Geomorphic approach to predicting degradation of streams in western Iowa

by

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PROBLEM STATEMENT

Most of the perennial and intermittent streams in Western Iowa have entrenched themselves into a thick Quaternary alluvial fill. In many places, channels have degraded from 1.5 to 5 times their depth since the turn of the century. This degradation has been accompanied by width increases of 2 to 4 times. As a result, bridges crossing these streams have been jeopardized, both through degradation around piers and piling and undermining of abutments.

Publications prior to this study have provided a good description of the degradation that some Western Iowa streams have experienced. However, there has been no general agreement on the causes and mechanisms of degradation. There is a need to define these mechanisms in an effort to find a method of predicting the amount and rate of degradation for these streams.

This thesis has the objective of using historical and geomorphic evidence to define or clarify the mechanisms which control degradation, and suggesting methods to predict rate and amount of degradation. Also, principles of soil mechanics have been applied so that predictions can be made regarding stability of streambanks as they relate to channel widening.

INTRODUCTION

The research for this thesis was conducted during 1979-1980 as a part of a larger study of alternate methods of stabilizing degrading stream channels in western Iowa. The study has the long range objective of recommending effective and economical methods of stabilizing the degrading stream channels in the region. Phase I, completed in September, 1980, defined the problems facing the engineer and suggested some stabilization techniques; phase II, currently underway, will include the construction of demonstration grade stabilization structures and monitoring their effectiveness.

Publications prior to this study have provided a good historical data base on the degradation of a few western Iowa streams, utilizing evidence from drainage district records, land plats and bridge surveys. These studies have documented: the Willow drainage ditch (Daniels, 1960), Tarkio River (Piest et al., 1976) and Keg Creek (Lohnes et al., 1980). State and county historical journals have been consulted as a part of this study to expand these data.

Horton (1945) showed that the composition of a stream system in a drainage basin can be expressed quantitatively in terms of the morphometric parameters of the basin: stream order, drainage density, circularity ratio, etc. During the current study, the data for calculating these parameters have been gathered from 1:24,000 and 1:250,000 scale U.S.G.S. topographic maps. These measurements have been made with the use of a chartometer, for measuring the distance along a stream, and a planimeter, for measuring the area of smaller drainage basins. Areas of the larger drainage basins were determined using the Iowa Highway Research Board Bulletin No. 7, "Drainage Areas of Iowa Streams" (Larimer, 1974). Morphometric parameters used in this thesis are defined in Table 1; unless stated otherwise, all references to stream length in this thesis are to the length as measured from the mouth of the stream.

Field investigations provided channel profiles at several locations on Keg and Willow Creeks, and data on the properties of the upland loess and alluvial materials. Shearing strength and unit weight of these materials was measured in-place, using the Soil-Test^{tm} Torvane and Ely Volumeter. Gradation of the soil materials was obtained by a standard hydrometer analysis (ASTM designation D 422-63); all clay as reported in this thesis is 2 micron clay.

There has been a trend, particularly in the last two decades, towards the combination of the engineering and geosciences, in order to gain a better understanding of the mechanics of natural processes. At Iowa State University, there have been cooperative efforts between the departments of Civil Engineering and Geology in working toward this end. This author has been a part of this general program. Thus, as a part of this thesis, a strong effort has been made to apply quantitative descriptions as a part of a rational approach to the problems encountered during this study.

The location of the study area is shown in Figure 1; Figure 2 shows the major streams within the study area. Within the larger study area, this research will focus on the Keg and Willow Creek drainage basins.

Table 1. Definition of morphemetric parameters used in this study

	Parameter	Symbol	How derived	Reference for definition
1.	Number of streams of each order	N_u (where u is the order)	Counted	Horton (1945)
2.	Total length of each order stream	L_u	Measured with chartometer	Horton (1945)
3.	Mean length of each order stream	L_u	$L_u = \frac{L_u}{N_u}$	Horton (1945)
4.	Basin Area	A_u	Measured with planimeter	Horton (1945)
5.	Drainage density	D	$D = \frac{L}{A}$	Horton (1945)
6.	Basin circularity ratio	C	$C = \frac{A_u}{\text{Area of circle having same perimeter as the basin}}$	Miller (1953)

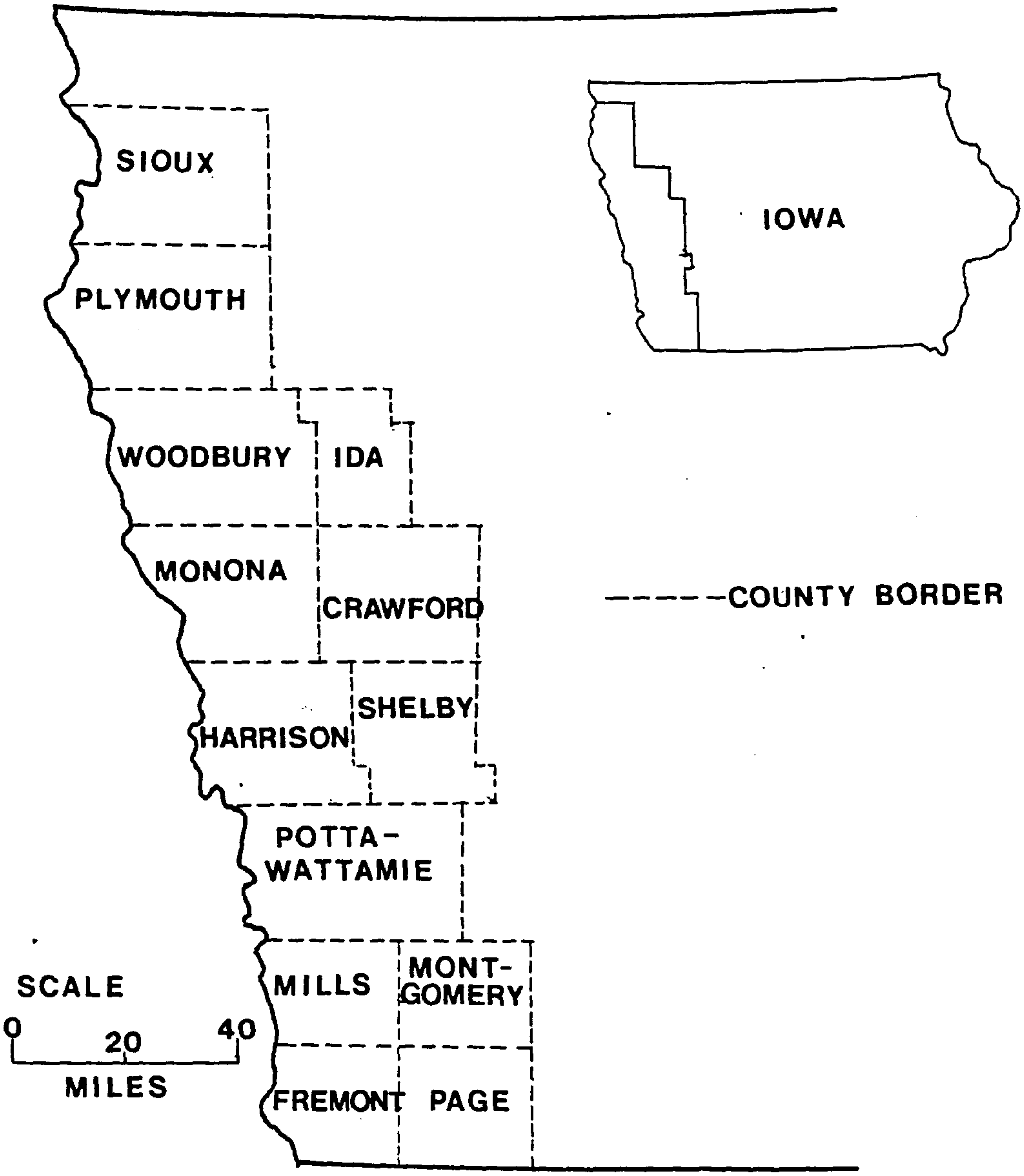

Figure 1. Location of study area

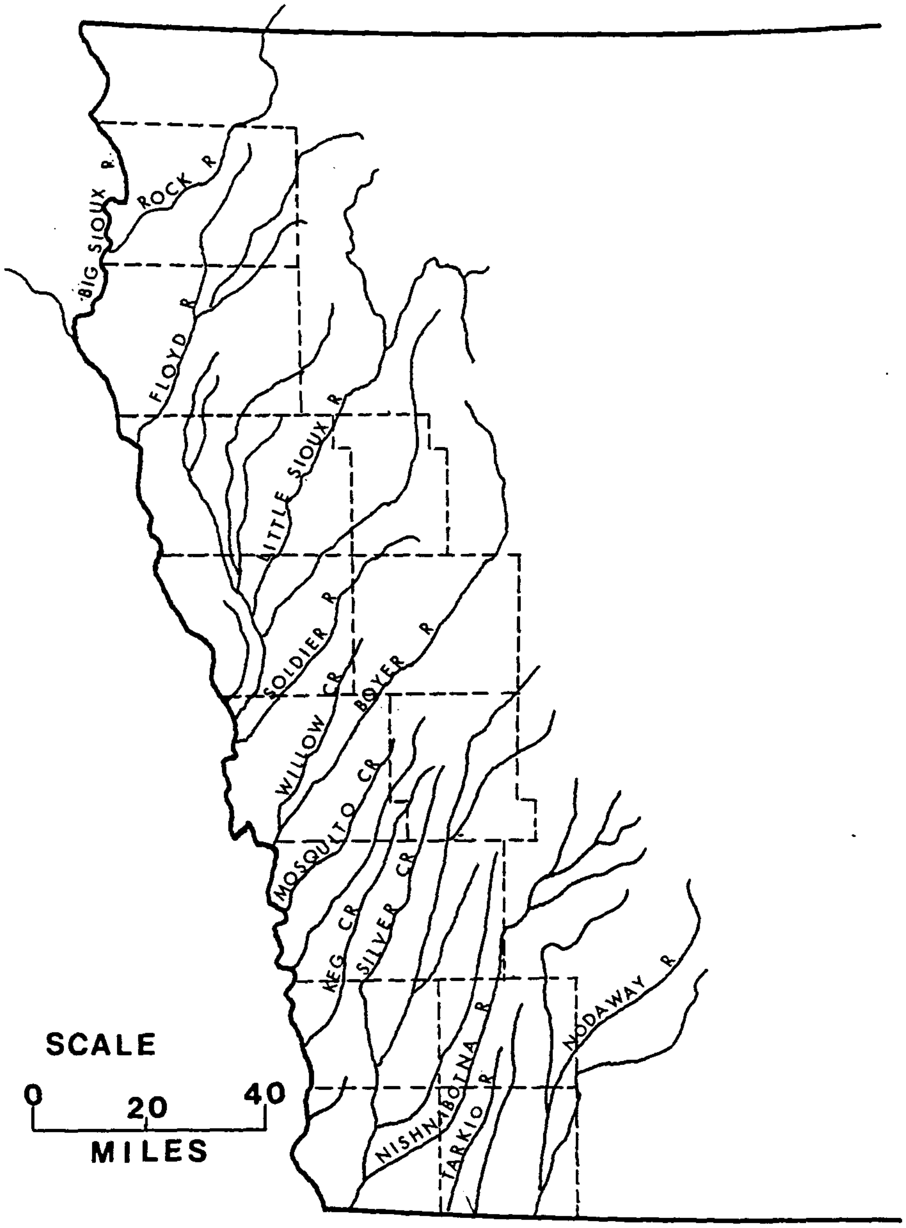

Figure 2. Selected streams in study area

REGIONAL SETTING

The surficial geology of Iowa is dominated by glacial and interglacial deposits of Pleistocene age. Western Iowa is covered with Wisconsin age loess deposited in the period from 29,000 to 14,000 years ago (Ruhe, 1969). This material is an unstratified and unconsolidated sediment of eolian origin, composed primarily of silt and clay sized particles.

In the northern-most portion of the study area (Sioux County, Plymouth County and a portion of Ida County) loess deposits 5 to 20 feet in thickness overlie glacial till, whereas the southern counties are covered by loess ranging from over 100 feet thick along the Missouri River bluff line to less than 15 feet thick in the southeast portion of the study area. Figure 3 shows a thickness contour map of western Iowa loess as reported by Dahl et al. (1958). Several studies have shown that the loess thins to the east and southeast.

Associated with the thinning, the properties of the loess exhibit a number of systematic trends that occur from west to east across the area. Median particle diameter and percent silt decrease (Davidson and Handy, 1952), clay content increases (Dahl et al., 1958), and in-place dry density increases (Davidson and Handy, 1952) from west to east. Ruhe (1969) has studied these trends and empirically developed a number of equations to relate loess properties to distance from the source area.

The topography also varies from west to east. As is typical of the loess deposits throughout the world, the western-most portion of the study area is dominated by a highly dissected topography where deep, narrow valleys are separated by narrow interfluves with steep slopes. The

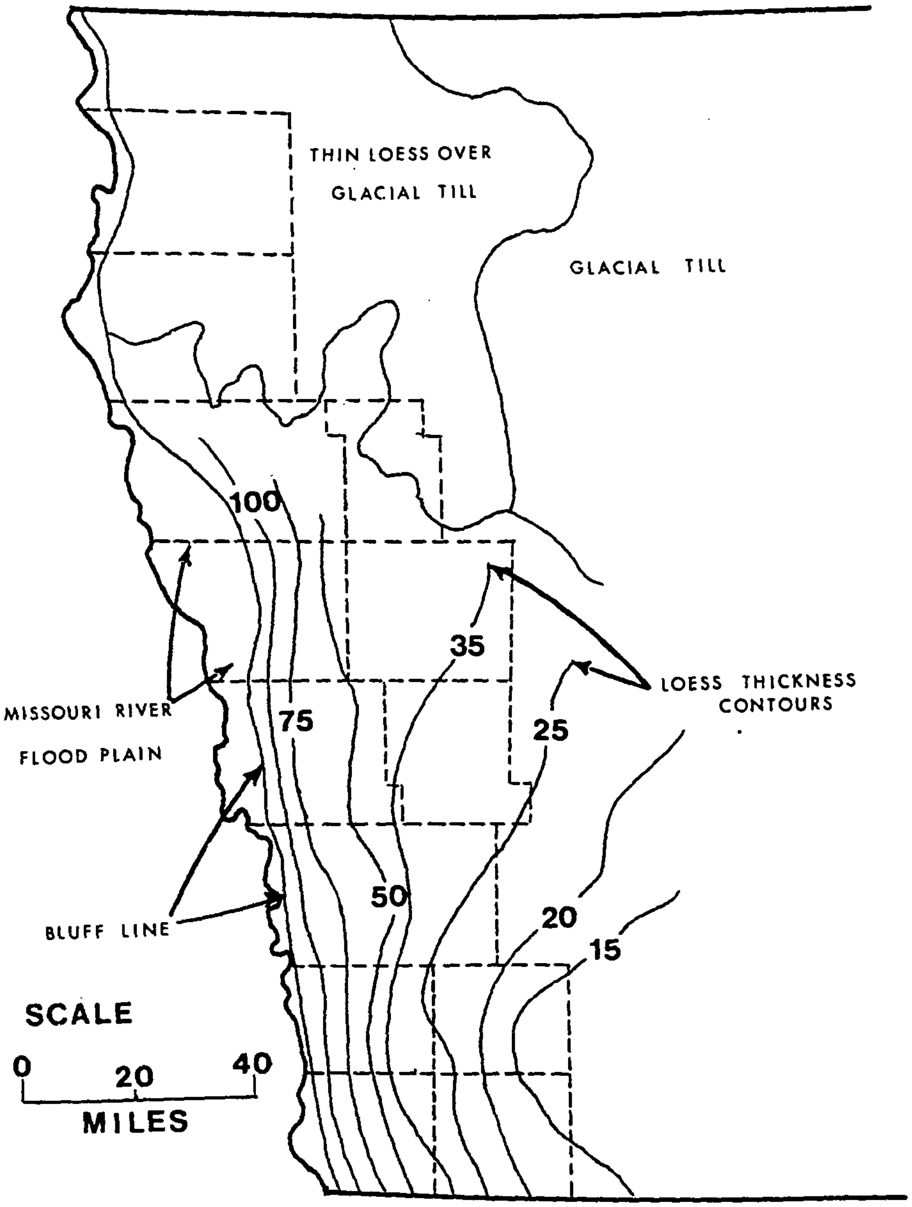

Figure 3. Surficial geology of western Iowa showing thickness of loess. After Dahl et al. (1958)

drainage network is highly integrated. Relief decreases and summit width increases from the bluff line eastward; maximum relief ranges from 220 feet near the bluffs to about 75 feet on the eastern edge of the study area. Ruhe (1969) observed that a linear relationship describes both topographic trends. Lohnes and Joshi (1967) found that the steepness of the valley sideslopes decreases with increasing distance from the bluffs according to a power function, and that absolute drainage density decreases with increasing distance.

It should be noted that the variations in loess thickness, loess properties, and topography are associated with the interpretation that the Missouri River floodplain was a major source for the loess and that the variations from west to east result from increasing distance from the source area.

Figure 4 is a section through the loess in southwestern Iowa as reported by Ruhe (1969). Note the lack of parallelism between the modern surface and the underlying erosional surface. Erosion and mass movement have been the major controls on the regional topography. Lohnes and Handy (1968) and Handy (1973) provided evidence that steep slopes along the Missouri River bluffs are primarily the result of mass movement, whereas the more gentle slopes are shaped by the erosive force of running water.

A generalized map of the major streams of Iowa and their drainage is shown in Figure 5. Larger streams that are part of the Mississippi River drainage basin flow to the southeast across the state, whereas streams within the study area join with the Missouri River by flowing to the south-southwest. Hallberg (1979) studied the alignment of stream systems in Iowa.

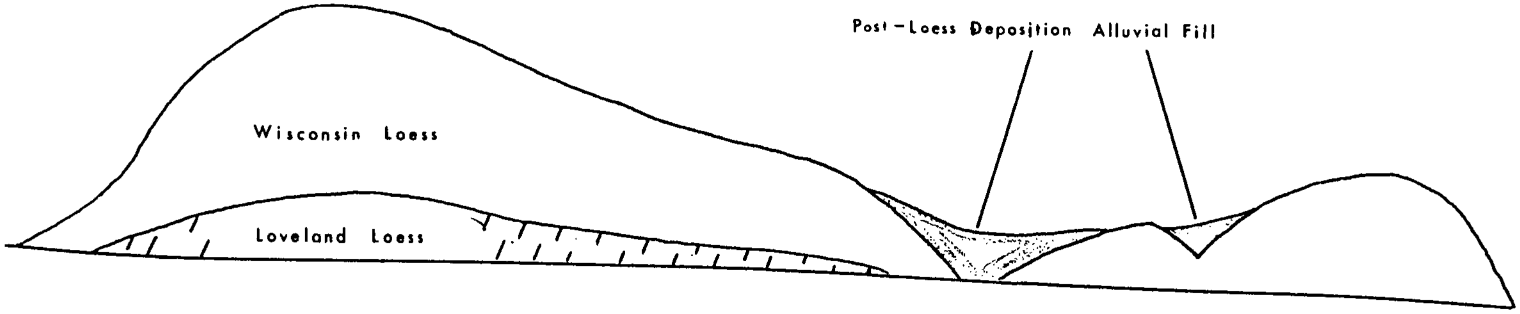

Figure 4. Cross-section through the loess in southwestern Iowa. After Ruhe (1969)

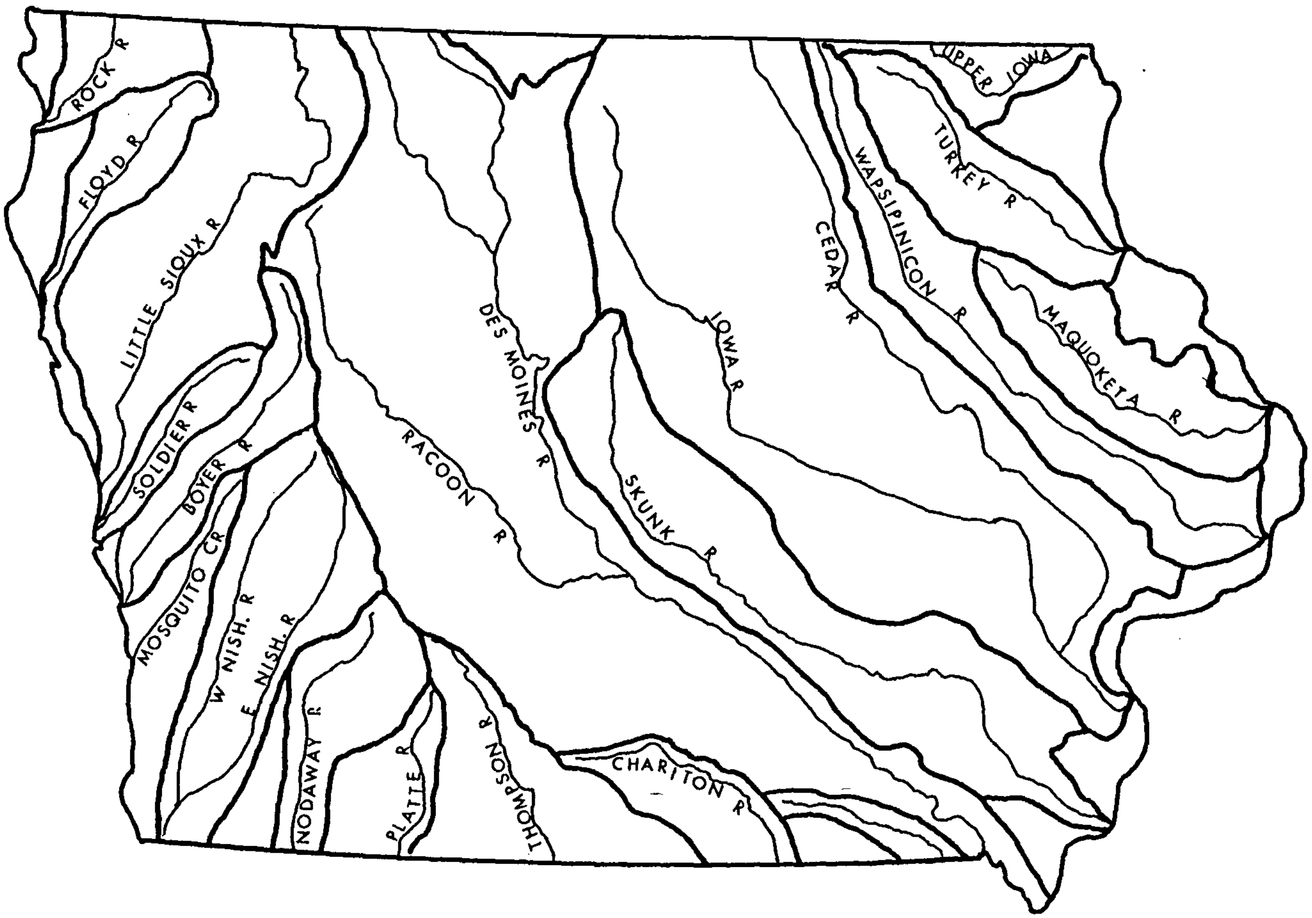

Figure 5. Generalized drainage map of Iowa. After Larimer (1974)

He concluded that the first-order stream valleys formed entirely within the Wisconsin loess have a strong preferred orientation of N 40-50° W, present in northwest, west central, and central Iowa. This feature of the smaller streams was interpreted to be wind-alignment of their valleys within the loess, caused by prevailing winds from the northwest during deposition of the loess. He also found that the higher order streams do not show this strong alignment, and that their direction of flow is probably controlled by the paleotopography of the underlying glacial till.

Characteristics of the drainage basins of major streams within the study area, as measured from 1:250,000 scale topographic maps, are listed in Table 2. Because drainage density is relatively high in western Iowa, the drainage network is more efficient than streams in other parts of the state. Basins within the study area will likely respond more quickly to a given precipitation event than do basins in other areas. Also, the circularity ratio of the Floyd and Little Sioux River basins is substantially higher than that of other streams in western Iowa. It appears that basins situated within the thin loess and till area have circularity ratios greater than 0.4, whereas basins in the deep loess have circularity ratios less than 0.3, i.e., the latter basins are more elongate than the former.

Annual precipitation and runoff averages for western Iowa, shown in Figures 6 and 7, are generally the lowest in the state. Precipitation ranges from 25 inches/year in the northwest to about 35 inches/year in the southeast of the study area. Runoff increases from less than 2 inches to between 5 and 6 inches in the same direction.

