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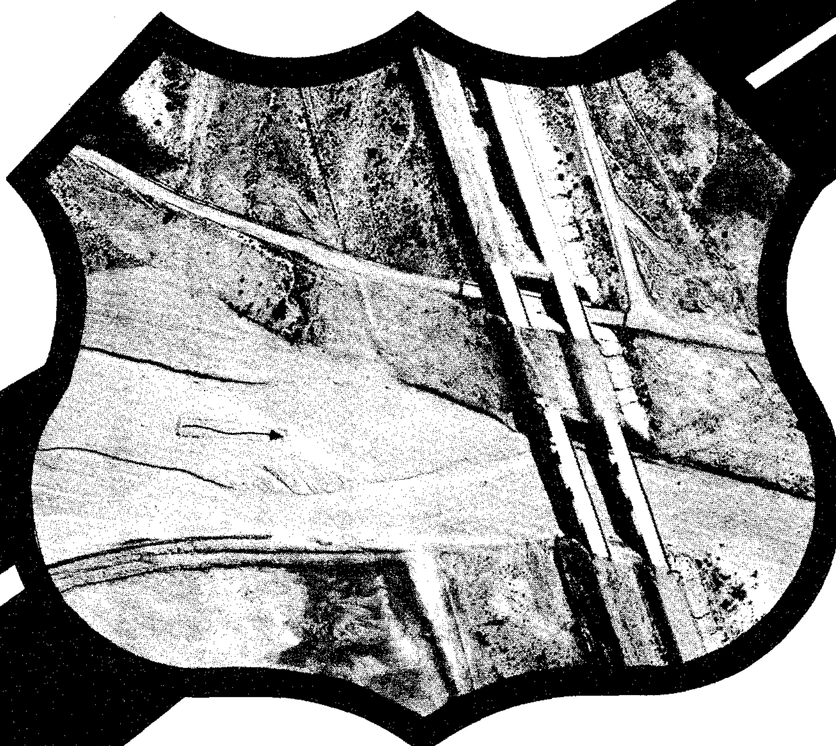
METHODS FOR ASSESSMENT OF STREAM-RELATED HAZARDS TO HIGHWAYS AND BRIDGES

March 1981
Final Report



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Prepared for
FEDERAL HIGHWAY ADMINISTRATION
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Environmental Division
Washington, D.C. 20590

FOREWORD

This report is a reference of techniques for evaluating stream-related hazards to highways and bridges. It is intended for use in conjuction with the publications "Highways in the River Environment-- Hydraulic and Environmental Design Considerations (available from the U.S. Government Printing Office, Washington, D.C. 20402, Catalog Number TD 2.8:H53/2) and Hydraulic Engineering Circular Number 16 (Available from FHWA, Office of Engineering, HNG-31, Washington, D.C. 20590). This report augments the preceding hydraulic design guides by providing insight into the application of remote sensing and slope stability evaluation. It also extends the perspective of crossing design to include the entire river system and the effects of land use changes. The report provide a procedure that permits evaluation of the relative stability of a river and identification of hazards that can affect a crossing.

Charles F. Scheffey
Director, Office of Research
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NOTICE

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16. Abstract River behavior at a highway crossing depends not only on the stability of that particular river reach, but also on the behavior of the entire fluvial system of which it is a part. Rivers are complex landforms. A simple and straight forward approach to the identification of river hazards is not always possible. A complete evaluation of hydraulic hazards cannot be solely based on on-site hydrologic, hydraulic and geomorphic factors; but must also include insight into historic trends, synoptic consideration of basin characteristics, and anticipation of future changes.

Because determination of stream-related hazards is a complex task it is beneficial to generalize relative stability based on stream type. Streams can be divided into five types based on channel pattern and mode of sediment transport. Each stream type exhibits its own characteristic stability. Detailed evaluation involves consideration of many variables. After evaluating stream variables a list of potential stream hazards can be developed. Each potential hazard can be evaluated on an individual basis and properly considered in either the design of a new crossing or maintenance of an existing one.

Numerous evaluation methods are available to hydraulic engineers that have not been fully utilized. To assess hydraulic hazards at a crossing it is necessary to understand the past, examine the present, and anticipate the future. Methods such as remote sensing, land use evaluation and slope stability analysis should not be overlooked.

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FEDERAL HIGHWAY ADMINISTRATION

SUBJECT	FHWA BULLETIN
FHWA/RD-80/160 "METHODS FOR ASSESSMENT OF STREAM-RELATED HAZARDS TO HIGHWAYS AND BRIDGES"	June 18, 1981

This Bulletin distributes the subject report which describes methods for evaluating the severity of hydraulic hazards at highway stream encroachments. The report covers hydraulic problems associated with erosion, deposition, stream pattern change, river metamorphosis, debris, and waves. It analyzes variables affecting stability of rivers and describes methods for measuring the importance of these variables at a specific site. The report will be of interest to, and serve as a reference for, bridge and hydraulic engineers.

This report provides a procedure for determination of stream-related hazards and the impact of land use, in and on streams. It includes evaluation techniques that account for geologic, geomorphic and geographic stream characteristics. The report provides guidance on remote sensing and slope stability evaluation. It also provides documentation of national data sources relative to stream-related hazards and assessment of data application to stream crossings.

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

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LIST OF ABBREVIATIONS

AGI	=	American Geological Institute
APFO	=	ASCS Aerial Photograph Field Office
ASCS	=	Agricultural Stabilization and Conservation Service
cfs	=	Cubic feet per second
EDIS	=	Environmental Data and Information Service
EROS	=	Earth Resources Observation Systems
km	=	Kilometers
m	=	Meters
NASA	=	National Aeronautics and Space Administration
NAWDEX	=	National Water Data Exchange
NCC	=	US Department of Commerce National Climatalogical Center
NCIC	=	National Cartograph Information Center
NOAA	=	National Oceanic and Atmospheric Administration
SLAR	=	Side-looking airborne radar
USDA	=	US Department of Agriculture
USGS	=	US Geological Survey

Chapter 1

INTRODUCTION

There are a number of reports that describe the morphology and dynamics of rivers (Morisawa, 1968; Shen, 1971; Gregory, 1977; Schumm, 1977; Simons and Sentürk, 1977) and some that consider highways and bridges in the river environment (Richardson et al., 1975; Brice et al., 1979; Neil, 1975), but none that specifically address the hazards, both natural and man-induced, that affect bridge stability and maintenance.

The objective of this report is to develop a procedure that permits evaluation of the relative stability of a river and identification of river-related hazards that can affect a bridge crossing. Techniques will be presented that can be utilized by the transportation engineer to evaluate the river hazards at a bridge site, and three examples of the procedure to be used in this evaluation are presented as a guide to its use.

The behavior of the river at a bridge crossing depends not only on the stability of that particular river reach, but also on the behavior of the fluvial system of which it is a part. It is clear that rivers are complex landforms, and therefore a simple and straightforward approach to the identification of river hazards is not always possible. Although detailed studies may indicate that a particular site is stable, nevertheless upstream and downstream changes may affect the future stability of the site.

Different types of channels behave and respond differently. Therefore, before a procedure for the recognition of river hazards can be presented (Chapter 9) with examples of the application of the technique (Chapter 10), it is necessary to discuss river channel types (Chapter 2), river hazards (Chapter 3), and the variables that affect river behavior and the hazards (Chapter 4). Additional chapters and appendices provide information on data sources, remote sensing, land use changes and bank stability.

Chapter 2

RIVER PATTERNS AND RIVER STABILITY

Rapid and otherwise unexpected river changes may occur in response to natural or man-made disturbances of the fluvial system, and it is important to the transportation engineer to be able to predict changes in channel morphology, location, and behavior. To a large extent the relative stability of a channel is revealed by its patterns. Therefore, in this chapter a discussion of channel pattern provides background information for a discussion of river behavior and hazards.

A major problem in predicting river behavior is that natural disturbances, such as floods, drought, earthquakes, landslides, forest fires, hurricanes, etc., may result in a large change in sediment load and and major channel change. It is difficult to anticipate channel changes due to these disturbances because these short-term episodic disturbances cannot be accurately predicted.

Man-made changes in the drainage basin and in the stream channel may cause significant channel response. Alteration of vegetation, surface materials and landforms changes water yield, snow accumulation and melt, water table configuration, timing and magnitude of flood peaks, sediment yield, and channel geometry. Alteration of stream courses by channelization, straightening and construction of streamside structures (e.g. dikes, levees, bridges, etc.) significantly modify the channel at the site of this activity and, in addition, can be expected to impact on the channels both downstream and upstream. Interbasin water transfer projects and impoundments of water in reservoirs can be expected to increase stream bed and bank erosion by increasing annual runoff and decreasing upstream sediment load, respectively. Land use can be expected to have potentially profound downstream effects on stream channels.

In spite of the complicating factors noted, transportation engineers can obtain at least a qualitative indication of the relative stability of a stream channel.

A stable channel can be defined as one with bed and banks that are spatially fixed. It is rarely the case that stream channels are stable unless they are influenced by bedrock or other resistant materials. Three major categories of channel can be identified as follows: bedrock-controlled, alluvial, and semi-controlled channels. The bedrock channel is fixed in bedrock, and its position is stable over the time span that concerns engineers. The alluvial channel is formed in sediment that has been transported by the stream, and therefore channel morphology and the alluvium reflect the type of sediment load transported by the stream. The third group is predominantly an alluvial channel that encounters bedrock and older resistant alluvium in its course, and it is, at least locally, influenced by this encounter. For example, the channel may be locally fixed in position by resistant materials which may significantly alter the meander pattern at that locality. Of course, such a location should be selected for a bridge crossing because the more resistant materials will partly reduce the hazards at the site.

Although the alluvial channel is most susceptible to change because both its bed and banks are erodible, even the bedrock channel may adjust to change by aggrading. In addition, the semi-controlled channel may shift away from the control and become an alluvial channel. Hence, all three types of channels must be evaluated in order to anticipate possible channel changes.

Stream Patterns

Alluvial channels are dynamic and subject to change, but changes are of different types and rates of change are highly variable. Alluvial channels are the cumulative result of a combination of climatic, geological, topographic, hydrologic and human disturbance factors. Basically, there are three types of channel patterns: straight, meandering, and braided. A straight channel has generally straight and parallel banks. Flow within the channel is mainly in the longitudinal direction. A meandering channel (Fig. 1) consists of many bends separated by short straight reaches ("crossings") between the bends. A braided stream (Fig. 2) usually has a large width-to-depth ratio, and islands, bars, and secondary channels within the main channel.

Rivers with different patterns behave differently and their other morphologic characteristics (e.g. channel shape, gradient) are different. Therefore, pattern identification can be the first step toward evaluation of river stability and the identification of potential river hazards.

Brice (1975) developed a descriptive classification of alluvial rivers that provides an excellent summary of the great range of channel patterns. The channel properties that he has selected as being important for classification are the degree of sinuosity, braiding and anabranching, and the character of meandering, braided and anabranched streams (Fig. 3).

Sinuosity is the ratio of channel length to valley length (length of centerline of channel to reach length, as measured along center of valley). A channel with sinuosity less than 1.05 is straight, one with sinuosity between 1.05 and 1.25 is sinuous, and one with a sinuosity greater than 1.25 is a meandering channel.

Concerning the character of sinuosity, Brice recognizes a single- and double-phase pattern. Two-phase sinuosity refers to a sinuous low-water channel within a wider, less sinuous bankfull channel (Fig. 3, Pattern f), or a bimodal distribution of loop sizes (Pattern g).

The degree of braiding is the percentage of channel length that is divided by islands or bars. Islands are defined as vegetated bars. According to Brice's description of the character of braiding, there appear to be two main types of braided channels: bar-braided (Patterns a and b) and island-braided (Patterns c and d).

Brice defines anabranching as the division of a river by islands whose width is greater than three times channel width at average discharge. The degree of anabranching is the percentage of reach length that is occupied by large bars or islands. The anabranched Pattern b is very similar to meandering Pattern d. Other anabranched patterns (d and e) are similar to the island-braided patterns.

In contrast to the anabranched channels, as described by Brice, anastamosing channels are those that have major distributaries that branch and rejoin the main channel. The individual anabranches can be meandering, straight, or braided,

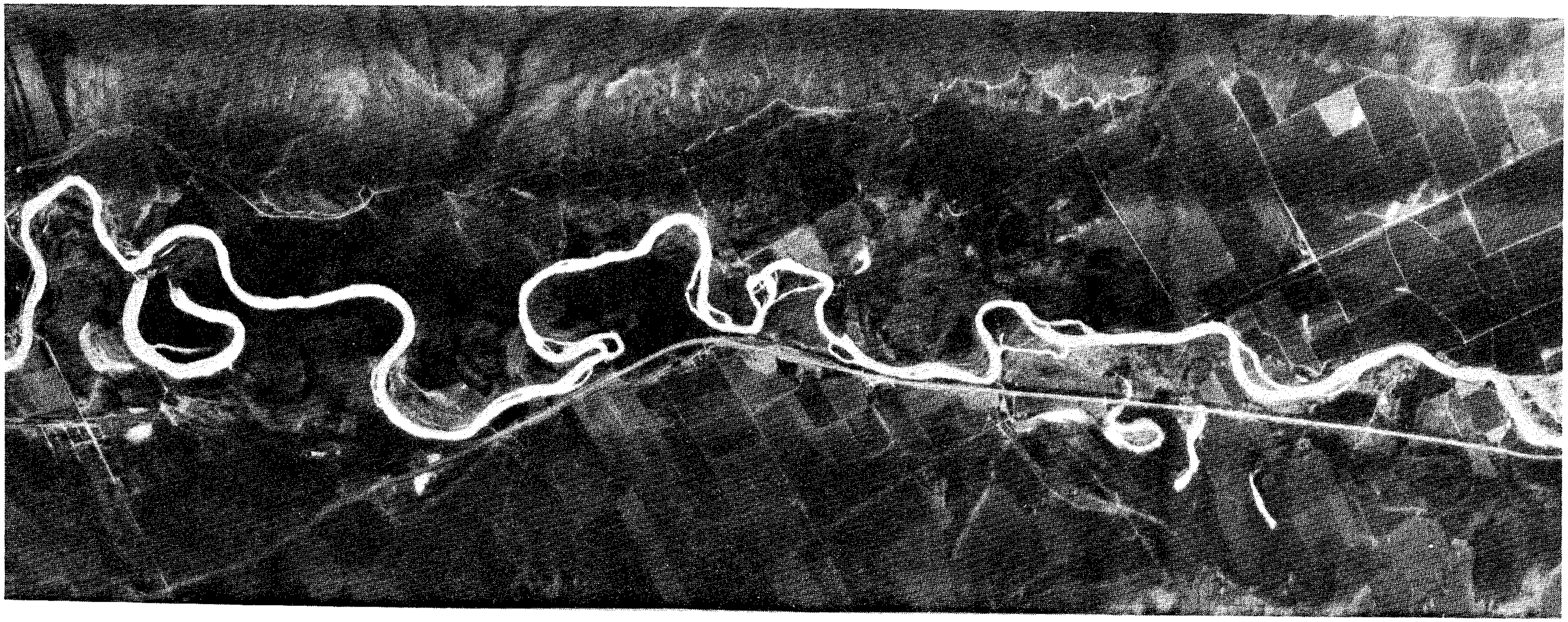


Figure 1. Meandering reach of Clark's Fork of the Yellowstone River (courtesy J. F. Ruff). Note recently formed oxbow lake which is the result of meander cutoff.

Figure 2. Braided reach of the Yellowstone River (after Ruff et al., 1973).

and therefore that category of channel will not be considered separately from the three basic patterns (Fig. 3).

Brice's description of channels is very useful because it emphasizes the great diversity of existing channels. For example, within the categories of meandering and braided channels, a considerable range of stability conditions exists.

A simple breakdown of channel patterns by Leopold and Wolman (1957) into straight, meandering and braided, although initially proposed as a very general subdivision of channel pattern, has been supported by field and experimental studies. Research demonstrates that for a given discharge, channels are straight at low gradients and with low velocity, and sediment load. As these variables increase the channel meanders, and at high values the channel braids (Schumm, 1977). For simplicity and convenience of discussion, the range of channel patterns can be illustrated by only five patterns (Fig. 4). These five patterns illustrate the overall range of channel pattern to be expected in nature, but of course they do not show the detailed differences within a pattern as described by Brice (Fig. 3) and Mollard (1973). Nevertheless, Fig. 4 is more meaningful than a purely descriptive classification of channels because it is based on cause and effect relations, and it illustrates the differences to be expected when the type of sediment load, flow velocity and stream power differ among rivers. It also explains why there are pattern differences along the same river (Schumm, 1977). Nevertheless, the distinction between patterns is not always clear. For example, at bankfull stage the bars in a braided stream may be submerged, and the channel may appear to be straight. However, at low stages the bars will emerge and the channel will clearly be braided. In addition, the

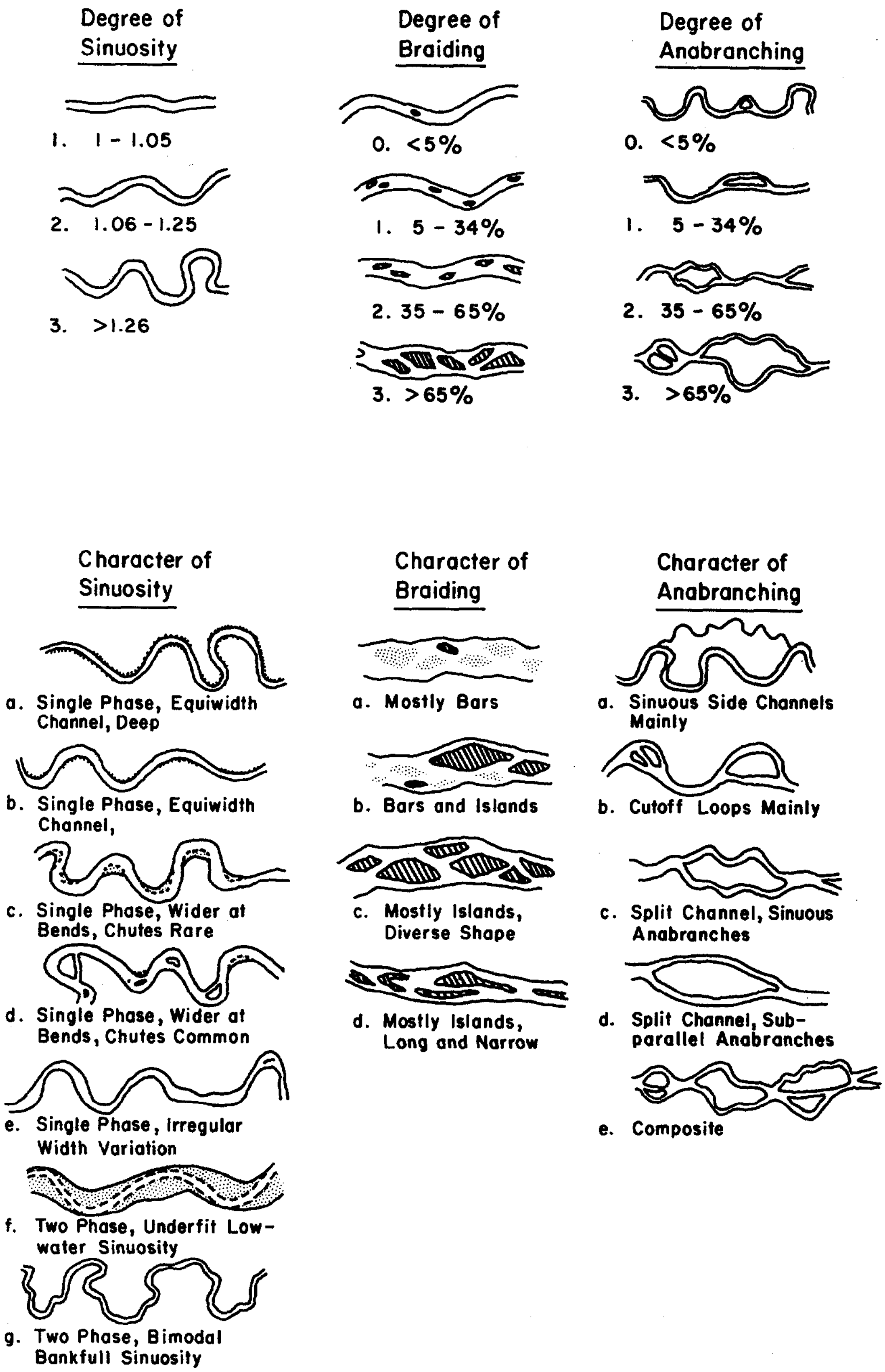


Figure 3. Types of channel patterns (after Brice, 1975).

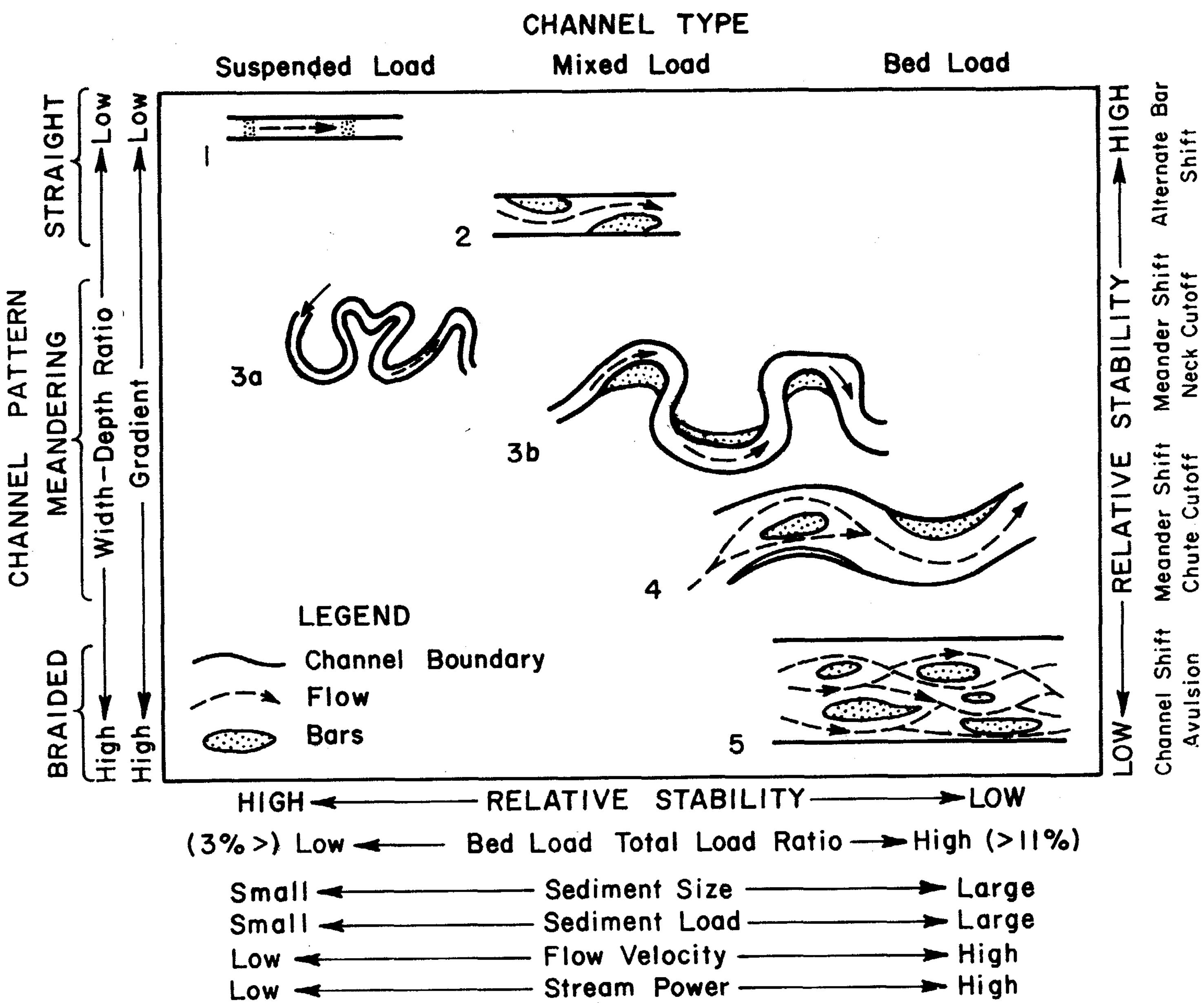


Figure 4. Channel classification showing relative stability and types of hazards encountered with each pattern.

width-depth ratio of the braided channel will be large (>50) as compared to that of a straight channel.

As noted above, a classification of alluvial channels should be based not only on channel pattern but also on the variables that influence channel morphology. This is particularly true if the classification is to provide information on channel stability. Numerous empirical relations demonstrate that channel dimensions are due largely to water discharge, whereas channel shape and pattern are related to the type and amount of sediment load moved through the channel. In nature there are large and small channels of each type illustrated in Fig. 4, and in each case the large channel forms in response to a large water discharge, but the pattern itself and the shape of the channel depends on the proportion of the total sediment load (silt, clay, sand, gravel) that is bed load or bed-material load (sand and gravel). Geomorphic history is important because it can determine the slope of the valley floor or alluvial plain upon which the stream flows. Some very straight rivers (the Illinois and the Mississippi below New Orleans) are flowing on alluvial surfaces that are relatively flat. The most sinuous reach of the Mississippi (Greenville Bends), before channel straightening, was localized on the steepest part of the valley floor below the confluence with the Arkansas River (Schumm, 1977).

When the proportion of bed load in a channel is small, the channel is narrow and deep (width-depth ratio less than 10, Fig. 4). Depending on valley slope, the channel can be straight (Pattern 1), or have a high sinuosity (Pattern 3a). When the percentage of bed load is intermediate, the width-depth ratio is less and sinuosity is between about 2.0 and 1.3 (Pattern 3b). This sandy or gravel channel may also be relatively straight, but the thalweg or the deepest part of the straight channel may be sinuous (Pattern 2). As the proportion of bed load increases, width-depth ratio increases (greater than 40) and sinuosity is low. There is a tendency for multiple thalwegs to form (Pattern 4). The greatest development of channels and bars occurs in the braided channel (Pattern 5) when the ratio of bed load to total load is high.

As indicated by Fig. 4, not only does the channel pattern change from Pattern 1 to Pattern 5, but other morphologic aspects of the channel also change; that is, for a given discharge, gradient increases and width-depth ratio increases. In addition, peak discharge, sediment size and sediment load will probably increase from Pattern 1 to Pattern 5. With such geomorphic and hydrologic changes hydraulic differences can be expected, and flow velocity, tractive force, and stream power increase from Pattern 1 to 5. Therefore channel stability decreases from Pattern 1 to 5, with Patterns 4 and 5 being the least stable.

In nature there is a continuum of patterns between Patterns 3 and 4 of decreasing sinuosity, increasing gradient and width-depth ratio, and decreasing bank and channel stability.

A brief discussion of the five basic patterns is presented because it will aid the transportation engineer in establishing the relative stability of the channel and in identifying some hazards that affect bridge stability.

Pattern 1 (Fig. 4). The suspended-load channel is straight with relatively uniform width. It carries a very small load of sand and gravel. Gradients are low and the channel is relatively narrow and deep (low width-depth ratio). Banks will be relatively stable because of their high silt-clay content. Therefore, the channel will not be characterized by serious bank erosion or channel shift. Bars may migrate through the channel (Fig. 5a), but this should not create undue instability. Pattern 1 channels are rare, but stable. However, it must be determined that the straight channel is naturally straight. If the straight channel has been artificially straightened, and therefore steepened, it can be very unstable, as it attempts to return to its original gradient by degradation, development of a more sinuous course, or both.

A naturally straight channel will pose few problems, but an artificially straightened channel will be subject to degradation and scour, bank erosion and an increase of sinuosity, which will cause serious bridge stability problems (see a discussion of these hazards in Chapter 3).

Pattern 2. The mixed-load straight channel has a sinuous thalweg. It is relatively stable, but carries a small load of coarse sediment, which may move through the channel as alternate bars (Fig. 5b). As these bars shift through the channel, banks are alternately attacked and protected by the alternate bars (Fig. 5b). Hence, at any one location the thalweg will shift with time. At a bridge this means that apparent deposition or fill at one side of the channel will be replaced by scour as an alternate bar migrates under the bridge (Fig. 4). Also, at any time one side of the channel may be filling while the other is scouring.

Pattern 3. This pattern forms a continuum depicted on Fig. 3 by the end points shown as 3a and 3b. Pattern 3a shows a suspended-load meandering channel that is very sinuous. It carries a small amount of coarse sediment. Channel width is roughly equal and the banks are stable, but meanders will cut off (Fig. 5c). Pattern 3b shows a less stable type of meandering stream. Mixed-load channels with high bed loads and banks that contain low cohesive sediment will be less stable than the suspended-load channels. The sediment load is large and coarse sediment is a significant part of the total load. The channel is wider at bends, and point bars are large. Meander growth and shift (Fig. 5e) and neck and chute cutoffs are characteristic (Figs. 4, 5c). The channel is relatively unstable, but the location of the cutoffs and the pattern of meander shift can be predicted. The shifting of the banks and thalweg follows a more or less regular pattern.

Other problems associated with this type of river behavior are degradation and scour that occur upstream of meander cutoffs (Fig. 5c) and the deposition that occurs downstream of the cutoff. Depending on a bridge location, a cutoff can cause filling below the bridge or scouring.

The shift of a meander (Figs. 4, 5e) into a bridge site creates major problems as the flow alignment is drastically altered, and bank erosion may become very serious (see discussion of Example 2 in Chapter 9). The rate of a meander shift will vary greatly depending on where in the continuum of meandering patterns the river fits. For example, Brice (1975) identifies seven meandering patterns (Fig. 3). His meandering Patterns a and g are analogous to Pattern 3a (Fig. 4). His Patterns c and d are analogous to Pattern 3b (Fig. 4). His Pattern f is analogous to Pattern 4 (Fig. 4). Brice's sequence of patterns from a to f represents the range of meander patterns with decreasing stability from Pattern a to f.

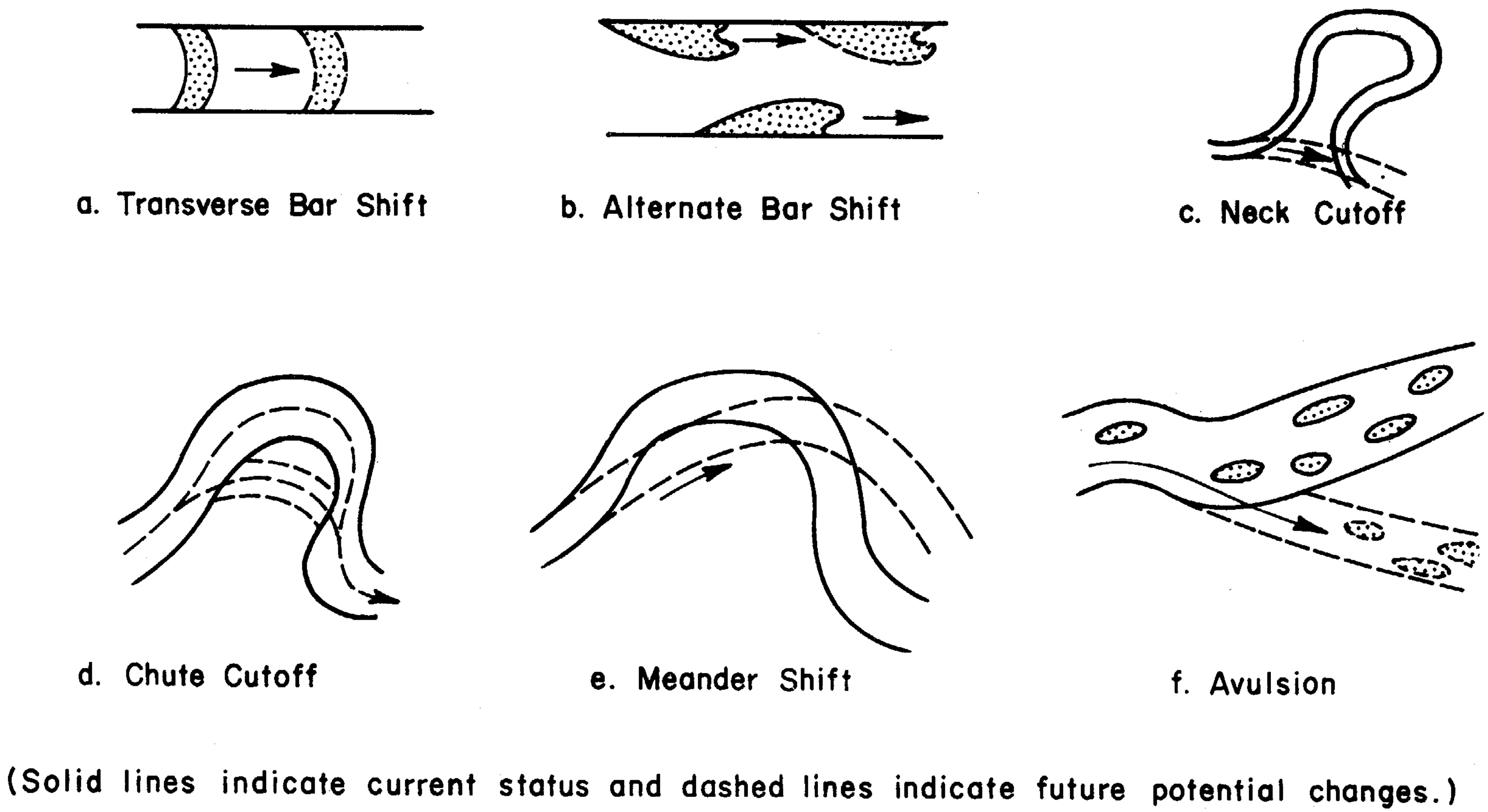


Figure 5. Typical channel changes.

Pattern 4. This pattern represents a meander-braided transition. Sediment loads are large, and sand, gravel and cobbles are a significant fraction of the sediment load. Channel width is variable. The channel is relatively wide and shallow (high width-depth ratio) and the gradient will be steep. Chute cutoffs and thalweg and meander shift and bank erosion are characteristic (Figs. 4, 5d, 5e). In addition to these problems, which are also characteristic of Pattern 4, the development of bars and islands may modify flow alignments and change the location of bank erosion (Fig. 4).

Pattern 5. This bed-load channel is a typical bar-braided stream. The bars and thalweg shift within the channel, and it is unstable. The sediment load and size are large. Braided streams are frequently located on alluvial plains and alluvial fans. Their steep gradients reflect a large and/or coarse sediment load. Bank sediments are easily eroded, gravel bars and islands form and migrate through the channel, and avulsion (Fig. 5f) may be common.

The other type of braided stream identified by Brice is the island-braided stream (Fig. 3, braided Patterns c and d). This is a much more stable channel, and it would appear to the left of Pattern 5 on Fig. 4. The Mississippi River above the junction of the Missouri River is of this type. Island formation, erosion and shift occur in these channels, but at a much slower rate than in a bar-braided channel.

The island-braided channel is not shown in Fig. 4 because it may be a channel in transition from a bar-braided pattern to either a straight or meandering pattern (Fig. 4, Patterns 2 or 3b). The typically bar-braided South Platte, Platte and Arkansas Rivers have, during the past century, changed to island-braided and to either straight, anabranching or meandering patterns as a result of decreased discharge and flood peaks. The island-braided channel may pose few problems for the transportation engineer, whereas the bar-braided channel can be very unstable. Each channel must be evaluated in order to anticipate siting and maintenance problems.

Summary

Although certain degrees of instability are typical of different stream channels, the preceding discussion of river patterns is for channels which are not undergoing pattern change. When sediment load or discharge transmitted by the channels is altered, they become unstable and respond by either eroding or depositing sediment. The channels change, but because they are composed of sediments with different degrees of resistance to erosion, and because the manner of erosion, deposition and transport is different, the response of the channels to altered hydrologic regime will also differ (Schumm, 1977).

Any change in the water and sediment load or any land use change that alters bank stability or the gradient of the channel can greatly alter the river pattern. A category of hazard that is discussed later (metamorphosis) relates to the conversion of one pattern to another as a result of such upstream changes.

Inspection of aerial photographs and comparison with the patterns of Figs. 3 and 4 provide the transportation engineer with a means of evaluating the relative stability of river channels. The discussion in this chapter has centered on pattern stability alone, and major hazards such as aggradation and degradation, which occur in bedrock-controlled, semi-controlled and alluvial channels, have not been considered. These and other hazards are discussed in Chapter 3.

Chapter 3

STREAM-RELATED HAZARDS

Introduction

A hazard is defined as any factor that may adversely affect the geomorphic, hydrologic and hydraulic conditions of a stream at a bridge site and in turn pose a danger to the highway crossing. Eighteen types of river channel changes that represent hazards to highways and bridges have been identified. These hazards may be divided into the following five groups (see Table 1):

A. Erosion Hazards
   1. Degradation and scour
   2. Nickpoint migration
   3. Bank erosion

B. Deposition Hazards
   4. Aggradation and fill
   5. Downfilling and backfilling
   6. Berming

C. Pattern-change Hazards
   7. Meander growth and shift
   8. Channel bars and islands
   9. Cutoffs
   10. Avulsion

D. River-metamorphosis Hazards
   11. Straight to meandering
   12. Straight to braided
   13. Braided to meandering
   14. Braided to straight
   15. Meandering to straight
   16. Meandering to braided

E. Miscellaneous Hazards
   17. Floating objects
   18. Waves and surges

Each of the 18 hazards will be discussed with regard to its consequences and methods of identification.

Erosion Hazards

Under the general heading of erosion there are three types of hazards: degradation and scour, nickpoint migration, and bank erosion. Degradation is the general lowering of a stream bed throughout a reach or over a considerable length of channel, in contrast to scour, which is local.

Nickpoint migration is the movement upstream of a sharply defined scarp or zone of increased erosion. Degradation, scour and nickpoint migration deepen the

Table 1. Relationships Between Variables and Hazards.

HAZARDS	VARIABLES: Time	Bank Vegetation	Channel Modification	River Use	Discharge	Sediment Load	Base Level
EROSION							
1 Degradation & Scour	3B	2B	1A	1A	1A	1A	1A
2 Nickpoints	1A	3B	1A	1A	2A	1A	1A
3 Bank Erosion	1A	1A	1A	1A	1A	1A	1A
DEPOSITION							
4 Aggradation & Fill	3A	1B	1B	3A	1A	1A	1A
5 Back- & Downfilling	1A	1B	1A	3A	1A	1A	1A
6 Berming	3A	1A	3A	3A	2C	1A	3C
PATTERN CHANGE							
7 Meander Growth & Shift	1A	1A	2B	2B	2B	2B	2B
8 Islands & Bars	1A	1A	1B	2B	2B	2B	2A
9 Cutoffs	1A	1A	1A	2B	1A	2B	1B
10 Avulsion	2B	2B	1A	3B	1A	2B	2B
METAMORPHOSIS							
11 Straight to Meandering	1A	3C	3A	3A	1B	1A	2C
12 Straight to Braided	3A	1A	1A	2B	1A	1A	1A
13 Braided to Meandering	3A	2B	3A	3A	1A	1A	2B
14 Braided to Straight	3A	1A	1A	3A	1A	1A	1B
15 Meandering to Straight	1A	2B	1B	3A	1B	1A	1B
16 Meandering to Braided	3B	1A	1A	2B	1A	1A	1B
MISCELLANEOUS							
17 Floating Objects	3A	2B	2B	2B	2B	3A	1A
18 Waves and Surges	3A	3A	2A	1A	2B	3A	3A

NOTE: Numbers 1, 2, 3 indicate severe, moderate or minimum impact, respectively.
Letters A, B, C indicate well-known relation, some information available, little-known relation, respectively.

channel. Bank erosion, on the other hand, widens the channel, but it also occurs in conjunction with degradation, scour and nickpoint migration.

1. Degradation and Scour

Definition. Degradation (AGI, 1972, p. 184) is defined as the lowering of a stream bed by erosion. Degradation is not local scour, but rather it is a major adjustment of a river to external controls. The adjustment takes place over long reaches of channel. Scour, on the other hand, is local erosion of the stream bed that, except locally, does not influence the longitudinal profile or gradient of the stream. Scour is also the temporary local erosion of the stream bed during floods. In a stable channel deposition or fill during waning stages of a flood can restore the scoured reach to near its pre-flood position, although in gravels scour holes may persist during oscillating flow conditions (Neill, 1973).

Consequences. The effect of degradation and scour is to deepen the stream channel. Many bridges are wholly or partially supported by the friction generated between the foundation and the underlying alluvium. When degradation and scour occur around the bridge foundation, the soil resistance support is reduced, and the bridge may fail. The deepening of the channel may also cause the undermining of banks and widening of the channel with failure of the approaches.

During floods, local scour around bridge supports may be so great that damage to or failure of the bridge may occur. This scour is caused by the obstruction to flow and not by natural stream movements. Constriction of the flow and the resulting increased velocity at the bridge generate deep scour holes. However, if a bridge is sited at a bedrock control or at a site where the channel is narrower, natural scour will occur owing to the natural constriction of the channel. Upstream and downstream, where the channel widens, there may be only minor scour.

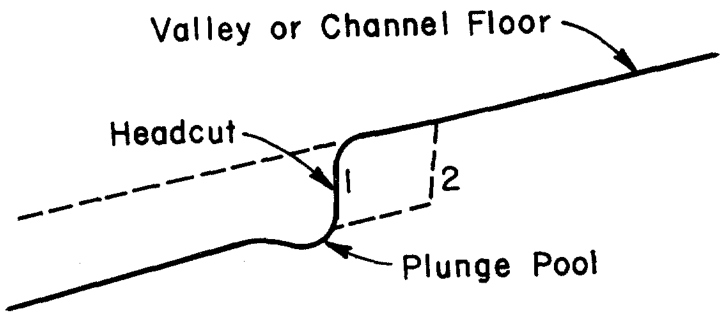
A bridge may be designed to accommodate scour caused by channel constriction, but when addition scour or degradation is imposed on the site, undermining of footings and bridge supports can lead to failure (see discussion of Example 3 in Chapter 9).

2. Nickpoint Migration

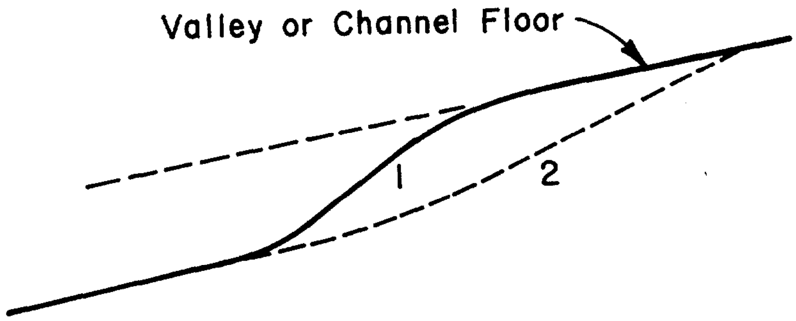
Definition. A nickpoint is an abrupt change or inflection in the longitudinal profile of the stream (Fig. 6a). This break in the smooth curve of the stream gradient results from rejuvenation of the stream or from the outcropping of a resistant bed. It is the former cause of nickpoints that is of concern here. A nickpoint in alluvium moves upstream, especially during floods. Above the profile break the river is stable; below the break there is erosion. As the nickpoint migrates past a point, a dramatic change in channel morphology and stability occurs.

Nickpoints are of two types: first is a sharp break in profile which forms an in-channel scarp called a headcut (Fig. 6a), and second is a steeper reach of the channel where the elevation change is distributed over a greater length of channel (Fig. 6).

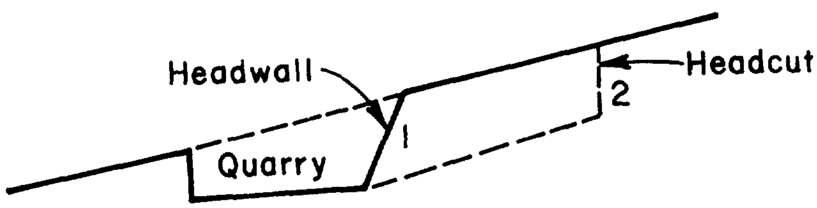
Consequences. The result of nickpoint formation and migration is, of course, lowering of the stream bed. Erosion will be dramatic as a headcut or nickpoint



a. Headcut



b. Nickpoint



c. Headwall of Gravel Pit

Figure 6. Types of nickpoint migration. Dashed lines show former and future position of channel floor and nickpoint

migrates under a bridge. During a major flood in Tujunga Wash, California, erosion above the headwall of a gravel pit (Fig. 6c) led to the failure of three highway bridges (Scott, 1973). In fine alluvium, headcut migration normally lowers the channel abruptly to its new position, but the steeper reach type of nickpoint (Fig. 6b) produces degradation that persists for some distance. In both cases scour continues until the gradient has been reduced and bank erosion has widened the channel to the point that deposition can begin.

As the nickpoint migrates further upstream, the quantity of sediment delivered to the reach at which a bridge is located increases greatly due to the erosion of the bed upstream and subsequent erosion of the banks of the stream. Therefore, a period of degradation may be followed at a bridge by a period of aggradation.

3. Bank Erosion

Definition. Bank erosion is the removal of bank materials by either a grain-by-grain removal or by mass movement (slumping or toppling, see Appendix C). Erosion can occur by river action that undercuts a bank or by simple erosion of the bank sediments. In addition, bank erosion can occur by mass failure of the bank as a result of surcharging the bank by constriction or dumping, or by seepage forces and pore water pressures related to increased water movement through bank sediment. In the latter case, the river is the transporting agent that removes the slumped bank materials rather than the primary erosive agent.

Consequences. The effect of bank erosion is a shift in the bank line of the river and the introduction of additional sediment into the channel. Erosion of both banks widens the channel, and it may lead to aggradation. According to a survey of various state highway engineers (Brice et al., 1979), bank erosion is rated as a major stream-related hazard. Therefore, a comprehensive analysis of this hazard and of slope stability in general is presented in Appendix A. Bank erosion is a major component of other hazards such as degradation and scour, meander shift, cutoffs, and various types of river metamorphosis (Table 1).

Deposition

There are three categories of depositional hazards: (1) aggradation and fill, (2) downfilling and backfilling, and (3) berming. Aggradation is the raising of the stream channel by the deposition of sediment. This occurs through long reaches of the channel. Fill, or local deposition, is the opposite of scour. Downfilling and backfilling refer to the filling of the channel from an upstream direction and from a downstream direction, respectively. Backfilling is analogous to nickpoint migration, except that a wave of deposition rather than erosion moves upstream. Berming refers to the deposition of sediments on the sides of the channel, and it is the opposite of bank erosion.

A distinction is made between backfilling and downfilling because, although the results are the same, the manner of channel filling is not, and the transportation engineer must consider not only the reach of river near a bridge site but upstream and downstream reaches if he is to evaluate the future stability of the channel at the site.

4. Aggradation

Definition. Aggradation (AGI, 1972, p. 11) is defined simply as the raising of a stream bed by deposition. Aggradation is not local fill, but rather a major adjustment of a river to external controls. Fill is a local raising of the stream bed that does not influence the longitudinal profile or gradient of the stream except locally. Fill is the opposite of scour and usually follows it.

Consequences. The main effect of channel bed aggradation and fill is to reduce bridge clearance. However, aggradation may continue to the extent that new hazards are generated. For example, it may cause avulsion, meanders to cut off, and channel pattern change. In addition, aggradation may lead to bank erosion as flow paths are changed by bar formation, and decreased channel capacity will increase flooding with the potential for damage to the bridge and its approaches.

5. Backfilling and Downfilling

Definition. Backfilling is deposition or channel filling from downstream to upstream. That is, the channel is partly or entirely blocked and deposition begins at this point and then proceeds upstream (Schumm, 1977, p. 150). Backfilling differs from aggradation as defined earlier because it starts at one location in the channel and then is propagated upstream.

Downfilling occurs when deposition progresses in a downstream direction and it is the reverse of backfilling. Both backfilling and downfilling are types of aggradation that influence long reaches of a channel, but it is important to recognize these processes, as they can affect a reach of river from either the upstream or downstream direction after it has been stable for a long time. More importantly, these two processes can be identified and their effect on the bridge site can be anticipated.

Consequences. Consequences of backfilling and downfilling at a bridge site will be similar to those of aggradation (Hazard 4). The channel bed will rise as the wave of sediment passes, and the clearance beneath the bridge will be decrease Increased flooding will result as the channel fills, and this may cause erosion of bridge approaches and perhaps even a bypassing of the bridge site. Deposition may also cause deflection of the thalweg of the channel to the extent that bank erosion will become important as the low-water channel attempts to find its way around the more recently deposited materials.

6. Berming

Definition. Berming refers to the deposition of sediments on the sides of the channel, and is the opposite of bank erosion.

Consequences. Berming will reduce the area of the channel and cause increased flood stages. Usually colonization of the berm by vegetation increases bank roughness and, in effect, further reduces channel capacity. The narrowing of the channel, however, may cause degradation and scour. This hazard is less common and serious than the other depositional hazards.

Pattern Change

Pattern change refers to the change of channel pattern and position that occurs naturally through time. This behavior of the river is usually natural and foreseeable, but nevertheless pattern changes such as meander shift cause serious problems for the highway or bridge engineer.

The four types of pattern change hazard occur in different ways. Meander growth and shift (7) and bar and island formation and shift (8) usually occur relatively slowly and at variable rates, but the change can be viewed as progressive, whereas cutoffs (9) and avulsion (10) occur relatively rapidly and episodically (Fig. 5c, 5f). Nevertheless, the condition leading to cutoffs and avulsion can be observed, and these hazards should be predictable.

Meander cutoffs are frequently caused artificially or as a result of engineering efforts to reduce flooding, but this benefit can be offset by enhanced channel instability.

7. Meander Growth and Shift

Definition. Meander growth involves a change in the dimensions of a meander. Meander amplitude and width increase as a meander enlarges and commonly the radius of curvature of the bend will increase (Fig. 7).

Meander shift involves the displacement of the meander in a downstream direction (Figs. 7a, 7b). Usually the meander both grows and shifts, although some parts of the bend can actually shift upstream (Figs. 7a, 7b). There is probably more information available on this hazard than on any other, with the exception of cutoffs (Hazard 10).

Fisk (1944) and his colleagues compiled large quantities of data to produce maps of Mississippi River channel changes since 1765. An example is shown on Fig. 7a, which displays both meander growth and shift.

Consequences. Meander growth and shift not only cause bank erosion at the crest and on the downstream side of the limbs of a meander, but it also changes the flow alignment. Increased meander amplitude results in a local reduction of gradient with possible aggradation in the bend. All of these factors represent hazards to a bridge.

Meander growth and shift will be of greatest significance where discharge is great, bank sediments are weak, and bank vegetation is negligible due to aridity or to agricultural practices.

8. Channel Bar and Island Formation and Shift

Definition. Bar and island formation and subsequent erosion and shift are within-channel phenomena. Unlike meander sweep or meander cutoffs, which involve the entire channel pattern, bars and islands can evolve within the channel and the bankline pattern itself may remain unchanged. Therefore, this hazard involves the development and migration of sediment accumulations, bars and islands, in alluvial channels.

Popov (1962) has classified the types of island changes that he observed occurring along the River Ob in the Soviet Union. He found that there were five

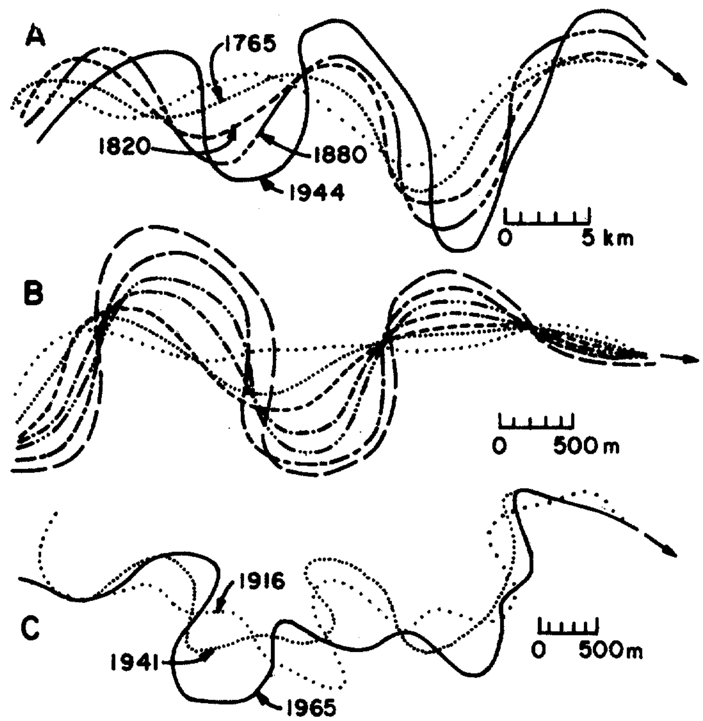


Figure 7. Evolution of simple meanders. A, Mississippi River between New Madrid, Missouri, and Dyersburg, Tennessee (Dyersburg 1:250,000); centerlines prior to 1944 interpreted from chronological sequence of alluvial deposits as illustrated by Fisk (1944, Pl. 22, Sheet 3). B, White River near Petersburg, Indiana (Iona 7½'); centerline of 1937 (heaviest line) from aerial photograph and prior centerlines interpreted from meander scrolls. C, Elkhorn River, Scribner, Nebraska (Scribner 7½' and Uehling 7½'). (From Brice, 1974.)

ways islands change (Fig. 8). A sixth and seventh could be added; that is, the formation of an island and the complete destruction of an island, but Fig. 8 does convey the important concept that bars and islands may be ephemeral and dynamic features of a channel.

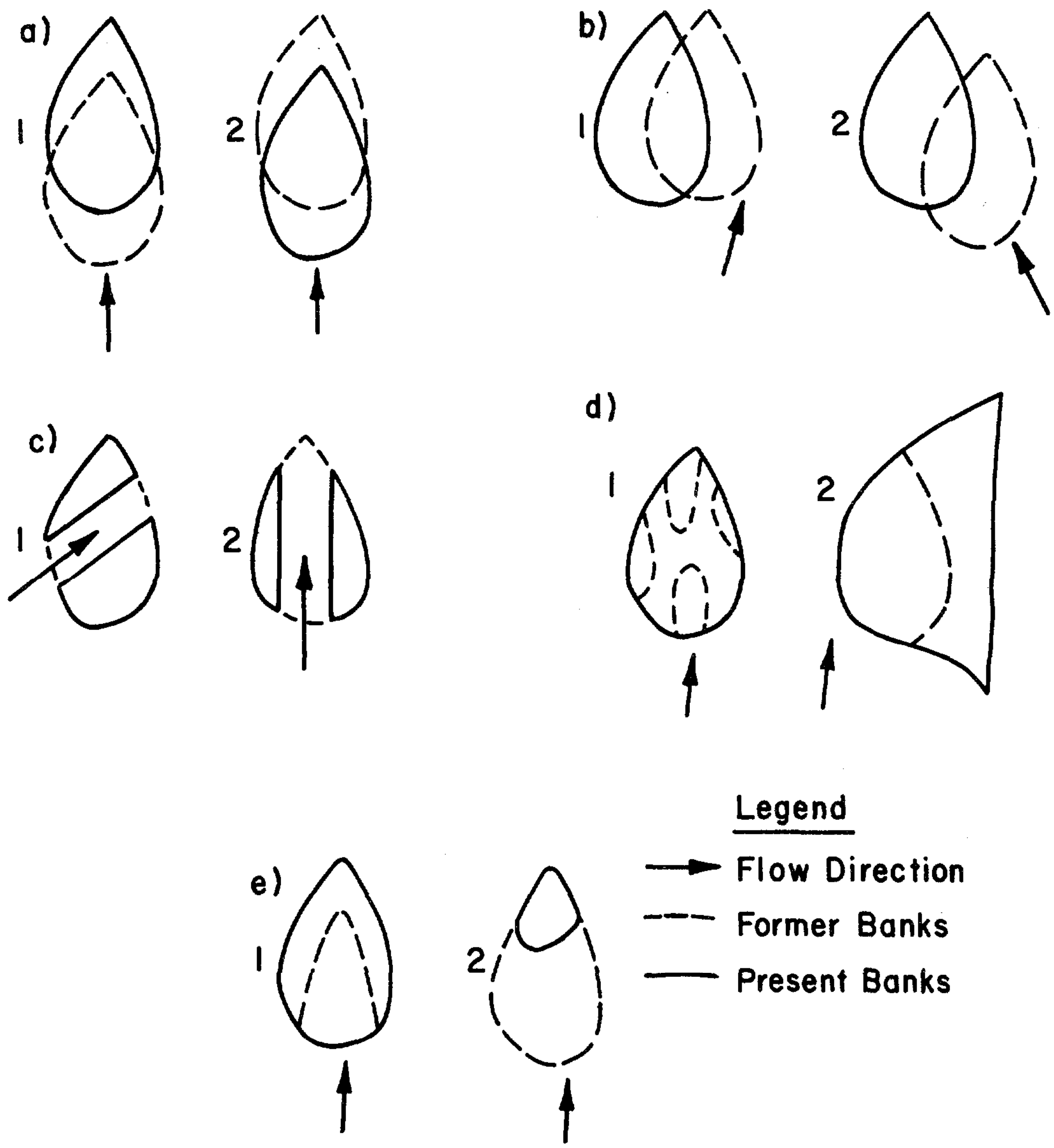


Figure 8. Island change according to Popov (1962). Arrows show direction of flow. Solid lines are original locations of islands; dashed lines show changes. (a) Island shifts up or downstream. (b) Island shifts laterally. (c) Island divided by channel. (d) Small islands coalesce and island joins flood plain. (e) Islands increase or diminish in size.

Consequences. The result of bar and island formation in a channel is to deflect the flow and perhaps to increase erosion of the banks of the channel. This erosion will enlarge the channel and, with reduced water levels, an island may form at the site of a gravel or sand bar. The worst case will be when a major bar or island forms at a bridge site. This can produce erosion of both banks of the river and scour along both sides of the island. Reduction in the flow capacity beneath the bridge can result as a vegetated island formed below or beneath the bridge. An island or bar that forms upstream can change flow alignment and create bank erosion or scour problems at the downstream site.

The shift of islands in the stream channel can be readily detected, but the movement of large sand or gravel bars beneath the water surface, particularly if the water contains a large suspended sediment load, is very difficult to document. Changes in the elevation of the thalweg or the floor of rivers have been noted as bars migrate through the channel (Laczay, 1973; Gyorke, 1973). Gyorke notes that sand bars move one to three kilometers per year during the floods, raising the bed level 20 cm as they pass. This may be a relatively insignificant change; however, on the Drava River, there is scour and fill during floods and there is migration of large bars that cause four meters of change in the thalweg of this river. This of course is a very significant change in channel morphology, and when it occurs near a bridge it will have effects similar to scour and fill.

9. Cutoffs

Definition. A cutoff is a new and relatively short channel formed across the neck of a meander bend (AGI, 1972, p. 176). This drastically reduces the length of the stream in that reach and significantly steepens its gradient. The neck cutoff has the greatest effects (Fig. 5c) on the channel. Another type of cutoff is the chute cutoff (Fig. 5d), which forms by cutting across a portion of the point bar. The chute cutoff generally forms in recently-deposited alluvium, whereas the neck cutoff forms both in recent alluvium and in older consolidated alluvium or even in weak bedrock.

Consequences. The consequences of cutoffs of both types is that the river is steepened abruptly at the point of the cutoff. This can lead to scour at that location and a propagation of the scour in an upstream direction. If a bridge is located upstream from the cutoff, the results are similar to those described for degradation and nickpoint migration (Hazards 1 and 2).

In the downstream direction, the gradient of the channel is not changed below the site of the cutoff, and therefore the increased sediment load caused by upstream scour will usually be deposited at the site of the cutoff or below it, forming a large bar. Downstream from the cutoff a bridge will be affected by aggradation, downfilling and bar formation (Hazards 4, 6 and 9).

An example of the effect of a meander cutoff on river behavior is provided by the artificial cutoff on the Peabody River in New Hampshire (Yearke, 1971). The cutoff was made in order to protect a highway that was being undermined by meander shift (Hazard 8). The river was shortened 850 feet by the cutoff, and its graident was changed from 52 ft/mile to 75 ft/mile. The abrupt steepening of gradient caused 18 ft of scour at the downstream end of the cutoff. Scour continued for 1000 ft upstream, and there was deposition downstream and bank erosion upstream.

10. Avulsion

Definition. Avulsion is the abrupt change of the course of a river (AGI, 1972, p. 50). A channel is abandoned and a new one formed as the water and sediment take a new course across the flood plain, alluvial fan, or alluvial plain. A meander cutoff is a type of avulsion because it is a relatively rapid change in the course of a river during a short period of time, but avulsion, as defined here, involves a major change of channel position below the point of avulsion (Fig. 5f).

Consequences. A new channel is formed below the point of avulsion. If the channel avulses into an existing, smaller channel, a large increase in discharge and sediment load will result, and the bridges downstream on this smaller channel will be inadequate and presumably destroyed. A bridge on the abandoned channel below the site of avulsion will appear to be significantly overdesigned. The avulsion of the Mississippi River into the smaller Kaskaskia River channel provides an illustration of this type of hazard (Fig. 9).

If, through avulsion, the river takes a shorter course to the sea, it will steepen its gradient, and scour above the point of avulsion is certain unless a bedrock control prevents upstream degradation. A bridge located above the point of avulsion will still span the channel, but it may be subjected to degradation and nickpoint migration (Hazards 1 and 2). The Mississippi River has through the last few thousand years shifted its course by avulsion many times, each time taking a shorter course to the sea (Schumm, 1977).

River Metamorphosis

River metamorphosis has been defined as a complete change of river morphology (Schumm, 1977, p. 159). As the word indicates, this consists of significant changes not only in the dimensions of the river, but in its pattern and shape. Considering the types of channel identified (Figs. 3 and 4), it is possible to consider six types of river metamorphosis as follows (Fig. 10): a straight channel changes to 1) meandering or 2) braided, a braided channel changes to 3) meandering or 4) straight, and a meandering channel changes to 5) straight or 6) braided. It is not necessary to define each type of metamorphosis, as the change is obvious based on pattern alone (Fig. 4), and the changes are illustrated in Fig. 10 for these six hazards.

Consequences. There is some similarity in the hazards posed by some types of metamorphosis, and they can be discussed as three pairs.

a) Straight and meandering to braided (Hazards 12 and 16). Both the straight and the meandering channel will widen and, of course, the meandering channel will straighten and steepen. The hazards associated with this type of metamorphosis are bank erosion, cutoffs, and bar and island formation. If the change is the result of increased sediment load, aggradation will be important, but the increased gradient of the straightened meandering channel will lead to degradation and bank erosion. The metamorphosis involves a dramatic and destructive alteration of the former channel and sometimes destruction of much of the former flood plain. Existing bridges will be too short and their approaches will be destroyed as the channels change.

