a time span of about the past 40 years. Maps have the advantage of a longer time span, but the scale and accuracy of maps made in the United States before 1900 (with the exception of some surveys of major rivers by the Corps of Engineers, and some topographic maps of the U.S. Geological Survey) are rarely adequate for reliable measurement of channel changes. The methods of measurement described in this section are intended mainly for airphotos but apply equally well to maps. Also, maps are usually needed to determine the scale of airphotos: information on height of aircraft and focal length of lens may not be readily available.

Reference points, which are needed for comparison of airphotos or maps made at different times, are likely to be much more common on airphotos than on maps. Field boundaries and trees are among the useful reference points that are discernible on airphotos but rarely on maps. Also, it would not be possible to reproduce on maps all the details of channel morphology that appear on airphotos, and some features are apparent on airphotos that would likely be missed by observation on the ground.

Acquisition of maps-- General map coverage of the United States, at a scale and accuracy suitable for measurement of stream channel changes, is represented by the National Topographic Maps of the U.S. Geological Survey. Maps of the series having the largest scale (7½-minute series, scale 1:24,000) are suitable for measuring changes in medium and large channels (width greater than about 30 m) but are not very satisfactory for smaller channels. According to the standard of accuracy for topographic quadrangle maps, no more than 10 percent of well defined map points tested shall be in error more than 0.02 inch at the publication scale. For maps of the 7½-minute series, an error of 0.02 inch amounts to 40 feet (12.2 meters) on the ground. Channels and channel properties are well depicted on most Geological Survey maps made by photogrammetric methods, which came into use about 1950. Earlier maps, made from field surveys, tend to be less satisfactory. On all the topographic quadrangle maps, an attempt is made to represent the channel width at "normal" discharge, as commonly represented by the line of permanent vegetation along the channel.

Most highway agencies routinely acquire topographic quadrangle maps for various purposes. Map indexes for each state and information on ordering maps are available on request from the Branch of Distribution, U.S. Geological Survey, 1200 South Eads Street, Arlington, Virginia, 22202.

Acquisition of airphotos-- The following steps are involved in locating and acquiring existing airphotos of a particular site: (1) Determine the name and address of agencies or companies that hold airphoto negatives of the site. (2) Determine the identification numbers of the desired negatives. This usually involves the acquisition of a photo index sheet. (3) Order prints of the desired negatives.

Assistance in determining existing (and planned) airphoto coverage of a site can be obtained from:

National Cartographic Information Center (NCIC)
507 National Center, Reston, Virginia 22092
Telephone (703) 860-6045

NCIC has established an automated information system for conventional aerial photography projects--the Aerial Photography Summary Record System, or APSRS. The principal products of this system are State Base Graphics, graphic indexes that show the coverage of conventional airphoto projects over each state. Each state catalog, which is published twice yearly, can be obtained by writing or telephoning NCIC. The present APSRS contains descriptions of over 100,000 projects sent in by 135 different contributors, including 43 federal, 23 state, and 15 local government agencies; 52 private companies; and two universities (Lauterborn, T. J., 1980, p. 1539).

The addresses and telephone numbers of contributors are listed in a Directory of Contributing Agencies, which can be obtained from NCIC on request. Information in each State Base Graphics catalog includes the approximate time at which each project was flown and the scale category of the photography. Airphotos listed at scales smaller than 1:40,000 are not suitable for measurement and interpretation of small or moderate sized channels, unless enlargements of good resolution can be obtained.

After the name and address of the agency holding project negatives of the site has been obtained, the agency must then be contacted for information about a photoindex or other means of ascertaining the identification number of specific airphotos. For most sites, the agency holding the negatives is likely to be either the Agricultural Stabilization and Conservation Service (ASCS) of the U.S. Department of Agriculture, or the EROS Data Center of the U.S. Geological Survey, Department of the Interior. From the ASCS, photoindexes of counties can be obtained either on microfilm (aperture cards) or as prints (20 x 24 inches) on paper. From EROS, photoindexes of 7.5' quadrangles can be obtained as prints on paper. About a month is required for delivery of photoindexes, and another month for delivery of airphotos that have been ordered.

Many state highway agencies obtain, by contract or with their own aircraft, repetitive airphoto coverage of sites that are under consideration for bridge or highway construction. The time span of such photography may well be adequate for assessment of lateral stability, particularly if the hydrologic events that occurred are representative of the flow history of the stream. In requesting airphotos from this source, as well as other sources, consideration should be given to overlapping coverage for stereoviewing, which is critical for airphoto interpretation and the identification of reference points.

Reference points on time-sequential airphotos-- Measurement of bank erosion on two time-sequential airphotos requires the identification of reference points that are common to both airphotos. Discernible reference points are either cultural or natural features, which can be identified with much greater confidence by stereoviewing than by examination of a single airphoto. If a stereopair is not available, a magnifying lens will assist in identification on a single airphoto. In most regions, and particularly on flood plains, cultural features are more likely to maintain recognizable identity over a period of several decades than are natural features.

Cultural features useful as reference points include road and fence corners, buildings, irrigation canals, and bridges. Examples are illustrated in figure 23, in which point 1 is a road corner, point 2 is a fence corner, point 3 is the end of a bridge, and point 4 is a farm building. Points close to the stream have been selected. Because of possible scale variation across the photograph, related to tilt, the usefulness of a reference point decreases with increasing distance from the channel.

Among the natural features that maintain recognizable identity are rock outcrops and sharp bends in small incised channels. Isolated trees are sometimes useful, as are drainage features on flood plains and lakes of distinctive shape. On some wide, densely forested flood plains, no reliable reference points may be discernible in the vicinity of the channel, and bank erosion distances can only be estimated.

Airphoto scale-- Measurement of bank erosion on an airphoto (or on the projected image of an airphoto) requires an accurate determination of its scale. The actual scale of an airphoto rarely corresponds with the nominal scale at which the project was planned, as based on height of aircraft and focal length of lens. For example, most Department of Agriculture photographs are flown at a nominal scale of 1:20,000 or 1:40,000, but the actual scale commonly differs from the nominal by as much as 5 percent.

Unless the length of some feature on the airphoto is accurately known, the scale of an airphoto is determined by the distance between two reference points identifiable both on the airphoto and on a map of the same area. If possible, the points should be selected so that a line connecting them passes through or near the center of the airphoto; this minimizes the effects of scale variation. The calculation of airphoto scale from map scale is simplified by use of the ratio, distance on map/distance on airphoto. For example, the distance between points x and y is 125.5 mm on a map and 161.5 mm on an airphoto, and the map scale is 1:24,000. The airphoto scale is then 125.5/161.5 X 24,000, or 1:18,650.

At a scale of 1:20,000, 1 mm on the airphoto equals 20 m on the ground. Small distances (up to about 15 mm) can be measured with a magnifying comparator to the nearest 0.1 mm and can be extrapolated to the nearest 0.05 mm, which represents 1 m on the ground. Longer distances measured with a millimeter scale and read with a magnifying lens can be extrapolated to the nearest 0.5 mm, which represents 10 meters on the ground. Except for large streams, a scale of 1:20,000 is too small for measurement of bank erosion, and a scale of 1:5,000 (for which 0.5 mm on the photograph represents 2.5 m on the ground) is more suitable.

Scale variations due to tilt are present to some degree in most airphotos, and the amount of potential variation increases with distance from the center of the photograph. Reference points near the edge of a photograph are best avoided, as are photographs in which the stream image is near the edge. Correction for tilt is difficult without specialized photogrammetric equipment, because the amount and direction of tilt is unknown. However, one instrument for comparing time-sequential airphotos, the Bausch and Lomb "Zoom Transfer Scope", is equipped with anamorphic lenses that permit compensation for geometric anomalies in a photographic image.

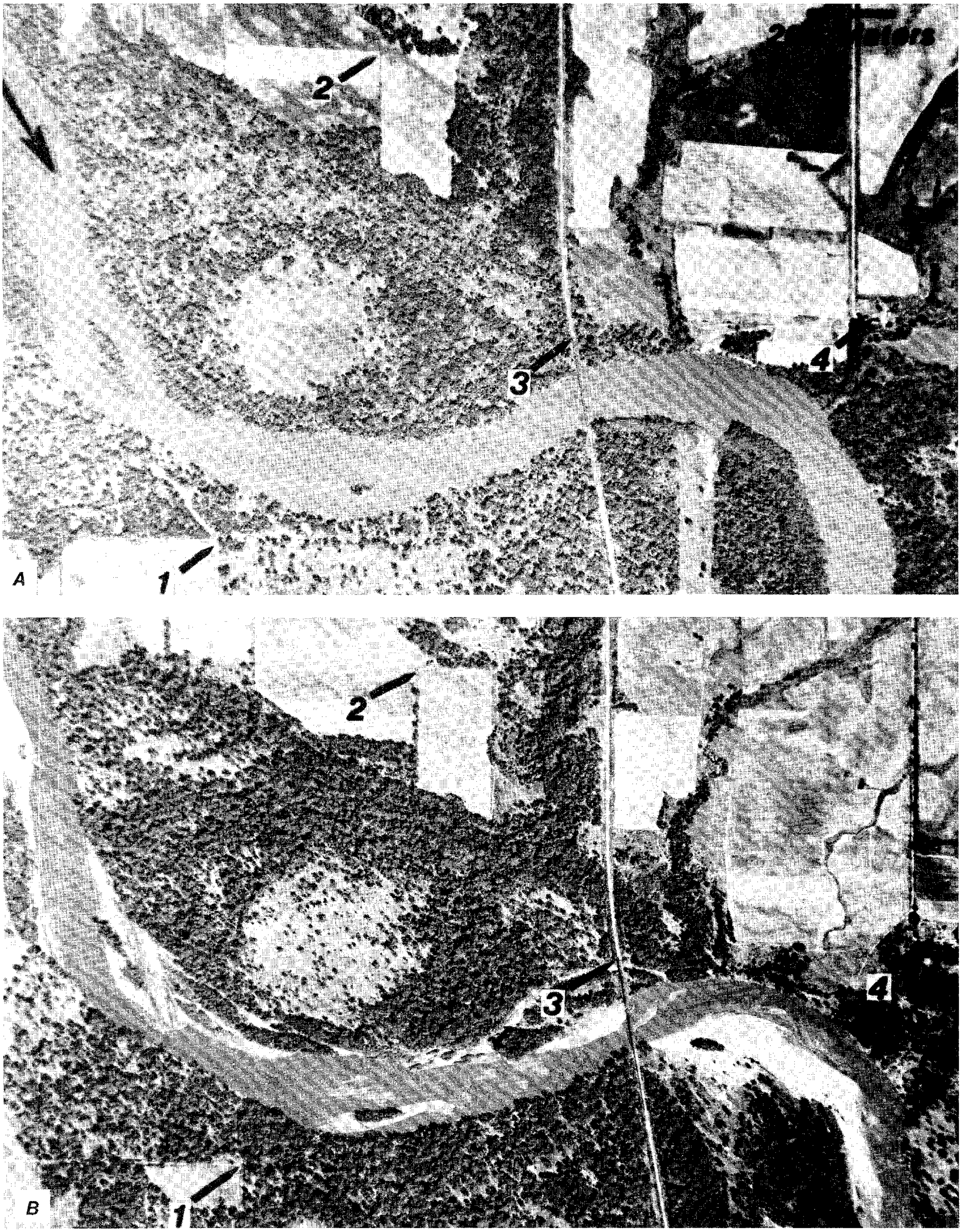

Figure 23. Example of reference points on time-sequential airphotos. A, Points, indicated by numbers, on 1969 airphoto of Cedar River, Iowa. B, Corresponding points on 1937 airphoto. (U.S. Dept. of Agriculture airphotos)