Discharge characteristics for major streams in the study area are contrasted in Table 3. Where available, gaged discharge averages for 10

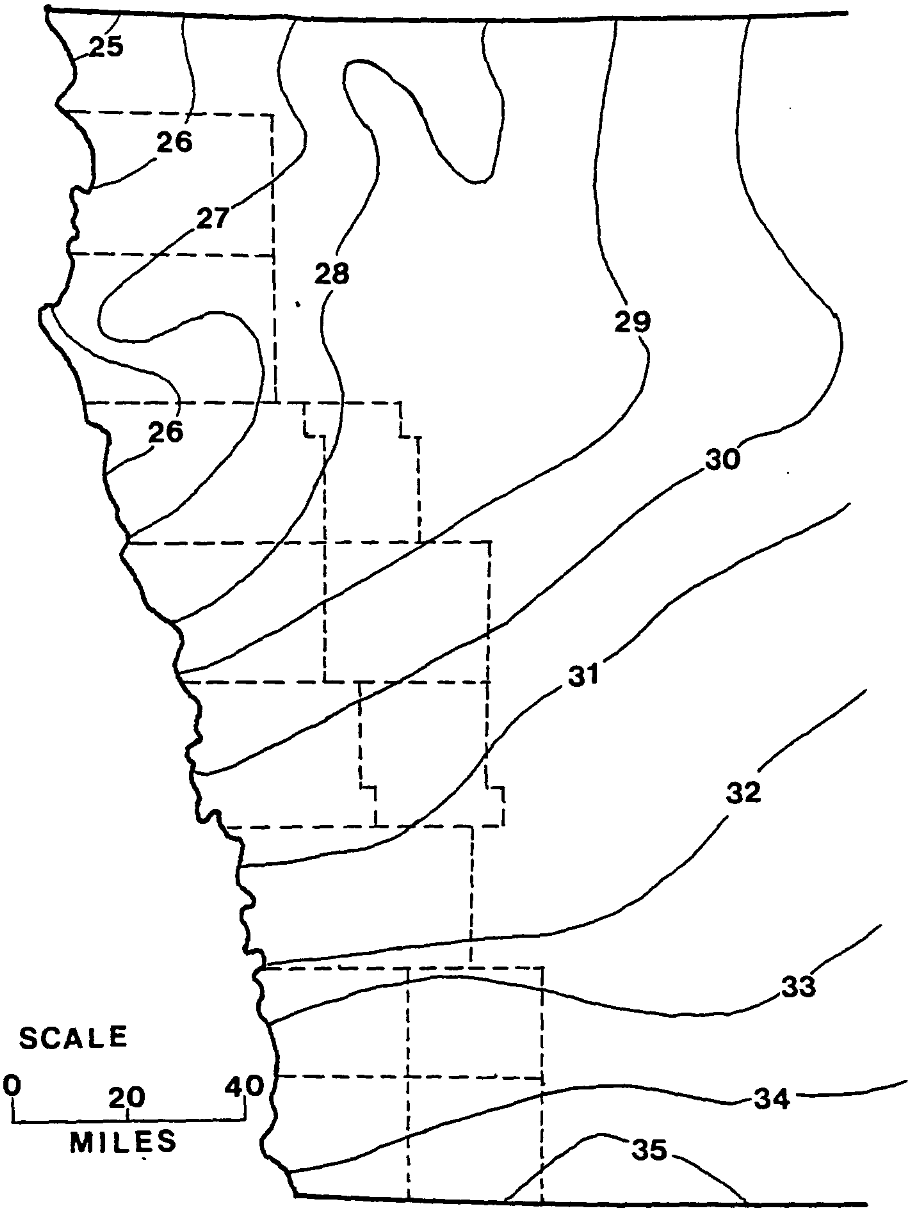

Figure 6. Normal amounts of annual precipitation in inches. From U.S. Geological Survey (1978)

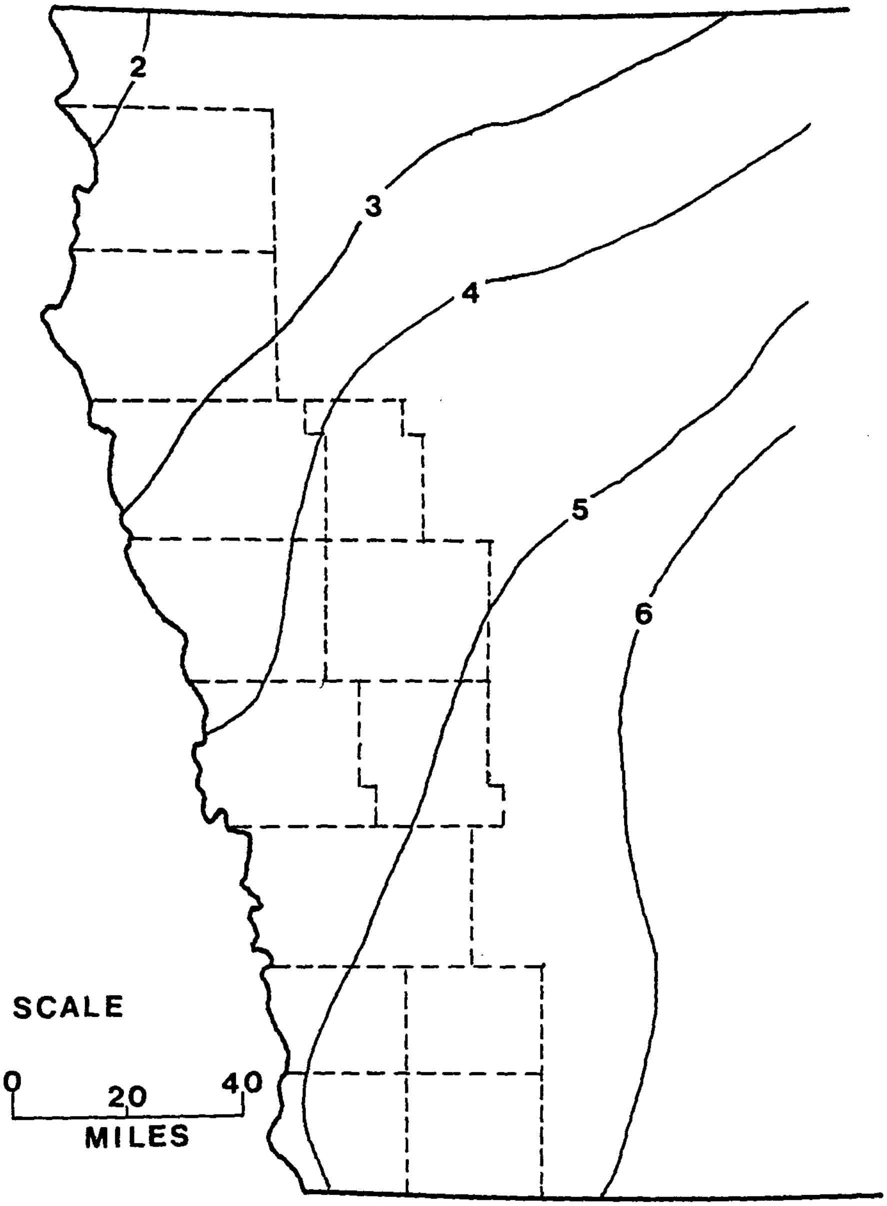

Figure 7. Average annual runoff in inches. From U.S. Geological Survey (1978)

Table 2. Quantitative geomorphology of selected western Iowa streams. After Lohnes et al. (1980)

Stream	Basin Order	Area (mi^2)	Drainage Density (mi^{-1})	Length of Main Stream (mi)	Circularity Ratio	Maximum Relief (ft)
Boyer	4	1,188	0.31	100	0.268	400
Keg	2	190[b]	0.32	65	0.277	525
Floyd	5	921	0.50	80	0.420	-
Little Sioux	6	4,507	0.23	130	0.664	430[a]
Soldier	3	445	0.33	65	0.266	575
Nishnabotna	5	2,819[b]	0.36	120[a]	--	650
Mosquito	2	267	0.41	60	0.277	450
Tarkio	3[a]	540	0.88	70	--	380
Willow	2	146	--	45	0.261	475

[a] Parameters for portions of streams within Iowa only.

[b] Measured 4.6 miles above mouth of stream.

or more years are listed. Lara (1979) developed equations for estimating average discharge for Iowa streams, based on a regional precipitation and runoff analysis (Figure 8). Using his procedure, average discharge for each of the streams was estimated and is compared with gaged data. This method allows the estimation of discharge for streams where no gaged data are available, and is used in a later section of this thesis to predict the average flow at several locations on Willow Creek.

Table 3. Average annual discharge for selected western Iowa streams. Modified from Lohnes et al. (1980)

Stream	Gaged Discharge[a] (cfs)	Drainage Area at Gage[a] (mi.^{2})	Drainage Basin Area (mi.^{2})	Estimated Discharge[b] (cfs)
Boyer	326	810	1,188	309
Floyd	207	918	921	236
Keg	-	-	210	79
Little Sioux	1,310	4,460	4,507	1,269
Mosquito	-	-	267	113
Nishnabotna	933	2,800	2,819[c]	1,373
Soldier	144	417	445	98
Tarkio	43	200	206[c]	99
Willow	-	-	146	34

[a] Gages not at mouth.

[b] From equations of Lara (1979); estimated for entire basin area.

[c] Within Iowa only.

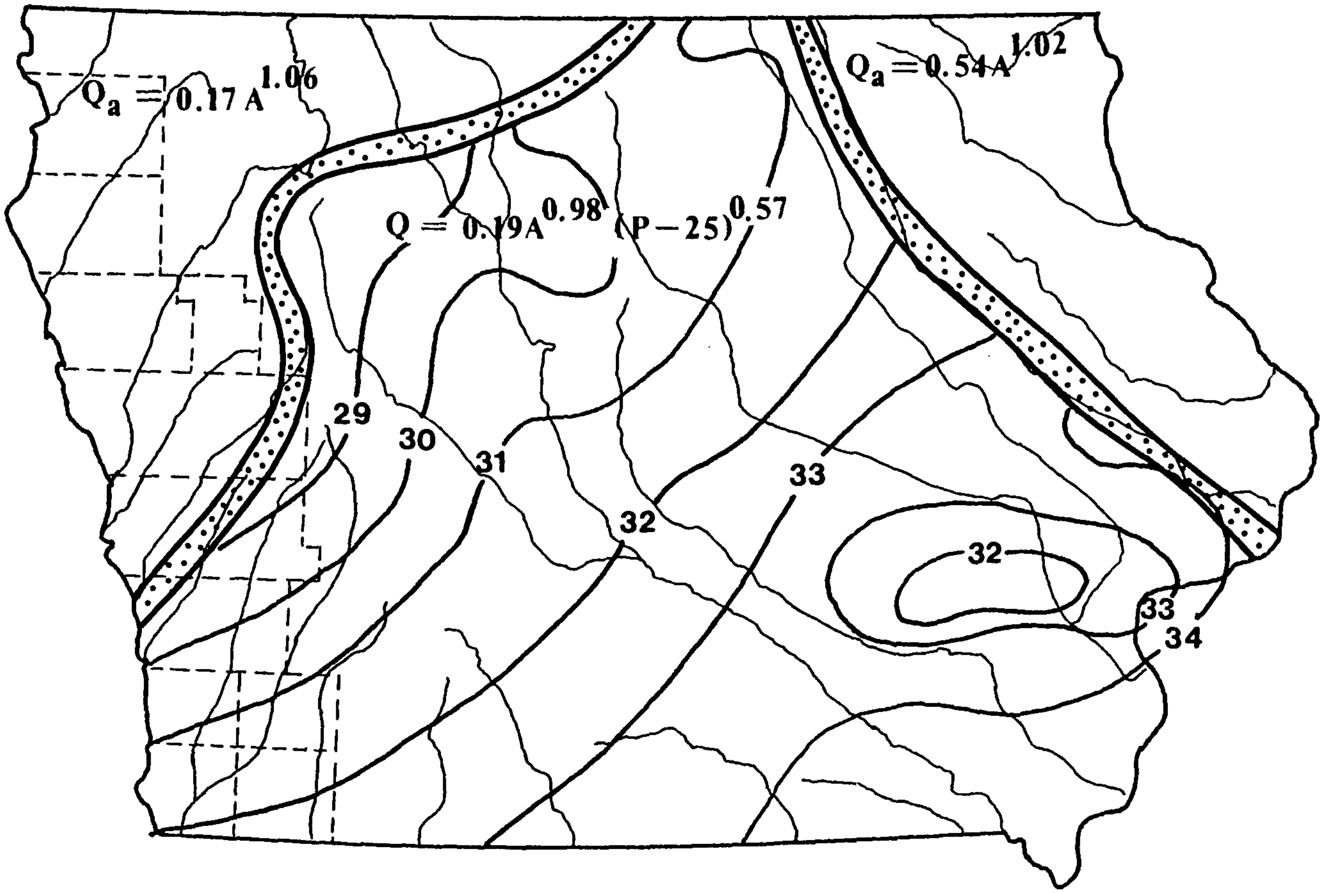

Figure 8. Regional equations for predicting average annual discharge. From Lara (1979)

LOCAL SETTING, KEG AND WILLOW CREEK BASINS

Topography

Within the region, a more complete study was made on the Keg and Willow Creek drainage basins, shown in an expanded view in Figure 9. Keg Creek heads in central Shelby County and flows southward through central Pottawattamie County before turning west to join with the Missouri River in west-central Mills County. Willow Creek heads in west-central Crawford County and flows southwest across Monona and Harrison Counties to empty into the Boyer River. Keg Creek is approximately 65 miles long and drains 210 square miles, whereas the Willow is about 49 miles long and drains 145 square miles.

Although the two basins are less than 22 miles apart, the topographical variations discussed previously are manifest in the nature of the stream valleys. Figure 10 shows the regional topographic variations of a traverse across Harrison and Shelby Counties. As noted previously, the height of the summits decreases and width increases from west to east.

It is apparent that other regional variations are also responsible for differences in the two basins. Most of the area within the Willow Creek basin is situated within loess between 50 and 75 feet thick; Keg Creek for the most part is set in 35 to 50 foot thick loess. The Keg Creek basin receives about an inch more precipitation near its head and nearly 3 inches more at its mouth than does the basin of the Willow, and consequently about an inch more runoff per year within the entire basin.

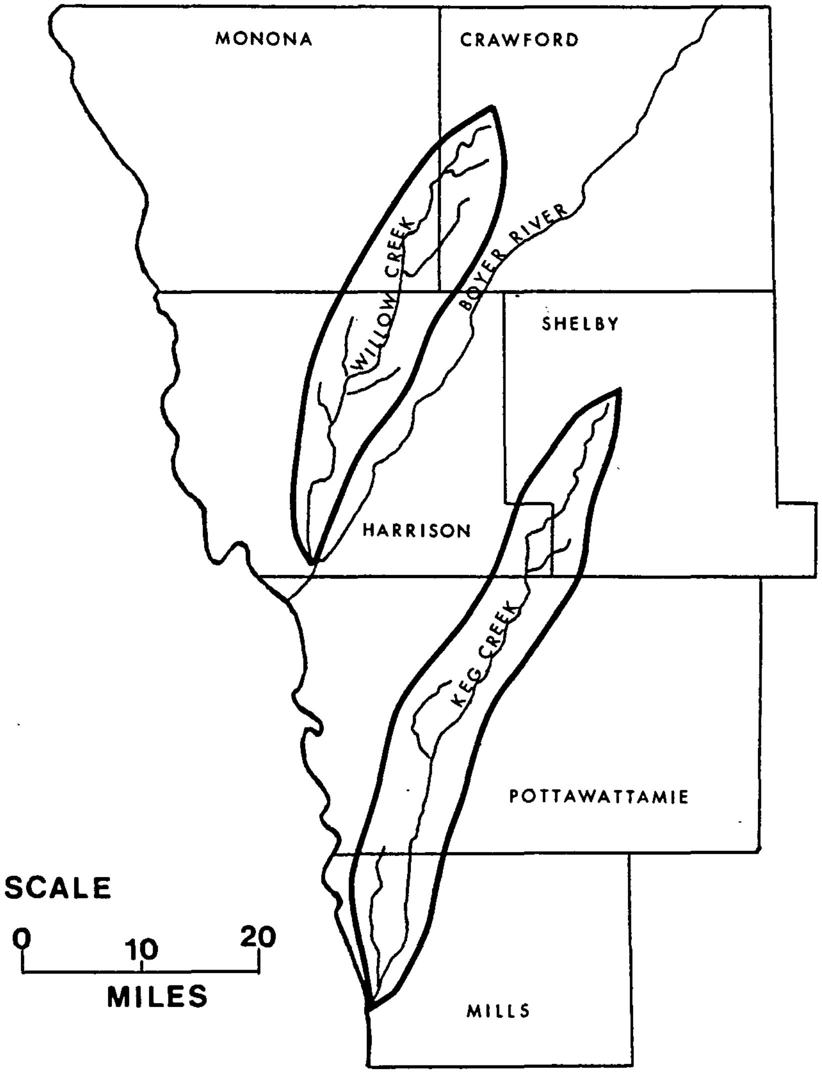

Figure 9. Location and extent of Keg and Willow Creek drainage basins

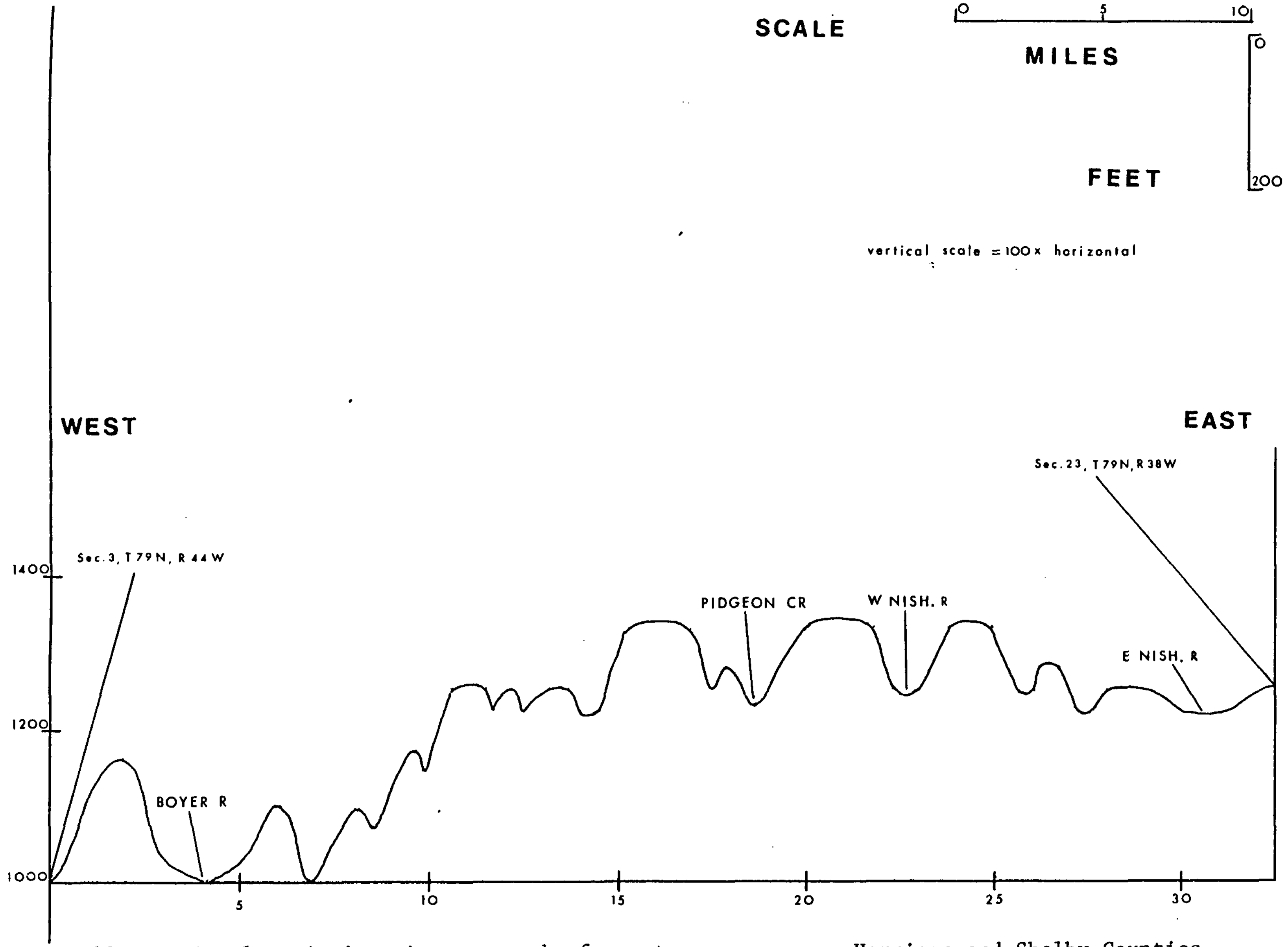

Figure 10. Regional variations in topography for a traverse across Harrison and Shelby Counties

Land Use

Most of the land within the study area is used for agricultural purposes. The major crops are corn and soybeans, almost exclusively in rowcropped fields planted in the late spring and tilled in mid-to-late fall. Livestock is pastured in some areas, but the cash crops mentioned above predominate.

Table 4 lists the percentages of land in cultivation for the counties in which the Keg and Willow Creek basins are situated. As used by the U.S. Department of Agriculture, the term cultivation applies to all land in pasture and rowcrop. All six counties have greater than 90% of their total area in cultivation as of 1976, and all but Pottawattamie County have over 95% in cultivation.

Table 4. Land use patterns in study area, 1976. From U.S. Department of Agriculture

	Land Use		
County	Acres in cult., 1976	Total Acres	% Cult.
Harrison	431,200	445,310	96.8
Monona	431,200	446,080	96.7
Shelby	371,220	375,680	98.8
Crawford	452,870	458,240	98.8
Pottawattamie	568,960	612,480	92.9
Mills	271,150	275,200	98.5

Cultivation of western Iowa did not begin until the first settlers arrived in about 1848, and the percentage of land put into cultivation continued to increase until about 1940. The relatively rapid change from tall grass prairie to rowcrops and pasture has been suggested as a cause of the stream degradation; this possibility will be discussed in a following section of this thesis.

Physical Properties and Stratigraphy of Soils

The streams of the study area, with the exception of those situated in the northern-most portion, have entrenched themselves into a thick alluvial fill derived from the upland loess. Iowa Department of Transportation drilling logs for bridges crossing state and interstate highways in the region provided data from which the thickness of alluvium was determined (Figure 11; original map from Antosch and Joens, 1979, modified by Lohnes et al. (1980)). With a few exceptions, a glacial till or paleosol is found directly beneath the alluvium, identifiable by the presence of a stone line noted in the drilling log.

Several authors have described the stratigraphic section of the upland glacial materials as they exist in the study area. As shown in Table 5, all materials are glacial or interglacial deposits of Pleistocene age. Each of the major deposits (i.e., Nebraskan Till, Kansan Till, Loveland Loess, Wisconsin Loess) has been modified at the surface by a period of soil formation and/or erosion, resulting in the presence of a paleosol separating that deposit from the overlying member. Within the Wisconsin loess, several substages of deposition have occurred, and erosion during non-deposition periods has resulted in a thick alluvial fill in the valleys.

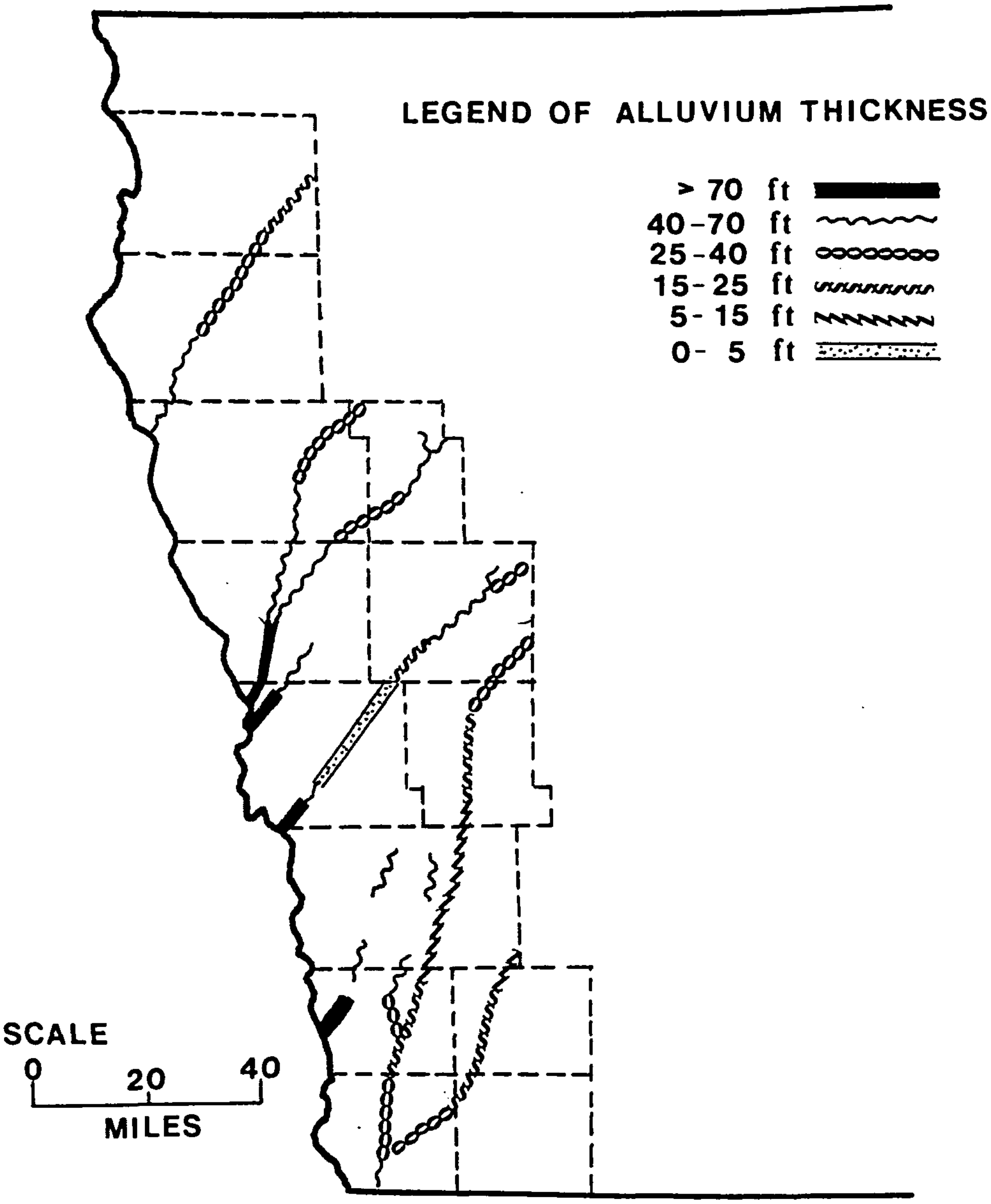

Figure 11. Thickness of alluvium beneath channel bottom. After Lohnes et al. (1980)

Table 5. Idealized stratigraphic section for study area. After Daniels and Jordan (1966)

Glacial Stage	Substage	Interglacial Stage	Evidence	Authority
Wisconsin	Cary		Drift	Ruhe
	Tazewell-Cary		Soil	Ruhe et al. (1957)
	Tazewell		Loess, Drift	Ruhe; Ruhe, Daniels & Cady (1966)
	Iowan		Drift	Ruhe et al. (1957); Ruhe, Daniels & Cady (1966)
		Sangamen	Weathered zones, soils, peat	Kay & Graham (1943); Ruhe, Daniels & Cady (1966)
Illinoian			Loveland loess	Kay & Graham (1943); Leighton & Willman (1950); Ruhe, Daniels & Cady (1966)
		Yarmouth	Soils, erosion, sediment	Kay & Apfel (1925); Ruhe, Daniels & Cady (1966)
Kansan			Drift	Kay & Apfel (1929); Ruhe, Daniels & Cady (1966)
		Aftonian	Soils, peat, weathered zones	Kay & Apfel (1929); Ruhe, Daniels & Cady (1966)
Nebraskan			Drift	Kay & Apfel (1929); Ruhe, Daniels & Cady (1966)

The change in the physical properties of the upland loess is illustrated in Table 6, for a traverse across Monona, Harrison and Shelby Counties (Davidson and Handy, 1952). These changes highlight the systematic trends previously described. Due to these variations, there is also a change in the engineering classification of the materials, as shown in Table 6 and Figure 12. Upland loess in the study area grades from an A-4 classification in the far west to A-6 in the center and A-7 in the east.