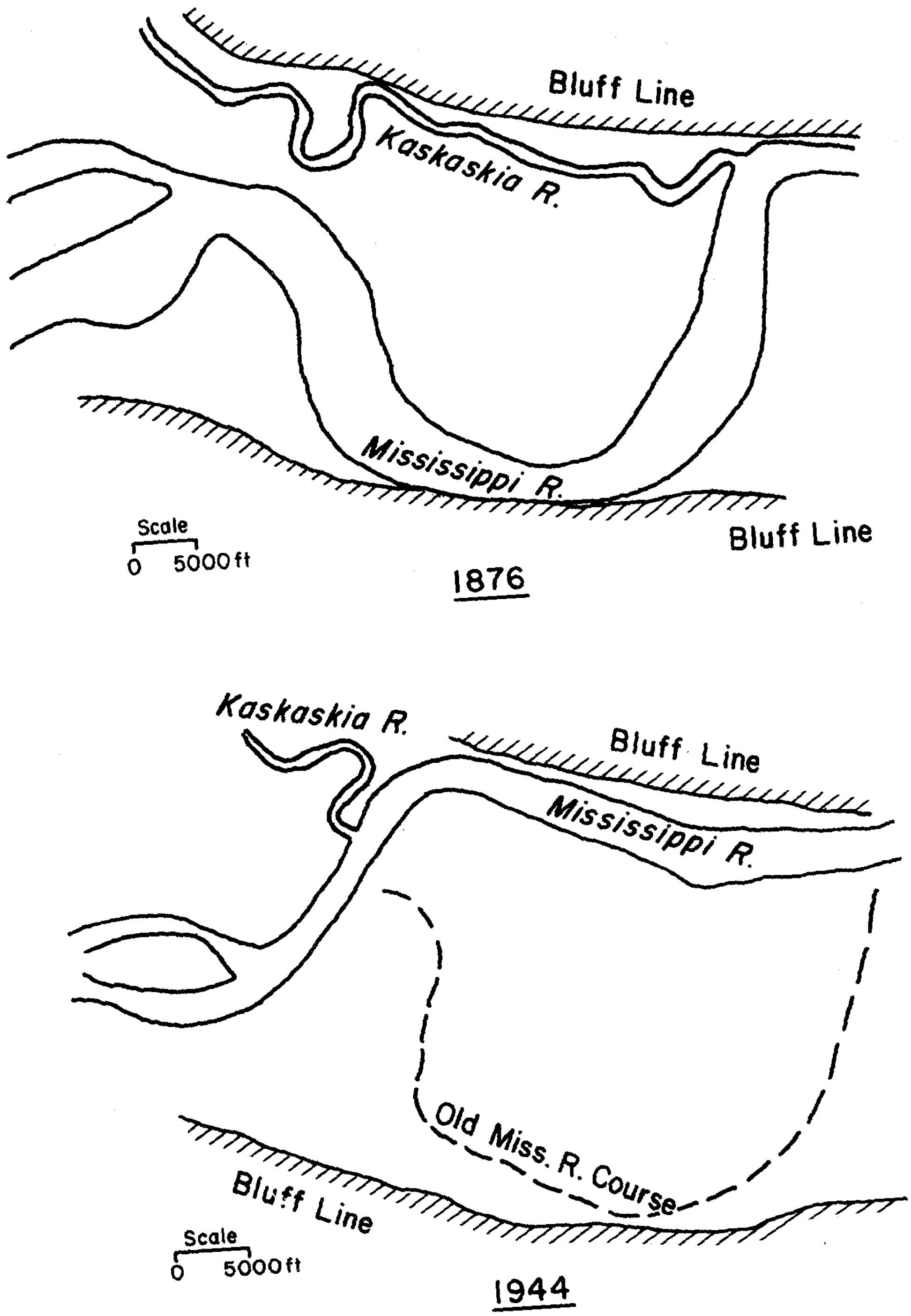


Figure 9. Patterns of Mississippi and Kaskaskia Rivers in 1876 and 1944 showing avulsion of Mississippi River (after Tiefenbrun, 1963).

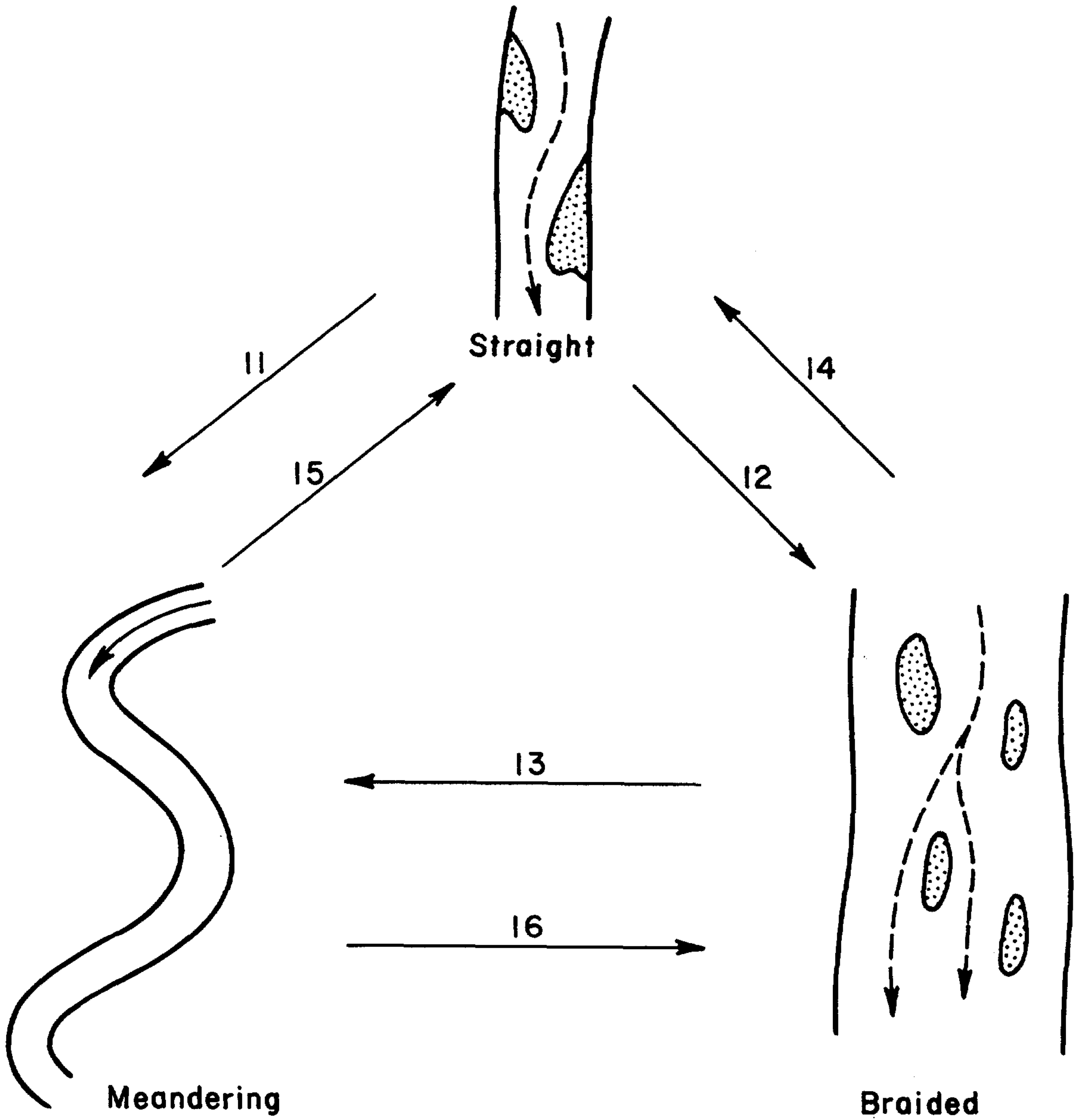


Figure 10. Types of river metamorphosis. Numbers refer to hazards listed in Table 1.

b) Straight and braided to meandering (Hazards 11 and 13). A straight channel may develop alternate bars and a sinuous thalweg if there is an increase of sediment load. If the straight channel begins to meander, bridges crossing the straight channel will be subjected to meander growth, shift, cutoff, and avulsion (Hazards 8, 10, 11) when the metamorphosis takes place.

In the case of a metamorphosis from braided to meandering, the change may actually result in increased channel stability. The decreased gradient will reduce the erosional forces acting on the channel, and although the development of meanders is a hazard itself (Hazard 7), they will form in the old channel, and existing bridges may appear too long for the new narrow sinuous channel.

In both cases the channel may degrade and this will adversely affect the bridge as described for Hazard 1.

c) Meandering and braided to straight (Hazards 14 and 15). A bar-braided channel can become island-braided when the bars are colonized by vegetation, and then the islands can be incorporated into a new flood plain. The narrowed channel should degrade, but not appreciably. The narrower channel will probably represent a more stable condition, although the increased presence of vegetation may raise the stage of large floods, which could damage a bridge.

The conversion of a meandering channel to a straight channel will be the result of a series of natural cutoffs. The steepened gradient will cause bank erosion and perhaps degradation. Unless there have been hydraulic changes, the channel will attempt to meander and the channel will be very unstable. This is especially true when the channel has been straightened artificially.

Miscellaneous Hazards

17. Floating Objects

Under this category are materials that are transported in a river in addition to its sediment load. The materials that can be most hazardous to bridges are debris (trees and trash), ice, and boats and barges.

Consequences. During floods, barges can break free from tows or their moorings. These large, heavy objects can cause structural damage to the bridge on impact, and they can aggravate the ice and debris problems.

During ice breakup, ice jams can form at bridges. Coupled with the flowing water, this can exert considerable pressure on a bridge. In addition, the ice jam reduces the capacity of the channel, thereby causing higher water stages and flood damage.

The collection of debris at a bridge during floods can have the same effect as an ice jam (Fig. 11). Debris and ice can have indirect effects by promoting deposition on bars and islands or by causing bank erosion and scour as flow directions are altered and turbulence is increased by the obstruction.

Figure 11. Debris accumulation at US 26 Bridge, Shitike Creek, Oregon, following 1964 flood.

18. Waves and Surges

Definition. Waves are minor disturbances on the water surface caused by wind or traffic. Surges are large and abrupt changes of water level caused by dam failure, rapid water release from storage, or on a smaller scale relating to changes of bed forms and hydraulic characteristics. In very steep channels the surge may be in the form of a mud flow.

Consequences. Waves generated by wind will not normally create a hazard, as the fetch in most channels is not large. However, waves generated by large boats or ships and high speed boats can cause bank, bar and island erosion.

Surges, if small, may not be of importance, but large surges can wash out bridge supports and approaches. Surges usually are associated with catastrophic events and cannot be predicted.

Chapter 4

VARIABLE AFFECTING RIVERS AND HAZARDS

Before planning and construction of a highway structure at a given stream reach, one must remember that the future stability of the reach may be determined by the long-term as well as short-term behavior of the fluvial system. For example, the export of sediment and water from upstream drainage basins, as well as downstream changes of base level, will determine both the morphology and the stability of the reach. There may be a considerable time lag before a nickpoint (Hazard 2) migrates upstream or a meander (Hazard 7) moves downstream to affect the site. Changes that occur upstream and downstream of the site, must be considered during site selection. It is essential, that not only the site but a reach of river be examined for potential hazards.

The variables that can affect river stability and cause hazardous conditions at bridge sites, (except land-use factors), will be considered in this chapter. The relation between the variables and river hazards are presented in Table 1, and the discussion in this chapter conforms to Table 1.

A. Time

Time is a variable only in the sense that it is an index of work done by the stream under natural conditions. It is stressed here to emphasize the need to be aware of natural river changes through time. For example, Hazards 2, 3, 5, 7, 9, 11 and 15 can significantly influence a river through time without a major change of another variable. An existing nickpoint (Hazard 2) will migrate upstream with time, as will the deposition associated with channel backfilling (Hazard 5). The natural shift of a meander downstream (Hazard 7) and downfilling (Hazard 5) both can occur without change of other variables.

Shifting of a bar or a meander can cause bank erosion (Hazard 3), or shift in the position of major bank erosion. The formation and erosion of bars and islands (Hazard 8) occurs naturally in many rivers through time, and it is very common in braided streams.

The natural growth and development of a meander frequently leads to cutoffs (Hazard 9), which, if extensive, may transform a meandering reach to a relatively straight reach (Hazard 15). Conversely, the development of meanders along a straightened channel is a common occurrence (Hazard 11). It is also possible that progressive aggradation (Hazard 4) can lead to avulsion (Hazard 10).

The dynamic nature of rivers leads to channel changes through time without change of other variables. This is especially true for the mixed-load and bed-load channels of Fig. 4. The suspended load channels change more slowly.

B. Bank Vegetation

Bank vegetation provides an increment of roughness that decreases flow velocity near the bank, and roots further provide a stabilizing influence on the banks of a stream. Therefore, any modification of the bank vegetation can affect the channel, and upstream changes of bank vegetation can alter the sediment load moved through the reach of concern. Bank vegetation changes will significantly affect the morphology and behavior of a river.

Removal or a decrease in the density of bank vegetation will leave the banks more susceptible to erosion (Hazard 3). This increased rate of bank erosion will lead to an increased rate of meander shift (Hazard 7) and cutoffs (Hazard 9). The greater quantities of sediment produced by extensive bank erosion can lead to aggradation (Hazard 4), backfilling and downfilling (Hazard 5) and the conversion of straight and meandering channels to braided (Hazards 12 and 16).

Although bank vegetation has not changed at a site, vegetation removal upstream will increase sediment loads at the site and cause berming (Hazard 6), additional bar and island growth (Hazard 8), and perhaps avulsion (Hazard 10) if deposition is sufficiently great. If dead or dying vegetation enters the channel, the amount of debris carried by the flow can be greatly increased (Hazard 18).

When bank vegetation increases, thereby decreasing bank erosion, the downstream reduction of sediment load may cause degradation and scour (Hazard 1) and possible conversion of a braided to a meandering (Hazard 13) or straight channel (Hazard 14). Growth of bank vegetation may also trap fine sediment and berming (Hazard 6) will result. This channel narrowing may promote scour (Hazard 1).

C. Channel Modification

To reduce flooding and to maintain navigation, channels are reconstructed and aligned. The most common modification is the elimination of a meander.

Channelization and cutoffs steepen the gradient of a stream, which has different effects depending on the location of the channel work and its extent. In fact, most of the hazards listed in Table 1 are significantly affected by one type or another of channel modification. It is true that the channel modification can stabilize the channel and for the most part eliminate hazards, but over a period of time most of man's works, if not maintained, will fail. Therefore inspection and maintenance is essential.

When a channel is constricted for any purpose, the increased velocity of flow will cause degradation (Hazard 1) or headcut migration (Hazard 2), or it will cause scour (Hazard 1) if the constriction is local. If the constriction is upstream of the site, the scour may increase sediment loads to the extent that there will be aggradation below the constriction (Hazard 4) or backfilling and downfilling (Hazard 5), depending on the location of the channel modification. Bars may form (Hazard 8) and straight and meandering channels may braid (Hazards 12 and 16). An example of the effect of constriction of a channel is provided by the middle Mississippi River in the St. Louis area, where the river has been significantly narrowed and about ten feet of degradation resulted (Stevens et al., 1975).

Any activity that changes the flow pattern or deflects the flow against a bank, such as dredging or gravel mining (Bull and Scott, 1974) will cause bank erosion (Hazard 3). In addition, a nickpoint may form as a result of dredging (Hazard 2).

Another major modification of a channel is straightening or channelization. This is normally accomplished by cutoffs (Hazard 9) which convert a meandering to a straight channel (Hazard 15). The decrease of sinuosity results in an increase of gradient, velocity of flow and tractive force exerted on the bed and banks of the channel. The result is degradation and scour (Hazard 1), nickpoint formation and migration (Hazard 2), and bank erosion (Hazard 3). The increased sediment transport from the degrading reach will cause downstream deposition (Hazards 4, 5 and 6) and conversion of straight and meandering channels to braided (Hazards 12 and 16), with the possibility of avulsion (Hazard 10).

Above the steepened and straightened reach nickpoint migration (Hazard 2) and degradation (Hazard 1) will cause bank erosion (Hazard 3), increased rates of meander shift (Hazard 7) and bar and island shift and erosion (Hazard 8), with the possibility of cutoffs (Hazard 9). Channel incision can convert braided and meandering channels to straight channels (Hazards 14 and 15). The process of channelization itself converts a meandering to a straight channel (Hazard 15). It is also likely that channel modifications can add to the debris load of the channel (Hazard 17). The effect of existing channel modifications can be evaluated, but the stability of a bridge can be threatened if modifications occur after bridge construction. Every effort must be made to determine which plans for river modifications are under consideration prior to bridge construction.

D. River Use

Rivers are used for many purposes, and of course the utilization of river water and its control are major factors to be considered (Kellerhals et al., 1979). Changes of discharge are considered as a separate variable below, and river use is defined here as due to navigation, recreation and dredging. The major impact of these uses is on the variables grouped under erosional hazards.

Increased barge and tow traffic and speedboats may generate waves (Hazard 18) that can cause some bank erosion (Hazard 3). Removal of bank vegetation, the construction of buildings along the banks, and an increase in water flow toward the banks greatly increase bank instability (Hazard 3). If bank erosion rates are increased, there is a possibility of increased meander growth and shift (Hazard 7) and meander cutoff (Hazard 9).

A major problem in many rivers is the increasing rates of sand and gravel extraction. The river is an ideal and readily available source of construction materials. Deep dredging or gravel mining in the channel and flood plain creates a nickpoint (Hazard 2) which may move upstream, causing degradation (Hazard 1) and bank erosion (Hazard 3) (Bull and Scott, 1974). If sufficient sediment is generated by the above processes, straight and meandering channels may braid (Hazards 12 and 16) with the possibility of bar migration (Hazard 8).

There is a need to be aware of the potential for future changes of river use during the life of a bridge. There have been serious bridge failures as a result of sand and gravel mining operations that have intensified after bridge construction (see discussion of Example 3 in Chapter 9).

E. Discharge

Discharge character is by far the most dominant variable influencing channel dimensions, as all stream-related hazards are related to flow in the channel. Three major hydrologic properties are flow magnitude, duration and the rate of change. These three properties can affect hazards differently under different situations. For instance, in two streams with the same average flow discharge, the stream with the greater peak flow discharge or the more rapid change of flow rate will have more bank erosion and be more unstable. Therefore, an analysis of the hydrologic character of the stream must be made by hydrologists.

Every hazard listed in Table 1 is affected by discharge characteristics. Most of the changes in long-term discharge are man-induced, as a result of flow regulation by dams and diversion (Hazard 18). Major floods may cause great channel changes, but hydrologic studies prior to bridge construction can be used to estimate the magnitude of floods that are anticipated, during the life of a bridge. Therefore, it is the man-induced changes of flow rather than natural floods that are of concern here.

An increase in either or both mean annual discharge and/or peak discharge will cause scour (Hazard 1) and bank erosion (Hazard 3), with an increase in the rate of nickpoint migration (Hazard 2). The increased erosion may well cause deposition farther downstream (Hazards 4 and 5). The increased flow will accelerate the rate of meander growth and shift (Hazard 8) and cause cutoffs (Hazard 9) and possibly avulsion (Hazard 10). The increased flow may cause straight and braided streams to develop meanders (Hazards 11 and 13), and increased flood peaks may cause meandering and braided streams to straighten (Hazards 14 and 15) and meandering streams to braid. All of these changes will result in more debris (Hazard 17).

A decrease in both mean annual flow and peak discharge may result in aggradation (Hazard 4) and berming (Hazard 6), and a braided stream may become straight (Hazard 14) or develop meanders (Hazard 13).

Any significant change of discharge characteristics will result in a channel change. In general, an increase of discharge will cause erosion and at least a temporary period of relative instability. Decreased discharge will also cause channel adjustments, but the changes will be less severe and will be generally opposite to changes caused by higher discharge.

F. Sediment Load

The amount and type of sediment load transported by a stream is a major factor that determines the morphology of the channel (Fig. 4). Major changes in sediment load can result from changes in land use, fire and hydrologic events, as well as the construction of dams, which retain water and sediment in the reservoir. As with discharge, almost every hazard is affected by this variable.

A significant decrease in bed load will lead to erosion (Hazards 1, 2 and 3). This erosion can affect the channel pattern by increasing the flow velocity and bank erosion (Hazards 7, 8, 9 and 10). If the decrease is sufficiently great, metamorphosis can occur (Hazards 11, 13 and 14).

A significant increase in bed load will cause deposition (Hazards 4 and 5), and this in turn will trigger cutoffs (Hazard 9) and possibly avulsion (Hazard 10). A large increase in bed load will lead to certain types of metamorphosis (Hazards 12 and 16).

If there is a significant increase of suspended load, the fine sediments will deposit along the banks (Hazard 6) and on the bars, which can convert straight channels to meandering channels (Hazard 11).

Any anticipated alteration of sediment load must be given serious consideration, for it will result in major changes at a bridge site.

G. Base Level

A change in base level will have an influence on most river hazards. The most common change is the rise of base level owing to dam construction. Base levels can be lowered as lakes and reservoirs are drained, or as a result of excavations in the stream channel.

Base level lowering will cause a gradient adjustment by degradation (Hazard 1) or by nickpoint migration (Hazard 2). The resulting incision will promote bank erosion (Hazard 3), meander shift (Hazard 7), and cutoffs (Hazard 9). The increased gradient may cause straight channels to meander or braid (Hazards 11 and 12), and meandering channels to straighten and braid (Hazards 15 and 16). The increased bank erosion and incision may produce more debris (Hazard 17).

A base level rise will promote aggradation (Hazard 4) primarily be back-filling (Hazard 5), which in turn can trigger cutoffs (Hazard 9) and even avulsion (Hazard 10). The decreased gradient accompanying aggradation will cause straight and meandering streams to braid (Hazards 12 and 16).

In summary, the effect of base level change is similar to that due to aggradation or degradation (Hazards 1 and 4).

Chapter 5

HAZARD IDENTIFICATION

There are basically two ways to identify hazards and to assess their potential effect on a bridge site. The first is a historical approach that utilizes existing information to recognize channel change. The second is more specific and relies on the recognition of the hazard from existing conditions at the site.

A. Historical

In many areas of the U. S. there is historical information available that will permit the engineer to identify a hazard and to estimate the relative seriousness of that hazard. Aerial photographs, old maps and surveying notes, and bridge design files and river survey data that are available at the various state departments of transportation and at federal agencies, as well as gaging station records and interviews of long-time residents can provide useful historical information. These resources can be used in the following ways:

1. If a sequence of aerial photographs can be obtained that were taken during a period of several decades, and particularly if the photographs were taken during low water, a comparison of the photographs will show changes in channel morphology during that period. If maps or aerial photographs of good quality are available, it is frequently possible to measure the amount of bank erosion that has occurred in the past. Measurement from a known point (road junction, building, etc.) to the bank of the channel can provide information on bank erosion. Change in the width of the channel through time also will provide a basis for calculating the rate of bank erosion, although it may not be possible to determine whether both banks or only one bank is eroding.

2. Old maps and field notes of surveys undertaken by the General Land Office and other agencies can provide information on river width and position and perhaps the position of nickpoints at the time of the survey. Comparison of the old maps with more recent U.S. Geological Survey topographic maps may provide information on the rate of channel change or the lack of it. Series of cross sections have been surveyed along some rivers by agencies such as the Corps of Engineers (e.g. Mississippi, Missouri, Ohio Rivers) and the Bureau of Land Management (e.g. Rio Grande). If repeat surveys have been made, they will provide a means of evaluating channel stability. If not, new surveys will provide a basis for comparison.

3. The history of bridge failures or bridge problems may provide clues as to nature of river change or the lack of it through time. At most bridge sites the height of the crown of the road above the channel is given on the plans of the bridge. A simple measurement from the road crown to the bed will provide a check on this distance and perhaps information on degradation or scour at that site.

4. Gaging station records for a given discharge will show if there is a change in the water surface elevation through time. For example, Borsuk and Chalove (1973) reported on the downcutting of the Lena River in the Soviet Union. They were able to establish that for a given discharge there has been a decrease in the gage height between 1946 and 1966 (Fig. 12). This progresive lowering of the water surface at a given discharge is clear evidence that the Lena River was degrading

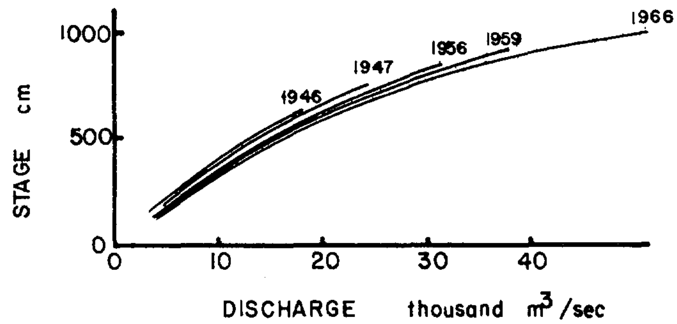


Figure 12. Relation between stage (H) and discharge (Q) of the Lena River, gaging station Tabaga (1946-1966). (From Borsuk and Chalov, 1973.)

during that period. In addition, the gage records may record the passage of a bar or sand wave through a section. Change in the low-water level at gaging stations on the North Platte River are cyclic (Fig. 13), suggesting the passage of large bars or sand waves through the channel (Williams, 1978).

5. Long-time residents of the area may remember channel changes that have occurred during their lives. Photographs from family collections and archives can frequently provide information on river characteristics back to the beginning of the 20th Century. The photographs in particular can provide excellent information on past bank conditions.

6. When no historical information is available, it may be possible to determine rate of channel shift by a study of vegetation distribution on the flood plain (Fig. 14). Hickin (1974), Hickin and Nanson (1975) and Everett (1968) have made use of dendrochronology to date the migration of the Beatton and Little Missouri Rivers. Figure 15 shows the present channel of the Little Missouri River with isochrones showing age of the valley floor. The downvalley shift of two meanders is clearly displayed. The smaller upstream meander was cut off about 20 years ago. Both meanders are confined by the bedrock walls of the valley.

7. A final method of determining channel change is to measure erosion by repeated surveys at the site of interest. This, of course, is an expensive and time-consuming operation, but if there is sufficient time it may be worthwhile to document site behavior and behavior of the reach of river within which a bridge will be sited for a few years prior to its construction.

In summary, a sequence of maps and photographs and a study of vegetation distribution is of great value in determining pattern change and metamorphosis. These techniques can provide information on lateral and longitudinal change.

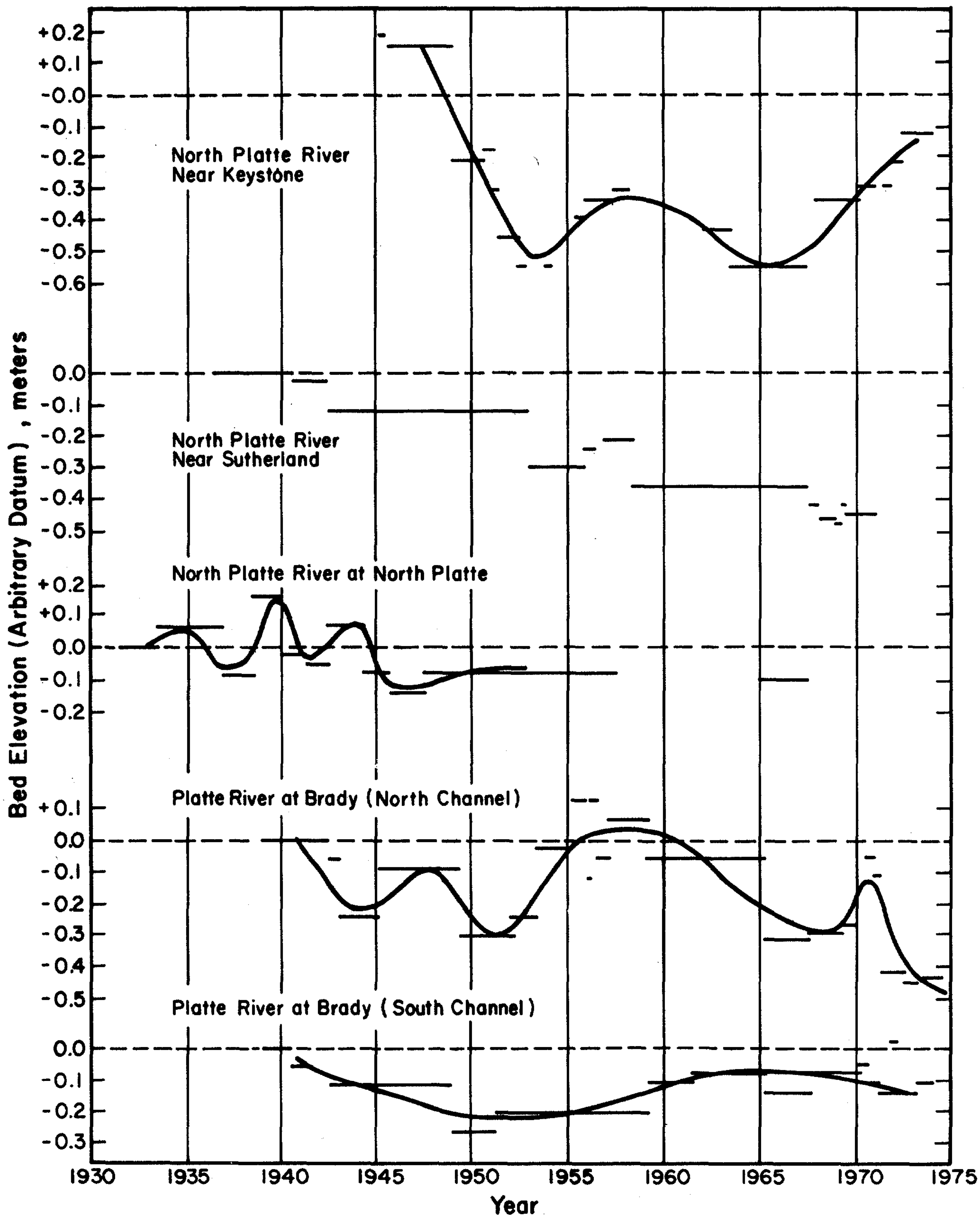


Figure 13. Changes in bed elevation - Platte River (from Williams, 1978).

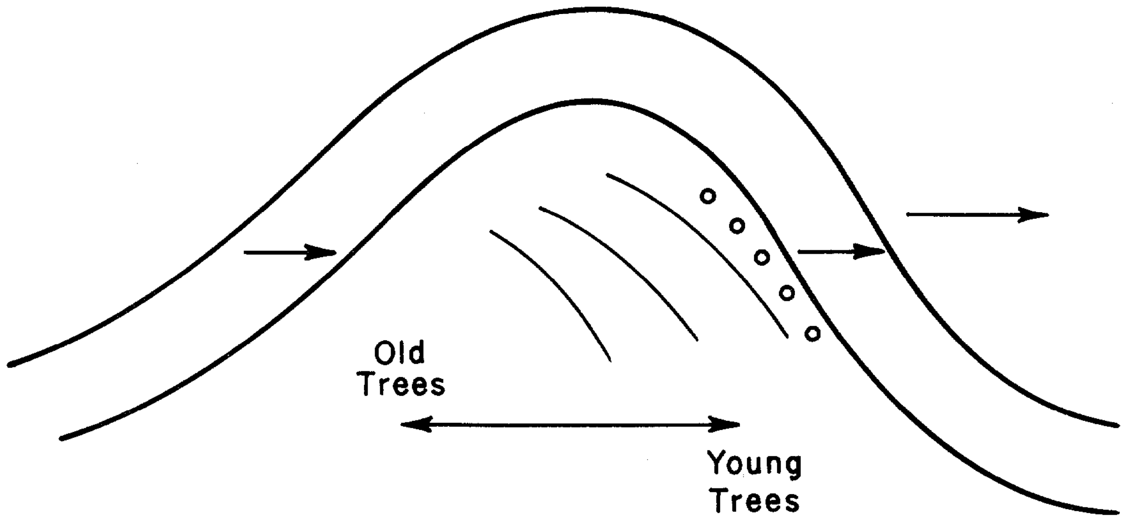


Figure 14. Distribution of trees on shifting meander.
Meander shift is from left to right.

Bank erosion and nickpoint migration can also be identified in this manner. However, slight or slow changes due to degradation and aggradation can only be identified from data that reveal the horizontal position of the bed. For this purpose cross sections and gaging station data are needed.

Site Conditions

The previous discussion has provided a general approach to the identification of hazards. A discussion of some common techniques that can be used to identify each hazard is presented here.

1. Degradation and Scour

It may be difficult to identify a reach of channel that is being degraded or scoured when the process is in its early stages or if the process is slow. In fact, without other data bed erosion may be recognized only after it has become a significant factor causing bank erosion or instability of structures. However, where the channel is being deeply and rapidly incised, the process is easily recognized.

Patterns of stream-bed erosion as reflected in scour holes that persist and deepen, deepening of the thalweg or low water channel, and the exposure of previously buried materials in the stream bed are all indicators of degradation or scour.

The development of a thin armor of coarse sediment due to hydraulic sorting usually indicates that degradation has occurred. The armor may have prevented further degradation, but a large flood may breech the armor and renew the process. A deep, narrow, entrenched channel suggests degradation, particularly if the bank

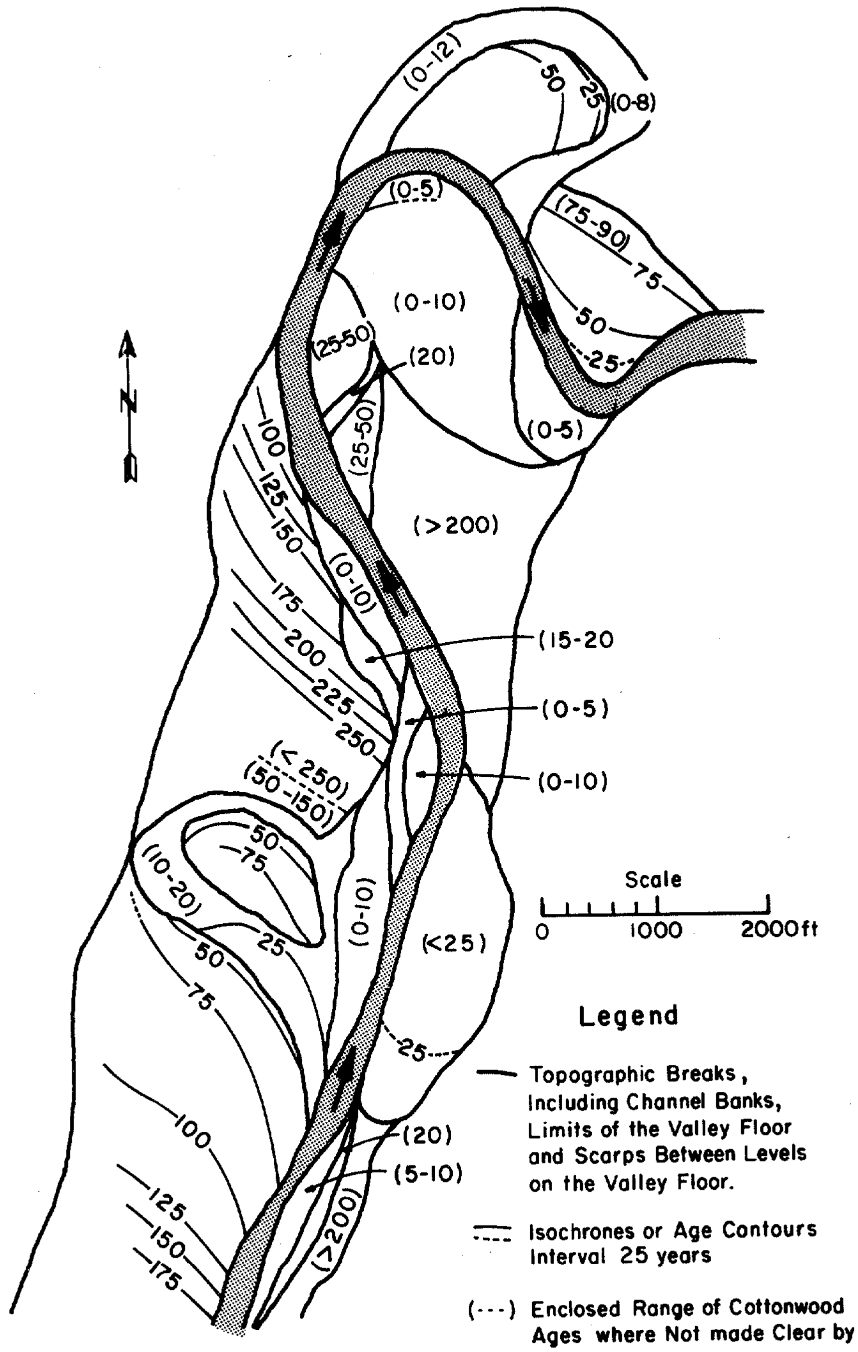


Figure 15. Distribution of tree ages on valley floor of Little Missouri River near Watford City, N.D. Contours are isochrones of tree age (from Everitt, 1968).

sediments are not fine-grained. Any channel that is bordered on either side by banks higher than the highest flood level is either actively degrading or has been doing so in the past (Galay et al., 1973). Local deepening and decreased width-depth ratio may also signify scour.

Relatively infrequent overbank flooding suggests increased channel capacity. If floodplain vegetation and soil indicate relatively infrequent overbank flows, then incision is a possibility.

Although the main channel may not show clear evidence of degradation, smaller tributaries to the channel will be degrading as a result of main channel incision, or they may contain nickpoints. If such a consistent pattern of tributary degradation and nickpoint distribution can be detected, it is evidence of main channel degradation.

2. Nickpoint Migration

The most obvious and simplest way to identify nickpoints is by the use of aerial photographs. Particularly in arid and semiarid regions, headcuts are very easily recognizable because the upstream valley floor or channel is essentially undisturbed, whereas the channel below the nickpoint shows significant erosion.

On topographic maps of large scale, the nickpoint will be represented by closely-spaced contours. Of course, if longitudinal profiles are available or can be surveyed, they will show the break in the longitudinal profile of the stream that is the nickpoint.

A change in the dimension of the channel and a change in the character of the bank line may indicate nickpoint migration. A low width-depth ratio below the nickpoint is an indication of scour and deepening of the channel. Bank erosion is also the possible consequence of nickpoint migration and a sharp change in the bankline characteristics representing a change from stability to instability may identify the position of a nickpoint.

It may also be possible to identify the location of a nickpoint by study of riparian vegetation. The passage of a nickpoint may cause the death of trees, which are frequently replaced by other types of hardy drought-resistant plants.

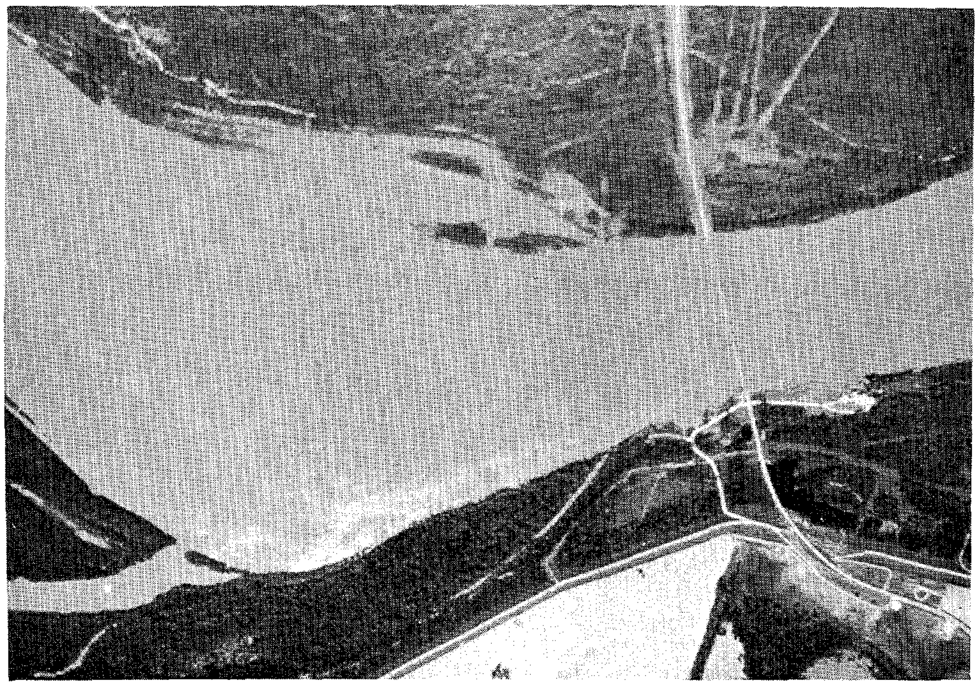
3. Bank Erosion

Bank erosion is easy to recognize (Fig. 16). Eroding banks show tipping and fallen vegetation adjacent to the outer bank, cracks along the bank surface, slump blocks, fresh vegetation laying in the flow, deflected flow patterns adjacent to the bank line, increased turbidity in the water, fresh vertical or sloping face cuts, new deposition in the form of bars immediately downstream from the eroding area and, in some instances, a deep scour pool adjacent to the toe of the bank slope.

The concentration of high velocity flow along a bank when identified on aerial photographs can also indicate the reach of bank that is susceptible to erosion (Fig. 17).

Color infrared aerial photography is particularly useful for noting most of the bank erosion indicators listed above. The majority of suspended material

Figure 16. Active bank erosion exhibits fresh cut scarps, bankline cracks, slump blocks, and falling vegetation.



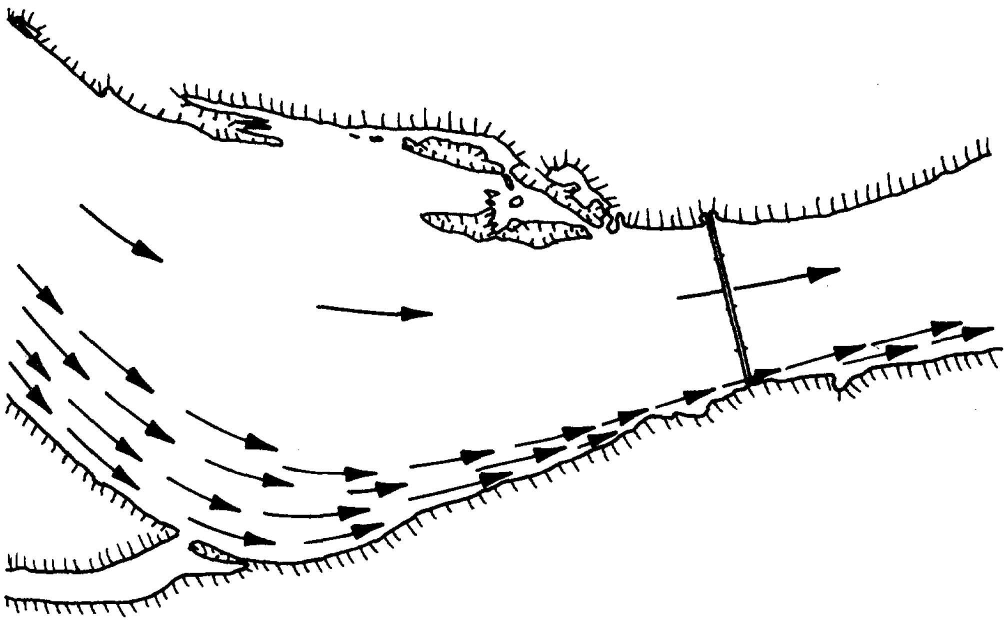


Figure 17. Color infrared photography enhances flow concentration pattern near bankline to indicate potential zone of severe bank erosion.

being transported by a river is obtained from the bed and banks of the river and its tributaries (Ruff, et al., 1973). Differences in turbidity manifested by suspended material concentration variation is particularly noticeable on color infrared photography.

A major difficulty is to determine the seriousness of the apparent erosion. In many cases the eroding bank, if comprised of resistant sediments, will be relatively stable (Appendix A).

Although active bank erosion is readily identified, it may be only a part of a larger problem and it may be symptomatic of other hazards that are related to channel shift or metamorphosis (Hazards 7, 9, 10, 11, 12, 13, 16). The rate of bank retreat can be estimated by comparing large-scale multi-date photography. Sequential aerial photography is an excellent tool for recording long-term trends in bank changes (Brice, 1971). Recent studies show that color infrared photography generally is superior for species identification, plant vigor measurements, and vegetation mapping (Jones, 1977), and these images may be useful in identifying bankline vegetation that is stressed by root exposure and bank failure. Lateral erosion rates of several Alaskan rivers were determined by comparing multi-date photographs. Brief on-site inspections utilizing a helicopter were valuable in the interpretation of the aerial photographs (Brice, 1971).

4. Aggradation

Identification of a reach of a river that is being subjected to aggradation, at least in the earlier stages of the process, may be difficult. Aggradation may be recognized only after it has become a significant factor causing overbank deposition and bank erosion. However, where the channel is being rapidly aggraded, the process is easily recognized. Patterns of deposition on the channel bed and flood plain and burial of trees, fences and other structures may be evidence of aggradation.

The clearest evidence of aggradation is usually morphologic; for example, a shallowing of the channel through time will suggest aggradation. This change in the normal hydraulic geometry relations is evidence of channel instability. A significant increase in the width-depth ratio with time may also be an indication of scour and degradation. If, for example, the width-depth ratio of a river increases from 20 to 50, and the channel has not widened appreciably, the channel is aggrading. A local change will be evidence of fill. Aggradation is also indicated by the appearance of sand and gravel bars where they did not previously exist (Pfankuch, 1975), and in general the development of a braided channel (Hazards 12 and 16).

Reaches near the confluence of large streams and immediately upstream of reservoirs are susceptible to aggradation, as are flow expansion zones downstream of bridges, areas upstream of culverts and locations where debris accumulates (Neill, 1973) (Fig. 18). An increase of overbank flooding may indicate aggradation or channel capacities are reduced.

Although the main channel frequently may not show evidence of aggradation, the smaller tributaries joining the channel will also be aggrading as a result of a rising base level. If such a consistent pattern of tributary aggradation and backfilling can be detected, it is evidence of main channel aggradation.

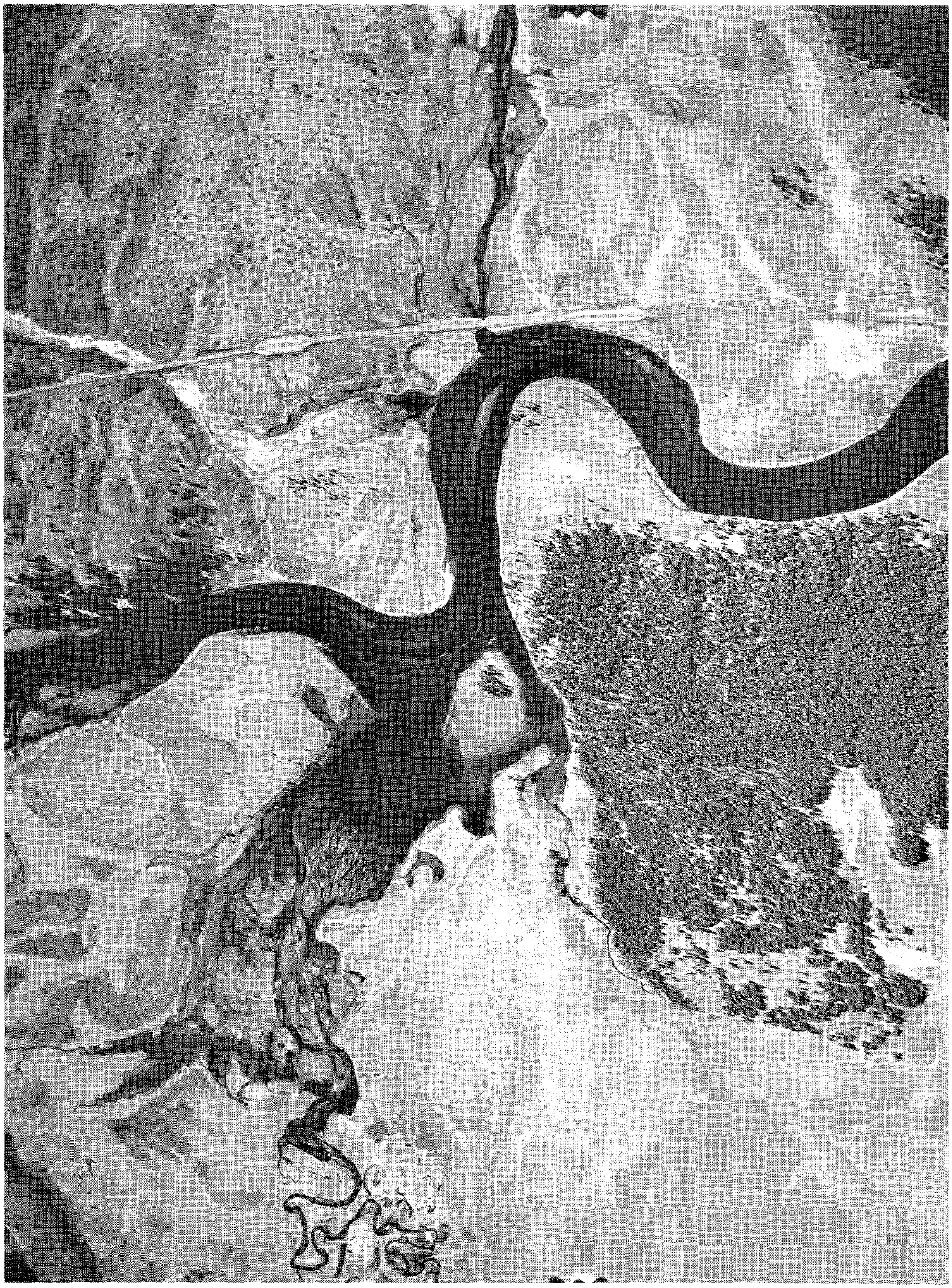


Figure 18. Deposition upstream of culverts at highway crossings and at confluences with large streams, (color infrared photograph - Yellowstone River, Yellowstone Park).

5. Backfilling and Downfilling

The identification of backfilling and downfilling will be much easier than the recognition of aggradation because in the former case not only is the change progressive through time, but it is progressive along the stream channel.

The clearest evidence will be morphologic; for example, the channel shape and dimensions will change from the as-yet stable reach to the reach where there is deposition. A change in the width-depth ratio of the channel from a low to a high value with no other apparent control will also indicate backfilling and downfilling.

The channel pattern may change to braided (see for example Hazard 17) in the reach where deposition is dominant, and evidence of more frequent overbank flooding should be apparent.

All of the evidence of aggradation, as discussed under Hazard 4, can be used as evidence for backfilling and downfilling once this process had begun in a reach.

6. Berming

Evidence for berming will be the obviously recent deposition along the bank of a river and the pioneering vegetation which is colonizing these recent deposits. Older bank and low floodplain vegetation may be partly buried by the recent deposits. The deposits probably will contain modern artifacts.

If this process has continued for some time, a low inner floodplain may develop.

7. Meander Growth and Shift

Lateral and downvalley movement of meander bends is a characteristic feature of alluvial rivers and one of the most conspicuous changes affecting fluvial landscapes (Gregory, 1977). Bank recession rates, due to the hazard, of 10 to 15 meters per year are by no means exceptional in large rivers, and 100 meters per year is not unknown. Such rates apply to certain bends only. Others on the same channel at the same time shift more slowly, if at all.

Where meander shift is rapid, evidence of the process should be apparent in the field. For example, sites of bank erosion and deposition should be recognizable (see Hazards 3 and 6) and they should occur in a pattern characteristic of meander shift (Figs. 7, 15, 16). However, this pattern of deposition and erosion may not provide an indication of the seriousness of the problem or the rate of meander shift. If, in fact, bank erosion is absent or minor following major floods, then the meander may be relatively stable. In order to determine the relative stability of the bend, a historical investigation (see Example 2, Chapter 9) using maps and aerial photographs is needed (see preceding discussion of Historical Approach and discussion of Example 2, Chapter 9).

If clear evidence of meander shift can be obtained by any of the abovementioned techniques and if it can be assumed that there will be no upstream alterations of the hydrology of the river, then an estimate of future channel change can be made. Obviously, if the shifting meander encounters bedrock or more resistant alluvium, the rate of shift will decrease. Therefore, a soils and geologic investigation of the site should be made to determine how variable is the resistance of the bank material.

In looking at pattern migration, care must be exercised in distinguishing between presently active processes and those active at an earlier stage, but whose traces may be well preserved on the valley flat. Features that assist in this evaluation are meander scrolls, scroll bars, point bar deposits, meander scars, linear vegetation patterns on the present floodplain.

8. Islands and Bars

The formation of islands and bars is characteristic of certain types of stream channels. A river that transports large quantities of bed material load will form bars. The presence of this bar, of course, obstructs the flow and there is then either lateral erosion of the banks on both sides of the bar or scour of the channels surrounding the bar. This lowers the water level at this location and the gravel bar then appears above the surface. It is then immediately susceptible to colonization by vegetation, and an island is formed. The presence of bars and islands in channels is not unusual; in fact, they may represent only a relatively minor hazard to bridges. Nevertheless, as with channel pattern change, it is well for the engineer to know that the configuration of the floor of the channel and some major morphologic features in the channel can change through time.

Island shift should be easily identified because active erosion at one location and active deposition at another on the edge of an island can be recognized in the field. Also, the development of flood channels or the abandonment of channels and the joining together of islands can be detected by observing vegetational differences and erosional and depositional patterns.

Bar shift can be documented by the use of a fathometer or any type of sounding device, and of course the changed position of bars at low water can be observed in the field or on photographs and maps.

9. Cutoffs

It is very easy to identify where a meander has been cut off (see discussion under Hazards 8 and 9). Not only is there a change in the river pattern--the river reach is straighter than upstream or downstream--but the cutoff portion of the channel, the oxbow lake, is also displayed on the flood plain (Figs. 9 and 10). However, the problem is not so much to identify where a cutoff has occurred, but where it will occur. Generally, this can be done by examining a sequence of aerial photographs to determine the rate at which bank erosion is decreasing the width of the meander neck. In addition, if through time an increase in the amplitude of a bend or the sinuosity of a reach can be noted, then that bend or reach may be susceptible to a cutoff, because the increasing length of the channel is accompanied by a decrease of gradient and the ability of the channel to transport its sediment load (see discussion of Hazard 4).

A recent cutoff may be documented by the local residents and, in fact, if the river is a boundary or is a major river, efforts probably will be taken to prevent the cutoff. On the other hand, efforts are frequently made to expedite the cutoff as a means of lowering flood peaks.

10. Avulsion

It is an easy matter to identify where avulsion has or is taking place (see discussion of Hazards 4, 8, 10). For example, on alluvial fans the continual shift of the channels on these alluvial deposits can be mapped and identified in the field without a great deal of difficulty. The problem is identification of a site of potential avulsion so that this can be prevented or steps can be taken to mitigate the effects of avulsion when it occurs. A careful study of aerial photographs will show where overbank flooding has been taking place consistently and where a channel exists that can capture or cope with the flow in the existing channel. In addition, topographic maps and special surveys may show that the channel is indeed on a high point in a valley and that it is perched above the surrounding alluvial surface, with the inevitability of avulsion (Fig. 19). Generally avulsion, as the term is used here, will only be a hazard on alluvial fans, alluvial plains, deltas, and wide alluvial valleys. In a progressively aggrading situation as on an alluvial fan, the stream will build itself out of its channel and be very susceptible to avulsion. In other words, in a cross profile on an alluvial fan or plain, it may be found that the river is flowing between natural levees at a level somewhat higher than the surrounding area. In this case, avulsion is inevitable. An example of this is provided by the Jubones River, Equador (Maddrell, 1973), where it crosses the coastal plain (Fig. 20). A major avulsion occurred in May, 1970.

This avulsion was the result of the construction of a fan-shaped deposit by the Jubones River. The river was aggrading and as a result it shifted from its high position on the fan to a shorter, steeper route to the sea. The existence of many channel traces on the Jubones fan is clear evidence that the potential for future avulsion exists (Fig. 20).

Crossings of alluvial fans often pose continual maintenance problems due to aggradation of the channel and its tendency to sudden and drastic shifts in alignment (avulsion). It is normally preferable to cross (with pipelines, highways, powerlines, etc.) near the apex or head of the fan where the opportunity for channel shifting is limited (Fig. 21).

11. - 16. Metamorphosis

Although the six types of river metamorphosis previously discussed involve a complete change of channel morphology, it is possible to identify these hazards by pattern change alone (Fig. 4). The historical approach as discussed previously will be of great value and it will reveal if metamorphosis is taking place.

Identification of a reach of river that is being subjected to metamorphosis at least in the earlier stages of the process, may be very difficult and the metamorphosis may be recognized only after it has become a significant factor causing bank erosion or instability of structures. In all cases, techniques used for the identification of other hazards can be used, and the reader is referred to the discussion of these hazards as follows:

Hazard 11, straight channel to meandering - see discussion of bank erosion (Hazard 3) and meander growth and shift (Hazard 7).

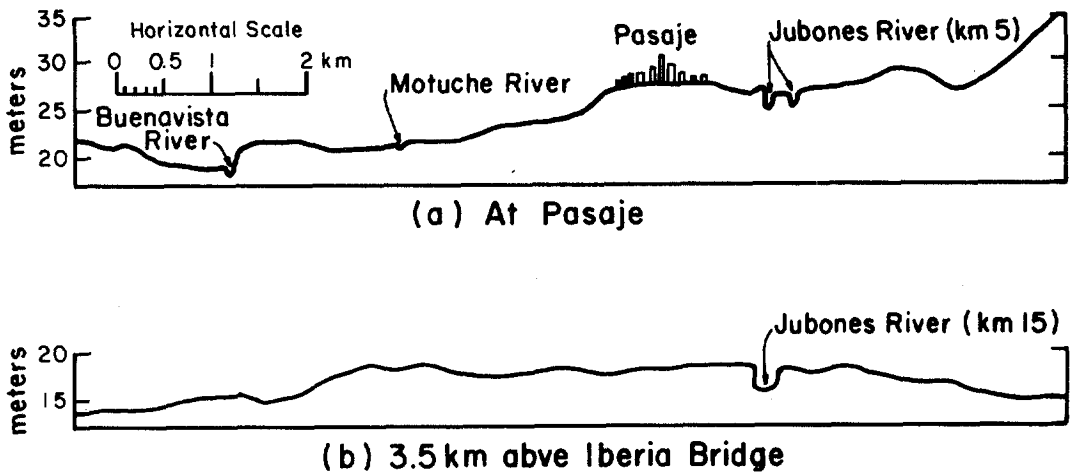


Figure 19. Cross section showing position of Jubones River on fan 3.5 km above Iberia Bridge. See Figure 20 for location. (From Maddrell, 1973.)

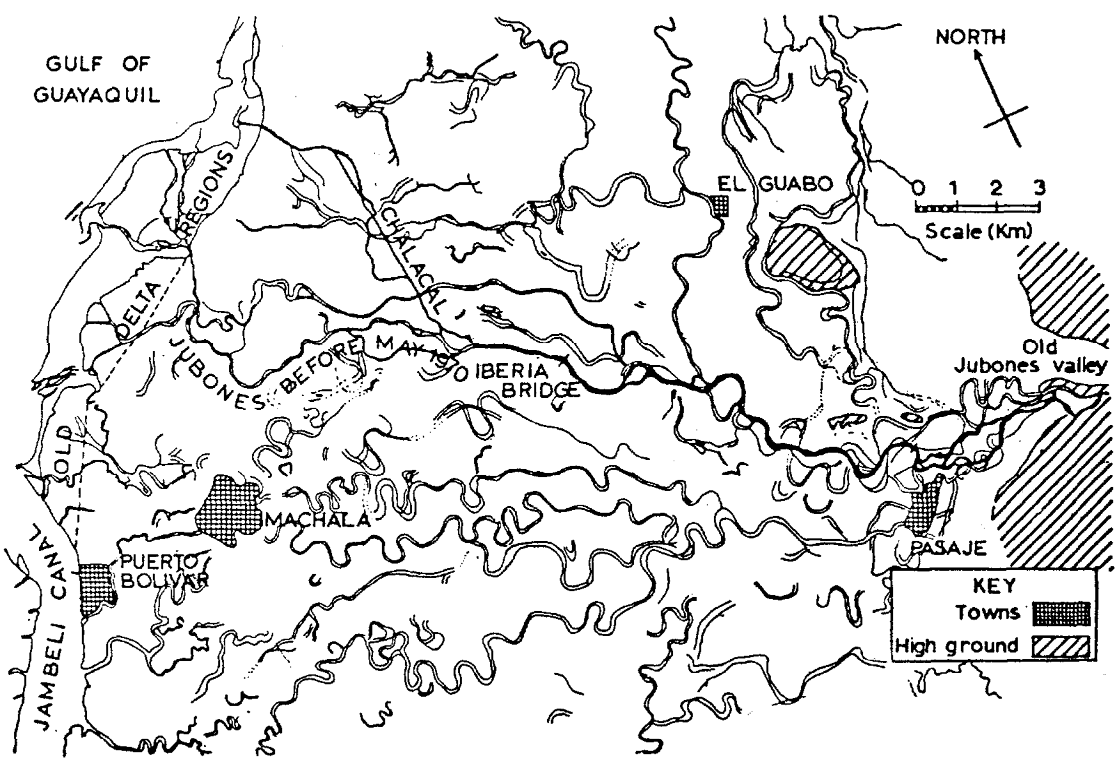


Figure 20. Avulsive changes of Jubones River. Note many former courses of river (after Maddrell, 1973).

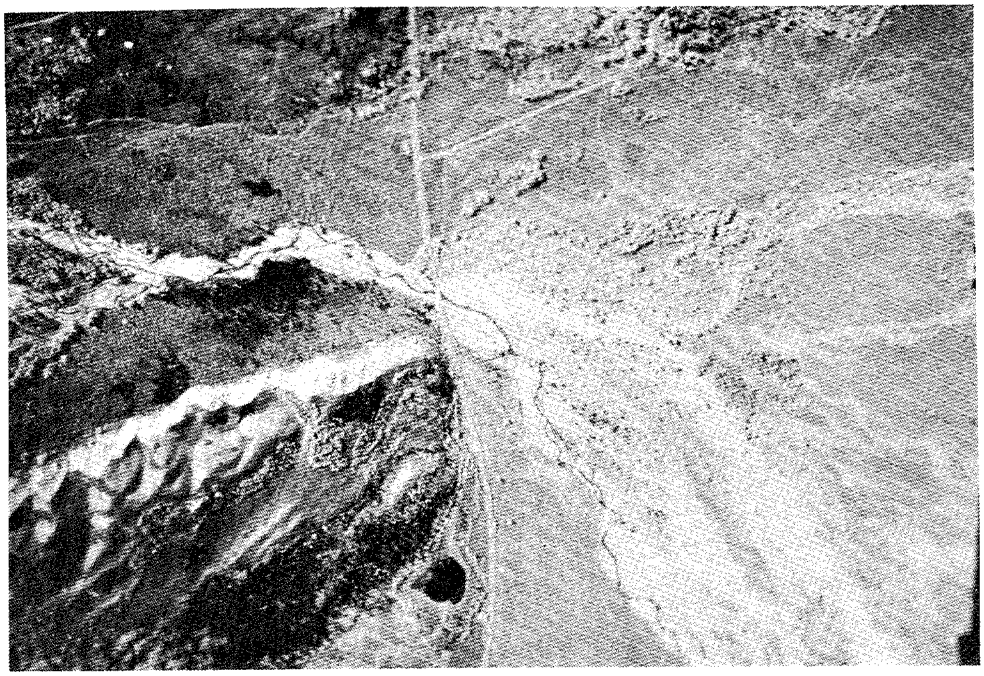


Figure 21. Bridge crossing at the head of a fan.

Hazard 12, straight channel to braided - see discussion of aggradation (Hazard 4), backfilling and downfilling (Hazard 5), and island and bar formation and shift (Hazard 8).

Hazard 13, braided channel to meandering - see discussion of bank erosion (Hazard 3), berming (Hazard 6), and meander growth and shift (Hazard 7).

Hazard 14, braided channel to straight - see discussion of berming (Hazard 6) and island and bar formation (Hazard 8).

Hazard 15, meandering channel to straight - see discussion of degradation (Hazard 1), nickpoint migration (Hazard 2) and cutoffs (Hazard 9).

Hazard 16, meandering to braided - see discussion of bank erosion (Hazard 3), aggradation (Hazard 4), backfilling and downfilling (Hazard 5) and island and bar formation (Hazard 8).

17. Floating Objects

It should be possible to identify a debris problem by observing the quantity of debris deposited on the floodplain. In addition, debris problems at other bridges will probably be recorded. An inspection of the upstream watersheds to study the condition of timber and the extent of lumbering operations can provide a rough estimate of the problem. However, a forest fire or an extremely severe wind storm can cause a great deal of floating debris to enter a reach of the stream. Timber harvesting methods and controls and the extent of upstream urbanization can also affect the amount of debris.

Analysis of records of periods of ice cover and temperature conditions in the drainage basin will provide information on the likelihood of ice jams.

Floating ice cakes following spring breakups in rivers of all magnitudes can pose serious hazards to highway embankments, bridge abutments and piers and to the stream equilibrium in general. During the spring ice breakup, bed and banks are oftentimes gouged and eroded by large ice blocks. Data on ice thicknesses, dates of breakup and freezeup, information on ice behavior and movement, especially ice jams, should be obtained.

On-site visits to bridges and embankments subject to ice flows are very important. Ice scars on a floodplain can indicate the elevation of spring floods. Ice scars on trees and other objects near the channel and on the floodplain can give some indication of the severity of ice conditions (Neill, 1973).