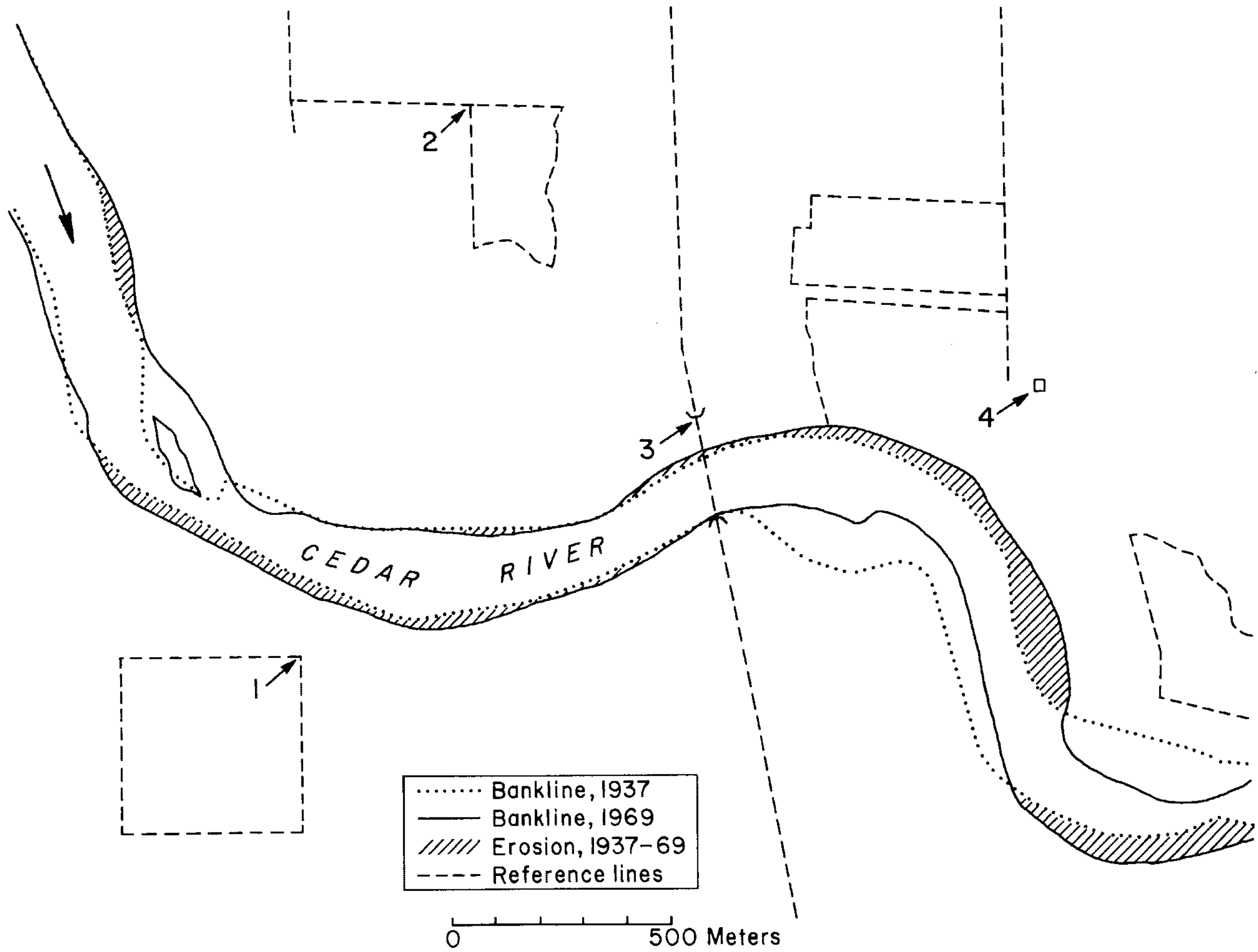

Figure 24. Time-sequential banklines for Cedar River, Iowa. Reference points and lines were traced from the projected image of the airphoto in figure 23A.

Methods of comparison-- Distances of lateral bank erosion can be (1) estimated by visual comparison of two airphotos flown at different times; (2) measured by scaling distances from fixed reference points common to both photographs; or (3) measured on a drawing (or photograph) on which the sequential channel banklines are superimposed at the same scale.

Visual comparison is useful for a preliminary assessment of stability. Significant changes in channel position can usually be discerned qualitatively without accurate determination of reference points or scales. In figure 23, for example, some migration of the right bank is evident downstream from reference point 1. Below point 4, a substantial migration of the left bank has occurred. These changes are discerned partly by perception of changes in the channel planform, to which the eye is sensitive, and partly by changes in relation to reference points or lines. In this example, the lines are the boundaries of fields.

Erosion distances in the vicinity of reference points can be determined by measurement from reference point to bankline. In figure 23, the distance from reference point 1 to right bank, as measured perpendicular to the bankline, is 138 m on the 1969 airphoto and 161 m on the 1937 airphoto; thus, the bank has eroded about 23 m in 32 years. If two reference points are so located that a line connecting them trends roughly parallel with the bankline, erosion distances can be measured from the connecting line. Similarly, linear features on the airphoto, such as field boundaries, can in some cases be projected parallel to a bankline.

Assessment of lateral stability and the behavior of meander loops is greatly facilitated by a drawing on which the time-sequential banklines are superimposed (fig. 24). In preparing such a drawing, the airphotos (or maps) are matched in scale and the pairs of fixed reference points are placed in register. This involves either (1) bringing the airphotos to the same scale by photographic enlargement, or (2) matching of scales by projecting the image of one airphoto onto another (or a tracing of the other). Some ways of doing this are described below.

The accuracy of bank erosion measurements made by comparison of airphotos is limited by several factors. These include (1) the number, sharpness, and reliability of reference points; (2) the accuracy with which the airphoto scales have been determined; (3) the scale size of the airphotos (or tracings) on which measurements are made; (4) scale variations in the airphotos resulting from tilt or from differences in elevation between channel and reference point; and (5) identification of the channel bankline, which may be obscured by vegetation or not clearly resolved on the airphoto. Because these factors differ from one site to the next, no general estimate of accuracy can be given.

Photographic enlargement-- Government agencies that hold the largest number of airphoto negatives (ASCS, Eros Data Center) offer standard enlargements at several stipulated magnifications from the original negatives. For example, ASCS offers an enlargement at 4.16 times the dimensions of the original negative, which changes a nominal 1:20,000 scale to a nominal scale of 1:4,800. Time-sequential airphotos of the same nominal scale can rarely be enlarged to exactly the same scale by the use of standard enlargement, because the scale of the original negatives is rarely the same.

The enlarged photographs are compared by superimposing a tracing of one over the other, or over a tracing of the other. Frosted acetate film is best for tracing, because it is more transparent than tracing paper. The tracings include not only channel features of interest (banklines, bars) but all reference points and other features that may be useful for registration: roads, buildings, trees, field boundaries. If the photo scales are not identical, or if scale variation is present in either photo, only a part of the image can be held in register at one time, and the channel reach must be examined in short segments. Registration can sometimes be facilitated by drawing lines between the reference points, to form a network of triangles.

Reflecting projector-- Time-sequential airphotos can be compared by the use of a vertical reflecting projector (fig 25) which may be available in photogrammetry divisions of state highway agencies. A standard paper photographic print is projected onto a horizontal table. Almost complete darkness is needed and the maximum enlargement is about 5 times. Thus, a print of scale 1:20,000 can be enlarged to 1:4,000. The projected image is too dim for projection directly onto another photograph. Instead, one photograph is projected at the desired scale onto a sheet of paper and a tracing is made of channel features, reference points and lines, and any other features that may be useful for registration (fig. 24). The image of the second photograph is now projected onto the tracing. The scale,

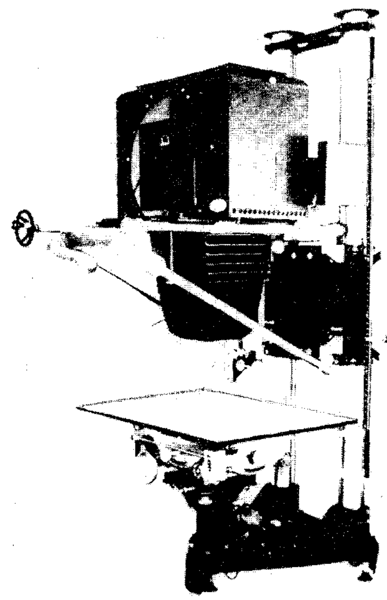

Figure 25. Vertical reflecting projector.

as determined by the spacing between reference points, is matched by adjustment of magnification. Reference points are matched in position by moving the tracing as required to register it with the projected image. Channel boundaries and other features of the projected image are now superimposed by tracing, preferably in a distinctive color.

Graphical data transfer instrument-- An instrument for transferring information from an airphoto to a map, airphoto, or other data base is available commercially (fig. 26). In the comparison of time-sequential airphotos, images of both photographs can be viewed simultaneously and handily matched in scale and position, so that the two images appear superimposed. The image of one photograph, projected by reflection, is matched with the other photograph lying flat on a table. An earlier bankline can be traced onto a later photograph. The possible range in magnification of the projected image is continuous from 1 through 14 times; however, at magnifications of 5 times and above, the field of view is only a small part of a standard 23 x 23 cm (9 x 9 inch) airphoto. For the field of view to include reference points not immediately adjacent to the stream, a scale in the range of 1:15,000 to 1:20,000 must be used. The writer has difficulty in accurately tracing a bankline with this instrument, because the position of the pencil point used in tracing is not in sharp definition.

Direct projection of transparencies-- Use of this method requires that the airphotos be copied, in whole or in part, to produce a "slide" or transparency. Fine grained color reversal film (ASA in the range of 25 to 75) is suitable for

Because no commercial instrument or device is available for the direct projection and tracing of slides in this manner, a set-up for the projection must be improvised or constructed. The simplest set-up consists of a table, about 1.5 m (5 feet) in length, placed perpendicular to a smooth wall. A space of about 1 m (3 feet) is left between the table end and the wall, for a place to sit or stand while tracing the projected images. The projector must be raised above the surface of the table, by placing it on a box, in order for the cone of projected light to clear the end of the table. The writer has constructed a more convenient arrangement by placing a 1.5 m (5 foot) table between two steel filing cabinets (fig. 27). Across the tops of the filing cabinets is placed a track for the projector and for mounting a plastic front-surface mirror at 45° to the plane of the table. The track is made of two round galvanized steel fence posts separated by squares of plywood, which are held in position with "brace bands".

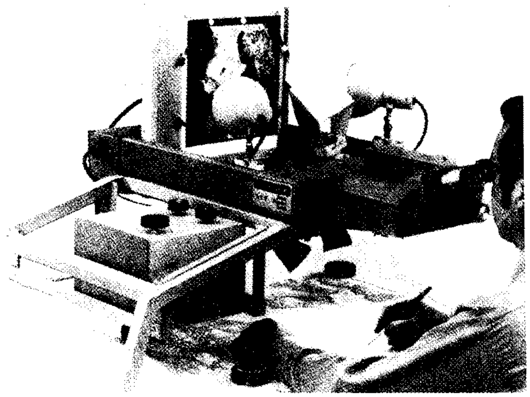

Figure 26. Graphical data transfer instrument. (Bausch and Lomb photograph)

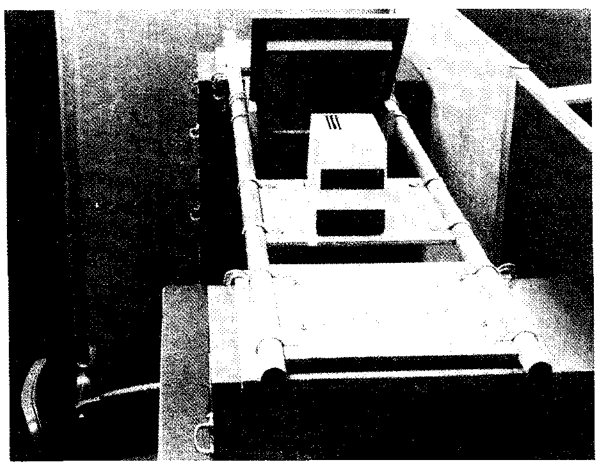

Figure 27. Device for direct projection of transparencies by 35-mm slide projector.

this purpose, and the film resolution is sufficiently good that very little detail is lost. Any good single lens reflex 35-mm camera, with either extension tubes or a macro lens, can be used for the copy work. A copy stand is needed, and care must be taken that the camera is level, that is, that the plane of the film is parallel with the plane of the copy.

A drawing, on which the channel banklines at different times are superimposed, is obtained by the same procedure as previously described for the reflecting projector. In this case, however, the banklines (and reference features) are traced from the slide as projected with a 35-mm slide projector equipped with a short-focus (2.5 inch or 63 mm) projection lens. The slide can be projected onto a vertical rigid screen (or smooth wall); or, by the use a front-surface mirror fixed at a 45° angle, onto a horizontal table top. The desired scale is obtained by changing the distance from projector to screen.

The direct projection method requires more effort than the other methods described, but it produces a sharp, bright image, has great flexibility with regard to scale and field of view, and is inexpensive. The range of magnification is controlled by the size of the photocopied area, as well as by the distance of projection.

LATERAL STABILITY IN RELATION TO CHANNEL TYPE AND SIZE

Information on lateral migration rates for channels of different sizes and types has been compiled to give an indication of what may be expected at a proposed crossing site. Reliance has been placed mainly on rates for a group of 36 streams in the United States, selected and measured for purposes of this report, but rates previously reported in the literature have been used for comparison. A tabulation of bank erosion measurements, described as "at best crude", had been compiled by Wolman and Leopold (1957), and more recently Hooke (1980) has compiled previous measurements in connection with his field measurement and analysis of bank erosion on rivers in Devon, England. Many of the available data are not very useful for analysis because of uncertainties as to how the measurements were made, whether they apply generally or only at a specific point, and a lack of information on stream characteristics. In addition to the sources listed by Hooke, maps showing the position of banklines at different times have been published for the Sacramento River in California (Brice, 1977) and for the Kansas River and tributaries (Dort and others, 1979). Local measurements of bank erosion have been reported for streams in Canada (for example, by Kellerhals, Neill, and Bray, 1972) and for streams in the United States (for example, by the U.S. Army Corps of Engineers, 1978).