Variations in the properties of the Wisconsin loess have had an affect on the soil-forming factors at work on the parent material, as discussed by Ruhe (1969) and others. Thus, the nature and thickness of the surficial soils also varies from west to east across the region, giving rise to a change in the principal soil association groups (Figure 13). In general, the increasing clay content and decreasing relief in an easterly direction has resulted in a higher degree of development in the soils to the east of the region.

The presence of the Wisconsin loess has had an effect on the amount and type of erosion experienced by the uplands and within the waterways. As witnessed by the highly dissected topography, high drainage density and the ease with which rills form in the loess, this material has a high degree of erodibility. This phenomenon stems in part from the low shearing strength (Table 7) that the loess has.

The alluvium present in the stream valleys of Keg and Willow Creek has been exposed by the degradational process and are easily observed. In the exposed section it appears to be similar to the upland loess, but are distinguishable from the upland material by several properties:

Table 6. Properties of the Wiconsin loess in the study area as reported by Davidson and Handy (1952)

Distance from east valley wall (mi.)	Sampling Depth (ft.)	Air-Dry Color	In-place Unit Weight (pcf)	Plasticity Index	Specific Gravity	Texture	Classification
0	2-3	Light yellow-brown	69.4	5.7	2.70	Silty loam	A-4(8)
9.8	2-3	Pale yellow	N.R.	5.3	2.71	Silty loam	A-4(8)
20.0	2-3	Light yellow-brown	73.5	5.2	2.71	Silty clay loam	A-4(8)
20.0	29-30	Pale yellow	89.5	5.5	2.71	Silty clay loam	A-4(8)
27.0	2-3	Light yellow-brown	N.R.	14.4	2.71	Silty clay loam	A-6(10)
27.0	7.5-8.5	Light yellow-brown	N.R.	12.1	2.70	Silty clay loam	A-6(9)
32.7	2-3	Pale yellow	76.2	12.5	2.70	Silty clay loam	A-6(9)
32.7	8-9	Light grey	87.4	17.8	2.69	Silty clay loam	A-6(9)
44.0	2-3	Light yellow-brown	N.R.	18.2	2.70	Silty clay	A-7-6(12)
55.3	2-3	Light olive-brown	79.6	16.2	2.70	Silty clay loam	A-6(10)
66.6	2-3	Pale yellow		18.0	2.70	Silty clay	A-6(11)
78.2	2-3	Pale yellow	83.5	26.6	2.70	Silty clay	A-7-6(16)

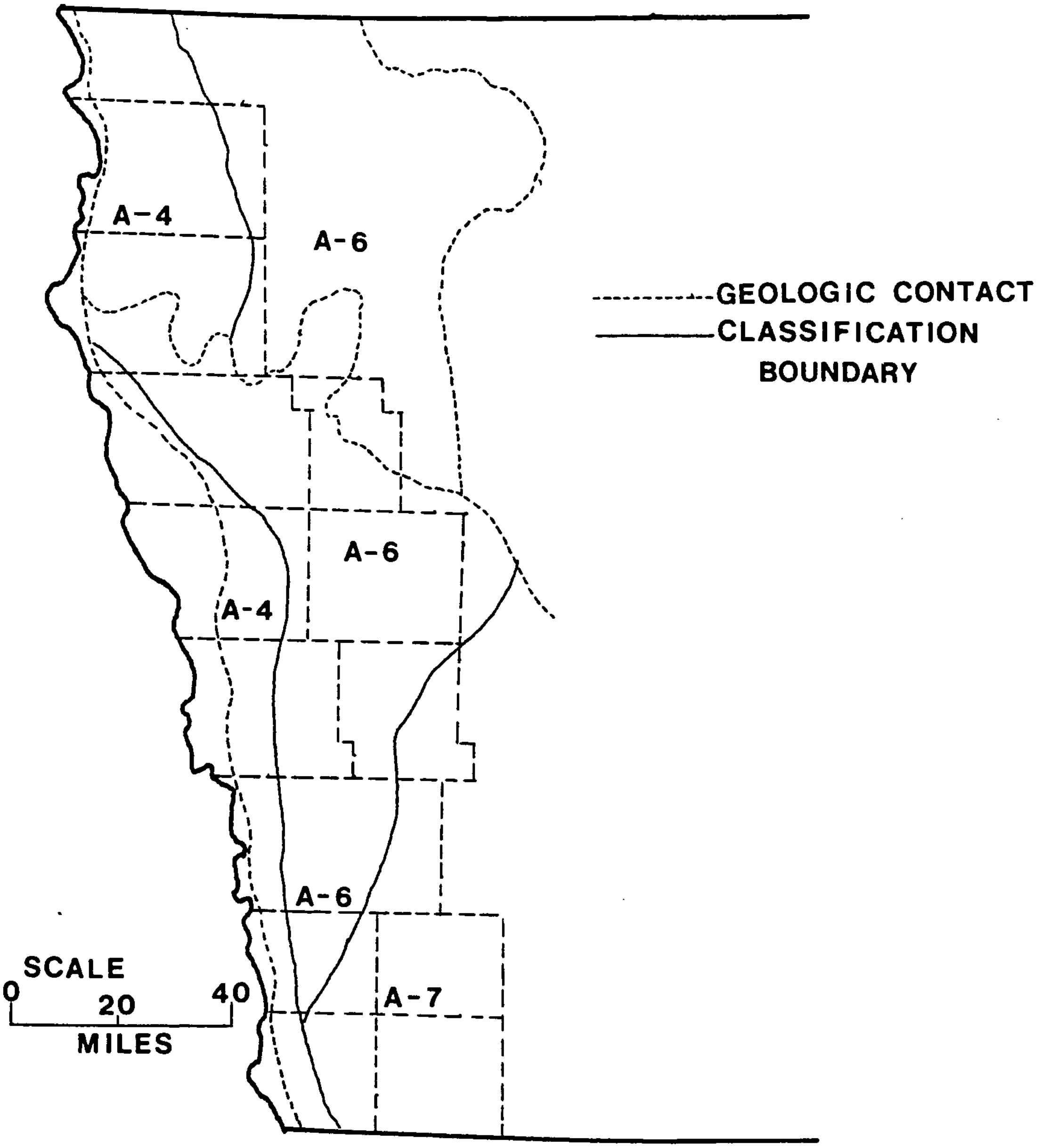

Figure 12. Engineering classification of loess in western Iowa. After Hansen et al. (1959)

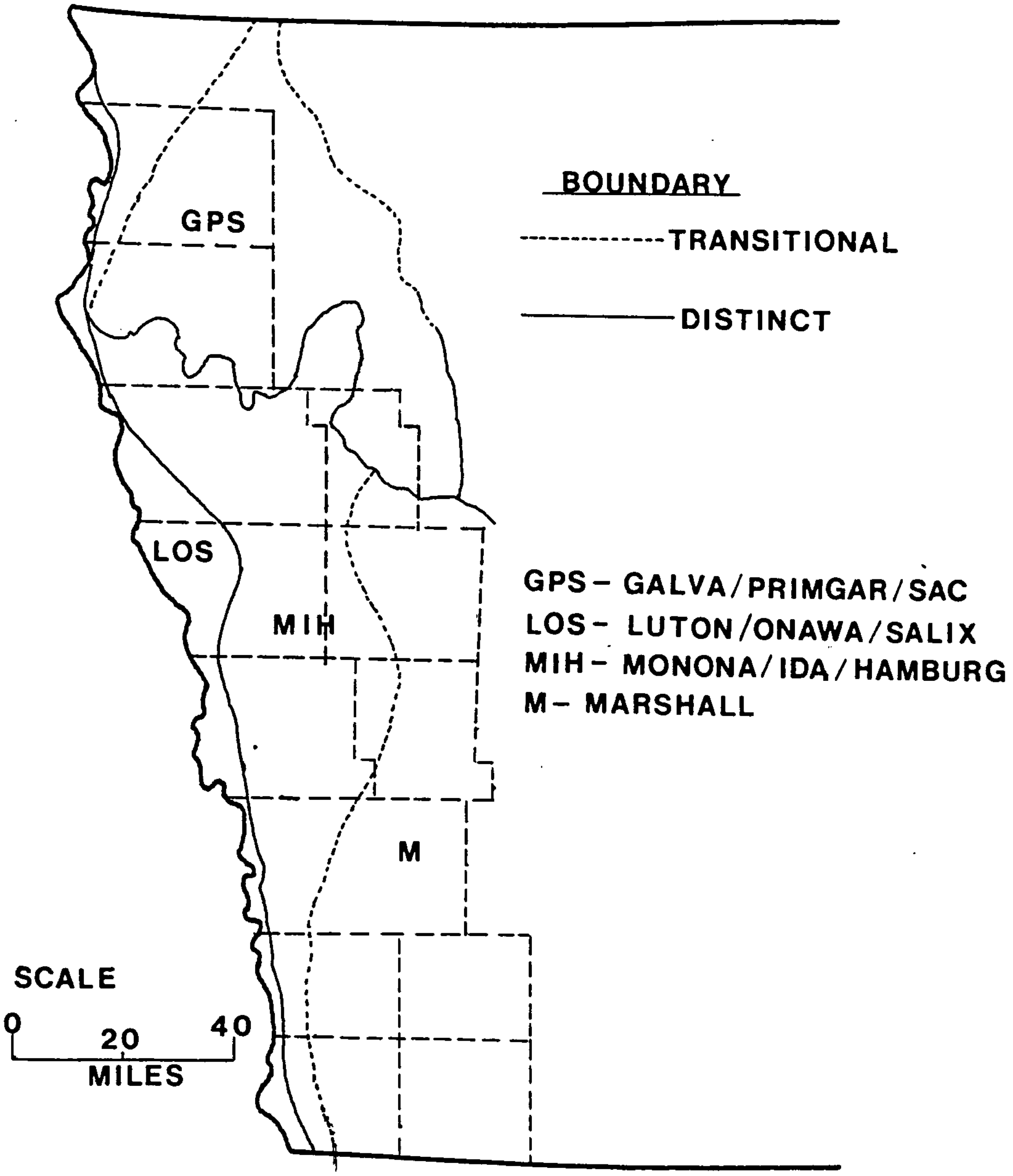

Figure 13. Principal soil association groups in western Iowa. After Simonson et al.(1952)

Table 7. Shearing strength of upland loess as measured at 11 locations in Harrison County

Sample No.	Location	Shearing Strength (psf)[a]
1	NW/NW Sec. 3 R42W, T81N	280
2	E. line Sec. 9 R42W T81N	380
3	SE/SE Sec. 20 R42W T81N	380
4	SE/SE Sec. 29 R42W T81N	240
5	W. line Sec. 32 R42W T81N	300
6	Center Sec. 31 R43W T81N	260
7	Center Sec. 5 R43W T80N	320
8	Center Sec. 7 R42W T80N	280
9	NE/NE Sec. 14 R43W T80N	260
10	E. line 23 R43W T80N	220
11	W. line 24 R43W T80N	340

[a] Measured in-place with Soil-Test^{tm} Torvane.

-Dry upland loess is brown and yellow-brown (10 YR 5/4); the alluvium as observed in Harrison, Shelby and Pottawattamie Counties is gray-brown and dark gray (10 YR 3/1, 4/1, 5/1).

-Upland loess contains concretions and ferrotubules that can be readily observed at the surface. Neither of these post-deposition features were found in the alluvium.

-Alluvium shows evidence of stratification in some areas; the upland loess shows none.

Daniels and Jordan (1966) did a comprehensive study of the stratigraphy and geomorphology of glacial and interglacial deposits in the Willow Creek drainage basin. All alluvium within the drainageways was identified as Tazewell-Cary and Recent age. The primary stratigraphic units present are members of the DeForest Formation, a late Pleistocene group of deposits ranging in age from 14,000 years b.p. (the termination of loess deposition) to less than 100 years b.p. A thin layer of post-settlement alluvial fill overlies these units.

A depiction of the stratigraphic relationship of these units to each other and to the Willow Creek channel is shown in Figure 14. From oldest to youngest, the DeForest Formation consists of the Soetmelk, Watkins, Hatcher, Mullenix and Turton members. The Mullenix, Hatcher and Watkins members are the thickest in the formation, and the ones most commonly exposed in the channel; the lower Soetmelk is in most cases not cut by the channel, or only exposed at the very bottom. The upper Turton member is not as laterally extensive as the other units. Daniels and Jordan reported finding Turton disconformably overlying Mullenix or Hatcher at various locations along the channel.

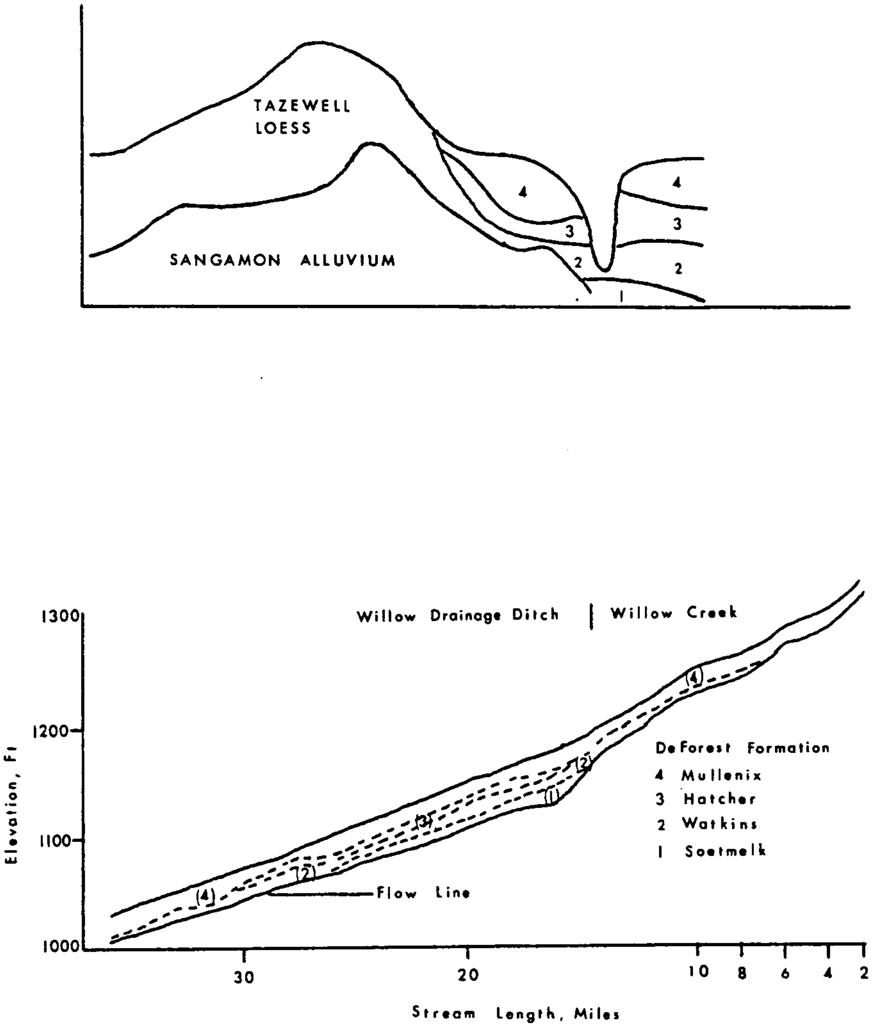

Figure 14. Stratigraphic relationships between members of the DeForest Formation and Willow Creek channel. After Daniels and Jordan (1966)

Because the processes of soil formation and erosion continued to occur between the depositional periods of these members, each has a paleosol, stone line or both present at its uppermost boundary (Figure 15). The thickness of these erosional features depends on the amount of time that lapsed between the end of deposition of the underlying unit and start of deposition of the overlying one.

Values of gradation, dry density, average thickness and age (via radiocarbon dating of wood samples) as reported by Daniels and Jordan (1966) for the members of the DeForest Formation are given in Table 8. All of these soils can be described texturally as silt loam. In this respect the Tazewell-Cary alluvium is very similar to the upland loess, with the exception that the alluvium has a slightly higher fine silt and clay content.

The stratigraphy of the alluvium observed along the Keg Creek channel at several locations is described in Appendix I. The appearance of this material is very similar to that described by Daniels and Jordan (1966) for the alluvium in Harrison County. Keg Creek valley alluvium was sampled at several locations along the length of the stream. Particle size data as determined by the standard hydrometer method are shown in Table 9. The gradation of these materials is much the same as the gradation of the Tazewell-Cary alluvium in the Willow Creek basin, although the Keg Creek alluvium has higher clay content.

A total of 40 tests for shearing strength using a Torvane were made at 20 different locations on Keg, Thompson and Willow Creeks (Table 10). At several of these locations, in-place unit weight of the alluvium was determined with an Ely Volumeter. Comparison of the data in Tables 8, 9

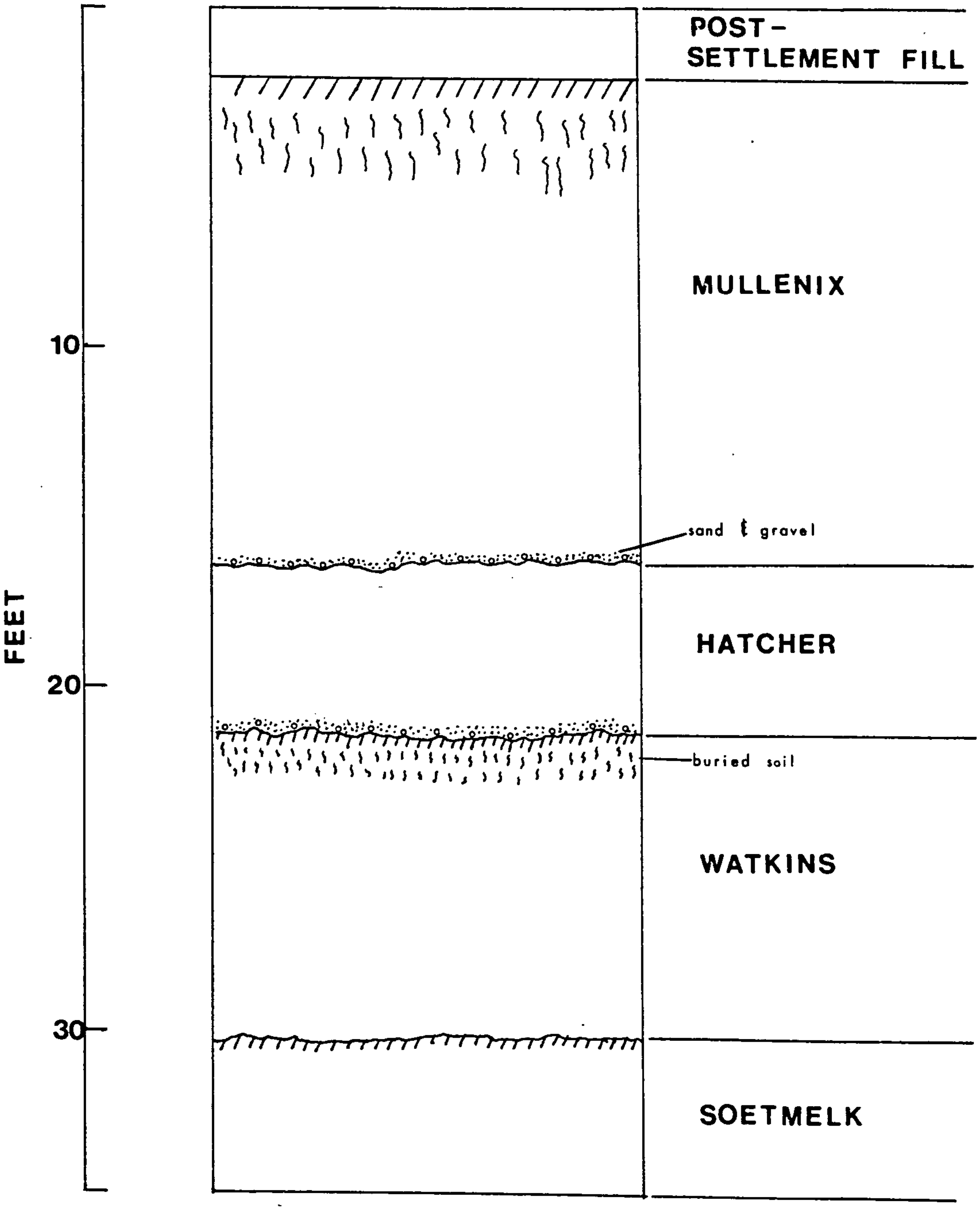

Figure 15. Stratigraphy of the DeForest Formation. After Daniels and Jordan (1966)

Table 8. Physical properties of the members of the DeForest Formation as reported by Daniels and Jordan (1966)

Member	DeForest Formation		Gradation[a]			
	Av. Thickness (ft.)	Density (pcf)	Sand	Silt	Clay	Age (years)
Turton	11'[b]	N.R.[c]	N.R.[c]	N.R.[c]	N.R.[c]	76-250
Mullenix	16'	75-87	2.1	83.4	14.5	1,100-1,800
Hatcher	9'	88[b]	4.6	79.3	16.1	1,800-2,020
Watkins	7'	N.R.[c]	3.3	80.3	16.4	2,020-11,000
Soetmelk	N.R.[c]	74[b]	N.R.[c]	N.R.[c]	N.R.[c]	11,120-14,300

[a] Representative - others exist.
[b] One sample only.
[c] N.R. - no report.

Table 9. Gradation of the Keg Creek alluvium at 5 locations

Location	% Sand	% Silt	% Clay
Secs. 14 & 15 R.41W T.77N	2.3	74.7	23.0
Sec. 6 R.39W T.78N	1.9	80.6	17.5
Secs. 15 & 22 R.42W T.75N	2.4	69.6	28.0
Secs. 4 & 9 R.42W T.74N	2.1	73.4	24.5
Center Sec. 25 R.42W T.76N	2.0	64.0	34.0

Table 10. Physical properties of the alluvium from the Keg, Thompson and Willow Creek drainage basins

Sample No.	Stream	Location (Miles above Mouth)	Location (Above Channel)	Dry Dens.	Shear Strength
1	Willow Creek	26.7	25'	-	600 psf
2	"	26.7	15'	-	460 psf
3	"	26.7	7'	-	420 psf
4	"	24.8	28'	81.33 pcf	700 psf
5	"	24.8	15'	-	500 psf
6	"	24.8	3'	-	260 psf
7	"	22.8	25'	-	640 psf
8	"	20.8	30'	76.15 pcf	620 psf
9	"	20.8	16'	71.95 pcf	520 psf
10	"	20.8	3'	83.18 pcf	460 psf
11	Thompson Creek		20'	68.64 pcf	740 psf
12	"		2'	68.64 pcf	460 psf
13	Willow Creek	16.9	15'	-	700 psf
14	"	16.9	8'	90.7 pcf	440 psf
15	"	16.9	1'	-	200 psf
16	"	15.8	20'	-	700 psf
17	"	15.8	10'	-	540 psf
18	"	15.8	1'	-	1000 psf (glacial clay)
19	"	13.0	23'	87.27 pcf	240 psf
20	"	13.0	8'	91.75 pcf	720 pcf
21	"	13.0	2'	78.42 pcf	280 pcf
22	"	6.0	15'	-	460 psf
23	"	6.0	3'	-	200 psf
24	"	2.0	15'	83.75 pcf	200 psf
25	"	2.0	3'	-	300 psf
26	Keg	21.9	25'	-	900 psf
27	"	21.9	15'	-	320 psf
28	"	21.9	4'	-	300 psf
29	"	25.9	25'	66.23 pcf	260 psf
30	"	25.9	12'	74.62 pcf	300 psf
31	"	25.9	4'	74.62 pcf	200 psf
32	"	29.5	20'	-	200 psf
33	"	29.5	20'	-	400 psf
34	"	35.9	19'	69.75 pcf	380 psf
35	"	35.9	6'	-	380 psf
36	"	39.9	18'	-	600 psf
37	"	39.9	18'	-	420 psf
38	"	49.0	15'	84.6 pcf	500 psf
39	"	49.9	5'	-	360 psf
40	"	54.0	15'	-	500 psf

and 10 shows that the physical properties of the alluvium in the Keg and Willow Creek basins are similar.

A comprehensive study of the stratigraphy of the Keg Creek basin alluvium was not undertaken. Consequently, diagrams similar to those presented in Figure 14 cannot be reproduced for Keg Creek. However, the alluvium from the Keg Creek basin may be of the same age and origin as the DeForest Formation of the Willow Creek basin. Further study of stratigraphy and radiocarbon dating of organic material within the alluvium of the Keg Creek basin would be necessary to produce a positive correlation between these two materials.

Quantitative Geomorphology, Keg and Willow Creek Basins

Drainage networks situated within homogeneous terrains are orderly systems, and parameters associated with the streams and their drainage basins at one portion of the system can often be predicted from information about another portion of the network. Characteristics such as peak discharge, flood frequency, and flood duration can be predicted from a knowledge of the drainage basin geometry. It is not the intention of this thesis to make such predictions about the Keg and Willow Creek basins, but to provide quantitative descriptions of the geometries of these basins.