18. Waves and Surges

The magnitude and duration of wind can be analyzed by data obtainable from the National Climatic Center, Asheville, North Carolina (see Appendix C). The fetch distance is an open-water distance upon which the wind acts. Based on these data, wave characteristics can be estimated and their potential for bank erosion estimated (U.S. Army Research Center, 1973).

If the river has navigation control locks and dams, a record of commercial river traffic can be obtained, but the effects of pleasure boat waves on bank erosion can probably be obtained only by observation. If surges are produced by upstream controls and water release, such information can be obtained from the operator of the facility. The effect of the water release on the channel must be observed during such release.

Chapter 6

LAND USE

Land use, as used in this report, refers to the various alternatives for the allocation of land-based resources exclusive of streams and stream channels. Therefore, land use is treated as a group of special factors which may influence the various variables.

Except for catastrophic events such as earthquakes or forest fires, land use change is probably the single most important dynamic process occurring within a watershed because it can alter significantly the hydrologic character of the basin, and therefore the upstream controls. Due to its importance, a separate Appendix B is addressed to the problem of land use.

Although inventorying of land use is fundamental to comprehensive planning, little specific information has been published on methods. This is understandable because the techniques employed are, to a large extent, dependent on the purpose of the inventory and the type of data available. Most authors have deemed it appropriate to discuss inventorying of land use in the context of a special example or broad discussion of the planning process. Nevertheless, some insights can be gleaned from published reports despite the fact that they were not intended to serve as examples of land use inventorying methods.

Selection of land use categories, map scales and the compromise between accuracy and cost are prime considerations. Two basic types of data can be used. Primary data are direct observations of land use, such as the information acquired from field canvassing or aerial photo interpretation. Secondary, or indirect, data may be equally useful and is often less expensive to collect. Examples of this type of data include number of permits issued, utility connections, school records, etc. A standard land-use code and measuring characteristic (Urban Renewal Administration and Bureau of Public Roads, 1965) are presented in Appendix B. For most areas of the United States, land use data are available from federal, state, and local governmental agencies.

In addition to census data, federal agencies can provide aerial photographs and other remotely sensed imagery. The U.S. Geological Survey publishes land use maps, as do other agencies such as the Bureau of Land Management and the Soil Conservation Service. Moreover, many federal agencies are sources of secondary types of data. State agencies often compile and distribute land use maps and other information, but perhaps the most accurate and current land use data are generally available from local (city, county and regional) governments.

The literature of planning is replete with methods and models for predicting and influencing future growth. The majority of the predictive models can be classified, depending on the basis of the model, as economic, transportation, demographic, physical constraints, and composite. On the other hand, planning models, such as comprehensive or master plans, usually are not predictive models but rather only provide a set of goals. Because the models, or more correctly, goals, are constantly subject to modification, it is usually impossible to determine, after the fact, how closely a plan has been followed.

Land use can be grouped into six types: open space, timber harvesting, grazing, farming, construction and urban. Any of these land uses can affect the watershed characteristics by removal of vegetation, disturbance of soil mantles, regrading, and the increase of drainage systems and impervious surfaces. The effects of these six types of land use on stream-related hazards through their respective water-related and sediment-related impacts are discussed in more detail in Appendix B. In general, an increase in 1) open space, 2) timber harvesting, 3) grazing, 4) all types of construction, or 5) urbanization will increase the peak flow and sediment yields. The effect of farming on flow and sediment varies with the cultivation season. During the height of the growth season, farming may decrease peak flows and sediment yields. However, at other times the effect may be just the reverse.

The following table presents the potential severity of land use changes on water flow and sediment inputs in streams downstream. The effects of the flow and sediment variables on various hazards are discussed in Chapter 5.

Table 2. Potential Severity of Land Use Changes. Potential Impacts: 1, Severe; 2, Moderate; 3, Minor or None; A, Well Documented Effect; B, Partially Understood; C, Not Well Understood or Documented.

Land Use Change	Water Flow Characteristics	Sediment Impacts
Open Space to Timber Harvesting	1A	1A
Grazing	1B	1B
Farming	2B	1A
Construction	1B	1A
Timber Harvesting to Grazing	1B	2C
Farming	1B	1A
Construction	1B	1A
Open Space	2B	1A
Grazing to Farming	3B	1A
Construction	2B	1A
Open Space	3C	3C
Farming to Construction	2C	1B
Open Space	3C	3C
Grazing	3C	3C
Construction to Urban	1B	3B Lack of sediment may induce erosion

Chapter 7

REMOTE SENSING TECHNIQUES

There is frequently very little available data for the analysis of hazards, and thus a data collection program for each case becomes necessary. Since data collection is a major undertaking, this chapter examines various remote sensing techniques that can be used to evaluate river hazards.

Remote sensing is the process of collecting information about an object without being in physical contact with the object. Aircraft and satellites are commonly used for observation platforms. Electromagnetic energy, including reflected sunlight, natural emission of radiant energy due to object temperature, and radio waves, is employed to detect and classify terrestrial scenes. Magnetic and electrical surveys commonly made from aircraft for evaluating force fields are termed airborne geophysical surveys, and are not classed as remote sensing.

Current operational remote sensing techniques employ aerial photography, thermal infrared imagery, multispectral scanner imagery, radar imagery, Landsat imagery and archival (existing) photography and imagery. Each of these forms of remotely sensed data may be applicable for recording certain features of a river system which pose hazards therein to bridges and highways.

An engineer must understand basic principles of electromagnetic energy radiation transmission and fundamentals of reflected and emitted radiation in order to realize capabilities and limitations of various proposed remote sensing processes. The proper interpretation of each form of remotely sensed data also depends upon understanding the interaction of selected wavelengths with the terrain, atmosphere and detector.

Modern remote sensing technology involves a variety of different sensors, including improved cameras, filters and films, and aerial photography still represents one of the most commonly available, economical, and effective forms of remote sensing. The superior resolution of terrain detail, both spatial and spectral, as well as the wide choice of different types of emulsions, provides a useful remote sensing system. Film emulsions are available for recording portions of the electromagnetic spectrum over regions of near-ultraviolet and the photographic infrared as well as the visible wavelengths.

Archival aerial photography consists primarily of black and white photography dating back to the late 1930's. This photography has considerable value for detecting pattern change and for identifying the occurrences and progress of certain of the other hazards described in Appendix D. Both color and color infrared aerial photography, however, have demonstrated much wider utility for interpreting and mapping many of the hazards related to flowing water. Continuous improvement in cameras, films, processing, and measuring techniques promises to maintain aerial photography's prominence as a cost-effective tool for the transportation engineer for years to come.

Aerial photography can provide a dual source of precise spatial and spectral information. Positional determination of an identificable point on two overlapping photographs, with a precision of one ten-thousandth (1/10,000) of the flying altitude above the ground, is commonly obtainable with modern photogrammetry equipment.

Slight changes in plant vigor, soil moisture, and water turbidity, for example, are clearly identifiable spectral variations on certain film types. Both the spatial and spectral attributes of a photographed scene may be used to interpret and deduce the ongoing physical process of a fluvial environment by utilizing the basic fundamentals of photo interpretation: size, shape, shadow, tone or color, texture, pattern and association (Lueder, 1959; Rabban, 1960; Avery, 1977).

The unique data gathering character of an aerial photograph is that all observable elements within the field of view of the lens are recorded. The film, lens and filtering mechanism represent a relatively simple data collection system for providing a permanent, high-resolution, synoptic record of the complete scene. Information content within a single photograph is limitless. One must understand what the hazard looks like, where to look for the hazard, and how the hazard is associated with the total physical process in operation.

In the past several years, considerable strides have been made in the development and use of systems and platforms for recording both emitted and reflected electromagnetic energy from terrestrial scenes. Many different disciplines have investigated the potential application of these new data acquisition, display and analysis systems (Reeves, 1975).

Thermal infrared imagery utilizes invisible electromagnetic energy having wavelengths slightly longer than the visible and photographic portions of the spectrum. These systems may be flown day or night. Modern thermal infrared line scanner systems are capable of discriminating terrain radiometric temperature differences on the order of a fraction of a degree.

Multispectral scanner imaging devices can record both visible and invisible portions of the electromagnetic spectrum over a relatively wide range of discrete, selected bandwidths. The potential for reducing the time and effort requirements for manual interpretation through multispectral scanner output and computer-assisted interpretation appears very promising.

RADAR, the acronym for radio detection and ranging, is an active remote sensing system in that it produces its own source of electromagnetic energy to illuminate the scene. The advantage of day or night, all-weather operations and the ability to highlight terrain relief such as geologic structure, lineaments, faults and subtle terrain roughness characteristics can be of paramount importance for mapping river characteristics. The military and a few United States firms are currently flying side-looking airborne radar (SLAR) for a variety of earth resource applications. The complexity of the acquisition system, the fact that only a few systems are available on a commercial basis, and the requirement for a large aircraft presently make the cost prohibitive for anything but large area surveys.

The space orbiting satellite Landsat provides multispectral scanner imagery in four banks and, except for the poles, maps the entire globe every 18 days, clouds permitting. Minimum specified resolution for each picture element is 1.1 acres.

Remote sensing technology potential for improved analyses of river processes is gaining wide acceptance. It enables a thorough study of changes in river patterns, rates of erosion and deposition, quantitative studies of water flow patterns at flood situations, etc. (Sundborg, 1973).

The use of a remote sensing technique(s) for identification of stream-related hazards to bridges and highways involves certain basic steps: 1) the identification of the specific objective(s), 2) specifications, 3) proposal and cost estimates, 4) selection of base maps, 5) acquisition of remotely sensed data, 6) acqusition of site-specific information, 7) consideration of the proper interpretation equipment, 8) selection of the proper data transfer mechanisms and data storage and retrieval process, 9) identification and analysis of the potential hazard, 10) application of the analysis to the site-specific hazards involved, and 11) a cost-benefit analysis. These steps are discussed in Appendix F-1.

Modern remote sensing technology now involves a variety of different sensors including improved cameras, filters and films (Kodak, 1976). Aerial photography still represents one of the most commonly available, economical, and effective forms of remote sensing.

Equipment

For standard nine (9) inch by nine (9) inch precision mapping camera photography, the working format is either positive transparencies in roll form, or separates in clear plastic sleeves, or prints. Several other film sizes are available and entirely suitable for photo interpretation use. Three basic pieces of photo interpretation equipment are commonly used: 1) light table with film drive (manual or electric), fitted with a stereoscope preferably with variable magnification, and/or a large magnifying glass, 2) table with overhead illumination fitted with a stereoscope (preferably with variable magnification), and/or magnifying glass, 3) a stereo transfer scope or similar piece of equipment for transferring the interpreted information onto a base map.

Monocomparators, stereocomparators and a variety of stereo plotting instruments may be used with aerial photography to determine the space coordinates of selected points along a river system. High speed digital and/or analog computers, interfaced to the above equipment, facilitate the analyses and presentations of output in the form of profiles and cross sections (Schilling, 1978). In those instances where current topographic maps of the proper scale are lacking, the stereo plotting instrument may be utilized for the contouring and simultaneously provide a certain amount of photo interpretation as well (Thompson, 1966; Wolf, 1974).

Sources

Aerial photography, space photography, aircraft thermal infrared and multispectral scanner imagery and satellite multispectral scanner imagery are available for purchase or loan from several government agencies (Appendix C). Aerial photography firms and universities have aerial photography and/or thermal infrared scanner imagery of limited area. The current high altitude photography (1:800,000 scale) program for production and updating of U.S. Geological Survey quadrangle sheets can provide excellent black and white photographic coverage of certain reaches of river systems in the United States.

Many commerical firms can provide excellent aerial photography and imagery for special project sites for updating earlier photo coverage and for special film-filter requirements. Commercial firm sources for acquiring new photography and imagery are listed in the Journal of the American Society of Photogrammetry, <u>Photogrammetric Engineering and Remote Sensing</u>, July, 1978. Sources of new photography and imagery missions for governmental agenices are listed (May 1978, Appendix D). The National Cartographic Information Center (NCIC), established in July, 1974, provides information services on existing aerial and space photography.

Color and infrared photography is now commonly used, particularly for river studies. Most older photography is black and white, panchromatic film, nine (9) inch by nine (9) inch format, generally in print form.

Existing photography and imagery is usually less expensive to acquire than new data. Since much more coverage at various scales, format and band-widths is being flown than in the past, the chances of obtaining recent data for a particular area are good. The cost of acquiring new photography and imagery specifically for project requirements may be very nominal as compared to the overall cost of the proposed study. The aerial photography business in the United States has become very specialized and competitive, and cost per mile for acquisition of new coverage can be minimized by careful planning and scheduling with the prospective contractor.

Chapter 8

DATA SOURCES

Sources of data that can be used for the identification of river hazards are many and varied. However, there are two main types of data that differ in the ease with which they may be obtained.

The first group is being assembled and published by certain agencies in an organized and continuous fashion. These data are readily available. The second group of data is assembled and analyzed for particular purposes in specific regions, and may or may not be published by the assembling agency. These data are usually stored in the agency files and they are not easy to locate.

The cost of obtaining data is usually only a small part of the cost of a project, and aerial photographs and maps, unless they are specially prepared for the project, are inexpensive. The time required for acquisition of data usually is between three to four weeks. A visit or a telephone call may expedite data acquisition processes considerably. It is difficult to make a general statement about the cost and benefits of acquiring data for specific hazard analysis. As a rule, if data are available, it is always economically justified to purchase them. If one has to collect his own data, a rough evaluation of its cost versus its benefit must be made in each case.

Appendix C provides a more complete description (including scales and types of information) of data sources and the following sections give a brief discussion.

A. Group 1 - Commercially Available Information

1. Remote Sensing Data (including aerial photgraphs)

For the study of hazards related to pattern changes and metamorphosis, maps of almost any scale which enable one to identify the rivers have some use, and it is difficult to specify the exact scales required because this depends on river size. However, it is recommended that the largest scale photographs that are available be obtained. For study of the details of a channel and not just the channel pattern, 1:20,000 scale with an upper limit of 1:60,000 scale photographs are preferred. Frequently when sets of photographs of different dates are acquired, they will be of different scales. If necessary, photographs can be ordered to a standard scale for comparison.

a. The Earth Resources Observation Systems (EROS) Program of the U.S. Department of the Interior, administered by the Geological Survey, was established in 1966 to apply remote sensing techniques to the inventory, monitoring, and management of natural resources. To meet its primary objective, the EROS Data Center, as part of the National Cartographic Information Center (NCIC), was established near Sioux Falls, South Dakota, to provide access to NASA's Landsat imagery, aerial photography acquired by the U.S. Department of the Interior, and photography and imagery acquired by the National Aeronautics and Space Administration (NASA) from research aircraft and from Skylab, Apollo and Gemini spacecraft. The primary functions of the Data Center are data storage and reproduction and user assistance and training.

Guidance in the use of remotely sensed data is available at the EROS Data Center in the form of scheduled training courses and workshops. Visitors to the Data Center will also receive assistance in the operation of specialized equipment such as densitometers, additive color viewers, zoom transfer scopes, and stereo viewers, and in the use of computerized multispectral systems to classify specific phenomena. The EROS data can also be obtained through the purchasing counters of the National Cartographic Information Center (NCIC).

b. The ASCS Aerial Photograph Field Office (APFO) in Salt Lake City is where all United States Department of Agriculture aerial photography is archived. Beginning in 1972, APFO began to acquire satellite imagery for the USDA. The APFO film library has on file all Landsat 1 and 2, Skylab 2, 3, and 4 imagery, and mosaics of Landsat imagery of conterminous United States and Alaska. Scale of the photography on file varies from 1:15,840 to 1:80,000, with about 15 percent at 1:15,840, 70 percent at 1:20,000, 10 percent at 1:40,000, and the remainder at various other scales, mainly 1:40,000.

Acquisition procedures and product cost are available upon request. Delivery time is normally 30 days after receipt of requisition.

c. SLAR (side-looking airborne radar) images acquired by the Strategic Air Command are available thorugh the Goodyear Aerospace Corporation (address in Appendix C). The scale of these images ranges from 1:100,000 to 1:600,000. Requests for imagery should include the latitude and longitude boundaries of the area of interest.

d. Landsat imagery is also available from General Electric Space Systems, and Gemini and Apollo photos are available from the Technology Application Center at the University of New Mexico.

e. Federal agency-held aerial photos taken prior to approximately 1940 are held in the National Archives in Washington, D.C., as special storage conditions are required for preservation of this film.

2. Maps and Charts

The main source of maps and charts is the U.S. Geological Survey. Topographic maps, including contour maps, base and outline maps, status maps, river survey maps, state maps, metropolitan maps, special topographic maps and National Topographic Map Series, geologic maps (including geologic, geologic quandrangle, geophysical investigation, miscellaneous geological investigation maps), mineral maps (including coal, oil and gas, and mineral), hydrologic investigation atlases, and land use, land covering and associated maps, are distributed at these centers.

3. Meteorological and Ocean Data

The main source of such information is the U.S. Department of Commerce National Climatological Center (NCC) at Ashville, North Carolina. The important daily surface data for the study of stream-related hazards are temperature, snowfall, snow depth, and wind. Solar radiation and rainfall data (yearly, monthly and daily to the nearest one-hundredth of an inch) are available on computer cards from the data collected by the U.S. Weather Service.

Hourly precipitation data are also presented in booklets entitled Precipitation Data, by the Environmental Data and Information Service (EDIS) of the National Oceanic and Atmospheric Administration (NOAA). The daily temperature, precipitation, evaporation and wind data are presented in booklets entitled Climatic Data by the EDIS of NOAA. Precipitation Data and Climatic Data can be purchased from the U.S. Government Printing Office.

Maps describing tidal and navigation information for oceans can be purchased from the NOAA at its National Distribution Division, C-44, 6501 Lafayette Avenue, Riverdale, Maryland 20840, and numerous retail outlets (such as book stores, boat rentals, etc.). Detailed data concerning tidal ranges are published annually in Tidal Tables by the National Ocean Survey. These tables are also available from the Government Printing Office, Washington, D.C. 20402.

4. Hydrological Data

The main source is the U.S. Geological Survey (USGS). A National Water Data Exchange system (NAWDEX) is located at the National Center of the USGS at Reston, Virginia. Data on surface water, ground water, and water quality (including biological, chemical, physical and sediment data) are available from this data bank. In addition, the USGS also publishes Water Supply Papers, special hydrologic maps, river survey maps, and Professional Papers. In its Water Supply Papers the ground water levels, daily river flow discharge, quality of water (including sediment) at special gaging stations for various river basins are presented. Water Supply Papers can be purchased either from the U.S. Government Printing Office in Washington, D.C., or from the Branch of Distribution, USGS, 1200 South Eads, Arlington, Virginia 22202. Most of the published daily river discharge data are published by the USGS. The daily discharge measurements as reported are not directly measured; rather they are obtained from river stages. Through a relationship between stage and river discharge developed for a particular gaging station, these daily stage measurements are converted into river discharge. The relationship between stage and river discharge is being continuously checked by actual measurements of river discharge and river stage. By special request, these actual measurements can be obtained from local USGS district offices.

River survey maps showing course and fall of the stream, configuration of the valley floor and adjacent slopes and location of towns, scattered houses, irrigation ditches, roads and other cultural features are also available for numerous rivers. As these river survey maps were prepared largely in connection with the classification of the public lands, most of them show areas in the western states. An index of river surveys is published as USGS Water Supply Paper 995. Special hydrologic investigations for different river and geographical locations are available through the USGS Water Supply Papers and USGS Professional Papers. Special catalogs are available from the U.S. Government Printing Office describing USGS publications.

5. Geologic and Soil Data

In addition to standard geologic maps, the USGS has made extensive studies of landslides, land subsidence and seismic activities at numerous regions across the United States.

The U. S. Soil Conservation Service has numerous field offices in each state. Three types of soil information are available at these field offices: 1) a general soil map of each state with a scale of 1:1,500,000, 2) general soil maps of each county with a scale of ½" to 1 mile (1:126,720), and 3) much more detailed maps for individual watersheds. Not all watersheds have been mapped. These maps include soil types and characteristics, and sometimes the depths of different soil types.

B. Group 2 - Scattered Information

This information is stored in the files of a number of "action" agencies. Access to the files is always granted, when the request is reasonable and for a legitimate purpose. The difficulty lies in determining what data is available and where it is stored. The first step in determining if useful information is available is to contact the local offices of the agency. If a project has been completed and when planning for a project is in progress, the data will be readily available. However, if the project was completed decades ago or if a project that was planned was not completed, only a senior employee of the office may be aware of the data. For example, the office manager may have occupied his position for only a few years, but a low grade employee who has worked in that office for his or her entire career can be of great help. Obviously it is necessary to locate such an employee and this can only be achieved by careful questioning of the office staff concerning people who are knowledgeable about the river and the potential site.

Chapter 9

PROCEDURE

A procedure for evaluating a highway crossing or stream encroachment, which permits the identification of stream-related hazards and which provides the user with a means of assessing the extent of the problem is outlined below.

A. Available Data

Collect and review the immediately available pertinent data. These data may include the following items.

1. Location, topographic, geologic and soil maps. Also, special land use and river survey maps may be available for the stream and the surrounding area.

2. Aerial photographs and satellite images.

3. Hydrologic data, especially river stage and flow records. Data on sediment, precipitation, and wave and tide frequency and magnitude may be useful, although the wave and tidal data are needed only for certain locations.

4. Meteorological data, including rainfall, snowfall and wind data. Temperature variations and solar data may also be useful.

5. Land use plans from local, state, and federal agencies, including any plans for river modification.

6. Any specific reports which consider variables, hazards, and land use, as related to the site.

B. Preliminary Analysis of Data

A preliminary data analysis is essential for planning a site visit as follows:

1. Channel Patterns

Examine the aerial photographs and maps to determine the types of channel patterns that occur at different reaches of the stream. Compare the given channel pattern or patterns with Figure 4 (Chapter 2). For instance, a meandering channel is Pattern 3 and a braided channel is Pattern 5. As a rough rule, the larger the channel pattern number, the more unstable is the stream.

2. Variables

Determine a preliminary list of variables that may cause stream-related hazards according to the data collected (including maps and aerial photographs) and the discussion given in Chapter 4. This may be difficult because it usually requires careful field inspection and detailed data analysis. Nevertheless, a preliminary analysis should be attempted.

3. Potential Future Land Use Change

As discussed in Chapter 6 and Appendix B, changes in land use , to timber harvesting, grazing, farming, construction and urban, can cause severe water- and sediment-related impacts to stream-related hazards. Prediction of future land use change is extremely difficult because most land use plans are being constantly modified.

4. Stream-related Hazards

Based on information discussed in the first three items above, the discussions in Chapter 4 and 5, and especially Table 1, Chapter 4, which indicates relationships between hazards and variables, list the possible stream-related hazards for the site.

C. Reconnaissance and Field Inspection

The bridge sites can be located on aerial photographs, and with these the field inspection can commence. An excellent reconnaissance technique is to fly over the site and the adjacent reaches of river at low altitudes. This provides a close look at the site and the character of the river. In fact, it is recommended that the flight from the site be at least 20 miles upstream and downstream from the site. Photographs of the channel, banks and floodplain can be taken for future reference, and any anomalous features should be recorded for further investigation.

Of the many hazards discussed in Chapter 3, several may be unrecognizable at the potential bridge site, but they may be identified either upstream or downstream. For example, a nickpoint may be present several miles downstream from the site. Gravel pits downstream although not visible from the site, can create a nickpoint and site degradation. In addition, aggradation by downfilling or backfilling will not be visible at the site, but a dramatic change in channel morphology either upstream or downstream may be an indication of these hazards. Finally, meander cutoffs or channel avulsion either upstream or downstream can seriously affect a site.

The need for a general reconnaissance of the river is obvious, and it is essential for evaluation of future stability at the site. The reconnaissance of the reach can be performed by the use of aerial photographs and by aerial reconnaissance. Obviously, if hazards are recognized either upstream or downstream, these reaches of the river should be visited in order to verify the nature of the hazard.

In addition to a general inspection of the stream, obvious changes of land use in the upper basin or alternations of riparian vegetation must be considered, as such changes will affect the hydrologic character of the stream. In addition, any channel modifications either up- or downstream must be evaluated as a potential source of channel adjustment at the site. Additional discussions on how to analyze data for stream-related hazards are presented in Appendices F-1 and F-2.

D. Site Inspection

A site inspection should involve a careful study of channel morphology and variations, bank erosion, sediment characterstics and vegetation type for some distance both up- and downstream. The present condition of the channel should be described in terms of channel dimensions, pattern and slope. Bank and bed sediment samples are required to determine the stability of banks at the site (see Appendix C).

In Chapter 5 the means of identifying each hazard were listed and described. For example, the exposure of tree roots, old bridge supports, etc. at a site will be evidence of degradation. Burial of vegetation on the flood plain and recent sediment deposits on the flood plain may reflect aggradation. Obvious bank erosion can be an indication of aggradation, degradation, meander shift or channel metamorphosis. A study of the present condition of the channel at the site will provide information on the relative character and stability of the site as noted in Chapter 5. When this is coupled with upstream and downstream studies, a reasonable understanding of present channel behavior can be obtained. In addition, the past and future behavior of the channel at the site can often be evaluated by a historical study of the river utilizing the photographs, maps and data compiled earlier in the study.

E. Hazard Identification

It is possible that preliminary inspection of available data and field inspection will provide all the necessary information on hazards that can be expected at the site. Chapter 3 will provide information on the effects of the hazards and the engineer can then design a structure to minimize these effects. However, in many cases it is necessary to predict what hazards may develop or to check for as-yet undetected hazards.

As discussed in Chapter 5, a historical study of the river and its behavior may provide a basis for evaluating the relative stability of the channel. A key concept in historical research is that an understanding of past events provides a basis for prediction. In human affairs the predictions are frequently inaccurate, but physical systems will behave in a more predictable fashion if there is no change in the variables that influence the system.

In any case, the documentation of past river morphology and change is of considerable value in determining the potential for future problems at the site. This can be accomplished as follows:

1. For a transportation engineer the logical first step is to determine a history of nearby bridges. If the new bridge is to replace an older one, considerable information should be available on the past morphology and behavior of the river at that site. For example, channel width and the distance from the crown of the highway to the stream bed will be available. Any change can be readily determined by a comparison of the present cross section characteristics with those at the time of the construction of the old bridge.

2. Conversations with long-time residents of the valley can be useful in establishing the relative stability of the river channel. Recollections are sometimes suspect, but old photographs of the river obtained from private collections, family albums and local historical societies can be invaluable. State archives and historical societies frequently contain photographs of old bridges and fords, and hence they are a source of valuable information.

3. In the mid-west and western United States, General Land Office surveys made in the 19th centruy frequently provide a basis for comparison of river width and pattern with present morphology. The earliest maps can be compared with U.S. Geological Survey topographic maps and, depending on the size of the channel and the scale of the maps, it is frequently possible to show considerable change during the past 100 years. However, these adjustments may be complete, and it is the present and future behavior of the river that is important.

4. Records such as newspaper reports, railroad company files (if there was a railroad nearby), church records, court transcripts, and accounts of early travelers are all possible sources for identifying possible channel changes.

5. Gaging station records will show for a given discharge if there is change in the water surface elevation through time at upstream stations (see discussion under Hazard 1) and hydrologic data will indicate flow character and the importance of large floods.

6. Perhaps the best means of studying river changes is by the use of aerial photography. This procedure has been of use in studying beach erosion, and examples of the comparison of aerial photographs to determine channel changes have been cited earlier. A procedure that has been of value to coastal engineers is presented here based on a report by Stafford and Longfelder (1971). Aerial photographs are better for this purpose than maps because they record much more ground detail. In addition, although an area may have been mapped twice in 50 years, aerial photographs are frequently available at five-year intervals.

A disadvantage of the use of aerial photographs is that they record conditions at a particular time. If they were taken immediately following a major flood or the passage of an ice gorge, the recorded conditions may be anomalous and provide a misleading record of the rate of change. Nevertheless, if several sets of photographs are available, an indication of the type and rate of change can be obtained.

Another problem is the time of photography. If two sets of photographs compare times of high and low water, or winter and summer when foliage is very different, a misleading impression of channel changes may result.

Also a disadvantage is the fact that usually only horizontal changes can be detected. On most aerial photographs a vertical change of a few feet due to aggradation or degradation will not be detected. Although such changes can be measured when good quality photographic and appropriate equipment is available, it is recommended that a photogrammetrist be utilized for such analysis.

Yet another problem relates to the photographs themselves. If they are of different scales or if inherent scale variation on the photographs exists as a result of camera tilt, the following procedure is recommended.

a. Determine number of coverages available from various governmental agencies and from private firms (see Appendix C).

b. For a sequence of flights order aerial photographs of the same scale if possible. Rectified photographs may also be obtained which minimize the inherent scale error in the photographs themselves. If rectified prints cannot be obtained, much of the error can be eliminated by confining measurements to the center of the prints.

c. Select a stable point of reference on the photographs. Measurements from those locations to the bank of the river when repeated on several sets of photographs will provide data on changes of bank position. These reference points may be buildings, road intersections or clearly-defined topographic or vegetation features. The spacing of the reference points depends on the scale of the river to be studied and can range from a few tens of feet to several hundred feet apart.

d. Make measurements from reference points to river bank. Care must be taken that the measurements are to the top bank line and not to the water surface. Usually a dramatic change between flood-plain vegetation and the bank and channel is apparent, and it is to this line that measurements must be made. In semiarid or arid areas this is easily done because the dry channel can be recognized with ease, but where there is a dense bank vegetation, as in the eastern and central United States, considerable care must be exercised. In any case, water levels fluctuate markedly in most river channels, and measurements should not be made to the water's edge unless it can be determined that the water stage is comparable on each set of photographs.

An interesting technique for identifying changed conditions between flights is to view photographs that were taken at different times but that are of the same scale. According to Strandberg (1967, p. 63),

> "If the photos can be matched directly in stereo, then changes, even very minor ones, sometimes can be detected and identified by flicker, or 'stereo-iridescence.' Images that exist on one plot but not on the other will alternately appear and disappear in stereo."

This technique can be used to identify bank line changes. Blinking the eyes rapidly when viewing the photographs enhances the flicker effect.

If a series of photographs is available, the change or lack of it between flights can be measured and the rate of change can be calculated.

It is clear that by disregarding the propensity for channel shift and alteration, serious consequences for bridges have resulted (Brice, 1978). However, the collection of accurate data on channel shift and bank erosion is not always easy. The most accurate method is to have repeat surveys over a long period of time, obviously a situation that is not possible for the transportation engineer. In addition, historical observations are frequently of questionable value because it is indeed difficult for a long-term resident to recall what may be to him subtle changes in stream character.

F. Limitations and Potential of Techniques

It is difficult to be specific about the limitations and potential of the various techniques for identifying stream-related hazards because the rate and magnitude of the changes are so highly variable. For example, meander growth and shift may be very rapid, or it may be very slow, depending on the nature of the sediment transported by the stream (Figure 4, Chapter 2). If the stream has and is presently transporting relatively small quantities of bed load, then the alluvium in which it flows will be cohesive and resistant to erosion. On the other hand, if the river is transporting a large bed load, the banks will be less cohesive and more easily erodible. In the first case, meander growth and shift may be slow, whereas in the latter case the rate of change should be rapid. It will be a definite hazard.

Since the deposition of fine sediments on the banks of a stream will normally be a slow process, the only variable of relatively small magnitude, is berming.

Avulsion and meander cutoffs, examples of rapid change, may take many years to develop. Avulsion of the lower Mississippi River has required several centuries for completion.

Obviously, after a rapid change,detection by the techniques described is easy,but if it is slow and progressive it may not be possible to detect this change. Furthermore, even if a change is rapid, if no maps, photographs, or other data are available, then none of the aforementioned techniques will apply. This situation will be unlikely because the United States has been photographed from the air on a systematic basis since the 1930's. However, if such a situation were to exist, the only way that hazards could be identified would be on the basis of recognition of change by an expert or by a long-term study of the channel.

In most cases, the time required for analysis of a site will be short. Even if soil mechanics analyses are required and if a series of aerial photographs must be purchased, only a few weeks are usually required. However, if no data are available, a study of channel change over a period of years is necessary to determine rate of change. Aerial photographs should be taken immediately, and cross sections should be surveyed at the site and both upstream and downstream of the site for comparison at some later time.

A serious limitation exists in the ability to predict changes of land use, and therefore future changes of the variables affecting stream hazards. As indicated in Appendix B, the reliability of predictions of land-use change is poor. Plans for major industrial and urban developments may be affected by economic changes. Therefore, the engineer probably should consider the worst case and assume that land-use changes will be detrimental to some extent.

In many cases the identification of hazards may be beyond the capabilities of the transportation engineer. If the changes are slow or if the evidence for hazards must be based on hydrologic or geomorphic evidence, it appears that assistance should be sought from experts in these fields. A few hundred dollars spent in such a case will be amply justified if maintenance problems do not develop early in the life of the bridge.

The fluvial system and river channel behavior is complex and the response of a channel to upstream and downstream variables, although qualitatively predictable, may occur at such different rates, or even episodically. For this reason expert advice is desirable.

Experts in the areas of hydraulic engineering, geology, and hydrology should be available within a state highway department, but if consultants are required, they can be located by checking the literature on the subject of concern. Any large consulting firm will have available "in-house" or "on-call" experts in a variety of fields that relate to river hazards.

In all cases the expense of utilizing the techniques discussed in this report to identify stream-related hazards will be a negligible part of the cost of bridge construction and maintenance. Purchase of aerial photographs and major field reconnaissance and preliminary analysis of conditions on the river will inv olve expenditure of only a few hundred dollars. Identification of a hazard may require extensive modification of a bridge design and require extensive modification of a bridge design and require extensive countermeasures or continued maintenance. These initial costs will be offset by the longer life of the crossing.

Chapter 10

EXAMPLES OF PROCEDURE

To demonstrate how the procedures outlined in Chapter 9 can be used by the transportation engineer, three examples were chosen. The primary hazards considered are aggradation, meander shift and nickpoint migration.

The examples were selected because the hazards are serious at the chosen sites and sufficient data are available to permit detection of the hazard.

A. Example 1 - Niobrara River at Niobrara, Nebraska

1. Background

Above its confluence with the Missouri River, the Niobrara River is a wide braided stream (Figures 22 and 23). Channel width varies from 1,000 to 1,500 feet, and sand bars rise from 12 to 18 inches above the low flow water level. The channel sediment is a well-sorted sand of about 0.012 mm. Much of the sediment load is derived from the Sand Hills region of Nebraska and therefore the bed load is a well-sorted fine sand.

Although little is known about the Niobrara River at the site, a report by Livesey (1976) describes the effect of the Niobrara sediment load on the Missouri River. Following closure of the Fort Randall Dam, the Niobrara River sediments that are delivered to the Missouri have not been carried downstream by large floods, and the Missouri River is aggrading as a result. It seems likely that the effect of this aggradation would be backfilling and aggradation at the bridge, which is about 1.3 miles above the mouth of the Niobrara River.

2. Procedure

a. Data Compilation

According to the procedure outline in Chapter 9, the available maps and aerial photogrpahs should be obtained. Aerial photographs can be obtained from the U.S. Army Corps of Engineers, Omaha District, and from the U.S. Geological Survey (Figure 22). U.S. Geological Survey topographical maps are available for the site at a scale of 1:24,000, (Verdel, Verdigre N.E. and Niobrara 7½ minute quadrangles). The bridge is shown on the Verdigre N.E. (1950) map.

Hydrologic data are available for the gaging station on the Missouri River and upstream near Verdel, Nebraska. Verdel gaging station is located on the left bank 4 ft downstream from the Pishelville Bridge, 6 mi south of Verdel and about 13.5 mi upstream from the State Highway 12 Bridge. The station is at Lat. 42°44'25" and Long. 98°12'45" and is the closest U.S. Geological Survey gage to the bridge site. Stage-discharge curves for this gaging station were obtained from the U.S. Geological Survey District Chief, Lincoln, Nebraska.

b. Preliminary Analysis

Aerial photographs and maps show the Niobrara at the bridge to be a very wide braided channel. The braided pattern is typical of the Niobrara upstream,

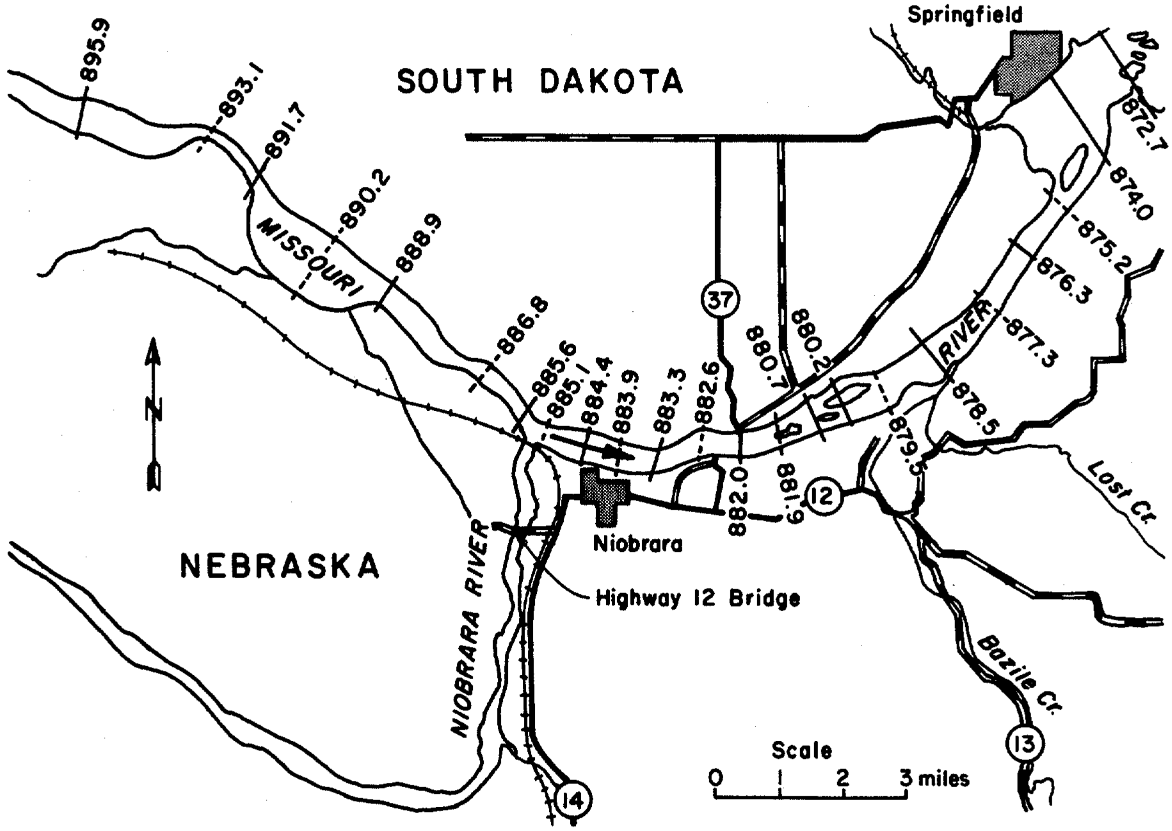


Figure 22. Confluence of Missouri and Niobrara Rivers (after Livesey, 1976).

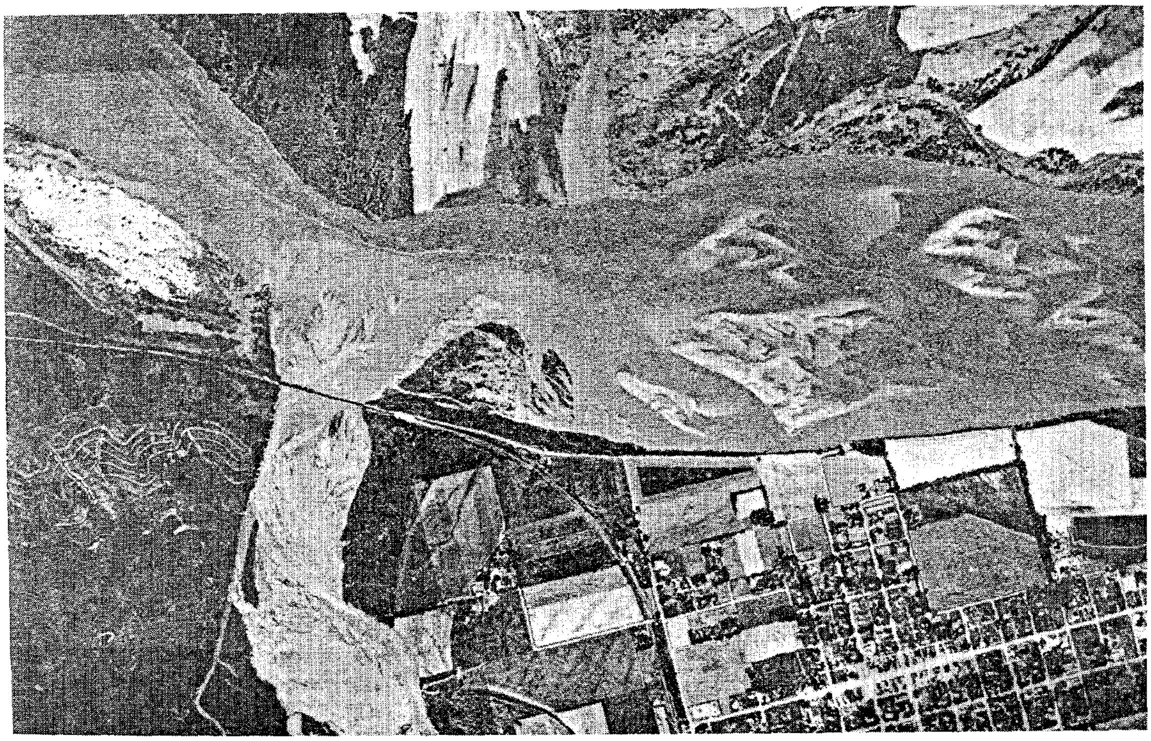


Figure 23. Aerial photograph of junction of Niobrara and Missouri Rivers (June, 1961). The bridge shown is a railroad bridge. Highway 12 Bridge is off the photograph to the south. (After Livesey, 1976.)

and other than this generally unstable pattern, no clear indication of a specific hazard is obvious, although bank erosion should be expected.

However, Livesey's (1976) analysis of the stage discharge data for the Missouri River gage shows that for a constant discharge of 30,000 cfs the stage has increased from 1212 to 1216 feet between 1956 and 1965. This is evidence of Missouri River aggradation (Figure 24) and suggests possible aggradation in the Niobrara River.

Surveys of the Niobrara River about one-half mile below the bridge show changes of the cross-sectional area, depth and width-depth ratio, which clearly indicate the aggradation is also occurring in the Niobrara River below the bridge (Table 3).

Table 3. Variation in Channel Dimensions at Niobrara River Near the Bridge Site.

Range	Date	Bank Top Elev. (MSL)	Cross Section Area (ft^2)	Cross Section Width (ft)	Cross Section Depth (ft)	Width/Depth Ratio
N-0.8	Sep 1956	1225	17,816	2,303	7.74	298
	Jul 1960		15,997	2,319	6.90	336
	Aug 1965		12,988	2,347	5.53	424
	Aug 1970		11,049	2,355	4.69	502

In summary, data from readily-available sources strongly suggest that aggradation is taking place at the bridge or that it will occur in the near future.

The data provided by the district office of the U.S. Geological Survey were analyzed for the Verdel gage located about 13 miles upstream of the bridge. Figure 25 shows both discharge and water depth for the period 1958-1976 at a stage of 4 feet. During the early part of the record, 1958-1963, there were large floods that caused scour at the site, as the increased discharge and water depths indicate, but by 1975 the discharge and water depth were about as they were in 1958. Therefore, there is no indication of degradation or aggradation at this location. The variations are due to scour and fill associated with major flood events and are not evidence of channel instability.

Figure 26 shows a plot of discharge and gage height for the Verdel gage. Although as expected there is a considerable range of gage height at a given discharge, there is no indication of a progressive change as at the Missouri River gage (Figure 24). Of interest, however, is the higher stage caused by ice cover. The presence of ice causes a 2-foot increase in stage at a given discharge. This means that the effect of ice on stage must be considered in the bridge design.

c. Field Observations

The river is wide and braided and clearly transports a large sand load.

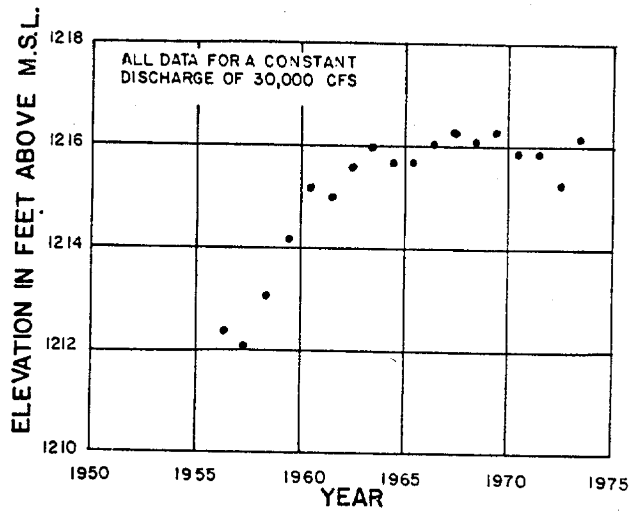


Figure 24. Missouri River stage trends at gage 884.2 (after Livesey, 1976).

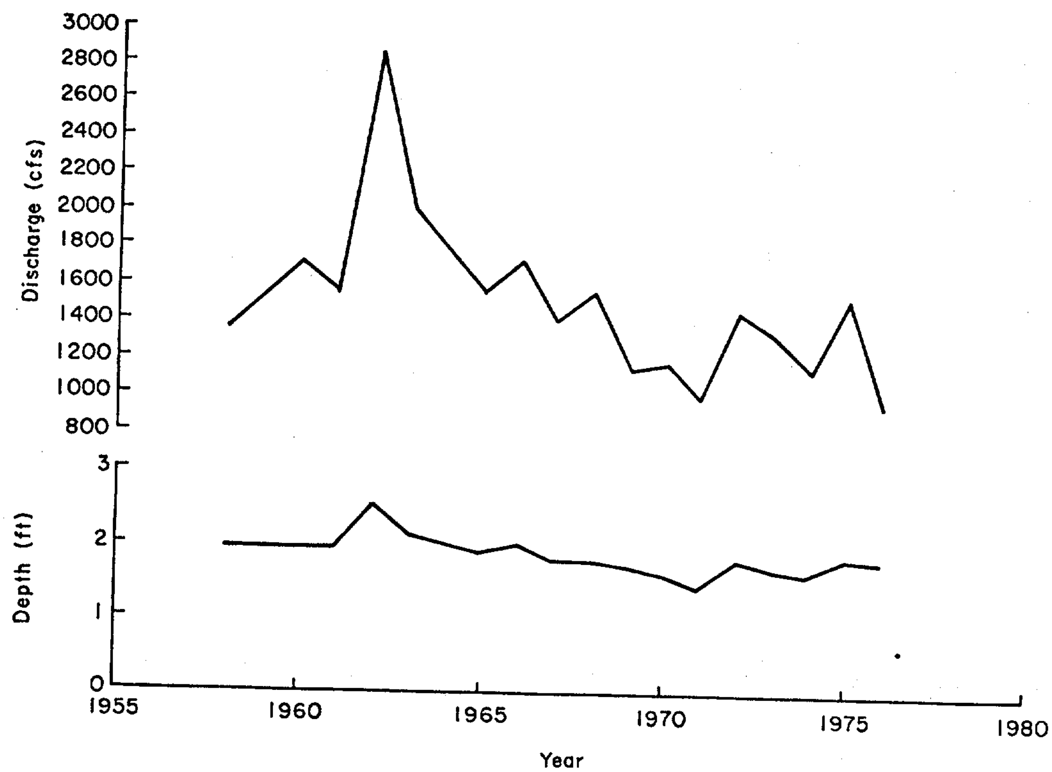


Figure 25. Variation of Niobrara River channel depth and discharge for 4-foot stage at Verdel gaging station, Nebraska

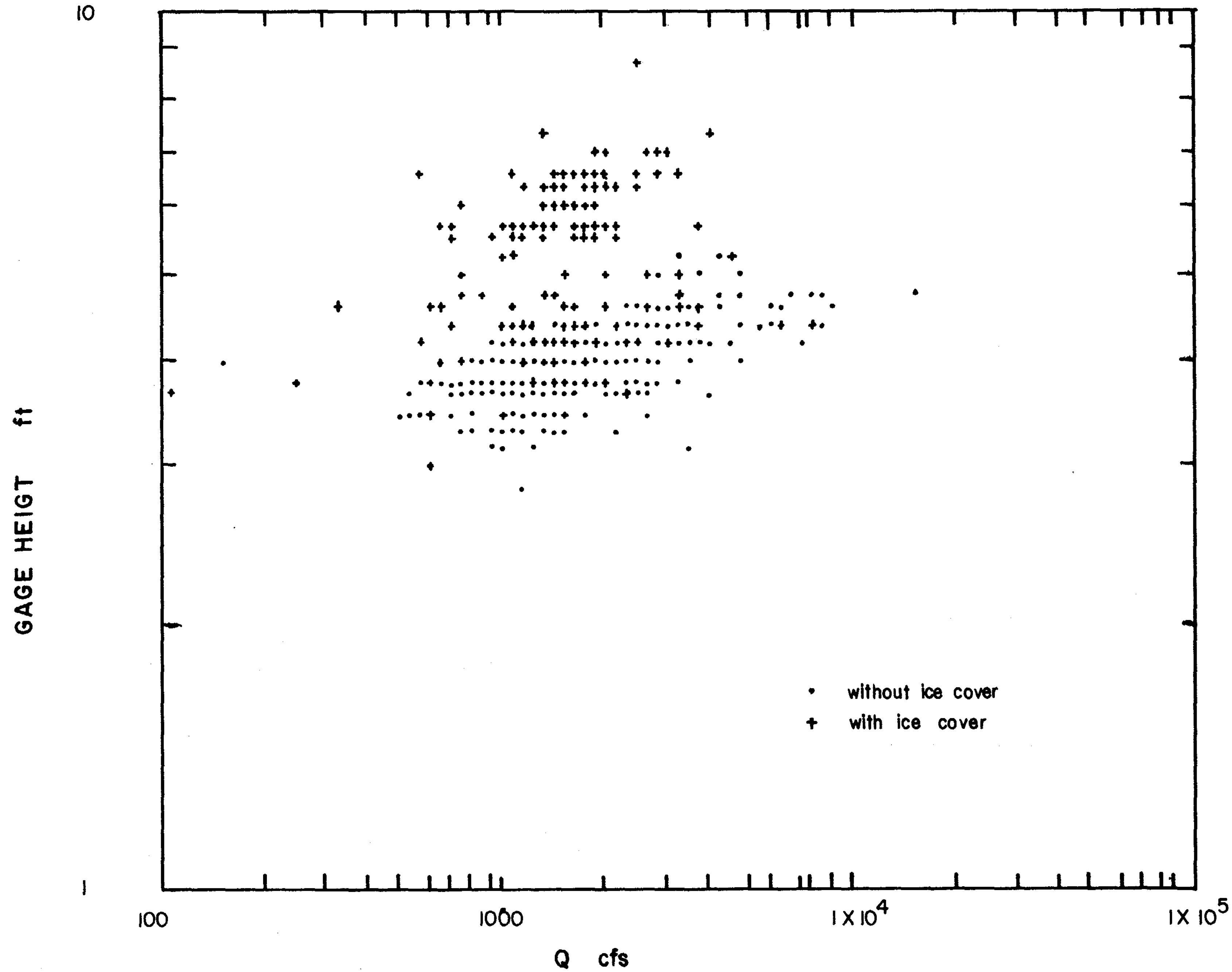


Figure 26. Stage-discharge relations at Verdel gaging station, Niobrara River.

Bank sediments are sandy and susceptible to erosion. Tree limbs and other trash were observed in the channel.

Aggradation at the site is not obvious because of the naturally braided pattern of the river, although it is clear that the channel is not degrading. Bank erosion can be attributed to natural shift of the braided channel and the readily erodible bank material, but it can be enhanced by aggradation.

The State Highway 12 Bridge over the Niobrara is an old single-lane bridge that is about 0.25 mile long. Construction of a new bridge is under way and the foreman of the crew stated that aggradation at the bridge had caused serious problems with ice jams. Clearance below the bridge has been reduced significantly as a result of backfilling from the Missouri River.

Long-term observations by the ferry operator at the Niobrara Ferry confirmed aggradation in the Missouri River. The ferry landing on the South Dakota side of the Missouri is now submerged and the operator estimated as much as 8 ft of aggradation at the ferry crossing, which is a short distance downstream from the Missouri River gage.

The Niobrara River south of Verdel is constricted at the bridge crossing because the north or left bank is controlled by a bedrock outcrop. The south bank is maintained by car-body riprap. Both upstream and downstream the channel is wide and braided. Bank erosion is occurring both up and downstream. This is the location of the Verdel gage.

Conversations with elderly fishermen at the bridge and observations of the channel at the bridge indicate that the channel is relatively stable at the bridge crossing. The sandy bed load is readily transported through the constricted partly-bedrock controlled reach.

d. Identification of Hazard

The gaging station data and cross section data near the bridge as well as conversations with residents of the area, indicate that aggradation is a major hazard at this site. Bank erosion is also obvious at the site and at upstream locations, but it is typical of a braided river, and it does not pose as serious a hazard as aggradation of the Niobrara River channel from its junction with the Missouri River. It is probable that deposition is taking place by backfilling (Hazard 5), but this is not confirmed. In any case, the results at the bridge site will be the same.

B. Example 2 - Cimarron River at Perkins, Oklahoma

According to Brice (1978), meander shift (Hazard 7) is one of the major problems at bridge crossings. Needless to say, this hazard should be one of the easiest to recognize if maps and aerial photographs for a period of years are available.

Utilizing the procedure set forth in Chapter 9, an example of this hazard will be considered using the background at the U.S. Highway 177 crossing of the Cimarron River near Perkins, Oklahoma.

1. Background

An excellent source of information for this site is provided by Keeley (1971), and the following summary of the history of the site is abstracted from his description.

In 1953 a new bridge was constructed downstream from an old bridge, which in 1949 was judged to be in poor condition with erosion concentrated on the south bank about 1500 ft above the bridge abutment.

1950 - 5 pile diversion structures were constructed downstream from old bridge site (Fig. 27).

1957 - Continued erosion of south bank immediately upstream of south abutment during a period of large floods. Following floods, 650 ft of riprap emplaced on south bank between piles and bridge abutment.

1959 - Second highest flood of record on 3 October; all 5 pile diversions damaged. Some bank erosion on northwest bank 1500 ft upstream of north abutment.

1959-1962- A period of high discharge; point of attack shifted from south bank to north bank. Up to 325 ft of erosion on north bank between north abutment and 2600 ft upstream. Five pile diversion structures constructed on north bank, and riprap extended upstream from north abutment.

1965 - Further scour of north bank.

1969 - 100 ft of riprap lost by scour.

The continuing problem at this crossing could have been anticipated if an evaluation of the stability of the channel had been made prior to or after construction.

2. Procedure

a. Data Compilation

All available maps and photographs should be obtained. In 1976 the U. S. Geological Survey Topographic Map Index for Oklahoma shows that the only maps available for the area prior to bridge construction were the Perkins (1907) and Agra (1906) 15-minute quadrangles. The Perkins 7½-minute quadrangle was published in 1978. In 1953 only 1938 photography was available. Subsequently aerial photographs were taken in 1956 and 1968.

The U.S. Geological Survey gaging station is located on the bridge near Perkins, Oklahoma. Geologic maps show bedrock on the south side of the channel, suggesting relative stability of the south bank, but a considerable expanse of alluvium to the north of the channel. The sandy point bar further suggests relatively rapid channel shift or aggradation in sandy alluvium.

b. Preliminary Analysis

The aerial photographs show that the channel was straight and braided at the site at the time of bridge construction, but there was a large meander about

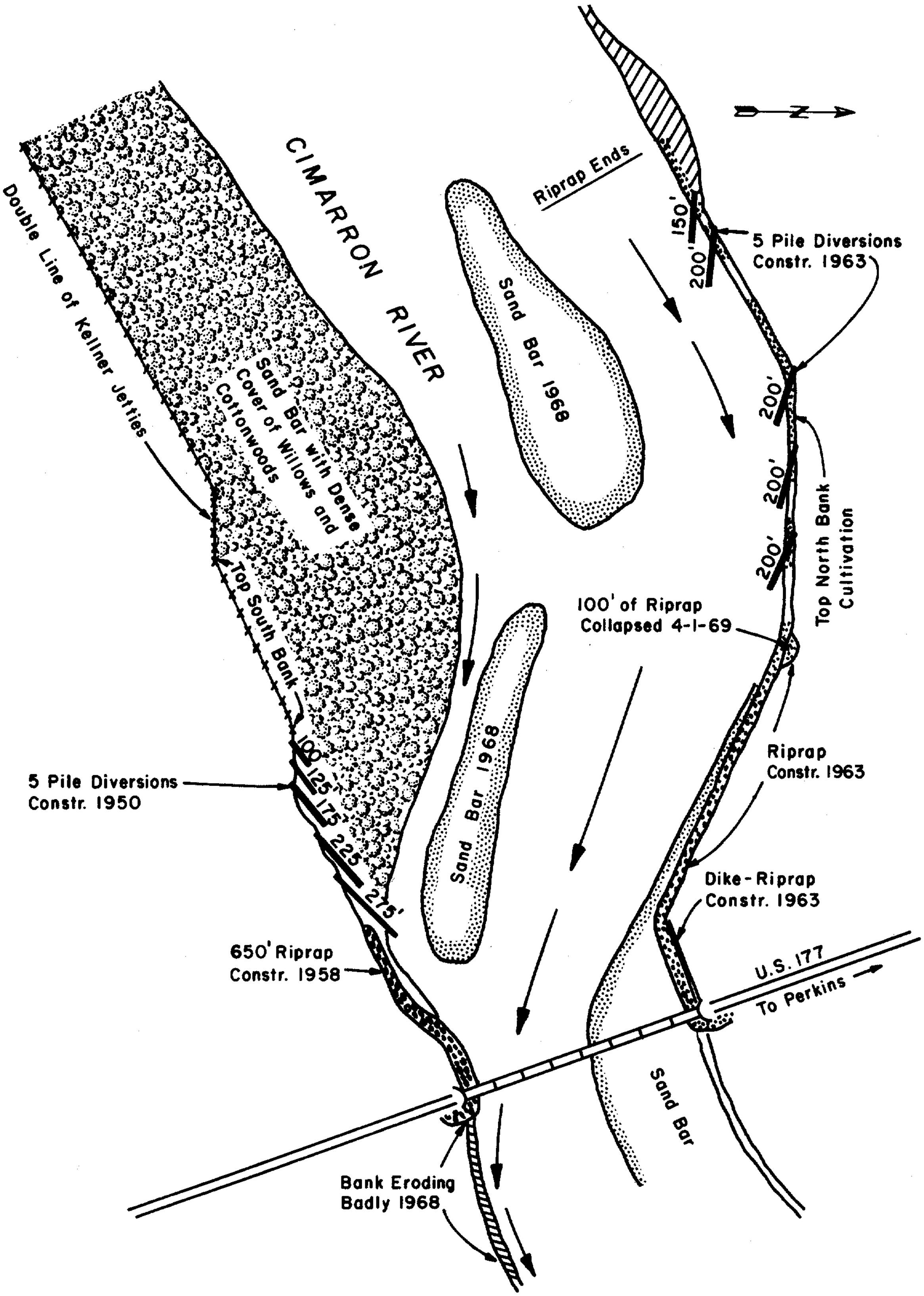


Figure 27. Map of Cimarron River at US 177 crossing (from Keeley, 1971).

one mile upstream (Fig. 28). The pattern, therefore, is best described as Pattern 4, a meander-braid transition pattern (Fig. 4). Obvious hazards associated with this pattern are meander shift, bar and island shift, chute cutoffs (Fig. 5) and a general instability of the thalweg and channel in the wide alluvial valley.

Available hydrologic and climatologic data suggest a flashy type of flow regimen that is likely to produce channel change. Analysis of the stage-discharge relationship for the Perkins gaging station shows that the stage at 100 cfs decreased 4.0 feet between 1939 and 1959 (Figure 29), which is evidence of degradation. Between 1959 and 1970 the water level at a discharge of 100 cfs was constant, but it decreased between 1970 and 1975. The obvious conclusion is that degradation is a major hazard at the site. However, in 1953 a cursory inspection of the channel upstream and a comparison with the 1938 aerial photographs would have revealed that the major hazard was meander shift.

It is possible that a chute cutoff might have at least partly eliminated the upstream bend, but the fact that the bend had maintained its general form during shift suggests that unless a major flood occurred, the bend would shift downstream onto the site (as it subsequently did, Figure 28).

c. Field Observations

With the readily available information and maps and photographs, the river should be visited and observations made on the extent and location of bank erosion, presence of gravel pits, etc. In 1953 the flood plain appeared to be little affected by man, but inspection of the channel shows that the large upstream bend visible on the 1938 aerial photographs had moved downstream about one-half mile.

The change of gage height at a discharge of 100 cfs for the period of record, 1939-1975 (Figure 29) probably reflects the shift of the meander toward the bridge. As the bend approached the bridge, the cross section changes from that of a realtively flat bed (a crossing) to a deeper channel characteristic of the deeper part of a bend.

3. Summary

Relatively little study is required to conclude that the Cimarron River is a relatively unstable channel at this site and that a major problem will be meander shift. In 1968 the apex of the meander had almost reached the bridge (Figure 28). According to Keeley (1971), there has been no damaging scour at the bridge piers in spite of the evidence of degradation supplied by the gaging station record. Therefore, this is a simple example of meander shift with the degradation being related to the development of a thalweg at the site. Further data analysis would not have suggested additional problems, and in fact examination of the 1938 aerial photographs with a rapid field examination of the channel would have revealed the potential problem of meander shift.

The shift of the maximum erosion from the south to the north side of the bridge between 1959 and 1962 (Keeley, 1971) was the result of the movement of the bend into the area of the bridge (Figure 28). Therefore, the obvious problem of bank erosion and channel scour was actually the result of meander shift.

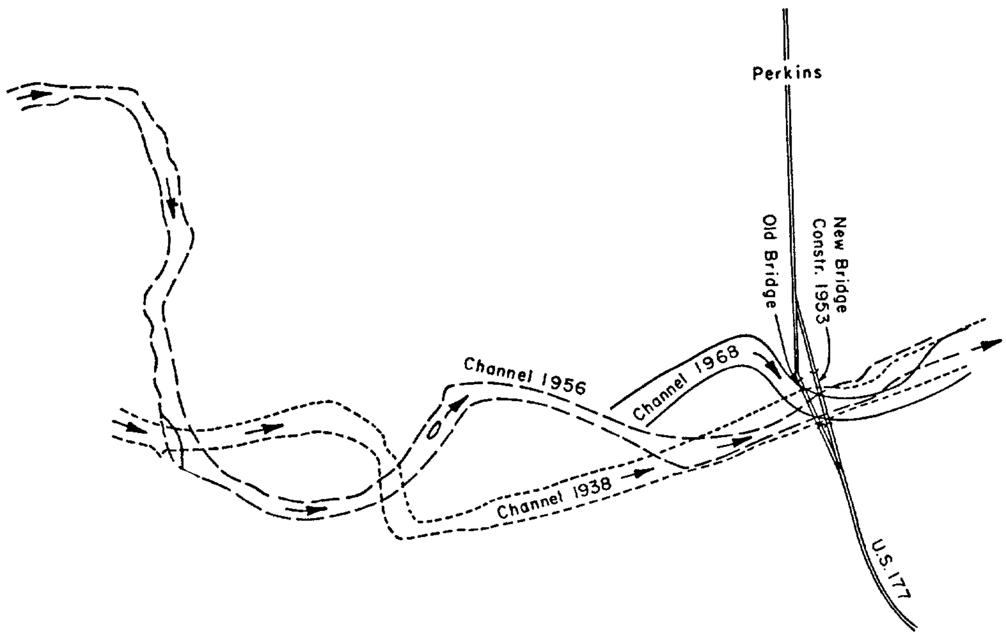


Figure 28. Meander shift as shown by 1938, 1956 and 1968 aerial photographs (after Keeley, 1971).