Table 1. Hydraulic factors and bank erosion

	Stream	Topographic quadrangle map	Average[1] discharge, in m^3/s	Drainage[1] area, in km^2	Reach length, in m	Sinu-osity	Channel width, in m	Time period, years
1a.	Apalachicola R.	Orange 7½', FL	660	44,000	7.390	1.8	180	29
1b.	Apalachicola R.	Bristol 7½, FL	660	44,000	6,940	1.7	180	29
1c.	Apalachicola R.	Rock Bluff 7½', FL	660	44,000	5,570	1.4	220	21.2
2.	Big Raccoon Crk	Mecca 7½', IN	13	1,140	3,330	1.2	25	32
3a.	Bighorn R.	Rairden 7½', WY	45	28,500	4,990	1.3	55	27
3b.	Bighorn R.	Greybull South 7½', WY	55	33,700	7,100	1.8	75	25
4.	Big Muddy R.	Gorham 7½', IL	50	5,600	7,300	2.4	55	27
5a.	Black R.	Alicia 15', AR	230	19,000	4,190	1.3	80	21.3
5b.	Black R.	Alicia 15', AR	230	19,000	7,000	2.3	80	32.4
6.	Brazos R.	Sugar Land 15', TX	207	90,100	8,380	2.0	150	23
7.	Brouilletts Crk.	New Goshen 7½', IN	8.4	860	2,340	1.2	20	22.5
8.	Cache Crk	Guinda 7½', CA	17	2,700	3,750	1.2	80	23.6
9a.	Choctawhatchee R.	Hinsons Cross Roads 7½', FL	150	9,100	5,820	1.8	95	31
9b.	Choctawhatchee R.	Caryville 7½', FL	150	9,100	5,600	1.4	95	31
10.	Cedar R.	Columbus Junction 7½' IA	113	20,165	4,730	1.2	150	32
11.	Congaree R.	Wateree 7½', SC	235	20,400	9,510	2.6	90	27.3
12.	Fishing Crk.	Enfield 7½', NC	14.5	1,350	6,230	2.0	30	27
13.	Frenchman Crk.	Wauneta West 7½', NE	2.1	2,500	10,000	2.3	10	20.6
14.	Greybull R.	Gould Butte 7½', WY	5.3	2,900	4,290	1.2	90	26
15.	Henrys Fork	Parker 7½', ID	53.5	7,550	7,590	2.2	55	15
16a.	Iowa R.	Hills 7½', IA	44	8,500	5,680	1.6	70	18.8
16b.	Iowa R.	Hills 7½', IA	46	8,530	5,675	2.1	75	33
17.	Lumber R.	Fair Bluff 7½', NC-SC	38	3,200	4,740	2.0	35	29
18.	Middle Crk	Pleasant Dale 7½', NE	--	150	2,384	2.2	10	16
19.	Middle Loup R.	Arcadia 7½', NE	22.6	2,120	5,350	1.05	200	32
20.	Niobrara R.	Monowi 7½', NE	44	28,230	3,450	1.05	350	28
21.	North Canadian R.	Guymon NE 7½', OK	0.9	3,050	3,830	1.2	70	30
22.	Rogue R.	Sparta 7½', MI	6	600	1,749	2.2	7	29
23.	Rolling Fork	Nelsonville 7½', KY	48	3,360	1,525	2.8	16	31
24a.	Sacramento R.	Ord Ferry 7½', CA Llano Seco 7½', CA	325	24,000	21,500	1.3	330	27
24b.	Sacramento R.	Sanborn Slough 7½', CA	325	24,000	11,660	1.4	255	27
25.	Snake R.	Menan Buttes 7½', ID Rigby 7½', ID	190	14,900	5,770	1.2	60	15
26.	Snoqualmie R.	Carnation 7½', WA	107	1,575	5,590	1.9	65	12.2
27.	Stevens Crk	Forsyth 7½', IL	--	113	1,584	1.4	8	15.5
28.	Sugar Crk.	Marietta 7½', IN	13.6	1,195	2,630	1.2	23	32
29.	Tallahala Crk	Ovett SE 7½', MS	24.9	1,585	3,960	1.4	37	28
30a.	White R.	Gregory 15', AR	700	23,350	5,650	1.9	160	31.3
30b.	White R.	Gregory 15', AR	700	23,350	5,055	1.5	160	31.3
30c.	White R.	DeValls Bluff 15', AR	715	23,400	4,650	1.5	160	31.3
31.	White R., East Fork	Seymour 7½', IN	70	6,050	5,690	1.7	60	31
32.	White R., West Fork	Lyons 7½', IN	130	12,175	9,840	1.7	85	29
33.	Williamette R.	Junction City 7½', OR	360	8,850	6,930	1.7	90	14
34.	Wisconsin R.	Mazomanie 7½', WI	198	23,200	4,660	1.1	360	27.6
35a.	Yellowstone R.	Crane 7½', MT Piche 7½', MT	365	68,825	4,680	1.2	250	29
35b.	Yellowstone R.	Savage 7½', MT	365	68,830	4,500	--	325	29
36.	Missouri R.	Elk Point 7½', SD-NE	895	814,800	2,600	--	600	27.7

[1]Approximate values, extrapolated from values measured at nearest gaging station.

[2]No erosion detected.

rates for selected reaches.

	P_{84} erosion rate, in m/yr	P_{50} erosion rate, in m/yr	P_{50} erosion rate, in chl. widths/yr	Percent of reach eroded	Erosion index	Stream type
1a	2.2	1.60	0.009	96	8.6	Equiwidth
1b	2.3	1.16	0.006	69	4	Equiwidth
1c	2.0	1.16	0.005	67	3.3	Equiwidth
2	1.2	0.49	0.02	54	1.1	Equiwidth
3a	1.8	0.90	0.016	61	9.7	Wide bend, locally braided
3b	4.5	1.10	0.014	82	11.5	Wide bend, locally braided
4	n[2]	n	n	n	n	Equiwidth
5a	1.7	0.6	0.008	76	5.8	Equiwidth
5b	1.1	0.47	0.006	91	5.4	Equiwidth
6	5.3	2.3	0.015	87	13	Wide bend
7	1.1	0.48	0.024	75	18	Wide bend
8	6.1	2.3	0.029	71	20.6	Braided point bar
9a	1.0	0.5	0.005	47	2.3	Equiwidth, locally anabranched
9b	--	0.64	0.006	50	3	Equiwidth, locally anabranched
10	1.3	0.65	0.004	81	3.2	Braided point bar
11	1.4	0.83	0.009	52	4.7	Wide bend, trans. to equiwidth
12	n		n	n	n	Equiwidth
13	--	0.29	0.029	--	--	Wide bend
14	4.4	1.7	0.019	76	14.4	Braided point bar
15	n		n	n	n	Equiwidth, anabranched
16a	1.5	0.91	0.013	43	5.6	Wide bend
16b	1.4	0.8	0.11	88	9.7	Wide bend
17	n		n	n	n	Equiwidth
18	0.8	0.26	0.02	45	9	Equiwidth, incised
19	--	0.48	0.002	28	0.7	Braided, no point bars
20	1.8	0.96	0.003	100	3	Braided, no point bars
21	5.5	4.5	0.064	50	32	Braided point bar
22	n	n	n	n	n	Equiwidth
23	n	n	n	n	n	Equiwidth, incised
24a	10.2	5.1	0.015	72	10.8	Wide bend, locally braided
24b	5.5	3.1	0.012	69	8.3	Wide bend
25	--	0.7	0.012	53	6.3	Braided point bar, anabranched
26	n		n	n	n	Equiwidth, incised
27	0.3	0.15	0.017	16	2.7	Equiwidth
28	--	0.12	0.005	22	1.1	Equiwidth
29	0.9		0.004	61	2.4	Wide bend
30a	1.3	0.72	0.004	95	4.2	Equiwidth
30b	1.1	0.75	0.005	72	3.4	Equiwidth
30c	3.6	1.8	0.011	100	11	Equiwidth
31	3.9	1.9	0.031	86	26.7	Wide bend
32	4.5	1.7	0.02	73	14.6	Wide bend
33	--	0.82	0.009	25	2.2	Wide bend, anabranched
34	1.3	0.36	0.001	60	0.6	Braided, no point bars
35a	8.1	5.3	0.02	91	18.2	Wide bend, anabranched and braided
35b	--	4.1	0.013	78	10.1	Wide bend, anabranched and braided
36	--	9	--	--	--	Braided point bar

An estimate of the extent and seriousness of streambank erosion in the United States has recently been made by the Corps of Engineers in connection with the Streambank Erosion Control Evaluation and Demonstration Act of 1974 (U.S. Army Corps of Engineers, 1978). Only a small amount of reliable data on the extent and nature of streambank erosion was found, and estimates were therefore necessary for 99 percent of the streams in the United States. According to these estimates, which apply to the total length of all streams in the United States, " * * * approximately 8 percent or about 575,000 bank-miles are experiencing erosion to some degree * * * . Much of the total erosion is quite mild in degree and low in damage. Consequently the evaluation concentrated on streambank erosion that appeared severe enough to merit further examination * * * ".

Although the Corps of Engineers has rightly concentrated efforts on stream reaches where the most severe erosion is occurring, it is improbable that bank erosion is occurring along only 8 percent of the total streambank length in the United States. From a geomorphic perspective, bank erosion occurs to some degree along all natural channels, and particularly along alluvial channels. Moreover, bank erosion can be discerned along most alluvial stream reaches in the United States by a comparison of time-sequential airphotos for which the time lapse is 20-30 years.

The streams selected here for bank erosion measurement represent most of the stream types that occur in the United States and a wide range of stream sizes (Table 1). Other criteria that were used in the selection of reaches include the availability of discharge measurements, of topographic maps, and of time-sequential airphotos. Bank erosion was measured according to a standardized procedure, in order that a consistent comparison of erosion rates could be made:

1. Time-sequential banklines were superimposed by tracing on a single sheet of paper (fig. 24). Tracings were made by projection of transparencies of time-sequential airphotos, at scales in the range of 1:4,000 to 1:7,000. Areas in which a later bankline extended laterally beyond an earlier bankline, were shaded.

2. The centerline of the later channel was drawn, and tick marks were made at intervals of two channel widths along the centerline. At each tick mark, the linear distance of bank erosion (shortest distance between the sequential banklines) was measured with a millimeter scale to the nearest half millimeter. The linear distances were tabulated according to magnitude. At points where no bank erosion was discerned, a zero was tabulated.

3. Several reaches were of sufficient length that the number of erosion points measured was in the range of 50-100. Frequency plots of erosion distance on arithmetic probability paper yielded approximately a straight line. It was assumed that the erosion-distance frequency distribution tends to be arithmetic normal, and that statistical measures applying to the normal frequency distribution can be applied. Thus, the median value for erosion distance is at P_{50}, and P_{16} and P_{84} are each one standard deviation from the median. The maximum value of erosion distance was also recorded. A dimensionless measure of erosion rate was obtained by dividing the erosion rate in meters per year by the average channel width in meters.

4. The percentage of channel reach along which erosion occurred (or was discerned) is taken to be the total number of points divided by the number of points at which an erosion distance was measured. A dimensionless erosion index for the reach is obtained by multiplying the erosion rate in channel widths per year by the percent of reach eroded (times 100).

Bank erosion rates for a stream are likely to differ from one time span to the next and also from place to place along the stream. In particular, the degree to which erosion rates are affected by the occurrence of floods must be considered. There is no conclusive evidence on this point. Hooke (1980 p. 145) concluded that most of the erosion on his selected group of streams in Devon " * * * appears to be achieved during or in association with events that occur several times a year". He also found that maximum erosion rates occur at discharges near bankfull. The erosion associated with a major flood probably depends more on duration than on magnitude. From a study of bank erosion on the Sacramento River in California, the Corps of Engineers concluded (U.S. Congress, 1960) that significant bank erosion begins when the water velocity in the channel reaches a certain range of values (for the Sacramento, 1.25-1.4 m/sec). Bank erosion was found to be roughly related to the time duration of the stages or discharges for which these values of velocity are exceeded.

For some of the streams listed in table 1, the bank erosion rate may have been affected by the closure of dams or other works of man that took place during the time interval between airphotos. At only one of the sites (Cache Creek, Calif.) did the general aspect of the stream, as influenced mainly by cut banks and the vegetal cover on point bars, change significantly during the time interval. This change is attributed to flood, although the bank erosion rate may also have been affected by dam closure. At two sites (Black River, Ark., and White River, Ark.) substantial clearing of the flood-plain forest occurred during the time interval between airphotos, but the effects of this on channel properties had not yet been manifested at the time of the latest airphoto. Significant changes in the bank erosion rate of a stream will probably be manifested by a change in channel properties or even in channel type.

Bank erosion rates tend to increase with increase in stream size. In figure 28, channel width is taken as a measure of stream size.