Some of the characteristics of the two drainage basins are shown in Table 11. Comparison of the morphometric parameters, as measured from 1:24,000 scale maps, shows that little difference exists between the first order streams of the two basins. However, divergence of some parameters occurs for the higher order streams. The following differences are notable:

Table 11. Selected morphometric parameters of the Keg and Willow Creek drainage basins

Order	Number of Streams	Average Length (mi.)	Average Area $(mi.^2)$	Average Density $(mi.^{-1})$	Average Circularity Ratio	Average Slope (%)
Keg Creek						
1	377	0.89	0.365	2.84	0.690	2.1
2	64	1.19	1.36	0.872	0.626	0.98
3	16	2.39	3.79	0.371	0.575	0.43
4	2	15.2	60.25	0.161	0.420	0.10
5	1	33	210	0.076	0.277	0.08
	420					
Willow Creek						
1	198	0.87	0.292	3.10	0.627	2.1
2	20	1.43	1.22	1.514	0.520	0.130
3	7	3.28	8.04	0.654	0.314	0.070
4	1	31.80	146	0.218	0.261	0.060
	226					

-the average length of the higher order streams in the Willow Creek basin is greater than that of streams in the Keg Creek basin.

-the higher order streams of the Willow Creek basin (2nd order and above) have an average slope steeper than those of the Keg Creek basin.

-circularity ratios of all basins tributary to the Willow Creek basin are less than those of the Keg Creek basin (the basins of the Willow are more elongate than those of Keg Creek).

- drainage densities of the basins tributary to Willow Creek are greater than those of the Keg Creek basins.
- the average areas of the higher order basins tributary to Willow Creek are greater than those of the Keg Creek basins.

The existence of most of these trends can be related to the changes in upland topography that occur from west to east across the study area. Inspection of 1:24,000 scale topographic maps shows that tributaries to Willow Creek are separated from the Willow by steep, narrow interfluves and tend to run parallel to the master stream for some distance before joining. On the other hand, the eastward decrease in regional relief and increase in summit and valley width is manifested in the more circular drainage basins of Keg Creek tributaries.

There are fewer tributaries above second order per unit length of Willow Creek than per unit length of Keg Creek. For Keg Creek there is a total of 18 third and fourth order tributaries; divided by a total stream length of 65 miles, this gives 0.27 tributaries per unit length of Keg Creek. For Willow Creek only 7 such tributaries exist, giving a tributary to length ratio of 0.14.

In Figure 16, drainage area is plotted versus stream length for several locations on Keg and Willow Creeks. Points from both streams fit on the same linear trend, indicating that both collect drainage area in about the same proportion per unit length of stream. However, it was noted above that Willow Creek has fewer tributaries per unit stream length than Keg Creek, and 4 of the 7 major tributaries to the Willow join it within a stream distance of only 4.4 miles in middle Harrison County. Using the Lara equations discussed earlier to predict the average discharge

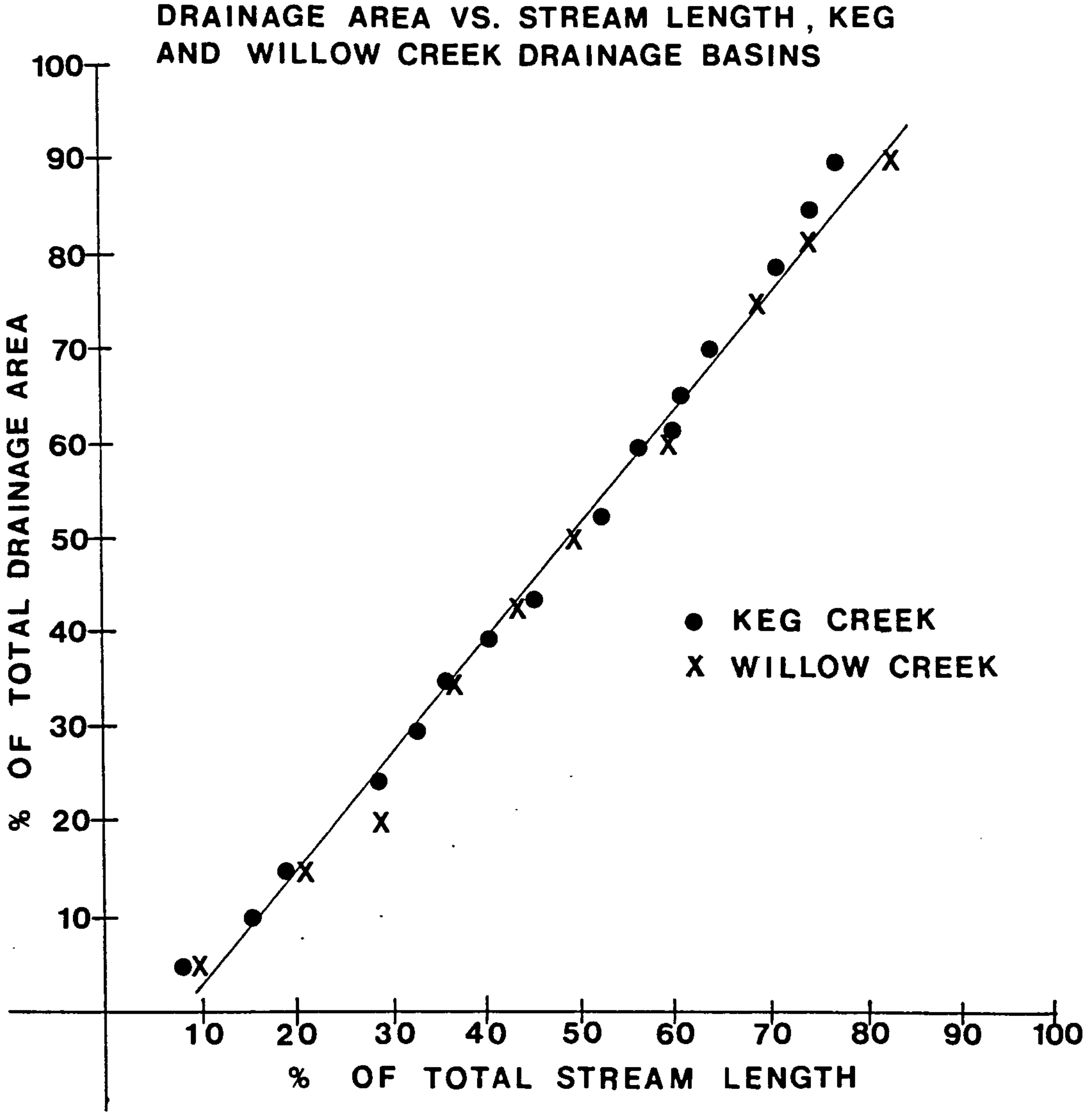

Figure 16. % of drainage area vs % of stream length, Keg and Willow Creek drainage basins

contributed by each of these tributaries to the Willow, it is estimated that over 40% of its total discharge enters the stream in less than 10% of its length. The data from Figure 16 do not reflect this, however, possibly because the data for this plot have been normalized.

Some mention should be made of the fact that the line fitting the data of Figure 16 appears to have an intercept on the x - axis. This figure is analagous to those presented by Hack (1957) in describing the "constant of channel maintainence," with the exception that Hack's data fit a log-log plot, with stream length on the abcissa and drainage area on the ordinate. It appears that if the axis' were reversed in Figure 16, the intercept would be on the abcissa, as was the case with the Hack data.

Because of the differences that exist between the nature of the two basins, there should be a difference in the discharge characteristics of the two drainage basins. The basins of the streams tributary to Willow Creek are likely more efficient in collecting and transmitting runoff than those of Keg Creek, because of their higher drainage density. However, because gaged discharge records exist for only a few years for Willow Creek and not at all for Keg Creek, data to support this interpretation are not available.

CHANNEL DEGRADATION

History of Degradation

Most of the perennial and intermittent streams in western Iowa have entrenched themselves into their alluvial fill at some location. Several authors have described the degradation of these waterways. Daniels (1960) described the entrenchment of the Willow drainage ditch between 1919-1958, and provided an expanded analysis of the erosional processes with two other publications (Ruhe and Daniels, 1965; Daniels and Jordan, 1966). A historical analysis of the deepening of the Tarkio River was performed by Piest et al. (1976) and Piest et al. (1977). Beer (1962) provided some data on the degradation of Steer Creek. Lohnes et al. (1980) updated the history of the Willow with recent longitudinal profiles, and provided new information on the degradational history of Keg Creek.

Table 12 summarizes the data presently available on the degradational history of Keg Creek and the Willow drainage ditch since the turn of the century. Figure 17 shows the changes that have taken place in the longitudinal profile of the Willow over this time period; Figure 18 shows a similar plot for the entire length of Keg Creek.

Evidence of degradation for all of these studies was obtained from land surveys and plats, drainage district records and bridge inspection reports and plans available at the county engineers' and auditors' offices. The earliest of these documents dates back to about 1900. To obtain information about the nature of these streams prior to this date, state and county historical journals and geological surveys were consulted.

Table 12. Degradational history of Keg and Willow Creek, 1919-1980
After Lohnes et al. (1980)

Stream	Distance from Mouth (miles)	Date	Channel Depth (ft.)	Status
Willow	11.4	1919	15	Degrading
		1931	21	Degrading
		1936	25	Degrading
		1958	29	Degrading
		1966	33	Degrading
		1980	32	Aggrading
Willow	15.4	1919	16	Degrading
		1931	22	Degrading
		1958	33	Degrading
		1966	22	Aggrading
		1980	27	Degrading
Willow	19.7	1920	12	Degrading
		1929	19	Degrading
		1942	30	Degrading
		1958	36	Degrading
		1966	33	Aggrading
		1980	32	Aggrading
Willow	25.6	1920	11	Degrading
		1950	22	Degrading
		1952	38	Degrading
		1958	39	Degrading
		1966	cross-section altered after 1958	
		1980		
Keg	23.0	1954	28	Degrading
		1973	32	Degrading
		1980	30	Aggrading
Keg	25.1	1927	21	Degrading
		1952	30	Degrading
		1976	32	Degrading
		1978	32	Stable
		1980	32	Stable
Keg	28.0	1954	17	Degrading
		1973	24	Degrading
		1980	25	Degrading
Keg	28.5	1958	14	Degrading
		1973	24	Degrading
		1980	27	Degrading

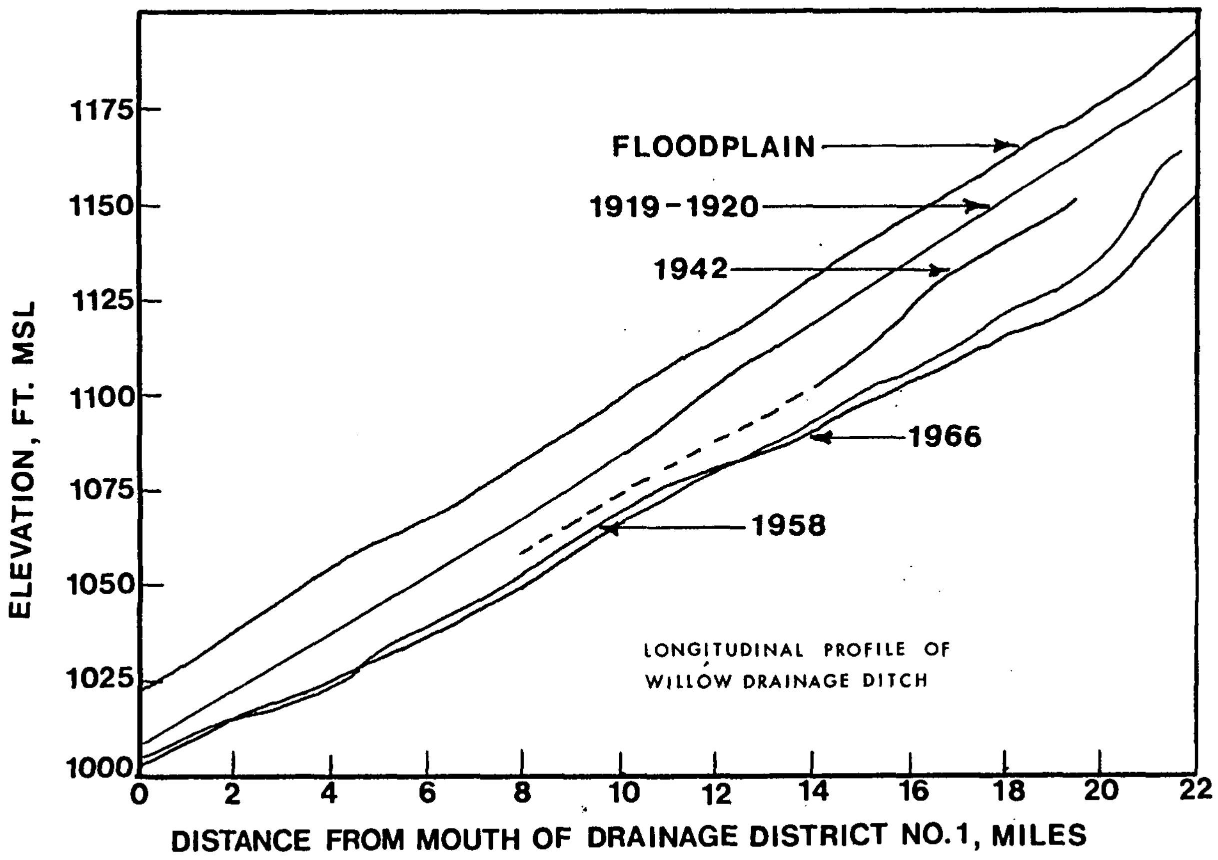

Figure 17. Changes in the longitudinal profile of the Willow drainage ditch, Modified from Daniels (1960)

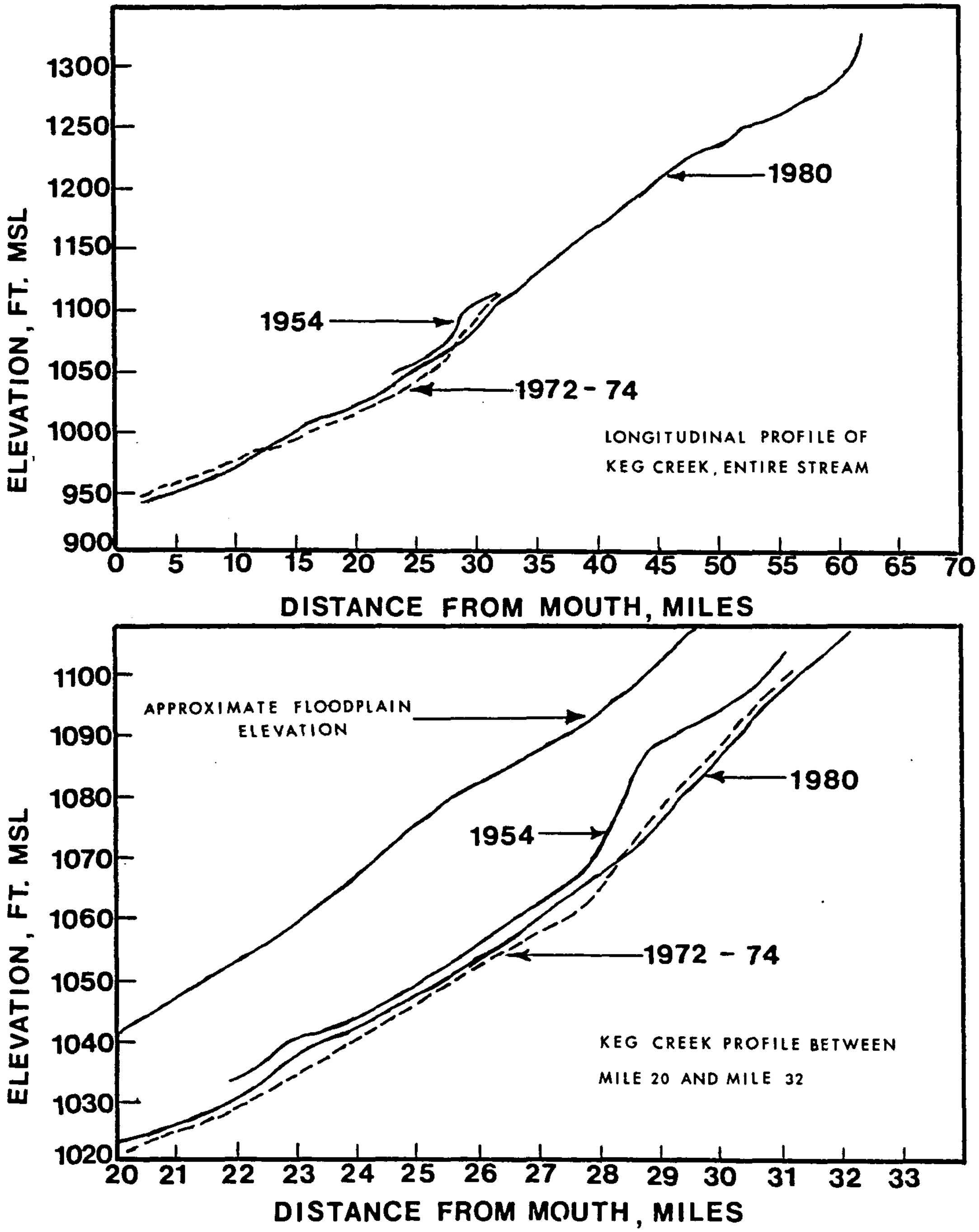

Figure 18. Changes in the longitudinal profile of Keg Creek
After Lohnes et al. (1980)

Prior to about 1900, the drainageways in proximity to Keg and Willow Creek frequently flooded their valleys. Several authors mention the swampy nature of the land surrounding the stream bottoms. In the tier of counties immediately adjacent to the Missouri River, much of the bottomland could not be cultivated. Because of this, in 1850 the federal government gave a sizeable number of acres termed "swamp land" to the state of Iowa. In 1853, the Fourth General Assembly of Iowa ceded all these lands to the respective counties with the declaration that all proceeds from their sale be used to reclaim the land by the construction of levees, roads and bridges. Smith (1888) noted that the area designated as swamp land in Harrison County alone amounted to 120,636 acres, but the 150,795 dollars collected by the county for the land was never used for corrective measures.

It appears that degradation of some western Iowa streams had begun to occur by about 1870. Smith(1888) stated that within Harrison County, both Pidgeon and Mosquito Creeks had "precipitous" banks, 10 to 20 feet in height. Shimek (1909) reported that an unnamed tributary to Willow Creek in Magnolia township was at least 40 feet deep, but that the width of the stream was less than the depth. By 1916, Willow Creek had deepened to 10 to 12 feet at most places in Harrison County and was 60-100 feet wide in some locations (Daniels, 1960). However, Lees (1912) described no degradation of Willow Creek in Crawford County at this time.

Similar evidence exists for the area in and around the Keg Creek basin. White (1868) observed smaller streams in Shelby County that had cut their channels 10-15 feet into "black" soils within their valleys.

Udden (1903) displays a picture of an obviously degrading Keg Creek in Mills County. He also noted that none of the swampy areas remained along the lower portion of the creek at this time, due to what he believed to be a general lowering of the groundwater level since settlement of the area.

To stop the flooding of these streams and reclaim the bottomlands for agricultural purposes, programs of stream straightening were undertaken in many western Iowa counties. These programs began on a small scale as early as 1870 in Monona County, but major projects were undertaken from 1890 to 1920 in Monona, Harrison and Pottawattamie Counties. Smaller projects continued until about 1960 in some locations. Willow Creek had approximately 26 miles of its channel in Harrison County straightened between 1916 and 1920, from its mouth headward to about the Monona-Harrison County border. Keg Creek was straightened from its confluence with the Missouri to about the Mills-Pottawattamie County border, and along several reaches in Pottawattamie County as part of bridge replacement projects.

A vigorous and almost immediate wave of degradation followed the straightening of the Willow Creek channel. In 1916, less than a year after construction, the lower portion of the Willow ditch in the Harrison and Pottawattamie drainage district had to be dredged because heavy sedimentation had filled the ditch to the point where many drainage outlets were below the channel bottom (Harrison County, Iowa, drainage record No. X, p. 469, 475, 510). This process was repeated in 1941, but by 1954 the bottom of the channel in the lower reaches of the ditch was only 1-2 feet lower than the natural ground level (Harrison County, Iowa, drainage record No. XI, p. 834). Short segments of Keg Creek have been surveyed periodically as a part of bridge inspection and replacement programs, but the auditors' offices in Pottawattamie and Mills Counties report that drainage records either were not kept or are not available for Keg Creek on the same basis that records were kept for the Willow drainage ditch.

Lohnes et al. (1980) reported that a comparison of the 1958 and 1966 longitudinal profiles of Willow Creek shows evidence of degradation in 11 locations and aggradation in 7 others; the magnitude of these changes is generally between 3 and 5 feet. These locations occur in a sequence of aggradation, degradation, aggradation, progressing headward through the ditch. From this evidence, the authors concluded that the channel bottom was essentially stable between 1958 and 1966, and the close proximity of the 1980 channel bottom to the 1966 bottom in the lower reaches of the ditch indicates that it has remained essentially stable since 1958.

With the use of bridge plans and Iowa D.O.T. inspection reports, historical data on the degradation of Keg Creek were gathered and plotted in relation to the 1980 longitudinal profile of the stream. Inspection of Figure 18 shows that the 1972 profile is 2 to 3 feet above the 1980 profile to mile 14.5, but that past this point the 1972 profile is 1 to 3 feet below the 1980 profile. Where data were available in the reach from mile 22 to mile 27.8, it was found that the 1954 profile was 1 to 2.5 feet above the 1980 profile. Lohnes et al. (1980) concluded that the reach of the stream below mile 14.5 has been relatively stable since at least 1954, but that active degradation (as much as 10 feet) had been taking place between mile 28.5 and mile 31 during the same period. In the upper reaches of the stream, comparison of the 1976 and 1980 profiles shows little evidence of recent degradation.

Further analysis of Daniels 1960 publication on the Willow drainage ditch was undertaken by Ruhe and Daniels (1965). Interested in the effects of straightening on morphologic parameters, they studied the changes in width and depth of the channel with time. From their work, several relationships were discovered:

-Width of the channel has increased linearly with time and can be expressed by the equation:

$$W = 40.1 + 1.41T$$

where W is the channel width in feet and T is the time in years since straightening. From 1919-1958, the average rate of increases was 1.41 ft./year.

-Channel depth has increased curvilinearly with time and is expressed by the equation:

$$D = 1.8 + 20.9\log T$$

where D is the channel depth in feet and T is the time in years since straightening. At 20, 30 and 40 years since straightening depths were 1.3, 1.5 and 1.6 times greater than the 10 year depth, but since 1958 only the upper 10 miles of the ditch has suffered degradation.

-Width/depth ratio has remained essentially constant, and is expressed by the equation:

$$R = 2.69 + 0.0004T$$

where R is the width to depth ratio, and T is the time in years since straightening.

From 1958 to 1980, the average rate of width increase continued at approximately 1.4 ft./year. However, degradation of the ditch did not continue at all locations after 1958, as shown in Table 12. The literature does not discuss the possibility of an expression for the change in stream gradient over this time period; this parameter has experienced sporadic changes since straightening and would undoubtedly be difficult to quantify, because data exist for only a few locations in the period between 1919-1958.

Degradational Mechanisms

Within the literature published on the stream degradation in Western Iowa, three causes have been suggested: the shortening of previously meandering streams, creating an increase in gradient; increased runoff in the region due to the change from native prairie vegetation to rowcropping; degradation of the Missouri River, lowering the base level of its tributaries. Physical and historical evidence, both geomorphic and hydrologic, is used here to better define the cause or causes of the degradation.

Stream straightening

Daniels (1960) pointed out that straightening of the Willow Creek Channel in Harrison County was associated with a shortening of this stretch from 26.3 to about 20 miles. In addition, a major change was made in the gradient of the stream. Average slope of the undisturbed channel had been 5.16 and 7.50 feet/mile in Upper Willow drainage districts 1 and 2, respectively; upon construction of the ditch these were increased to 7.66 and 8.48 feet/mile. The combination of these changes caused an increase in the velocity of the water flowing in the channel. Daniels concluded that the smooth, straight sides of the new ditch, combined with an increase in streamflow velocity, were responsible for the degradation that has been observed.

In the first publication on the Willow drainage ditch, Daniels (1960) interpreted the mechanism of entrenchment to be upstream migration of overfalls in the channel. These overfalls are termed knickpoints. Knickpoints of a wide range of sizes, from less than 1 foot in height to over 20 feet, are reported in the literature by several authors. These overfalls are a vivid expression of an erosional surface that is retreating upstream, leaving a new, lower streambed below.

Holland and Pickup (1976) recognize three basic knickpoint types: stepped knickpoints, retreating knickpoints die out as their oversteppened points. Stepped knickpoints maintain a vertical face as they retreat headward, whereas rotating knickpoints die out as their oversteepened faces rotate backward and lengthen. Minor erosional knickpoints are in effect riffles on the stream bottom.

The stepped knickpoint is the one typically described in the literature on the loess hills streams, although it is not commonly referred to as such. Most of the knickpoints observed in the field had vertical faces and a single overfall. However, Lohnes et al. (1980) reported that a 5 foot high overfall observed on Keg Creek at mile 28.5 separated into 3 riffles 1 to 3 feet in height in moving to mile 29; in the next year it separated again into four smaller riffles located between mile 29.5 and mile 31.5. This behavior suggests that the rotating knickpoint may be a transitional form of the stepped knickpoint.

Plate 1 displays a knickpoint. The turbulent action of water in the plunge pool is very important in the erosional process. By concentrating the energy of flowing water at the base of the knickpoint, turbulence plucks at the basal sediments and is a least partly responsible for the advance of the overfall. Daniels (1960) noted that seepage of water beneath the base of the knickpoint is possibly as important in the undercutting process as the wave action of the falling water.

Formation of knickpoints has generally been attributed to one of two mechanisms: change in stream gradient at one or more reaches of the channel, causing a change in hydraulic regime, or channel degradation to an interface between two materials of differing erosional resistance, allowing formation of a vertical face capable of migrating upstream.