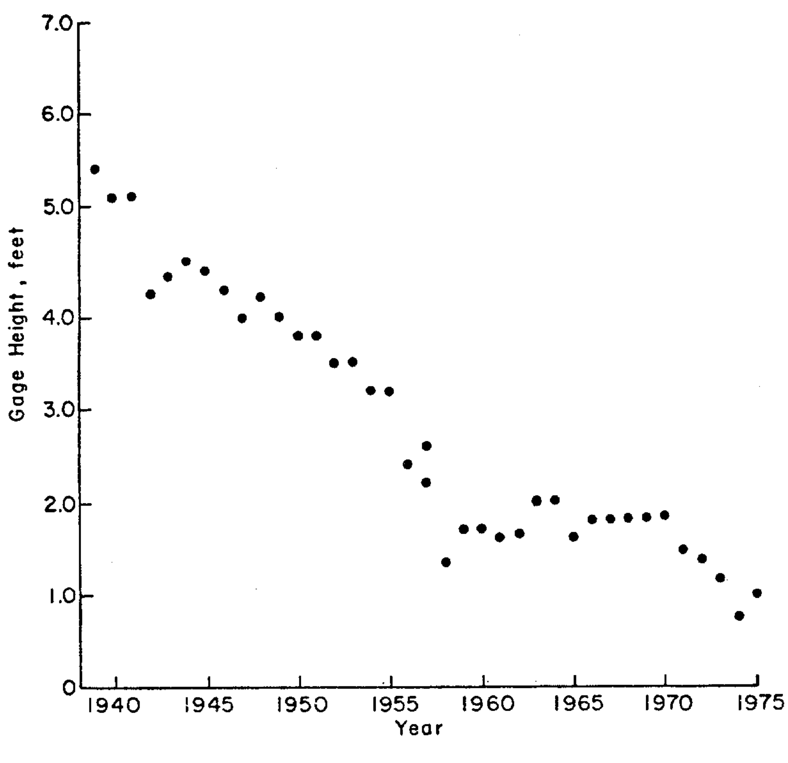


Figure 29. Change of gage height at discharge of 100 cfs, Cimarron River at Perkins, Oklahoma.

The major hazard was meander shift, but the accompanying shifting pattern of bank erosion and scour attracted the most attention.

From the point of view of the engineer, the site selected in 1958 was a reasonable one, as the channel was straight and it was near bedrock on the south side of the channel. Only if the upstream changes in the channel position were recognized and the hazard identified could the engineer have anticipated the problems that developed at this site.

At this site additional historical studies are unnecessary. However, further detailed studies of the valley alluvium could reveal resistant alluvium or bedrock that might reduce the rate of meander shift. In this case the sandy alluvium was very susceptible to bank erosion and the downstream shift was not delayed. Elsewhere such studies should be made and if more resistant materials are located, the bridge should be located on them.

C. Example 3 - Interstate 10, Salt River, Phoenix, Arizona

A major problem for the transportation engineer is to anticipate upstream and downstream changes of flood plain and bank utilization and channel alterations. An excellent example of what may be the worst possible case is provided by the Salt River at Phoenix, Arizona, where the river and its flood plain are a convenient and abundant supply of sand and gravel. Man-induced changes have significantly altered the Salt River in the Phoenix reach, thereby causing changes of flow alignment, constriction of the channel and degradation (Arizona Department of Transportation, 1979).

1. Background

The Interstate 10 bridge over the Salt River was constructed in 1962. The Salt River Bridge was designed to accommodate a 50-year flood with a peak discharge of 175,000 cfs. Discharges were relatively low or nonexistent for a number of years, but a large flood (67,000 cfs) occurred in January, 1966, and a 22,000 cfs flood in April, 1973. The river was essentially dry until a series of floods in 1978 and 1979. In March, 1978, there was a 115,000 cfs flood, and it was followed by a 120,000 cfs flood in December, 1978. In January, 1979, there was an 80,000 cfs flood, and finally in March, 1979, a 48,000 cfs flood.

During the latter flood, scour undermined the footing of the No. 11 pier (Figure 30), causing subsidence and tilting of one of the spans. The spread footing was 20 ft below the channel in 1962. However, a low water channel was dredged artificially to the north of this pier, between Piers 5 and 10 (Figure 30). The spread footings of these piers was 10 ft deeper than Piers 11 through 19.

2. Procedure

a. Preliminary Data Collection

Available aerial photographs and maps of the Phoenix reach were obtained. The Phoenix and Tempe U.S. Geological Survey topographic maps showed the river as it was in 1951, the 1:250,000 Army Map Service Phoenix topographic map was available

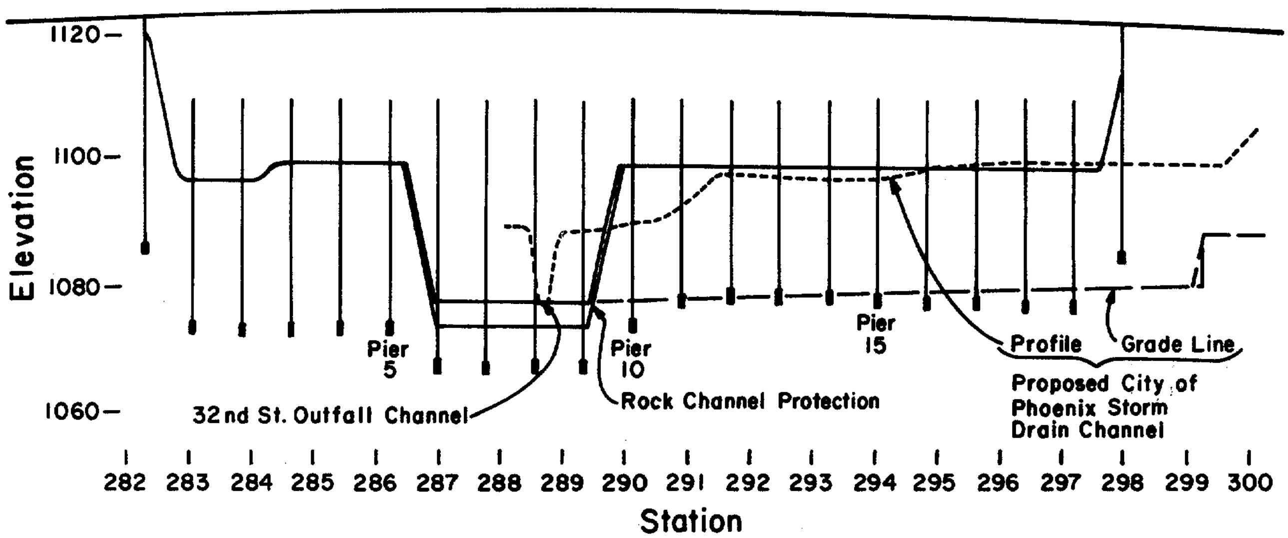


Figure 30. Cross section at I-10 Bridge, Phoenix, Arizona, showing channel cross section and location of low-water channel and bridge piers and footings (after Arizona Department of Transportation, 1979).

in 1954, and aerial photographs are available for 1960 and 1961.

Hydrologic data were available only upstream at the Granite Reef Diversion and downstream below the junction with the Gila River; therefore, a hydrologic record for the reach was lacking. Nevertheless, the upstream gage provided information on the occurrence of major floods.

b. Preliminary Evaluation

The river pattern is braided and the sediment in the channel ranges in size from sand to boulders. The river makes a gentle turn to the right at the site, and upstream left-bank erosion with bend shift could have been a problem (Figure 31). The 1952 Phoenix USGS topographic maps show extensive gravel mining in the channel downstream from the bridge site (Figure 31).

Hydrologic data reveal that the river only flows during floods. It is, therefore, highly susceptible to change and the details of the channel (bar and thalweg patterns) change rapidly during large floods.

c. Field Reconnaissance

The character of the site cannot be clearly reconstructed as it was in 1962, but the erodible bank and bed material, the flashy nature of the discharge, and extensive downstream gravel mining all indicate a tendency for change, and especially degradation. Observation of the gravel mining operation downstream and a survey of the river channel would have demonstrated a considerable base-level lowering downstream.

3. Analysis

When the bridge was designed, it was assumed that the low water thalweg would remain fixed in position at the height of 5 ft above the deepest pier. However, as the city of Phoenix grew during the period following bridge construction, gravel mining increased and gravel pits were opened near the bridge. In addition, the extension of the Phoenix airport runways involved drastic constriction of the channel upstream. Also, a power transmission line was established in the channel.

Gravel pits 30 feet deep were excavated upstream and downstream, and through landfilling and sanitary fills, the channel was narrowed in the Phoenix reach. A 30-ft deep gravel pit was dredged on the south side of the river about 2000 ft downstream and 750 ft south of the low water channel (Figure 32).

Study of aerial photographs shows that during the large 1968 flood, another thalweg developed as the existing low-water channel was filled with sediment. At least 15 ft of aggradation occurred above the bridge during the 1978 and 1979 floods, and this filled the 20-ft deep low-water channel with sediment. Flood water flowed into the gravel pit (Figure 32) and head cut erosion resulting from the lowering of base level caused development of the new channel, which was centered on Pier 11. Scour and undermining of Pier 11 resulted, with serious damage to that span of the bridge.

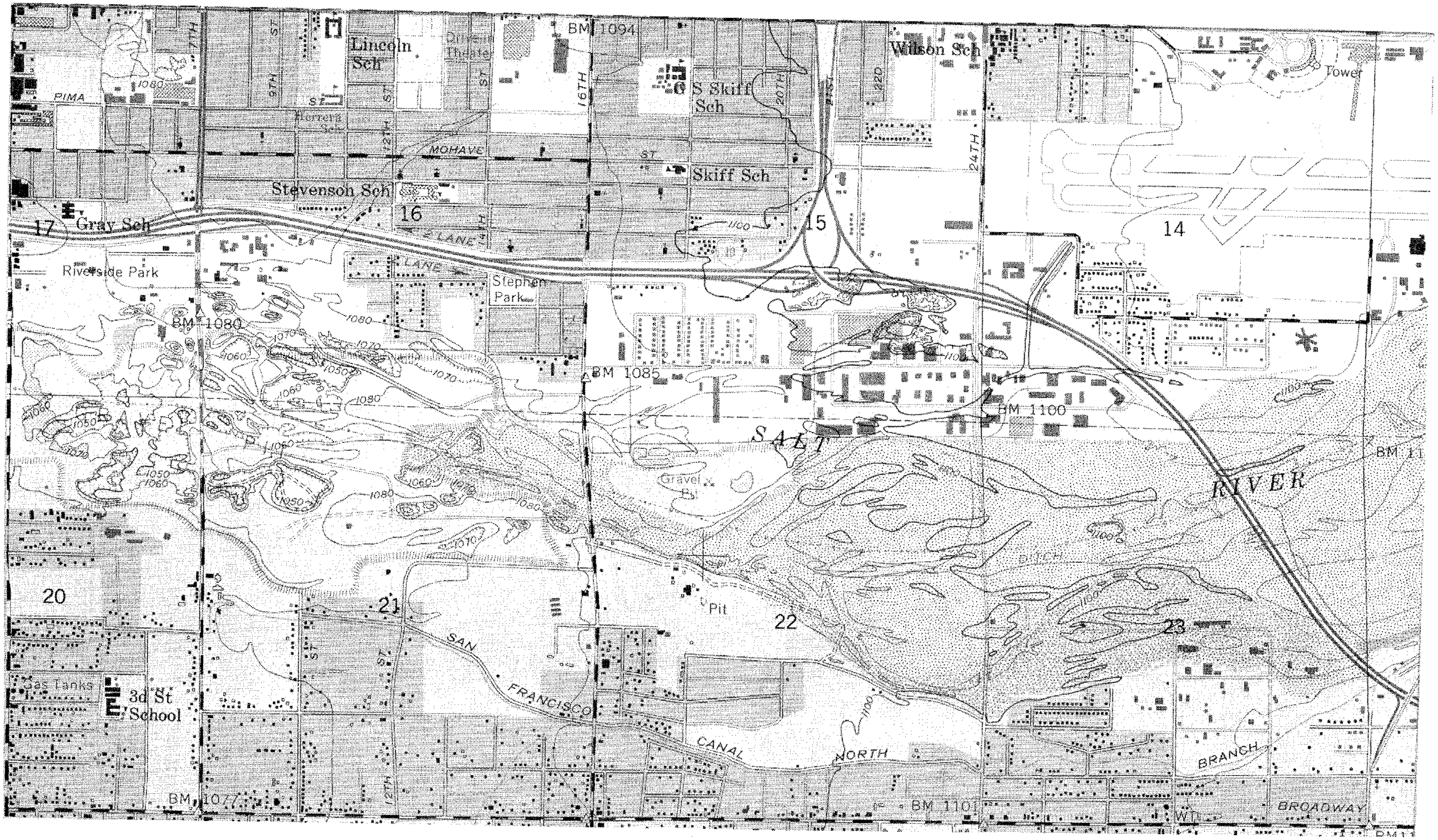


Figure 31. Salt River at Phoenix, from U.S. Geological Survey Phoenix 7½' quadrangle (1952, revised 1967 and 1973). Note extensive gravel mining and channel narrowing to left (west) below I-10 Bridge.

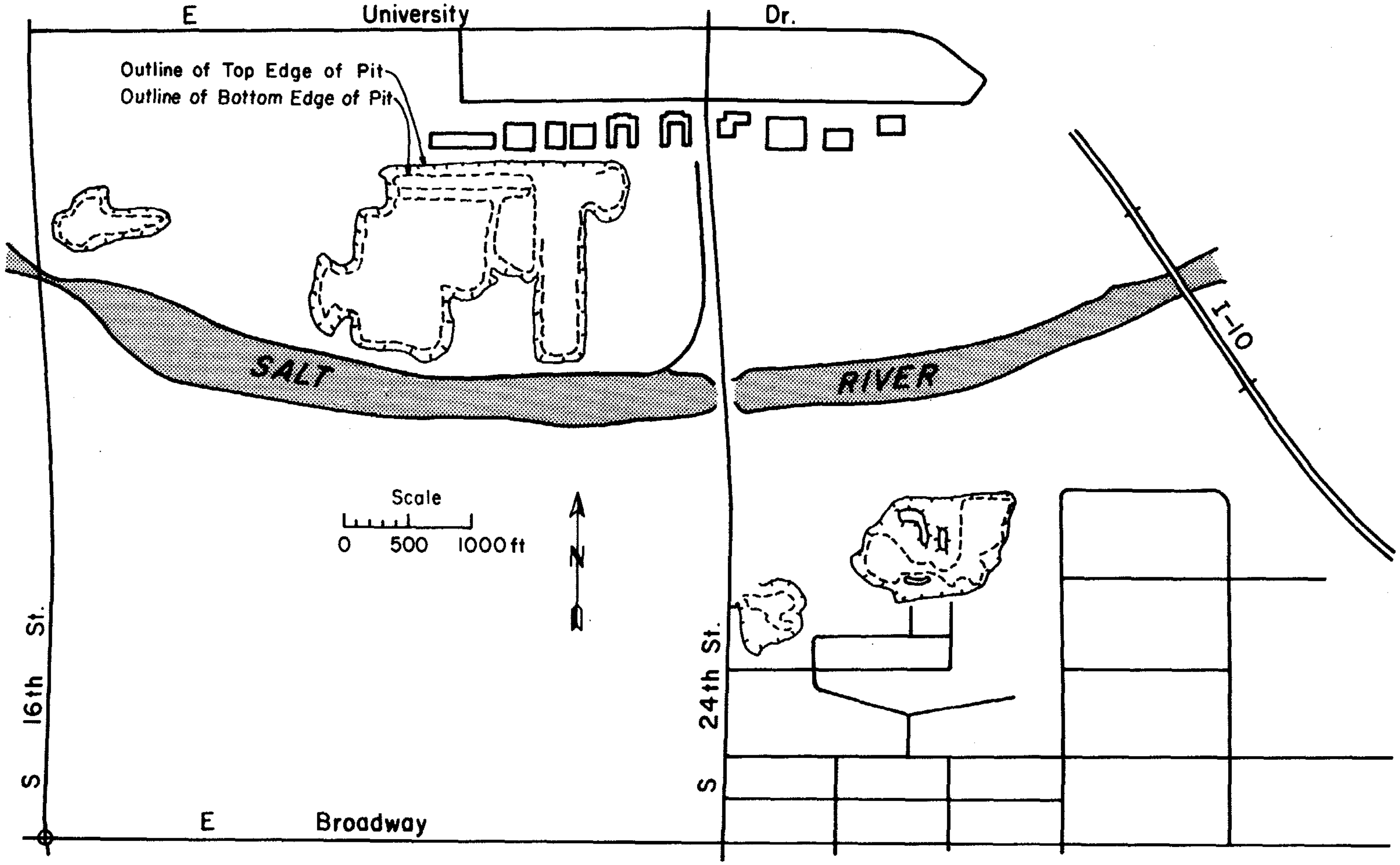


Figure 32. Map showing location of I-10 Bridge, Phoenix, Arizona, and downstream gravel pits (after Arizona Department of Transportation, 1979).

4. Summary

The nature of the channel pattern and its bed and bank materials clearly indicate a river that is relatively unstable. Because of the intensified constriction of the channel upstream and gravel mining both upstream and downstream, the low-water channel changed position and degraded during floods. The rapidly developing Phoenix area ensured that such would be the case.

An even more dramatic case of the effects of gravel mining on bridges is provided by Scott's (1973) documentation of the failure of the Foothills Boulevard over Tujungo Wash, California.

CONCLUSIONS

This report provides the transportation engineer with an appreciation of the hazards presented by rivers to highway structures, and a means of recognizing and evaluating the magnitude of the hazard at a bridge site. Unfortunately, the great variety of rivers and the number of hazards render what may appear to be a simple task very complex. In some cases the lack of data will prevent the engineer from identifying a hazard, and in other cases the rate at which the hazard develops is too slow for easy identification. Nevertheless, in numerous cases the hazard can be recognized and steps can be taken to alleviate the condition prior to and after bridge construction. It is strongly recommended that the procedures for hazard recognition be followed prior to bridge construction and, in fact, a survey of existing bridge sites and the upstream and downstream reaches of the river may permit identification of future problems at bridges that have been essentially maintenance-free. Changing land use patterns are difficult to predict, but it is clear that the effect of land use change on variables can affect the hazards in such a way that a stable bridge site will be rendered unstable. Nevertheless, with all the weaknesses, the techniques can be used to identify an unstable site that is threatened by stream-related hazards, and to predict future changes at a potential or existing bridge site.

The variety of stream patterns and their relative stability provide a guide to the evaluation of the natural stability of a channel. The many variables that influence river morphology and behavior, and that can change as a result of man's activity, emphasize the need not only for careful preconstruction evaluation of a site, but continued monitoring of the site after the bridge has been built.

Three examples of unstable bridge sites are presented as a guide to the use of the procedure. These examples were chosen partly because of the abundant information available at each site; therefore, they show how the procedure can be followed to identify the existing hazards. Unfortunately, the recognition of hazards at other sites may not be as easy. In some questionable cases consultants who are experts in river behavior should be asked to evaluate the site.

No rigid procedure can be followed for the identification of the hazards, and judgment is needed. However, in most cases the transportation engineer, with the assistance of others (geologists, hydrologists) on the staff, can successfully utilize the procedure. The cost of such an analysis is minimal, and even when consultants are required the expenditure will be only a very small portion of the cost of planning and bridge construction. However, once a hazard is identified the cost of developing countermeasures may be high.

Further study of the hazards is desirable and the transportation engineer can assist the scientist and river engineer by providing documentation of river-induced problems at bridge sites. Further refinement of the proposed relations between river pattern and river stability will be of considerable value and additional research in this area is needed.

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APPENDIX A

SLOPE STABILITY AS RELATED TO STREAM HAZARDS TO BRIDGES

by
John D. Nelson and Joseph P. Martin

I. INTRODUCTION

The stability of slopes along valley or canyon walls and river banks constitutes a major factor in defining stream hazards associated with bridge planning and design. At any particular point in time, the channel and the flood plain of a river are defined by the enclosing banks and slopes. Over extended time, however, the location and stability of these slopes and banks are determined by the geologic, climatic, hydraulic and land use features of the watershed. The river is the conduit for all soil, water, debris and sediment movement from its drainage area. It also defines the base line elevation. Thus, riverside banks and slopes are subject to scour, deposition, weathering, ground water and surface water discharge, and mass movement from higher upland elevations. The stability of a slope is a function of its resistance to these forces.

The performance and integrity of a bridge structure is dependent upon both stream morphology and local hydraulics. Thus, slope stability represents a necessary consideration in stream hazard assessment. Slopes along a river are constantly failing during the natural process of changes in the banks, floodplains and valley walls. However, the extent, degree and rate of these changes are different at different locations along a river. The primary objective in bridge siting with respect to slope stability is to avoid locating the bridge at a point of rapid change, and to adjust the bridge design to accommodate effects of rapid or extensive slope change elsewhere in the valley. Figure 1 shows two bridges located at sites in which slope stability and bank erosion pose an immediate threat.

Slope failures may occur on different scales of magnitude. Small localized failures in the banks are easily identified and their hazards may be assessed ahead of construction. Slope failures encompassing a large area, often in the uplands above a river, are more difficult to identify and correct. It is necessary to assure that highway and bridge construction will not trigger further failure.

Detailed study of soil conditions at a particular bridge site is undertaken as a matter of course. However, in planning a new structure, or in assessing the hazard at an existing site, investigation of the stability of all slopes which may influence the stream is necessary. This may also include slopes at locations other than the immediate site under consideration.

Slope instability may manifest itself in many ways. It is integrally associated with the geohydraulic environment. The most immediate concerns for bridge planning and design are bank caving, creep effects on bridge foundations and stability of approach fills or abutments. Potential instability of larger slopes in the immediate vicinity of the site will have a direct effect. Instability of slopes at locations remote from the particular site would have an indirect effect insofar as it influences the general stream characteristics.

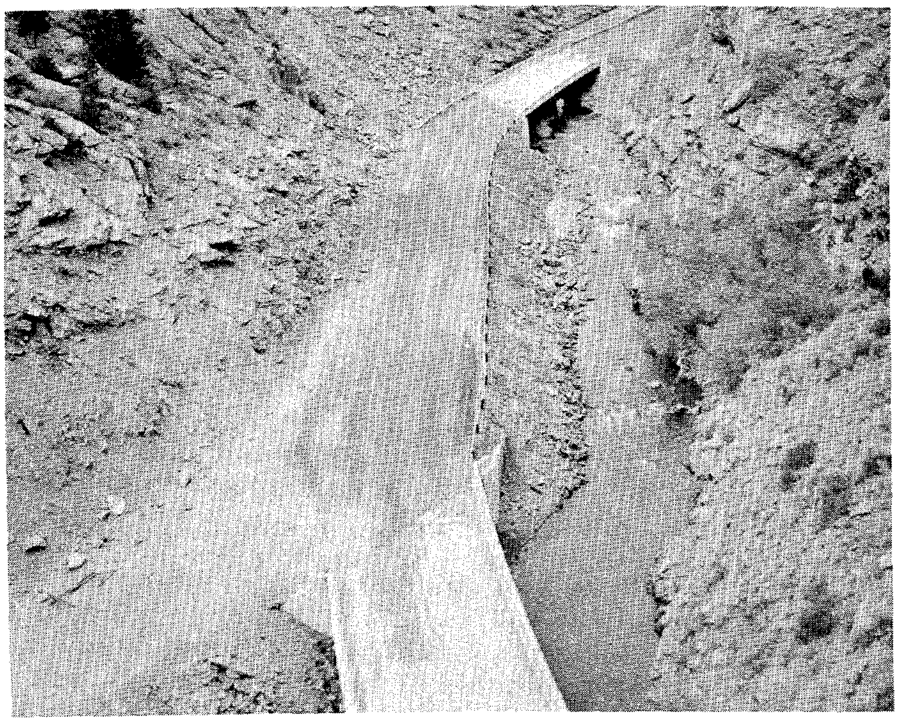


Figure 1. Bridge and Highway Embankment Showing Distress Due to Slope Movement.

If a potential instability exists at the site, debris falling or flowing from the slide would impose a hazard to the bridge or its approaches. Landslides or bank caving upstream from the bridge would pose a hazard by introducing debris into the river that may be carried into the bridge. If the sliding mass constricts the channel, the sediment load, flow characteristics and flood profile of the river will change.

Landslides at a downstream location are of less concern. Backwater from a river obstruction caused by a landslide may have some of the same results as noted above, plus a number of possible baselevel effects. However, downstream slope failures would probably have a minimal effect unless they were of very large mangitude.

Many different factors may cause or influence slope failures. Also, there may be a number of ways in which slope failures may be observed or detected prior to their occurrence. In some cases, a slope may actually be moving or may be impending failure although distress to roads, bridges, banks and valley slopes may not yet be evident. In these situations it is important to identify that a hazard exists, to assess the degree of hazard to bridge structures, and to identify remedial measures prior to failure on a larger scale.

In the following text the influencing factors, failure types and mechanics of slope stability are discussed. Based on this information, techniques of recognizing potential slope instability are presented. Guidelines for identifying locations where slope failure may be significant to highway structures are indicated.

The document is intended to provide a basic presentation of the factors influencing slope stability along rivers. It is intended for use by bridge designers to assess the potential hazard posed by potential slope instability at a site. Whereas it is assumed that the personnel utilizing this document will have some technical background, it is not prepared for specialists in geotechnical engineering. Consequently, throughout the report, those situations in which geotechnical or geological experts should be consulted, are noted.

II. MECHANISMS, PATTERNS AND FORCES IN RIVERSIDE SLOPE INSTABILITY

The following section is included for purposes of providing a framework for the discussion of detection of instability and to assist in classifying slope movements. It is not complete enough to define rigorous analyses of slopes. For actual details of applications the reader is referred to various soil engineering textbooks, manuals, and published papers.

A. Slope Movements

The river valley is in a state of constant change with regard to topography, surface and subsurface hydrology, local slope geometry and soil or rock properties. Assessment of slope hazards to structures is a process of predicting slope movements under future as well as present conditions.

There are two basic mechanisms of failure. One is failure by creep and the other is shear failure of the slope material.

Slope movement starts as plastic deformation of a zone within the mass. Because earth materials are non-uniform, have nonlinear properties, and are inelastic, analysis by principles of continuum mechanics is generally quite difficult.

Stress changes within the moving mass may result from the weight of the slope materials, external loading, or unloading of portions of the slope. Changes in the ability of the soil or rock to resist yielding may also lead to movement. Creep movements may continue for long periods of time. If the displacements are sufficiently large and if they progress at a sufficiently fast rate as to cause distress, the slope can be considered to be in a state of failure. Due to creep movements within the slope, the shear strength of the soil and rock within the zones of concentrated movement will decrease.

If the shear strength along a continuous surface within the slope is exceeded due either to a reduction of the original shear strength or to an increase in stress due to construction, movement will occur relatively rapidly. This relatively sudden movement represents the second mechanism of failure termed shear failure. Mass movement during shear failure may occur as rotation, translation or a combination of the two. Breakup of the moving mass usually follows. The soil and rock may move farther downslope, or be later removed by erosion.

Shear failure may be analyzed by limit equilibrium methods. In such methods the resisting forces are considered to result from the shear strength of the soil and rock. Forces tending to cause movement (driving forces) are those due to the weight of the mass and external loads. The resisting forces are compared to the driving forces to express the factor of safety. Because a creeping slope is undergoing local failure, and its soil is weakening due to the plastic strain, sites exhibiting relatively rapid creep rates may have a factor of safety near unity and should be investigated for potential shear failure.

B. Forces Causing Slope Movement

Figure 2 shows various manifestations of bank and slope movements. The general tendency in all cases is obviously downslope movement.

For a slope failing either by shear failure along a shear surface or by accelerated creep within a concentrated zone, the forces acting on the moving mass are as shown in Figure 3. With all other factors being equal, the steeper a slope is, the greater will be the shear stresses (Force T) relative to the normal effective stresses (Force $\bar{N}$). Consequently, steeper slopes will exhibit a greater probability of movement.

For any center of rotation such as point O on Figure 3, unloading the base by erosion, channel degradation or excavation will move the weight vector to the right and thus increase the moment of the driving forces. If the removal of material from the toe also intercepts the shear surface, the moment due to resisting forces can be decreased. Thus, removal of toe material will decrease the stability of a slope. Similarly, placement of fill or external loads at the head of a slope will also decrease the stability of a slope.

For the above reason, slope failure along rivers will tend to be progressive. A small slope failure will unload the toe of the slope above the area of failure. The material in the area of the escarpment will also be exposed to weathering and the introduction of water. After sufficient time, a slope of greater magnitude may be triggered. Figure 4 shows a slope failure progressing headward by such a mechanism.

In Figure 3 it is seen that the resultant of the stresses normal to the shear surface consists of two components. The concept of effective stress states that the normal resultant force is equal to the sum of $\bar{N}$, the resultant of effective stresses, and U, the resultant of pore water pressures. If the pore water pressure, and hence U, increases, the effective stress, and hence $\bar{N}$, will decrease. The converse is also true.

Because the shear strength of a soil is a function of the normal effective stress, an increase in $\bar{N}$ will enhance the stability whereas a decrease in $\bar{N}$ will decrease stability. Thus, if the phreatic line rises, the pore pressures will increase and stability will decrease. A fairly common method of attempting to increase the stability of a slope is to install drains near the toe to lower the preatic surface and decrease the pore water pressures.

The introduction of water into a slope may cause weathering or decrease the shear strength of the soil, thereby decreasing stability. If the slope is in

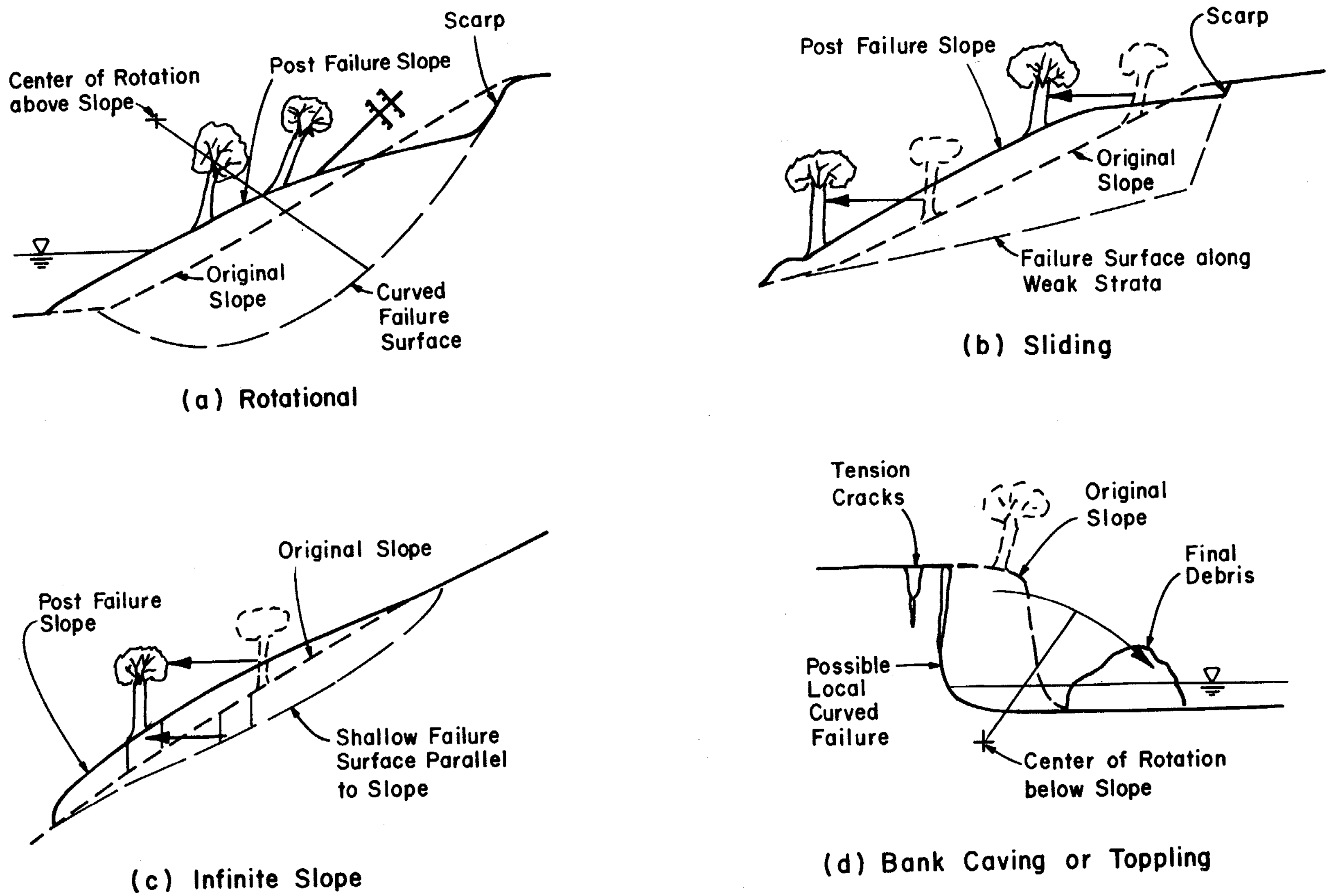


Figure 2. Mechanisms of Slope Failure.

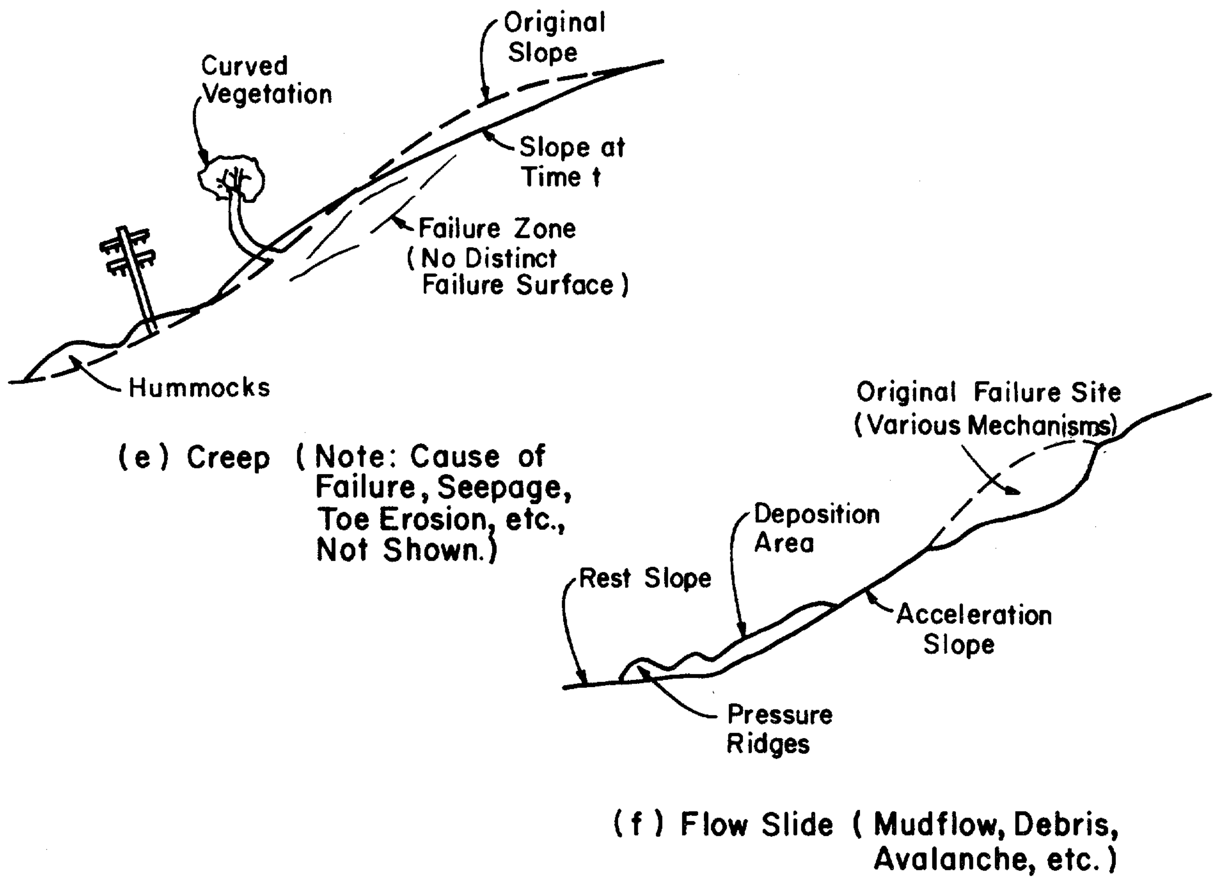


Figure 2 (continued)

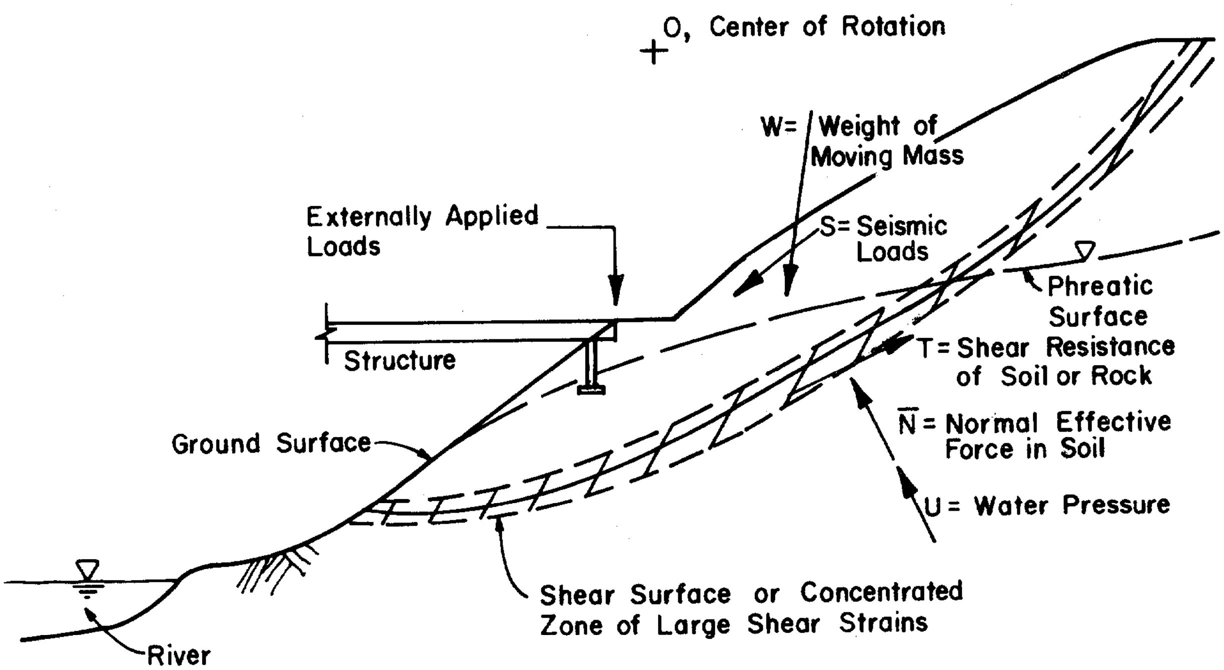


Figure 3. Forces Acting on Slope Failure.

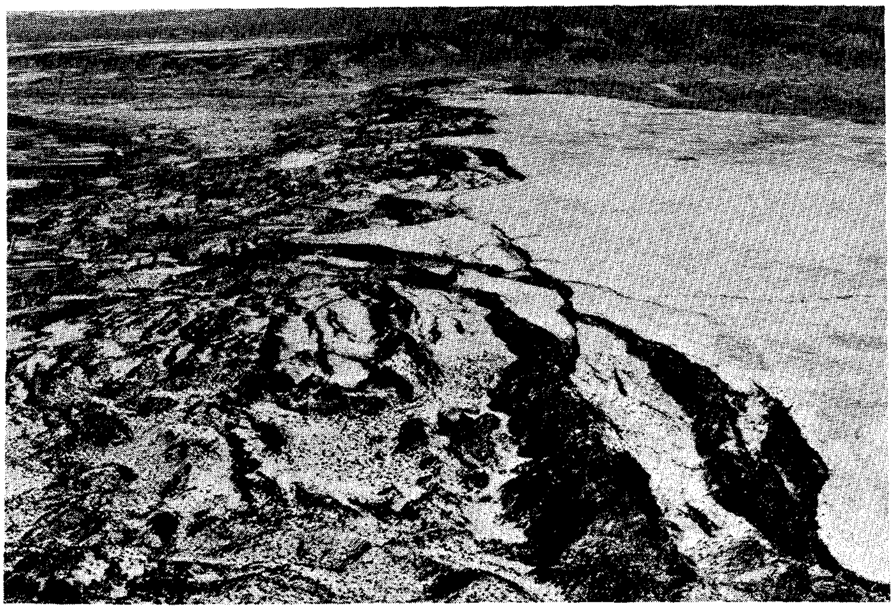


Figure 4. Headward Progression of Slope Failure Along Rio Grande as Evidenced by Series of Escarpments (photo by Donald O. Doehring, Colorado State University).

granular soils, saturation would decrease apparent cohesion caused by capillary tension in the pore water. Consequently, many failures may be associated with rainfall, lowering of river stages, or the introduction of seepage due to land use changes.

Any changes in the riverine environment that could influence or change any of the forces acting within the slope will influence the stability. Potential bridge sites must be evaluated with respect to factors such as construction, land use changes, or natural phenomena, as they will influence the internal forces.

C. Types of Slope Failure

Potential slope failures may be classified into one of the several types of failure that have been identified, based on the mechanics involved. Not only does this classification aid in analysis, but also it aids in identifying the extent of failure or its effect on adjacent banks. Classification helps to delineate the conditions likely to cause such failure and its effects.

Most local and riverside slope failures fall into one or a combination of several of the following failure modes. These failure modes were shown in Figure 1 and are discussed individually following.

1. Rotational failure

A rotational shear failure, shown in Figure 5, consists of a mass of soil moving along a curved surface where the soil or rock has failed in shear. In slopes of fairly homogeneous soils, the failure surface is nearly cylindrical. However, in most natural slopes, zones of weakness or heterogeneity in the soil will cause distortions generally resulting in a curved non-circular failure surface. An example of such a slope failure is shown in Figure 6. The general shape of the shear surface between the escarpment and the point at which it exits near the toe can be inferred.

Following movement of the slope, the mass may break up as shown in Figure 6. The general principles of analysis are similar for both circular and non-circular failure surfaces except that the complexities of the mathematics involved differ somewhat. The most commonly used methods of analysis generally consider the sliding mass as a series of slices as shown in Figure 5. Equilibrium of each slice is considered and the resisting forces are compared to the driving forces to determine the factor of safety. Because the analysis is statically indeterminate, a number of assumptions must be made to determine all of the forces and their lines of action. The nature of these assumptions comprises the differences between the many various methods of analysis in use at the present time.

Rotational shear failure is characteristic of embankments and deepseated failure in natural slopes. This type of failure may also be exhibited in bank caving or other situations where the toe of the slope is unloaded.

2. Sliding

Sliding slope failure is depicted in Figure 2b and occurs along one or more planar surfaces. This failure results when the shear strength of a distinct plane of weakness is exceeded. This type of failure is similar to a rotational failure except that the analysis can be simplified considerably. The analysis generally consists of considering equilibrium of the individual blocks comprising the sliding mass to determine the resisting and driving forces. Whereas the method of analysis is generally not complex, the major difficulty lies in identifying the failure plane. Typically the failure plane will follow a plane of weakness such as the intersection of the slope with a bedding plane, stratifications within or between soil types, a previously developed ancient shear plane or a fault or joint in the bedrock. Of particular interest in fluvial deposits are thin weak zones of silts or clays. Erosion due to ground water flow or anomolous excess hydrostatic pressure in confined strata are also often involved.

Sliding is usually associated with anisotropic soils and strata having large differences in strength, whereas rotational failure generally occurs in relatively homogeneous or continuously graded soils. Sliding is also a common mechanism of failure in jointed rock. In that case the introduction of pore pressures in the joints, especially in freeze-thaw regions, may have a major influence.

3. Infinite slope failure

"Infinite slope" failure, shown on Figure 1c, takes place on a shear plane that is shallow relative to the length of the sliding slope. The shear plane is

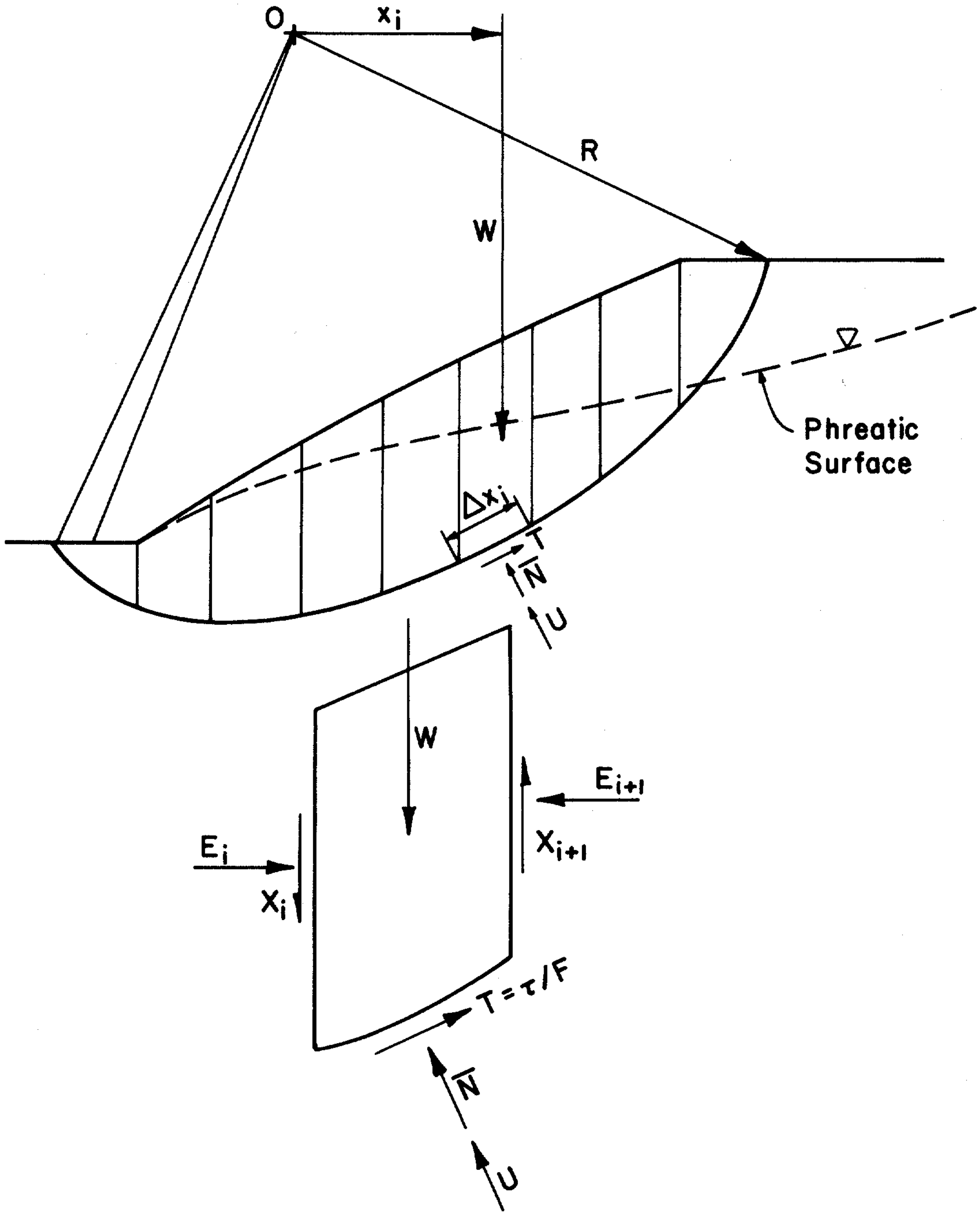


Figure 5. Slope Above Cylindrical Shear Surface Divided into Slices for Purposes of Analysis.

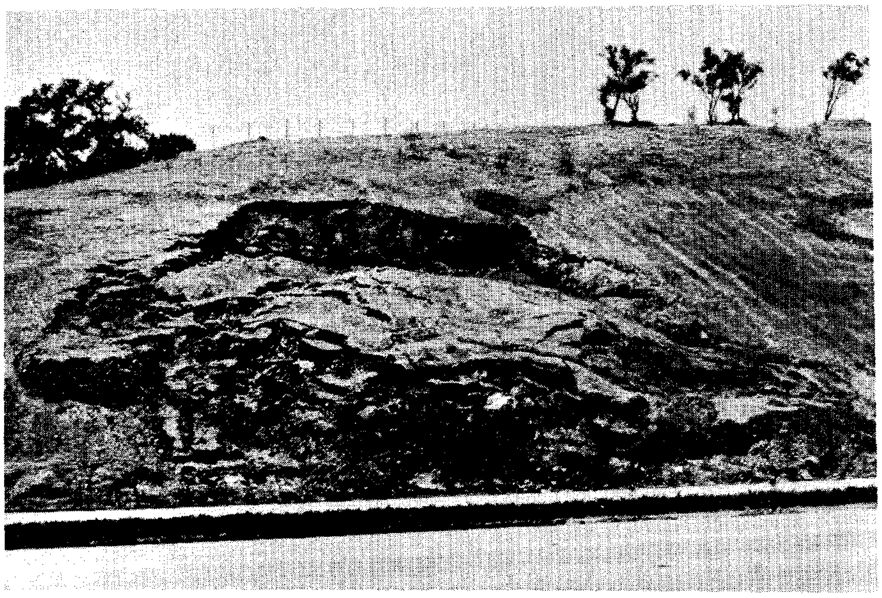


Figure 6. Photograph of Rotational Shear Failure Caused by Excavation for Highway (photo by Donald O. Doehring).

generally parallel to the surface of the slope. Shallow soughing of surface soils on long slopes is a classic example.

This form of failure may occur along a plane of weakness defined by the root zone of plants and trees, at the bottom of a zone of weathering, along a plane of evaporation of capillary water, at the contact between surface soils and bedrock, or along bedding planes oriented parallel to the slope.

Soil strata in alluvial deposits are generally nearly horizontal, so that "infinite slope" failures along rivers are usually restricted to colluvial slopes. Such an example is shown in Figure 7. In Figure 7 failure took place along a shallow plane defined by the contact between the soil and the bedrock. In that case failure was triggered by an excess of water during an extreme precipitation event.

4. Bank caving or toppling

Bank caving or toppling is depicted in Figure 2d and generally occurs along banks of moderate height in soils capable of standing at nearly vertical slopes. The primary triggering mechanism is erosion at the toe of the slope. An example of this type of failure is shown in Figure 8. After sufficient erosion of the toe of the slope has proceeded, tension cracks will appear at the top. As the cracks propagate along the bank, a portion of the bank eventually topples into the river.

Frequently the introduction of water into the tension cracks will induce toppling. In soils of low permeability, hydrostatic pressure in the cracks may be

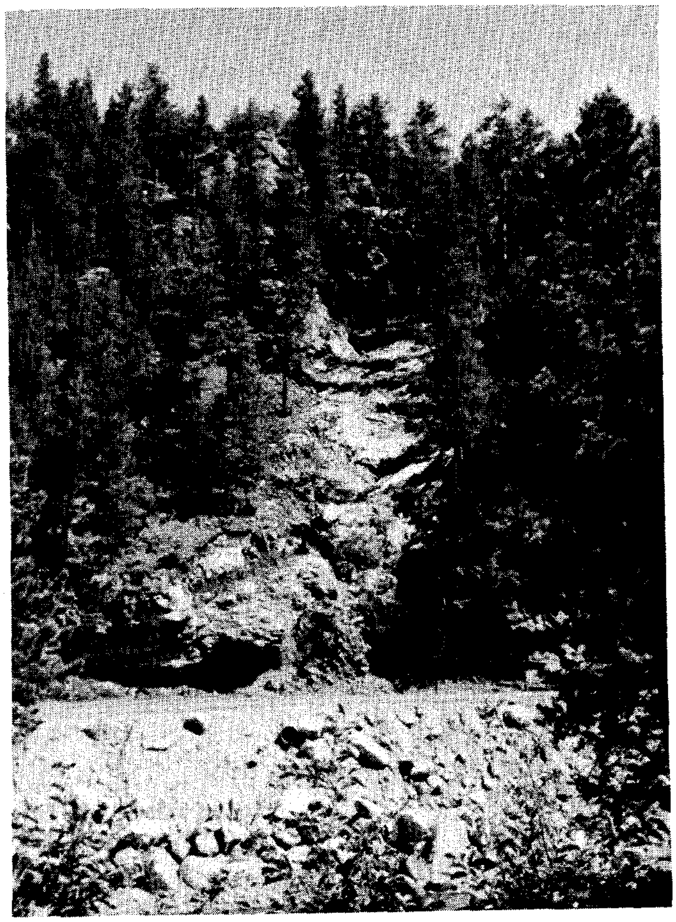


Figure 7. Shear Failure Along Shallow Plane Depicting Infinite Slope Failure (photo along Big Thompson River by Thomas V. Edgar, Colorado State University).

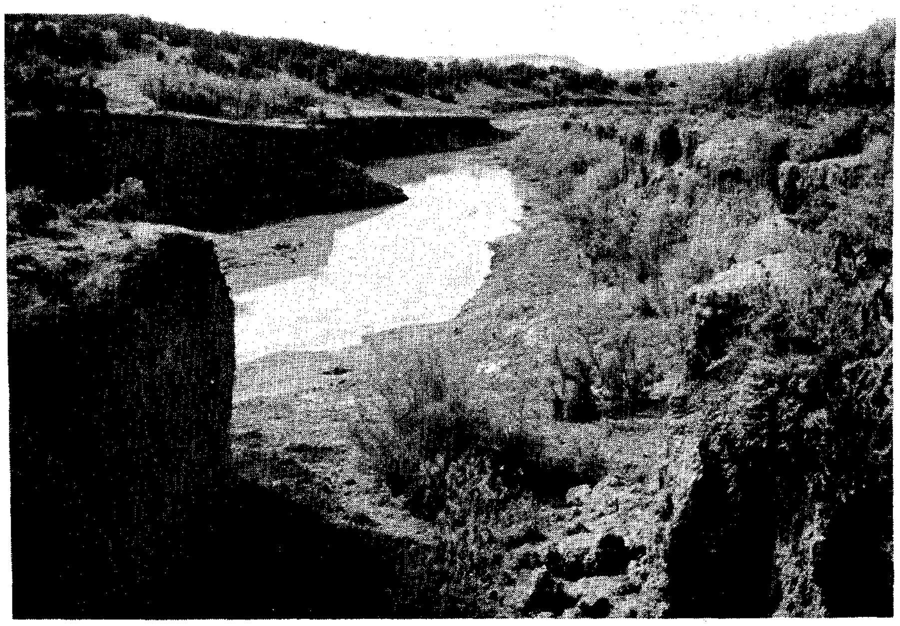


Figure 8. Evidence of Bank Toppling Along Stream in Mount Taylor Area, New Mexico. "Toppled" Material is Evident in Foreground. (Photo by T. R. Boutwell, Gulf Mineral Resources Co.)

of significant magnitude and may provide the impetus for banks that were in equilibrium for long periods of time to fail during rainstorms or flooding. Toppling will be most pronounced in easily eroded cohesive soils such as silty clays.

A special case of toppling that is common in arid or semi-arid regions results when river or surface flow erosion removes a weak stratum of soft rock underlying a stronger caprock, thereby causing the upper layer to fail in tension. This mechanism is shown in Figure 9.

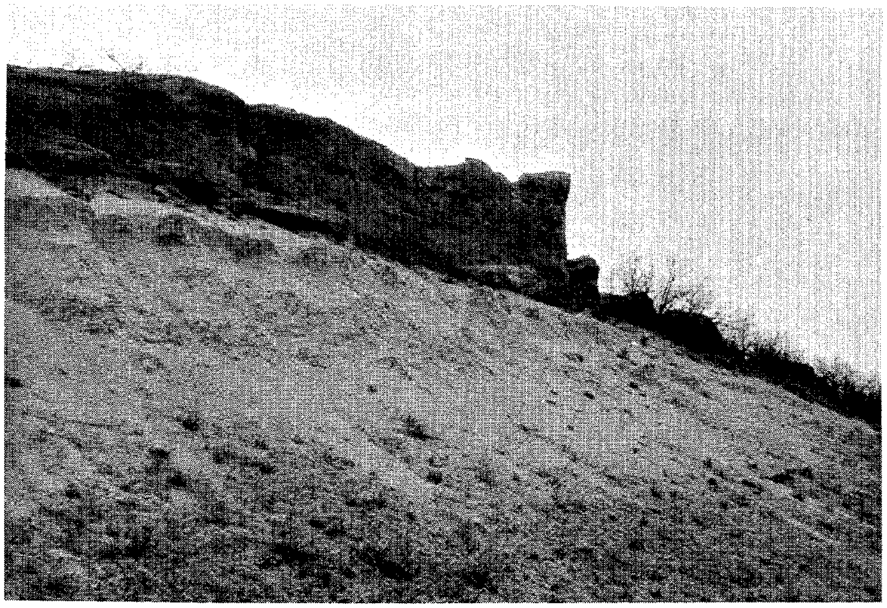


Figure 9. Erosion of Strata Underlying More Resistant Rock Leading to Toppling.

5. Creep

Creep is the continual, timewise accumulation of strains or displacement of the slope as driving forces cause local yielding and readjustment under a constant load. Creep movements are generally evidenced by a hummocky surface as indicated in Figure 2e. Creep movement does not necessarily occur along a distinct failure plane. However, within the slope, creep strains may be concentrated in zones of creep-susceptible materials. Although creep movement does not cause sudden movement of a large mass of material, the creep displacements may cause continual distress to bridge approaches, abutments and foundations. In some instances creep movements may lead to progressive failure of the slope which could cause accelerated movement and which could lead to eventual shear failure.

In general, creep rates will be higher as the level of stress approaches the shear strength of the soil. Some materials, such as plastic clays or clay shales, exhibit larger amounts of creep than do granular materials. Creep will result in a continual downward movement of the surface, and may continue for hundreds of years if removal of material from the slope base matches the rate of slope movement. A slope showing evidence of creep movement is shown in Figure 10. The hummocky appearance of the surface can be seen.

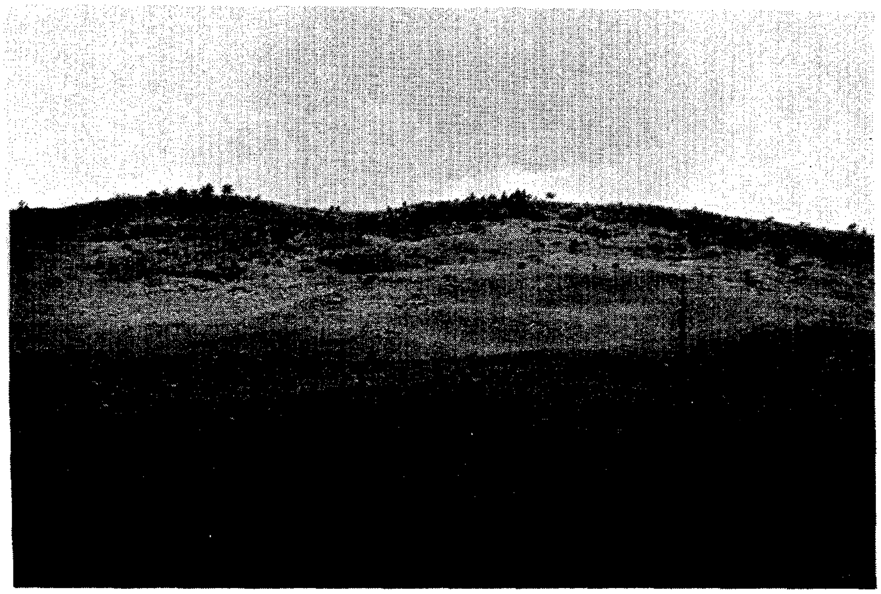


Figure 10. Hummocky Slope Surface Indicative of Creep Movement.

Generally, creep movement is characterized by an increase in movement rates during wet seasons and a decrease in creep rate during dry seasons. Figure 11 shows a typical displacement-time record for Threatening Rock in Chaco Canyon, New Mexico. Figure 12 shows the rock cliff before failure. In that case the creep movements led to eventual toppling of the rock. The increased creep rates during the wet winter months and the decreased rates during the dry summer months are evident in Figure 11. In January, 1941, movements increased to the point at which failure then occurred. The accelerated creep and progressive failure of the slope can be seen in Figure 11. Thus, even if creep movements are not problematical in themselves, they can serve as indicators of impending shear or toppling failure.

6. Flowslides

Flowslides include mudslides, avalanches, debris flows and other fast-moving mixtures of material which flow much as a viscous fluid. Except for avalanches, flowslides are usually associated with water and steep terrain often during intense, erosive storms. Flowslides may range from the collapse of ditch slopes to spectacular mountainside movements, such as the Gros Ventre slide shown in Figure 13. Many of the more destructive historical slides are of this type, since they can travel at great speeds for a long distance, and can trigger other instabilities in their paths. Figure 14 shows a large mudflow that occurred in the past. Pressure ridges, a lobate form and irregular drainage are evident at that slide.

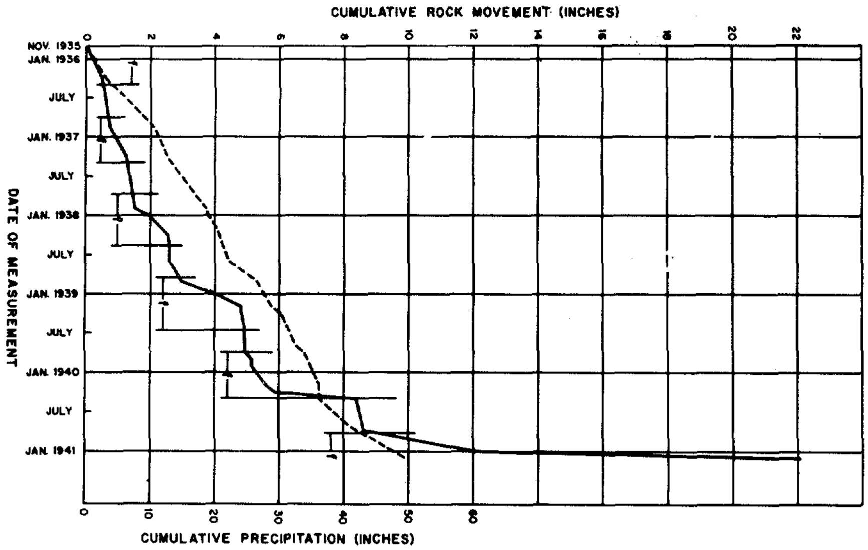


Figure 11. Displacement-Time Record for Threatening Rock, Chaco Canyon, New Mexico (photo by U.S. National Park Service).

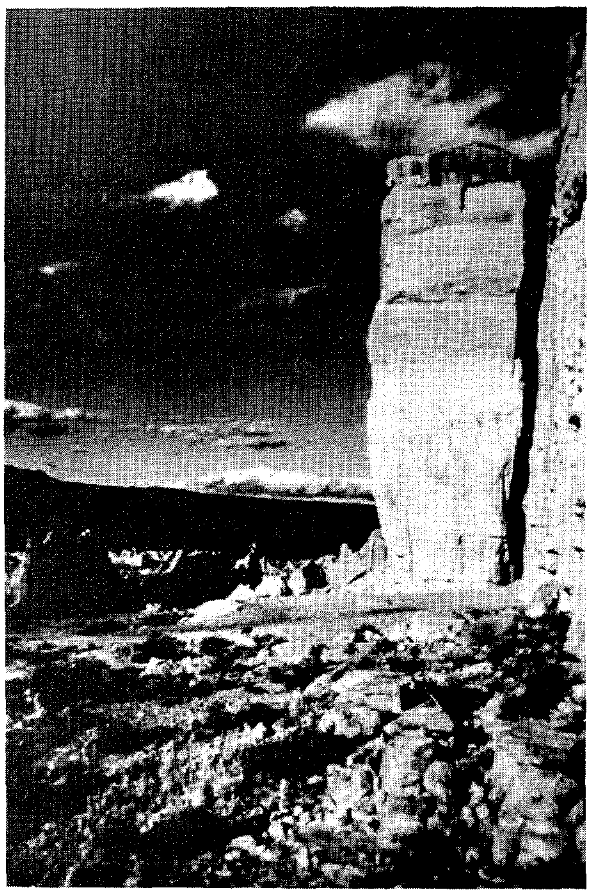


Figure 12. Threatening Rock Before Failure (photo by U.S. National Park Service).