The dashed curve is drawn arbitrarily to have a slope of 1 and a position (intercept) to separate most equiwidth streams from most wide-bend and braided point-bar streams. For a given channel width, equiwidth streams tend to have the lowest erosion rates, and braided point-bar streams the highest. No erosion could be discerned, by comparison of airphotos, for the streams at the bottom of the graph and an arbitrary erosion rate of 0.01 meter per year was assigned them. Their erosion rates are probably in the range of 0.01 to 0.1 meter per year.

Braided streams without point bars (diamond symbol,fig. 28) plot well below the arbitrary curve because their channels are very wide relative to their discharges. Channel width is an imperfect measure of stream size, as are drainage area and discharge, particularly for the comparison of streams in arid and semiarid regions with streams in humid regions. If braided streams and braided point-bar streams (which are uncommon in most parts of the United States) are excluded, the dashed curve in figure 28 provides a preliminary estimate of erosion rates that may be encountered at a particular site.

An increase in erosion rate with stream size is also indicated when drainage basin area is used as an indirect measure of stream size. Hooke (1980, p. 150) presents a log-log graph of mean erosion rate in meters per year vs. drainage basin area, on which are plotted his data for 16 streams in Devon together with data for 43 streams as compiled from the literature. All data apply to meandering streams. The erosion rates range from 0.5 m/yr for a drainage area of 3 km^2 to 800 m/yr for a drainage area of 1,000,000 km^2. Despite

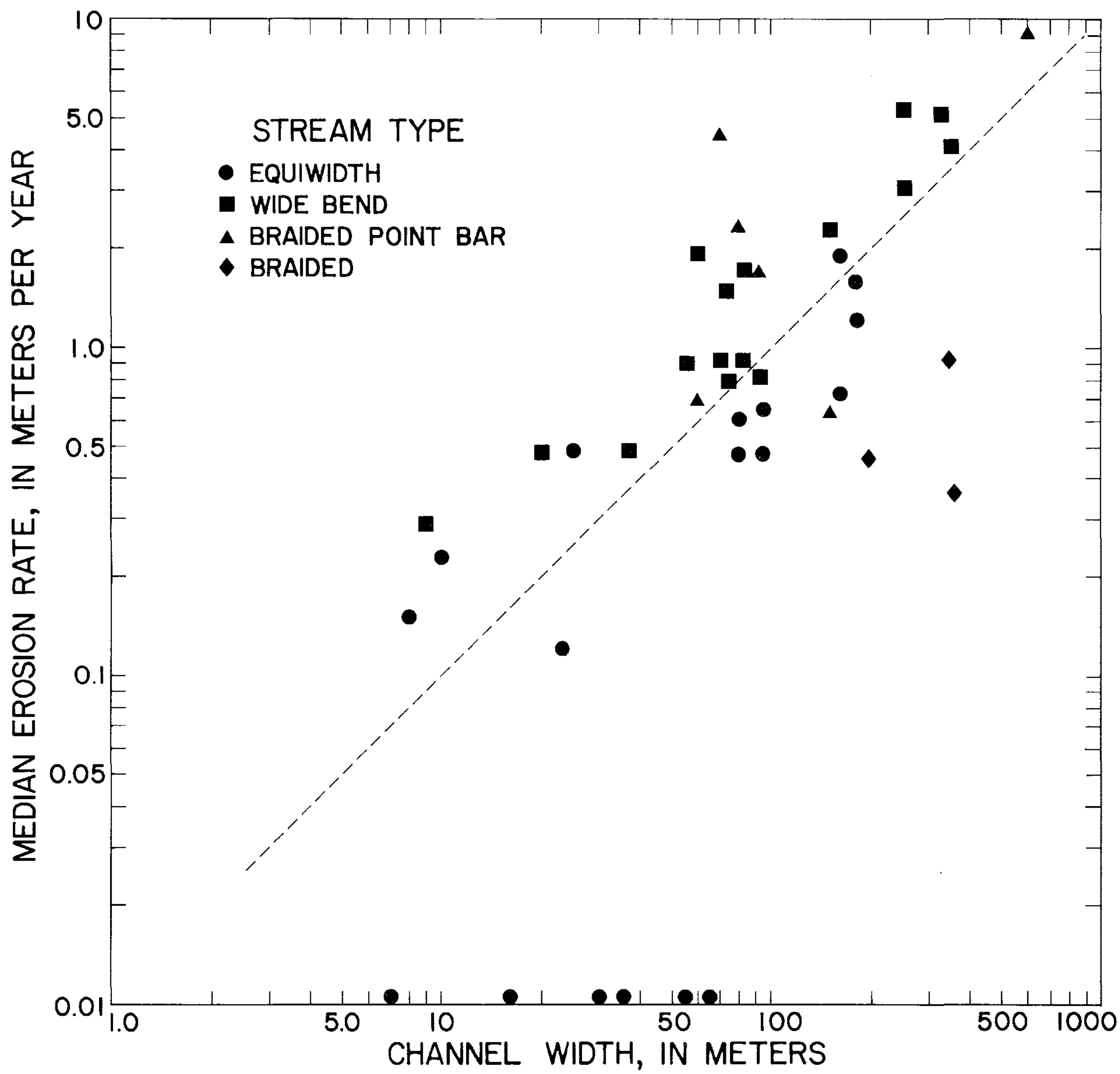

Figure 28. Median bank erosion rate in relation to channel width for different types of streams.

a rather wide scatter of points, his analysis indicates that erosion rate increases approximately as the square root of drainage basin area.

The relation between sinuosity and the erosion index for streams of different type is shown in figure 29. (The erosion index was obtained by multiplying the erosion rate in channel widths per year by the percent of reach eroded, times 100). The length of most reaches is in the range of 25-100 channel widths, and the shorter reaches (as expressed in multiples of channel width) are of wide, straight, braided channels. The generally meandering reaches include some straight segments. For engineering purposes, the relations between sinuosity and stability are summarized as follows:

1. Meandering does not necessarily indicate instability. In figure 29, equiwidth streams having sinuosity in the range of 2-2.8 are among the most stable streams. An unstable stream will not remain highly sinuous for very long, because the sinuosity will be reduced by frequent meander cutoffs.

2. Where instability is present along a reach, it occurs mainly at bends. Straight segments may remain stable for decades.

3. The highest erosion index values are for reaches whose sinuosity is in the range of 1.2 to 2 and whose type is either wide bend or braided point bar. An erosion index value of 5 (horizontal dashed line in figure 25), separates these types from most equiwidth streams, and it also approximates the rate of erosion at which loss of agricultural land becomes obvious. It is a suitable boundary between stable and unstable reaches.

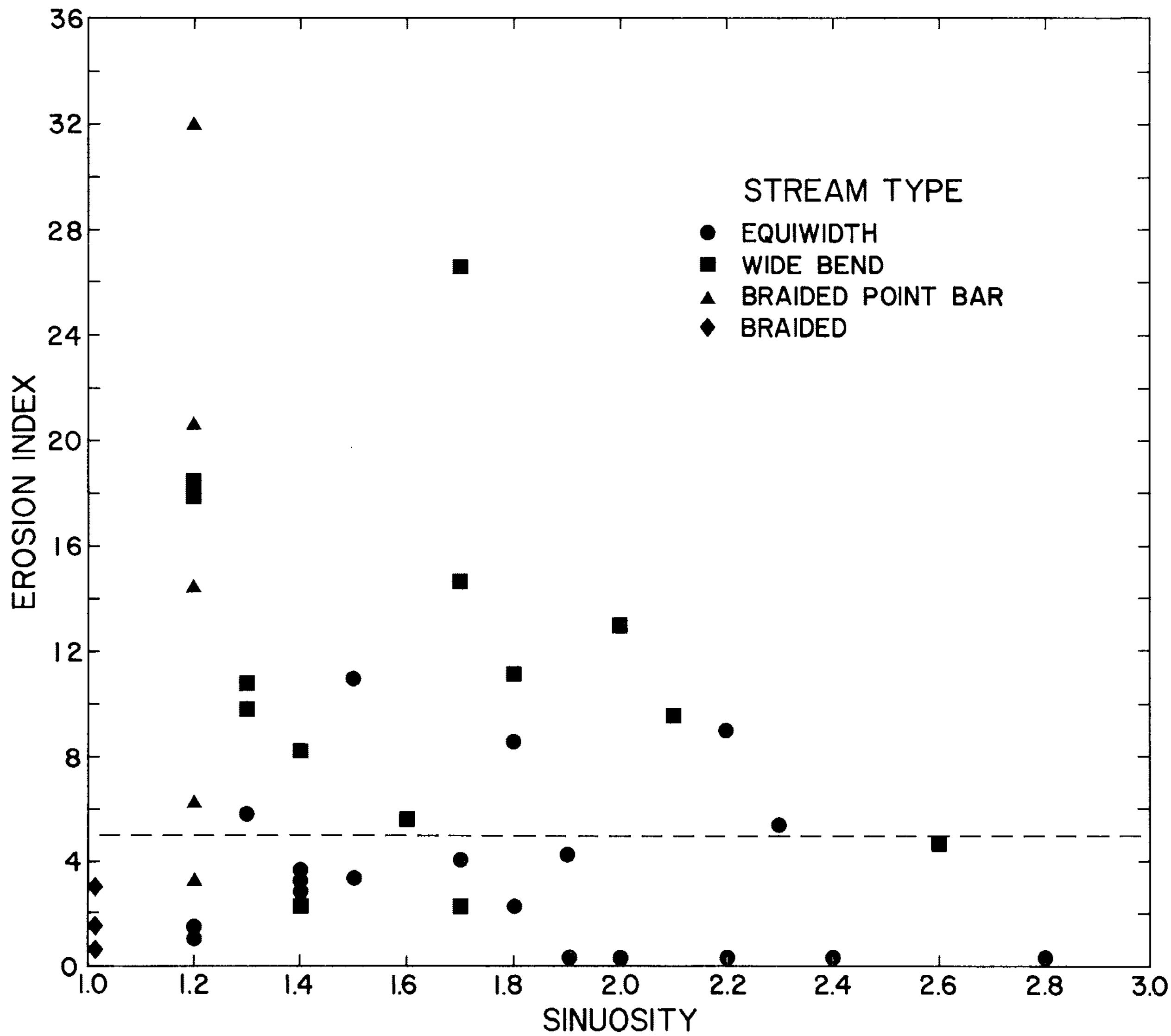

Figure 29. Erosion index in relation to sinuosity for different types of streams.

Bank erosion rates -- Although it is theoretically possible to determine bank erosion rates from factors such as water velocity and resistance of the banks to erosion, no practical means of making such a determination has been devised. Past rates of erosion at a particular site provide the best estimate of future rates. In projecting past rates into the future, consideration must be given to the following factors: (1) The past flow history of the site during the period of measurement, in comparison with the probable future history during the life span of the bridge. The duration of floods, or of flows near bankfull stage, is probably more important than the magnitude of floods. (2) Man-induced factors that are likely to affect bank erosion rates. Among the most important of these are urbanization and the clearing of flood plain forests.

Behavior of meander loops-- If the proposed bridge or roadway is located near a meander loop, it is useful to have some insight into the probable way in which the loop will migrate or develop, as well as its rate of growth. No two meanders will behave in exactly the same way, but the meanders on a particular stream reach tend to conform to one or another of several modes of behavior, as illustrated in figure 30.

Mode A (fig. 30) represents the typical development of a loop of low amplitude, which decreases in radius as it extends slightly in a downstream direction. Mode B rarely occurs unless meanders are confined by valley sides on a narrow flood plain, or are confined by artificial levees. Well developed meanders on streams that have moderately unstable banks are likely to follow Mode C. Mode D applies mainly to large loops on meandering or highly meandering streams. The meander has become too large in relation to stream size and flow, and secondary meanders develop along it, converting it to a compound loop. Mode E also applies to meandering or highly meandering streams, usually of the equiwidth point-bar type. The banks have been sufficiently stable for an elongated loop to form (without being cut off), but the neck of the loop is gradually being closed and cutoff will eventually occur at the neck. Modes F and G apply mainly to locally braided sinuous or meandering streams having unstable banks. Loops are cut off by chutes that break diagonally or directly across the neck.

Effects of meander cutoff-- If cutoffs seem imminent at any meanders in the vicinity of a proposed bridge site, the probable effects of cutoff need to be considered. The local increase in channel slope due to cutoff usually results in an increase in the growth rate of adjoining meanders, and an increase in channel width at the point of cutoff. On a typical wide-bend point-bar stream the effects of cutoff do not extend very far upstream or downstream, for example, no farther than the next two or three loops (Brice, 1974, p. 191). On the Marias River in Montana, natural cutoff of a large meander loop occurred just upstream from the US-91 crossing (Brice and Blodgett, 1978, site 234). The approach roadway was jeopardized by rapid bank erosion, and extensive counter measures were required. A case history further illustrating the effects of a natural meander cutoff is given below.