Holland and Pickup (1976) created knickpoints in a flume by layering materials of differing erosional resistance one on top of the other, and reported observing the overfalls forming at the interface between the two materials. In addition, studies being conducted at the Soil Conservation Service Sediment Laboratory at Oxford, Mississippi have found that knickpoints in tributaries to the lower Mississippi River tend to form at the interface between a loess-derived alluvium and a more erosion-resistant paleosol (Colin Thorne, SCS Sediment Laboratory, Oxford, Miss., 1980).

Plate 1. A knickpoint in a Fremont County stream

As shown previously, all members of the DeForest Formation have a paleosol and/or stone line present in their uppermost portions. Daniels and Jordan (1966) reported that knickpoints along Thompson Creek were cutting into the Mullenix and Hatcher fills. While they did not mention it, it is possible that the stone line at the top of the Hatcher is acting to create the erosion-resistant interface. Referring back to Figure 14, it can be seen that the Hatcher member is a lens of alluvial fill in the Willow Creek channel, pinching out several miles upstream from its mouth. The location of this member coincides with the reach of the Willow drainage ditch in which knickpoints have been observed by Daniels (1960).

Extensive study of the soils and their stratigraphic relationships as they exist in the stream basins of the study area was not a goal of this study. In retrospect, it appears that these relationships may play an important role in knickpoint formation. It is recommended that future studies of the degradational phenomenon include such research.

Paleosols and stone lines are not ubiquitous features, but knickpoints are common in the degrading streams in western Iowa. Thus, it is possible that overfalls may be caused to form in a homogeneous materials through a change in hydraulic regime. This would most likely be a result of stream straightening, through an increase in channel slope between the pre-straightened and post-straightened channel or between two different reaches of the straightened channel. These hydraulic changes are discussed further in a later section of this thesis.

Changes in runoff and discharge

Up to this point, emphasis has been placed on the hypothesis that channel straightening was the cause of the instability that has lead to stream entrenchment in western Iowa. Another hypothesis, suggested by Piest et al. (1976) and Piest et al. (1977), is that the introduction of rowcropping into the area has increased runoff, thereby creating an erosional cycle.

Prior to settlement by European immigrants (app. 1850), the loess hill règion was primarily covered with a thick natural grass prairie. In the first fifty years of settlement, almost 40% of the area was put into tillage, as estimated by Smith (1888). Much of the cultivated land went into rowcropped corn and soybeans.

Piest et al. (1976) estimate that, at minimum, surface runoff was increased 2 to 3 times by rowcropping, and peak discharge down the waterways increased as much as 50 times. Estimates by Leopold et al. (1964) for prairie regions converted into rowcrop go as high as 80 times the original peak discharge.

Thus, increased runoff may have been the mechanism that triggered degradation of the streams in the region. Discharges of greater magnitude would have the effect of increasing streamflow velocity. Evidence presented earlier of entrenched streams in Shelby County as early as 1868 indicates that such a mechanism may have taken place to some degree, because the earliest stream straightening was not before 1870. From Figure 19, it can be seen that the number of acres in cultivation in Harrison County increased from zero to about 430,000 in the period between 1850 and 1920.

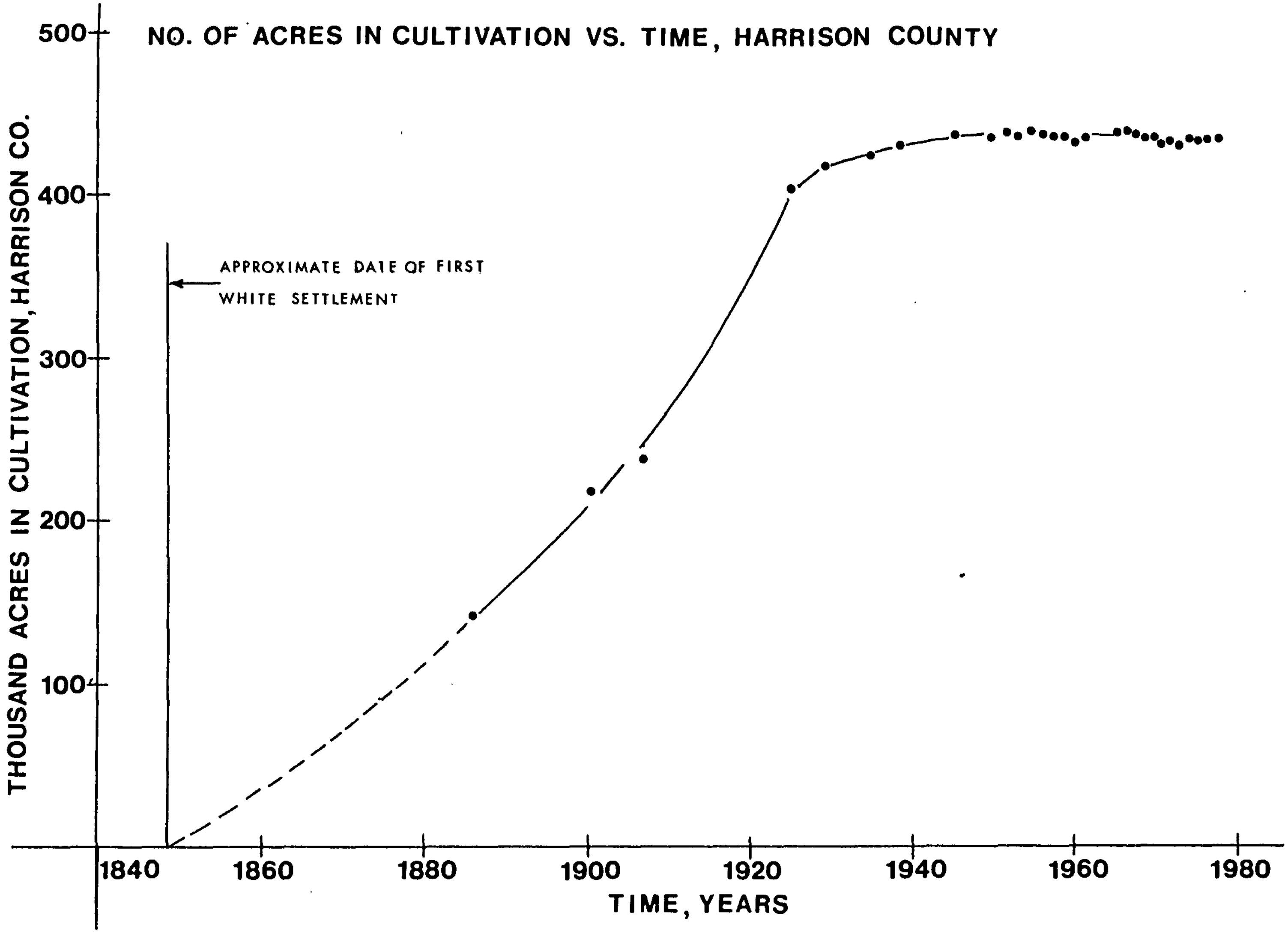

Figure 19. Number of acres put into cultivation with time, Harrison County
Source: U.S. Department of Agriculture

It is not clear over what period of time an increase in upland runoff continued to have an effect on the discharge experienced by these streams. If increase in discharge alone is to have been the cause of the massive amount of degradation observed since the turn of the century, there should have been an observable increase in mean annual discharge for the degrading streams. Figure 20 shows a plot of average annual discharge for the Boyer River since 1918, and Figure 21 shows the peak discharge for the same period. The wide scatter of points on the former graph is such that no trend is obvious, yet referring to Figure 22 it can be seen that the number of acres being put into cultivation in Harrison County continued to increase to a maximum of about 450,000 acres in 1945.

Two trends from these figures are apparent. From Figure 20, note that the width of scatter of data points increased by about 33% between 1918 and 1979. Also, there have been large fluctuations in the size of the peak annual discharge, particularly between 1918 and 1942. These fluctuations may have been due to climatic variations during this period; Hallberg et al. (1979) showed that annual precipitation decreased below the norm between 1915 and 1940, and then increased from 1940 to 1950.

Due to the conflicting evidence presented in the preceding paragraphs, it is not possible to conclusively state that increased runoff has or has not been a cause of stream degradation in western Iowa. Lack of gaging stations on the smaller streams and a lack of gaged data prior to 1900 make a quantitative evaluation of this hypothesis difficult. However, if a flood discharge parameter could be introduced, more work could be done.

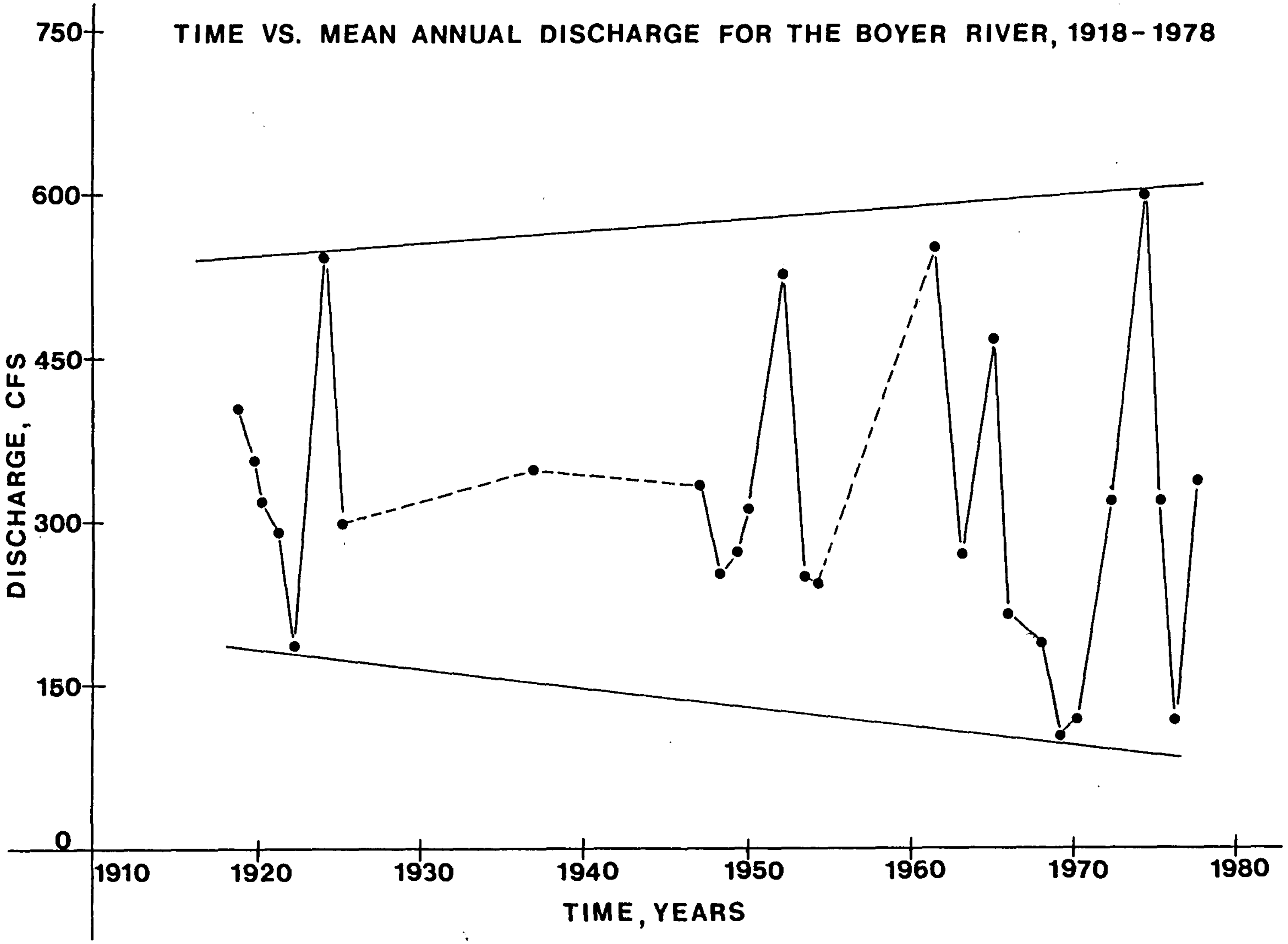

Figure 20. Time versus mean annual discharge, Boyer River; 1918-1979. Source: Iowa Geological Survey Water Supply Bulletins

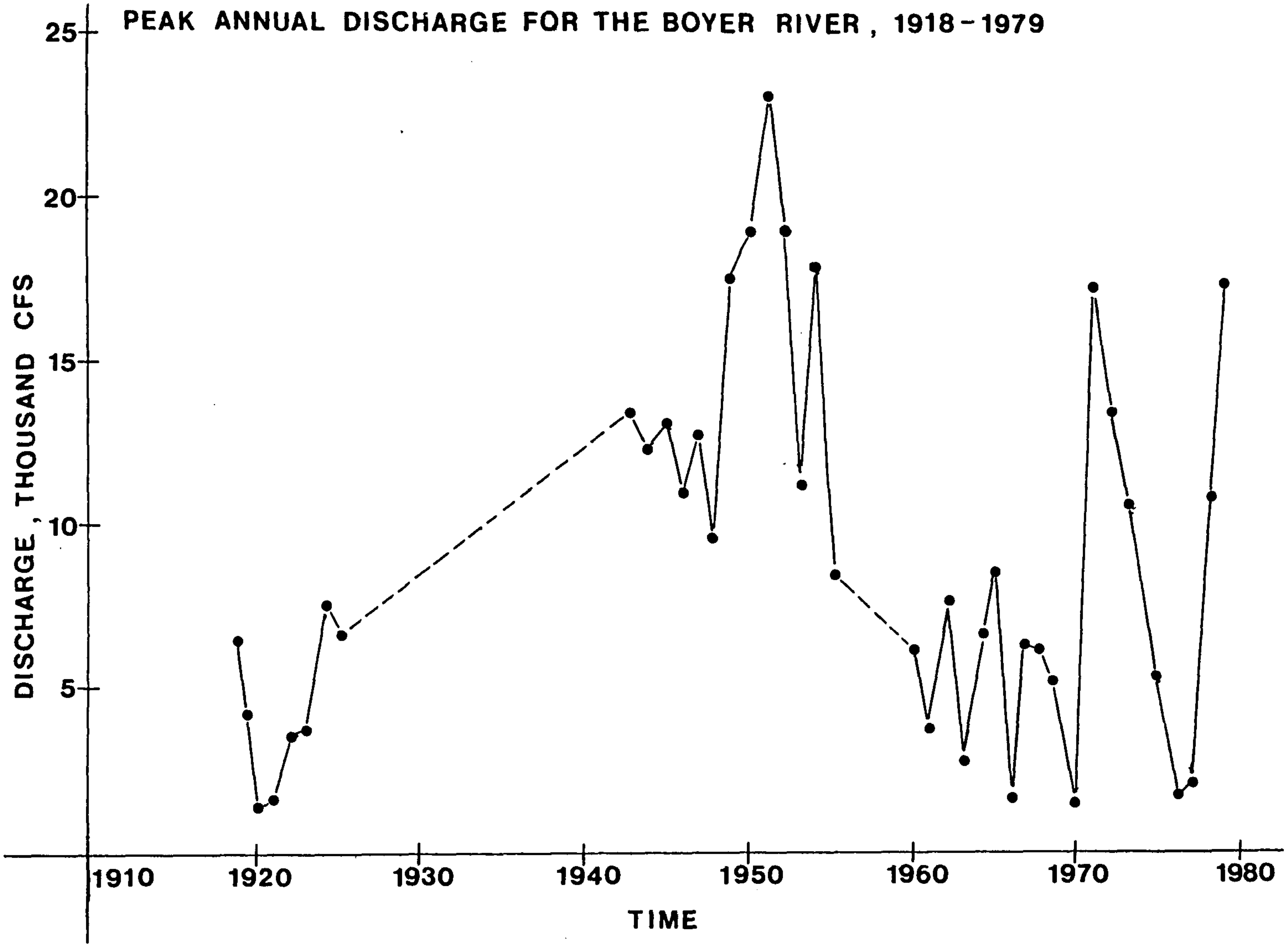

Figure 21. Time versus peak annual discharge, Boyer River, 1918-1979. Source: Iowa Geological Survey Water Supply Bulletins

Changes in the Missouri River Channel

There is physical and historical evidence that the entire portion of the Missouri River adjacent to Iowa was undergoing natural degradation over the period from 1804 to 1879. As discussed in an earlier section of this thesis, historical evidence indicates that degradation of the tributaries to the Missouri had been taking place prior to 1868. Thus, it is possible that lowering the base level of these tributaries could have been a cause for their entrenchment.

Several authors, including Dahl (1961) and Lohnes et al. (1977) have used Missouri River surveys from 1804, 1870 and 1890 to show that the river underwent a change from a meandering stream to a braided or semi-braided stream during the middle 19th century. During this same period 10-15 feet of degradation was experienced by the Missouri. Evidence suggests three possible causes for the degradation: a temporary change in climate (Hallberg et al. (1979), an increase in runoff due to introduction of rowcropping into the area, or an inordinate number of neck cutoffs of the meanders along the Iowa-Nebraska border, leaving a shortened river channel in this reach.

Geomorphic evidence by Lohnes et al. (1977) indicates that the Missouri River has had vertical stability in the reach of the channel between Sioux City, Iowa and Omaha, Nebraska, between 1879 and 1952. Because most of the streams in the study area are direct or indirect tributaries of the Missouri between these two locations, it was tentatively concluded by Lohnes et al. (1980) that degradation of the Missouri has not been a cause of the degradation of its tributaries since 1900. Thus, it appears that there may have been two periods of entrenchment of the tributaries, one prior to stream straightening and one after. It is difficult, however, to separate the factors involved, and more study is needed.

Hydraulic Changes

Another method of describing the degradation of the Willow drainage ditch is by the hydraulic changes that have occurred since channel straightening. One approach to the problem is to look at how the energy of water flowing in the channel has changed with time.

In the analysis of open channel flow the Bernoulli and Continuity equations are used. It must be recognized that in using this approach, it is assumed that the flow within the channel is both steady and uniform; that is, that the nature and amount of discharge does not change from section to section within the channel. This method was developed for use with man-made drainage or irrigation ditches where all of the discharge enters at some specific location. Natural drainage systems have tributaries and thus do not behave in this manner, but if a short enough segment of stream is studied, these conditions are closely approximated.

The velocity of water flowing through a given section of stream channel can be described by the equation:

$$V = Q/A$$

where Q is the discharge at that section, A is the cross sectional area of the channel wetted by the flow and V is the velocity of flow. A second expression for streamflow velocity is given in Manning's equation, where:

$$V = 1.49 \frac{R^{2/3} s^{1/2}}{n}$$

in this equation R is the wetted perimeter of the channel, s is the channel slope at the location in question, and n is the roughness coefficient for the material exposed in the channel bottom and banks.

The wetted perimeter of the channel can also be expressed by $A/(2d+w)$, where d is the depth of flow, w is the width, and A is the wetted channel area. Because the wetted cross-section within the Willow drainage ditch is sufficiently close to rectangular, the area is approximated by depth times width of flow. Roughness coefficient is assumed to be 0.025 for the loess-derived alluvium, thus, the preceding equation becomes:

$$V = \frac{Q}{dw} = 59.6 \left(\frac{dw}{2d + w}\right)^{2/3} s^{1/2}$$

From the published data of Daniels (1960), channel width and slope at several locations along Willow drainage ditch are known at four periods of time; this study has added the 1980 value of these parameters at each location. Unknown are depth of flow and velocity at these times, but with the two equations presented for determining streamflow velocity these two unknowns can be determined. The solution to the problem is iterative; solving it is a matter of trial and error choosing of values of depth until the two expressions are equated. The iteration is relatively simple, and for this study a program was written for a hand-held TI-57 programmable calculator to solve it. The value of discharge used in the solution was estimated from the Lara equation.

The change in streamflow velocity in the Willow drainage ditch since straightening was calculated for the four locations at which Daniels (1960) provided cross-secional data (Lohnes et al., 1980). This study updates these calculations by adding the 1980 values of velocity and estimations of the velocity in the pre-straightened channel at three locations. These estimations are made possible because Daniels (1960) was able to estimate the width and slope of the Willow Creek channel before straightening from a 1916 survey of the creek.

Table 13, Figure 22 and Figure 23 show the results of these calculations. At mile 11.4 and 15.4 there has been a steady decline in velocity with time, but at mile 19.7 and mile 25.6 there has been an increase in velocity followed by a decrease. Figure 23 shows the associated changes in width and depth of flow that have occurred over the same period of time. In both cases where there has been an increase in velocity after 1920, it has been accompanied by a sudden increase in depth of flow.

Daniels (1960) reported that a knickpoint was observed just upstream of mile 25.6 in 1953. In 1952, a sudden increase in depth of flow occurred at this location, along with an increase in streamflow velocity. It is concluded that these increases mark the passage of the knickpoint as it moved upstream past mile 25.6. Similar increases occurred at mile 19.7 in 1929; if they were due to movement of the same knickpoint that was active at mile 25.6 in 1952, it had moved very little in 33 years. The depth of flow at miles 10.7 and 15.5 has changed very little since 1935, and has not experienced the increase indicative of knickpoint passage at any time since straightening.

The changes in streamflow that have occurred as a result of straightening the Willow Creek channel are illustrated by increases in velocity and depth of flow at miles 11.4, 15.4 and 19.7 from 1916 to 1920. Part of

Table 13. Channel velocity variations with time for selected sections of the Willow drainage ditch. Modified from Lohnes et al. (1980)

Station	Distance From Mouth	Discharge[a]	Date	Slope (%)	Channel Depth (ft.)	Width[b] (ft.)	Depth of Flow (ft.)	Velocity (ft./sec.)
1	11.4 miles	28 cfs	1916	0.090	10-12	60[c]	0.28	1.65
			1919	0.145	15	22	0.725	1.76
			1935	0.161	23	45	0.44	1.39
			1936	0.166	27	49	0.42	1.34
			1958	0.127	32	66	0.38	1.10
			1966	0.127	39	68	0.375	1.09
			1980	0.127	38	72	0.370	1.07
2	15.4 miles	25 cfs	1916	0.090	10-12	60[c]	0.30	1.38
			1919	0.145	15	22	0.68	1.68
			1931	0.161[c]	24	40	0.44	1.40
			1958	0.127	33	66	0.36	1.06
			1966	0.127	35	69	0.35	1.04
			1980	0.127[c]	31	70	0.345	1.034
3	19.7 miles	16 cfs	1916	0.142	10-12	60[c]	0.21	1.25
			1920	0.160	11	20	0.53	1.52
			1929	0.161	20	18	0.57	1.56
			1942	0.165	32	33	0.37	1.31
			1958	0.127	37.5	53	0.31	0.95
			1966	0.127	47	60	0.29	0.92
			1980	0.127[c]	42	60	0.29	0.92
4	25.6 miles	13 cfs	1920	0.230	11	20	0.46	1.65
			1950	0.240	22	48	0.25	1.15
			1952	0.270	38	45	0.30	1.38
			1958	0.172	39	73	0.21	0.65
			1966	-				
			1980	-	Cross-section articically altered			

[a] Estimated from $Q = 0.17A^{1.06}$ (Lara, 1979).

[b] As measured 5 feet above channel bottom.

[c] Estimated, no data.