Figure 13. Gros Ventre Slide (photo by Stanley A. Schumm).

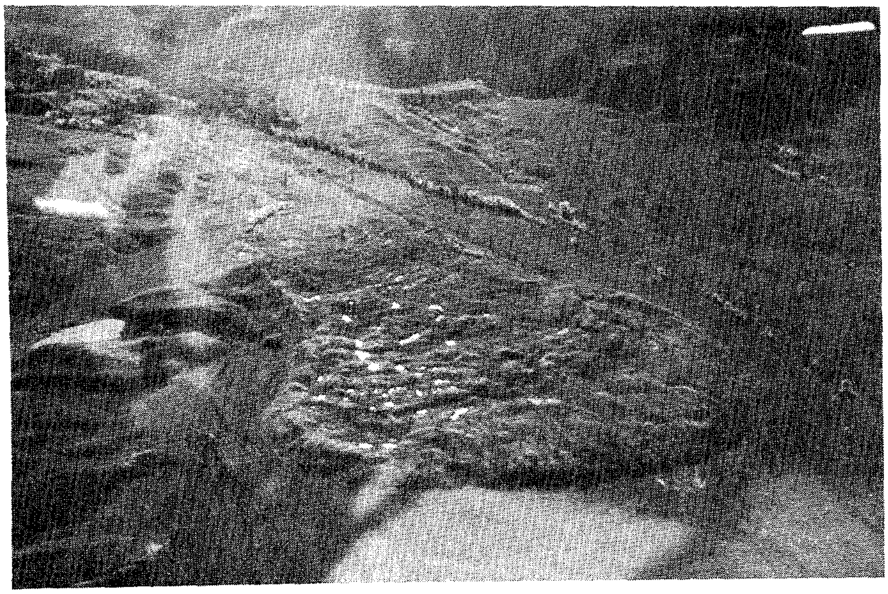


Figure 14. Evidence of Old Mudslide (photo by Stanley A. Schumm).

Thus, in the case of flowslides, even if the failure occurs at some distance, the danger to riverside construction is obvious. Flowslides may disrupt the roadway as shown in Figure 15 or they may contribute large sediment loads after stopping in or near a riverbed, as shown in Figure 16.

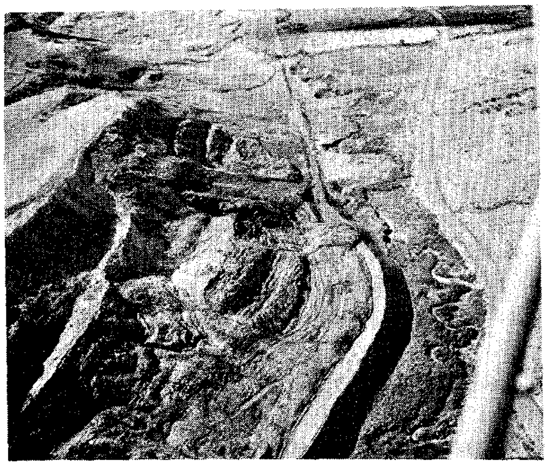


Figure 15. Disruption of Highway and Railroad Due to Mudflow (Varnes, D. J., U.S. Geological Survey).

D. Analysis of Slope Failures

The failure types that move as a block are generally analyzed by a limit equilibrium approach. In those approaches the forces tending to cause movement of the slope are compared to those available to resist movement in order to compute a factor of safety. For a given slope geometry and set of subsurface conditions, various failure surfaces are considered and the resisting and driving forces are analyzed. The surface with the lowest factor of safety is identified, and the corresponding factor of safety is considered to be the factor of safety for the slope.

Creep failure and flowslides are more complex to analyze. Observational techniques as shown in Figures 11 and 12 are often necessary to identify creep movement and potential failure. Nelson and Thompson (1977) discuss potential means of analyzing creep slope failures. Flowslide analyses are usually an empirical and judgmental combination of soil mechanics, geology and hydrology. Prediction of liquefaction of soil is difficult. Such movements often occur after another form of slope movement has loosened or disrupted the soil. Careful reconnaissance for previous slide evidence is often the only means of predicting future flowslides.

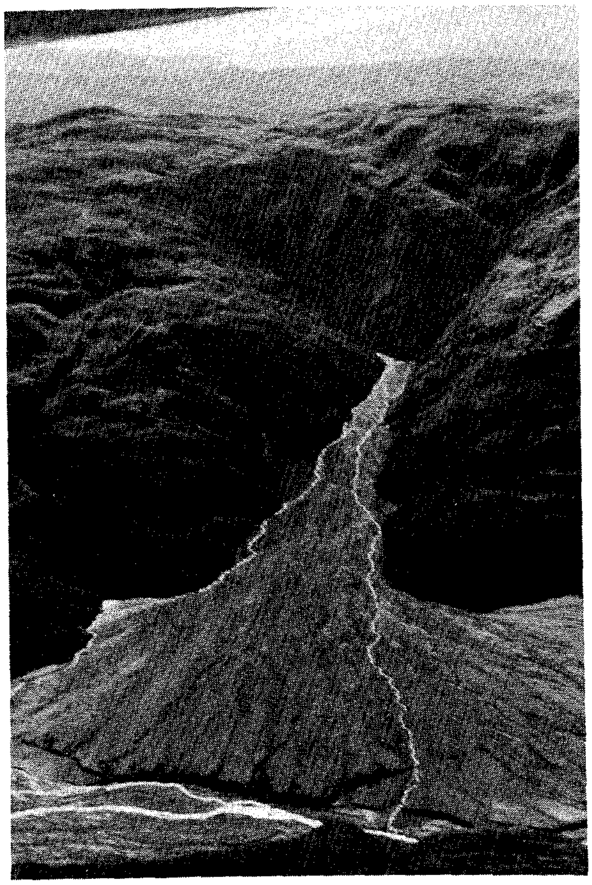


Figure 16. Alluvial Fan Contributing Sediment Load to Stream (photo by Stanley A. Schumm, Colorado State University).

III. ASSESSMENT OF BRIDGE HAZARDS FROM SLOPE AND BANK FAILURE

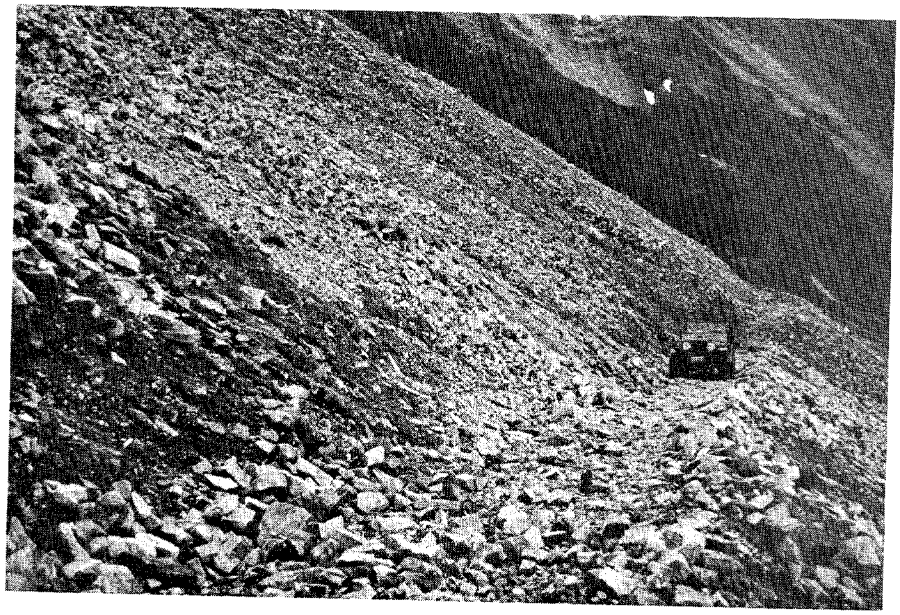
A. Factors Influencing Slope Stability

A variety of different factors will influence the stability of slopes along a river. These factors will also affect the nature and magnitude of changes in stability resulting from changes in conditions. Those factors that have been identified as having a major influence on stability will be discussed below with regard to the manner in which they relate to the mechanisms of failure that were previously discussed.

1. Soil type

In this context the term "soil" refers to the relatively uncemented or loose material overlying the bedrock. It comprises the alluvium in the bottom of valleys or canyons. Where residual soils exist, it would consist of the weathered soil overlying the sound rock. Figure 17 shows slopes in different soil types. The general geometry and nature of slope can be seen to differ considerably from one soil type to another.

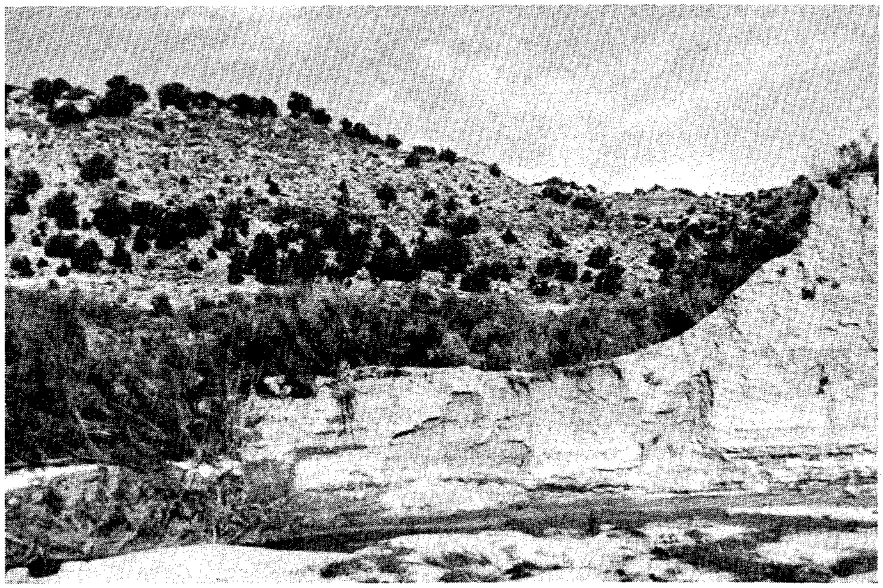
The soil property having the primary influence is the shear strength of the soil and its susceptibility to a decrease in strength due to changes in water content.



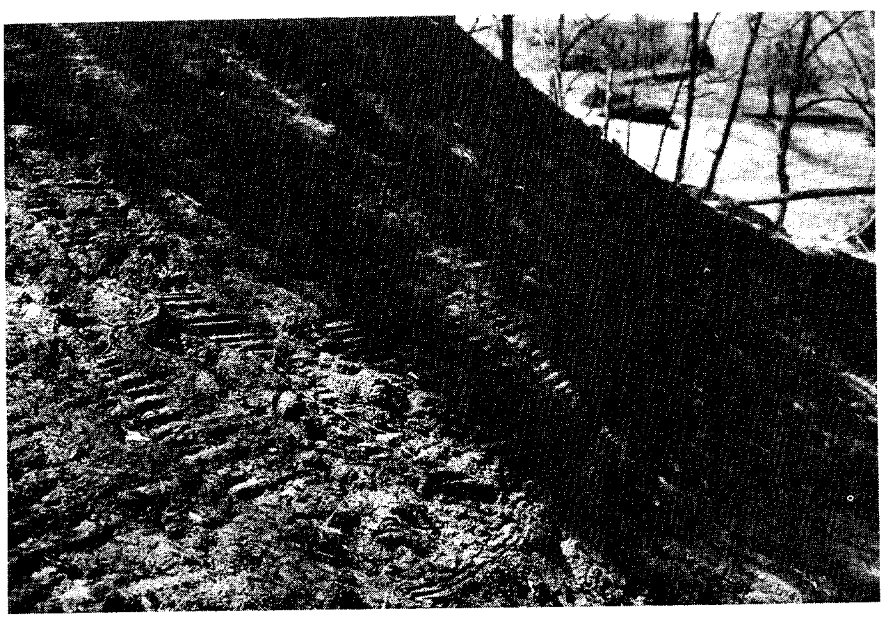
a. Rock Talus

b. Sand and Gravel

Figure 17. Slopes in Different Soil Types.



c. Silt and Clay



d. Clay

Figure 17 (continued)

In the first three mechanisms of failure (rotational, infinite slope and sliding along planar surfaces) the shear stress along the potential shear planes provides the resistance to movement. In a stable slope, the shear stresses that are required in order to prevent movement are less than the soil shear strength. However, due to changes in drainage patterns, land use or climatic factors, water may be introduced into the slope. If the increase in water content causes a sufficient decrease in shear strength the stability may be lowered to a point at which failure may occur.

In general, the shear strength of clays and clayey soils depends more on water content than does that of sands and gravels. As water content increases, interparticle forces in the clay decrease, the soil becomes less stiff, and the ultimate shear strength decreases considerably. On the other hand, the shear strength of saturated sand or gravel is nearly the same as that of the soil in a dry state. In cohesionless sands or gravels the presence of small amounts of water results in capillary tension between particles which can cause an increase in shear strength. The greater the clay content of a soil, the more susceptible it will be to changes in shear strength.

Seepage forces may be induced in a slope due to changes in drainage patterns or climate. This factor will be discussed in more detail at a later point. Also, as noted previously, lowering the phreatic line enhances stability.

The degree to which seepage influences stability will depend to some extent on the nature of the soil. Coarse grained soils are more permeable and pore water pressures will dissipate more rapidly than in fine-grained soils.

In fine-grained soils, silts will drain more freely than clays. However, in fine silts, soil particles may be carried by seepage water if the velocity is sufficiently high. If this occurs, erosion may take place from within the slopes. This phenomenon is termed "piping" because of its tendency to form tubular void spaces or "pipes" in the soil structure.

Clay soils generally exhibit greater amounts of creep than do cohesionless soils. In pure sand or gravel, creep is of little or no concern. Usually plastic clays exhibit a greater tendency toward creep movement than do less plastic clays.

The erodibility of a soil will also be related to soil type. This, in turn, will influence many of the other factors as well as the soil's susceptibility to bank caving or toe erosion. The general characteristics related to soil erodibility are primarily its grain size and plasticity. Coarse sand, gravel, cobbles and boulders decrease in erodibility in that order. For fine-grained soils, very fine sand and silt is more erodible than clay. Erosion of soil will be discussed in more detail at a later point.

In summary, coarse-grained granular soils may be expected to be more stable and less subject to decreases in stability due to creep, changes in environment, erosion or seepage effects. Fine sand and silt are more susceptible to erosion and seepage effects. Clay is more susceptible to changes in shear strength due to change in water content.

2. Bedrock type

Along the length of a river several different bedrock formations may be encountered. Depending on the geologic history of the area and the thickness and dip of the rock strata, different types of rock will be encountered at different locations. Figure 18a shows steeper slopes in more resistant metamorphic formations as compared to more gentle slopes in the marine sediment deposits of Figure 18b.

Rock formations will be continuously undergoing slope steepening near the toe due to erosion by the river. Also, as drainage patterns change, the shear strength of the rock will be subject to potential change. Clay minerals in the bedrock will undergo more rapid reduction in shear strength due to the introduction of water than will non-clay minerals in the bedrock. In addition, clay-shale bedrock will exhibit more creep and be more susceptible to progressive failure resulting therefrom. Consequently, marine formations that contain clay-shales will be more landslide-prone than will non-clay formations.

Resistant sandstone formations may exhibit greater long-term stability. However, weathering can break down cementing agents between particles.

Metamorphic and igneous rock formations have a fairly high resistance to weathering and exhibit a high degree of stability. Consequently, slopes in those areas will be steeper than in marine formations. That can also be seen in Figure 18. Thomson and Morgenstern (1977) investigated slope failures along the areas in which the bedrock was a marine formation, slope failures were much more numerous than in metamorphic or igneous formations.

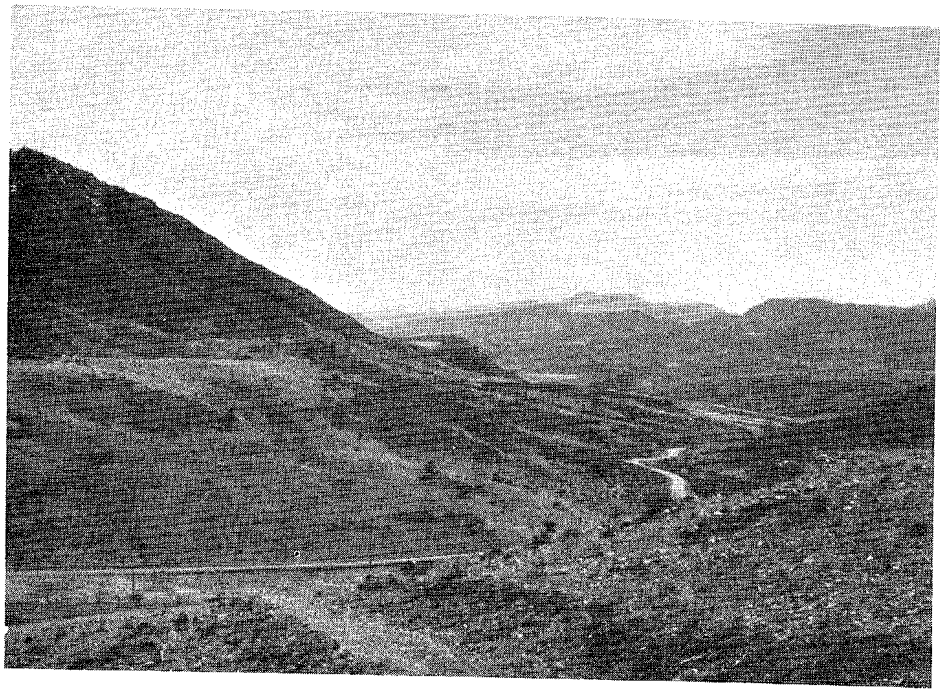
Thus areas in which the bedrock is a sedimentary formation will be more landslide-prone than will be areas where metamorphic or igneous formations comprise the bedrock.

3. Erosion of the toe

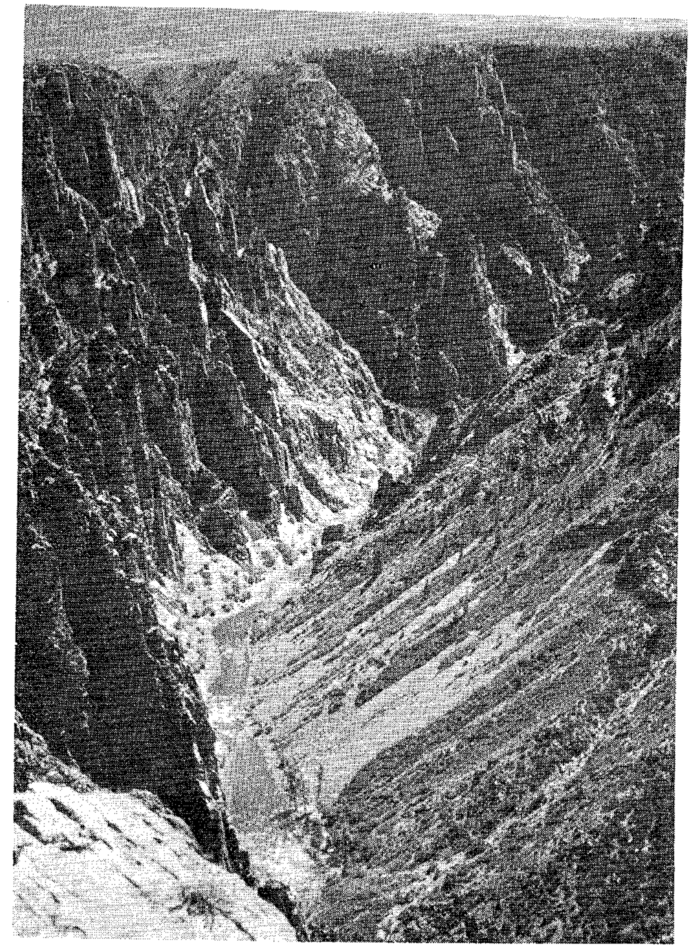
In their investigation of rivers in southwestern Alberta, Thomson and Morgenstern (1977) observed that toe erosion was responsible for approximately 90 percent of the landslides that were observed. The mechanism by which toe erosion contributes to landslide movement is evident from Figure 3. Removal of the soil at the toe reduces the shearing resistance and, because the slices at the toe lie to the left of the center of rotation, the removal of those slices increases the driving moment. The result is a decrease in the stability of the slope.

Figures 19, 20 and 21 show examples of slopes that are failing due to erosion of the toe. An escarpment denoting the top of a rotational type shear surface is indicated by arrows in Figure 20. In some cases continued removal of the failed material results in the occurrence of a series of slides and continued headward progression of the slide area. A series of such slides can be seen in Figure 25 presented at a later point.

Along a stream, the most critical point for toe erosion, and hence the area of greatest landslide activity, occurs immediately downstream from the point of maximum curvature at a meander or river bend. The slope failures shown in Figures 20 and 21 demonstrate this.



a. Marine Deposit



b. Metamorphic Formation

Figure 18. Slopes in Different Bedrock Types.

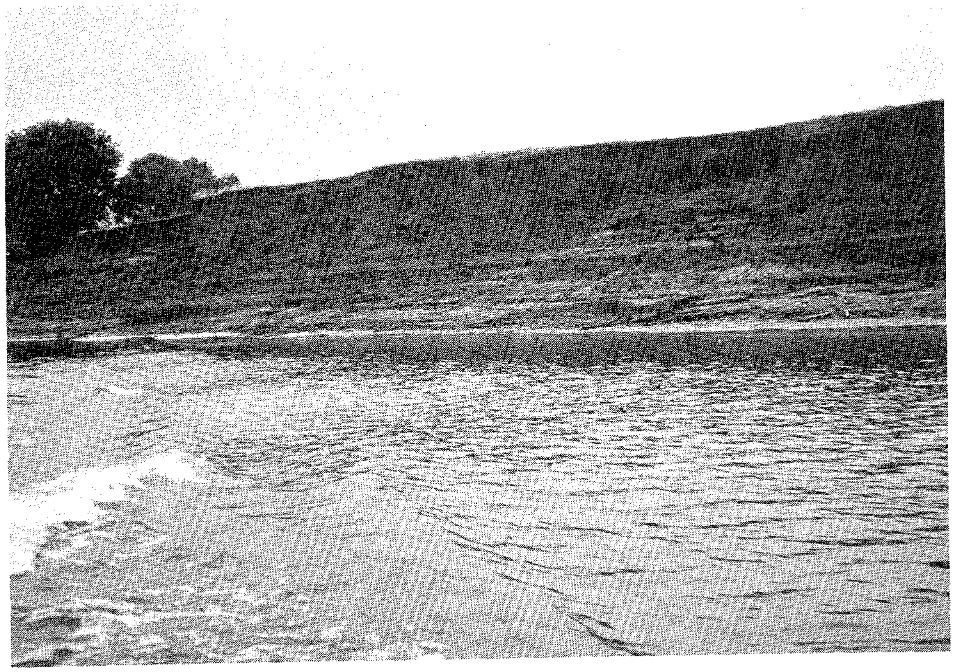


Figure 19. Toe Erosion Along River Bank Due to Wave Action.

Figure 20. Toe Erosion at Bend in Stream.

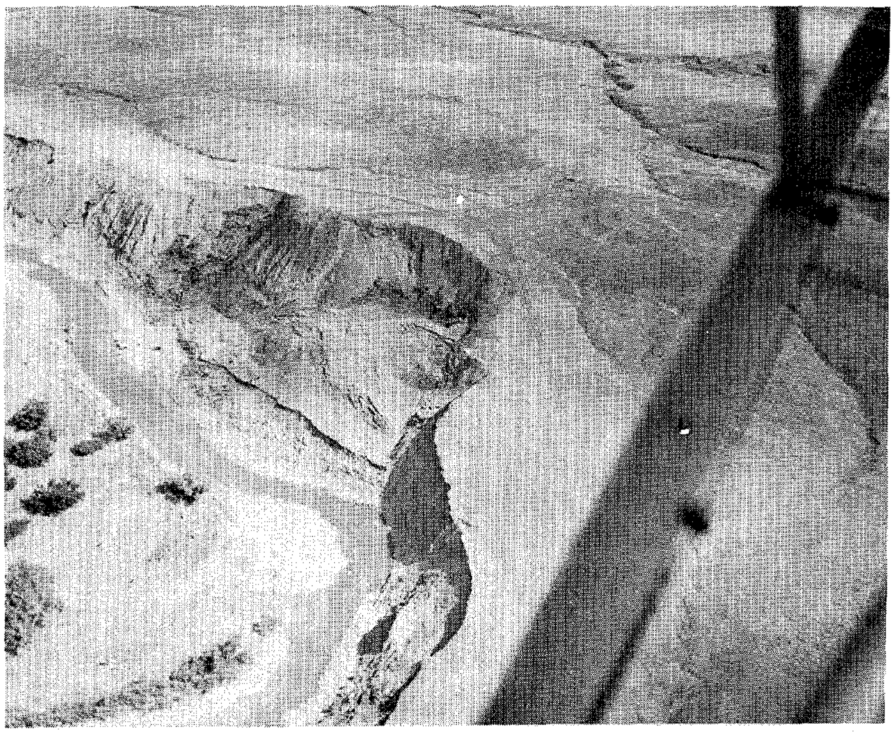


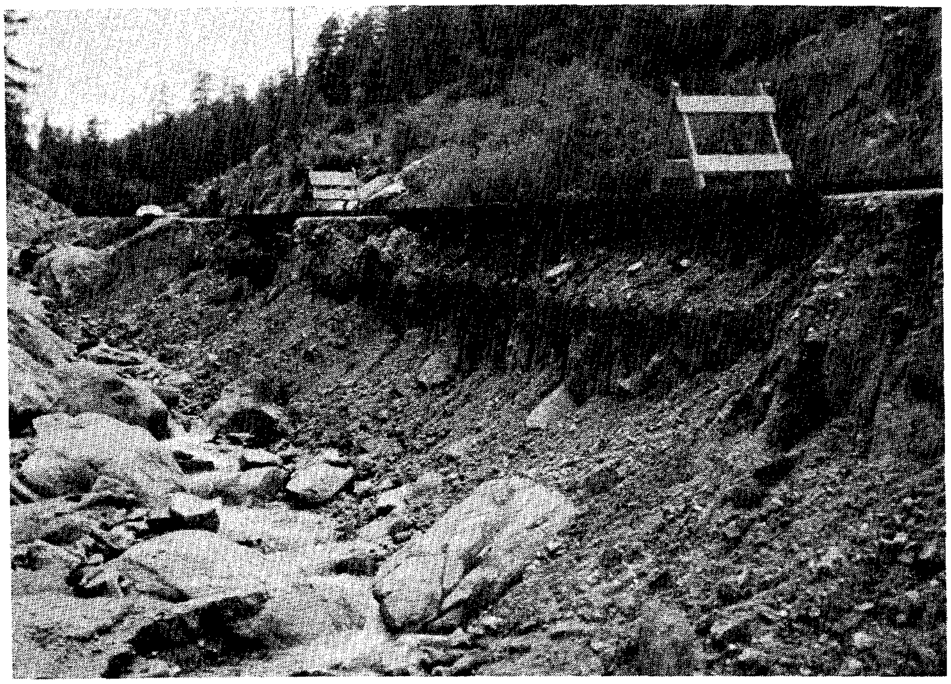
Figure 21. Shear Failure in Clay Shales
Caused by Toe Erosion.

Increased toe erosion and slope failure can also occur due to increased stream flow due to floods or changes in man's activity on the river. This is indicated in Figure 22. Erosion of terraces or debris fans can trigger a considerably large landslide that can progress headward for relatively large distances. Figure 23 shows severe toe erosion along a debris fan. Continued removal of the toe material and sloughing of the surface is causing progressive failure of the slope to occur. The small slide at the left of Figure 23 is one part of the progressive slope failure.

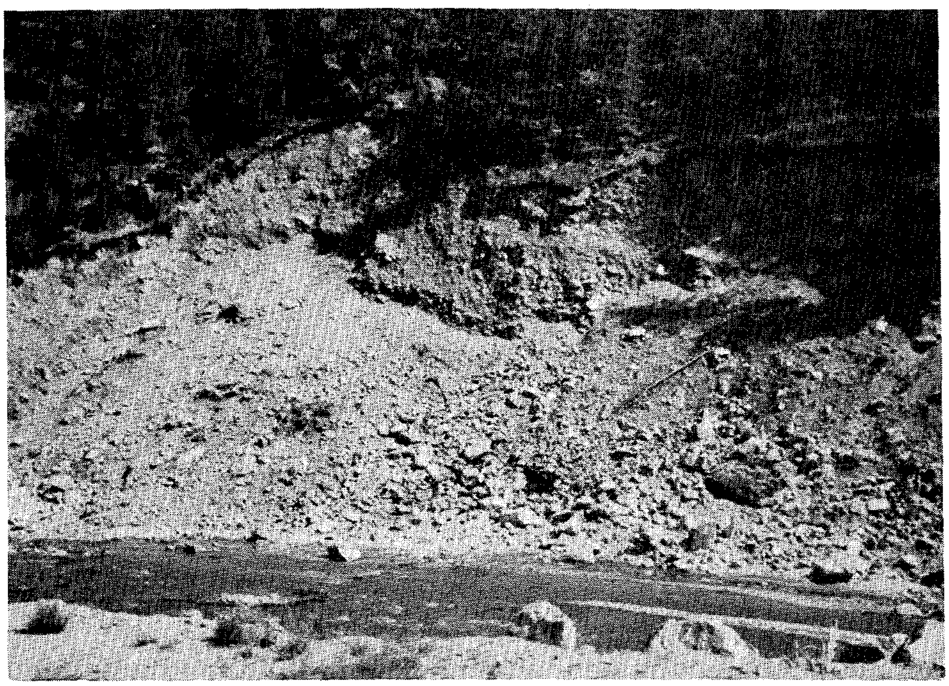
Flowslides may also be triggered by erosion of the toe. In deposits of soft clay having high sensitivity, the disturbance of a small area at the toe can cause liquefaction of that area, resulting in disturbance of the area further up the slope. As the disturbance progresses, a larger and larger area liquefies, resulting in a flow of an area that can be of considerable extent. Figure 24 shows a flowslide that occurred along a stream in Maine.

Areas particularly susceptible to such flowslides are those in which soft sensitive clays exist. Normally consolidated or underconsolidated marine clays generally exhibit high sensitivities, particularly if they have been subjected to leaching by fresh water. Such clays are commonly called "quick clays" and occur most frequently near coastal areas.

Toe erosion is relatively easily identified. Slope movement can sometimes be detected by the existence of escarpments or vegetation patterns on the slope, as shown in Figure 25. In some cases, tension cracks forming at the top of the slope also indicate slope movement. A discussion of the detection of potential instability is included at a later point.



a. Undercutting of Pavement Along North Fork Big Thompson River.



b. Slope Failure Near Glen Comfort.

Figure 22. Slope Failures Due to Increased Stream Flow During Big Thompson Flood.

Figure 23. Severe Toe Erosion Along Debris Fan.

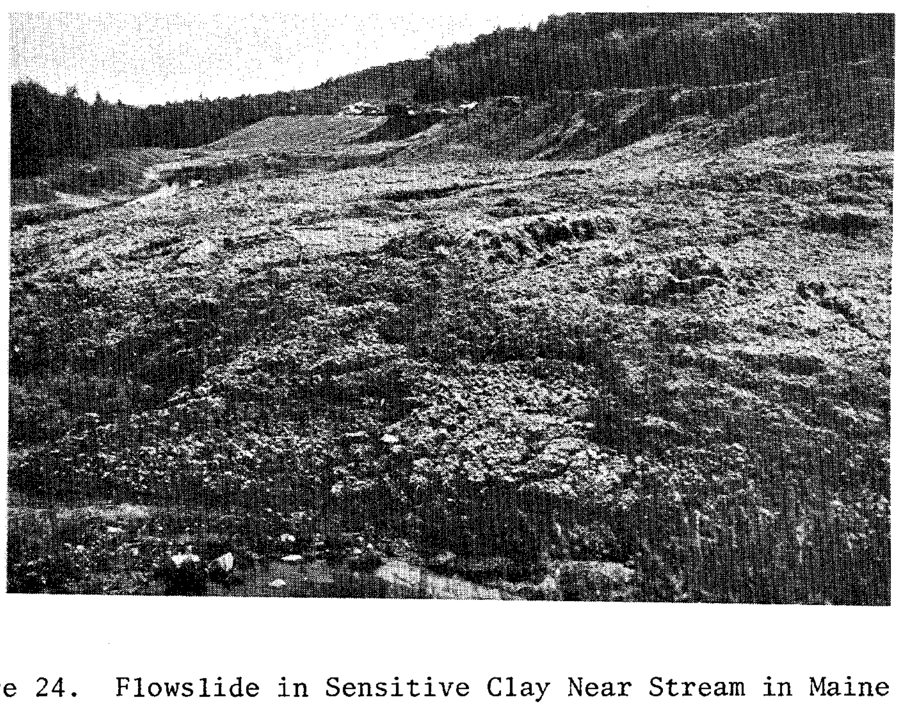


Figure 24. Flowslide in Sensitive Clay Near Stream in Maine (photo by R. E. Wardwell, University of Maine at Orono).

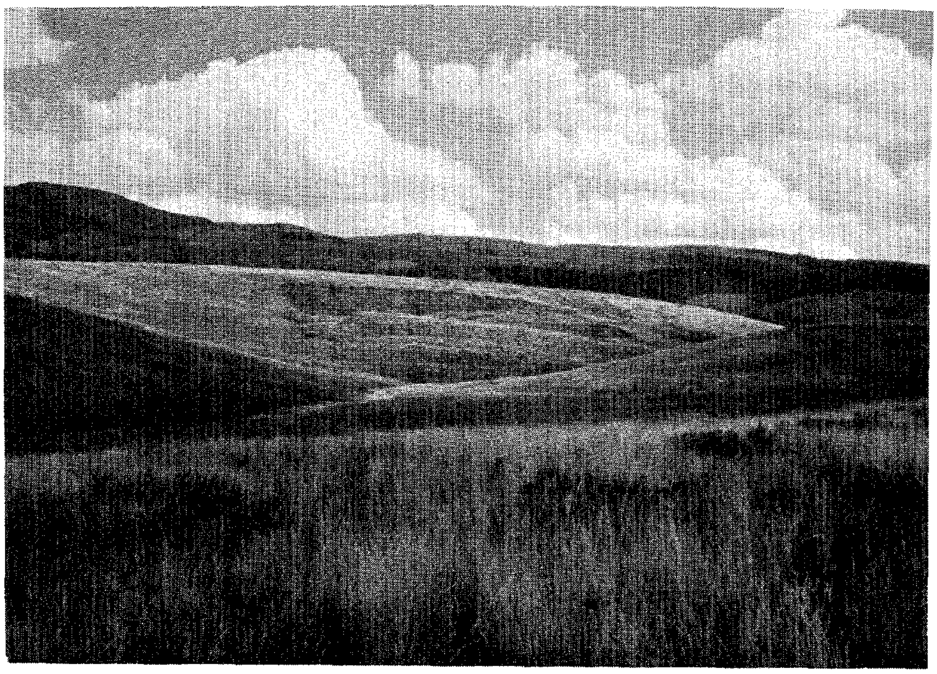


Figure 25a. Slope Movement Indicated by Visible Escarpment.

Figure 25b. Slope Movement Indicated by Vegetation in Old Escarpment Areas.

When toe erosion is causing slope movement, remedial measures may be of little value unless the erosion potential is checked. To do so, of course, requires either routing of water away from the slope or the placement of erosion-resistant material at the toe. If the erosion-resistant toe material is placed so as to serve as a buttress, it will also help to enhance the stability of the slide.

To determine whether toe erosion will endanger the stability of a slope or to design appropriate toe erosion protection, analysis by an appropriate limit equilibrium method may be necessary. These analyses require relatively accurate characterization of the slope and subsurface soil, rock and water conditions. That characterization should be done by an experienced, qualified geotechnical engineer. Soil boring, sampling and laboratory testing will be necessary to define the parameters necessary in the analysis. The geometry of the slope must be defined. In some cases, it may be necessary to install piezometers to determine pore water pressures and the location of the phreatic surface. The integration of all the measurements to define a reasonable model for analysis requires experience and should be done by an expert in the field. On the basis of the results of the analysis, decisions can be made regarding possible remedial measures. These will be discussed in more detail at a later point.

4. Drainage patterns and ground water level

In Figure 3 it can be seen that if the pore water pressure, and hence the term U, increases, the effective stress term, $\bar{N}$, will decrease. Because the shear strength of the soil, T, is directly related to $\bar{N}$, a decrease in $\bar{N}$ will lead to a decrease in factor of safety.

For two slopes that are similar in all other respects, the one with the higher ground water level or phreatic line will have the lower factor of safety against failure. Thus, if the phreatic line rises, the stability of a slope will decrease.

Another factor influenced by the groundwater level is the shear strength of the soil itself. In clays and clayey soils the shear strength will decrease with an increase in water content. Thus, the introduction of water into a slope can decrease stability due to either or both changes in pore pressures or changes in shear strength parameters.

Consequently, the drainage patterns on top of a slope can be very significant in terms of influencing slope stability at a site. Problematical situations can be created when irrigation ditches or reservoirs are established either directly on slopes or on the surface above a slope at locations where seepage would enter the slope.

Changes in land use may cause a change in ground water patterns. Development of an area for purposes that require irrigation may raise the ground water level and decrease stability. In dry climates, the introduction of irrigation may create perched water tables in slopes where no water table previously existed.

Thus, in evaluating a potential bridge site, the possibility of developing nearby areas for such applications as agriculture, golf courses, or even residential landscaping must be considered.

Other activities that may not involve irrigation but which may also introduce water into a slope must also be considered. Figure 26 shows a slide that occurred near DeBeque, Colorado, along the Colorado River. Water was introduced into the slope by the hanging valley evidenced by the stream above the slide. The slope movement was arrested by installation of drains and rerouting of the stream above the slide.

Another consideration would include the potential for paving the upper areas of a slope or in some other way redirecting drainage off the slope such that the stability is decreased. Frequently those potential changes in land use cannot be identified and become apparent only "after the fact." Early identification of those causes and subsequent measures to redirect water away from the slopes can do much to solve potential problems before they gain major proportions.

Identification of a rise in ground water level can only be definitely established by the installation of piezometers and the measurement of water pressures. Changes in land use as discussed above may indicate potential seepage problems. In natural slopes, vegetation patterns can also indicate drainage patterns that may not be conducive to slope stability. Figure 27 shows a natural slope on which trees are growing only on an isolated location on the slope. Examination of the patterns indicates that the area on which the trees exist is a moving slide. In Figure 25 escarpments are shown which create depressions on the surface that collect water. The water thus introduced into the slope will decrease the stability.

When conditions of potential instability arise as a result of high ground water, remedial measures would consist of either reducing the inflow of water or providing a drainage path for the water in the slope. Seepage into the slope can be minimized by sealing diversion ditches or reservoirs. Common sealing methods usually consist of lining the ditch or impoundment with impermeable soils such as bentonite, or placement of a synthetic liner. Regrading the surface to direct water away from the slope area is also possible.

Drainage of the slope can be accomplished by drilling horizontal drains into the slope or by pumping from wellpoints or wells. The installation of drains to function properly, however, is not a simple task. To be effective the drains must be of adequate length and inclination to intercept the ground water and be of sufficient size to be able to lower the phreatic surface. The spacing of drains will also be a critical factor.

The drain system should be designed by a competent geotechnical or ground water engineer experienced in that field. A significant number of slopes have had drains installed only to find that they were ineffective. However, if they are installed correctly and if they are, in fact, the correct solution to the problem, underdrain systems can be very effective in increasing the stability of slopes. They have been successfully used to stop slopes that are in the process of sliding.

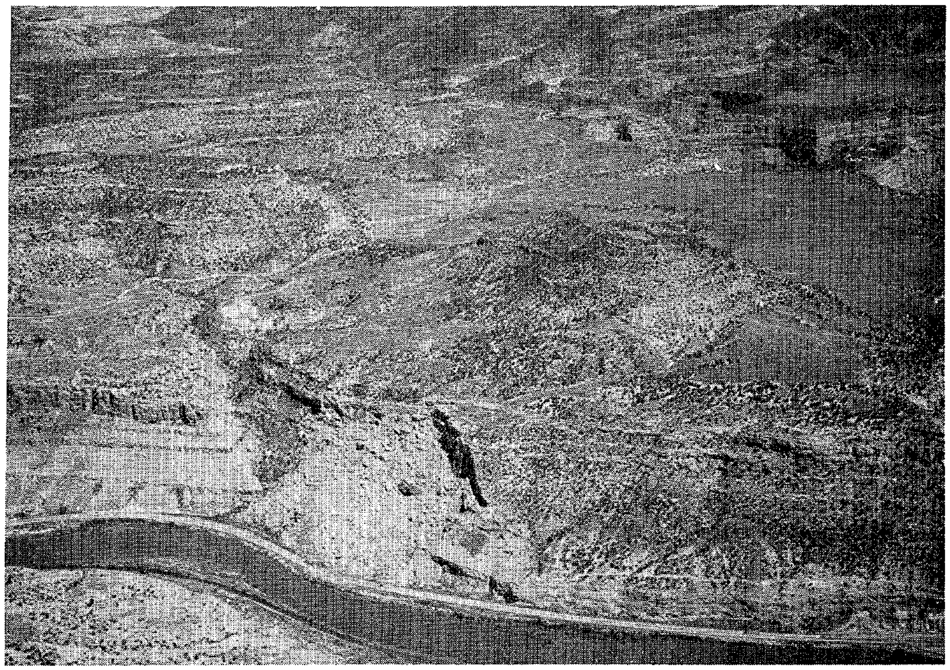


Figure 26. Slope Failure Caused by Water Introduced by Stream at Top of Slope (photo by Stanley A. Schumm, Colorado State University).

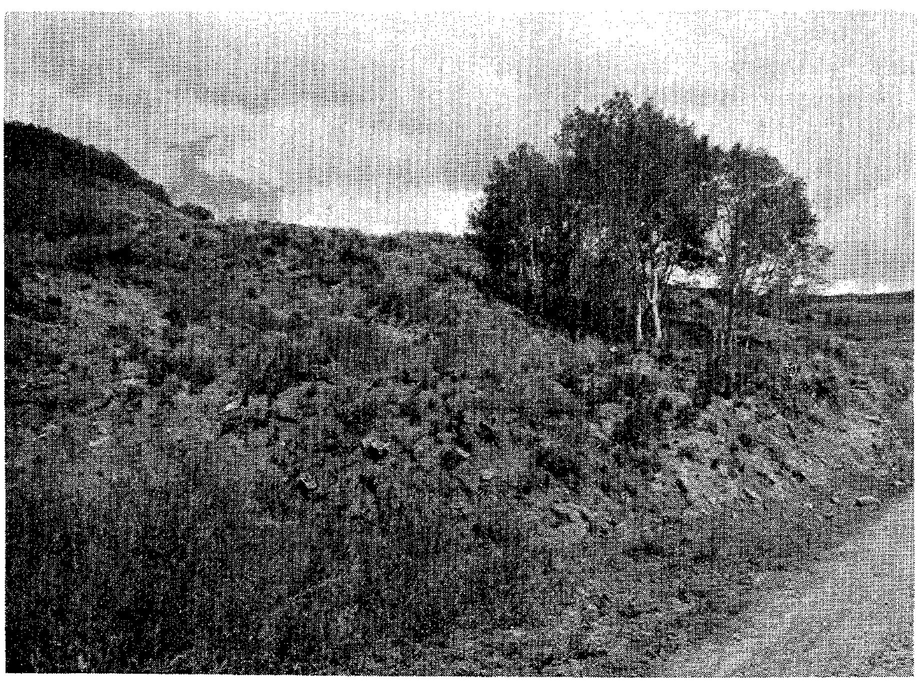


Figure 27. Trees Growing in Isolated Area Due to Drainage Patterns Contributing to Slope Failure.

5. Creep movement

Creep movement of slopes occurs as a result of shear stresses induced in the slope due to the weight of the soil or surface loads. Generally, creep strains are distributed throughout the soil mass but tend to be greater near potential failure surfaces where the stress level is closer to the critical state (shear strength). Continuing creep movements may cause misalignment of bridge piers and abutments. If the movements reach a critical state, accelerated creep can occur and progressive failure may result. The creep rate will, in general, be higher for stresses closer to the critical state.

Creep may be recognized in a slope by the presence of misalignment of features such as telephone poles or fence posts. Figure 28 shows a yard by a farmhouse constructed near the toe of a slide undergoing creep movement. The misalignment of the various features is evident. Also, bends in trees are rather definite indicators creep movement.

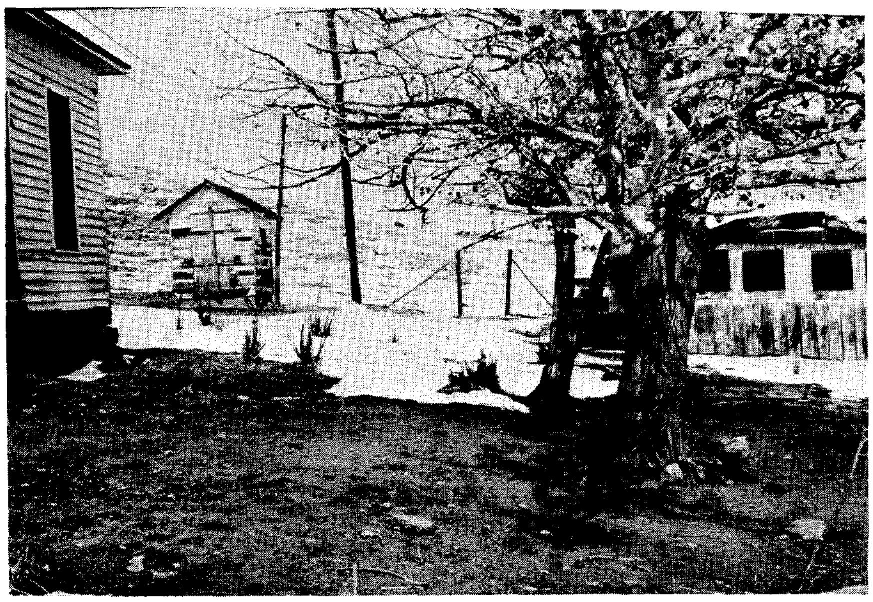


Figure 28. Misalignment of Telephone Poles and Fence Posts Due to Creep Movements (M. J. Kluth, 1976).

Another feature that may indicate continued creep movement of a slope is the appearance of a hummocky topography on the slope, as was shown previously in Figure 10. The hummocky surface results because of heterogeneity of the natural materials in the slope and nonuniform movement over long time periods.

To monitor creep movements, monuments may be constructed on the surface and surveyed on a periodic basis. Data of that nature were shown previously in Figure 11. Slope movement instrumentation is also available commerically that can determine displacement profiles at various locations in the slope. The latter has the advantage of also indicating zones of concentration of slope movements. This is helpful in identifying the overall mechanism of movement and is useful in assessing the potential for progressive failure.

The general nature of the solution for arresting creep movement consists of reducing the stresses in the slope everywhere to points lower than the critical state. Slopes may be excavated to reduce the stresses to a point where movement is not excessive. Unloading the top of the slope by excavation or removal of structures can also be done. Or the toe may be loaded by means of a berm or buttress to prevent movement.

Although a fairly good degree of success can be expected from the above solution methods, analysis of creep movements is complex. Determination of stress within a slope and comparison with residual shear strengths, however, provide a fairly reasonable assessment of the potential for creep failure (Nelson and Thompson, 1977).

6. Weathering

Weathering is the process by which the soil or rock properties of the slope will change due to the action of wind, frost, water, and chemicals in the environment. Materials particularly susceptible to weathering include clayshales, siltstones, and clays. Depending on the nature of the cementing agent, sandstones and cemented soils are less susceptible to effects of weathering. Metamorphic and igneous rocks, or sand, gravel, cobbles and boulders are generally relatively resistant to effects of weathering. However, significant changes can occur over long periods of time.

In Figure 18a slopes in metamorphic rock were shown. On the left side of the photo the slopes are very steep. On the right side weathering has flattened the slopes in the same rock. The weathering is greater on the right side due to the fact that the slopes are facing north and, therefore, retain more snow and moisture.

Weathering influences the stability of a slope by decreasing the shear strength of the soil. For a slope consisting of residual soil over rock, the effective depth of soil increases as the rock continues to weather. In an infinite slope (Figure 2) in cohesive soil, the factor of safety decreases as the depth of the failure surface increases. Thus, as weathering progresses downward, stability of the slope will decrease.

Alternatively, in sedimentary formations some strata are more resistant than others. Thus, if a less resistant stratum continues to weather, it can undermine a more resistant stratum above it. An example of this was shown previously in Figure 9. As weathering and removal of the weak stratum continues, the overlying stratum will eventually "topple."

Another mechanism of weathering is somewhat more indirect. Joints and fractures in rocks provide access to water which can contribute to oxidation or chemical changes. Also, water in the joints can freeze, forcing cracks to progressively open more. Failure can occur along those joints and fractures if the orientation of the planes is such as to promote movement.

Although weathering will progress more rapidly in more weakly cemented sedimentary formations, even relatively resistant formations are susceptible to weathering-induced slope failures. The identification of potential instability problems due to weathering consists primarily of identifying locations in which relatively rapid weathering is occurring. For example, if construction of a bridge would require excavation of the rock or soil, subsurface investigation should indicate whether or not the strata that will be exposed will undergo rapid weathering. Clayshales and weakly cemented sandstones are particularly vulnerable.

Observation of weathering patterns in formations at a potential bridge site by a competent geologist will indicate whether future weathering during the lifetime of a bridge would be expected to cause future instability problems. Also, if joints or fractures would be exposed by construction ("daylighted") or if drainage patterns would be altered to introduce water into joints and fissures, mitigating measures should be taken.

In the above situations the solution to the problem of potential instability by weathering lies in the protection of the soil and rock from water and wind. To retard weathering, slopes may be covered with concrete or cement compounds to prevent ingress of water. Such measures, however, also restrict drainage and may reduce stability due to a rise in the phreatic surface. Chemical stabilization may also be possible, but is not widely used.

Infinite slopes in residual soils will continue to weather and slide. In residual soils (soils that are formed by weathering of the underlying rock and are not transported from their point of formation), slopes are generally in a constant state of impending failure (DeMello, 1972). Mitigation of potential landslides involves either reducing the rate of weathering or designing slope changes to minimize the potential for failure. The former is difficult to accomplish in areas where weathering occurs so rapidly as to create the accumulation of residual soils. The latter would consist of flattening slopes or loading the toe to the point where even though weathering progresses, failure would not occur. Problems associated with that type of solution are that it is difficult to determine rates of weathering and shear strength changes for use as input to analyses. Observation of stable slopes in the surrounding area in similar materials will provide indications of general slope angles that can be expected to remain stable.

7. Land use patterns

Land use patterns influence slope stability insofar as they influence each of the previously discussed factors. Land use changes that change drainage patterns and groundwater levels were discussed previously. Figure 29 shows a slope failure that occurred as a result of construction of a mill tailings impoundment on the cliff above the slope. Failure was induced due to seepage from the impoundment. Industrialization and construction of structures at tops of slopes will load the slopes, thereby decreasing stability.

A pronounced influence on slope stability frequently arises from clear cutting of forested slopes along a stream. Initially the removal of shear forces caused by wind action on trees may result in a short-term increase in slope stability. However, the eventual decay of roots and an increase in soil water content due to elimination of evapotranspiration result in an overall decrease in stability.

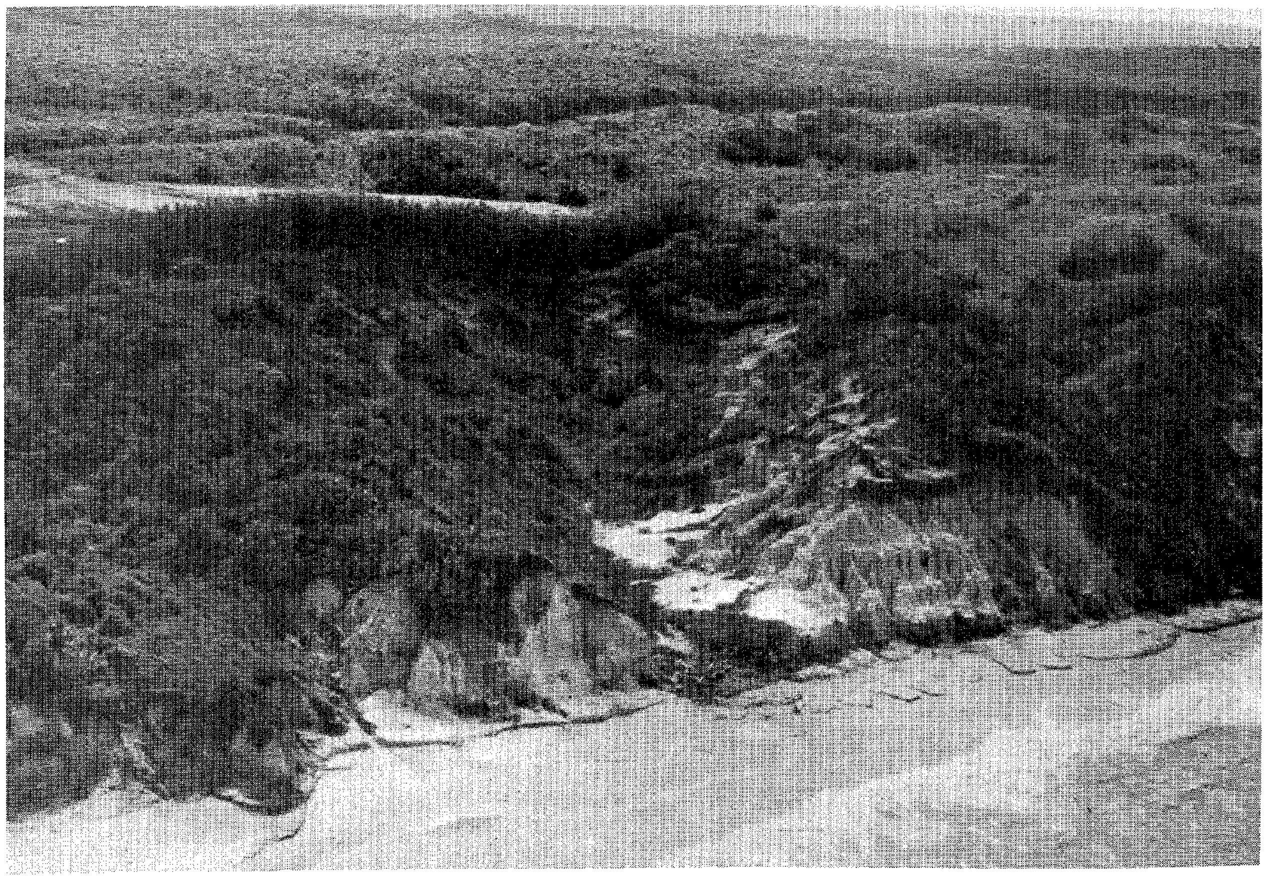


Figure 29. Slope Failure Induced by Seepage from Mill Tailings Impoundment (photo from A. Mac G. Robertson, Steffen, Robertson Kirsten and Assoc., Vancouver, B.C.).

Grazing of slopes may also decrease stability. Trampling of the ground cover by livestock and a decrease in grass cover will enhance erosion of the surface. Sediment yield to the stream will also increase.

Changes in stability due to land use changes are difficult to predict. Furthermore, once some changes in land use have been accomplished, the mitigating measures are not always simple. For example, once clear cutting has been accomplished, erosion control would be necessary. However, erosion control can introduce water into the slope causing deepseated failures. Appropriate remedial measures would be site-specific following the general discussion presented previously.

B. Soil and Rock Properties Affecting Bank Erosion

1. Mechanics of erosion

Erosion is the general transport of particles away from their location on the river bank. For erosion to occur, the soil particle must first be dislodged from the soil mass, and then it must be transported away from that location. In order to dislodge the particles, water must impinge on the soil surface, or the water must create shear stresses large enough to remove the particle from its surroundings. If the water is carrying sediment, sediment particles may impinge on the soil, dislodging it. In surface erosion that phenomenon is termed "Saltation."

In general, points of greatest erosion occur imediately below the bend in a river where the water impinges more directly on the river bank. The force required to change the velocity direction of the water dislodges the particles and the flow of the river then carries the sediment downstream.

Analyses of erosion generally relate some critical shear stress of the soil to the forces exerted by water (Rowlison and Martin, 1971). For granular soils in which interparticle forces consist only of interlocking between particles, erosivity is related primarily to grain size and shape. The larger the particles, the less erodible the soil will be. Also, the more angular the particles are, the greater the amount of particle interlocking that will occur and the lower the erosivity of the deposit would be. Grain size, however, is the dominant factor.

During extreme flows, boulders even tens of feet in size can be transported by water. However, under normal river flows boulders and cobbles down to several inches in size would be considered to be non-erodible.

Sands and gravels erode more easily. During periods of low flow or in rivers having low velocities, sand and gravel would not be transported under normal conditions. However, flow from even relatively small floods could cause erosion of those soils.

Silt is a very fine-grained granular soil that exhibits little or no cohesive strength. The division between silt and sand for purposes of soil classification is generally done at the No. 200 sieve size (74μ). This is approximately the limit of grain size that can be distinguished by the naked eye.

Silts are perhaps the most erodible of all soil groups. Because of the lack of interparticle forces, the particles are dislodged easily and because of their small grain size, they are easily transported. Although silts are differentiated from sands, there is obviously no distinct division of erodibility between the two soils at exactly the No. 200 sieve size. Fine sands may be as erodible as silts and the ease of erosion will decrease in a continuous manner from silt to sands as the grain size increases.

Clay particles are plate-shaped in contrast to the bulky shape of silts and sands. Clay particles consist of platelets about 10 Å to 100 Å* in thickness and about 10 to 100 times larger in lateral dimensions. The clay structure consists of many molecular layers arranged in sheets. The clay particle is similar to a miniature pad of paper with the pages glued together.

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*1 Å = 10^{-8} cm (Angstroms)

A particular characteristic of clay is the fact that the particles carry electrical charges due to charge deficiencies in the molecular structure. As a result, interparticle electrical forces govern the behavior of clays and give rise to the cohesive nature. The electrical forces, in turn, are influenced greatly by the chemistry of the pore fluid. The chemical composition of the pore fluid, therefore, may have a pronounced influence on the soil properties.

Because of the small particle size, individual clay particles may be dispersed in water and may be very easily transported. In fact, for some types of clays, individual particles may be subject to colloidal suspension and never settle out. However, because of the interparticle forces, individual clay particles may or may not be easily dislodged from the soil mass. In some cases the forces of aggregation between particles may be so large as to cause clay to be dislodged from the mass as aggregates, thereby increasing the effective grain size.

Some clays are easily dispersed and therefore are easily eroded. These clays are termed "dispersive" clays. In recent years several tests have been developed to identify dispersive clays, particularly with regard to erosion of embankments and embankment dams. It has been observed that clays that contain significant amounts of sodium either on the clay particles or in the pore fluids exhibit dispersive characteristics. Attempts have been made to relate the dispersivity of clay to the Atterberg limits, which are an indirect indication of the interparticle interaction and electrical forces. It has been observed that no correlation can be developed between the Atterberg limits and dispersivity. Instead, the controlling variable appears to be the sodium adsorption ratio and the exchangeable sodium percentage (Sherard, Dunnigan, and Decker, 1976). Clays having a high sodium content are more dispersive than clays having a low sodium content. Also, montmorillonitic clays exhibit a more dispersive nature than others.

Rarely do soils exist in nature solely as silts or clays. Usually soils will consist of a mixture of silt and clay. In those cases, as the percentage of silt increases, the erodibility of the soil will increase. If sufficient silt exists to decrease the plasticity of the clay sufficiently, the dispersivity or erodibility will increase. Sherard, Dunnigan and Decker (1976) observed that for silty clays with a plasticity index of less than about 10, the soils exhibited a dispersive nature.

On the other hand, if one considers a soil that is primarily silt, the presence of some clay will help to decrease its erosion potential. In sandy soils containing clay, the clay particles exist largely as coatings around the sand grains. Clays, therefore, have a less pronounced effect on the erosivity of sand than on silt.

Another form of erosion is a phenomenon termed "piping." Piping consists of underground erosion due to the introduction of water from the surface and lateral flow below the surface to a side slope or drainage feature in the landscape. Figure 30 shows a diagram depicting the mechanism by which piping occurs.

Figure 31 shows some drainage features on the surface of alluvium that appear to end abruptly at the point shown by the arrows. In actuality, the water in those drainage areas enters the ground surface and exists at the points indicated by the arrows with double heads. The erosion at the exit points is evident from the gullies

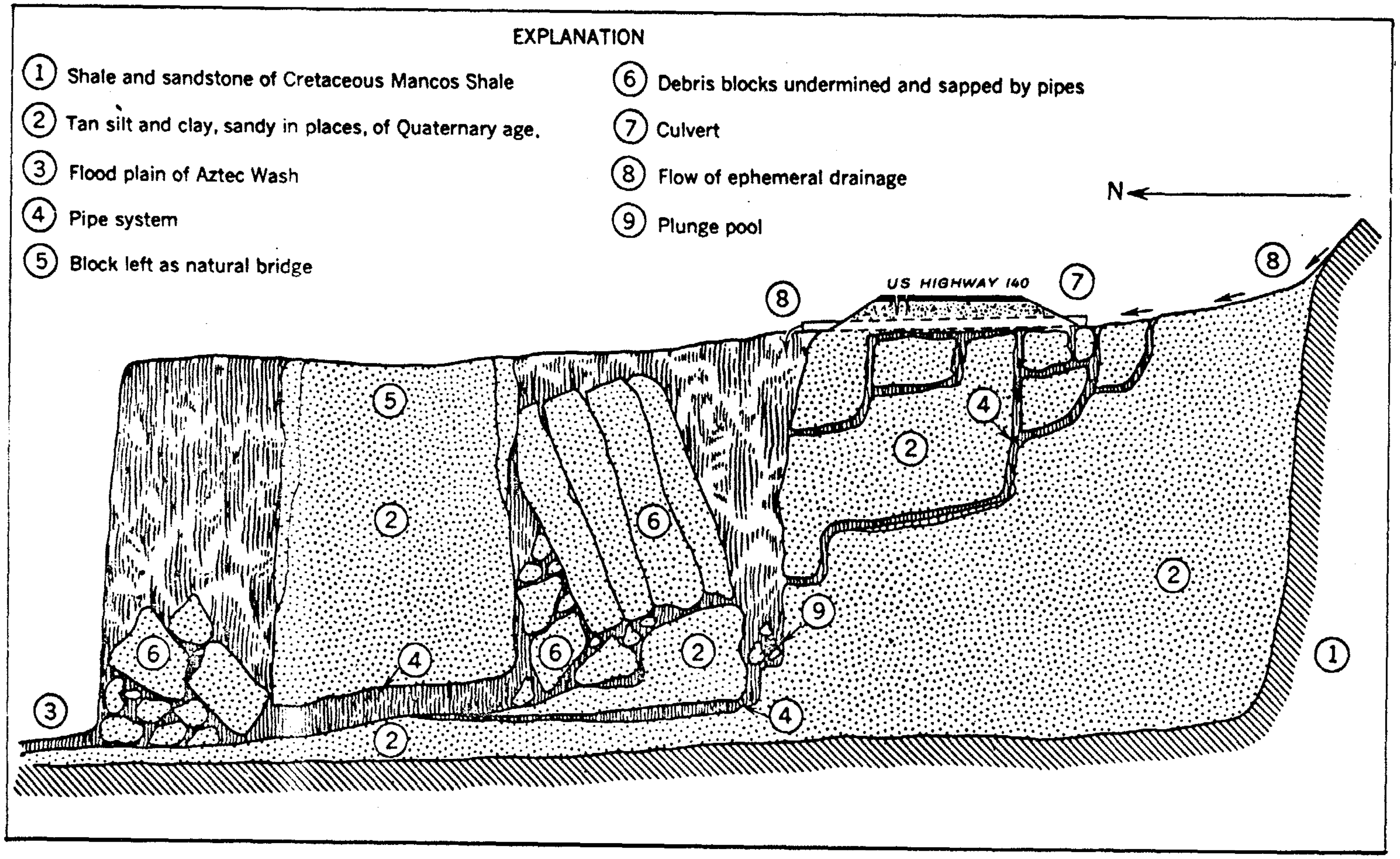

Figure 30. Idealized North-South Cross Section Under US 140 Built on Aztec Wash Valley Fill, 4-Corners Area of Southwestern Colorado. Note Incipient Piping System Beneath Roadway (from Parker and Jenne, 1967).