Meander cutoff on the South Santiam River, Oregon-- On an airphoto taken in 1955 (fig. 31A), the South Santiam River is identified as a wide-bend point-bar stream, locally braided. Bank protection work (by the Corps of Engineers) is evident. Where unprotected, the banks at the outside of bends are cut, but the presence of vegetal cover indicates that the erosion rate is moderate. The channel had no history of instability at the old truss bridge on SR-226. Point bars are marked by irregular overflow

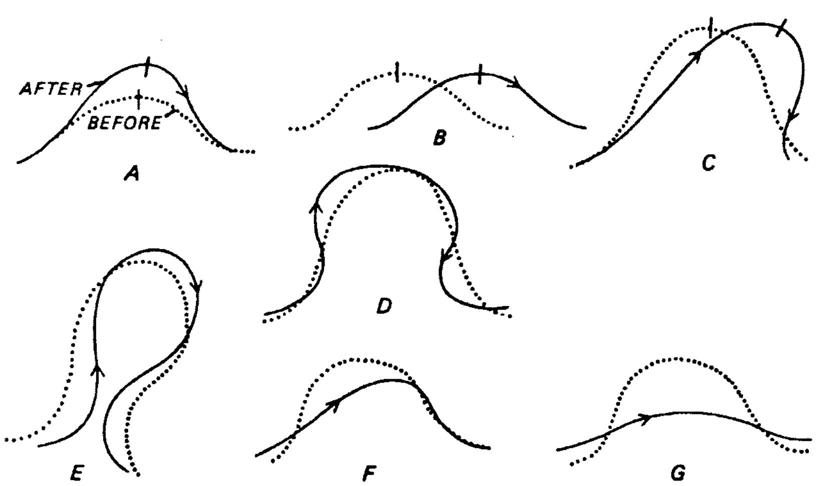

Figure 30. Modes of meander loop development. A, Extension. B, Translation. C, Rotation. D, Conversion to a compound loop. E, Neck cutoff by closure. F, Diagonal cutoff by chute. G, Neck cutoff by chute. (From Brice, 1977, p. 38)

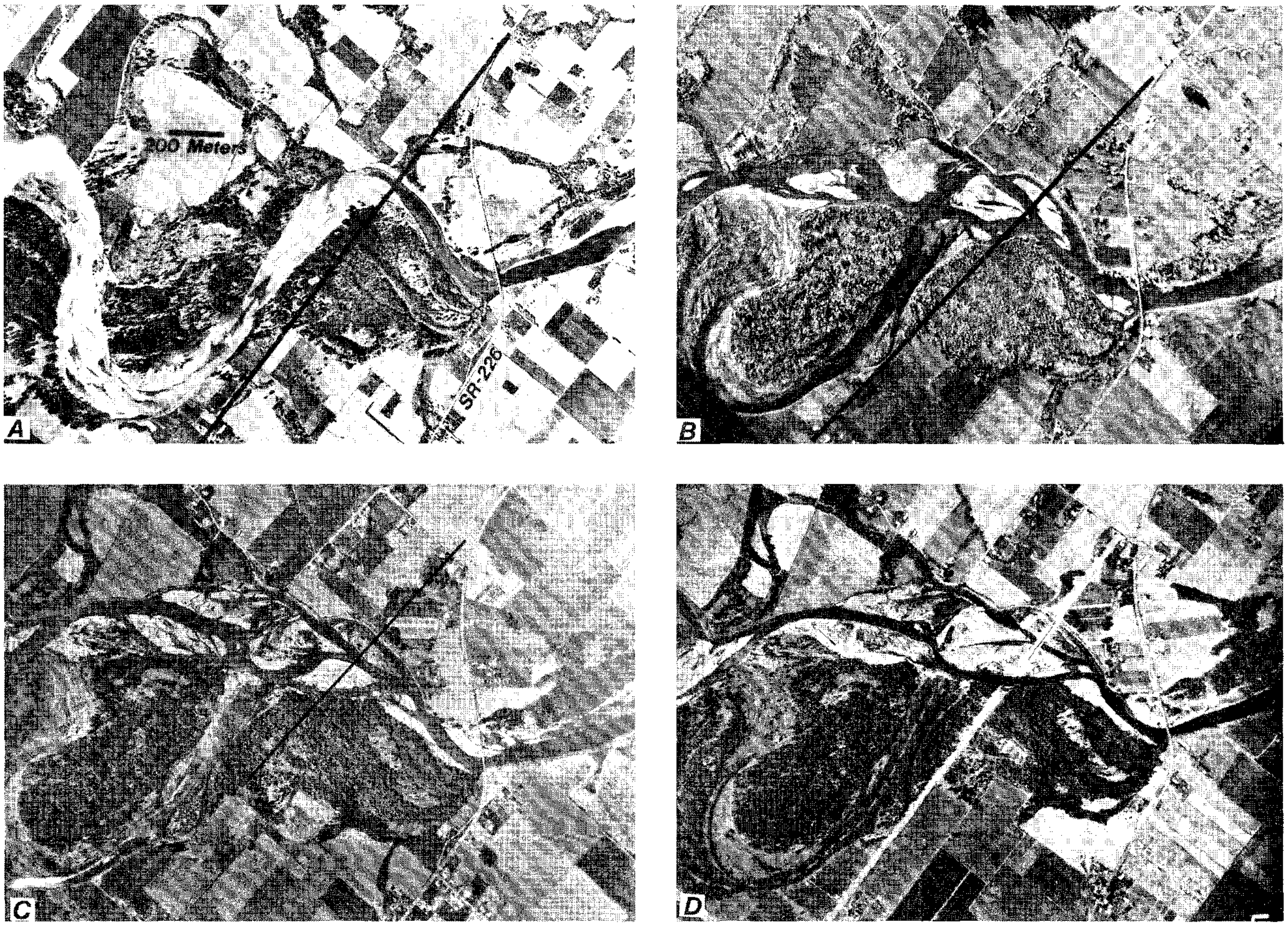

Figure 31. South Santiam River at SR-226 near Albany, Oregon. A, 1955 airphoto, taken prior to meander cutoff. Future route of SR-226 is shown in solid line (from U.S. Geological Survey). B, 1967 airphoto, taken about 3 years after meander cutoff (from U.S. Geological Survey). C, 1972 airphoto (from U.S. Dept. of Agriculture). D, 1973 airphoto; new bridge is partially completed (from Oregon Dept. of Transportation).

channels rather than by concentric scrolls, and this indicates that chute cutoffs of meanders are more likely than neck cutoffs.

The next available airphoto was flown in 1967 (fig. 31B). The large meander loop upstream from the truss bridge was cut off during a flood of greater than 100-year recurrence interval in 1964, and the length of channel cut off was about 2.4 km, large for a stream of this size. In response to the shortening and consequent increase in slope, channel width increased by a factor of 2 (to 300 m from a previous width of 150 m), and the new wide channel had a braided pattern. No degradation was reported. This response to meander cutoff is typical of many streams.

In connection with plans for a new bridge along the alinement indicated by the black line in figure 31B, a hydraulic study of the new crossing site was carried out by the Oregon Department of Transportation in 1971. Shifting of channels within the braided cutoff during the period 1965-71 was noted, and also a tendency for the river to open a main channel along the right bank. It was concluded that the main river channel would probably form along the right bank, which would be rapidly eroded and recede toward the right abutment of the new bridge. A tentative proposal to construct a revetment along the right bank was not seriously considered because of the costs and the lack of sufficient data on the progressive direction of channel movement.

During the period 1971-74, airphotos of the site were taken after each flood season. The progressive movement of the main channel toward the right bank was documented (figs. 31C and D) as well as the rapid bank erosion, which amounted to about 9 m during the winter of 1972-73. The expense of protecting the right bank now seemed justified, and it was revetted with riprap for a distance of about 365 m. (Further information on this site is given in Brice and Blodgett, 1978, v. 2, p. 247-250).

CHANNEL DEGRADATION

Progressive vertical changes in bed elevation (degradation or aggradation) are a common cause of hydraulic problems at bridges in some regions of the United States, and a potential cause in any region where channels are underlain by erodible materials. Degradation occurs more frequently than aggradation, and its consequences are more serious. Of the total number of gradation sites reported by Keefer, McQuivey and Simons (1980), sites having degradation problems were about three times more numerous than sites having aggradation problems. Most channel degradation in the United States is probably man-induced, and it occurs either downstream from dams, along channels that have been straightened or otherwise altered, or in regions of deep erodible surficial materials (loess, alluvial valley fill, or deeply weathered regolith) where the natural vegetal cover has been removed or overgrazed. In addition, degradation is caused by the mining of sand or gravel from streambeds.

No general compilation of rates (or amounts) of degradation has been published for streams in the United States, but information has been collected for special purposes. In connection with a study of countermeasures for hydraulic problems at bridges, Brice and Blodgett (1978) reported 34 sites where degradation was involved in hydraulic problems, but measured amounts were not available for many of these. In a more comprehensive study of channel gradation in relation to highways, Keefer, McQuivey, and Simons (1980) have prepared case histories for 110 sites. In connection with the agricultural consequences of channel degradation, information on channel degradation rates has been assembled by the U.S. Department of Agriculture (for example in Piest, Beer, and Spomer, 1976).

Channel degradation has been measured below many dams in the United States, and a brief but useful tabulation of representative sites is given by Leopold, Wolman, and Miller (1964, p. 454).

Table 2. Examples of channel degradation

Stream	Drainage area, km^2	Time period, years	Degradation, meters	Probable cause [1]	Reference [2]
East Fork One Hundred and Two River near Bedford, Iowa	240	14	2.1	cs, lu	(1)
Homochitto River at SR-33 at Rosetta, Miss.	1,942	33	4-5	cs	(2)
Logan Creek at SR-9 near Pender, Nebr.	1,875	22	2	cs, lu	(3)
Mill Crk at Oregon, Mo.	13	24	0.15	lu	(1)
North Fork Walnut Creek at US-62 nr Blanchard, Okla.	120	39	3-4	cs, lu	(4)
Peabody R., N. H.	80	7.4	3-5	cs	(5)
Thompson Crk, Iowa	18	80	5-11	lu	(6)
South Fork Forked Deer River at US-51 near Halls, Tenn.	2,688	9	2.5-3	cs, lu	(3),(4)
East Fork Trinity R. at AT&SF RR Bridge near Lavon, Tex.	779	19	1.5-2.4	dm	(3)
South Canadian R., N. Mex. (Conchas Dam)	19,000	7	0.8[3]	dm	(7)
Missouri R., N. Dakota (Garrison Dam)	470,000	8	0.2[3]	dm	(7)
Sand Creek at Denver, Colo.	----	30	3	sg	(3)
South Platte R. at US-83 at North Platte, Nebr.	63,000	28	2	un	(3)

[1]Probable cause(s): cs, channel straightening; dm, downstream from dam; lu, land use; sg, unknown.

[2]References: (1) Piest, Beer, and Spomer, 1976; (2) Wilson, 1979; (3) Brice and Blodgett, 1978; (4) Keefer, McQuivey, and Simons, 1980; (5) Yearke, 1971; (6) Daniels and Jordan, 1966; (7) Leopold, Wolman, and Miller, 1964.

[3]Average lowering of bed for all measured cross sections downstream from dam. Maximum degradation is 3.1 m for South Canadian River and 2.1 m for Missouri River.

Maximum degradation within the first 15 km below a dam is typically in the range of 1.5 to 2 m, and the average annual rate of degradation is on the order of 0.03 m for the first 10-15 years following closure of the dam.

Annual rates of degradation that are averaged over a period of time following some man-induced event, such as the closure of a dam or the straightening of a channel, are not a good basis for estimation of future rates. According to Simons and Senturk (1977, p. 714), the rate of degradation downstream from a new dam is rapid initially and gradually decreases as a new stable profile evolves. Similarly, available evidence suggests that the rate of degradation following channel straightening is likely to be rapid initially and to gradually decrease (Yearke, 1971; Wilson, 1979). On the other hand, Keefer, McQuivey, and Simons (1980, p. 49) report a slight increase in degradation rate, over a 20-year period, for the straightened channel of Caddo Creek in Oklahoma. No useful generalizations can be made on the length of time that may be required for a degrading channel to attain equilibrium, even on the condition that it is subject to no additional man-induced effects. The time may range from less than a decade to many decades. The best estimate of the future progress of degradation is probably based on extrapolation of the curve for past degradation as a function of time.

Sites that represent moderate to severe degradation, attributed to a variety of man-induced causes, are listed in table 2. There is no apparent relation between the size of a stream (as indicated by its drainage area) and its potential for degradation. Some of the largest measured values for degradation apply to small streams in parts of Iowa, Missouri, and Nebraska that are mantled with deep loess. Other cases of severe degradation have occurred in Mississippi and Tennessee on tributaries to the Mississippi River that have been channelized. In any region where the stream channel is not underlain by resistant bedrock, degradation is likely to result from the artificial straightening of long reaches of channel, from sand and gravel mining, or from the closure of a dam.

ASSESSMENT OF DEGRADATION

Stream terraces are evidence for naturally occurring episodes of channel degradation, and most alluvial streams are bordered by terraces. A terrace is an abandoned flood plain, the surface of which is rarely flooded because the stream channel has gradually cut below it. Most terraces are probably formed by degradation rates too slow to affect a bridge; nevertheless, low terraces along a stream are worth noting, because they suggest that the stream has been vertically unstable and that instability may be easily induced.