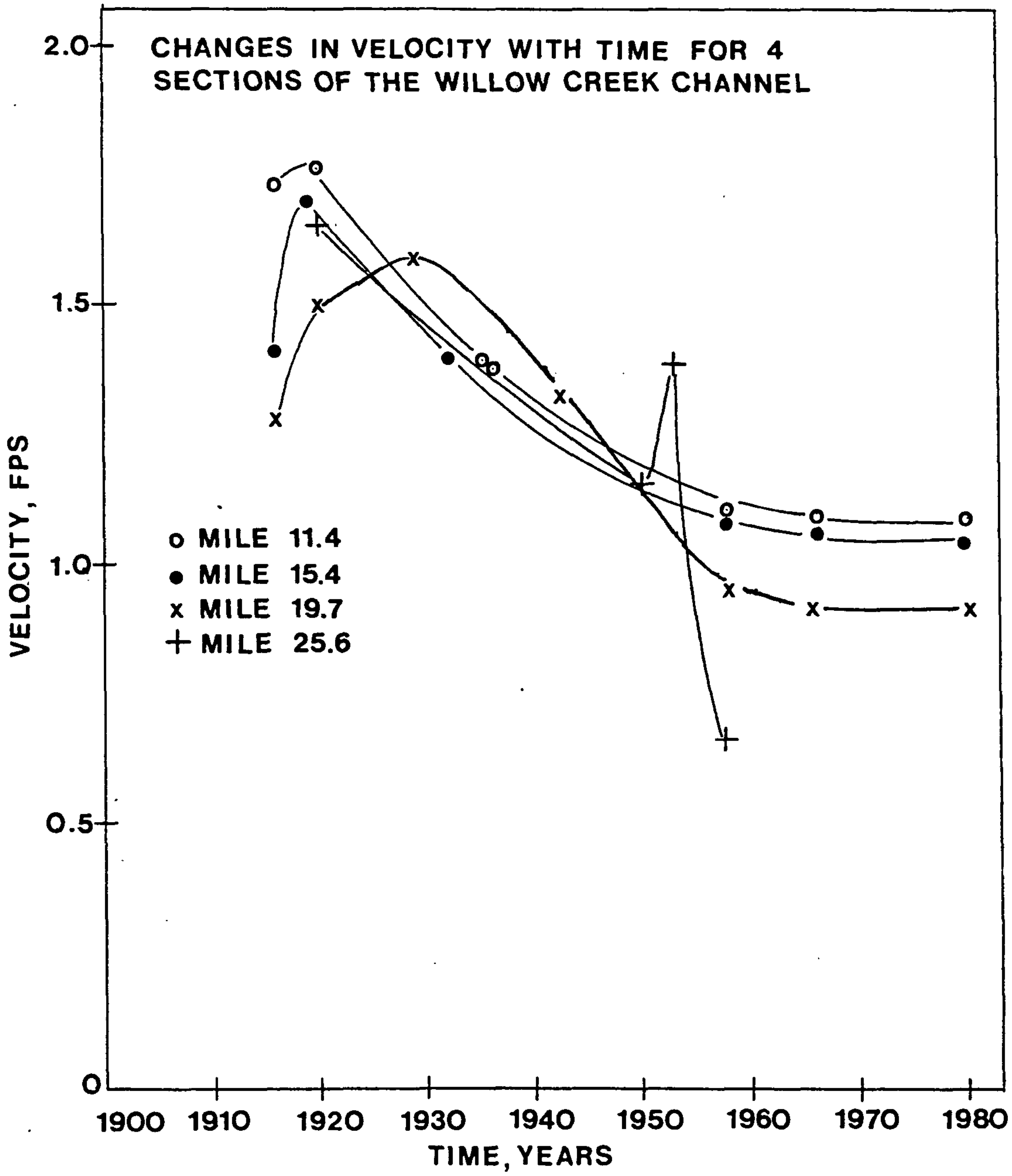

Figure 22. Velocity variation with time for 4 sections of the Willow drainage ditch. Modified from Lohnes et al. (1980)

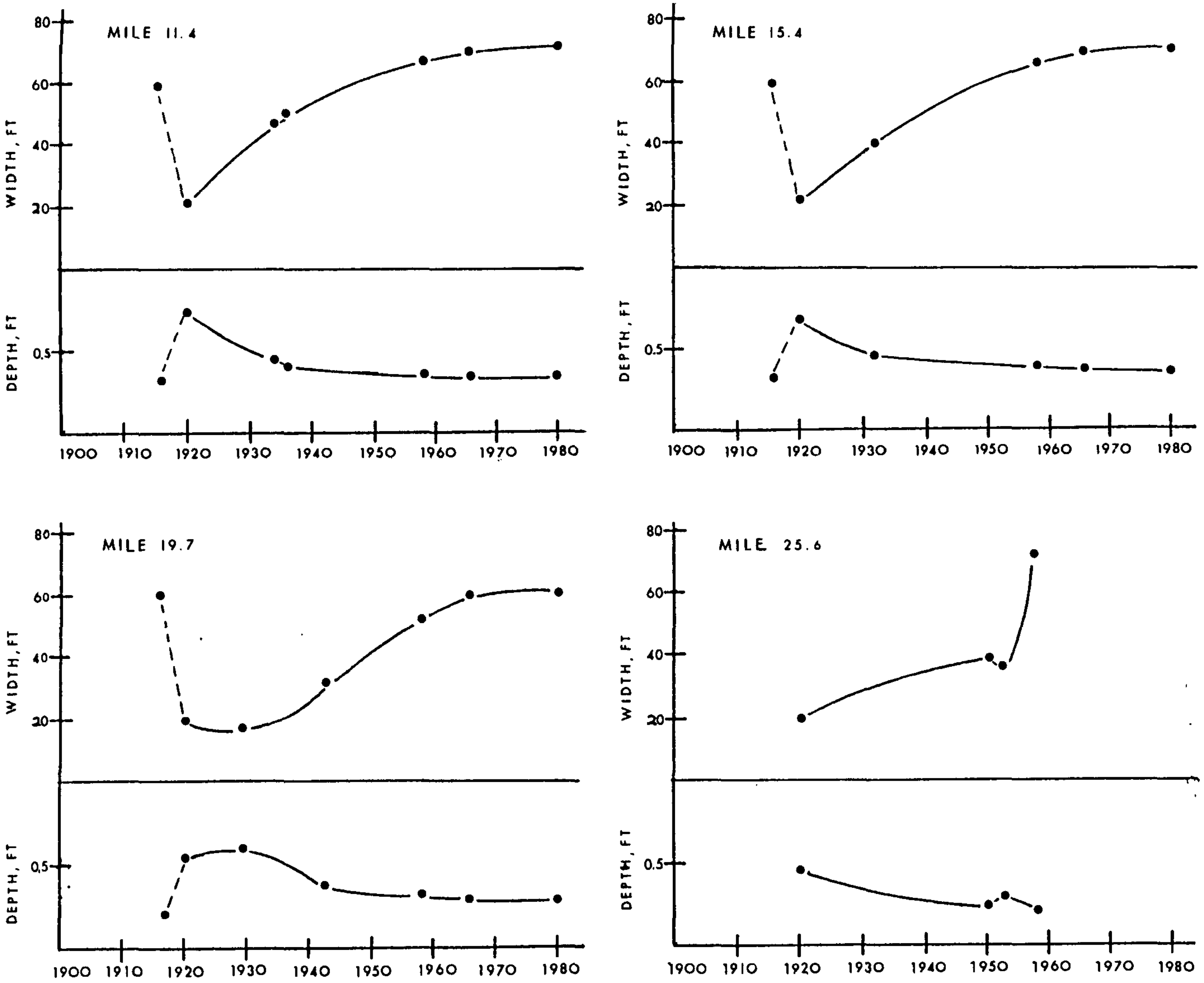

Figure 23. Variations in width and depth of flow with time for 4 sections of the Willow drainage ditch

these increases can be explained by the fact that the slope of the channel was increased when it was straightened, but the decrease in channel length and the smooth sides of the new ditch also had an effect. By cutting off the natural meanders of Willow Creek and clearing the banks of natural vegetation, it is estimated that the value of roughness coefficient for this channel could have decreased from as much as 0.045 to 0.025 over the short period of time that the project took to complete (Dr. Merwin Dougal, Director, Iowa State Water Resources Research Institute, personal communication, January 1981).

Since it is assumed that the discharge does not vary from the point that the water enters to the point that it exits the section under study, the Continuity equation can be used to express the unchanging nature of flow from point 1 to point 2:

$$Q = A_1V_1 = A_2V_2$$

Knowing the changes that have occurred in the channel slope and in the velocity and depth of flow, the previous relationship can be used to show how the energy of flowing water has changed since channel straightening. The Bernoulli equation for steady flow applied to a reach of open channel is:

$$z_1 + d_1 + \frac{V_1^2}{2g} = z_2 + d_2 + \frac{V_2^2}{2g} + h_f$$

where z is the elevation of the channel bottom in feet, d is the water depth, V is the mean velocity, g is the acceleration due to gravity and h_f is the head loss between sections. The subscripts 1 and 2 are assigned to quantities at section 1 and 2, respectively. Figure 24 shows how this

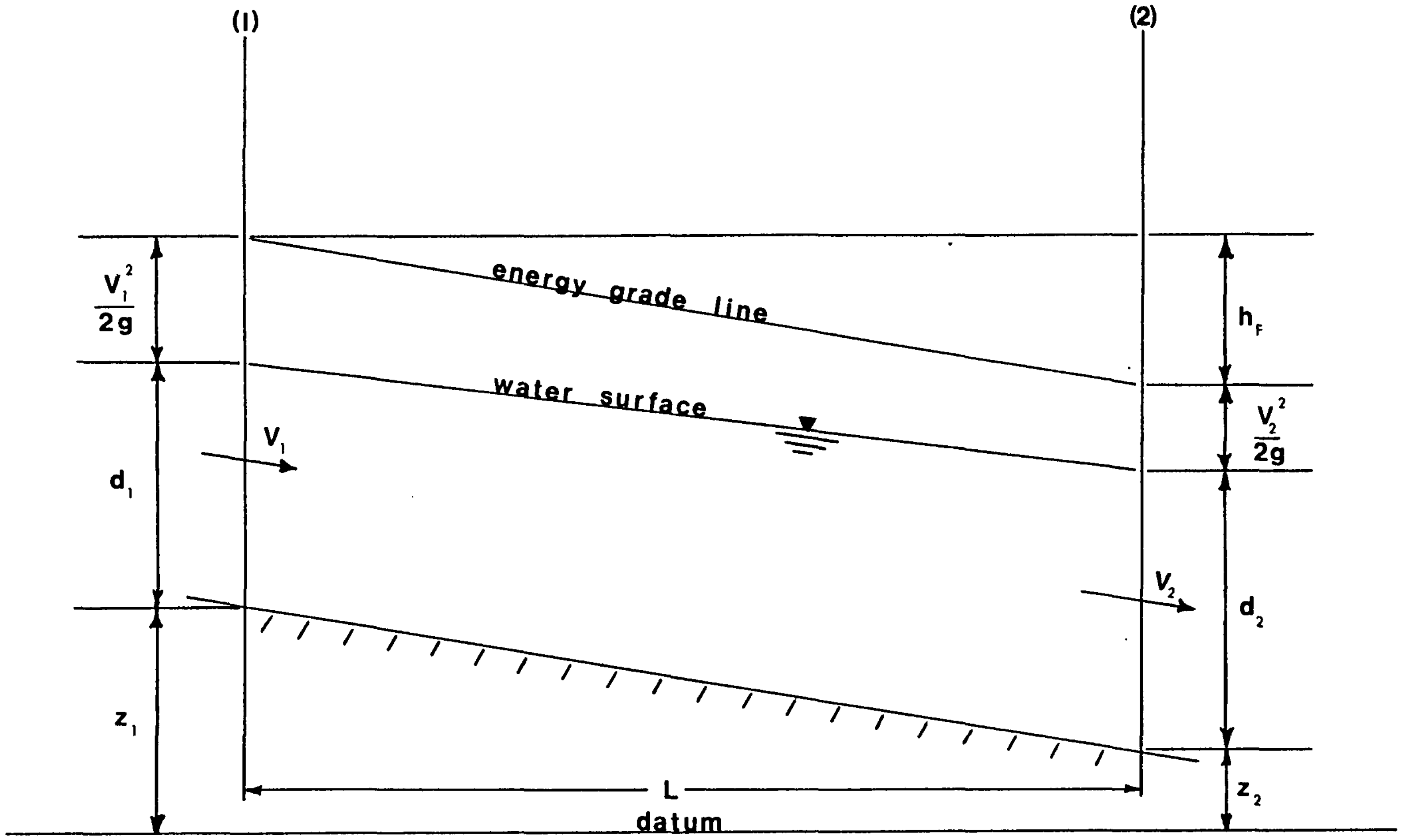

Figure 24. Steady flow in an open channel. From Dougherty and Ingersoll (1954)

relationship can be portrayed graphically.

The principles from the Bernoulli equation can be used to demonstrate some of the changes that take place in the vicinity of a knickpoint. In doing this, two different flow regimes must be taken into account, one of low flow and/or small floods, and the other of large floods. These two regimes are depicted in Figure 25. The symbols S_1, S_2 and S_3 denote the values of slope that exist above, at and below the knickpoint, respectively; D_n represents the depth of normal flow as calculated by the Manning equation, and D_c represents the depth of critical flow as calculated by the equation:

$$D_c = 3 \; \overset{3}{-} \frac{Q^2}{gw^2}$$

where Q is the discharge present during the particular period of flow, w is the width of flow and g is the acceleration due to gravity.

For the case of low flow and small floods, the depth of normal flow as it exists above and below the knickpoint is greater than the depth of critical flow. However, as the water flowing in the channel passes from the upstream section into the vicinity of the knickpoint, the increase in slope causes the flow to go supercritical (i.e., the depth of normal flow is less than the depth of critical flow). As the water exits below the knickpoint,it undergoes a hydraulic jump back to the point where normal flow is occurring at a depth greater than that of critical flow.

In the second case, the depth of normal flow for the floodwaters is less than the depth of critical flow at all three sections. Note the absence of the hydraulic jump as the water passes downstream of the knickpoint. However, there is a decrease in the depth of flow in the vicinity

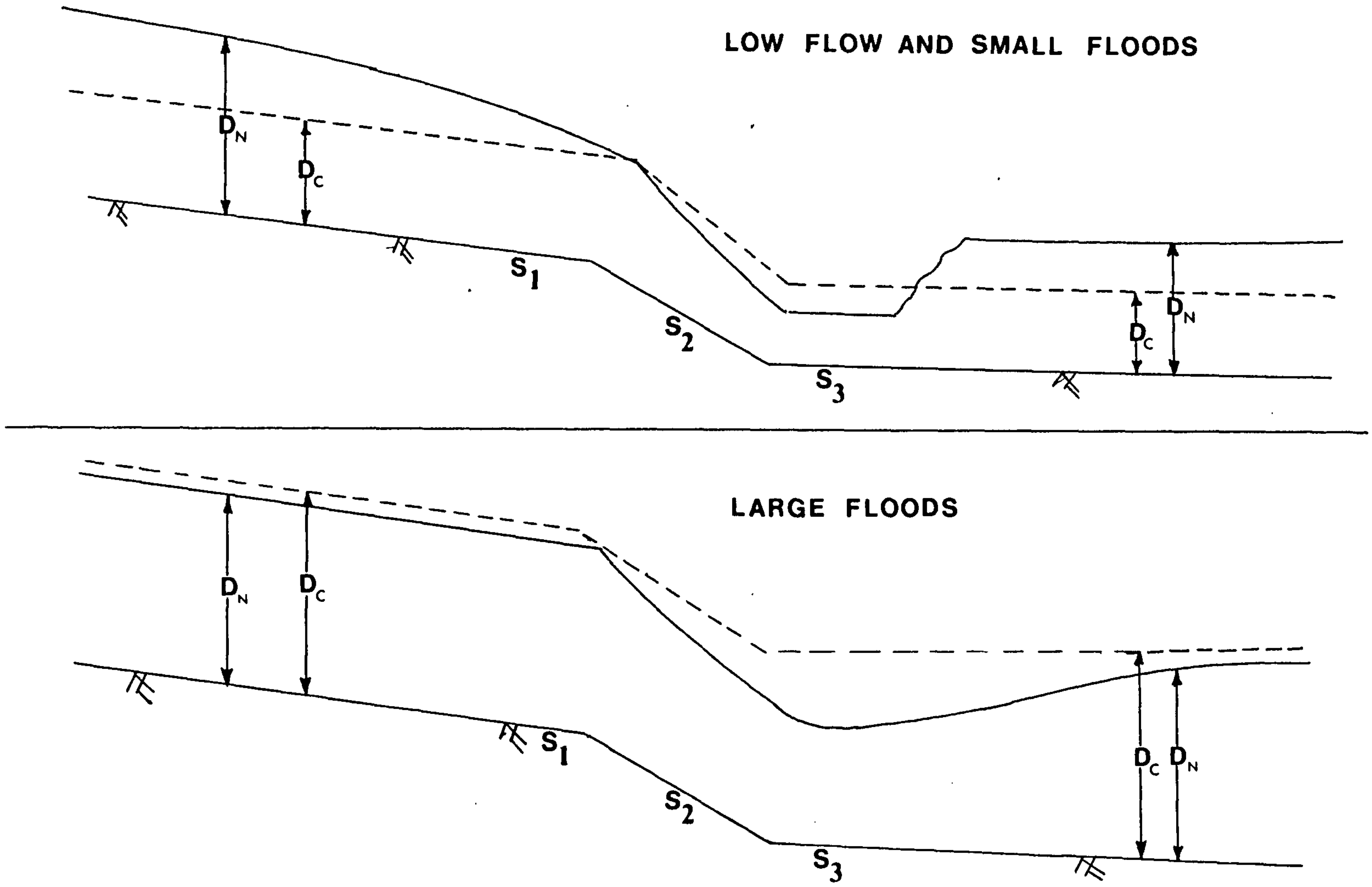

Figure 25. Hydraulic changes in the vicinity of a knickpoint, small and large flows

of the knickpoint, similar to what occurs in the case of low flow.

Figure 26 shows a conceptual view of the changes in depth of flow, streamflow velocity and head loss between sections that occur above, below and in the vicinity of a knickpoint. Head loss is greatest in the region of the knickpoint, slightly less above the knickpoint and a great deal less below the knickpoint. Since the head loss represents the energy of flowing water being used up by contact with the channel bottom and banks (through friction and heat losses), the diagram suggests that greater erosion will take place in the section with the most head loss.

Figure 26 supports the conclusion of Lohnes et al. (1980), who speculated that degradation occurs at a knickpoint and just above it, but not for very long distances below it. As an example of this, Figure 22 can again be referred to. Although knickpoint caused a substantial increase in the velocity of flow at mile 25.6 in 1952, just 6 miles downstream at mile 19.7 the velocity and depth of flow continued to decrease. The flume studies of Holland and Pickup (1976) support these observations.

It should be noted that the Willow drainage ditch was artifically altered after 1966 by addition of two flume bridges. These grade stabilization devices have altered stream slope and the nature of flow in the ditch. However, the data from Table 13 and Figure 22 show that velocity of flow in the ditch has continued to decrease since 1966, indicating continuation of the trend toward stability of the channel.

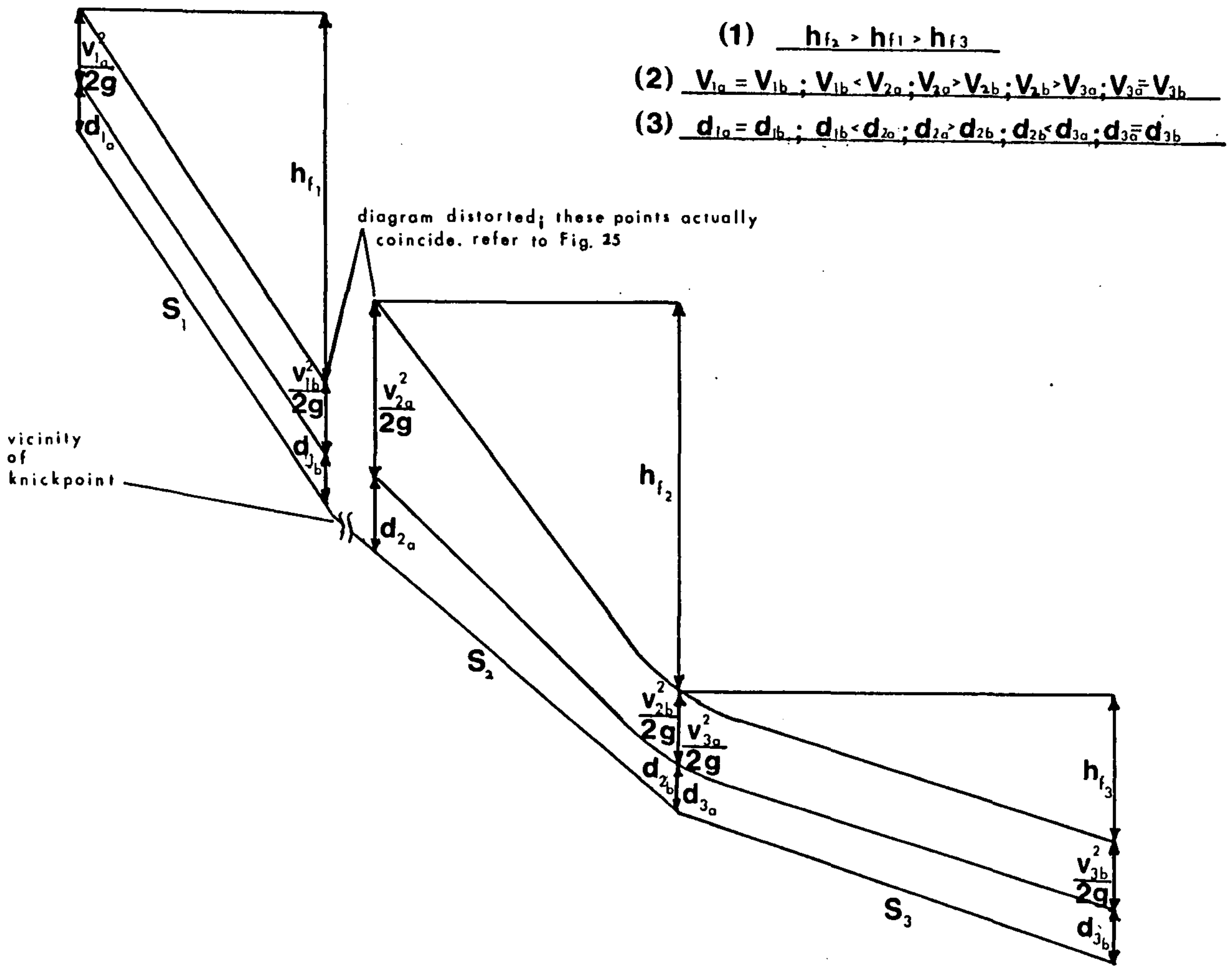

Figure 26. Changes in energy of flow in the vicinity of a knickpoint

PREDICTIONS OF DEGRADATION

Stable Longitudinal Profile

Hack (1957) has shown that the longitudinal profile of a stream flowing over a region of homogeneous lithology can be described by the equation:

$$B = C - k \ln (L)$$

where B is the elevation in feet at a given point along the stream, L is the river length in miles at that point as measured from the drainage divide, and k and C are constants. When plotted on semi-logarithmic graph paper, the longitudinal profile of a stream is a straight line. A series of straight lines, each with a different value of k would indicate various reaches of the river are flowing over regions of varying lithology.

The constant k can be determined from a topographic map, without having to draw the longitudinal profile of the stream in question. For a given reach of stream, k is equivalent to the expression:

$$k = \frac{H_1 - H_2}{\ln L_1 - \ln L_2}$$

where H_1 is the elevation at a given point along the reach, H_2 is the elevation at another point, and L_1 and L_2 are the respective stream lengths at these points. It can be seen that this expression is equal to the slope of the line that this section of the stream would form if plotted on semi-log paper.

Willow Creek

Daniels and Jordan (1966) plotted the 1958 profile of Willow Creek on semi-log graph paper and found that two straight-line segments were present, one for the lower 33 miles of the stream and one for the upper 16. These segments had two difference values of slope, the lower (for the degraded reach) being steeper than the upper (the non-degraded reach). Based on historical data gathered during the Daniels (1960) study of Willow drainage ditch, it was tentatively concluded that the lower reaches of the stream were stable in regard to vertical degradation by 1958.

Using Hack's equation, Daniels and Jordan projected the profile of the lower 33 miles of the Willow Creek channel beneath that of the upstream segment, and compared the difference in elevation that existed between the two profiles in the upper 16 miles of channel. It was assumed that the upper section would be stable when the plot of its longitudinal profile superimposed itself on the extension of the plot from the lower reaches. Using this assumption, the amount of downcutting that would eventually be experienced by the upper reaches of the channel was predicted.

In Figure 27, the semi-log plot of the 1966 channel profile for the lower 33 miles of Willow Creek is compared to the 1958 profile. Points from the 1966 profile fit the line representing the average 1958 profile, except for the upper 8 miles of the section. This confirms the Daniels and Jordan prediction, and indicates that further degradation could have been expected after 1958. The installation of 3 grade stabilization structures after 1966 altered the profile of Willow Creek, and comparison

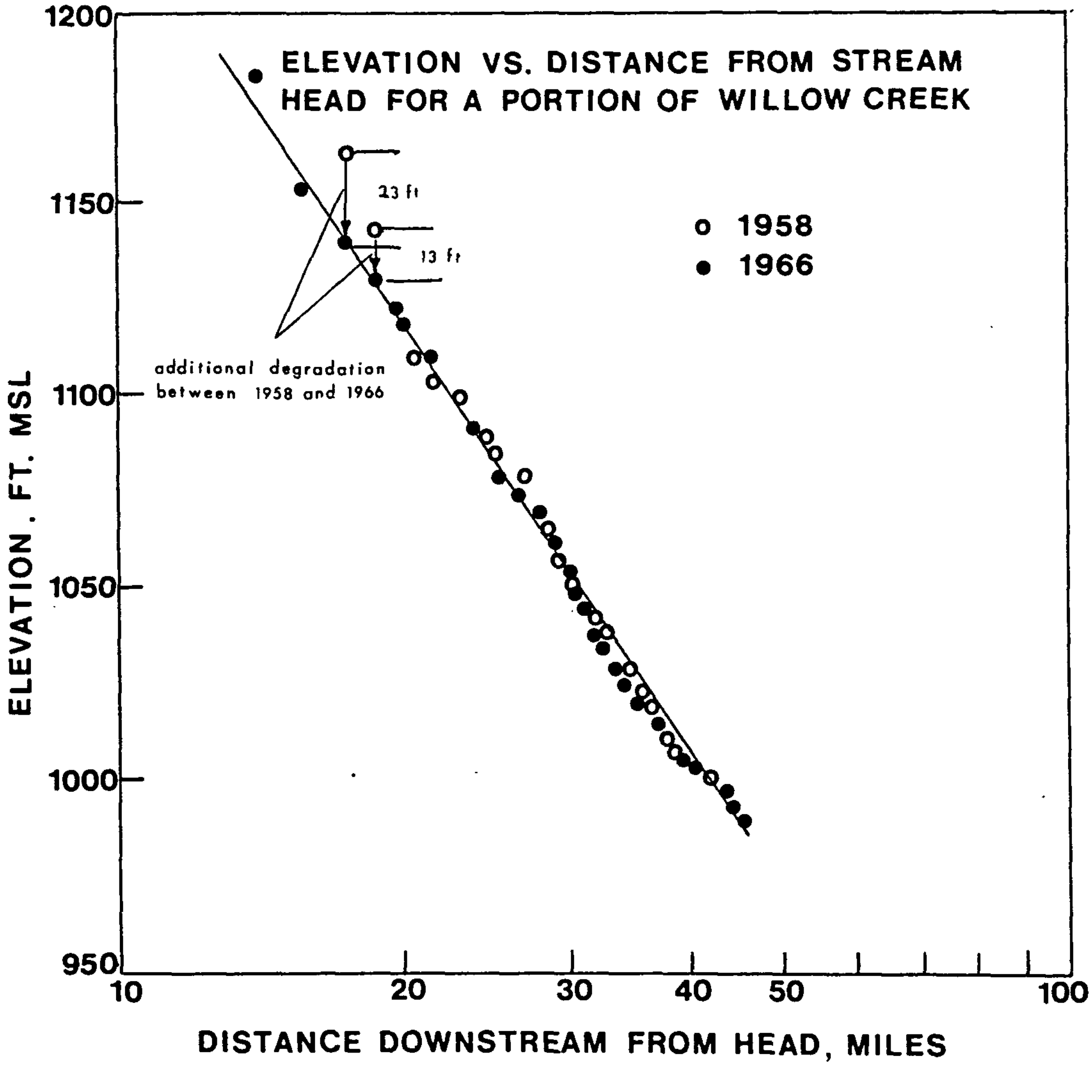

Figure 27. Longitudinal profile of Willow Creek on semi-log plot. After Lohnes et al. (1980)

of the 1966 and 1980 profiles does not show whether further degradation occurred. However, it does appear that the method used by Daniels and Jordan is plausible for predicting the amount of degradation that can be expected on a given stream.