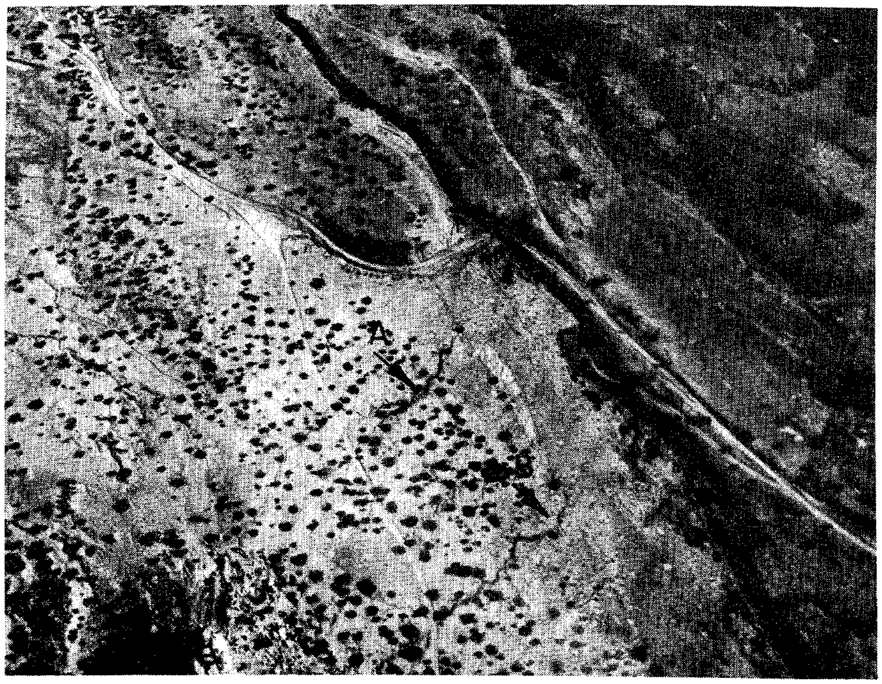

Figure 31. Evidence of Piping From Apparent Disappearance of Surface Drainage Features (Photo Compliments of Jay Lazarus, New Mexico Environmental Improvement Division).

being formed at those points. Figure 32 shows pipes of rather large size can be formed which, if they progress to the surface, can cause the development of large erosional features.

Piping occurs in arid or semiarid climates in dispersive soils. Its effect on slope stability is to cause a continual erosion of parts of the slope structure. As pipes are enlarged the soil above them will collapse, thereby leading to gully formation and bank erosion.

2. Classification of Soils and Rocks According to Erosion Potential

Little has been published with regard to classification of soils and rocks according to erosion potential. Yelverton (1969) presented a classification system of rocks in the southern California area in connection with erosion of slopes. That system was generalized and modified slightly to arrive at a classification of rocks as shown in Table 1.

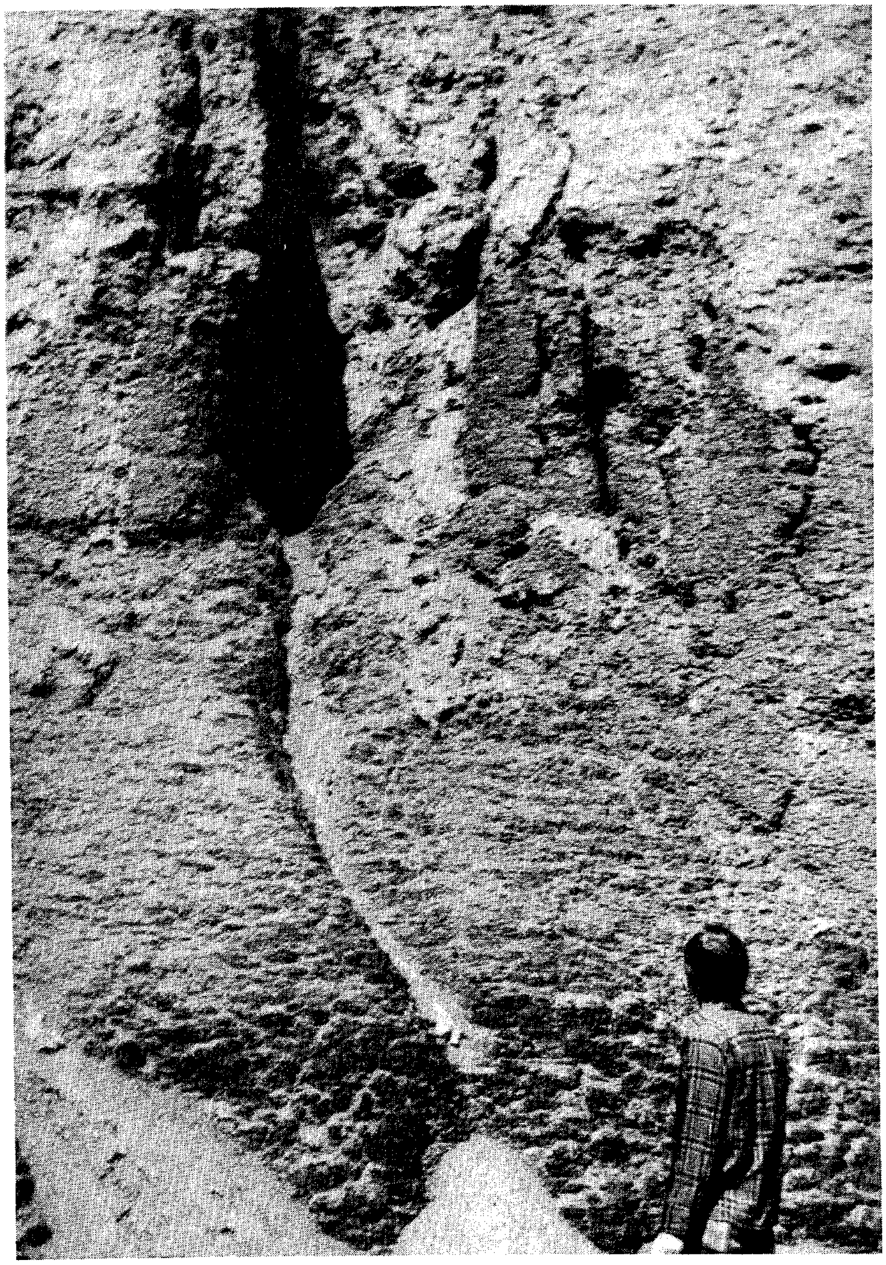

Figure 32. Pipe Formed in Loessial Deposits (Photo Compliments of Jay Lazarus, New Mexico Environmental Improvement Division).

Table 1. Rock Classification.*

Class		Physical Properties
Class RI	Non-erosive	Intrusive-extrusive rocks, crystalline, dense, usually hard and massive. Joints and fracture patterns are closely to widely spaced and the rocks are generally very resistant to weathering and erosion except in deep, wide, broken and brecciated shear zones. Metamorphic rocks which are hard and resistant to erosion but possess strong foliation and joint patterns.. Sedimentary rocks of this class are of wide range in age. Generally hard, massive, well-cemented, thickly to poorly stratified and very resistant to weathering and erosion. These rocks are usually fractured and jointed. Local shear and fault zones reflect a wide diversity of effects of granulation and gouge.
Class RII	Moderately erosive	Rocks of this class exhibit a wide diversity of type and basic composition. However, they are generally soft, poorly cemented, weathered to considerable depth or because of their composition subject to rapid weathering and decomposition. The rocks are predominantly siltstone and clay shale but include soft, friable sandstone phyllite, weathered basalt, granite and highly fractured metamorphic rocks.
CLASS RIII	Highly erosive	Poorly cemented to loose rocks subject to extensive rapid weathering. Soft, poorly cemented sandstones and siltstones. Montmorillonite clayshales and clay-shales with high sodium content.

*Modified from Yelverton (1969).

Class RI rocks are called "nonerosive" and include those rocks having high erosion resistance. Class RI rocks include granite, hard sandstone, quartzite, conglomerate, limestone, schist, slate, and unweathered basalt. Unweathered igneous, and metamorphic rocks would generally fall in this class.

Class RII rocks are moderately to highly erosive and are classified as "moderately erosive." They include poorly cemented sandstone, siltstone, shale, weathered basalt, and zones of closely fractured and sheared Class RI rock.

Class RIII rocks are termed "highly erosive" and are represented by unconsolidated, uncemented, soft friable rocks. This class includes soft siltstone, soft sandstone, some conglomerates, and some dispersive shale. Also included are highly sheared, granulated, and gouged zones in Class RI and RII rocks. Yelverton (1969) also included soils in Class RIII. However, soils will be considered as a separate entity herein.

Table 2 presents a classification system for soils that follows lines similar to those in Table 1. Class SI soils are those that could erode only during times of unusually high flows. These include riprap and large-sized talus. Class SII soils include those that do not erode during normal stream flows, but which can be transported during peak flow periods such as during spring runoff. These soils include the medium and coarse gravels. Class SIII soils comprise fine-grained soils that have some resistance to erosion by virtue of interparticle forces or cementation. These include primarily clay and cemented silt. Class SIV soils include the highly erosive soils such as silts and fine sands. Dispersive clays are also included in this class.

C. Evaluation of Stability of a Site

To evaluate the stability of a proposed bridge site the following questions must be addressed:

1. Are slopes at the site currently stable?

2. Will the proposed construction activity influence slope stability at the site?

3. Could potential future changes in land use or the environment decrease slope stability at the site?

4. If the site is currently unstable, what countermeasures can be implemented that would make the site suitable?

5. If the site is currently stable but construction or future activities will make the site unstable, what countermeasures are necessary?

Table 3 summarizes the evaluation of site stability. This table is intended to provide the basis for development of a site investigation program. Individual site charactersitics may indicate particular features or factors that must be considered in addition to those included in Table 3.

1. Current stability of slopes

a. <u>Short-term considerations</u>

Table 2. Soil Classification.

Class		Soil Description	Unified Classification System or AASHTO Classification Group
Class SI	Non-erosive	Cobbles and boulders of erosion-resistant material	------
Class SII	Moderately erosive	Medium to coarse sands and gravels	GP, GW, GM, GC SP, SW, SM, SC A-1, A-2
Class SIII	Easily erosive	Non-dispersive clays, very silty clay and sandy clay. Silts having some degree of cementation.	CH, CL A-6, A-7
Class SIV	Highly erosive	Fine sands and silts with little or no cementation. Dispersive clays with high sodium content.	ML, MH CL, CH SP, SW, SM, SC (fine-grained) A-3, A-4, A-5 (Some A-6 or A-7)

Table 3. Summary of Site Evaluation.

Observed Feature	Indicated Type and/or Cause of Failure	Severity of Failure	Information Needed for Analysis*	Method, Ease and Reliability of Solution
1. Changes in historic levels, elevations of structure or monuments.	Creep	Variable - slight if movement is slow.	Movement rates and amounts.	Load toe or flatten slopes. High probability of success.
2. Increased required maintenance of roads, pipelines, buildings, etc.	Any type or cause. Site-specific.	Depends on magnitude of slide. If movement is rapid, imminent progressive failure is indicated.	Cause of movement. Location of shear surface.	Depends on nature of slide.
3. Changes in channel alignment, aggradation or degradation.	Increased toe erosion may be indicated.	Site-specific. Generally is more severe for higher slopes.	General slope geometry and subsurface conditions. Extent of potential erosion.	Protection of toe. High probability of success if magnitude of required protection is not excessive.
4. Presence of escarpments.	Rotational or block failure.	Depends on magnitude of sliding mass and age of escarpment. Old revegetated escarpment indicates present stability.	General slope geometry and subsurface conditions.	Site-specific.
5. Scalloped topography (due to series of escarpments).	Rotational failure. Probable toe erosion causing successive failures.	Failure will progress headward. Severity depends on height of slope.	General subsurface conditions. Toe erosion and drainage conditions.	Site-specific. Depends on magnitude of failure.
6. Abrupt cross-slope changes in vegetation.	Old rotational failures. Changes in drainage patterns.	Generally low. Failure can be induced by changes in environment or construction.	Depends on potential changes or construction.	Site-specific.
7. Lobate, hummocky topography on slope.	Creep failure.	Low. Increases with rate of movement.	General material properties.	Site-specific. May load toe or flatten slope as necessary.

Table 3 (continued)

Observed Feature	Indicated Type and/or Cause of Failure	Severity of Failure	Information Needed for Analysis*	Method, Ease and Reliability of Solution
8. Isolated longitudinal areas bare of vegetation.	Avalanche, rock slide, mud flow.	Low. Failure of adjacent areas may be possible.	General subsurface profiles and material properties.	Avoid areas of potential large flows. Protect against falling debris.
9. Single age, young vegetation on slope.	Large past mass movement such as mud flow.	Low if slide is currently stable. Future movement may be induced by construction.	Material types, magnitude and origin of flow.	Avoid disturbance or excavation if sensitive soils.
10. Steep slopes of fresh bare soil or sparse vegetation.	Progressive failure of steep residual soils.	In proportion to height of slope.	General subsurface conditions.	Construction will induce failure. Each action requires countermeasures.
11. Bank scour.	Will induce rotational or block failure.	Depends on extent of scour and size of potential failure.	General soil properties.	Placement of riprap or protective structures. High probability of success.
12. Seepage on face.	High phreatic surface.	Low to high, depending on slope conditions.	Phreatic surface location. Soil profile and permeabilities.	Diversion of recharge water can provide high degree of success. Drainage of toe has variable success.
13. Swampy areas on slope or near toe.	High phreatic surface and poor drainage.	Low to high, depending on slope conditions.	Phreatic surface location. Soil profile and permeabilities.	Same as 12.
14. Formation of pipe in bank.	Piping erosion.	May affect large area back from bank.	Soil types. Source of water.	Change drainage above bank. Place filter material on bank surface. Degree of success is variable.
15. Abnormal termination of drainage features on surface.	Piping erosion.	Same as above.	Same as above.	Alter drainage patterns, place filter on slope or drain slope. Degree of success is variable.

Table 3 (continued)

Observed Feature	Indicated Type and/or Cause of Failure	Severity of Failure	Information Needed for Analysis*	Method, Ease and Reliability of Solution
16. Turbid seepage on face of slope.	Piping erosion.	May affect large area back from bank.	Soil types. Source of water.	Alter drainage patterns, place filter on slope or drain slope. Degree of success is variable.
17. Tension cracks parallel to slope.	Rotational or block failure. Potential infinite slope type of sliding.	Failure imminent. Severity depends on magnitude.	General slope conditions and subsurface profile.	Site-specific.
18. Tilted vertical features.	Creep	Low if movement is slow.	General material properties.	Flatten slope or load toe.
19. Curved tree trunks.	Creep.	Same as 18.	Same as 18.	Same as 18.
20. Misalignment of roads, fences or other linear features.	Indicates relative slope movement. Nature of slide is site-specific.	Depends on magnitude.	Cause of movement. General slope conditions.	Site-specific.
21. Open jointed rocks.	Potential rockfalls due to water, ice or weathering.	Site-specific.	Susceptibility of rock to weathering. Joint patterns, spacing and inclination.	Anchors, protect against falling rock, seal surface.
22. Fresh unweathered rocks on cliff faces.	Spalling due to weathering.	Generally low. Depends on magnitude of potential failure.	Same as above.	Protect against falling rock. Seal surface to decrease weathering.
23. Land use changes.				
a. Construction	Site-specific	Generally low if potential failure is recognized and corrected. Large slides can be induced.	General slope conditions.	Countermeasures against construction. Generally, changes in slope geometry are effective.

Table 3 (continued)

Observed Feature	Indicated Type and/or Cause of Failure	Severity of Failure	Information Needed for Analysis*	Method, Ease and Reliability of Solution
b. Irrigation or changes in drainage patterns.	Raise phreatic surface.	Can induce large slope failures.	Subsurface conditions and permeabilities.	Revision of drainage patterns can be successful. Installation of drains has variable success.
c. Reservoir backwater.	Raise phreatic surface.	Can induce large failures.	Subsurface conditions and permeabilities.	Sealing reservoirs can be successful. Installation of drains has variable success.
d. Clear cutting or overgrazing.	Surface erosion and sloughing (infinite slope)	Depends on magnitude of potential slide. Can also cause continued sliding of small areas.	Depth and type of soil cover.	Protect slope against erosion.

*Slope geometry and material properties will generally be required.

Evidence of past or present slope movement is a primary factor to be used to indicate potential instability. At the time of movement of an old slide, the Factor of Safety against sliding was unity. Therefore, such locations should be considered to be potentially unstable and capable of failure due to even small disturbing factors.

Past movement of a slope may be indicated by one or more of several factors. The existence of an old escarpment rather definitely indicates a previous slide. In some cases, escarpments are easily identified such as shown on Figure 25a. In other cases, however, the escarpment may be old, it may be obscured by construction or vegetation, and it may be difficult to identify.

The ease of identification of escarpments depends on the degree of obscurity. For the scarps shown previously in Figure 25a, there is little or no difficulty in identification. In Figure 20 a scarp is shown but is is not as evident as that in Figure 25a. However, the vegetation patterns shown in Figure 25b indicate depressions in which relatively high water contents exist. The shape of these depressions are suggestive of scarps. The fact that an old landslide exists is confirmed by the general profile of the slope and the existence of landslide-prone areas adjacent to it.

Another feature that provides fairly definite indication of slide movement is the existence of cracks at the top of the slope. Such cracks are formed by tension zones created by movement of the slide mass. Precipitation or drainage water entering the cracks will decrease stability and increase slope movement.

Upward or outward movement of features on the toe is also indicative of slope movement. If cracks appear in structures located near the toe, slope movement may be responsible.

If actual movement is not evident, the existence of factors that may aggravate stability may indicate the need for some concern. For example, the existence of springs and seeps on the face of a slope are evidence of a high groundwater level. The potential for the ground water to fluctuate must be evaluated with regard to the extent to which it may influence stability.

Also, recent construction activity or land use changes should be considered, insofar as they may decrease potential stability in the near future.

Finally, toe erosion may indicate future potential instability problems even in currently stable slopes. Toe erosion is the single greatest factor causing slope failure along rivers (Morgenstern and Thomson, 1977). Toe erosion at a particular site is relatively easy to identify by visual inspection of the site. The potential for changes in the river location to initiate erosion at a site must be considered. An example would be the initiation of erosion due to upstream meander cutoff.

Another form of erosion is piping. Piping was discussed previously. The observation of piping may or may not be difficult. Generally, piping is of most concern in fine-grained soils having low cohesion. If pipes can be seen in river banks, the existence of piping is evident. However, pipes themselves may not be readily apparent. Features such as shown in Figure 31 in which surface drainage features appear to disappear into the ground may be suggestive of piping. Also, the collapse of soil in blocks above old pipes may indicate piping even if the pipes themselves have been obscured. Piping is of most concern in alluvial or aeolian materials. Although it generally does not induce failure of large slides, it can influence the river bank for large distances back from the river. It can cause particular problems at bridge abutments if the piping undermines the foundation supports.

In connection with large slides, the above features may not be evident from ground surveys, but often can be readily seen from aerial photographs. Aerial photographs provide the ability to observe differences in topography and vegetation on a much large scale than ground surveys would.

Infrared aerial photographs can also be used to indicate slope movement. Differences in vegetation that are not apparent in the visual spectrum often show up in the infrared reflectance of vegetation. These differences may be the result of differences in soil moisture due to drainage patterns. Alternatively, at points where the shear plane is sufficiently shallow to intercept plant and tree roots, the stress in the roots caused by slope movement will influence the infrared response of the plants. Such differences in vegetation, however, are not, in themselves, indicative of slope movements. They must be used together with other factors.

b. Long-term stability

Although slowly progressing creep movement may or may not be indicative of an incipient sudden massive failure, creep movements may accelerate in the future to a point where relatively rapid movement of full-scale failure does occur. Even if sudden failure did not occur, the continual movement of the slope may result in misalignment of the bridge abutments, loss of support, or excessive maintenance costs.

Features indicative of creep movement are the misalignment of vertical features such as telephone poles or structures. Also, trees growing on a moving slope will attempt to realign themselves vertically with the result that the trunks will curve upward. Creep movement may also be observed by the presence of a hummocky topography. This topography results from unevenly distributed movement at different points in the slope.

Infrared photography employing precise color slicing techniques has been used to indicate the onset of potential long-term movement of slopes (McKean, 1976). Those techniques are currently in the early stages of development but do indicate the usefulness of remote sensing methods in assessing very long-term slope stability.

2. Effects of construction activity

It has been noted previously that reduction of slope stability may result from unloading the toe of the slope, loading the top of the slope, or the introduction of water into the slope. Construction activities that would produce such effects will decrease the factor of safety against slope movement. It is not intended to imply that any construction effort will cause failure, but if such effort is proposed, the slope must be analyzed to determine if the resulting factor of safety is adequate.

In hilly terrain, it is not uncommon for the rotation of a sliding mass to form a relatively level area on the slide mass directly below the escarpment. That level area provides an inviting area for construction of buildings, bridge supports or other construction activity. However, even relatively low loads placed thereon can induce failure unless countermeasures are employed. If the slide is of relatively large extent, it may be difficult to identify that such level areas are part of a slope failure. Aerial photographs are particularly useful in that regard.

On the other hand, large slides or flow slides frequently result in formation of a pronounced "hill" at the toe. If proposed construction activity requires sufficient excavation of the toe, the old slide may be reactivated. Reactivation of the slide may also occur if excavation causes an old sliding plane or a stratum of particularly weak material to daylight.

Another factor that must be protected against is the exposure to wind and water of strata containing easily weathered materials. If excavation were to expose a clay shale or poorly cemented sandstone stratum, weathering of that stratum could undermine the upper slope. Such strata should be identified prior to construction during the subsurface investigation. Design provisions should include protection of the strata by placement of concrete slabs, other sturctures, or vegetation to minimize weathering.

Construction of suspension-type bridges on the tops of slopes creates outward and downward forces on the top of the slope that tend to reduce stability considerably. Those bridges generally require fairly solid rock abutments where slope stability is not a major problem.

To generalize about construction activities that will induce slope instability is difficult. Each site or construction activity is unique and must be treated individually. The general principles outlined in the preceding report provide guidelines for assessing the general nature of slope stability as influenced by construction activities.

3. Effects of land use changes

In assessing the stability of a site it is necessary to also consider environmental changes that may occur in the future that could influence stability. The most pronounced environmental effect would come from changes in land use. Logging operations that may denude slopes can result in instability. Agricultural activities involving irrigation or grazing of slopes may decrease stability. Urbanization may change drainage patterns. These factors have all beeen discussed previously with regard to the manner in which they influence the various mechanisms.

The primary problem in assessing these effects is in anticipating land use changes. Land use predictions are discussed elsewhere in this report.

Considerations of sites must also take into account the stability of slopes upstream and downstream of the site. If the site is in a landslide-prone area, slope failures upstream from the site may increase the sediment load or potential for debris to be carried to the bridge site. In areas that exhibit present instability it may be expected that landslides will continue to occur and be accentuated during flood periods.

Downstream reaches of a river will have a less pronounced effect on the site except to the extent that slope failures could affect backwater at the site. It is doubtful that either upstream or downstream conditions would have an influence sufficiently significant to preclude establishment of a bridge at a particular site. However, slope instability at all locations would relate to the hazards discussed in the main body of this report.

4. Mitigating measures

If a site is determined to be presently unstable, the questions becomes one of determining what can be done to stabilize the slide area under present and anticipated future uses. If a site is currently stable but is is determined that future anticipated construction would reduce the factor of safety below tolerable levels, it is necessary to ascertain what changes in proposed construction would result in tolerable factors of safety. Alternatively countermeasures may be implemented that would counteract the effects of the construction.

Prior to design of remedial measures for any of the above cases, a site investigation and analysis are required to determine the cause of slope movement and to provide data for use in the design of remedial measures. The site investigation may consist of a preliminary observation of the slope indicating movements and seepage patterns. If the instability is not complex, an experienced engineer may be able to provide adequate recommendations from those observations. However, for larger slopes and more complex failures, it may be necessary to determine the material properties from subsurface exploration and to map the surface exploration and to map the surface profile. If seepage is indicated, piezometers may need to be installed to measure water pressures. The degree of investigation will depend on site-specific factors and must be determined by the project engineer.

If creep movement is indicated, investigation should be conducted to determine, insofar as possible, the rate of movement and the magnitude of the mass that is moving. Monuments may be erected on the surface of the slope and surveying would then monitor rates of movement. Also, instrumentation is commercially available that will monitor movements with depth in drill holes. Such instrumentation would indicate time rate of movement by periodic readings and will also indicate depth of movement and the mass of soil involved.

Methods of analysis would follow one of several which may be appropriate for the particular situation. Because mathematical analyses of slopes vary in the assumptions involved and therefore vary in applicability, the selection of an appropriate method of analysis must be done by a competent and experienced engineer. The sophistication of the analysis that is required would depend on the complexity of the slide and the ability to define the geometry and material parameters. The use of sophisticated analyses cannot be justified if only estimates of material properties are available.

Remedial action to enhance stability generally consists of one or a combination of three factors. These are;

1) Increase the load at the toe of the slide.
2) Unload the top of the slide.
3) Dewater the sliding mass or lower the phreatic surface.

The first two would be accomplished by construction works to alter the geometry. In areas where major structures exist at the toe of the slope, stability has been enhanced by excavation to flatten the slope. This was done, for instance, at the Fort Peck Dam spillway on the Missouri River. In other cases where it has been undesirable to excavate the top of the slide, a buttress has been placed at the toe. The buttress at the toe can consist of a variety of schemes ranging from coarse rock that is dumped at the toe to engineered structures incorporating some function of the project such as a highway embankment (e.g. Munõz, 1974).

If water is present or could be introduced into the slope, the toe structure must be very permeable and free-draining. If the construction at the toe were to block drainage, the potential rise in water surface would decrease stability and could negate the benefits derived from loading the toe. Also, the material used for the buttress must be sound material that will not degrade. For example, broken clayshale may provide a free-draining toe initially. However, clayshale is susceptible to weathering, and the action of precipitation or stream water may cause the shale to disintegrate. The toe would become relatively impermeable, resulting in a rise in the phreatic surface.

Toe protection should be placed to protect against erosion as well as to load the toe. The material to be placed may consist of rocks, boulders, gabions or commerical riprap. Retaining walls of concrete or timber may be used, but care must be taken to ensure that drainage patterns are not disrupted.

If the toe erosion is the result of piping from within the slope, remedial measures would follow similar lines. Coarse material may be placed on the slope, or retaining structures may be implemented. It is very important that the material that is placed have a grain size distribution compatible with the bank material such that it will not permit fine material from the bank or slope from being washed out. That can be accomplished by specifying a grain size distribution for the material to be placed, such that it is compatible with filter criteria for the grain size distribution of the material in the bank. Filter criteria are outlined in many textbooks on soil mechanics or seepage (see for example Cedergren, 1977).

Piping has also been resisted successfully by placement of steel or timber structures around bridge abutments. Such structures also help to route drainage from around abutments or areas in which piping erosion would be a problem.

If the instability is the result of water decreasing the shear strength of the soil or the phreatic surface being too high, the solution may lie in dewatering the slope. If the source of water is from a recharge area above the slope, it may be possible to merely divert the water away from the slide area. If the source of water is large, such as a reservoir or river, diversion of water away from the slope may be more difficult than relocating the bridge. Liners can be installed on the bottom of reservoirs, but it must be recognized that all liners will leak to some extent. To achieve a total seal is almost impossible. Nevertheless, if its quantity of expected leakage will not significantly affect stability, then such measures may provide a solution.

If the source of water on the slope is small, such as a canal or a topographical drainage feature, regrading or sealing may be possible. Alternatively, the canal may be relocated or drainage areas may be regraded.

If the source of water to the slope cannot be eliminated, it may be possible to remove water from within the slope. Pumping from wells or well-points at the top or on the slope can be employed to effect a short-term solution. However, the need for continued maintenance of well-point systems renders their use too expensive for long-term solutions.

In many cases the installation of horizontal drains near the toe of the slope has been used to enhance stability. However, the design of such drainage systems must be done by a competent, experienced engineer. The drains must be spaced closely enough to provide adequate lowering of the phreatic surface across the slide area. They must extend far enough into the slope to intercept a significant portion of the ground water. Finally, the drain material must be designed to remain open and hence not be rendered ineffective due to plugging by fine material. For stream banks, damage or sediment blockage of the outlet in flood stages must also be considered.

A toe drain may also be placed transverse to the direction of the slide. If the location of the phreatic surface is such that this type of drain would be effective, it can be accomplished by trenching and filling with free-draining material. Again, the drain material should meet filter criteria. Also, construction should progress in stages to avoid slope failure due to excavation of the toe by the trench.

5. Summary of site evaluation

The general evaluation of a site is summarized in Table 3. The characterization of a slope failure according to this table, however, is very general. It must be recognized that each situation will be unique and must be evaluated individually. Also, the general nature of the solution will vary from site to site depending on site-specific considerations and ease of implementation.

Table 3 must be recognized to be only a summary and should not be implemented indiscriminately. The features noted therein indicate potential slope instability, past slope movements and ongoing river instability. These features are only indicators that may forecast a probability of failure. The importance of each feature is site-specific depending on site conditions and proximity to the bridge site.

IV. SUMMARY AND CONCLUSIONS

A river channel is in an ever-changing state of equilibrium. The valley or canyon of the river is contained by the walls on either side. As the river changes, these walls and the river banks are subject to continued change. Hence, river banks and valley walls are in a continual state of potential instability.

Thus, slope instability forms a major factor in assessing stream-related hazards to bridges. The most evident effect that slope stability will have on a bridge is if slope failure should occur at a particular bridge site. That situation would also be expected to exert the largest particular influence on a bridge. However, slope failure at adjacent sites may also influence a particular bridge insofar as it may change the characteristics of the river at the bridge site.

Slope failure may take one of several forms. The preceding discussion has classified them for purposes of evaluating severity, means of analysis and identification of the extent of their influence.

Slope failure results from either increasing the stresses in a slope or decreasing the strength of the material in the slope to the point where the resistance to movement is less than the driving forces. Generally, those changes are the result of the toe of the slope being unloaded, the top of the slope being loaded or the introduction of water into the slope. The first two factors represent an increase in the driving stresses in the slope. The introduction of water either decreases the shear strength parameters of the soil or decreases the effective stress in the soil. Thus, it represents a decrease in the resisting forces in the slope.

In evaluating the stability of a prospective bridge site or an adjacent site, the first consideration is of present stability. Features that may indicate the existence of past or present movement are observed. If such features exist, the site should be considered in a state of impending failure and any change that would decrease the factor of safety would be expected to induce failure.

If the site can be considered to be presently stable, it is necessary to assess whether or not potential future changes or construction would lead to potential instability. Any change that could lead to an intolerably low factor of safety must be counteracted.

Countermeasures implemented to enhance stability of a site would be opposite to those leading to a decrease in stability. Those would be to load the toe, unload the top, divert water away from the slope, or drain the slope.

Table 3 in the report summarizes the general features that would indicate some form of potential instability. That table also indicates the type or cause of failure indicated by the particular feature, the general severity of such failures, and the nature of the analysis and correction of the situation causing the failure. Table 3 is intended only as a guide to the evaluation of a site. It is emphasized that each site must be evaluated individually. Exceptions to the guidelines listed in Table 3 are to be expected.

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APPENDIX B

ASSESSING THE IMPACT OF LAND USE CHANGE ON STREAM-RELATED HIGHWAY HAZARDS

by

D. O. Doehring

INTRODUCTION

Except for catastrophic events such as earthquakes or forest fires, land use change is probably the single most important dynamic process occurring within a watershed in terms of an ability to rapidly alter its fluvial characteristics. Gregory and Walling (1973) have said, "In many areas man exerts an important control over the spatial pattern of fluvial processes, and this is particularly so at the mesoscale (regional) where, for example, contrasts in agricultural practice or between rural and urban areas can be more important than differences in geology and topography or meteorological conditions."

The strong influence of transportation routes on land use is well established and accepted (see for example, Highway Research Board, 1968 or Krueckeberg and Silvers, 1974). Accordingly, highways often serve as focal points for major changes in land use (Figure 1). One of the consequences, or feedbacks, of this relationship is the impact of land use on stream-related highway hazards.

Highway bridges and other structures are vulnerable to hazards from the streams they span and may be damaged, destroyed or otherwise rendered useless. Although transportation engineers strive to avoid or mitigate these hazards, not all potential problems are evident from site analysis because many result from changes in the watersheds distant from the structures.

In changing land use Man alters watershed characteristics through a number of different activities: removal of vegetation, disturbance of the soil mantle, grading of the soil and subsoil, installation of efficient artificial drainage systems and paving of the surface with impervious material. All of these activities tend to cause changes in the water and sediment being supplied to stream channels. Because the pattern and geometry of a particular reach of stream channel are very much dependent upon the water and sediment being supplied by the watershed above it, changes in land use can cause a stable channel reach to become unstable and a hazard to highway structures not designed to accommodate possible channel metamorphosis. Table 1 (Gregory and Walling, 1973) gives some examples of watershed changes effected by Man.

Figure 2 is a model developed by Wolman (1967) for the Middle Atlantic Piedmont region of the United States. It illustrates the changes in sediment yield and channel conditions which may have occurred concomitant with changes in land use from pre-agriculture to urban.

This report is aimed at providing assistance to the transportation engineer recognizing potentially serious land use-generated hazards to highways. The report addresses the following five topics associated with the prediction of land use-generated stream hazards.

1. Overview of techniques for inventorying land use.
2. Appraisal of land use models for forecasting and guiding future development.

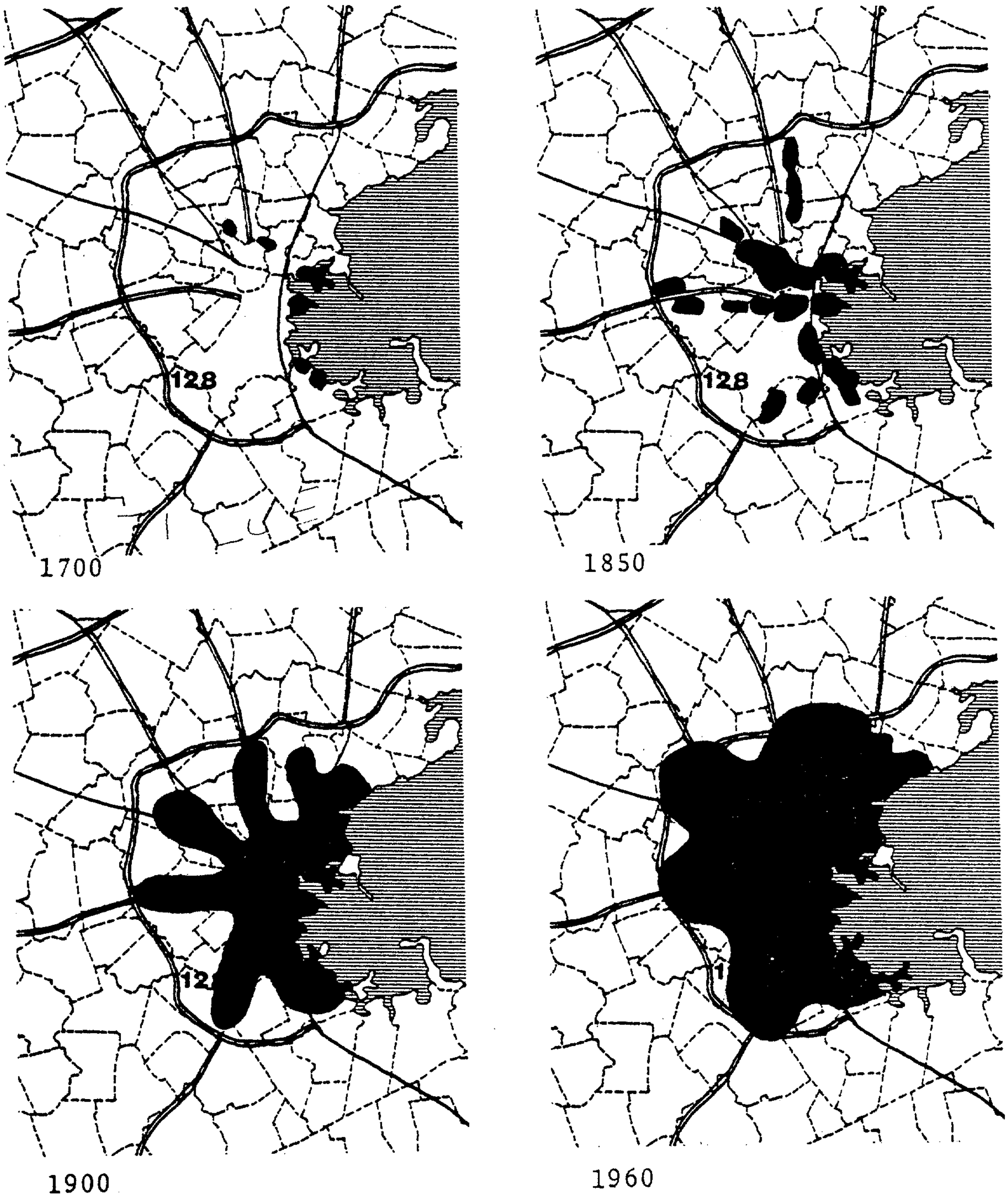

Figure 1. Urbanization of the Greater Boston Area from Colonial Times to the Present. The Pattern of Development First Follows Trails and Wagon Roads, in the 1930's Streetcar Lines and Today Interstate Highways. (Massachusetts Department of Public Works, 1969.)

Table 1. Impacts on Channel Geometry (g), Channel Pattern (p), Drainage Network (n) (Gregory and Walling, 1973).

	Direct changes	Form affected		
Drainage Network Changes:	irrigation networks		n	
	drainage schemes		n	
	agricultural drains		n	
	ditches		n	
	road drains		n	
	storm water sewers		n	
Channel Changes:	river regulation	g	p	
	bank stabilization, protection	g	p	
Water & Sediment Balance:	abstraction of water	g		
	return of water	g		
	waste disposal	g		
	Indirect Causes			
Land Use:	cropland	n	p	g
	building construction		p	g
	urbanization	n	p	g
	afforestation	n	p	g
	reservoir construction		p	g
Soil Character:	drainage	n		
	ploughing	n	p	
	fertilizers			

Note particularly that all types of land use have an indirect effect on channel geometry and channel pattern.

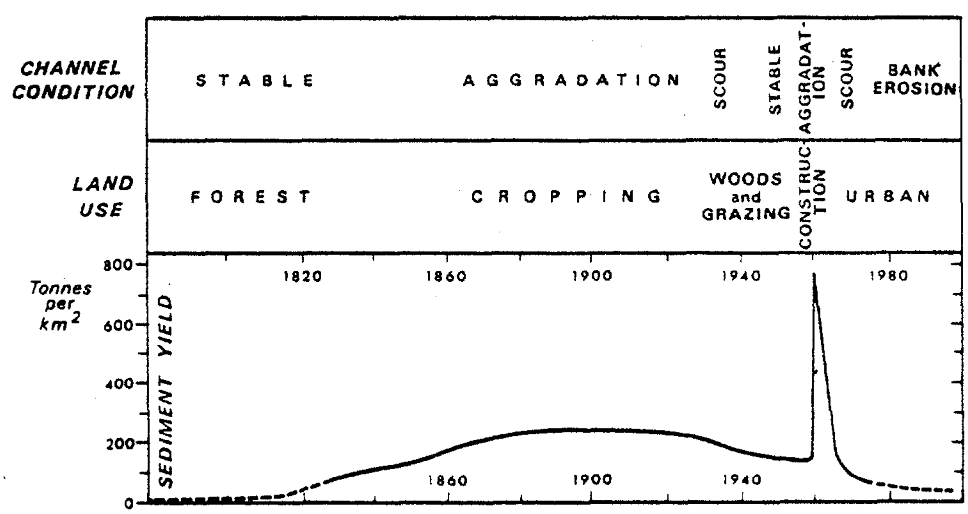

Figure 2. Relationships Between Land Use, Sediment Yield and Channel Condition for the Middle Atlantic Piedmont Region (Wolman, 1967).

3. Changes in watershed characteristics that produce increases in stream hazards.
4. The relationships between specific changes in land use and change in watershed characteristics.
5. Applying land use information to highway design.

If the transportation engineer is aware of planned or probable changes in land use that will impact on streams and can assess these impacts, design criteria can be adjusted to accommodate these future changes.

Unfortunately, the prediction of land use-generated stream hazards is an extremely complex task as development of resources and future land use is determined by a multitude of factors (including economic, sociological, political and others) and often cannot be accurately predicted in the long term. Moreover, given a future land use change, the fluvial impacts may be influenced more by the intensity and specific nature of activities than by the general land use type. For example, the impact of changing from open space to agricultural land use is greatly influenced by the agricultural practices used and the particular crops grown. Nevertheless, guidance on the magnitude of change in hazard is possible and will serve to identify potentially dangerous situations.

1. Overview of Techniques for Inventorying Land Use

Although inventorying of land use is fundamental to comprehensive planning, little specific information has been published on methods. This is somewhat understandable because the techniques employed are, to a large extent, dependent on the purpose of the inventory and the type of data available. Most authors have deemed it appropriate to discuss inventorying of land use in the context of a specific example or broad discussion of the planning process (e.g., Landscape Architecture Research Office, 1967; McHarg, 1966; Lewis, 1963; Hill, 1960). Some insights can be gleaned from published reports despite the fact that they were not intended to serve as examples of land use inventorying methods.

Selection of land use categories, map scales and the trade-offs between accuracy and costs are prime considerations. Information on land use type, density and spatial location is generally sought. Two basic types of data can be used. Primary data are direct observations of land use, such as the information acquired from field canvassing or aerial photo interpretation. Secondary, or indirect, data may be equally useful and is often less expensive to collect. Examples of this type of data include issuance of permits (e.g. building, domestic or agricultural wells, mining, logging, etc.), utility connections, school records and numerous other land use-related parameters. The drawback to using secondary data is the reduction in accuracy that is attendant to it. For example, the issuance of a building, well, or other permit does not always result in a new building, well, or other change of land use.

The major categories of a standard classification of land use and characteristics used to measure land use are given in Table 2. This classification scheme is used by the Urban Renewal Administration and Bureau of Public Roads (1965). Note that both primary and secondary evidence is advocated for land use assessment.

Table 2. Standard Land Use Codes and Measuring Characteristics (Urban Renewal Administration and Bureau of Public Roads, 1965).

	Standard Land Use Code	Commonly Measured Characteristics
1000	Residential	Population density, car ownership, income, family size, number of dwelling units
2000	Manufacturing	Number of employees, acres, shipments
3000	Manufacturing (cont.)	
4000	Transportation, communications, and utilities	Employees, acres, parking capacity, berths
5000	Trade (e.g., wholesale, retail)	Employees, floor area, acres, parking capacity
6000	Services (e.g., medical, educational)	Acres, attendance, capacity, employees
7000	Cultural, entertainment and recreational	Acres, attendance, capacity
8000	Resource production and extraction (e.g., agriculture, mining)	Acres, employees, shipments
9000	Undeveloped land and water areas	Acres, development and capacity, zoned use

Among the most ambitious projects of land use mapping is the work of Professor William P. McConnell of the University of Massachusetts (McConnell and Garvin, 1956; McConnell, 1973). In 1951 and again in 1972, the entire state of Massachusetts was mapped from relatively large scale aerial photographs. The McConnell Land Use Inventory System identifies, defines and types 126 classes of land use from the six general categories of Agricultural and Open Land, Forest, Wetland, Urban, Recreation and Mining/Waste Disposal. Mapping was accomplished at a resolution of approximately three acres. The relatively slow and costly aspects of the work can be greatly reduced by the application of machine processing of multispectral imagery as exemplified by Todd et al., 1975. The restricted number of land use types that can be recognized and the loss in resolution are the primary disadvantages of the remote sensing approach.

For most areas of the United States, land use data are available from federal, state and local governmental agencies. In addition to census data, federal agencies can provide aerial photographs and other remotely sensed imagery. The U.S. Geological Survey published land use maps as do other agencies such as the Bureau of Land Management and the Soil Conservation Service. Moreover, many federal agencies have secondary types of data available.

State agencies often compile and distribute land use maps and other information (e.g., Colorado Land Use Commission, 1974). State planning and land use commissions, agricultural extension services, forest services, geological surveys and other resource management agencies are sources of this information.

The most accurate and current land use data is usually available from local (city, county, regional) government. In addition to census data and land use maps, zoning maps, building permits, school district records and tax rolls are available. Other sources of information include utility connections, city maps, chamber of commerce data, auto registrations, and other secondary sources of information. Because there is a symbiotic relationship between transportation routes and land use, federal, state and local highway commissions as well as other organizations involved with transportation constitute an excellent source of land use data.

2. Appraisal of Land Use Models for Forecasting and Guiding Future Development

The literature of planning is replete with a multitude of methods and models for predicting and influencing future growth. Harris, 1968; Robinson, 1972 and Wilson, 1974 discuss more than 30 such models. The majority of the predictive models can be classified by basis as economic, transportation, deomgraphic, physical constraints, and composite (e.g., Fabos and Caswell, 1977). On the other hand, planning models, such as comprehensive or master plans, usually are not predictive models but rather a set of goals. Through enforcement of laws and regulations (at many levels of government) the goals can be met and planned growth achieved. These planning tools tend to be dynamic models because they deal with changing trends of development and societal values. Because the models, or more correctly goals, are constantly subject to modification, it is usually nearly impossible to determine, after the fact, how closely a plan has been followed. Planning strategies regarding hazards and physical factors tend to be among the more stable. For example, once a community recognizes the hazards associated with disposing of wastes in aquifer recharge areas, it is not likely to reverse its decision to protect the resource. Even so, standards do change with time. Until passage of the National Flood Insturance Program in 1968, the 50-year floodplain was the standard planning norm. After passage of the act, the 100-year floodplain became the norm and issuance of a Presidential Executive Order in 1978 is redirecting certain land use above the 500-year floodplain. Owing to the complexity and specialized nature of predicting the changes in land use patterns, this task is best left to planning specialists at the local level.

3. Changes in Watershed Characteristics that Produce Increases in Stream Hazards

a. Removal of vegetation

Initially, alterations of open space or natural settings to new land uses involve the removal of vegetation. Vegetation plays an important role in controlling the amount of rainfall which ultimately reaches stream channels. Plants intercept precipitation on their leaves, allowing it to evaporate. Water which eventually does reach the ground is detained by the cover of litter, causing runoff to be delayed and presenting an opportunity for infiltration into the soil mantle. Plants also remove moisture from the soil, thereby increasing the soil's holding capacity for future rainfall.

In addition to total water yield, the rate of overland flow is accelerated through vegetation reduction. By removing the retarding effects of plant cover, lag time of the hydrograph is decreased and peak discharge is amplified.

Ellison (1948) points out that raindrop impact on bare soil tends to compact it and thereby decrease its capacity to soak up water flowing over it. Increases in water yield and peak discharge due to removal of plant cover are therefore compounded by the soil compaction caused by loss of protection from direct raindrop impact.

Vegetation also plays a role in minimizing erosion due to overland flow. Plants anchor the soil with their root systems and they provide a protective cover of litter. By shielding slopes from direct raindrop impact, the resulting downslope movement of soil particles as described by Ellison (1948) is reduced. In addition, denudation of vegetation results in increased soil moisture which tends to accelerate mass wasting processes. Vegetation removal therefore creates a potential for increased erosion and stream sediment yield.

The degree to which a particular vegetative cover can alter runoff and sediment yield is of course dependent upon the types of plants present and the their density. Large trees have a larger sphere of influence than shrubs or smaller plants and generally the more dense the stand of plants, the more water and sediment yield is affected. Accordingly, the magnitude of changes in fluvial processes is proportional to the amount of plant cover removed. Forest or brush fires, for example, would have the most extreme effects because of their tendency to destroy all of the existing vegetation.

Factors such as soil type, climate, slope, rates of plant regeneration and the locations of cleared areas with respect to stream channels all have an effect on the capacity for vegetation removal to alter water and sediment yield. These factors should be kept in mind when trying to assess the effects of future vegetation removal.

b. Disturbance of Soil Mantle

Disturbance of the soil mantle as it occurs in various agricultural practices normally results in the total destruction of the natural vegetation and therefore produces the effects outlined above. In addition, because the soil is loosened and more fully exposed to overland flow, sediment yields are drastically accelerated. The effects of raindrop impact are more pronounced (especially in areas with higher slopes), which also increases sediment yield.

The magnitude of these changes in fluvial processes is very much dependent upon the amount and type of conservation measures employed. Practices such as crop rotation, contour plowing, strip cropping and terracing can signficantly reduce the water and sediment impacts resulting from soil disturbance.

c. Regrading

Regrading, as used here, is associated not only with construction but with land uses such as mining or any activity which involves the disturbance of subsoil and bedrock as well as the upper soil mantle. Earth moving, excavation and the operation of heavy machinery can cause very large magnitude changes in fluvial processes, particularly sediment yield. Relatively small areas which have been denuded and regraded can undergo very large rates of erosion due to the exposure of large amounts of unconsolidated material to rainfall and runoff.

Through most regrading activities are relatively short-lived and transitory, their effects can linger long after they are completed. For instance, highway cuts and fills can continue to be an erosion problem if not revegetated or otherwise stabilized. The enormous amounts of sediment deposited in mainstream channels and their tributaries as a result of the erosion of regraded areas can later become a renewed source of sediment after the area has been stabilized and the streams begin eroding their oversteepened beds.

Regrading can also disrupt normal drainage patterns for a particular area and thereby alter drainage dynamics. Changes in total runoff and lag time of the hydrograph would occur although they would not be expected to be as pronounced as the change in sediment yield because regrading usually involves relatively small areas at any one time.

d. Drainage Systems

The efficient drainage systems associated with urbanization most significantly affect lag time or the time interval between the center of mass of the storm precipitation and the center of mass of the resultant storm hydrograph.

Installation of drainage systems usually involves alterations of the natural drainage network. Small tributaries are often infilled or diverted into pipes or concrete-lined channels. The new drainage network is artificially extended with surface water drains, street gutters and even roof gutters. The efficiency of artificial channels, gutters and storm sewers decreases lag time. As a result, water is accumulated in the stream channels at a faster rate and peak discharges are significantly increased. Once water reaches these artificial, impervious drainage systems, there is no longer an opportunity for infiltration into the soil, more water reaches the mainstream channel and total water yield is increased. In addition, there is less ground water to sustain base flows during periods of little or no precipitation and low flow levels are therefore reduced. Sediment yields are also reduced because water is flowing through artificially lined channels rather than unlined natural channels.

e. Impervious Surfaces

Urbanization is characterized by the replacement of large areas of soil and vegetation with impervious surfaces such as paved streets, parking lots, sidewalks and buildings. Rates of runoff across these surfaces are very high because of the reduced roughness resulting from the lack of vegetation or debris. Lag time is therefore decreased and peak discharge increased interception of rainfall by vegetation is reduced and since nearly all of the rainfall which impacts impervious surfaces runs off, total water yield for stream channels draining these areas is significantly increased. Little or no infiltration occurs on impervious surfaces, groundwater is not replenished as it would be in areas of exposed soil and low flows are therefore reduced.

Since areas of soil which were previously exposed to erosion are protected by a covering of non-erodible impervious material, sediment yields tend to be lower as an area approaches complete urbanization.

4. The Relationships Between Specific Changes in Land Use and Change in Watershed Characteristics

For the purposes of this discussion, land use is grouped into six types: Open Space, Timber Harvesting, Grazing, Farming, Construction and Urban. These terms are used loosely to characterize a group of similar activities but are not necessarily restricted to the same land use. For example, some crops that do not require annual working of the soil (orchards, tree farms, and bramble fruits) should not be classified as Farming, but rather as Open Space. Likewise, some land use categories contain several diverse activities that have a common impact on watershed conditions. For example, most mining operations should be included with Construction owing to the similarity of effects on the watershed. The various land use categories are defined below and are related to the previously described changes in watershed characteristics which are typical to them.

Open Space, refers to land either in its natural state or otherwise not currently being utilized for the production of natural resources. Although open spaces may commonly be managed for future extraction of resources or other attributes as in the case of national forests, golf courses, cemetaries and others, they may be readily recognized by the fact that the vegetation and earth materials are not being significantly disturbed by Man. Parks, orchards, wetlands and greenbelts are a few examples of open space.

Timber Harvesting is used to categorize lands affected by present or past logging activities. The main effect of these activities is the removal of vegetation. In conjunction with vegetation removal, some disturbance of the soil mantle takes place through related activities such as the building of temporary roads and skidding of logs. Areas subject to periodic denudation of vegetation through fire or disease should also be considered in this category.

Grazing applies to all range and pasturelands that are used intensively for browsing of livestock resulting in a periodic reduction of grasses and shrubs but without planting or cultivation of the soil. Livestock also tend to disturb the soil mantle in limited areas such as along established trails or at streambanks where they come to drink or to cross the stream (Johnson et al., 1978).

Farming refers to land which is subjected to cultivation or other disturbance of the soil mantle and removal of vegetation at least once each year. The greatest impact occurs at the time of initial clearing. It must be emphasized that the mangitude of these impacts is dependent on the setting and the farming practices employed.

Construction includes activities that require the reduction of vegetation, disturbance of the soil mantle and regrading of the surface. Commonly, the disruption and displacement of natural drainage systems also results. The magnitude of these effects depends on such factors as slope, climate, soil characteristics and proximity to stream channels along with the size and duration of the project.

Urban areas include residential, commercial and industrial land use. Demographers often consider population centers of 2000 or greater as urban areas but for the purposes of assessing hydrologic impacts, the density of building, extent of artificial drainage and relative amount of pavement, regardless of population, is of prime concern. Typically urbanization produces increased impervious surface area and highly efficient drainage systems.

5. Applying Land Use Information to Highway Design

Changes in land use alter the stream-related parameters used by engineers for highway design. Prediction of land use changes will permit the use of design criteria that take into consideration future as well as present stream conditions. The following three-step procedure is intended as a guide to making these assessments.

a. Each stream should be considered in terms of its entire watershed. Land use changes anywhere in the basin, i.e., both upstream and downstream from the highway, may ultimately affect the highway.

b. In the next step, both the potential for land use change and the magnitude of such changes are appraised. Present land use and setting impose constraints on future land uses that are possible. For example, watersheds that are entirely urban are unlikely to change in the future. Likewise, treeless areas will not be subjected to timber harvest for at least 40 to 50 years and other combinations of slope and vegetation can be used to eliminate possible future land uses. The magnitude of impact within a given basin is dependent on the relative proportion of the basin subjected to the new land use. Five hundred acres of urbanization in a 200 square mile basin will have far less impact than the same change in a five square mile basin if all else is equal. Of course, the effects in either basin may be the same near or adjacent to the tract of land that has changed use.

Special attention should be given to cases where future construction and urbanization are likely and to terrains with steep slopes. Construction and mining commonly produce dramatic increases in erosion and sedimentation. Increases in peak discharges and decreases in hydrograph lag time are common consequences of urbanization. In most cases, the impacts of land use change on stream-related hazards are greater in areas of steep topography.

c. The third step in the assessment is appropriate for watersheds that hold potential for significant land use change. Predictions of extent and nature of these changes should be acquired from agencies or institutuions managing the land in question or, in the case of multiple ownership, from professional planners. In general, more localized planning agencies (e.g., municipal vs. state) can provide more detailed and authoritative predictions.

Given the predictions of nature and extent of future land use, two approaches to assessing the impact on stream-related hazards may be taken. The first, an empirical approach, uses local analog basins. This method is only useful when there are nearby basins with equivalent settings that have already undergone the predicted land use change. Assessment of changes in terms of current nature and rate of processes is used for establishing design criteria. The accuracy of this method is, of course, a function of the validity of the analogs.

If local analogs are not available, then more general models of land use impact must be relied upon. The concluding sections of this report provide prominent published models that deal with impacts of the various land uses discussed in this report. Within this coverage, impacts have been further subdivided into water-related and sediment-related impacts. All possible permutations of land use change and setting cannot be covered within the scope of this report. However, a selected bibliography of other important references is included at the end of the report to provide additional sources of information to the user.

OPEN SPACE

Water-Related Impacts

Gregory and Walling (1973) provide a listing of multivariate regression equations which have been developed by a number of researchers in attempts to find statistical relationships between runoff volumes and watershed characteristics (Table 3). The number and variety of independent variables in the equations indicate the complexity of the relationships. Similar equations have been developed for predicting flood magnitudes (Thomas and Benson, 1970; Wong, 1963; Nash and Shaw, 1966; Rodda, 1969).

Sediment-Related Impacts

Fleming (1969) in Figure 3, relates annual sediment load to four major vegetation zones and mean annual discharge. Fournier (1960) found that sediment yield is also a function of basin relief. He developed the following empirical equation:

$$\text{Log DS} = 2.65 \text{ Log } \frac{p^2}{p} + 0.46 \text{ Log } \frac{H^2}{S} - 1.56$$

where DS = suspended sediment yield ($t/km^2.yr$)

H = mean relief of the basin or the difference between the mean altitude and the minimum altitude (m)

S = catchment area (km^2)

TIMBER HARVESTING

Many studies have been done which provide empirical data concerning timber harvesting in different areas and climates of the world. A large percentage of these experiments use what is termed the "paired watershed" approach. Two watersheds with similar physical characteristics are chosen and baseline data is gathered from each of them. One watershed is then cut and the resulting differences in runoff and sediment production are used to gauge the effects of the timber harvest.

Water-Related Impacts

Dunne and Leopold (1978) present a graph showing the relationships between changes in vegetation cover and increases in water yield for different geographical regions (Figure 4). Table 4 summarizes the findings of Harris (1977). Three watersheds were compared to determine the impacts of clearcutting versus patch cutting. Flynn Creek watershed was left uncut as a control, Needle Branch was clearcut and Deer Creek was patch cut. Only Needle Branch showed statistically significant increases in total runoff and high flows.

Dunne and Leopold (1978) point out that increases in annual water yield do not necessarily persist but rather tend to decline as the forest cover is regenerated. They plotted the results of several studies and have found a very

Table 3. Multivariate Relationships Between Annual Runoff Volume and Mean Annual Discharge and Controlling Factors (Gregory and Walling, 1973).

Worker	Region	Equation
Mustonen (1967)	Finland	$R_a = -11 + 0{\cdot}83\,P_w + 0{\cdot}73\,P_f + 0{\cdot}57\,P_s - 0{\cdot}21\,PET - 21T + 0{\cdot}29\,\Delta SM - 0{\cdot}99\,FD - 0{\cdot}77\,VFS + 0{\cdot}86\,CS$ $(R = 0{\cdot}94)$
Busby (1964)	Conterminous United States	$R_b = 150 + 0{\cdot}42\,P - 2{\cdot}23\,T + 0{\cdot}083\,S - 0{\cdot}38\,W + 0{\cdot}071\,D_p + 0{\cdot}054\,D_t - 0{\cdot}008\,d$
Thomas and Benson (1970)	Potomac Basin U.S.A.	$Q_m = 2{\cdot}89 \times 10^{-4} . A^{1{\cdot}06} . S^{0{\cdot}10} . P^{1{\cdot}87} . S_n^{0{\cdot}18}$
Taylor (1967)	New Zealand catchments	$Q_m = -11.398 + 0{\cdot}74\,A - 3.42\,L_b + 0{\cdot}028\,H + 0{\cdot}363\,P$ $(R = 0{\cdot}923)$

where R_a = mean annual runoff (mm)
P_w = winter precipitation (mm)
P_f = autumn precipitation (mm)
P_s = summer precipitation (mm)
PET = potential evapotranspiration in summer (mm)
T = average annual temperature (°C)
ΔSM = change in soil moisture deficit during the year (mm)
FD = frost depth 31 March (cm)
VFS = volume of forest growing stock (m^3/ha)
CS = percentage of area with coarse soils

R_b = mean annual runoff (inches)
P = mean annual precipitation (inches)
T = mean annual temperature (°F)
S = mean annual snowfall (inches)
W = average wind velocity (m.p.h.)
D_p = average number of days with measurable precipitation
D_t = average number of days with temperatures of 90°F or more
d = average heating degree days

Q_m = mean annual discharge (cfs)
A = drainage area (mi^2)
S = main-channel slope (ft/mi)
P = mean annual precipitation (inches)
S_n = mean annual snowfall (inches)

Q_m = mean annual discharge (cfs)
A = catchment area (mi^2)
L_b = maximum basin length
H = total relief
P = perimeter

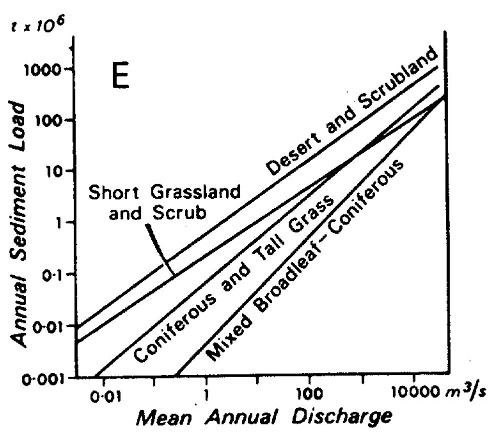

Figure 3. Relationships Between Sediment Loads, Discharge and Vegetation (Fleming, 1969).

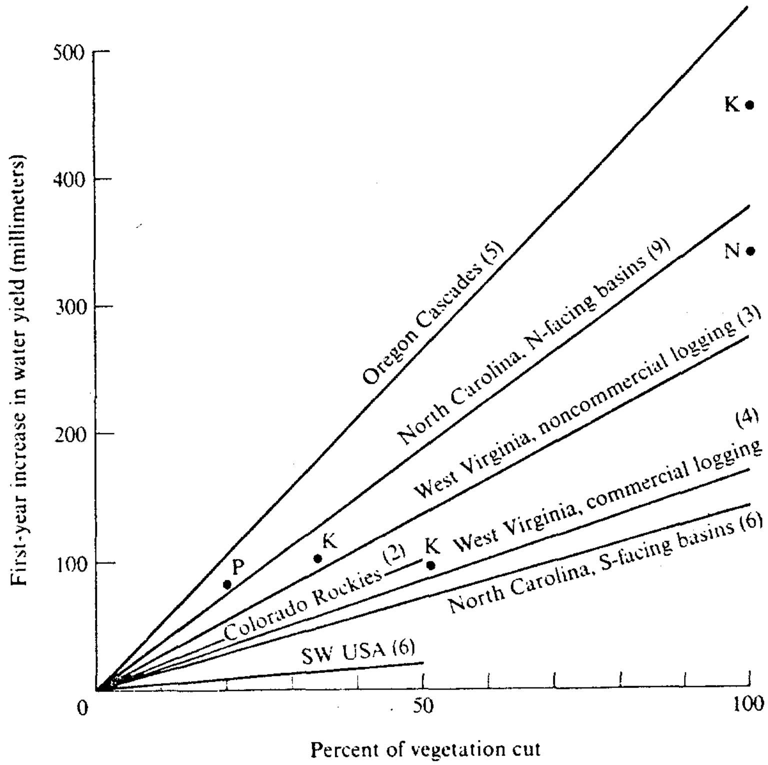

Figure 4. Relationships Between Changes in Vegetation Cover and First Year Increases in Water Yield. Individual Points are Plotted, Identified by Letters, to Show Results of Experiments on Drainage Basins in Various Regions: K = Kenya highlands, N = New Hampshire, P = Pennsylvania. (Dunne and Leopold, 1978).

Table 4. Summary of Postlogging Values and Changes in Hydrologic Characteristics After Logging (Harris, 1977).