For engineering purposes, the objective of stability assessment is to identify channels whose degradation rate during the past few decades has been rapid enough to be significant in the planning of a new bridge or of countermeasures for an existing bridge. Also the potential for degradation at a site needs to be considered, whether degradation has occurred in the recent past or not. The need to recognize the potential for degradation at a site is illustrated by the following examples.

A bridge in Wyoming was damaged in the 1960's by channel degradation, which progressed upstream along an ephemeral channel by the migration of a channel scarp or "headcut". At the time of bridge repair, other channel scarps were observed downstream from the bridge. Countermeasures were applied to minimize the effects of these scarps as they passed beneath the bridge.

In 1963, a bridge was built in western Tennessee across the South Fork Forked Deer River, which is a tributary to the Mississippi River and flows across a densely forested flood plain. Although the stream had been straightened in the 1920's, the flood plain forest was not cleared and degradation was not a problem at bridges. In 1969, the channel was enlarged and straightened downstream from the bridge. About this same time, extensive clearing of the forest, for agricultural purposes, was begun. The bridge piers were undermined by degradation and bank erosion, and the bridge was rebuilt in 1975.

During the past few decades, many streams in Nebraska have severely degraded, because of channelization and land-use practices. The state highway agency now designs bridges and pier foundations on the assumption that degradation is likely to occur. This precaution has evidently prevented the loss of bridges at many sites.

Crow Creek in eastern Arkansas drains a hilly area adjacent to the Mississippi River flood plain. In connection with the construction of I-40 in 1964, a large meander loop was cut off to improve channel alinement beneath the I-40 bridge. Prior to construction, the natural channel had high, unvegetated banks and recent degradation was indicated by the deep incision and gully-like form of minor side tributaries. During construction, degradation occurred at pier footings, and a check dam was built. Subsequently, the toe of the check dam has been undermined and the banks have slumped downstream from the dam. A stream that has degraded in the recent past is likely to degrade further, especially if additional cause for degradation is provided.

Field assessment of degradation-- A channel that is slowly degrading, at a rate that is within the geologically "normal" range, cannot be discerned by field observation and, in fact, detection of the degradation by any method is difficult because of the slowness of the rate. If, however, a channel has been recently degrading at a rate significant to the planning of engineering works, there is likely to be some observable evidence for this along the channel, as seen in the field and by stereoviewing of airphotos. Indicators of degradation are listed below, in approximate order of reliability.

1. Channel scarps (headcuts, knickpoints). A migrating scarp in the long profile of an alluvial channel is unequivocal evidence for degradation, and the rate of degradation is related to the height and migration rate of the scarp. Channel scarps are easy to observe in ephemeral streams or small permanent streams, but are rarely observed in large permanent streams.

2 Gullying of minor side tributaries. As a stream degrades, its tributaries also degrade. Although channel scarps are rarely discernible in a large stream, their presence in minor ephemeral side tributaries is an indication of degradation.

3. High, steep, unvegetated banks. Some channels have higher banks than others of about the same width. Among the factors that determine bank height are degree of incision and erosional resistance of the banks. Incision takes place by degradation, but the rate may have been very slow. If, however, high banks are also raw and ungraded, recent degradation at a rapid rate is suggested.

4. Rapid rate of bank erosion. Rapid degradation is usually accompanied by rapid bank erosion. However, rapid bank erosion can also occur with aggradation, and on streams for which neither aggradation nor degradation has been established.

Other methods of assessment-- Other methods of assessing channel degradation in relation to highways have been described by Keefer, McQuivey and Simons (1980, p. 42-77) and will only be mentioned here. Changes in the elevation of the water surface or the channel bottom are determined over a period of years, in relation to a fixed datum. Such determination can be done by (1) Periodic measurements from bridge deck to streambed, if allowance can be made for local or general scour at the bridge; (2) Plotting changes in the stage-discharge relation at gaging stations. At some gages, allowance must be made for the effect of bed forms on the stage-discharge relation; (3) Repetitive measurement of the longitudinal or cross profile of the stream channel.

Keefer, McQuivey, and Simons (1980) describe methods of hydraulic analysis for predicting the probable gradation effects of a change in stream regimen, as would result from the closure of a dam. Computational methods for predicting scour, which apply also to degradation and aggradation, are summarized in Vanoni (1975, p. 44-65). According to Neill (1973, p. 77), "Progressive channel profile degradation * * * is not usually susceptible to computation, and should, where appropriate, be estimated on the basis of past trends or future project plans".

NATURAL SCOUR AND FILL

DEFINITION AND MEASUREMENT

Natural scour and fill refers to fluctuations of streambed elevation about an equilibrium position, which is commonly taken to be the position at low flow. These fluctuations are mainly associated with floods, and they occur without artificial constriction of the channel and without the presence of artificial obstructions such as bridge piers. The scour induced by a bridge is additive to natural scour. A bed elevation that has been raised or lowered is likely to return to its equilibrium position during the falling stages of the flood, although a return period of weeks, months, or even years, may be required by some streams, particularly those having coarse bed material. For most streams, the magnitude of scour is substantially greater at some places along the channel than at others. Natural scour and fill occurs by three different mechanisms, which may operate jointly or independently: (1) bed form migration, (2) convergence and divergence of flow, and (3) lateral shift of thalweg or braids.

According to Neill (1964, p. 29), "The location of a bridge with respect to the river channel pattern in plan has an important bearing on its liability to bed scour. Bends and narrow sections may be liable to scour at high stages, regardless of the effects of bridge structures * * * . Straight or gently curved reaches with stable banks are to be preferred". Of course, straight or gently curved reaches with stable banks are also preferred as bridge sites for reasons of lateral stability. The purpose of this section is to amplify the quoted statement and to summarize available information on scour and fill in relation to channel configuration and channel type. If a crossing must be made on a meandering reach, identification of the segments of least potential scour may be a deciding factor in site location.

The distribution of natural scour and fill has apparently not received much consideration as a factor in bridge site location, although the tendency for scour to occur at bends and fill to occur at crossovers has long been known, perhaps for centuries, in connection with the navigation of rivers. E. E. Dittbrenner, a Division Drainage Engineer for the U.S. Bureau of Public Roads, reported some relevant observations in 1954 (see discussion of Lane and Borland, 1954, p. 1082). He noted that, for certain streams in New England, pier scour occurred at bridges crossing at pools and did not occur at bridges crossing at rapids. Dittbrenner was of the opinion that most bridges on midwestern streams were located at pools, where a meander impinged against the valley walls, and were therefore unduly subject to scour at piers. A scrutiny of about 100 of the bridge sites studied by Brice and Blodgett (1978) indicates that most bridges are located on nearly straight reaches, at sites that are probably transitional between pools and riffles.

Natural scour and fill has been neglected as a factor in bridge site location probably because of the lack of useful information about it and also because of its complexity. Useful information is scarce because bed elevation is difficult to measure during floods and a reliable analysis of scour and fill requires measurement of several cross sections, at different locations, at about the same time. A continuous longitudinal bed profile along the thalweg is also highly desirable. Few such measurements have been published. In a particular cross section, the amount of scour or fill is unevenly distributed, and both the reference bed and the scoured bed are likely to be of irregular shape. Thus, the amount of scour is difficult to express numerically without ambiguity.

At some gaging stations, impressive amounts of scour have been recorded for specific floods, but it is unlikely that such amounts occurred everywhere along the stream. Among the best known examples are the San Juan River at Bluff, Utah, for which a maximum scour of about 3 m is apparent from the cross sections of Leopold and Maddock (1953, p. 32); and the Colorado River at Yuma, Arizona, for which a maximum scour of about 12.5 m is shown on the cross sections of Lane and Borland (1954, p. 1076). These gaging stations, like many others, are at places where the channel width is less than average; furthermore, the cross sections are confined laterally by rock walls. Lane and Borland (1954, p. 1079) argue that in rivers such as the Rio Grande, the bed scours during flood at the narrow sections and that most of the material thus removed is deposited at the next wide section downstream. They deny the general lowering of the river bed during flood. On the other hand, Emmett and Leopold (1965) concluded, from scour-chain studies on three western streams, that scour was more or less continuous throughout the study reaches at flood flows; the amount of scour was not dependent on channel configuration, riffles and pools, straight reaches, or bends. The depth of scour was not large, typically less than 0.5 meter.

Scour below preflood bed elevation probably occurs at most cross sections of an alluvial stream at some time during the passage of a flood, although not at the same time nor to the same degree. At some sections, the scour is due to the migration of bed forms and the mean streambed elevation does not change significantly. In a detailed field study of scour and fill at 11 cross sections on the East Fork River in Wyoming, Andrews (1979) measured "significant" scour (less than 0.5 m) during flood crests at 6 of the 11 cross sections, and fill at five of the sections. At some time or other during the flood, net scour occurred at all except two of the sections.

In a study of scour at nine bridge sites in Alaska, Norman (1975, p. 135) observed that, at all sites, the <u>minimum</u> streambed elevations in cross sections remained significantly constant even though their locations changed as the discharges changed from low flows to flood flows. The streams studied by Norman were mainly braided, with gravel beds, and constancy of minimum bed elevation clearly does not apply to all types of streams. On most streams, however, the location of minimum bed elevation is subject to change. Klingeman (1973, p. 2179) recommends that "the lowest undisturbed streambed elevation at or near the bridge crossing (other than a local scour hole) be used as a reference level in setting scour elevations of principal piers at or near the main channel".

BED FORM MIGRATION

Bed form migration is one of the mechanisms by which natural streambed scour occurs. As commonly defined (for example, in Vanoni, 1975, p. 119 and 151), bed forms consist of ripples, bars, dunes, flat bed, and antidunes. The height of bars approximates mean flow depth. The height of dunes is typically about one-third of mean flow depth, although dune height and flow depth are not consistently related. Mean bed elevation may be the same after the passage of a dune as it was before; but at the time of passage, the trough of the dune represents scour (below mean bed elevation) to a depth equal to about half the height of the bed form. In measuring scour at bridge piers on Alaskan rivers, Norman (1975, p. 2) found that, where dunes were present, the minimum streambed elevation of the scour hole at the nose of the pier fluctuated with a magnitude of about half that of dune height. Neill (1973a, p. 100) recommends that, " * * * in channels subject to bed forms, allowance should be made for a possible depth of scour below general bed levels of up to 25 percent of the average depth of flow at flood stage".

From sonic measurement near bankfull stage of the longitudinal profile of two sandbed streams in Canada, Neill (1973b, p. 325-326) distinguished three orders of bed forms. On the Beaver River, where the mean water depth at bankfull stage was about 3.5 m, the smallest forms were ripples on shallow bars; the intermediate forms were generally on the order of 10 m in length and 0.5 m in height, but as large as 30 m long and 2 m in height; the large forms were on the order of 400 m long by 2 m in height. The largest forms are not dunes and are sometimes described as "sand waves". On longitudinal fathometer profiles of the Mississippi River, Cary and Keller (1957, p. 1331-7) report "super sand waves" having amplitudes of 6-9 meters. They hypothesize (p. 1331-2) that, by the migration of sand waves, bends are scoured at high stages and that much of the scoured material is simply moved to the first crossover. During lower stages, this material is gradually removed from the crossover and deposited in the bend below. Simons and Anding (1969, p. IV-1) report that the largest forms of bed roughness on the lower Mississippi River are sand waves having heights in the range of 3 to 9 meters and base widths of 120 to 180 meters. Also, dunes having a height of 3 m may be superimposed on the sand waves.

Foley (1976) measured scour and fill on a steep, sand bed, ephemeral channel with scour cords. Analysis indicated that all the measured scour and fill could be explained theoretically by bed form (antidune) migration. The maximum calculated amplitudes of antidunes were equal to, or greater than, the measured scour and fill.

Dunes usually occur in streams having bed material finer than about 0.6 mm in diameter, but migrating bed forms resembling dunes (in that the downstream face is steep) have been reported in gravel-bed streams (Neill, 1973a, p. 103). However, gravel bars are the typical bed forms of gravel-bed rivers. The bars may migrate, or they may remain fixed in position at a riffle. Leopold, Wolman, and Miller (1964, p. 212) regard a gravel bar or riffle as a kind of kinematic wave in the traffic of clastic debris. A kinematic wave consists of a concentration of units, particles, or individuals which move through the wave. A concentration of cars at a traffic signal is a kinematic wave through which the individual cars move. Where gravel bars are fixed, as at a riffle, little scour is to be expected. A moving gravel bar may concentrate flow at a bridge and cause local scour at piers or lateral erosion.