Keg Creek

In Figure 28, the longitudinal profiles from 1954, 1972-73 and 1980 for the Keg Creek channel between mile 20 and mile 32 are shown on a semi-log plot. Points from the 1954 channel lie slightly above the line fitted to the 1980 data points, but the close proximity of both the 1954 and 1972-73 channels to the 1980 channel in this reach suggests that it has been essentially stable since 1954. The value of k for the 1980 profile of these 12 miles is -254.

Taking the same approach as Daniels and Jordan (1966) used for Willow Creek, the k value from miles 20-32 is extended upstream and compared to the 1980 profile above mile 32 (Figure 29). Between mile 32 and mile 48, it appears that as much as 18 feet of degradation may occur in the future. However, above mile 48 the two profiles diverge and the theoretically stable profile crosses above the actual channel bottom. This may be due to the fact that in the last 20 miles, Keg Creek crosses an area where the loess thickness declines from over 75 feet to less than 35 feet. The corresponding decrease in relief of the surrounding terrain may have an effect on the profile of the upper portion of the stream.

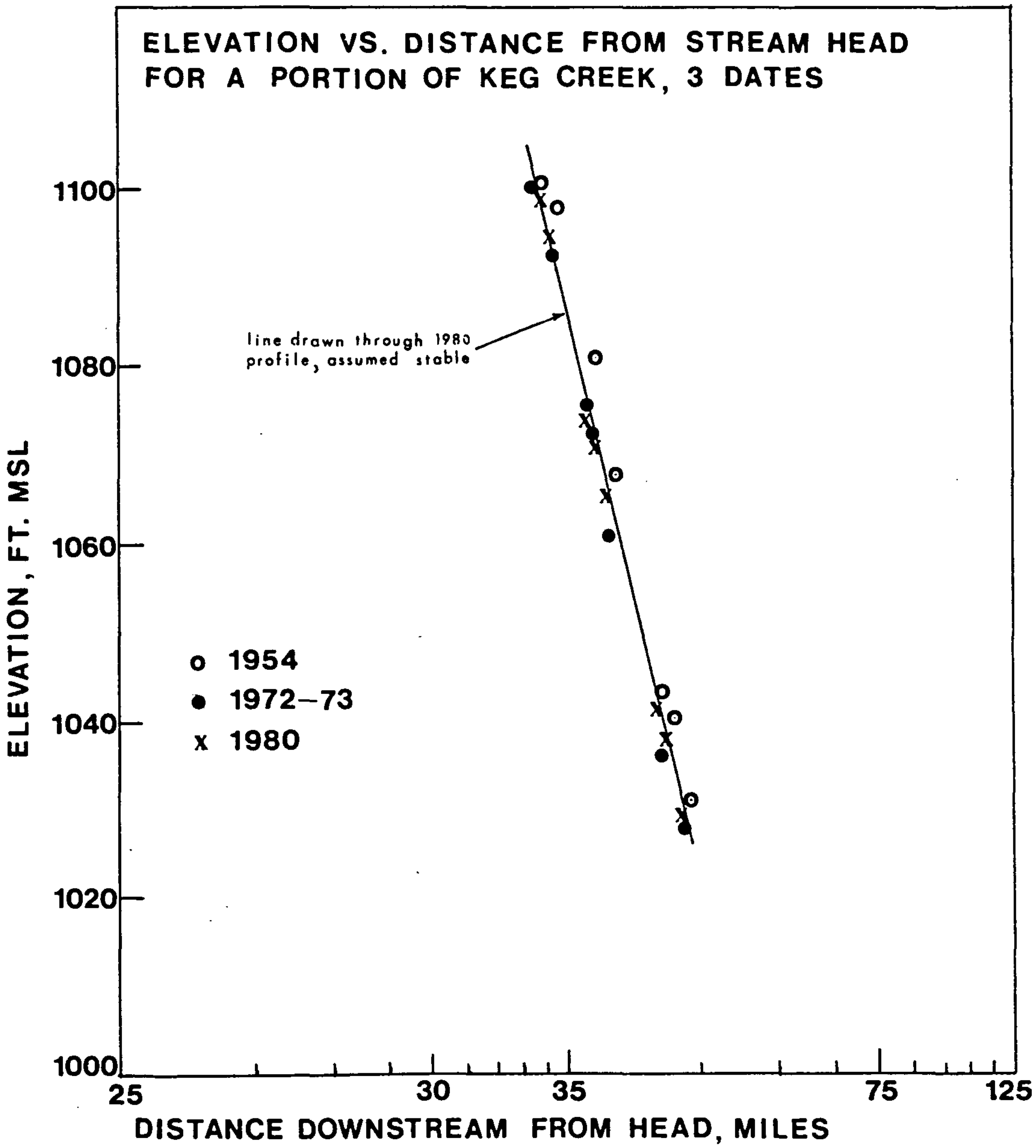

Figure 28. Longitudinal profile of Keg Creek on a semi-log plot

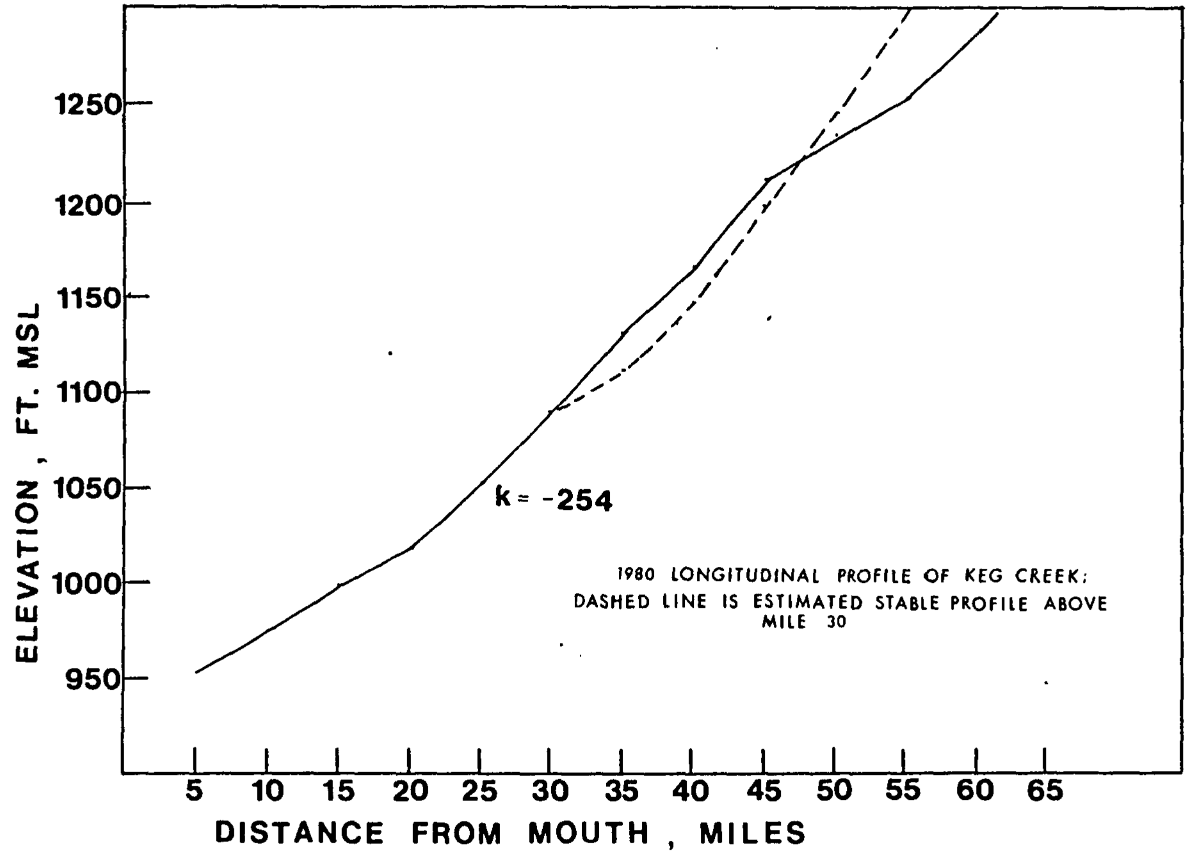

Figure 29. 1980 profile of Keg Creek and predicted stable profile above mile 32

Rate of Degradation

Model

A method for estimating the ultimate entrenchment of a stream would be a useful tool to the highway engineer. Knowing the final width and depth of the channel at any given location would help in planning safe span widths and depths of pile penetration for bridges crossing these streams. A possible approach to the problem was suggested in the phase I study; additional analysis will be presented here in hopes of clarifying this approach.

Leopold and Langbein (1963) performed a theoretical study of fluvial systems in which entropy was considered in relation to landscape evolution. They argue that the most probable longitudinal river profiles approach the condition in which the downstream rate of production of entropy per unit mass is constant. Two conclusions of this work are:

1) The longitudinal profile of a stream system subject only to the constraint of base level is expotential with respect to elevations above base level.
2) The profile of a stream subject only to the constraint of length is expotential with respect to stream length, and logarithmic with respect to elevation.

As is the case with most streams (except those in mountainous regions) the base level of the western Iowa streams exerts a much greater influence on its longitudinal profile than does its length. Thus, any model for predicting the rate of degradation should include an expression in which longitudinal profile is expotential with respect to elevation.

Lohnes et al. (1980) presented a rational theory for determining the rate of vertical degradation of a stream system. They proposed that, when viewed over the long term, there is a systematic decrease in the rate of downcutting with time. Following this proposal, it was theorized that the rate of downcutting at a given point in the stream channel is proportional to the elevation of that reach above the base level of the stream, as expressed by:

$$dh/dt = -k' h$$

where dh/dt is the rate of vertical degradation, h is the elevation of the point of interest above base level, and k' is a constant describing the rate of degradation.

There are several assumptions underlying this theory:

- The most recent period of entrenchment in western Iowa is the result of channel straightening;
- The average discharge at the point of interest has remained essentially constant since channel straightening;
- The streams were near equilibrium with respect to degradation prior to straightening;
- The variables that have adjusted to increased streamflow velocity have been width, depth and slope;
- Average discharge since straightening has been most important in shaping channel geometry.

Figure 30 displays the basis for this mathematical relationship. By rearranging terms and applying the boundary conditions that h_o exists at $t = 0$ and h_1 exists at $t = 1$, the differential equation can be solved. After integration, the relationship can be written as:

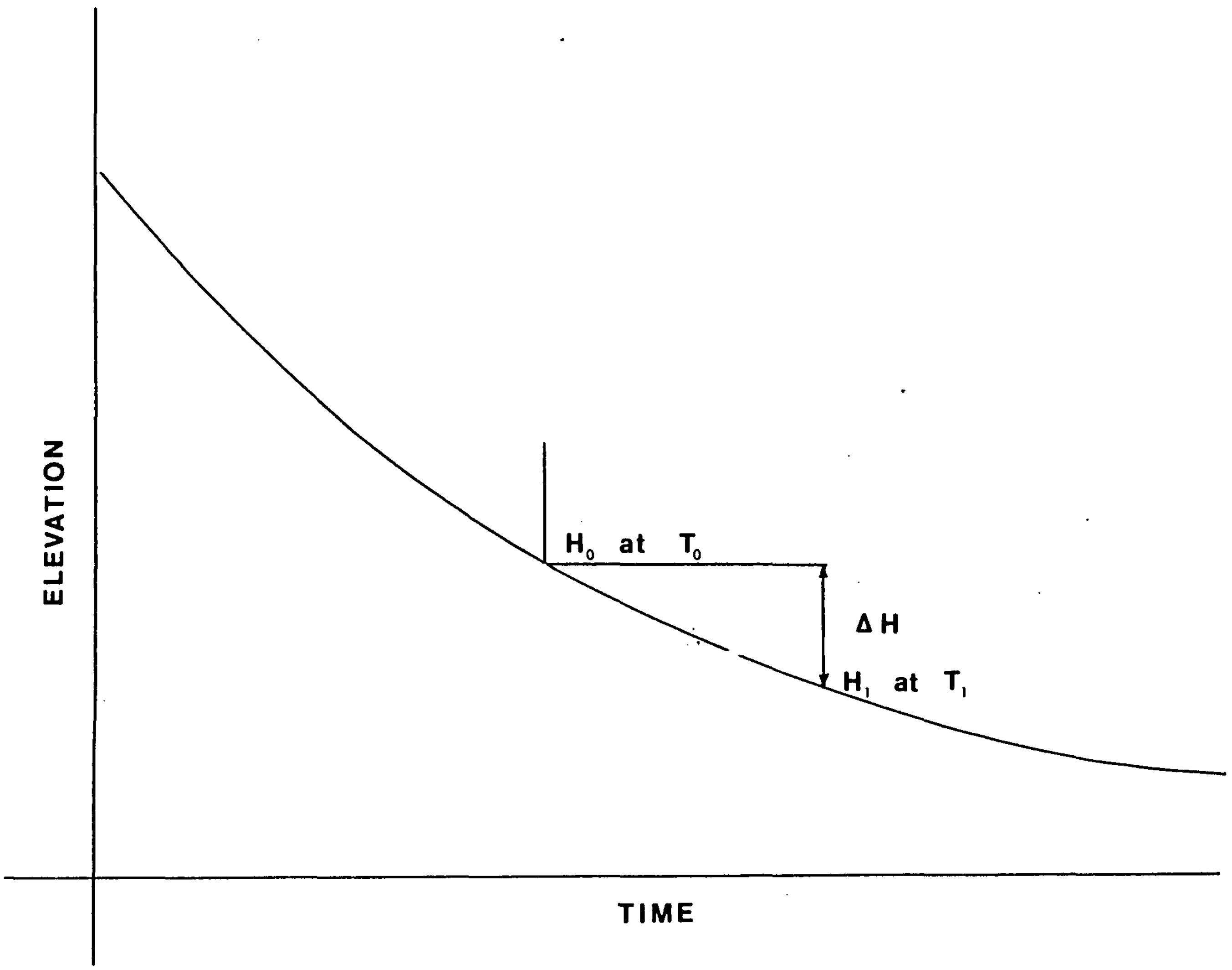

Figure 30. Model for degradation at a point on a stream

$$\ln(h_1/h_o) = -k' t$$

where h_1 is the elevation of the channel bottom above base level at time t_1 and h_o is the elevation of the channel bottom above base level at time t_o.

Realizing that the term h_1/h_o is simply the change in elevation since the time of straightening, the expression can be rewritten in a more useful form as:

$$\Delta h = e^{-k' t}$$

where Δh is the change in elevation with time at the point of interest.

Lohnes et al. (1980) showed that the relationship between the variables of elevation and time is linear when plotted on semi-log paper (Figure 31, modified from Lohnes et al., 1980). The data for this plot were obtained from the historical evidence of the degradation of the Willow drainage ditch (Daniels, 1960); lack of sufficient data prevented making a similar plot for Keg Creek. The relationship not only fits the data but is also intuitively pleasing, as it shows that a standard rate decay equation can be used to describe the degradation of the stream system at the point of interest.

Degradational constant

From Figure 31, note that the values of k' increase with decreasing distance from the drainage divide. This suggests a relationship between k' and some parameter associated with the drainage basin. Lohnes et al. (1980) proposed that the value of k' should be proportional to the discharge at the reach of the stream under study. Figure 32, a log-log plot

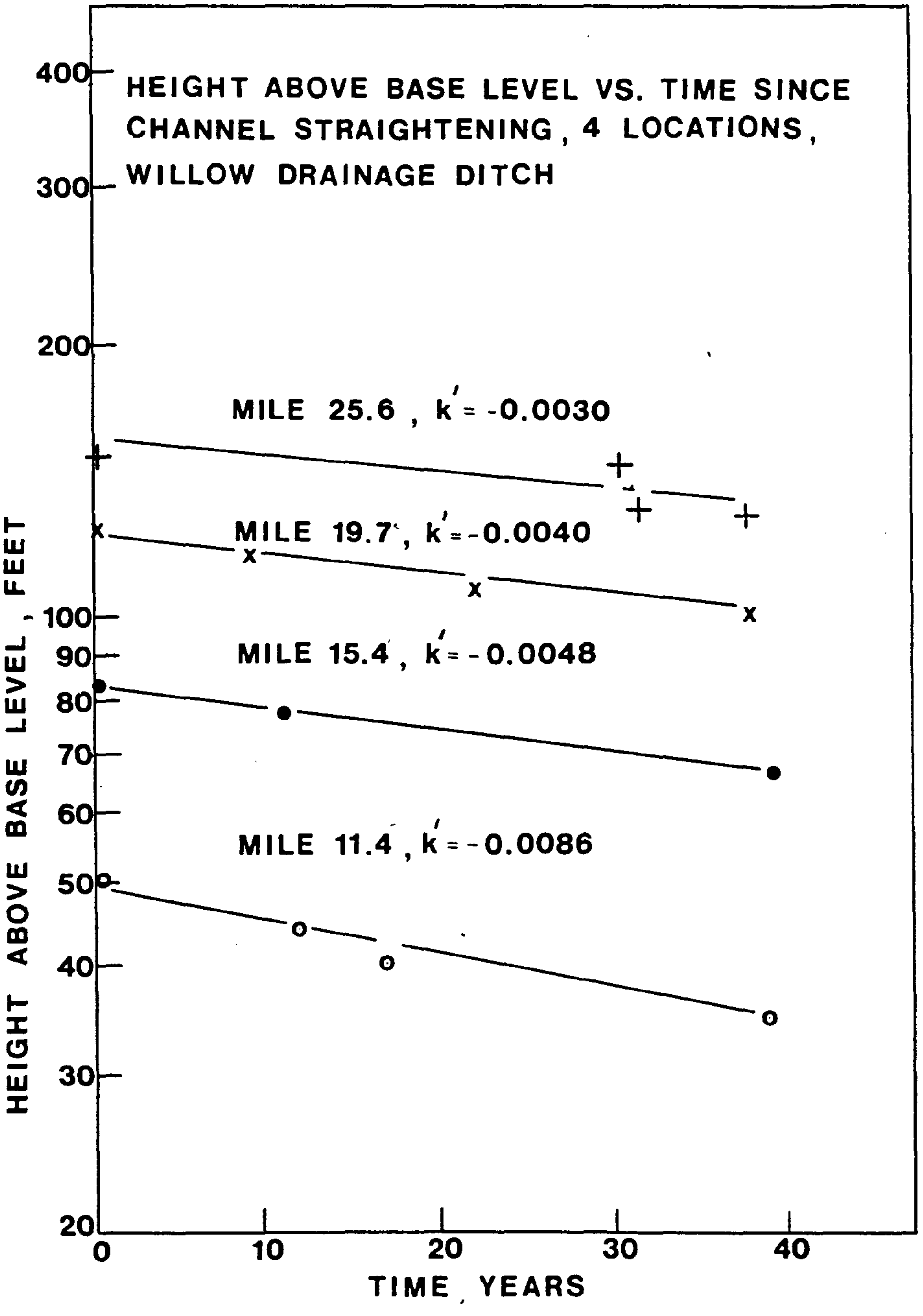

Figure 31. Time versus log height above base level for 4 reaches of the Willow drainage ditch. Modified from Lohnes et al. (1980)

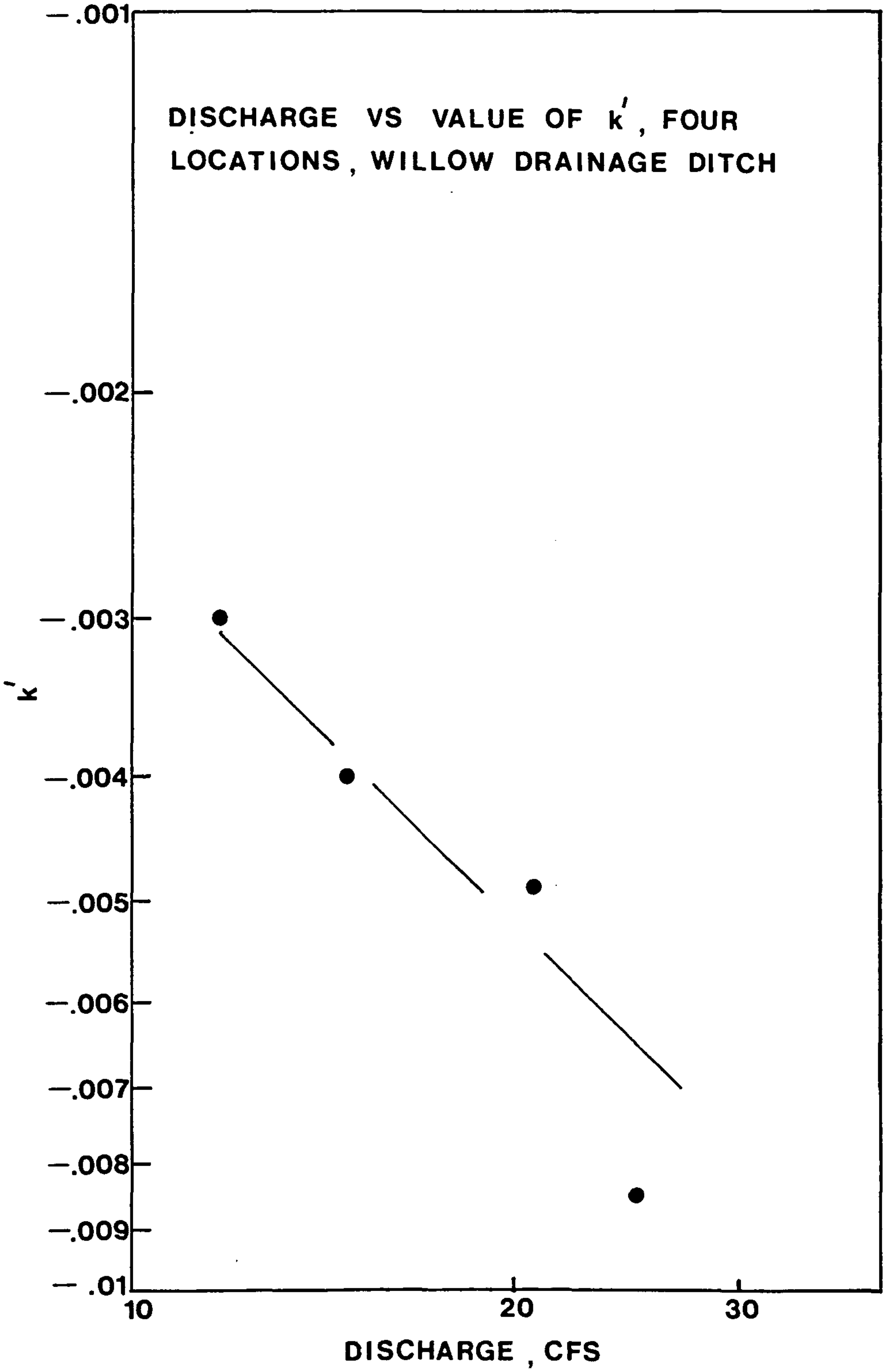

Figure 32. Plot of k' versus estimated discharge, 4 sections of the Willow drainage ditch

of the values of k' from the Willow drainage ditch versus average discharge as estimated by the Lara equation, indicates that there is a logarithmic relationship between the two variables.

Because the Lara equations for estimating discharge use drainage area at the point of interest as part of the calculation, a similar logarithmic relationship should exist between k' and drainage area. Figure 33 shows that this is true for the data from the Willow drainage ditch. It is desirable to be able to use drainage area to form this relationship, for it shows that the value of the degradational constant can be related to the geometry of the drainage basin.

This relationship is tenative because it is based on limited data. However, it appears that k' values from different streams do not plot on the same straight line. Lohnes et al. (1980) reported a k' value of 0.0038 for a point on the Tarkio River that has about 175 square miles of drainage area above it; this point falls well off the trend established in Figure 33 for the points from the Willow drainage ditch. This indicates that k' may also be related to another basin parameter, perhaps total drainage area or circularity ratio. Further study is recommended.