Hydrologic characteristics	Flynn Creek	Needle Branch				Deer Creek			
				Change				Change	
		Predicted	Actual	Amount	Percent of predicted	Predicted	Actual	Amount	Percent of predicted
Annual runoff (in.)	77.00	73.59	92.62	[1]+19.03	+26	74.34	76.84	+2.50	+3
Peak flow [(ft³/s)/mi²]	75.00	91.2	109.0	+17.8	+20	78.5	80.3	+1.8	+2
Three-day high flow (in.)	4.58	4.78	5.91	[1]+1.13	+24	4.58	4.60	+.02	+<1
Low flow (ft³/s)	.17	.03	.03	0	0	.36	.29	−.07	−19
Discharge-weighted mean sediment concentration (mg/l)	40.0	27.1	67.1	[1]+40.0	+148	42.1	52.7	+10.6	+25
Sediment yield (tons/mi²)	263	163	458	[1]+295	+181	271	338	+67	+25
Average monthly April–October maximum water temperature (°C)	12.0	12.0	17.5	[1] 5.5	+46	12.5	14.5	[1]+2.0	+16

[1]Indicates statistically significant change.

rough trend which indicates that streamflow increases decline exponentially with time and have a half-life of about two to seven years.

Sediment-Related Impacts

Table 5 lists some of the site factors which should be considered in evaluating the potential for sediment production in a given watershed. This table comes from an excellent publication by the U.S. Environmental Protection Agency (1976) which gives a comprehensive discussion of the impacts of activities associated with logging as well as techniques for prediction and mitigation.

Fredrickson (1970) compared sediment yields from patch-cut versus clearcut watersheds. He attributed the much larger sediment yields from the patch-cut basin to differences in log removal procedures. Logs were moved in the clearcut area by aerial ropeways while roads constructed for timber removal in the patch-cut basin contributed to severe mudflow and landslide activity, producing massive amounts of sediment and debris.

Harris' study (Table 4) shows that sediment production from clearcut basins exceeds that from patch-cuts when the findings are not complicated by differing log removal methods.

GRAZING

Water-Related Impacts

Figure 5 illustrates the findings of Noble (1965) for rangeland in intermontane Utah. Good ground cover (60-75 percent) showed 2 percent surface runoff, while fair ground cover (37 percent) showed 14 percent and poor cover (10 percent) showed 73 percent). Sarty (1970) in a study of small watersheds in southwestern Wisconsin found that for five large storms in one year peak flow rates for heavily grazed pasture were three times those from lightly grazed areas.

Sediment-Related Impacts

Gregory and Walling (1973) using data from Brown (1950) show the erosion rates from pasture and range lands relative to those from various agricultural crops in the Pacific Northwest in Figure 6. Lusby (1970) found that for catchments in Badger Wash Basin, Colorado, the non-grazed basins documented 34 percent less sediment yield than the grazed basins. Figure 5 indicates the differences in soil loss found in the previously mentioned study by Noble (1965).

FARMING

Water-Related Impacts

Figure 7, taken from Ursic and Dendy (1965) illustrates contrasts in annual runoff amounts between cultivated and pasture areas and abandoned fields and woodlands. Differences also exist between crop types as is shown in Table 6 compiled by Gregory and Walling (1973). These relationships are extremely complex and variable;however, as is revealed by the findings of Kuznik (1954) in the

Table 5. Relative Erosion Hazard of Logging Areas in Relation to Site Factors (U.S. Environmental Protection Agency, 1976).

Site Factors	High Erosion Hazard	Moderate Erosion Hazard	Low Erosion Hazard
Parent Rock	Acid Igneous Granite, diorite, volcanic ash, pumice,	Sedimentary and Metamorphic Sandstone, schist, shale, slate, conglomerates, chert	Basic Igneous (Lava rocks) Basalt, andesite, serpentine
Soil	Light textured,[a] with little or no clay	Medium textured, with considerable clay	Heavy textured, largely clay and adobe
Mantle Stability	Unstable mantles (cutbank stability Class V)	Mantles of questionable stability (cutbank stability Class IV)	Stable mantles (Classes I, II and III
Slope	Steep (over 50%)	Moderate (20-50%)	Gentle (0-20%)
Precipitation	Heavy winter rains or intense summer storms	Mainly snow with some rain	Heavy snow or light rain
Vegetation and other organic matter on and in the soil	None to very little	Moderate amounts	Large amounts

[a]Soil texture refers to the size and distribution of the mineral particles in the soil, the range extending from sand (light texture) to clay (heavy texture).

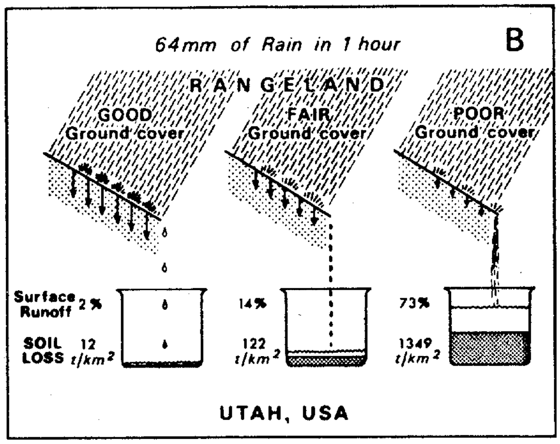

Figure 5. Influence of Range Condition on Runoff and Sediment Yield in Utah (Noble, 1965).

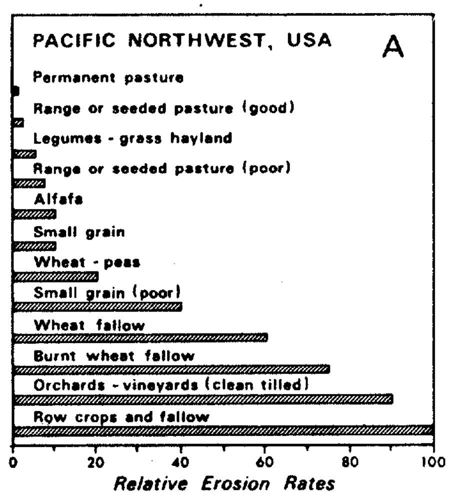

Figure 6. Relative Erosion Rates for the Pacific Northwest, U.S.A. (Gregory and Walling, 1973).

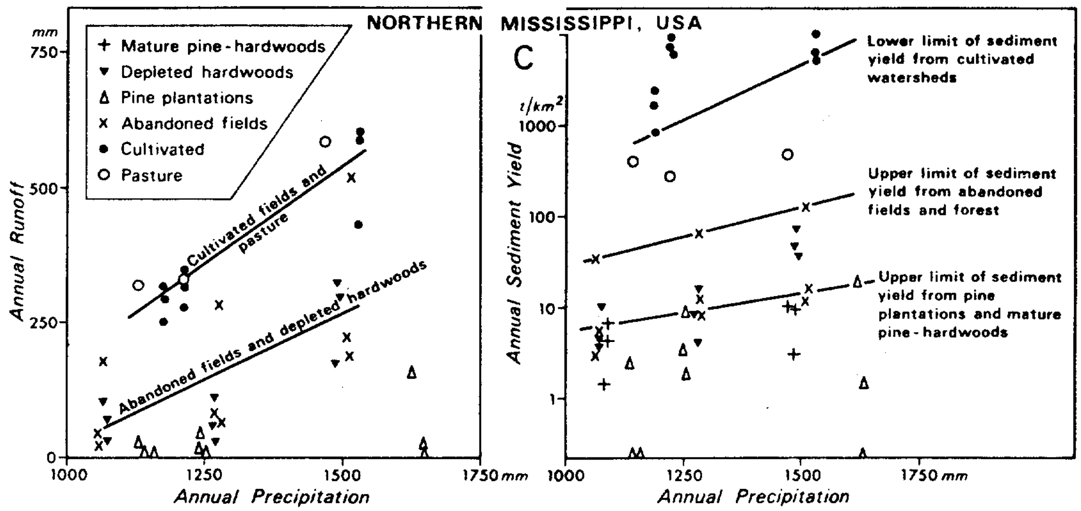

Figure 7. Influence of Land Use on Runoff and Sediment Yield in Northern Mississippi (Ursic and Dency, 1965).

Table 6. Comparison of Runoff and Sediment Yield from a Clean-Tilled Crop and a Dense Cover Crop at Five Locations in the United States (Gregory and Walling, 1973).

		Clean-Tilled Crop		Dense-Cover Crop	
Location	Average Annual Precipitation (mm)	Annual Soil Loss (tonnes)	Annual Runoff (%)	Annual Soil Loss (tonnes)	Annual Runoff (%)
Bethany, Missouri	884	69.88	28.31	0.29	9.30
Tyler, Texas	1037	28.40	20.92	0.13	1.15
Guthrie, Oklahoma	838	24.68	14.22	0.033	1.23
Clarinda, Iowa	681	19.12	8.64	0.061	0.97
Statesville, N. Carolina	1149	22.94	10.21	0.012	0.33

Source: American Society of Civil Engineers (1962)

U.S.S.R. where runoff as a result of spring snowmelt was 3.3 - 13 times greater from unplowed stubble than from plowed land. Sharp, Gibbs and Owen (1966) found that a procedure for estimating the effects of land and watershed treatment on streamflow in agricultural areas could not be developed if based on studies of river basins and research watersheds. Instead, they used a rational approach using logic and known effects and breaking the system down into various components. They have developed a series of curves for use in predicting the effects of various land and watershed treatments on stream flow.

Sediment-Related Impacts

Meade and Trimble (1974) have produced a graph showing the relationships between sediment yield and vegetation cover factors for the drainage basin of the Lloyd Shoals Reservoir in Georgia (Figure 8). The highest erosion rate was reached between 1900 and 1920 when the composite cover factor was 0.6, equivalent to 60 percent of the area being in row crops with poor conservation practices. Figure 7 shows the relative sediment yields found by Ursic and Dendy (1965). Sediment yields from cultivated watersheds were over 10 times greater than from areas of abandoned fields and forest covers and over 100 times greater than from pine plantations and mature pine-hardwoods.

The U.S. Department of Agriculture, Soil and Water Conservation Research Division, has developed the Universal Soil Loss Equation (F.A.O., 1965). This equation relates soil loss to a number of different factors:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P$$

where
- A = average annual soil loss
- R = rainfall factor
- K = soil erodibility factor
- L = length of slope factor
- S = steepness of slope factor
- C = cropping and management factor
- P = supporting conservation practice factor

CONSTRUCTION

Water-Related Impacts

Yorke and Davis (1971) in a study of construction sites related to urban expansion in the Bel Pre Creek basin, Maryland, found that storm runoff from the basin during a 30-month period of active construction was about 30 percent higher than that expected with the original grass and forest cover (Figure 9).

Only about 15 percent of the basin was under construction at any one time during the study period. Figure 10 from the same study compares two similar storm events, the earlier before and the other during development. The total rainfall of the 1963 storm was 0.9 inch greater than that of the 1966 storm, but the total runoff from the two storms was 40 and 35 cfs-days (cubic feet per second - days), respectively. The peak discharge was 80 cfs in 1963 and 84 cfs in 1966.

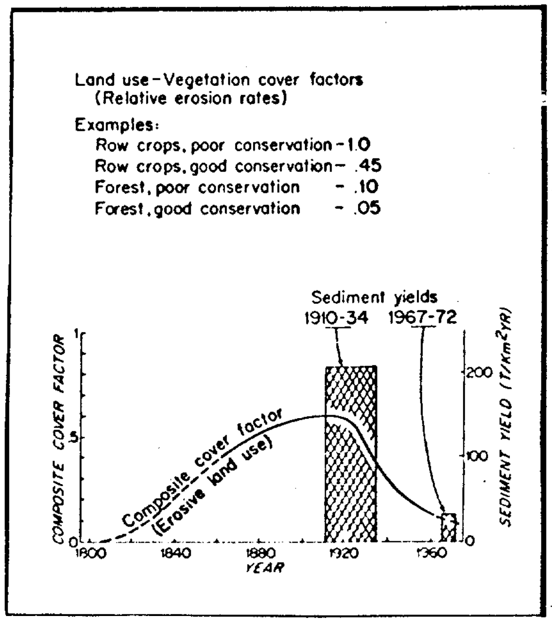

Figure 8. Changes in Land Use and Sediment Yield, Lloyd Shoals Watershed (Meade and Trimble, 1974).

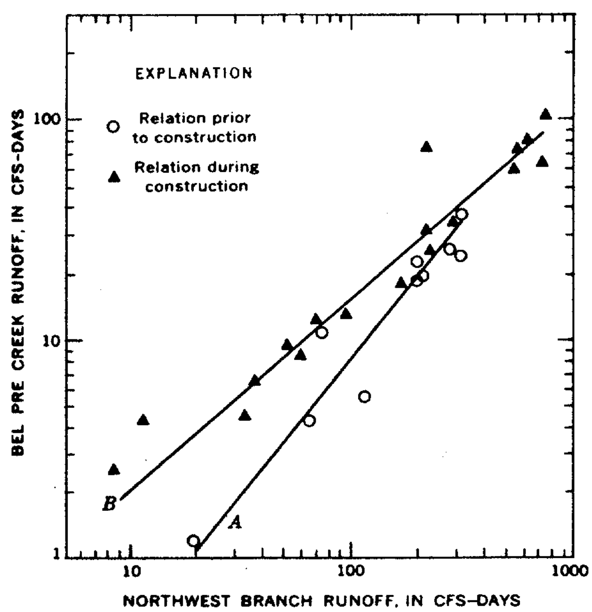

Figure 9. Relation Between Storm Runoff of Bel Pre Creek and Northwest Branch Anacostia River, Md. A, Prior to Construction; B, During Construction (Yorke and Davis, 1971).

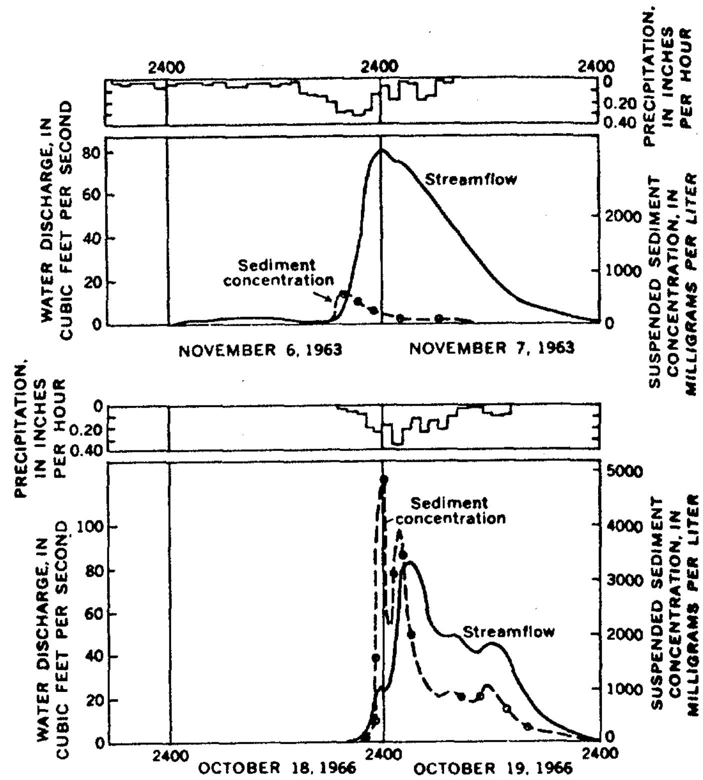

Figure 10. Variation of Precipitation, Sediment Concentration, and Water Discharge During Two Storm-runoff Periods for Bel Pre Creek, Md. (Yorke and Davis, 1971).

Surface mining has effects on runoff dynamics similar to those of construction. Dobroumov (1967) studied the Kursk iron mining region of the U.S.S.R. He found that as a result of pumping to maintain a cone of depression in the groundwater table, the Mikhaylov mine produced a discharge of 180 l/s into the drainage system and the flow of the Oskolets River was at one point 39 percent higher than the presumed natural discharge.

Sediment-Related Impacts

Large increases in sediment production are the primary impacts of construction activity. Wolman and Schick (1967) have compared data taken from a number of rural drainage basins and a number of drainage basins undergoing construction in the Baltimore, Maryland and Washington, D.C. areas (Figure 11). The stratification according to "dilution" is a rough separation based on the percentage of area under construction. They found that sediment was roughly 700-1800 tons per 1000 increase in population. Vice, Ferguson and Guy (1968) studied an area of extensive highway construction in a drainage basin of 4.54 square miles in Fairfax County, Virginia, during 1961 and 1964. They found that an average of 179 acres of construction area contributed 94 percent of the 37,000 tons transported from the basin during the 3.4-year period of record. If normal precipitation had prevailed, the estimated gross erosion in the construction area would have been more than 10 times that normally expected from cultivated land, and more than 500 times that expected from the low yield pasture and

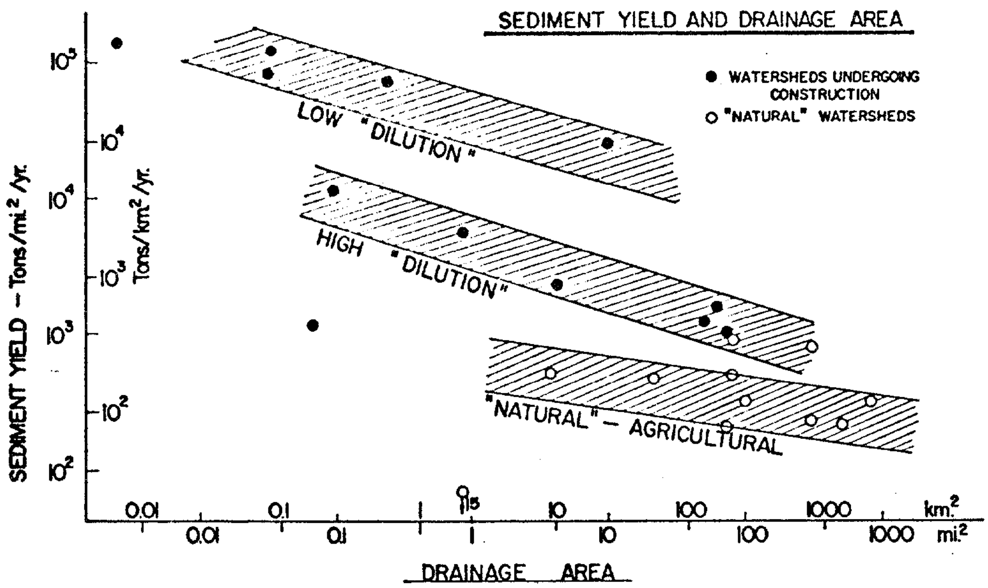

Figure 11. Sediment Yield, Drainage Area, and Construction Activity (Wolman and Schick, 1967).

forest areas. Guy (1963) points out that the rate of construction involved with urbanization in the Kensington, Maryland, area results in the movement by streams of 10 tons of sediment for each person added to the city.

URBAN

Water-Related Impacts

Figure 12 illustrates the relationships Wilson (1967) found to be true for streams near Jackson, Mississippi.

Anderson (1970) in Figure 13 depicts flood frequency curves relating recurrence intervals to ratios of selected recurrence interval floods and the average-flood magnitude (magnitude at 2.33-year recurrence interval) using the data in Table 7. The graphs show the effects of different degrees of imperviousness on flood recurrence intervals. Leopold (1968) assembled data from seven studies similar to those described above (Table 8) to relate the percentage of an area served by storm sewerage and the percentage of impervious area to the ratio of discharge after urbanization and discharge before urbanization in Figure 14.

Figure 15 by Leopold (1968) defines what is meant by lag time and how it is typically affected by urbanization. Figure 16 is the lag time relationship developed by Carter (1961) for the Washington, D.C. area. L is the total length from the gaging point to the rim of the basin measured along the principal channel and S is the weighted slope of an order of 3 or greater of all stream channels in the basin.

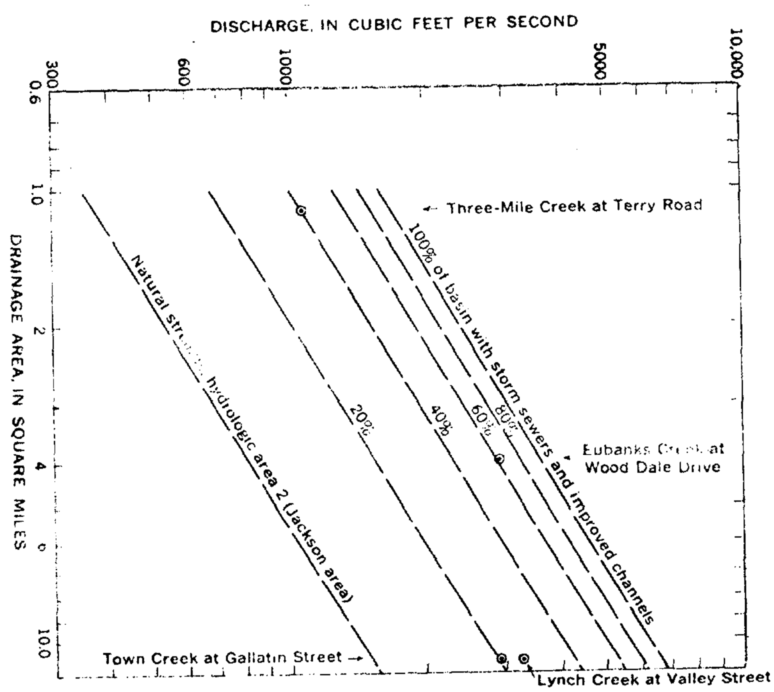

Figure 12. Mean Annual Flood Curves for Streams in Jackson, Miss. The Upper Five Curves Are for the Indicated Percentages of Basin with Storm Sewers and Improved Channels. The Lowest Curve is for Hydrologic Area 2 of Wilson and Trotter (1961), after Wilson (1967).

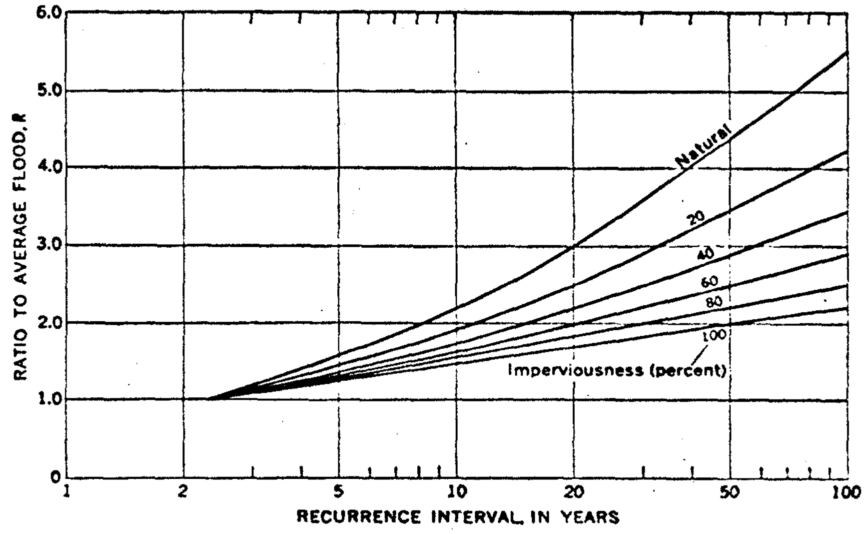

Figure 13. Flood-frequency Curves for Selected Degrees of Imperviousness (Anderson, 1970).

Table 7. Flood-Frequency Ratios for Basins with Long Flood Records (Anderson,1970).

Stream and Location	Recurrence Interval, In Years 2.33	10	25	50	100
Linganore Creek near Frederick, Md	1.00	1.48	1.74	1.92	2.10
Seneca Creek near Dawsonville, Md	1.00	2.17	3.35	4.05	6.52
Difficult Run near Great Falls, Va	1.00	1.78	2.44	3.05	3.75
Rock Creek at Sherill Dr., Wash.D.C.	1.00	2.36	3.14	4.78	6.07
Northwest Branch Anacostia Rvr nr Collesvll,Md	1.00	2.18	3.25	4.05	5.00
Little Patuxent Rvr at Gullford, Md	1.00	2.26	3.38	4.41	5.50
Piney Run near Sykesville, Md	1.00	2.00	3.24	4.57	6.52
Median ratios	1.00	2.17	3.25	4.41	5.50
Ratios used	1.00	2.2	3.3	4.4	5.5

Table 8. Increase in Discharge as a Result of Urbanization in a 1-Square-Mile Area (Leopold, 1968).

Discharge is mean annual flood; recurrence interval is 2.3 years. Data are expressed as ratio of discharge after urbanization to discharge under previous conditions. Data from James (1965) have no superscript.

Percentage of area served by storm sewerage	Percentage of area made impervious 0	20	50	80
0	1.0	[1]1.2	[1]1.8	[1]2.2
		[2]1.3	[2]1.7	[2]2.2
		1.3	1.6	2.0
20	1.1	[3]1.9	1.8	2.2
		1.4	—	—
50	1.3	[4]2.1	[1]3.2	[1]4.7
		[1]2.8	2.0	2.5
		[5]3.7	—	—
		[6]2.0	2.5	[3]4.2
		1.6	—	—
80	1.6	1.9	—	3.2
100	1.7	[1]3.6	[1]4.7	[4]5.6
		2.0	2.8	[1]6.0
		—	—	3.6

[1] Anderson (1968).
[2] Martens (1966).
[3] Wilson (1966).
[4] Carter (1961).
[5] Wiitala (1961).
[6] Espey, Morgan, and Masch (1966).

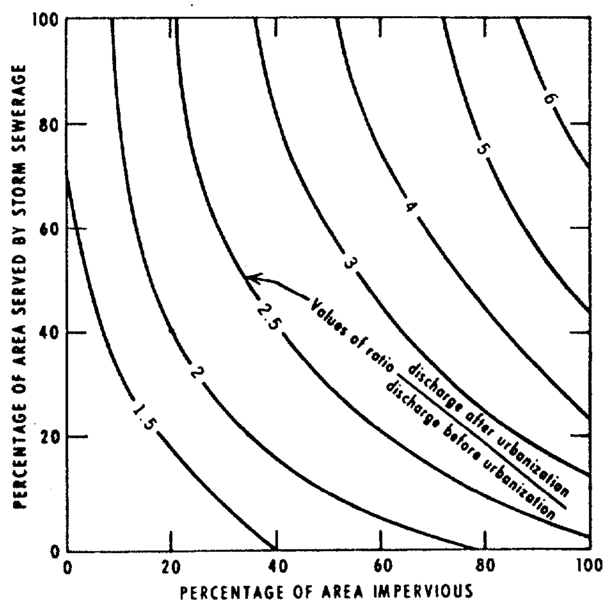

Figure 14. Effect of Urbanization on Mean Annual Flood for a 1-Square-Mile Drainage Area (Leopold, 1968).

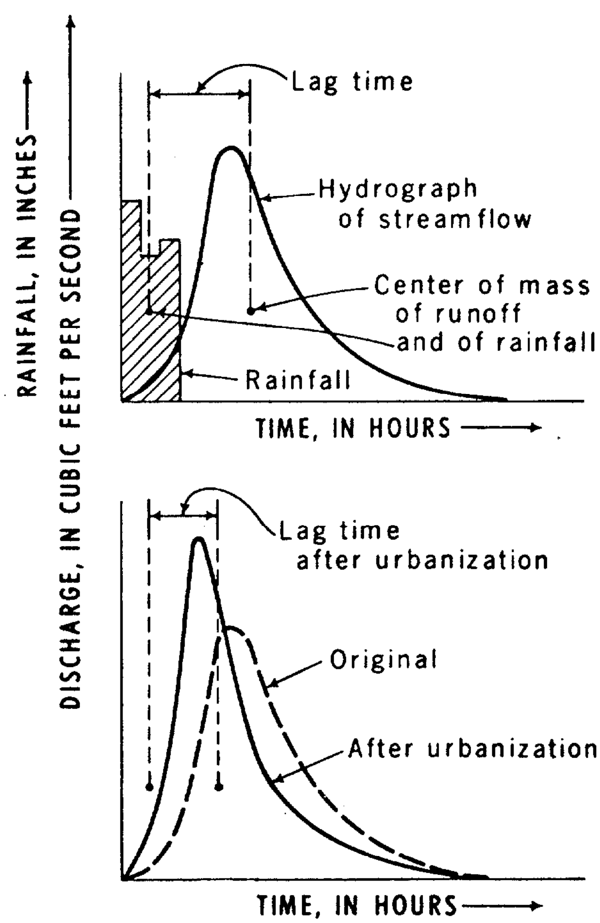

Figure 15. Hypothetical Unit Hydrographs Relating Runoff to Rainfall, With Definitions of Significant Parameters (Leopold, 1968).

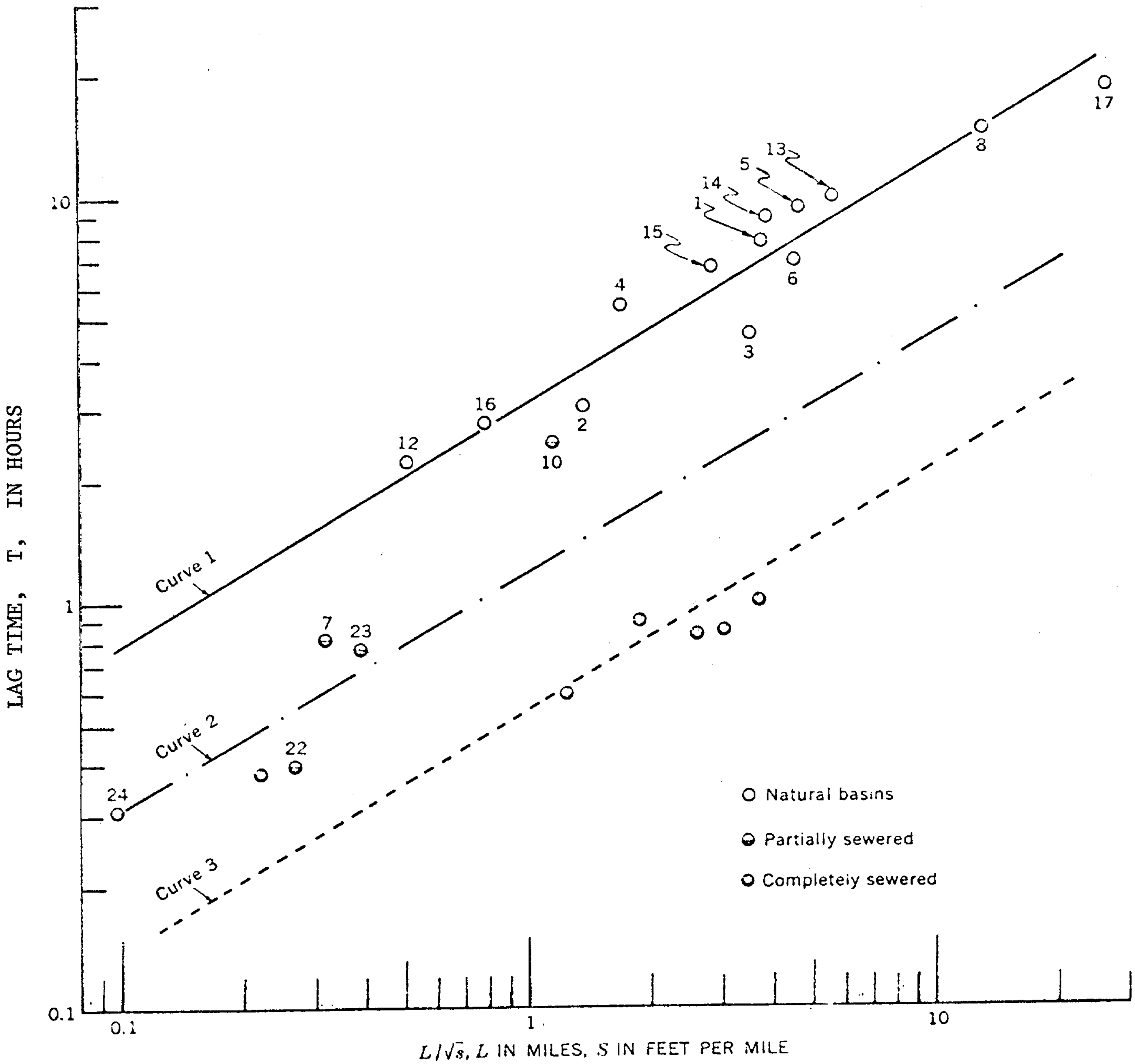

Figure 16. Effect of surburban development on lag time (Carter, 1961).

Antoine (1964) found that the percent of impervious area in urbanized basins is a function of lot size, as shown in Table 9.

Table 9. Lot Size vs. Impervious Surface Area (Antoine, 1964).

Lot size of residential area (sq ft)	Impervious surface area (percent)
6,000	80
6,000–15,000	40
15,000	25

In a study done by the U.S. Army Corps of Engineers (1973), impervious area was related to population density in Figure 17. Here "u" equals the ratio of imperviousness to the drainage area. The variable (1 + y) provided a parameter ranging from 1.0 for an undeveloped area to 2.0 for a completely urbanized (impervious) area.

Sediment-Related Impacts

Leopold (1968) in reviewing findings by various researchers, concludes that generally sediment yields from urbanized areas exceed those from rural areas due to the construction activities associated with urban development. An assessment of sediment production from urban areas should therefore be done using the information included above under Construction and Construction portions of the Additional Selected References on Land Use Impacts.

Upon the completion of urbanization in a particular area, construction, and therefore sediment production, can be expected to decline. Sediment yields may decrease to below levels found previous to urbanization as a result of the presence of artificial drainage systems and impervious surfaces. The erosive capability of the storm discharge will increase due to decreases in sediment load.

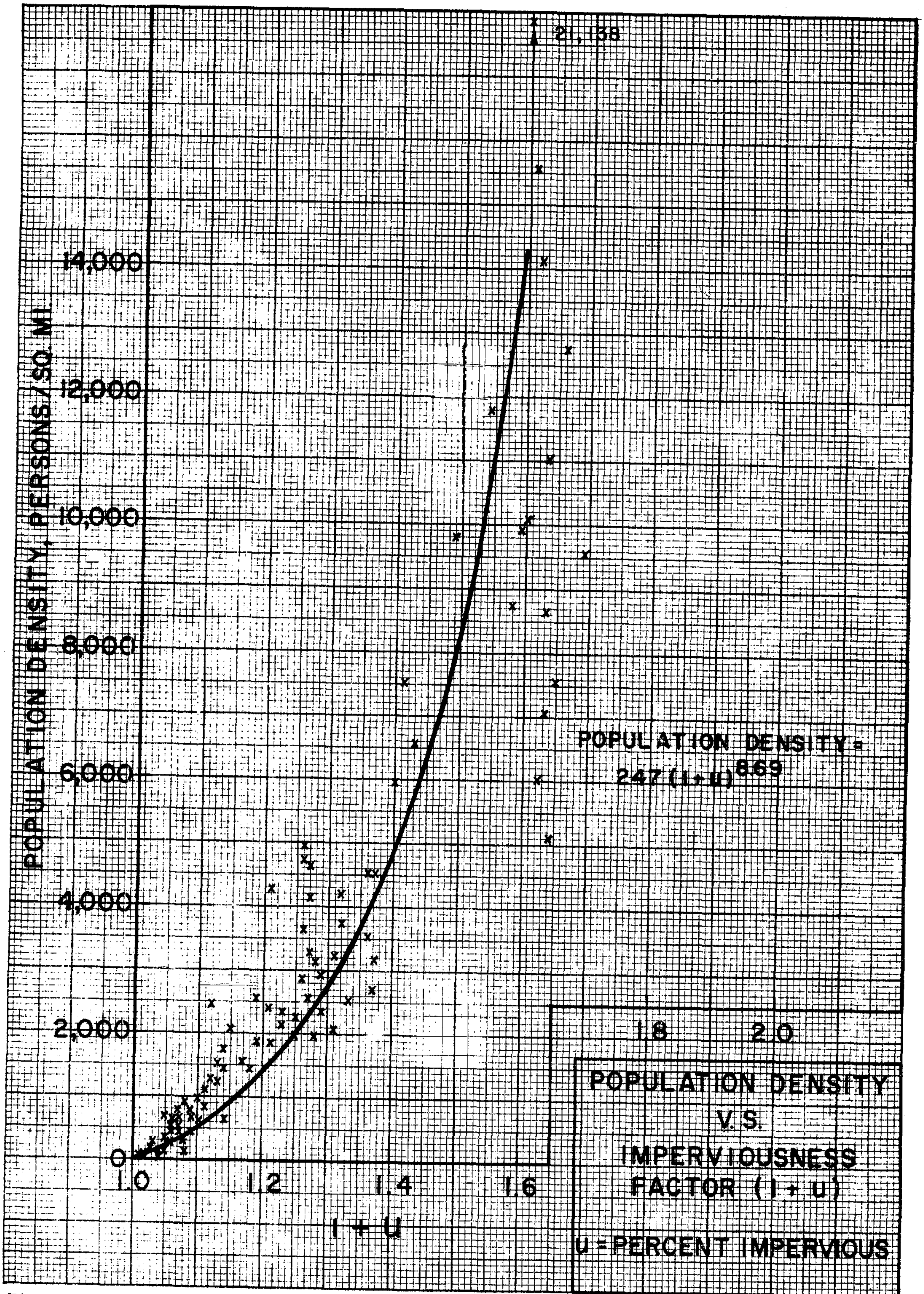

Figure 17. Population Density vs. Imperviousness Factor (U.S. Army Corps of Engineers, 1973).

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APPENDIX C

DOCUMENTATION OF NATIONAL DATA SOURCES RELATIVE TO STREAM-RELATED HAZARDS AND ASSESSMENT OF DATA FOR APPLICATION TO HIGHWAY AND BRIDGE SITES

By

G. L. Smith

I. INTRODUCTION

Maps, aerial photographs, and hydrologic, geologic, soil and other data are important tools to be used by engineers to analyze stream-related hazards. Usually these data are scattered among federal, state, and local agencies and private industry. The purpose of this Appendix is to document the sources and types of data which are generally obtainable from various agencies and which are useful in the evaluation of stream-related hazards.

This Appendix includes 1) documentation of data sources, the type of data archived, and an assessment of the usefulness of the data; 2) the identification of national centers which provide technical assistance for an indepth analysis, interpretation, and assessment of specific types of data applicable to site selection of highways and bridges; and 3) compilation of the addresses of the major agencies which provide the data sources and a list of reports which describe data sources.

The cost of obtaining this data obviously varies. Usually the expense is minimal because state and federal agencies produce these data at cost. Obtaining data from private industry can be a problem because such data may be proprietary information. It is difficult to make a general statement about the costs and benefits of acquiring data for specific hazard analysis. As a general rule, if data are available it is economically justified to purchase them. If it becomes necessary to collect data, a rough estimate of the cost/benefit ratio should be made.

The time needed for obtainment is normally about three to four weeks for data from national centers. A telephone call or visit may expedite the process.

II. DATA ORIENTATION

A. Remote Sensing Imagery

Remote sensing, and especially aerial photography, is a very important data source for the transportation engineer. The methods of obtaining these data with examples of their use are given in Appendix D.

The U.S. Army Corps of Engineers has collected many aerial photographs and other remote sensing data for the various river basins for which they have authority. However, there are numerous other agencies that store this type of data in their district offices. The amount of this data will increase with time.

Table 1 is a general listing of federal agencies having remote sensing imagery, according to the type of products. In this section remote sensing data listed are available at various federal agencies (Table 2), Corps of Engineers (Table 3), and state agencies (Table 4).

Table 1. Governmental Sources* of Remote Sensing Imagery.

Panchromatic	Color	Color Infrared	Black & White Infrared	Thermal Infrared	Side-looking Airborne Radar	Multiband	Photo Indexes
ASCS	BPA	ASCS	DIA	DIA	DIA	DIA	ASCS
BPA	BLM	BLM	NOSCMD	TVA			NOSCMD
BLM	DIA	DIA	SCS				
DIA	NOSCMD	NOSCMD	TVA				
NARS	NOSLSC	SCS	USFS				
NOSCMD	SCS	TVA					
NOSLSC	TVA	USBR					
SCS	USBR	USFS					
SRBC	USFS	USGSERC					
TVA	USGSERC	USGSEROS					
USBR	USGSEROS						
USFS							
USGSERC							
USGSEMC							
USGSWMC							
USGSEROS							
USGSMCMC							
USGSRMMC							

*See Chapter V for definition of acronyms.

Table 2. Some Types and Scales of Remote Sensing Imagery Available from Federal Government Agencies*.

Agency*	Products Available	Scales Available (Predominant Scale)
ASCS	Panchromatic, Color IR	1:10,000 to 1:120,000 (1:20,000 for Color IR, 1:120,000 for Panchromatic)
BPA	Panchromatic, Color	1:6,000 to 1:48,000 (1:12,000)
BLM	Panchromatic, Color, Color IR	1:12,000 to 1:125,000 (1:31,680)
DIA	Panchromatic, Color, Color IR, Black and White IR, Thermal IR, SLAR, Multiband	1:1,000 to 1:100,000
NARS	Panchromatic, Photo Indexes	1:15,840 to 1:56,600
NOSCMD	Panchromatic, Black and White IR, Color, Color IR	1:5,000 to 1:60,000
NOSLSC	Panchromatic, Color	1:10,000 to 1:30,000 (1:30,000)
SCS	Panchromatic, Black and White IR, Color, Color IR, Photo Indexes	1:6,000 to 1:80,000 (1:15,840)
SRBC	Panchromatic	1:12,000 to 1:19,500 (1:12,000)
TVA	Panchromatic, Black and White IR, Color, Color IR, Thermal IR, Photo Mosaics	----
USBR	Panchromatic, Color, Color IR	1:600 to 1:24,000

Table 2 (Continued)

Agency*	Products Available	Scales Available (Predominant Scale)
USFS	Panchromatic, Black and White IR, Color, Color IR, Photo Indexes	1:6,000 to 1:80,000 (1:15,840)
USGSERC	Panchromatic, Color, Color IR	1:600 to 1:24,000
USGSEMC	Panchromatic, Photo Indexes	1:12,000 to 1:56,000 (1:24,000)
USGSWMC	Panchromatic	1:6,000 to 1:40,000
USGSEROS	Panchromatic, Color, Color IR	USGS: 1:12,000 to 1:90,000 (1:24,000)
		NASA: 1:30,000 to 1:120,000
USGSMCMC	Panchromatic	1:11,000 to 1:80,000
USGSRMMC	Panchromatic	1:11,000 to 1:80,000

*See Chapter V for definition of acronyms.

Table 3. U.S. Army Corps of Engineers Remote Sensing Imagery.

District	Products Available	Scales Available (Predominant Scale)	Available Dates
Lower Mississippi Valley Division			
Memphis	Panchromatic, Color	1:3,000 to 1:36,000	1943-1975
New Orleans	Panchromatic, Color, Color IR	1:2,000 to 1:48,000 (1:10,000 to 1:20,000)	1930-1975
St. Louis	Panchromatic, Black and White IR, Color, Color IR	1:12,000 to 1:24,000	1929-1975
Vicksburg	Panchromatic, Color IR	1:4,800 to 1:20,000	1930-1975
Missouri River Division			
Kansas City	Panchromatic, Color, Color IR, Black and White IR, SLAR	1:4,800 to 1:250,000	1930-1975
Omaha	Panchromatic, Color, Color IR	1:6,000 to 1:24,000	1928-1975
New England Division			
	Panchromatic, Color, Color IR, Thermal IR	None listed	None listed
North Atlantic Division			
Baltimore	Panchromatic, Color, SLAR, Thermal IR, Color IR	1:600 to 1:125,000	Late 1940's to 1975
New York	Panchromatic	1:4,800	1963-1975

Table 3 (Continued)

District	Products Available	Scales Available (Predominant Scale)	Available Dates
Norfolk	Panchromatic, Color, Color IR	1:1,200	None listed
Philadelphia	Panchromatic, Color	1:600 to 1:24,000	
<u>North Central Division</u>			
Buffalo	Panchromatic, Color	1:2,400 to 1:120,000	1940's-1975
Chicago	Panchromatic, Color, Black and White IR	1:3,000 to 1:24,000	Early 1960's
Detroit	Panchromatic, Color	1:6,000 to 1:10,000	1973-1975
Rock Island	Panchromatic, Color IR	1:6,000 to 1:30,000	1973-1975
St. Paul	Panchromatic	1:5,000	1920-1975
<u>North Pacific Division</u>			
Alaska	None availble		
Portland	Panchromatic, Color, Color IR	1:6,000 to 1:24,000	1936-1975
Seattle	Panchromatic, Color, Color IR	1:36o to 1:48,000	1930-1975
Walla Walla	Panchromatic, Color	1:2,000 to 1:84,000 (1:4,800 to 1:6,000)	1949-1975
<u>Ohio River Division</u>			
Huntington	Panchromatic, Color, Color IR	1:3,000 to 1:24,000	1958-1976

Table 3 (Continued)

District	Products Available	Scales Available (Predominant Scale)	Available Dates
Louisville	Panchromatic, Color, Color IR, Thermal IR	1:3,000 to 1:12,000 (1:12,000)	1937-1975
Nashville	Panchromatic, Color	1:5,000 to 1:24,000	1930-1975
Pittsburgh	Panchromatic, Color, Color IR	1:4,800 to 1:16,500	Late 1930's to 1975
South Atlantic Division			
Charleston	Panchromatic, Color	1:7,200 to 1:24,000	Late 1960's to 1975
Jacksonville	Panchromatic	1:7,200 to 1:10,000 (1:10,000)	1930-1975
Mobile	Panchromatic, Color, Color IR, Black and White IR	1:2,400 to 1:30,000	Early 1940's to 1975
Savannah	Panchromatic	1:1,200 to 1:24,000	1952-1975
Wilmington	Panchromatic, Color, Color IR, Black and White IR	1:4,800 to 1:20,000	1963-1975
South Pacific Division			
Los Angeles	Panchromatic, Color	1:2,400 to 1:24,000	1939-1975
Sacramento	Panchromatic, Black and White IR, Color	1:2,400 to 1:24,000 (1:6,000)	1937-1975

Table 3 (Continued)

District	Products Available	Scales Available (Predominant Scale	Available Dates
San Francisco	Panchromatic, Color, Color IR, Thermal IR, SLAR, Multispectral	1:4,600 to 1:250,000	1939-1975
Southwestern Division			
Albuquerque	Panchromatic, Color	1:1,200 to 1:6,000	1966-1975
Fort Worth	Panchromatic	1:4,800 to 1:36,000	None specified
Galveston	Panchromatic, Color	1:1,200 to 1:24,000	Early 1960's to 1975
Little Rock	Panchromatic, Black and White IR	1:4,800 to 1:20,000 (1:12,000)	1932-1975
Tulsa	Panchromatic, Color	1:10,000 to 1:40,000	1940-1975
Huntsville Division			
	Panchromatic, Color IR	(1:7,200)	1935-1975
Coastal Engineering Research Center	Panchromatic, Black and White IR, Color, Color IR	1:1,200 to 1:24,000	1940's-1975
Topographic Laboratories	Panchromatic, Color, Color IR, Thermal IR	1:5,000 to 1:100,000 (1:20,000)	1937-1975
Cold Regions Research and Engineering Lab.	Panchromatic, Color, Color IR	1:2,400 to 1:24,000	1971-1975

Table 4. Available Remote Sensing Imagery--State Agencies

State	Agency or Organization	Type	Range of Scales	Coverage Period	Contact
Alabama	Alabama Highway Dept. 11 South Union St. Montgomery, AL 36104	Black-and-white	1:4,800-1:40,000 Predominant-- 1:20,000	1952-1975	Chief Engineer, Bureau of Surveys and Plans
	Alabama State Dept. of Revenue Ad Valorem Tax Div. 1021 Madison Ave. Montgomery, AL 36111	Black-and-white	1:3,600-1:24,000	1972-1975	Evaluation Supervisor, Mapping Section
	Geological Survey of Alabama PO Drawer O University, AL 35486	Black-and-white Black-and-white IR Color IR Thermal IR	1:6,000-1:24,000	1970-1974	Chief, Remote Sensing Division
Arizona	Arizona Highway Dept. 1731 W. Jackson Room 61 Phoenix, AZ 85007	Black-and-white	1:3,000-1:90,000 Predominant-- 1:36,000	1936-1975	Cartographer, Photogrammetry and Mapping Section
Arkansas	Arkansas Highway Dept. PO Box 2261 Little Rock, AR 77203	Black-and-white Color (planned for near future)	1:3,000-1:20,000 Predominant-- 1:20,000	1967-1975	Chief, Photogrammetry Section
	Dept. of Parks and Tourism State Parks Div. 1510 Broadway Little Rock, AR 72202	Black-and-white	1:2400-1:4800	1969-1975	Assistant Director, Planning and Development Section
California	California Dept. of Transportation 1120 N Street Sacramento, CA 95805	Black-and-white Color	1:2400-1:180,000 Predominant--1:3000	1927-1975	Office of Chief, Geometronics

Table 4 (Continued)

State	Agency or Organization	Type	Range of Scales	Coverage Period	Contact
Colorado	Dept. of Highways 4201 E. Arkansas St. Denver, CO 80222	Black-and-white Color (limited)	1:1200-1:12,000	Early 1950's - 1975	Asst. Chief Engineer for Engineering
	Dept. of Natural Resources Colorado Geological Survey Room 254, Columbine Bldg. 1845 Sherman St. Denver, CO 80203	Black-and-white	1:80,000	1970-1975	Director, Colorado Geological Survey
Connecticut	Dept. of Environmental Protection Natural Resources Center 165 Capitol Ave. Hartford, CT 06109	Black-and-white Color Color IR	1:2400-1:12,000 Predominant-- 1:12,000	1932-1975	Chief, Natural Resources Center
	Dept. of Transportation 24 Wolcott Hill Rd. Wethersfield, CT 06109	Black-and-white	Predominantly 1:2400	1960-1975	Chief, Surveys and Mapping Section
Delaware	Dept. of Highways and Transportation PO Box 778 Dover, DE 19901	Black-and-white	1:4800-1:12,000	1937-1975	Chief, Mapping Section
	Delaware Geological Survey University of Delaware 101 Pennsy Hall Newark, DE 19711	Black-and-white Color Color IR	1:20,000-1:24,000 Predominant-- 1:20,000	1954-1973	State Geologist
	Kent County Planning & Zoning Office 56 The Green Dover, DE 19901	Black-and-white	1:2400-1:19,200	1968-1975	Planning Director

Table 4 (Continued)

State	Agency or Organization	Type	Range of Scales	Coverage Period	Contact
Delaware (cont'd)	Newcastle County Dept. of Planning Advanced Planning Div. 2701 Capitol Trail Newark, DE 19711	Black-and-white	1:2400-1:4800	1946-1968	Director, Dept. of Planning
	Sussex County Dept. of Finance County Courthouse Georgetown, DE 19947	Black-and-white	1:12,000	1968-1972	Head, Tax Mapping Section
Florida	Central & South Florida Flood Control District PO Box V W. Palm Beach, FL 33402	Black-and-white	1:4800-1:24,000	Early 1950's -1975	Chief, Right-of-Way Div.
	Florida Dept. of Transportation Topographic Office Hayden-Burns Bldg. Tallahassee, FL 32304	Black-and-white Color Black-and-white IR Color IR	1:12,000-1:24,000	1958-1975	Topographic Engineer
	Northwest Florida Water Management Dist. 325 John Knox Road Room C-135 Tallahassee, FL 32303	Black-and-white	Predominantly 1:24,000	1970-1975	Director
	St. John's River Water Management District Rt. 2, Box 695 Palatka, FL 32077	Black-and-white Color IR	1:24,000	1972-1975	Director

Table 4 (Continued)

State	Agency or Organization	Type	Range of Scales	Coverage Period	Contact
Florida (cont'd)	Suwanee River Water Management District PO Drawer K White Springs, FL 32096	Black-and-white Color IR	1:24,000-1:60,000	1972-1973	Director
	Southwest Florida Water Management District PO Box 457 Brooksville, FL 33512	Black-and-white	1:2400-1:12,000	1970-1975	Supervisor, Aerial Mapping and Flood Delineation Section
Georgia	Georgia Dept. of Transportation Office of Location 2 Capitol Square Atlanta, GA 30334	Black-and-white Color Color IR	1:2400-1:24,000 Predominant--1:16,000	1953-1975	State Highway Location Engineer
Idaho	Idaho Dept. of Lands State House Boise, ID 83720	Black-and-white	1:15,840-1:60,000	1965-1975	Supervisor, Technical Services Section
	Idaho Transportation Dept. Div. of Highways PO Box 7129 Boise, ID 83707	Black-and-white Color Color IR	1:6000-1:30,000	1957-1975	Environmental and Corridor Planning Supervisor
Illinois	Illinois Dept. of Transportation Div. of Highways Bureau of Design and Highways 3200 S. 31st St. Springfield, IL 62706	Black-and-white Color IR	1:3000-1:24,000	1955-1975	Secretary, Dept. of Transportation, 2300 Senator Dirksen Parkway, Springfield, IL 62764

Table 4 (Continued)

State	Agency or Organization	Type	Range of Scales	Coverage Period	Contact
Indiana	Indiana Dept. of Natural Resources Div. of Water, Rm 605 State Office Bldg. Indianapolis, IN 46204	Black-and-white	1:5000-1:7920	1965-1975	Chief, Div. of Water
	Indiana Dept. of Natural Resources Geological Survey 611 N. Walnut Grove Bloomington, IN 47401	Black-and-white	1:20,000	1937-1964	Asst. State Geologist, Survey Dept.
	State Highway Commission Room 1301 100 N. Senate Indianapolis, IN 46204	Black-and-white	1:7200-1:24,000	1969-1975	Manager, Photogrammetry and Reproduction Div.
Iowa	Dept. of Transportation Highway Div. 826 Lincoln Way Ames, IA 50010	Black-and-white Color (limited)	1:2400-1:90,000	1958-1975	Design Engineer, Design Dept.
	Iowa Geological Survey Remote Sensing Laboratory 123 N. Capitol St. Iowa City, IA 52240	Black-and-white Color Color IR Multiband	1:8000-1:80,000	1971-1975	Chief, Remote Sensing Laboratory
	State Conservation Commission 300 Fourth St. Des Moines, IA 50319	Black-and-white	1:1200-1:2400 Predominant-- 1:1200	1961-1975	Director, State Conservation Commission
Kansas	Kansas Dept. of Transportation State Office Bldg. Topeka, KS 66612	Black-and-white	1:1200-1:36,000 Predominant-- 1:24,000	1958-1975	Secretary, Dept. of Transportation

Table 4 (Continued)

State	Agency or Organization	Type	Range of Scales	Coverage Period	Contact
Kentucky	Kentucky Dept. of Commerce 133 Holmes St. Frankfort, KY 40601	Black-and-white	1:24,000 (predominant) to 1:52,800	1948-1973	Map Sales
	Kentucky Dept. of Transportation State Office Bldg. High St. Frankfort, KY 40601	Black-and-white Color (limited)	1:3000-1:24,000	1970-1975	Chief, Div. of Photogrammetry
Louisiana	Louisiana Dept. of Public Works Box 44155 Capitol St. Baton Rouge, LA 70804	Black-and-white	1:20,000	1944-1975	Chief Engineer
	Louisiana Dept. of Highways PO Box 44245 Capitol St. Baton Rouge, LA 70804	Black-and-white	1:2400-1:14,400	1962-1975	Director, Dept. of Highways
Maine	Maine Dept. of Conservation Bureau of Public Lands State Office Bldg. Augusta, ME 04330	Black-and-white	Predominantly 1:15,840	1974-1975	James Sewell Co., Oldtown, Maine
	Maine Dept. of Transportation Div. of Bureau of Highways Augusta, ME 04330	Black-and-white Color Color IR	1:3000-1:12,000 Standard--1:12,000	Mid-1950's -1975	James Sewell Co., Oldtown, Maine
	James Sewell Co. Box 433 Oldtown, ME 04468	Black-and-white Color Color IR	1:3600-1:30,000 Predominant--1:15,840	1964-1975	----

Table 4 (Continued)

State	Agency or Organization	Type	Range of Scales	Coverage Period	Contact
Maryland	Maryland Dept. of Natural Resources Water Resources Admin. Tawes State Office Bldg. Annapolis, MD 21401	Color Black-and-white IR Color IR	1:12,000	1971-1972	Wetlands Permit Section
	Maryland Dept. of State Planning 301 W. Preston St. Baltimore, MD 21201	Black-and-white Color Color IR	1:60,000-1:130,000	No information	Comprehensive State Planning Div.
	Maryland Dept. of Transportation 300 W. Preston St. Baltimore, MD 21203	Black-and-white	1:3000-1:24,000	1950-1975	Bureau of Project Planning, Box 707, Room 404, Baltimore, MD 21203
Massachusetts	Massachusetts Dept. of Public Works 100 Nashua St. Boston, MA 02114	Black-and-white	Predominantly 1:7200	Mid-1950's -1975	Chief, Photogrammetrics
Michigan	Michigan Dept. of Highways and Transportation State Highway Bldg. PO Drawer K Lansing, MI 48904	Black-and-white Color IR (limited and poor quality)	Predominantly 1:3000	1950-1975	Director, Dept. of Highways and Transportation
	Michigan Dept. of Natural Resources Div. of Forestry Lansing, MI 48926	Black-and-white	1:15,840	1968	Abrams Aerial Surveys, Inc., Lansing, MI
	Michigan Dept. of Natural Resources Div. of Water Resources Lansing, MI 48926	Color	1:10,000	April 1974	Water Development Section, Div. of Water Resources, DNR

Table 4 (Continued)

State	Agency or Organization	Type	Range of Scales	Coverage Period	Contact
Michigan (cont'd)	Environmental Research Institute of Michigan Resources & Technology Div. Ann Arbor, MI 48106	Black-and-white Color, Color IR Multispectral Radar	1:2000-1:250,000	1966-1975	Director, Resources and Technology Div.
	Southeast Michigan Council of Governments (SEMCOG) 1249 Washington Blvd. Detroit, MI 48226	Black-and-white	1:24,000-1:36,000	1966-1975	Information Services, SEMCOG
Minnesota	Department of Highways Office of Surveying and Mapping Rm 711 Minnesota Highway Bldg. John Ireland Blvd. St. Paul, MN 55155	Black-and-white Color (limited) Color IR (limited)	1:3000-1:24,000	1961-1975	Director, Office of Surveying and Mapping
	Institute of Agriculture Remote Sensing Laboratory University of Minnesota St. Paul, MN 55108	Black-and-white Color Color IR Multispectral	1:2000-1:80,000	1960-1975	Chief, Remote Sensing Laboratory
	State Planning Agency Capitol Square Bldg. 550 Cedar St. St. Paul, MN 55101	Black-and-white	1:90,000	1968-1969	Chief, Mapping Section Room 101
Mississippi	State Highway Dept. Transportation and Planning Section PO Box 1850 Jackson, MS 39205	Black-and-white	1:20,000-1:40,000	1956-1975	Director of Highways

Table 4 (Continued)

State	Agency or Organization	Type	Range of Scales	Coverage Period	Contact
Mississippi (cont'd)	State Highway Dept. Roadway Design Div. PO Box 1850 Jackson, MS 39205	Black-and-white Color (near future)	1:2400-1:24,000	1958-1975	Director of Highways
Missouri	Missouri Dept. of Agronomy 214 Waters Hall University of Missouri Columbia, MO 65201	This department has compiled an "Index of Aerial Photography and Space Images of Missouri" which includes all known photography flown before May 1, 1975, within the state. Only photography available for purchase or loan is included in this index.			
	Missouri Dept. of Natural Resources PO Box 250 Rolla, MO 65401	Color Color IR Thermal IR	1:17,000-1:62,500	1970-1975	Div. of Research and Technical Information
	State Highway Commission Div. of Surveys and Plans State Highway Bldg. Jefferson City, MO 65101	Black-and-white	1:3000-1:36,000	1959-1975	Division Engineer, Div. of Surveys and Plans
Montana	Montana Highway Dept. Sixth Ave. & Roberta Helena, MT 59601	Black-and-white	1:480-1:7200	Late 1950's -1975	Chief, Photogrammetry Unit
Nebraska	Nebraska Dept. of Natural Resources State Capitol Basement Room 17A Lincoln, NE 68508	Black-and-white	1:6000-1:12,000 Predominant-- 1:12,000	1965-1975	Photogrammetry Section
	Nebraska Dept. of Roads PO Box 94759 Highways Bldg. Lincoln, NE 68509	Black-and-white	1:6000-1:24,000	1955-1975	Head, Reproduction Room 110

Table 4 (Continued)

State	Agency or Organization	Type	Range of Scales	Coverage Period	Contact
Nebraska (cont'd)	Conservation & Survey Div. Remote Sensing Center University of Nebraska Nebraska Hall Lincoln, NE 68508	Black-and-white Color Color IR	1:40,000	1970-1975	Chief, Remote Sensing Center
Nevada	Nevada Bureau of Mines University of Nevada Reno, NV 89507	Black-and-white Black-and-white IR Color, Color IR	1:32,000-1:120,000	1954-1975	Director Nevada Bureau of Mines
	Nevada Dept. of Conservation & Natural Resources Div. of Water Resources Carson City, NV 89710	Black-and-white Color	1:7200-1:24,000	1970-1975	Office Engineer, Div. of Water Resources
	Nevada Dept. of Highways 1263 S. Stewart Carson City, NV 89712	Black-and-white Color Color IR	1:3000-1:30,000	1959-1975	Chief Planning Survey Engineer
	State Land Use Planning Agency 201 South Fall St. Carson City, NV 89701	This agency has compiled a "Nevada Mapping and Aerial Photography Index" dated June, 1975. The index describes aerial photography flown primarily by federal agencies within the State of Nevada.			
	152 Tactical Reconnaissance Group/IN May ANG Base Reno, NV 89502	Black-and-white	1:25,000-1:70,000	1962-1975	CO, 152 TRG/IN
New Hampshire	Central New Hampshire Regional Planning Commission 10 Grand View Road Bow, NH 03301	Black-and-white	1:12,000	Spring 1975	Director, Central New Hampshire Regional Planning Commission

Table 4 (Continued)

State	Agency or Organization	Type	Range of Scales	Coverage Period	Contact
New Hampshire (cont'd)	New Hampshire Dept. of Public Works & Highways 85 Loudon Road Concord, NH 03301	Black-and-white	1:600-1:4800	1956-1975	Commissioner, Dept. of Public Works and Highways.
	New Hampshire Dept. of Resources and Economic Development 5 Langdon St. Concord, NH 03301	Black-and-white Color	1:18,000-1:90,000	1962-1975	Chief, Graphic Arts Section
New Jersey	New Jersey Dept. of Environmental Protection Bureau of Geology and Topography PO Box 2809 1474 Prospect St. Trenton, NJ 08625	Black-and-white	1:24,000	1972	Chief, Topographic Section
	New Jersey Dept. of Environmental Protection Office of Environmental Analysis Labor and Industry Bldg. Room 710 John Fitch Way Trenton, NJ 08625	Black-and-white Color Color IR	1:12,000	1971-1972	Office of Environmental Analysis
	Dept. of Transportation 1035 Parkway Ave. Trenton, NJ 08625	Black-and-white	1:360-1:4800	1969-1972	Head Drafting Technician, Bureau of Data Resources, Room 3300
New Mexico	State Engineer's Office Bataan Memorial Bldg. Santa Fe, NM 87501	Black-and-white	1:6000-1:24,000 Predominant-- 1:18,000	1950-1975	State Engineer's Office

Table 4 (Continued)

State	Agency or Organization	Type	Range of Scales	Coverage Period	Contact
New Mexico (cont'd)	State Highway Commission PO Box 1149 Santa Fe, NM 87501	Black-and-white Color (limited)	1:3000-1:6000 Predominant--1:6000	1958-1975	Asst. Section Head, Location & Photogrammetry Section, Room 137-A
New York	Dept. of Transportation State Campus 1220 Washington Ave. Albany, NY 12226	Black-and-white Color Color IR	1:3000-1:12,000 Predominant-- 1:12,000	1950's-1975	Head, Map Information Unit, Bldg. 4, Room 105
North Carolina	Dept. of Transportation State Highway Bldg. PO Box 25201 Raleigh, NC 27611	Black-and-white	1:2400-1:48,000 Predominant--1:6000	1959-1975	Head, Photogrammetry Unit
North Dakota	State Highway Dept. State Highway Bldg. Capitol Grounds Bismarck, ND 58501	Black-and-white Color (limited)	1:2400-1:12,000	1955-1975	Chief, Photogrammetry and Surveying Div.
Ohio	Dept. of Natural Resources Div. of Water Building E, Fountain Sq. Columbus, OH 43224	Black-and-white Color IR (limited)	1:24,000-1:80,000 Predominant-- 1:24,000	1973-1975	Remote Sensing Manager
	Dept. of Transportation 450 E. Town St. Columbus, OH 43215	Black-and-white	1:2400-1:80,000	1946-1975	Chief, Aerial Engineering Section
Oklahoma	Dept. of Highways Jim Thorpe Bldg. Oklahoma City, OK 73105	Black-and-white	1:3000-1:24,000	1955-1975	Department Head, Survey Div.
	Dept. of Librarys 200 N. 18th St. Oklahoma City, OK 73105	Black-and-white	1:20,000	1939-1946	Head, Archives and Records Div.