Where the supply of transportable bed material is not uniformly distributed along the channel, as may occur in gravel-bed streams, the movable bed material may be transported downstream from one storage area to the next; and the streambed elevation may change in accordance with this transport. Meade, Emmett, and Myrick (1981) made daily measurements of streambed elevation on the East Fork River in Wyoming at 39 cross sections in a reach 3,300 m in length. The rise and fall of the streambed during the runoff season showed the passage of sediment out of the storage areas, across the intervening areas, and into the next downstream storage areas. The storage areas were centered 500-600 m (about 25-30 channel widths) apart and were characterized by a relatively low surface-water slope at low stream stage; their spacing evidently corresponds to the mean annual distance of bedload transport.

CONVERGENCE AND DIVERGENCE OF FLOW

The mean-bed elevation of a natural channel is not usually changed by the migration of a train of bed forms, but measurements have shown that mean bed elevation does change, sometimes drastically, from place to place along a channel. The flow conditions associated with changes in mean-bed elevation are summarized by de Leliavsky's convergent-divergent flow criterion, as set forth by Leliavsky (1955, p. 102, 162-165). This criterion, derived from measurements of flow direction and velocity in natural streams, has been applied in Europe to the design of river training works. According to the criterion, convergent currents in a natural stream are associated with erosion (scour), and divergent currents are associated with deposition (fill). From his measurements of flow direction and velocity, de Leliavsky postulated that contiguous streamlines in a natural alluvial channel are never parallel to one another nor to the banks of the channel. The non-parallelism results from local accelerations and decelerations of flow, which arise from irregularities in the configuration of the channel. Convergence is associated with an acceleration of flow, and divergence with a deceleration of flow. The convergence-divergence criterion refers to local but consistent trends in current velocity and direction; it excludes turbulence, which is superimposed on these trends.

Convergence and divergence of flow are associated with variations in channel configuration both in plan view and profile view:

Variations in plan configuration of channel

- Flow entering a bend (convergence)
- Flow at inflection points between bends (divergence)
- Contraction of channel width (convergence)
- Expansion of channel width (divergence)

Variations in profile configuration of channel

- Deepest part of cross profile (convergence)
- Shallowest part of cross profile (divergence)
- Deep in the long profile (convergence)
- Shallow in the long profile (divergence)

The effects of channel contraction provide a familiar example of convergent flow. Mean-bed scour occurs in a contracted reach owing to an increase in stream velocity at the contraction. The velocity is greater because the reduction in width decreases the area of flow and, in order to maintain continuity of discharge from upstream, velocity in the contracted reach must increase to compensate for the reduced area. With increased velocity, the capacity of the stream to move bed material is also increased. The stream can not only transport the bed material supplied from upstream, but also can remove bed material from the contracted reach, thus lowering the mean bed elevation.

SCOUR IN RELATION TO CHANNEL CONFIGURATION

The term "configuration" refers here to the aspect of a channel in plan view, in cross profile, and in longitudinal profile along the thalweg. In the long profile of many meandering streams, a succession of deeps and shallows, spaced at fairly regular intervals, can be discerned, which tend to remain in approximately the same position from one year to the next. In other streams, which are usually braided, deeps and shallows in the profile occur at random and shift in position from one year to the next. The rivers having fixed deeps and shallows were considered to be stable by Lokhtine in 1909 (Leliavsky, 1955, p. 8) and the others as unstable. This concept of stability refers to the location of the channel for navigational purposes and not to the potential magnitude of scour and fill.

The stable deeps tend to occur at bends, downstream from the apex, and the stable shallows tend to occur at crossovers, which are near the inflection points between bends or where the thalweg shifts from one side of the channel to the other (fig. 32). In sand-bed streams, the deeps are best defined at high stage and tend to be filled, to some degree, at low stage. In many gravel-bed streams, the deeps (or pools) and the shallows (or riffles) are discernible at both high and low stage. The spacing of pools in alluvial stream channels tends to be normally distributed, with average values in the range of 5 to 7 channel widths (Keller and Melhorn, 1978). This corresponds to the average spacing of meander bends (at half a meander wavelength) as reported by Leopold and Wolman (1960). However, wide deviations from these average values are common along most channels.

According to Fargue's "laws" (Leliavsky, 1955, p. 112), the deepest part of a pool at a bend is somewhat downstream from the point of greatest curvature, and a similar lag occurs between the location of a riffle (or crossover) and the inflection point between successive bends. According to Haas (1969, p. II-4), " * * * the deepest portions of the pools are usually in the lower half of the bend, sometimes stated to be at the two-thirds point in the bend". Pools are usually associated with point bars at bends, but they may occur in straight reaches where the flow converges on the banks opposite alternate bars.

During a flood, the change in bed elevation at a pool tends to follow a trend that is a mirror image of the flood hydrograph, such that scour occurs on the rising stage and fill on the falling stage. However, the timing of the scour and fill at a particular cross section depends on, among other factors, the availability of bed material from upstream, and the minimum bed elevation is commonly not attained at peak discharge. From detailed surveys of a well defined crossover on the Mississippi River, Hines (1979) concluded that the bed elevation follows a pattern similar to that of the stage hydrograph. Scour occurs at the upper end of the crossover at the beginning of a flood. As the stage rises, the crossover moves upstream; as the stage crests, the volume of fill stabilizes and then slowly increases. After a short lag, the bed begins to scour. In general, scour at a crossing results in a return to preflood bed elevation. There is some evidence that, with increasing discharge, the velocity in pools increases faster than in riffles, and may exceed the values attained in riffles (Keller and Melhorn, 1978, p. 729).

Along most of the length of natural channels, the channel cross section is probably transitional between that of a pool (triangular, asymmetrical) and that of a crossover or riffle (rectangular, symmetrical) (fig. 25). For the Mississippi River, Haas (1969, p. II-5) distinguished three types of river cross sections: the pool, the crossover, and the transition. He suggests that transition sections have the most desirable hydraulic characteristics, including less variation of water-surface slope with river stage and a more uniform roughness due to bed form configuration. Of the 11 cross sections selected for measurement on the East Fork River in Wyoming by Andrews (1979), most were transitional between pools and riffles and were characterized either as scouring or filling sections on the basis of their measured changes in bed elevation during flood. At small discharges, the scouring (pool-like) sections were relatively deep and rough and had small velocities; the filling (riffle-like) sections were relatively shallow and smooth and had large velocities. With increasing stage, a velocity reversal occurred and the mean velocity of the pool exceeded that of the riffle. At bankfull discharge, the scouring sections were narrower and deeper than average for the study reach, and the filling sections were wider and shallower.

SHIFT OF THALWEG

Attention is confined here to shifts of the thalweg that take place without significant change in the position of the banklines. On most meandering streams, the thalweg shifts in position with increase in stage but, with falling stage, returns to its preflood position. Braided point-bar streams may have a "wandering" thalweg that shifts to a different position with each flood. In a braided stream, the position of the braided channels is subject to almost continuous shift during flows sufficient to move bedload.

Shift of the thalweg with increase in stage is a significant factor in bridge design not only for estimation of the point of maximum bed scour (and bank erosion), but also for alinement of the piers with flood flow. The assumption is made here that the path of maximum current velocity corresponds with the thalweg, or trace of greatest depth of the channel, but this may not always be true. As the point of minimum bed elevation shifts laterally, the bed is scoured in the direction of shift and filled in the opposite direction. Such scour and fill may be accompanied by a change in mean or minimum bed elevation, or it may not, depending on whether shift occurs at a pool, a riffle, or a transitional section. Measurements on braided gravel-bed rivers in Alaska (Norman, 1975) indicate that the minimum streambed elevation on these streams remains almost constant in value but shifts in location as the discharge increases from low flow to flood flow.

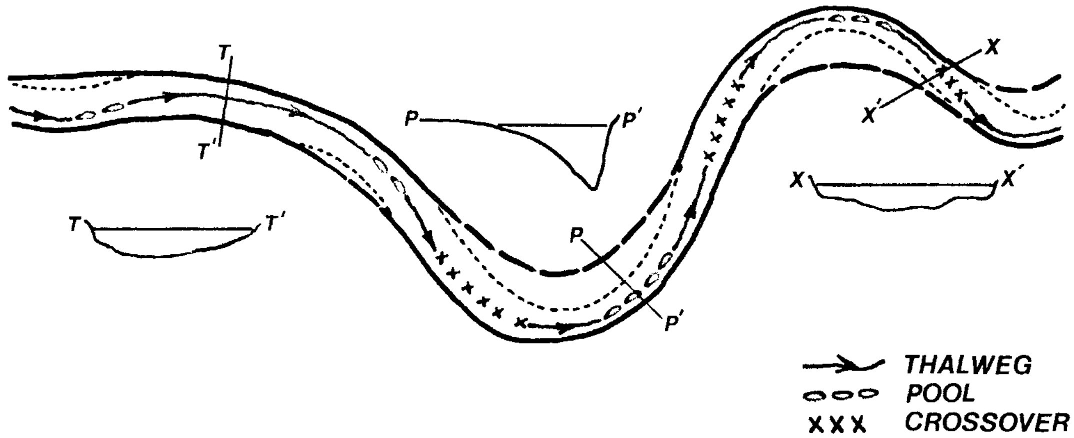

Figure 32. Pools, crossovers, and trace of thalweg on a hypothetical wide-bend point-bar stream at low flow. T-T', transitional cross section; P-P', cross section at pool; X-X', cross section at crossover.

At low stage, the thalweg tends to follow the concave bank at bends and to swing from one side of the channel to the other at crossovers (fig. 32). At flood stage, the thalweg at bends tends to straighten, so that the path of maximum current velocity approaches the concave bank somewhat farther downstream than at low stage. The zone of maximum bank erosion during flood lies downstream from the apex of a bend, as indicated by the failure of bank revetment there (Parsons, 1960) and by the downvalley migration of meanders with time. Shift in position of the thalweg at bends may also result in a shift in position at crossovers. On the Mississippi River, two parallel deeps commonly occur in the vicinity of a crossover, one formed during high flow and the other during low flow (Haas, 1969, p. I-12).

ASSESSMENT OF NATURAL SCOUR AT A SITE

In assessing the potential for natural scour at a site, the probable effects of each of the three mechanisms of scour (bed form migration, convergence of flow, shift of thalweg) need to be considered separately.

Bed form migration-- The migration of dunes may result in an amount of scour that is sufficient to warrant consideration in the design of pier foundations. Allowance for scour due to the migration of sand waves is more problematical and would have to be determined from a continuous long profile of the stream at high stage. The maximum scour induced by the migration of a dune is about one-half dune height, and dune height is roughly estimated at one-third the mean flow depth. In sand-bed streams, dune migration can be expected if the quantity of bed load in transport is sufficient for dune formation. Stream type is a reasonably good indication of the bed-load characteristics of a stream. Equiwidth streams having very narrow point bars are likely to be transporting minor amounts of bed load. Wide-bend point-bar streams and braided streams are likely to be transporting substantial quantities of bed load.

In gravel-bed streams, the bedforms developed during flood stage are likely to be exposed at low stage. Bed form height can be measured, and the minimum effects of bed form migration on streambed elevation are apparent. Most migrating bed forms in gravel-bed streams can be regarded as bars, whose height is related to flow depth. Migration of a bar through a bridge waterway is mainly of concern because of its deflection and concentration of flow. Bar migration tends to be a random process, and the tendency of bars in a stream to migrate is best determined from time-sequential airphotos. If a gravel-bed stream is distinctly braided, the shifting of bars is related to the shifting of braids.

Convergence of flow-- Persistent pools in the long profile of an alluvial channel mark the sites that have the strongest convergence of flow and the greatest potential for scour. Such pools are best identified by a continuous bed profile along the thalweg, as sounded at high stage. On a gravel-bed "pool-and-riffle" stream, the water-surface profile at low stage is flattest over the pools and steepest over the intervening riffles. On a sand-bed stream, however, persistent pools may fill at low stage, their position may shift to some degree, and they may be difficult to distinguish from random irregularities in the long profile. Pools, as well as riffles and crossovers, tend to be several channel widths in length, which is longer than most random irregularities. As the degree of braiding of a stream increases, the probability of persistent pools in the long profile decreases. Scour holes in braided streams are usually at the confluence of channels.

For streams having wide point bars, crossovers can usually be identified on airphotos taken at low flow (fig. 33). Pools cannot be observed directly, but they are typically located downstream from the apexes of bends and opposite the point bar. Pools may also occur in straight reaches, where their position is some-

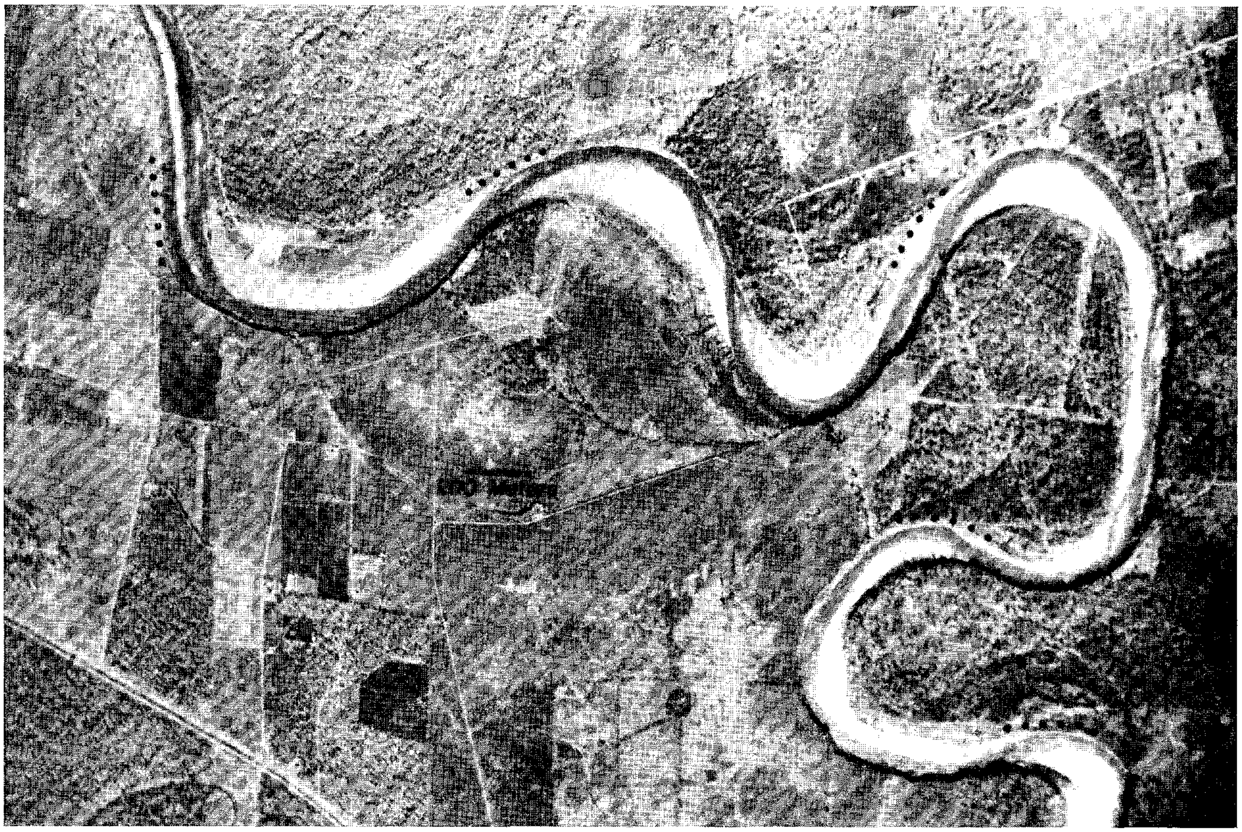

Figure 33. Airphoto of Brazos River near Richmond, Texas, at low stage on January 9, 1964. Crossovers, as identified by riffles and bars, are indicated by dotted lines along the channel. (U.S. Dept. of Agriculture photograph)

times marked by an alternate bar. At low stage, water-surface width tends to be least at pools, greatest at riffles, and of intermediate value at transitional sites. At bankfull stage, the water-surface width tends to be greater at pools than at crossovers or transitional sections.

Several computational methods are available for estimation of general scour in a contracted reach (for example, in Neill, 1973, p. 85-94), but published measurements of natural scour at pools for different streams are too few to provide grounds for estimation. As suggested by Blench (in Neill, 1973, p. 87) field measurement of cross sectional area and flow velocity at an "incised" (straight) reach near bankfull stage provides a good basis for calculation of scour by extrapolation to the design flood. Furthermore, a comparative measurement of this same section at low stage gives the amount of scour from low stage to bankfull stage, which is valuable for a confirmation of results obtained by computational methods.

Shift of thalweg-- Of the 224 bridge sites studied by Brice and Blodgett (1978), hydraulic problems attributed to shift of the thalweg occurred at 6 sites. One of these (site 164, Fort George River, Fla.) was in a sand-bed estuary, subject to strong tidal currents. Two (site 207, Leaf River, Miss., and site 170, Red River, Ark.) were wide-bend point-bar streams with sand beds. At both sites, the thalweg shift was related to a slight curvature of the channel and took place over a period of years, rather than during a single flood. Two sites (site 16, Deer Creek, Calif., and site 186, White River, S.D.) were on braided point bar channels in which the thalweg tended to "wander". One site (site 266, Boulder Creek, Wash.) was on a steep braided stream with a cobble-boulder bed. The bridge clearance was greatly reduced by aggradation, and the thalweg shifted against an abutment. Although braided streams are commonly regarded as unstable because of the rapid and unpredictable shift of bars and braids, they are readily controlled with suitable countermeasures and are not a particular cause of hydraulic problems.

Instability of the streambed that results from shift of thalweg (or braids) is, like bank instability, related to stream type and can be assessed from study of airphotos. On equiwidth point-bar streams (figs. 5 through 10), shift of the thalweg during flood is probably minimal. The channel tends to be relatively deep, narrow, and uniform from one place to another. In some reaches of the Red River of the North (a stable equiwidth stream), the thalweg is on the inside of bends, rather than the outside (Welch, 1973, p. 287). In straight reaches, the alternate bars that indicate meandering of the thalweg are rarely present.

A greater shift of the thalweg, both at bends and in nearly straight reaches, can be expected on wide-bend point-bar streams (figs 11 through 15). Flood flow cuts across the ends of the point bars, which are wide and bare at low stage. In straight reaches, alternate bars, visible on airphotos taken at low stage, are commonly present (fig. 13). These alternate bars are significant in the planning of bridges and countermeasures, because they indicate the potential for shift of the thalweg and also for bank erosion at points where the current is deflected against the bank.

The greatest potential for shift of the thalweg is on braided point-bar streams (figs. 16 and 17) and braided streams (figs. 18 and 19). On braided point-bar streams, shift of the thalweg occurs mainly during floods, and the pattern of shift is unpredictable for wide sand-bed channels having a "wandering" thalweg. On braided streams, shift of the thalweg and of braids occurs whenever the flow is sufficient to transport bed material. The pattern of shift is unpredictable, but the depth of natural scour is not likely to be great.

CONCLUSIONS

1. For engineering purposes, an unstable channel is one whose rate or magnitude of change is great enough to be a significant factor in the planning or maintenance of a bridge, highway, or other structure. Channel instability is manifested as progressive lateral migration (bank erosion), progressive vertical change in bed elevation (degradation, aggradation), or fluctuations in bed elevation about an equilibrium value with change in stage (scour and fill).

2. For the estimation of scour and other aspects of stream behavior, many engineers have evidently relied on engineering judgment, as based on prior experience and hydraulic analysis of flow. Channel stability assessment, by field observation and the interpretation of time-sequential airphotos, provides a further basis for decisions in site selection and bridge design.

3. A preliminary assessment of lateral stability, having a fair degree of reliability, can be made by interpretation of channel properties visible on an airphoto made at or near normal stream stage. Streams having a uniform width and narrow point bars (equiwidth streams) tend to be the most stable. Streams that are wide at bends and have wide point bars (wide-bend point-bar streams) tend to be less stable; and the most unstable streams have wide point bars and are braided (braided point-bar streams).

4. Airphotos taken 20-30 years ago are available for most regions of the United States and comprehensive information on airphoto coverage is on file at a central agency (National Cartographic Information Center). Several techniques are suitable for measuring distance of lateral migration on time-sequential airphotos with an accuracy sufficient for planning purposes.

5. Available measurements of bank erosion indicate that median erosion rates, in meters per year, tend to increase with stream size. The increase is directly proportional to the increase in stream width, and to the square root of drainage basin area. For a given channel width, equiwidth streams tend to have the lowest erosion rates and braided point-bar streams, the highest.

6. There is no consistent relation between degree of sinuosity (meandering) and degree of instability. Some equiwidth streams having sinuosities in the range of 2 to 2.8 are among the most laterally stable of streams. Along an unstable stream, however, the instability occurs mainly at bends. Straight segments may remain stable for decades. The highest erosion index values were found for wide-bend or braided point-bar streams having sinuosities in the range of 1.2 to 2.

7. Channel degradation is a common cause of hydraulic problems at bridges in many regions of the United States. Most degradation is man-induced and results from the artificial straightening of long reaches of a channel, from sand-gravel mining, or from the closure of a dam. Past degradation is established by measurement of the change of streambed elevation in reference to a fixed datum, but the occurrence of degradation can, in many cases, be discerned from field evidence. The curve of cumulative degradation vs. time is more likely to be asymptotic than linear, but it is difficult to predict the equilibrium bed elevation.

8. Natural scour and fill occurs by three different mechanisms, each of which can lower the local streambed elevation by an amount that is significant for the depth of pier foundations: (1) bed form migration; (2) convergence of flow, which is associated with scour at bends, pools, and channel constrictions, and divergence of flow, which is associated with fill at crossovers and riffles; and (3) shift of thalweg or braids within a channel. Sites having the greatest potential for natural scour can usually be identified from channel configuration and can therefore be avoided as crossing sites.

9. Scour by bed form migration is of consequence mainly in sand-channels. The height of dunes is typically about one-third of mean flow depth, and the passage of a dune results in scour to a depth of about half dune height. The height of antidunes may approximate mean flow depth. Gravel bars are the typical bed forms of gravel-bed streams, and their height approximates mean flow depth. Bars tend to migrate on braided

streams and to remain fixed at riffles on unbraided pool-and-riffle streams. A migrating gravel bar may concentrate flow at a bridge and cause local scour at piers or lateral bank erosion.

10. Scour by convergence of flow is related to channel configuration and is greatest at persistent deeps or pools in the channel long profile, where the water velocity during floods is likely to be greatest. Such pools tend to occur at bends and to alternate with persistent riffles or crossovers. During a flood, the change in bed elevation at a pool tends to follow a trend that is a mirror image of the flood hydrograph, with scour on the rising stage and fill on the falling stage. At a crossover or riffle, the change in bed elevation tends to follow the flood hydrograph, with fill on the rising stage and scour (to preflood bed elevation) on the falling stage. Many cross sections along a stream are transitional between pools and riffles. In general, the scour induced by a bridge will be greater at pools or pool-like cross sections than at riffles or riffle-like cross sections.

11. Shift of the thalweg with increase in stage is a significant factor in bridge design not only for estimation of the point of maximum bed scour (and bank erosion), but also for alinement of piers with flood flow. Thalweg stability is related to channel stability and to stream type, and can be assessed from airphotos.

RECOMMENDATIONS

Aerial photography is much used by highway agencies for photogrammetric and planning purposes. Analysis of channel stability and stream behavior by photo-interpretation is much less common, but it can be done by engineers and it can provide valuable information. Illustrations and descriptions of technique in this report are intended to serve as a guide for the application of fluvial geomorphology to engineering problems.

Airphoto interpretation needs to be supplemented by field study of the stream, not only at the crossing site but for a distance of 25-50 channel widths upstream and downstream from the site. The purpose of field study is to make observations on such features as bank stability, stream depth at pools and riffles, size of bed material, and the potential for floating drift. A continuous profile along the thalweg at a stage near bankfull will yield valuable information on scour and the location of pools and riffles, although it may not be feasible. Similarly, cross profiles and water velocities at a stage near bankfull are desirable.

The following geomorphic factors, presented as a check list, are recommended for consideration:

SELECTION OF A CROSSING SITE

A. Site on a nearly straight reach

1. Is site at a pool, riffle (crossover) or transition section? (p. 36-38)
2. Are alternate bars visible at low stream stage? (p. 11, 38-39)
3. If midchannel bars are present, what would be the effect of their migration through the bridge waterway? (p. 35,37)
4. Is cutoff imminent at adjacent meanders? (p. 4,6,29-30)

B. Site at a meander

1. What has been the rate and mode of migration of the meander? (p. 18-23, 29)
2. What is its probable future behavior, as based on the past? (p. 18-23, 29)
3. Is site at pool, riffle (crossover) or transition section? (p. 36-38)
4. Is cutoff of the meander, or of adjacent meanders, probable during the life span of the bridge? (p. 6, 18-23, 29)

DESIGN OF BRIDGE

A. Piers on flood plain, or adjacent to channel

1. Is the channel migration rate sufficient to overtake piers during the life span of bridge? (p. 6, 14, 18-23, 26-28)

B. Piers in channel

1. For pier orientation, what is probable position of thalweg at design flood? (p. 36-39)
2. For scour estimation, what is probable bed form height at design flood? (p. 34-35, 37)
3. For scour estimation, what is natural mean bed scour at design flood? (p. 37-39)
4. For scour estimation, what is lowest undisturbed streambed elevation at or near the crossing site? (p. 34)
5. Does the stream have an unstable thalweg that has shifted with time? (p. 12, 36-37)
6. Is there evidence for recent channel degradation? (p. 32-33)
7. Are any works of man in prospect that are likely to induce degradation or bank erosion? (p. 6, 31-33)

LOCATION OF HIGHWAY PARALLEL TO STREAM COURSE

1. Is main stream degrading, such that side tributaries crossed by highway may also degrade? (p. 32-33)
2. Is the rate and mode of meander migration a potential hazard to the highway? (p. 18-23, 26-29)

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The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

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Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

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