Table 4 (Continued)

State	Agency or Organization	Type	Range of Scales	Coverage Period	Contact
Oregon	State Forestry Dept. 2600 State St. Salem, OR 97310	Black-and-white	1:64,000	1968-1975	Mapping Supervisor
	Dept. of Transportation State Highway Bldg. Salem, OR 97310	Black-and-white Color Color IR	1:3000-1:12,000	1955-1975	Photogrammetric Engineer, Room 26
Pennsylvania	Dept. of Transportation Transportation & Safety Bldg. Commonwealth & Forster Sts. Harrisburg, PA 17123	Black-and-white Black-and-white IR Color Color IR	1:3000-1:24,000	1960-1975	Chief, Photogrammetry and Surveys Div.
Rhode Island	Dept. of Transportation State Office Bldg. Providence, RI 02903	Black-and-white	1:1200-1:12,000	1970-1975	Aerial Data Reduction Associates, c/o Village Green Associates, Inc., 11 North Road, Pease Dale, RI 02883
South Carolina	Land Resources Commission Dept. of Mining and Reclamation PO Box 11708 Columbia, SC 29211	Black-and-white	1:12,000	1974-1975	Mr. Jack Whisnant, Geologist
	Water Resources Commission Land & Water Resources Div. 3830 Forest Drive PO Box 4515 Columbia, SC 29240	Color Color IR	1:12,000-1:24,000	1973-1974	Director, Water Resources Commission
	Wildlife and Marine Resources Dept. South Carolina Resources Center PO Box 12559 Charleston, SC 29412	Color Color IR	1:6000-1:12,000	1973-1975	Mr. Robert H. Dunlap, Resource Geographer

Table 4 (Continued)

State	Agency or Organization	Type	Range of Scales	Coverage Period	Contact
South Dakota	South Dakota State University Remote Sensing Institute Brookings, SD 57006	Black-and-white Black-and-white IR Color, Color IR Thermal IR Multispectral	1:3000-1:95,000	1969-1975	Director, Remote Sensing Institute
	State Highway Dept. State Highway Bldg. Pierre, SD 57501	Black-and-white Color	1:3000-1:24,000 Predominant-- 1:24,000	1965-1975	Head, Photogrammetry and Surveys
	State Planning Bureau State Capitol Pierre, SD 57501	Maintains computerized listing of all known state and federal photography flwon in South Dakota.			
Tennessee	Dept. of Transportation 4113 Bldg. Vultee Blvd. Nashville, TN 37217	Black-and-white	1:2400-1:24,000	1968-1975	Director, Aerial Surveys Div.
Texas	Dept. of Highways and Public Transportation 38 & Jackson Sts. Austin, TX 78731	Black-and-white	1:2400-1:24,000	1962-1975	Head, Div. of Automation
	General Land Office Stephan F. Austin State Office Bldg. Austin, TX 78701	Black-and-white Color IR	Predominantly 1:24,000	1960-1975	State Land Commissioner, State of Texas, Stephan F. Austin Bldg., Austin, TX 78701
	Texas Forest Service College Station, TX 77843	Black-and-white Color IR	1:4000-1:24,000	1973-1975	Director, Texas Forest Services
	Texas Parks & Wildlife Dept Engineering Div. John H. Reagan Bldg. Austin, TX 78701	Black-and-white Color Color IR	1:3000-1:12,000	1960's-1975	Director of Engineering

Table 4 (Continued)

State	Agency or Organization	Type	Range of Scales	Coverage Period	Contact
Utah	Dept. of Natural Resources Div. of Parks and Recreation 1596 West N. Temple Salt Lake City, UT 84114	Black-and-white	1:12,000-1:24,000	1966-1975	Director, Div. of Parks and Recreation, c/o Landscape Architect and Environmental Planner
	Dept. of Transportation State Office Bldg. Salt Lake City, UT 84114	Black-and-white Color (limited)	1:6000-1:24,000	1957-1975	Location Engineer, Room 408
Vermont	Dept. of Highways State Administration Bldg. Monpelier, VT 05602	Black-and-white Color (limited)	1:3000-1:20,000	1954-1975	Aerial Engineer, Planning Div.
Virginia	Dept. of Highways and Transportation 1401 E. Broad St. Richmond, VA 23219	Black-and-white Color (limited)	1:12,000-1:36,000 Predominant-- 1:16,800	1963,1975	Div. Engineer, Location and Design Div.
Washington	Dept. of Highways Highway Administration Bldg. Olympia, WA 98501	Black-and-white Color Color IR	1:2400-1:24,000	1950-1975	Asst. Director for Highway Development
	Dept. of Natural Resources Technical Services Div. Resource Inventory Section Olympia, WA 98504	Black-and-white Color Color IR	1:12,000-1:63,000	1948-1975	Dept. of Photogrammetry
West Virginia	Dept. of Highways Route and Project Planning Sec. 1900 Washington St., E. Charleston, WV 25305	Black-and-white	1:2400-1:24,000	1956-1975	Commissioner of Highways

Table 4 (Continued)

State	Agency or Organization	Type	Range of Scales	Coverage Period	Contact
Wisconsin	Dept. of Natural Resources Bureau of Water Regulation and Zoning PO Box 450 Madison, WI 53701	Publishes an "Inventory of Coastal Imagery," in which available aerial photographs and other remote sensing imagery of Wisconsin's Lake Michigan and Lake Superior shorelines are indexed. Updated periodically. Copies will be furnished on request.			
	Dept. of Transportation Hill Farm State Office Bldg. Madison, WI 53702	Black-and-white	1:3000-1:72,000	1961-1975	Engineering Services Section, Room 5B
	State Cartographer's Office 144 Science Hall University of Wisconsin Madison, WI 53706	Publishes a "Catalog of Aerial Photography" for the state of Wisconsin, in which all photography flown by state and federal agencies during 1970-1974 is indexed. Catalog will be updated annually and is available on request.			
Wyoming	Wyoming Highway Dept. Box 1708 Cheyenne, WY 82001	Black-and-white Color (limited)	1:3000-1:12,000	1958-1975	Chief, Photogrammetry and Surveys

NOTE: Table condensed from May, John R., 1978, "Guidance for Application of Remote Sensing to Environmental Management. Appendix A: Sources of Available Remote Sensor Imagery." Instruction Report M-78-1, Mobility and Environmental Systems Laboratory, U.S. Army Engineer Waterways Experiment Station, March.

Figure 1. Meandering Reach of Clark's Fork of the Yellowstone River (after Ruff et al., (1)). Note two recently formed Oxbow Lakes which are the result of meander cutoff.

The usefulness of remote sensing imagery is related directly to scale. To study general stream pattern changes and metamorphosis, any scale of imagery is tolerable as long as the stream pattern can be observed. To study detailed river behavior, a scale of 1:20,000 is preferred, with an upper limit of 1:60,000.

As shown in Figure 1, numerous details can be resolved from aerial photographs. The U.S. Geological Survey National Cartographic Information Centers provide maps showing the status of aerial photography in the United States as of July, 1970. This map shows areas that have been photographed, as reported by federal agencies and commercial firms. The agencies holding the film are given only if reproductions are available for purchase. The text on the back of the map gives detailed explanation, the names, and addresses of the reporting agencies and firms.

Also available from the USGS is a map showing the status of aerial mosaics in the United States as of September, 1970. This shows areas in the United States where mosaics have been prepared from aerial photographs, scale of the negatives, and dates of photography. The text on the back of the map includes the names and addresses of the reporting agencies and firms.

USGS aerial photographs are available through the EROS Data Center. Requests can also be placed through the National Cartographic Information Center.

Side-looking airborne radar (SLAR) images acquired by the Strategic Air Command are available through the Goodyear Aerospace Corporation. The scale of these images ranges from 1:100,000 to 1:600,000. Requests for imagery should include the latitude and longitude boundaries of the area of interest.

Federal aerial photos taken before 1940 are held in the National Archives in Washington, D.C., as special storage conditions are required for preservation of this film.

B. Satellite Imagery

A satellite picture is usually on a very large scale. Even a very large-scale photograph can indicate a change in river pattern. Sometimes satellite pictures can show change of river pattern better than a ground investigation. A transportation engineer should check satellite data when dealing with a large river system.

Satellite imagery is available from the USGS EROS Data Center in Sioux Falls, South Dakota, and from the National Cartographic Information Center (NCIC) in Reston, Virginia. In addition, Landsat imagery is available from General Electric Space Systems. Gemini and Apollo photographs are available from the Technology Application Center of the University of New Mexico.

Table 5 indicates the products and scales available from federal agencies.

C. Maps and Charts

The primary source of maps and charts is the U.S. Geological Survey, through its National Cartographic Information Centers (NCIC). Address mail orders to the

Table 5. Satellite Imagery.

Agency*	Satellite	Products Available (Color Bands)	Scales Available
ASCS	Landsat 1 & 2	MSS (G, R, NIR); RBV (G, R, NIR)	1:1,000,000 to 1:3,369,000
	Skylab		
	Multispectral System	Panchromatic (G,R); Black and White IR (IR); Color IR (G, R, IR); Aerial Color (B, G, R)	1:1,850,000
	Single Lens System	Panchromatic, Color IR, Aerial Color	1:950,000
SCS	Landsat 1	Mosaic (R, IR)	1:500,000 to 1:5,000,000
USGSEROS	Landsat 1 & 2	Black and White; Computer Compatible Tapes; Color IR, MSS (G, R, IR); RBV (G, R, IR)	1:250,000 to 1:3,369,000
	Skylab		
	Multispectral System	Panchromatic (G, R); Black and White IR (IR); Color IR (G, R, IR); Aerial Color (B, G, R)	1:1,250,000 to 1:2,850,000
	Single Lens System	Panchromatic, Color IR, Aerial Color	1:125,000 to 1:950,000
USGS	Landsat 1	MSS (G, R, IR)	1:500,000 to 1:5,000,000

*See Chapter V for definition of acronyms.

G = green
R = red
NIR = near infrared
IR = infrared
B = blue
MSS = multispectral scanner
RBV = return beam vidicon

Distribution Section, 1200 South Eads Street, Arlington, Virginia 22202, for maps of areas east of the Mississippi River, including Puerto Rico and the Virgin Islands, and to Distribution Section, Federal Center, Denver, Colorado 80225, for maps of areas west of the Mississippi including Alaska, Hawaii, Louisiana, Minnesota, Guam, and American Samoa. An order for both eastern and western maps should be sent to the closer Distribution Section. Residents of Alaska may also order Alaska maps from Distribution Section, 310 First Avenue, Fairbanks, Alaska 99701.

Maps and charts may be purchased over the counter at the following USGS offices: 1200 South Eads Street, Arlington, Virginia; 1028 General Services Administration Building, 19th and F Street, N.W., Washington, D.C.; 1109 North Highland Street, Arlington, Virginia; 900 Pine Street, Rolla, Missouri; Building 41, Federal Center, Denver, Colorado; 345 Middlefield Road, Menlo Park, California; 445 Federal Building, 709 West Ninth Street, Juneau, Alaska; and 310 First Avenue, Fairbanks, Alaska.

For a complete list of the publications available from the USGS, the reader is referred to the catalog "Publications of the Geological Survey." This catalog is free on application to the USGS, Arlington, Virginia 22202.

The following types of maps are available from the USGS.

1. Topographic maps

a. Contour maps with a scale of 1:7,000,000.

b. Base and outline maps showing state and county boundaries and names. Scales range from 1:5,000,000 to 1:16,500,000.

c. Status maps, including status of topgraphic maps, aerial photography and aerial mosaics.

d. River survey maps showing course and fall of the stream, configuration of the valley floor and adjacent slopes, and locations of towns, scattered houses, irrigation ditches, roads, and other cultural features.

If the valley is less than a mile wide, topography is shown to 100 feet or more above the water surface; if the valley is flat and wide, topography is shown for a strip of 1 to 2 miles. Potential reservoir sites are mapped to the probable flow line of the reservoir. The usual scale is 1:81,680 or 1:24,000, and the normal contour interval is 20 ft on land and 5 ft on the water surface. Many maps include proposed dam sites on a larger scale and a profile of the stream.

Most of these maps are printed in black and white, some show the contours in brown, and a few show the streams in blue. The standard-size sheet is 22 by 28 inches.

As river-survey maps were prepared largely in connection with classification of the public lands, they can concentrate on the western states. An index of river surveys is published as Water Supply Paper 995.

Published river-survey maps are shown on the state indexes to published topographic maps.

e. State maps include base, topographic and shaded-relief editions. Small base maps at a scale of 1:1,000,000 are printed in black and white. Larger base maps at a scale of 1:500,000 show drainage in blue. Base maps show county boundaries, cities, towns, villages, most smaller settlements, railroads, and water features. Base maps do not show highways or contours. Topographic maps at a scale of 1:500,000 are overprints of base maps showing highways, contours, national parks, forests, monuments, wildlife refuges, and Indian reservations. Shaded-relief maps at scales of 1:1,000,000 and 1:500,000 are overprints of base maps showing only county boundaries, larger cities, and water features; the physical features are brought out by shaded relief in color or shades of brown on the conventional plan of assumed diagonal illumination from the northwest. Contours are not shown on shaded-relief maps.

f. Metropolitan area maps are composed of several quadrangle maps of the National Topographic Map Series covering selected cities and adjacent areas.

g. Special topographic maps.

h. National Topographic Map Series. The National Topographic Map Series is a term used to designate several quadrangle map series of the United States, its territories and possessions. Each series is intended to fulfill a specific type of map requirement and is classified generally according to its scale. Large-scale maps (1:20,000, 1:24,000, and 1:30,000) are for densely settled areas and areas where detailed map information is needed for engineering planning and similar purposes. Medium-scale maps (1:62,500 and 1:63,360) are considered adequate for general use where detailed planning is not contemplated. Small-scale maps (1:125,000, 1:250,000, and 1:1,000,000) cover large areas on a single sheet and are useful in planning state and nationwide projects. A few special maps are published on other scales.

2. Geologic maps

a. Geologic maps for all states except Hawaii are available.
b. Geologic quadrangle maps with contour lines
c. Geophysical investigation maps for some special areas
d. Miscellaneous geologic investigation maps

3. Mineral resources maps.

a. Coal
b. Oil and gas
c. Minerals

4. Hydrologic investigation atlases. Special studies on geology, hydrology of alluvial deposits, ground water availability, surface drainage, stream composition, floods, and tides for different events at different locations are available.

5. Land use, land covering and associated maps. Scale is 1:250,000. Master sets of the land use, land cover and associated maps are on open file at the U.S. Geological Survey Regional Mapping Center. Information for ordering maps may be obtained from the Eastern Mapping Center, Mid-Continent Mapping Center, Rocky Mountain Mapping Center and Western Mapping Center.

Additional land use maps are available at the regional office of the U.S. Bureau of Land Management and the U.S. Soil Conservation Service.

D. Meteorological Conditions

The main source of such data is the U.S. Department of Commerce National Climatological Center (NCC). There are four types of data.

1. Daily surface data for the United States. The source of these data is the U.S. Weather Bureau. The data include maximum temperature; minimum temperature; temperature at observation time; precipitation (24-hour amount); snowfall (24-hour amount); snow depth on ground; days with smoke-haze, fog, drizzle, sleet, glaze, thunder, hail, dust-sandstorm, blowing snow, high wind, tornado; wind movement for 24 hours; amount of evaporation; maximum water temperature, pan; and water equivalent of snow on ground. In addition, prior to September, 1963, data included maximum temperature departure, maximum temperature change, minimum temperature departure, minimum temperature change, mean temperature, and degree days. Prior to 1950, data also included river stage condition, river stage gage reading, river stage, height of crest, psychrometric temperature - dry bulb, psychrometric temperature - wet bulb, and relative humidity. The entire U.S. is covered by these data, including Alaska and Hawaii.

Through cooperative agreements with state universities and other state organization, records as early as 1879 are available. Approximately 600 stations have 30 or more consecutive years of data. These long-term records are usually from suburban areas. A status of the period for each station is maintained at the National Weather Records Center, Ashville, North Carolina.

2. Information on solar radiation data, including various types of radiation, minutes of sunshine, time of collateral surface observation, ceiling height, sky condition, visibility, weather, pressure, temperature, wind, clouds, and snow cover indicator is available for the entire United States, from 1952 to date.

3. Rainfall, temperature, evaporation and wind data. Yearly, daily and monthly precipitation to the nearest one-hundredth of an inch, temperature, evaporation and wind data are available from first-order, second-order and cooperative stations, and are published in booklets entitlted Climatic Data by the Environmental Data and Information Service (EDIS) of the National Oceanic and Stmospheric Administration (NOAA). The hourly precipitation data are published in booklets entitled Precipitation Data by EDIS. These booklets are available from the U.S. Government Printing Office.

4. Airport meteorological conditions are also available.

E. Hydrologic Data

A National Water Data Exchange system (NAWDEX) is located at the National Center of the USGS at Reston, Virginia. Data on surface water, ground water, and quality of water (including biological, chemical, physical and sediment) are available through this data bank.

A list of the hydrologic data provided by the USGS is given in "Publications of the Geological Survey," which can be obtained free from the USGS in Arlington, Virginia 22202. There are normally six different types of data available.

1. Ground water levels in various parts of the U.S.

2. Surface water supply of various river basins. In these publications the location, drainage area, records available, type of gage used, average and extreme discharge and daily discharge are available for each gaging station. Most of the daily discharge values are obtained through stage measurement and the relationship between stage and discharge. These stage-discharge curves are checked periodically.

3. Data on quality of surface water, including chemical analysis to obtain the different mineral concentrations in solution, temperature and sediment measurements.

4. Some special investigations of particular floods or hydrogeology and many other special items for particular regions are also available.

5. Stage-discharge curves. The actual data collected to determine the stage-discharge curves for various gaging stations are available upon special request from USGS local district offices.

6. Maps to indicate tides and navigation information on oceans can be purchased from the National Ocean Survey at its National Distribution Center in Maryland, and from numerous retail outlets (such as bookstores, boat rentals, etc.). Detailed data concerning tidal ranges are published annually in Tidal Tables by the National Ocean Survey. These tables are also available through the Government Printing Office.

In addition, some navigation charts for coastal regions as well as rivers are available from the U.S. Army Corps of Engineers, the NOAA and the Tennessee Valley Authority.

F. Geology and Soils

The USGS has made extensive studies of landslides, land subsidence and seismic activity across the United States. These data are available from the publications offices of the USGS.

The Soil Conservstion Service has available soil maps prepared on a county basis. Contact the state SCS office (listed under the Department of Agriculture in the telephone directory) to find out what maps are available for the area of interest. In addition to offices in every state (usually in the capitol city), the SCS also maintains offices in many counties.

III. CENTER ORIENTATION

A large amount of data are available from the following data centers:

A. ASCS Aerial Photography Field Office (APFO) in Salt Lake City is where all USDA aerial photography is archived. Beginning in 1972, APFO began to acquire satellite imagery for the USDA. The APFO film library has on file all Landsat 1 and 2, Skylab 2, 3 and 4 imagery, and mosaics of Landsat imagery of conterminous United States and Alaska. The scale of the photography on file varies from 1:15,840 to 1:80,000, with about 15 percent at 1:15,840, 70 percent at 1:20,000, 10 percent at 1:40,000, and the remainder at various other scales.

Acquisition procedures and product cost are available upon request. Delivery time is normally 30 days. Contact the Aerial Photography Field Office.

B. The Earth Resources Observation Systems (EROS) Program of the U. S. Department of the Interior, administered by the Geological Survey, was established in 1966 to apply remote-sensing techniques to the inventory, monitoring, and management of natural resources. To meet its primary objective, the EROS Data Center was established near Sioux Falls, South Dakota, to provide access to NASA"s Landsat imagery, aerial photography acquired by the U.S. Department of the Interior, and photography and imagery acquired by the National Aeronautics and Space Administration (NASA) from research aircraft and from Skylab, Apollo, and Gemini spacecraft. The primary functions of the Data Center are data storage and reproduction and user assistance and training.

Guidance is available at the EROS Data Center in the form of scheduled training courses and workshops. Visitors to the Data Center also receive assistance in the operation of specialized equipment such as densistometers, additive color viewers, zoom transfer scopes, and stereo viewers, and in the use of computerized multispectral systems to classify specific phenomena.

C. The National Cartographic Information Center (NCIC) is headquartered in the Geological Survey's National Center in Reston, Virginia. It provides information on the availability of cartographic data, including multiuse maps, geodetic control, aerial photography, and space imagery. Qualified personnel in the fields of geodesy, photogrammetry, photography, and cartography are available to assist those with specialized needs. Some of the USGS Water Supply Papers are also available through the NCIC. Requests for data from EROS can be made through the NCIC; these are processed promptly through a direct computer link with the EROS Data Center.

IV. ADDRESSES

Aerial Photography Field Office
USDA-ASCS
2222 West 2300 South
PO Box 30010
Salt Lake City, UT 84125

Bonneville Power Administration
Photogrammetry Unit
PO Box 2631
Portland, OR 97208

Bureau of Land Management
Denver Service Center
Denver Federal Center
Building 50
Denver, CO 80225

Defense Intelligence Agency
Attn: DC-602
Washington, D.C. 20301

Eastern Mapping Center
(see U.S. Geological Survey listings)

EROS Data Center
User Services
Tenth and Dakota Avenue
Sioux Falls, SD 57198

General Electric Space Systems
Photographic Engineering Laboratory
5030 Herzel Place
Beltsville, MD 20705

Goodyear Aerospace Corporation
Department 408A
Litchfield Park, AZ 85340

Government Printing Office
Superintendent of Documents
Washington, D.C. 20402

Mid Continent Mapping Center
(see U.S. Geological Survey listings)

National Archives and Record Service
Cartographic Archives Division
Eighth Street and Pennsylvania Avenue N.W.
Washington, D.C. 20408

National Cartographic Information Centers

Map Mail Orders

Distribution Section
USGS
1200 South Eads Street
Arlington, VA 22202 (East of Mississippi River)

Distribution Section
USGS
Federal Center
Denver, CO 80225 (West of Mississippi River)

Distribution Section
USGS
310 First Avenue
Fairbanks, AK 99701 (Alaska)

Remote Sensing Imagery

National Cartographic Information Center
USGS
507 National Center
Room 1C107
Reston, VA 22092

National Climatological Center
Asheville, NC 28801

National Ocean Survey
NOAA
Coastal Mapping Division
C-3415
Rockville, MD 20852

National Ocean Survey
Lake Survey Center
630 Federal Building
Detroit, MI 48226

National Oceanic and Atmospheric Administration
Distribution Division (C-44)
National Ocean Survey
Riverdale, MD 20840

National Water Data Exchange
USGS
421 National Center
Reston, VA 22092

Rocky Mountain Mapping Center
(see U.S. Geological Survey listings)

Soil Conservation Service
Cartographic Division
Federal Center
Bldg. No. 1
Hyattsville, MD 20782

Susquehanna River Basin Commission
5012 Lenker Street
Mechanicsburg, PA 17055

Technology Application Center
University of New Mexico
PO Box 181
Albuquerque, NM 87106

Tennessee Valley Authority
Maps and Engineering Section
416 Union Avenue
Knoxville, TN 37902

Tennessee Valley Authority
Maps and Survey Branch
Chattanooga, TN 37401

U.S. Army Corps of Engineers

Remote Sensing Imagery and Aerial Photography

Cold Regions Research and Engineering Laboratory
PO Box 282
Hanover, NH 03755

Lower Mississippi Valley Division
PO Box 80
Vicksburg, MS

Missouri River Division
PO Box 103
Downtown Station
Omaha, NE 68101

New England Division
424 Trapelo Road
Waltham, MA 02154

North Atlantic Division
90 Church Street
New York, NY 10007

North Central Division
536 So. Clark Street
Chicago, IL 60605

Remote Sensing Imagery and Aerial Photography (continued)

North Pacific Division
210 Custom House
Portland, OR 97209

Ohio River Division
PO Box 1159
Cincinnati, OH 45201

South Atlantic Division
510 Title Building
30 Pryor Street S.W.
Atlanta, GA 30303

South Pacific Division
630 Sonsome Street
Room 1216
San Francisco, CA 94111

Southwestern Division
1200 Main Street
Dallas, TX 75202

Huntsville Division
PO Box 1600
West Station
Huntsville, AL 35807

River Maps and Navigation Charts

Vicksburg District
PO Box 60
Vicksburg, MS 39180 (Lower Mississippi River)

Chicago District
219 South Dearborn Street
Chicago, IL 60604
(Middle and Upper Mississippi River and Illinois Waterways to Lake Michigan)

Omaha District
6014 U.S. Post Office
and Courthouse
Omaha, NE 68102 (Missouri River)

Ohio River Division
PO Box 1159
Cincinnati, OH 45201 (Ohio River)

Mobile District
PO Box 2288
Mobile, AL 36628
(Black Warrior, Alabama, Tombigbee, Apalachicola and Pearl Rivers)

U.S. Bureau of Land Management
(see Bureau of Land Management)

U.S. Bureau of Reclamation
Engineering and Research Center
Building 67, Federal Center
Denver, CO 80225

U.S. Forest Service
Division of Engineering
Washington, D.C. 20250

U.S. Geological Survey

Land Use, Land Covering and Associated Maps

Eastern Mapping Center
USGS, 536 National Center
Reston, VA 22092

Mid Continent Mapping Center
USGS, 1400 Independence Road
Rolla, MO 65401

Rocky Mountain Mapping Center
USGS, Topographic Division
Stop 510, Box 25046
Denver Federal Center
Denver, CO 80225

Western Mapping Center
U.S. Geological Survey
345 Middlefield Road
Menlo Park, CA 94025

Over-the-Counter Map Purchases

1200 South Eads Street
Arlington, Virginia

1109 North Highland Street
Arlington, Virginia

Building 41
Federal Center
Denver, Colorado

310 First Avenue
Fairbanks, Alaska

445 Federal Building
709 W. Ninth Street
Juneau, Alaska

U.S. Geological Survey (continued)

Over-the-Counter Map Purchases (continued)

345 Middlefield Road
Menlo Park, California

900 Pine Street
Rolla, Missouri

1028 General Services Administration Building
19th and F Street, N.W.
Washington, D.C.

Publications Catalog

U.S. Geological Survey
Arlington, VA 22202

Topographic Maps
(see National Cartographic Information Centers, Map Mail Orders)

University of New Mexico
(see Technology Application Center)

V. ACRONYMS

APFO	Aerial Photography Field Office
ASCS	Agricultural Stabilization and Conservation Service
BLM	Bureau of Land Management
BPA	Bonneville Power Administration
CRREL	Cold Regions Research and Engineering Laboratory
DIA	Defense Intelligence Agency
EROS	Earth Resources Observations System
NARS	National Archives and Records Service
NAWDEX	NAtional WAter Data Exchange
NCC	National Climatological Center
NCIC	National Cartographic Information Center
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Survey
NOSCMD	National Ocean Survey, Coastal Mapping Division
NOSLSC	National Ocean Survey, Lake Survey Center
SCS	Soil Conservation Service
SRBC	Susquehana River Basin Commission
TVA	Tennessee Valley Authority
USBR	U.S. Bureau of Reclamation
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
USGSEMC	U.S. Geological Survey Eastern Mapping Center
USGSERC	U.S. Geological Survey Engineering and Research Center
USGSEROS	U.S. Geological Survey Earth Resources Observations System

USGSMCMC	U.S. Geological Survey Mid Continent Mapping Center
USGSRMMC	U.S. Geological Survey Rocky Mountain Mapping Center
USGSWMC	U.S. Geological Survey Western Mapping Center

APPENDIX D

REMOTE SENSING TECHNIQUES FOR STREAM-RELATED HAZARDS

By

M. M. Skinner

INTRODUCTION

Definition: REMOTE SENSING is the process of collecting information about an object without being in physical contact. Aircraft and satellites are commonly used for the observation platforms. Electromagnetic energy including reflected sunlight, natural emission of radiant energy due to object temperature, and radio waves is employed to detect and classify terrestrial scenes. Magnetic and electrical surveys commonly made from aircraft for evaluating force fields are termed airborne geophysical surveys, and are not classed as remote sensing.

The purpose of this paper is to acquaint the highway engineer with practical techniques that have proven to be effective in river studies and are applicable for the identification of river hazards to bridges and highways. This report discusses basic principles of electromagnetic radiation, general procedure for the use of remote sensing, recommended remote sensing techniques for specific hazards, and a selected reference list.

Current operational remote sensing techniques employ aerial photography, thermal infrared imagery, multispectral scanner imagery, radar imagery, landsat imagery, multispectral scanner imagery, radar imagery, landsat imagery, and archival (existing) photography and imagery. Each of these forms of remotely sensed data are applicable for recording certain features of the river system which pose hazards therein to bridges and highways.

Historically, aerial photography has been by far the most common form of remotely sensed data. Tremendous amounts of archival aerial photograph are available. Great strides have been taken to inventory and disseminate information about this valuable data base by the U.S. Department of the Interior, Geological Survey. The National Cartographic Information Center (NCIC) established in July 1974, provides an information service on existing aerial and space photography as well as maps, charts, geodetic control and digital terrain data.

Continuous improvement in cameras, films, processing, and measuring techniques promise to maintain aerial photography's prominence as a cost effective tool for the highway engineer. The superior resolution of terrain detail, both spatial and spectral, as well as the wide choice of different types of emulsions provide a most useful remote sensing system. Film emulsions are available for recording portions of the electromagnetic spectrum over regions of near ultraviolet and the photographic infrared, as well as visible.

Thermal infrared imagery utilizes invisible electromagnetic energy having wavelengths slightly longer than the visible and photographic portions of the spectrum. The distinct advantage, however, is that the composite target characteristic of emittance and temperature can be recorded. Additionally these systems may be flown day or night. Modern thermal infrared line scanner systems are capable of discriminating terrain radiometric temperature differences on the order of a fraction of a degree. The imagery may be recorded on film or tape and viewed in real time on a cathode ray tube in the aircraft. Figure 1 depicts an example of thermal infrared imagery of an area near Sheridan, Wyoming. The darker tones represent cooler temperatures (lower emittance), the lighter tones represent warmer temperatures (higher emittance). Note the sharp temperature gradients in the body of water (Lake DeSmet) in the lower right hand portion of the image.

Multispectral scanner imaging devices can record both visible and invisible portions of the electromagnetic spectrum over a relatively wide range of discrete, selected bandwidths. Analog and digital classification procedures have been developed. The total system for acquisition, analyses and display is currently under consideration by various agencies as an improved method for generating repetitive data bases over large areas. The potential for reducing the time and effort requirements for manual interpretation through multispectral scanner output and computer assisted interpretation appears very promising. Over a decade of research using multispectral scanner systems as a means for automated identification of terrain features has been undertaken by several agencies and private companies in the United States. The multispectral scanner carried on an aircraft or satellite platform consists basically of a rotating scan mirror, a prism (or other device) for separating the signal into different bandwidths, detectors sensitive to the respective bandwidths, amplifiers, and recording mechanisms. An example of a multispectral scanner image is shown in Figure 2. The different colors correspond to vegetative types that have been automatically classified through computer assisted interpretation. This is a section along the Colorado River between Parker and Blythe, Arizona. The scale is approximately 1:200,000.

RADAR, the acronym for radio detection and ranging, is an active remote sensing system in that it produces its own source of electromagnetic energy to illuminate the scene. The advantage of day or night, all-weather operations and the ability to highlight terrain relief such as geologic structure, lineaments, faults and subtle terrain roughness characteristics can be of paramount importance for mapping river characteristics. The military and a few United States firms are currently flying side-looking airborne radar...SLAR...for a variety of earth resource applications. The complexity of the acquisition system, the fact that only a few systems are available on a commercial basis, and the requirement for a large aircraft presently make the cost prohibitive for anything but large area surveys. Archival radar imagery is currently available for most of the United States. An example of a side-looking airborne radar iamge of a large area of northwest Montana is shown in Figure 3. Even at a scale of 1:250,000 a good deal of information about rivers and lakes are identifiable.

A space orbiting satellite (Landsat) provides multispectral scanner imagery. The entire globe except for the poles is mapped every 18 days, clouds permitting. The resulting imagery covers an earth area of approximately 115 x 115 miles. Minimum specified resolution for each picture element (PIXEL) is 1.1 acres. The original scale of imagery is approximately 1:1,000,000. The resulting interpreted imagery can be presented as color coded output, similar to Figure 2.

Archival photography for the United States dates back to the time of the first aerial photograph taken of Boston, Massachusetts from a tethered balloon in 1860. In sharp contrast, more recent photographs from Apollo, Gemini and Skylab missions were taken over selected target sites of the earth from several hundred miles in space. Existing aerial photography representing a variety of scales, films, and filter combinations is particularly useful for change detection studies

FIG. 1 Lake DeSmet Area near Sheridan, Wyoming. Thermal Infrared Image (8-14μm)

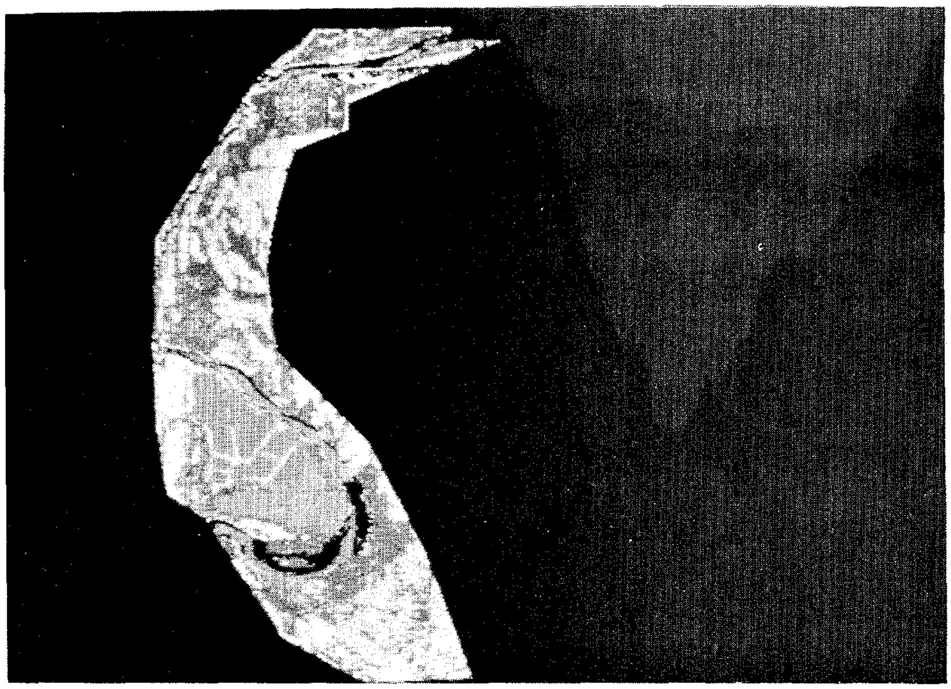

FIG. 2 Aircraft Multispectral Imagery; (Scale ≈ 1:200,000) Color-Coded Vegetation Types along Lower Colorado River between Parker and Blythe, Arizona. (Courtesy of U.S. Bureau of Reclamation, Engineering Research Center, Division of Research, Remote Sensing and Engineer Physics Section)

FIG. 3 Side Looking Airborne Radar (SLAR) Image East Look of an Area of Northwest Montana (Courtesy of Corps of Engineers, Seattle District)

on rivers. Archival thermal infrared imagery and multispectral scanner imagery are available for many parts of the United States. Information on available archival imagery and photography can be obtained from NCIC and the EROS Data Center, Sioux Falls, South Dakota.

II. BASIC PRINCIPLES

A brief review of the principles of electromagnetic radiation, transmission through the atmosphere and the fundamentals of reflected and emitted radiation is useful for understanding the basic operations of all remote sensing systems. The engineer must understand these basics in order to realize capabilities and limitations of various proposed remote sensing processes. Additionally, the proper interpretation of each form of remotely sensed data depends critically upon understanding the interaction of selected wavelengths with the terrain, atmosphere and detector.

Radiation, one of the three processes of energy transfer, is encountered in everyday experiences in many different forms; sunlight, heat rays, radio waves, and radar signals, to name a few. All of these forms of energy are inherently similar in nature and are grouped under the single classification of electromagnetic radiation. They are commonly ordered on the electromagnetic spectrum according to wavelength or frequency. For example, where the spectrum is arranged in order of increasing frequency (decreasing wavelength) the following order is given: radio waves, microwaves, infrared, visible light, and ultraviolet light.

All forms of electromagnetic radiation travel in a straight path at the speed of light; obey similar laws of reflection, refraction, diffraction and polarization; can be focused and imaged; and do not depend on the presence of matter for propagation.

Wavelengths of importance in transferring the electromagnetic energy from the sun to the Earth range from about 0.1 to 4.0 μm (micrometers). Radiant energy with these wavelengths is commonly referred to as short wave radiation or solar radiation. About 10 percent of the total energy in the solar stream is in the ultraviolet region, from 0.1 to 0.4 μm; the remainder is nearly evenly distributed between visible light, 0.4 to 0.7 μm, and infrared radiation, 0.7 to 4.0 μm. Emitted radiation from the Earth's surface in turn, is in the infrared region from 4.0 to 100 μm, commonly called long wave radiation or terrestrial radiation. Absorption of the solar radiation results in the transformation of the emitted radiant energy to longer wavelengths.

Of the total amount of radiant energy reaching the surface of the Earth part may be reflected, part absorbed and re-emitted at longer wavelengths, and part transmitted (if the terrain object is partially transparent to the particular incident radiation wavelengths). Alternately, the sum of the radiant reflectance, radiant absorptance, and radiant transmittance is 100 percent.

Reflected and emitted energy in the 0.4 to 0.7 μm wavelength region allows one to perceive the presence of objects in both spatial and spectral format (human vision or photography). The color of an object is determined by the relative amount of the primary colors of blue, green, and red that are reflected or emitted from the surface of the object. Reflected energy in wavelengths other than the visible (as well as the visible) bands may be detected and imaged with electromechanical scanners employing appropriate detectors. Specially sensitized films are also available for recording scenes with electromagnetic energy outside the visible region: in the ultraviolet, 0.3 to 0.4 μm, and in the photographic infrared, 0.7 to 0.9 μm.

Almost all objects emit electromagnetic energy in proportion to their respective emissivity and absolute temperature to the fourth power. This energy may be recorded remotely with a radiometer or detected with a special detector and imaged through the use of an electromechanical scanner. Consequently, terrestrial objects may be mapped with infrared imaging systems even in total visual darkness.

Electromagnetic energy transmission through both the atmosphere and water in rivers and lakes is a very important factor for consideration in practical remote sensing studies of the landscape. Optimum transmission of light in water and the transmission of ultraviolet, visible, near infrared, and thermal infrared electromagnetic energy through the atmosphere need to be considered. Radiant energy is attentuated in a path of fluid, either water or air, by a general process called extinction. The amount of electromagnetic energy that can be transmitted through a fluid medium is a function of the extinction coefficient and the path length. The extinction coefficient is a consequence of both absorption and scattering of the radiation. Both the absorption and scattering are strongly wavelength dependent. For example, the attenuation of visible light in distilled water is a minimum for the blue-green portion of the spectrum, 4800 °A(Angstrome). The longer wavelength energy in the red band (7000 °A) suffers severe attenuation. As water becomes more turbid, studies have shown that the wavelength of minimum attenuation shifts slightly to the longer wavelengths. The scattering of light back toward the observer in water and particularly in turbid water conditions reduces the visibility.

Since the transmission of electromagnetic energy through the atmosphere is strongly dependent on the wavelength of the radiant energy, of particular interest are the "windows" (high transmittance) in the atmosphere for wavelengths in the visible, 0.4 to 0.7 μm, the near infrared 0.7 to 0.9 μm, and the thermal infrared, 2.0 to 5.5 μm and 8.0 to 14.0 μm. Water vapor absorption bands at 1.4 μm, 1.8 μm, 2.6 μm to 2.8 μm, and 5.5 μm to 7.5 μm reduce the transmission of electromagnetic energy at those wavelengths. Aerial photography is accomplished with electromagnetic energy ranging from approximately 0.3 to 0.9 μm; thermal infrared imagery is accomplished in the windows, facilitated by high transmittance in the region from 2.0 to 5.5 μm and 8.0 to 14.0 μm.

For consideration in photographic and imaging systems, the scattering of "light" is attributed to three categories of suspended particle size in the atmosphere: Rayleigh scattering, where the particle diameters are considerably smaller than a wavelength of light; Mie scattering, where the particles range in size from approximately one tenth of a wavelength to 10 wavelengths; nonselective scattering occurs when the scattering particle diameters are on the order of ten wavelengths or more in size. Air molecules are the predominant particle size in the case of Rayleigh scattering. Rayleigh scattering is inversely proportional to the fourth power of the wavelength, so blue light (4500 °A) is scattered almost six (6) times as strongly as red light (7000 °A). This type of scattering makes the sky appear blue and sunsets red. Rayleigh scattering is paramount on clear, bright days; whereas Mie scattering predominates as the particles in the atmosphere increase in size and visibility decreases. Again, the scattered light tends to be in the blue part of the spectrum and minus-blue filters on aerial cameras can materially enhance the contrast of the terrain scene. Non-selective scattering scatters all light wavelengths, and clouds appear white, for example. Although water vapor is the most common cause of non-selective scattering, smoke and dust particles can be important, too. Color infrared or black-and-white infrared photography taken with a minus-blue filter can produce very sharp pictures even under such adverse conditions.

Since a terrestrial scene analysis may require relative temperature determinations; or imagery is required under reduced visible light conditions or even in total darkness; or interpretation is enhanced by the variation in the temperatures and the emissivity between target and background in a particular area, it is of interest to consider both reflected energy and emitted energy. Only a very basic discussion will be presented in this paper, but hopefully in sufficient detail to give the reader adequate understanding of what terrestrial targets may be photographed (reflected energy) or recorded on thermal infrared imagery (emitted and reflected energy); and to assist the user in interpretation of photography and imagery.

Radiant reflectance from a particular material surface is a function of the wavelength of the incident radiation, the character of the reflecting surface, the material itself, and on the illuminating and viewing angles. For opaque materials, the sum of the radiant absorptance and the radiant reflectance must be one (100%); radiant absorptance varies between zero for a perfect reflector and one (1.0) for a perfect absorber --a black body. Reflectance, absorptance, and transmittance are strongly wavelength dependent. This dependence of reflectance upon wavelength is used in multispectral scanner systems for the identification and discrimination of selected scenes. Color variations in an aerial photograph, for example, are the direct result of the relative proportions of blue, green, and red light reflected from a terrestrial scene.

Reflectance can be described for monochromatic radiation (narrow band width on the electromagnetic spectrum) or for all wave radiation; or it may be defined for a wide band such as visible light (0.4 μm to 0.7 μm), solar radiation (0.1 μm to 4.0 μm), or some other specified wide-band radiation. A commonly used term, albedo, refers to the reflectance of the entire solar radiation band or to the visible portion. Usage varies and caution should be exercised in interpreting the literature on reflectance where specific band widths are not identified.

For detecting and imaging the terrestrial environment, two types of reflectance are important, specular and Lambertian. The simplest type of reflectance is the specular or mirror reflectance where the angle of incidence and the angle of reflectance are equal. Smooth surfaces such as metal rooftops and smooth water surfaces, for example, may produce undesirable specular reflectance or "bright spots" on aerial photography. Generally this undesirable phenomenon may be minimized by proper planning of the photographic mission. In certain limited applications, the specular reflectance is used to enhance the surface texture of the water surface which may be an indication of the magnitude and distribution of the velocity in the stream.

Most terrain features however, reflect more or less diffusely. If the reflectance is uniformly diffuse, that is, the reflected radiant flux is the same in all directions, then the surface is said to be a Lambert surface. For a flat, Lambert surface, radiant energy (either reflected or emitted) is travelling in all directions, not just perpendicular to the surface.

All objects emit energy at all wavelengths. The total radiant emittance from a particular object increases rapidly with temperature and the peak emittance value shifts to the shorter wavelengths with increasing temperature. For example, the heating element of an electric stove glows red as the temperature of the element reaches a certain point. The shift in peak emittance with temperature and the fact that warmer objects produce a greater radiant flux allows one to select the proper detector for electromechanical scanners depending upon the temperature of the scene and the detector's sensitivity characteristics. For example, if the requirement was to detect the radiation from natural scenes having a temperature of approximately 300 °K, any detector with good sensitivity in the 8.0 to 14.0 μm region could be used. If forest fire detection were of importance, then a detector with good sensitivity in the 2.0 to 5.5 μm region could be used. These band widths correspond to the atmospheric windows and to maximum radiant emittance for that temperature range.

III. GENERAL PROCEDURE

The use of a remote sensing technique(s) for identification of river hazards to bridges and highways involves certain basic steps: 1) the identification of the specific objective(s), 2) specifications, 3) cost estimates, 4) selection of base maps, 5) acquisition of remotely sensed data, 6) acquisition of site-specific information, 7) identification and analyses of the potential hazard, and 8) application of the analyses to the site-specific hazard involved.

First and foremost, the highway engineer must identify the specific purpose(s) for using remotely sensed data. The engineer must identify in advance the potential hazards and understand the capability and limitations of a selected remote sensing technique for identifying such hazards. The prime purpose of this report is to give the highway engineer guidelines for the proper remote sensing technique to use.

After identifying the purpose of the project and deciding on the remote sensing technique to be employed, specifications for acquiring remotely sensed data and supporting site-specific information need to be prepared. Such specifications should clearly identify why the remotely sensed data is needed, where the data is to be collected, when the data is to be collected, how it is to be collected, and who should collect what information. In limited cases, all or portions of the required site-specific information may already exist, but in almost all instances, some new site information will need to be obtained.

A detailed proposal and cost estimate for acquiring, interpreting and applying the remotely sensed data should be developed either by prospective contractors, or by the user agency. At this point in time, information contained within the proposal as far as the procedure and cost may dictate an alternate method for acquiring similar information about the potential hazard. Remote sensing techniques do afford unique observation characteristics, but other processes such as detailed on-site measurements and observations may be more cost effective. In any case, the proposal must indicate the appropriate degree of success for satisfying the initial specific objectives.

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Base maps of a suitable scale for controlling the interpreted scene overlay are required. Considerable care should be taken in deciding on proper map scales for this purpose. Recent orthophoto quandrangel sheets at scales of 1:24,000 or larger are extremely useful. Base maps with scales larger than 1:24,000 may need to be established by photogrammetric procedures; or in certain instances, for very large scale, actual on-site surveys for base map construction may be needed. In some instances, enlargement of the existing vertical aerial photographs may provide suitable base maps.

The acquisition of remotely sensed data generally involves archival and new site-specific remotely sensed data. A considerable amount of archival remote sensing information representing aerial photography and imagery presently exists. This data base is catalogued and disseminated through such agencies as the National Cartographic Information Center. New site-specific remotely sensed data may be acquired by private contractors, government agencies, and some universities.

The acquisition of pertinent site-specific information necessary for the proper interpretation and analyses of remotely sensed data can represent the major time and effort and cost of the total project. A list of required information is provided in the appendix on Aerial Photographic Identification of Stream Related Hazards.

After the potential river hazard has been identified on one or more forms of remotely sensed data, the impact of the hazard on a selected highway bridge or highway section needs to be analyzed. This analysis step is greatly facilitated through the basic characteristic of remotely sensed data. Remotely sensed data from either an aircraft or a space platform affords an overall, synoptic view of the potential consequence of a given hazard or hazards. It affords the engineer an opportunity to observe the potential interaction of a hazard with other portions of the surrounding environment. Oftentimes the cause and effect relationship of a given hazard upon a bridge or highway section can be synthesized directly from the planimetric display of the interpreted remotely sensed data. Extensive reaches of the river system both upstream and downstream from the affected bridge or highway site can be observed, and the interaction of the total system evaluated. This characteristic synoptic overall perspective of the hazard and the interaction with the rest of the river system may justify the use of remotely sensed data over an intensive on-site ground survey.

At this point in time different engineering solutions can be evaluated for mitigating or eliminating the threat of the hazard to a bridge site or highway section. Any proposed remedial measure may be considered directly on the planimetric display of the problem area. This phase of the total process involves appropriate specialists trained in dealing with the specific hazards.

IV. SPECIFIC TECHNIQUES

Each remote sensing technique begins with recording the feature(s) that represents or induces the hazards. This feature is then identified and evaluated by interpreting the photograph or image through either manual, analog or analytical interpretation procedures. The process of identification and evaluation is most effectively accomplished by a person experienced in interpretation and also trained in the basic science of the pheonomenon involved. For example, if crop identification were the problem, an agronomist trained in interpretation would be an ideal person to have on that project. The forms of remotely sensed data and the interpretation equipment are identified alphanumerically below and summarized as recommended combinations in the following table.

The following section includes a brief discussion of the selected forms of remotely sensed data and a description of interpretation equipment suitable for interpreting such data.

(a) Tri-X Aerographic (Estar base) 2403 is a high speed, high dimensional stability film for aerial mapping and reconnaissance under low levels of illumination. This is a panchromatic negative black and white film with a spectral sensitivity from 0.25 to 0.75 μm. The film is relatively inexpensive and has a wide latitude of exposure.

(b) Infrared Aerographic (Estar base) 2424 is a black and white film sensitive to infrared radiation as well as ultraviolet and the visible portions of the spectrum. The spectral sensitivity ranges from approximately 0.25 to 0.93 μm. Thermal photography cannot be done with infrared films. These films are not thermal or heat detectors. They are sensitized only to the near infrared spectral region. Thermal recording involves the use of thermal infrared scanners with specialized detectors. The 2424 film exposed with a Kodak wratten filter No. 25 provides sensitivity over the range from 0.60 to 0.93 μm. This band width is especially suited for reduction of haze effects. The black and white infrared film exposed with a Kodak wratten filter No. 89B provides a sensitivity over the spectral region from 0.70 to 0.93 μm. This band width is particularly suited for identifying land-water interfaces.

(c) Aerochrome Infrared (Estar base) 2443 is a false color reversal film of high dimensional stability useful for delineating vegetation types, soil moisture variation, suspended material concentration variation, flow patterns, bed forms in shallow clear water, and surficial sediment deposits. A Kodak wratten filter No. 12 or 15 must be used since all three layers of the film are sensitive to blue light. The false rendition produces a false color in that green objects look blue, red objects appear green, and objects having high reflectance in the infrared, appear red. Note the film cannot be used to directly photograph temperature variations.

(d) Aerocolor Negative (Estar base) 2445 is a high speed color negative film for aerial mapping and reconnaissance. This film was specially designed for processing to a colored negative and is ideal for producing prints and plates and positive transparencies. The spectral sensitivity ranges from 0.40 to 0.70 μm. The film also allows wide exposure latitude.

Recommended Combinations of Remotely Sensed Data and Interpretation Equipment

General Category for Recognition	Specific River System Feature	Combinations*	Interpretive Key Used
Water and Sediment	Discharge	a-6	size, shape, pattern
	Flow patterns	c-1,2,8; g-1,8; h-1,8	tone, color, texture
	Bed material transport	c-2,3; f-3	size, shape, pattern, association
	Surface indication of suspended sediment distribution	c-1,8	color
	Surficial sediment deposits	b-1,3; c-1,3; g-1; h-1; j-1	shape, tone, color, association
	Aggradation	c-1, 3,6; f-1,3,6	pattern, association
	Bed form effects	c-1,8; d-1,8; e-1,8; f-1,8	texture, pattern, association
	Degradation and Scour	f-6	shape, pattern, association
	Nickpoint formation	c-1,3	shape, shadow, pattern
	Back-filling and down-filling	f-6	size, shape, pattern, association
	Berming	b-1; c-1; f-1	shape, pattern, association
	Velocity field at a stream cross-section	a-1,8; c-1,8; d-1,8; e-1,8	texture, pattern, association
	Temperature patterns	h-1,8,9	tone
	Ice	h-1,8,9; i-9; j-9; k-9	size, shape, shadow, tone, texture, pattern
Riverbanks, Floodplain, and Watershed	Bank erosion	b-1,3,4,9; c-1,3,4; g-1; h-1; 1-1,3,4,9	size, shape shadow, tone, color, pattern, association
	Earth slides	b-1; c-1; g-1; h-1; i-9; j-1; k-1; 1-1	size, shape, shadow, tone color, texture, pattern association
	Vegetation type and extent	b-1,6,7,8,9; c-1,2,3,4,8,9; g-1,8,9; j-9; k-9	size, shape, shadow, tone, color, texture, pattern, association
	Soil type and moisture content	b-1,3,8; c-1,3; d-1,3; e-1,3; g-1,8,9; h-1,8,9; i-9; j-1; k-9	tone, color texture, association
River Geometry	Alignment	a-1,5,6; g-1; h-1; j-1	shape
	Channel slope	a-5,6	size
	Radius of bends	a-1,5,6	size
	Width of channel	a-1,5,6	size
	Depth of channel	c-2; f-5,6	size, tone, color, association
	Base level change	f-5,6	size, association

*see alphanumeric designation listing in Section IV and abbreviated listing at bottom of this table.

Recommended Combination of Remotely Sensed Data and Interpretation Equipment

General Category for Recognition	Specific River System Feature	Combinations*	Interpretive Key Used
	Meander growth and shift	a-1,3,4,5,6; c-1,3,4,5,6	shape
	Island and bar shift	b-1,3,4,5,6; c-1,3,4,5,6	size, shape, association
	Cutoffs	a-1; b-1; c-1; d-1; e-1	shape, association
	Avulsion	a-1; b-1; c-1; d-1; e-1; g-1; h-1; i-1; j-1; k-1; 1-1	association
	Metamorphosis	a-1; b-1; c-1; d-1; e-1; g-1; h-1; i-1; j-1; k-1; 1-1	shape, pattern, association
Man's Activities	Evaluation of rip-rap	c-1,3,4,5,6; g-1; h-1	size, shape, shadow, tone, texture, pattern, association
	Channel modification	a-1,3,4,5,6,8,9; b-1,3,4,5,6,8,9; c-1,3,4,5,6,8,9; d-1,3,4,5,6,8,9; e-1,3,4,5,6,8,9; f-1,3,4,5,6,8,9	size, shape, shadow, tone, color, texture, pattern, association
	Effect of structures	b-1;c-1; d-1; e-1; f-1	size, shape, shadow, tone, color, texture, pattern, association
	River use	c-1; e-1	size, shape, shadow, tone, color, texture, pattern, association
	Debris	a-1;b-1; c-1; d-1; e-1; g-1; h-1,9; i-9; j-1; k-9	size, shape, shadow, tone, color, texture, pattern, association

Forms of remotely sensed data: a) Tri-X Film, b) 2424 Film, c) 2443 Film, d) 2445 Film, e) 2448 Film, f) SO-397 Film, g) T.I.R. 2.0-5.5 μm Imagery, h) T.I.R. 8.0-14.0 μm Imagery, i) MSS Imagery, j) RADAR Imagery, k) Landsat Imagery, 1) Archival Photography and Imagery.

Interpretation equipment/processes: 1) Direct Observation (unaided), 2) Direct Observation (aided), 3) Stereoscopes, 4) Transfer Scopes, 5) Stereo Plotters, 6) Computer Assisted Stereo Plotters, 7) Multiband Viewers, 8) Scanning Densitometers, 9) Computer Assisted Interpretation.

(e) Aerochrome MS (Estar base) 2448 is a color reversible film for low to medium altitude aerial mapping and reconnaissance. The film is designed to be processed directly to a positive transparency. Subsequently the film may be viewed on a light table. The spectral sensitivity ranges from 0.40 to 0.70 μm.

(f) Ektachrome EF Aerographic (Estar base) SO-397 is a high speed, very fine grained, color reversible film for aerial mapping and reconnaissance. This film is ideal for water penetration (with a Kodak wratten filter No. 3) in clear water conditions. The film can be overexposed 2 to 3 stops for maximizing water penetration and still maintain good rendition of detail on the land surface. While not a primary recommendation, SO-397 film with forced processing can be used for situations in which the illumination level is low or marginal and in applications where sufficient exposure cannot be obtained with other slower speed color reversible film.

(g) Thermal infrared imagery (2.0 to 5.5 μm) detects the radiant temperature of the scene which is a function of both the absolute temperature and the emissivity. The imagery may be obtained either day or night under good weather conditions from any altitude. During day time operation the reflected solar radiation in the 2.0 to 4.0 μm band may strongly influence the strength of the signal. High humidity conditions may attenuate the signal. The imagery may be recorded on tape or film and viewed in real time on a cathode ray tube in the aircraft.

(h) Thermal infrared imagery (8.0 to 14.0 μm) detects the radiant temperature of the scene which is a function of both the absolute temperature and the emissivity. The imagery may be obtained day or night under good weather conditions from any altitude. During day time operations, however, the reflected solar radiation is not included in the signal and temperature-emissivity characteristics (only emitted energy) of the scene are recorded. Since peak radiant emittance occurs for 300°K black bodies in the 8.0 to 14.0 μm region, this is a particularly good band width to use for temperature measurements.

(i) Multispectral scanner imagery (0.3 to 14.0 μm) utilizes two or more selected band widths which are obtained simultaneously. Depending on the band width selected, both reflected and emitted energy may be recorded. Generally, the multispectral scanner is flown under good weather conditions during the day time hours. The reflectance spectra of a particular scene type can be compared to spectral signatures of selected scene types for computer assisted interpretation. Dual-channel, thermal infrared imagery, that is, the 2.0 to 5.5 μm and 8.0 to 14.0μm bands, may afford important multispectral signatures for the classification of certain scene types.

(j) Radar imagery (1.0 to 25.0 cm wavelength band) detects surface roughness and topography. Day or night operation under most weather conditions is a most useful attribute. Special applications include mapping fractures and surface roughness. Radar imagery has been used successfully to map, for the first time, very large areas under complete cloud cover.

(k) Landsat Imagery with spectral bands ranging from 0.5 to 1.1 μm is presently available for use by the general public. The Eros Data Center, Sioux Falls, South Dakota disseminates this imagery. Repetitive coverage on an 18-day basis provides a useful format for detecting changes in river systems. Cloud cover, however, may reduce the usefulness of such data for many areas.

Existing photography and imagery, available through the National Cartographic Information Center on a routine basis at a relatively low cost, affords a most useful form of remotely sensed data for change detection.

The following section summarizes key features of the various types of interpretation equipment recommended in the above table. The price range for such equipment varies from a few hundred dollars to several hundred thousand dollars, depending upon the degree of sophistication required.

Manual interpretation techniques are the simplest to use and are the least expensive. Equipment commonly used for this process includes light tables fitted with variable magnification stereoscopes, zoom transfer scopes, and stereo plotters. The interpreted information may be transferred to a base map or overlay of suitable scale. Recent developments in computerized photogrammetry systems effectively combine manual interpretation and precisely locating interpreted data onto an original manuscript.

Analog interpretation techniques involve multiband viewers and scanning densitometers. The input may be prints, transparencies, or magnetic tapes. The output from the scanning densitometer can include color coding, edge enhancement, three-dimensional presentations, area determinations, and temperature contours.

Several corporations in the United States are presently marketing computer assisted interpretation systems. These are generally interactive digital imaging processing systems coupled to fairly large computers. A variety of processing functions may be applied to the imagery to provide automated interpretation of selected scenes. Multispectral signatures are incoporated to provide rapid interpretation of relatively large areas. In addition, very subtle evidence of a particular hazard condition may be detectable through the analytical processes.

(1) Direct observation. Evaluation of prints or transparencies using reflected light and light tables is the simplest and least expensive interpretation technique. It is effectively employed even if other equipment is to be used in the interpretation process. Photographic interpretation with the unaided eye often times provides better overall prospective of the problem area.

(2) Aided Direct Observation. To take advantage of the high spatial resolution of most photography and imagery, magnification is generally useful. A variety of simple magnifying glasses are available at very nominal costs. Handheld or mounted viewing systems are available from local suppliers. Color infrared transparencies when viewed with a simple magnifying glass produce a pseudo-stereo effect is useful in which differentiating vegetation types, depth variation, and bed forms in clear streams.

(3) Stereoscopes. Fixed and variable power magnification stereoscopes provide the valuable combination of magnification and three - dimensional viewing. Two basic systems are commonly used: the Old Delft Scanning Stereoscope and the Zoom Stereoscope.

(4) Transfer Scopes. These instruments are particularly useful for transferring interpreted information directly from transparencies or prints onto base maps. In areas of high relief, the Stereo Zoom Transfer Scope is recommended. In addition, even in flat terrain, the Stereo Zoom Transfer Scope affords the important third dimension for improving the interpretation. Commonly, separate stereo pairs of prints or transparencies are used in these instruments.

(5) Stereo Plotters. Conventional stereo plotters provide high resolution, three-dimensional viewing of stereo pairs of aerial photographs. Trained stereo plotter operators may also function as photointerpreters and produce photo interpretation output directly upon the contour map manuscript. In addition, photogrammetric techniques may be employed to produce large scale base maps required in localized areas of interest around bridges and adjacent to highways.

(6) Computer Assisted Stereo Plotters. Computer assisted procedures for stereo plotter operations and map manuscript compilation are relatively recent developments of considerable value to the highway engineer. The basic concept is to continuously monitor three-dimensional coordinates in the stereo plotter model space and process the data in the system computer by transforming the coordinates to a three-dimensional control grid. The transformed coordinates are used to build data bases involving elevations, areas, and interpreted features. The data can be stored in raw coordinate form, as processed information, or it can be used to plot manuscripts. Plans, profiles, and schematic maps at selected scales may be produced.

(7) Multiband viewers. These use either conventional roll film or prepared individual transparencies representing the same scene area in a variety of separate spectral bands. Two or more multiband impages may be composited into a single image in order to enhance a particular feature or hazard condition. These have been found to be particularly useful for looking at large area features with satellite imagery.

(8) Scanning densitometers. Densitometers may be utilized with transparencies or prints to produce color coded images depending on density variations in the emulsion. A scanning densitometer consists of a scanning camera and consoles for viewing the electronically processed image. Many different functions may be performed with such instrumentation including color coding, edge enhancement, area determination, three-dimensional presentations, and density plots. An electronic scanning densitometer allows the operator to rapidly enhance various features on photography or imagery and to view this display in real time.

(9) Computer assisted Interpretation. High speed digitial computer assisted interpretation equipment available at the present time. Most of the systems are interactive in that they allow the operator to manipulate the system in order to identify and enhance the particular feature. A variety of digitized imagery on tape may be used, ranging from multispectral scanner data to digitized information from prints and transparencies. From the interactive user's station, many different processing algorithms may be selected and the result displayed on a cathode ray tube for evaluation. Portions of this interpretation may be stored before proceeding to the next algorithm and the process continued until the desired interpretation goal is achieved. The intermediate and final output may be viewed on cathode ray tubes or output with plotting devices.

V. CONCLUSIONS

Remote sensing techniques provide the highway engineer with relatively new procedures for effectively identifying and evaluating river hazards to highways and bridges. Remote sensing provides a unique spatial and spectral perspective of the river system that is not available through any other method of analysis. A range of interpretive techniques have been presented depending upon what feature is to be identified and what interpretation equipment is available. The engineer must gain experience and capability in using specific remote sensing systems through actual participation; or contract for services with appropriate agencies or private organizations.

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FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

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.

2. Reduction of Traffic Congestion, and Improved Operational Efficiency

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.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements that affect the quality of the human environment. The goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge and technology of materials properties, using available natural materials, improving structural foundation materials, recycling highway materials, converting industrial wastes into useful highway products, developing extender or substitute materials for those in short supply, and developing more rapid and reliable testing procedures. The goals are lower highway construction costs and extended maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highways at reasonable costs.

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This category is concerned with the research, development, and implementation of highway construction technology to increase productivity, reduce energy consumption, conserve dwindling resources, and reduce costs while improving the quality and methods of construction.

7. Improved Technology for Highway Maintenance

This category addresses problems in preserving the Nation's highways and includes activities in physical maintenance, traffic services, management, and equipment. The goal is to maximize operational efficiency and safety to the traveling public while conserving resources.

0. Other New Studies

This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.