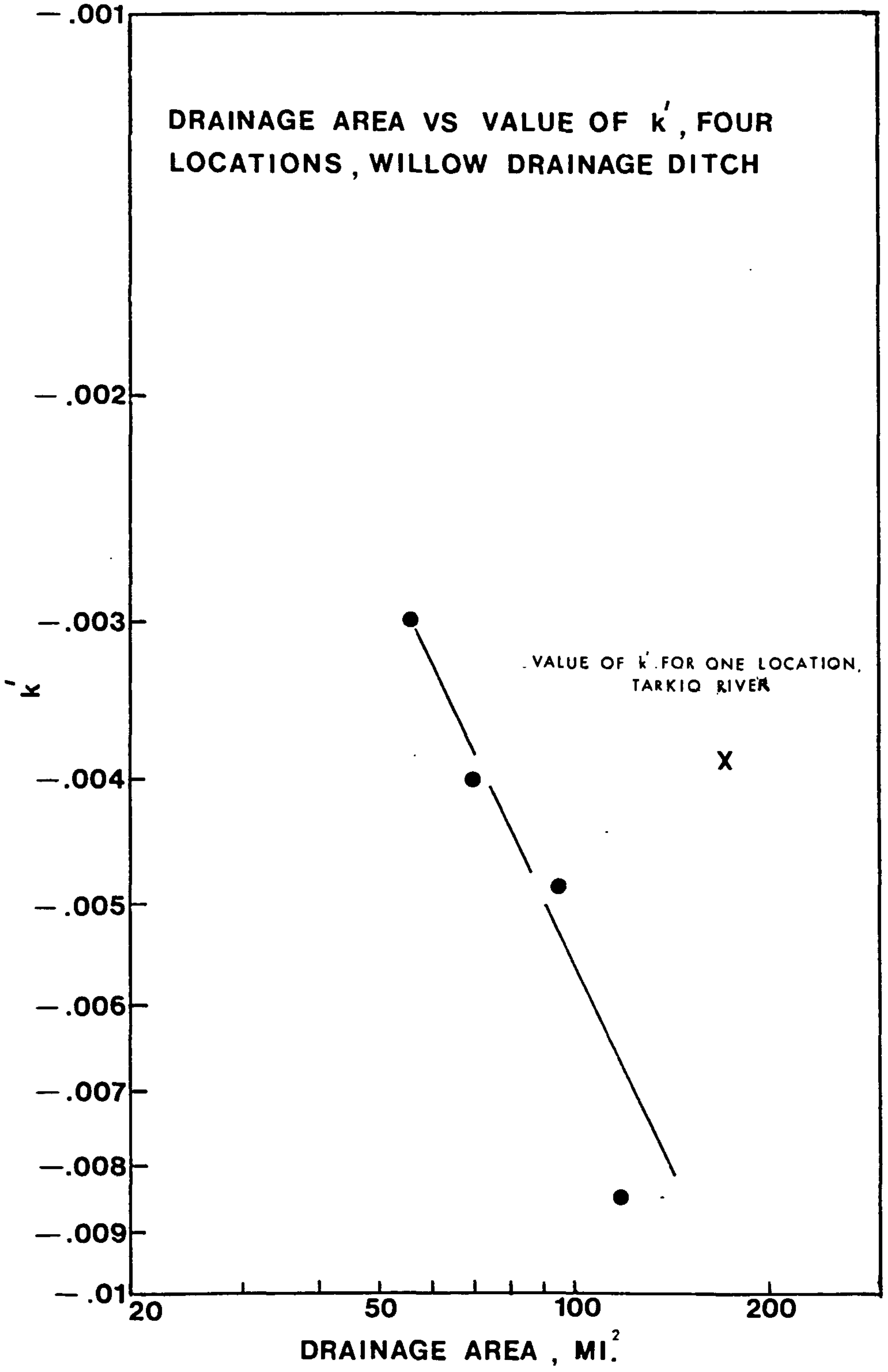

Figure 33. Plot of k' versus drainage area, 4 sections of the Willow drainage ditch and 1 section of the Tarkio River

STREAMBANK SLOPES

Natural slopes are classically viewed by geomorphologists as products of erosion and/or mass movement of slope materials. Thus, individual components of the overall slope may be an expression of one of two processes:

(1) Mass wasting of slope material, either by erosion or mass movement. Slopes formed as a result of mass wasting can display either concave-upward or convex-upward profiles; water-gathering slopes tend to have convex-upward profiles, whereas water-spreading slopes tend to have concave-upward profiles. Mass movement of material usually creates concave-upward slopes, except in the case of soil creep or debris flow.

(2) Deposition of alluvial/colluvial materials, particularly on lower portions of the slope, tending to result in convex-upward slope profiles.

With regard to the slope components associated with stream banks, wasting of slope materials is most commonly accomplished through mass movement of bank materials and erosion by water flowing in the channel. Sheet erosion from water running over the streambank and into the stream may play a minor role in this process. Slope components made up of loose alluvial and/or colluvial deposits are generally not stable landforms, because flowing water within the channel can easily remove these materials. However, mass movement of banks does result in the deposition of talus, which forms a slope component resting at or near the angle of repose of the talus material.

Degradation of the stream channel has an important effect on the nature of the slopes that make up the streambanks. Mass movement of material is not likely to be a dominant process in a non-degraded reach of channel, and therefore erosion by running water probably plays a major role in shaping the stream banks in these locations. Where degradation like that experienced by the Keg and Willow Creek channels has occurred, mass movement becomes increasingly likely. Also, there is evidence that flowing water within the channel may never reach upper portions of a degraded streambank. Daniels (1960) stated that water flowing in the Willow drainage ditch has rarely, if ever, completely filled its banks since straightening; he notes that 7 inches of precipitation in a 24 hour period in 1942 failed to fill the banks of the ditch more than half full.

This section of the thesis will be developed in two parts. In the first, a quantitative description of the streambanks observed for each of the streams will be provided, and an attempt will be made to relate the individual slope components to a specific mechanism (i.e. mass movement, talus material, etc.). Second, principles from soil mechanics will be applied to a slope stability analysis of the steep portions of degraded streambanks.

Cross-Sectional Channel Profiles

At 12 locations along Keg, Long Branch, Thompson and Willow Creeks cross-sectional channel profiles were observed and measured with the use of a spirit level and tape measure. The geometry of the various streambanks is presented in Appendix II. These profiles are thought to represent the components of natural slopes formed through the processes of erosion and mass movement, with the exception of the section at mile 49.0 on Keg Creek, which may have been artificially altered as a part of bridge replacement.

Keg Creek

Figures 46, 47 and 48 show cross-sectional channel profiles observed on Keg Creek during this study. Note that the banks of the section from mile 30.7 are nearly twice as deep as either of the other two sections. As shown previously, the reach of channel between mile 20 and mile 32 has undergone degradation in the last 25 years, but that as much as 18 feet of additional degradation can be expected above mile 32. Thus, the profiles from mile 45.0 and mile 49.0 may reflect the streambanks of a relatively non-degraded reach of Keg Creek.

The streambanks at mile 45.0 and mile 49.0 each display three components of slope. At mile 45.0 a vertical segment about 2 feet in height exists just below the floodplain, but the major portion of the slope has an average inclination of only 16° as it retreats from the top of the bank. The lower 4 feet of slope is inclined at 30°; the fact that it is steeper than the overlying segment gives the lower slope a convex-upward profile.

At mile 49.0 the lower two-thirds of the slope is very similar in profile to that at mile 45.0; the middle segment is inclined at 15° and it joins with a segment inclined at 36° at the bottom of the slope. The upper 4 feet of slope at mile 49.0 does not display a vertical face, but joins with the floodplain at an average inclination of 30°. The overall profile shows a concave-upward slope in the upper half, grading to a convex-upward slope in the lower.

Degradation of the channel has taken place at mile 30.7, which accounts for the steep slopes of its streambank. The upper 17 feet of the 25 foot deep bank is nearly vertical, shallowing slightly at its base. The lower segment of slope is talus, indicating that mass movement of bank materials has acted to shape the upper slope. The overall profile of the slope is concave-upward.

Long Branch Creek

Figures 49, 50 and 51 show the channel profiles observed on Long Branch Creek during this study. This stream lies in the eastern-most portion of the study area; it flows through northeastern Shelby County for a distance of about 12 miles. There is limited evidence available from state and county bridge records to show that most of the stream has undergone degradation, particularly the lower 8 miles of channel.

The slopes observed along Long Branch Creek are more complex than those observed along any of the other 3 streams studied. At miles 10.4, 6.5 and 4.0 there are 4, 5 and 6 components of slope present, respectively. While the Long Branch channel at mile 4.0 attains a depth of nearly 29 feet, the high near-vertical slopes observed at mile 30.7 on Keg Creek do not exist at this location on Long Branch Creek.

At mile 10.4, a vertical segment 6 feet in height exists just below the top of the bank. Below this two segments were found; the uppermost is a bench-like feature with an inclination of about 5°, below which was found a segment inclined at 23°. The bottom 2 feet of slope drops off sharply into the channel. The overall profile is convex-upward to the point where the lower slope joins the vertical upper bank.

At mile 6.5 two short vertical segments are present, one at the top of the slope and one approximately a third of the way down the slope. The slope component lying between these segments was covered with soil debris, but it is not a talus slope. Below the second vertical segment lies a shallower slope, inclined at about 18°. The bottom 5 feet of slope is somewhat steeper, with an average inclination of 36°. As was the case with the streambank at mile 10.4, the overall slope profile is convex-upward, except where broken by the short vertical segments.

The components of the streambank at mile 4.0 display some similarity to those at mile 6.5 in that two short vertical segments are present, one at the top of the slope and a second further downslope. However, these two segments are separated by a portion of the bank that displays a concave-upward profile. This profile is made up of two segments; a talus slope with an average inclination of 37° and a shallower segment inclined at 15°. The streambank profile below the second vertical segment is convex-upward, made up of an upper segment inclined at 30° and a lower nearly vertical segment 7 feet in height.

Thompson Creek

Thompson Creek is a tributary to Willow Creek in Central Harrison County with a length of about 7 miles. The channel of this stream has undergone massive degradation since the straightening of the Willow; Daniels and Jordan (1966) described some of this degradation. In some locations the stream is flowing as much as 35 feet below the top of its banks.

Only one location along Thompson Creek was observed, as shown in Figure 52. Most of the streambank at this location is composed of a single 25 foot high segment, inclined at 75^o. The lower 2 feet of the slope has an inclination of 18^o, and is not a talus slope.

Willow Creek

Cross-sectional channel profiles were observed at 5 locations along Willow Creek, four in the Willow drainage ditch and one near the mouth of the stream. With the exception of the section near the mouth of the stream, all exist at locations where the channel has undergone degradation at some time since straightening.

Figures 53 - 57 show the streambanks observed on Willow Creek. Note that the general form of the overall slope profile for each is concave-upward. The four sections from the Willow drainage ditch have high, steep slopes in the upper bank, beneath which lies some talus.

At mile 24.8 four slope components are present. At the top of the bank a 15 foot high segment inclined at 75^o exists. Below this, a bench-like component is present. The bottom 9 feet of slope consists of a segment inclined at 18^{o} and a bottom-most segment inclined at 35^{o}.

Four slope components also exist at mile 20.8. A vertical segment sixteen feet in height is present just below the top of the bank, and a talus slope lies immediately beneath it. The bottom 8 feet of the slope displays a convex-upward profile with an 18^{o} segment at the top and a 30^{o} segment at the bottom.

From top to bottom, the streambank at mile 16.9 exists of 75^{o}, 25^{o} and 30^{o} slope components, respectively. At mile 13.0, the profile is convex-upward, with an 85^{o} upper segment, a talus slope below it and a 15^{o} bottom-most segment.

The channel, at mile 2.0 has not experienced the large amount of degradation that the upstream channel has. Three components of slope exist at this location: a short vertical segment in the upper four feet of the bank, below which lies a segment with an inclination of 35^{o}. The bottom 6 feet of the channel is inclined at about 30^{o}.

Interpretations

Although there is a wide divergence of the profiles of the streambanks presented in the previous section, there are certain segments of slope that appear at several locations. These segments may be attributable to one or more of the slope-forming processes mentioned earlier, as will be discussed in the following section.

At 5 of the 12 sections observed the lower 8-10 feet of the streambank displays a convex-upward profile consisting of two segments, an upper segment of 15-18° inclination and a lower segment of 30-36° inclination. Three other locations also have a convex-upward profile in the lower 10 feet of bank. Since these portions of the streambank occur at non-degraded as well as degraded reaches of stream, it is suggested that they are the result of sheet erosion by water running down the banks during and after a precipitation event. The convex-upward profile is typical of slope components that gather water (Bloom, 1978).

The talus slopes observed at 7 locations had inclinations ranging from 28-37°. Lohnes and Handy (1968) reported that the theoretical angle of repose for talus in the upland loess is 38°; these observations indicate that it is similar for the alluvium that makes up the streambanks. Talus slopes observed were located at least 10 feet above the channel bottom; as mentioned previously, slope components composed of loose colluvial materials are quickly dismantled by the action of water flowing in the channel.

Vertical or near-vertical slope components greater than 15 feet in height were observed at 7 of the 12 locations. Large slump blocks that have separated from the upper bank but moved only a short distance can be observed at these and many other locations along the degrading portions of stream channels in western Iowa (Plate 2). During this study, blocks as thick as 10 feet have been observed, but Daniels (1960) reported observing blocks as thick as 30 feet in the Willow Creek Channel. These observations suggest that the steep slope components

Plate 2. Slump blocks on a Western Iowa stream channel

are a product of mass movement of streambank materials. This possibility will be pursued further in the following section of this thesis.

At four locations a vertical segment of slope 2-4 feet in height was observed to exist at the upper-most portion of the streambank. These segments were formed entirely within a thin layer of yellow-brown silt loam, assumed to be post-settlement alluvium because of the presence of cans, bottles and wire incorporated within the alluvium at various places. The post-settlement fill is not buried by other units and as such is less consolidated than the alluvium below it; thus, it is suggested that the stratigraphic break between the post-settlement fill and the underlying alluvium may act to stimulate formation of these components. A similar mechanism may also be responsible for the presence of the short vertical segments present near mid-slope of the streambanks at miles 6.5 and 4.0 of Long Branch Creek.

Slope Stability Analysis

Basis for analysis

Lohnes and Handy (1968) have utilized soil mechanics to explain slopes found in nature. In this section of the thesis, an attempt will be made to use the strength data obtained for the alluvium of the streambanks along Keg and Willow Creeks to provide clarification of the way(s) in which mass movement affects the slopes observed.

The shearing strength of the alluvium was measured in situ, on the face of the slopes encountered within the channels (strength measurements were not taken on talus slopes). As mentioned previously, a hand-held Torvane was used for this purpose, with the Soil-Test^{tm} CL-600 foot attached. Using this foot and a rate of loading equivalent to 0.1 tons per square foot/second, the Torvane directly gives shearing strength in tons per square foot. Strength values obtained in this manner represent the undrained strength of the alluvium; thus, they are judged to be a reasonable estimation of the cohesion of this material and will be used as such in this section.

In Figure 34 the total height of streambank H_t some of the measured cross-sections is plotted against the ratio of strength to unit weight of the alluvium. Figure 35 is a plot of the latter parameter versus the observed angles of the dominant slope components at these locations. Both of these trends are linear and suggest that higher and steeper slopes occur where the strength to unit weight ratio is higher.

The method in which the strength of the alluvium was measured may account for divergence of some of the points from a straight line on Figures 34 and 35. The most critical time for slope failure is probably after decline of high water in the channel, when the alluvium is saturated and excess positive pore pressures exist. However, in nearly all cases this material was sampled in a dry state, and the values of shearing strength obtained are probably a function of both cohesion and the angle of internal friction. This does not invalidate the approach taken here; the fact that any trend exists suggests a

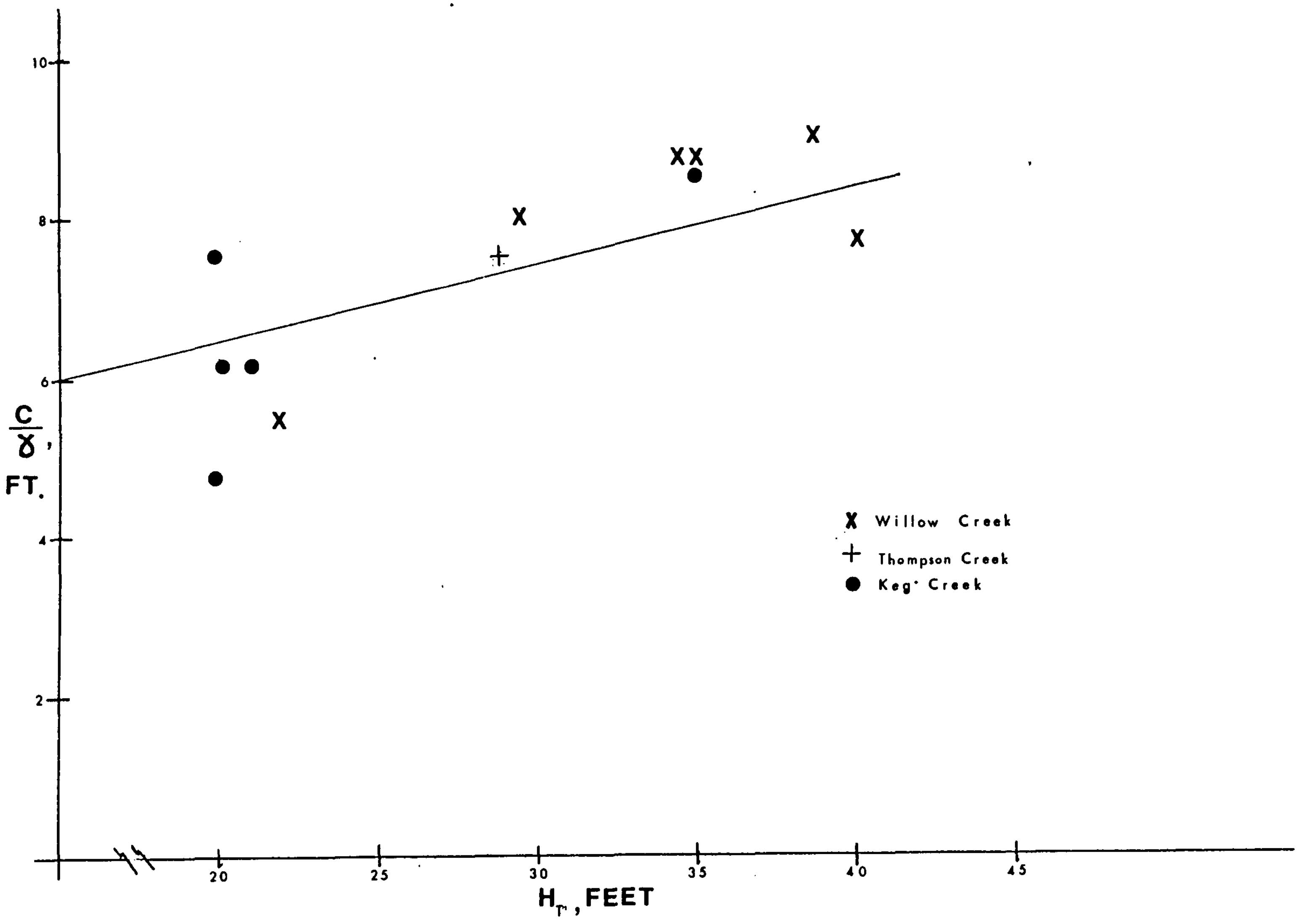

Figure 34. Total height of streambank versus ratio of cohesion to unit weight of alluvium

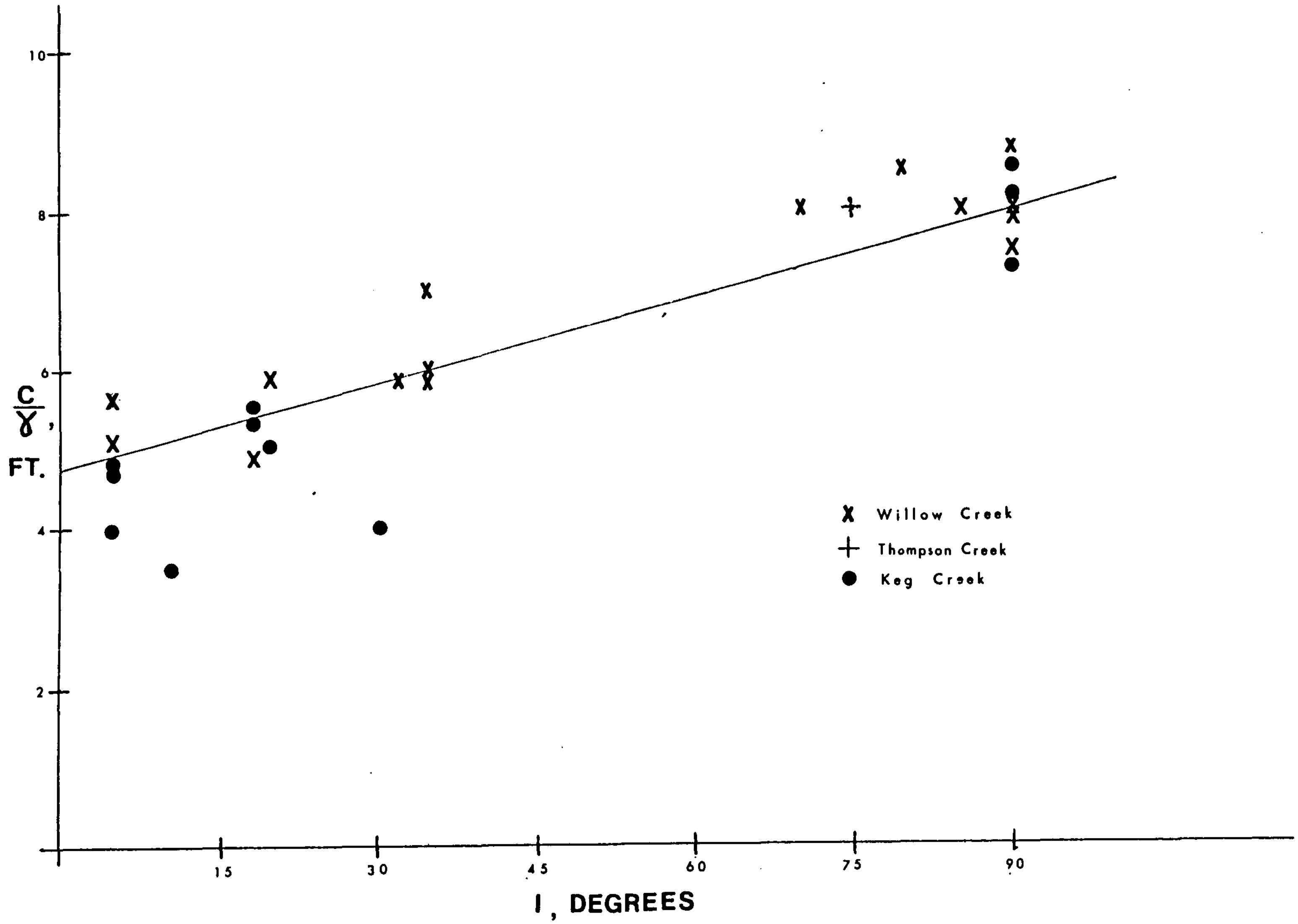

Figure 35. Angle of individual slope components versus ratio of cohesion to unit weight of alluvium

relationship between the slope height and the physical properties of the alluvium.

Based on observations of tension cracking and slump blocks associated with the Keg and Willow Creek Channels, it is concluded that the failure surfaces within the alluvium are more closely represented by planes than by arcuate surfaces. Entire slump blocks have been observed that have broken away from the main bank and moved nearly vertically downslope, or rotated only slightly. Lohnes and Handy (1968) add further evidence to this argument. From a study of the upland loess, they concluded that the failure surfaces in this material are normally planar.

Approach

Terzaghi (1943) emphasized that soil adjacent to the upper part of a slope is in tension. This state of stress causes vertical cracking with the slope, which creates a slab of soil supported only by a small wedge of underlying soil. The depth of the tension crack can be determined by the equation:

$$Z_o = \frac{2c}{\gamma} \tan \left(45^o + \frac{\phi}{2}\right)$$

where Z_o is the depth of cracking, c is the soil cohesion, γ is the unit weight of the soil and ϕ is the angle of internal friction. Tension cracking at the top of streambanks is a common feature along Keg and Willow Creeks, and probably along most degrading streams.

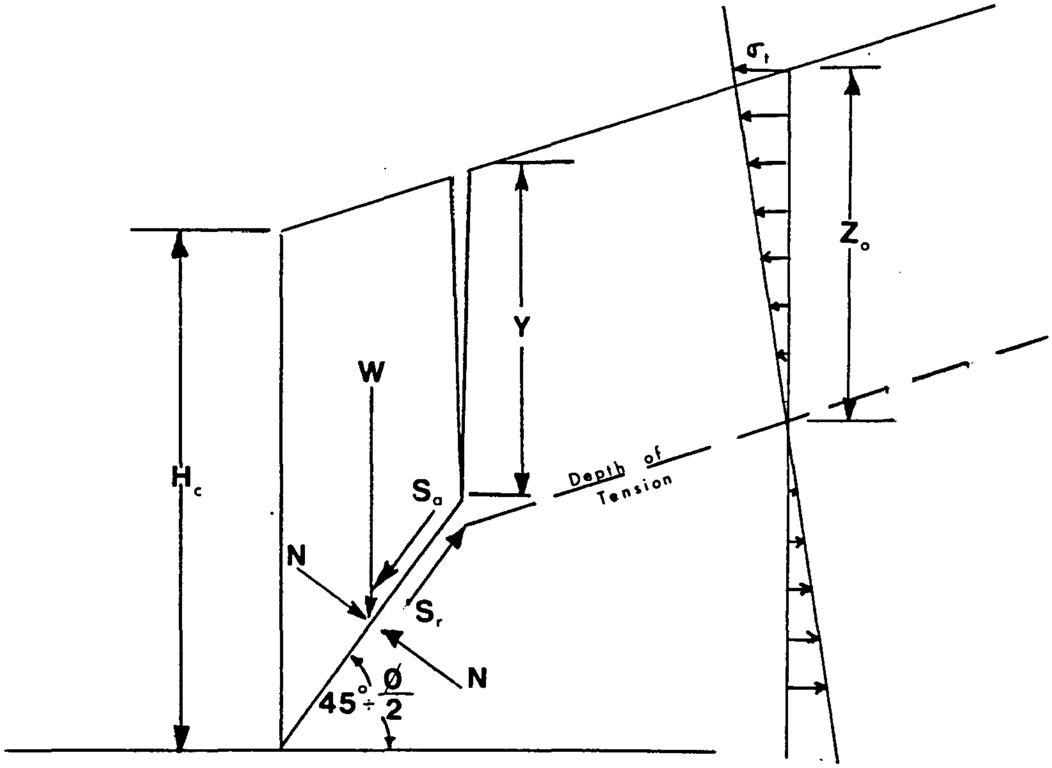

Figure 36. Rankine earth-pressure theory, indicating tension leading to vertical cracking in upper slope

Rankine theory can be used to show a slope subjected to this state of stress and the forces involved. Figure 36 shows how the forces affect the slab of soil in question. If undrained loading can be assumed, the friction angle of the soil can be equated to zero and the depth of the tension failure can be related to soil properties by the equation:

$$Z_o = \frac{2c}{\gamma}$$

The forces acting along the failure plane due to the weight of the overlying soil and interstitial water are summed to a component force S_a. The resisting force S_r is simply equal to the shearing strength of the soil acting along the failure plane. Since ϕ is assumed to be zero, S_r in this case is a function of cohesion alone.

Using the Culmann analysis for slope stability, which assumes a planar failure surface, Lohnes and Handy (1968) determined that vertical downcutting in the Wisconsin loess would lead to a sequence of failures, as shown in Figure 37. In the first stage, vertical downcutting would occur to a maximum depth H_c, as determined by the equation:

$$H = \frac{4c \sin i \cos \phi}{\gamma(1-\cos(i - \phi)}$$

where c is the cohesion of the soil in question, i is the slope angle, ϕ is the angle of internal friction of the soil, and γ is the unit weight of the soil.

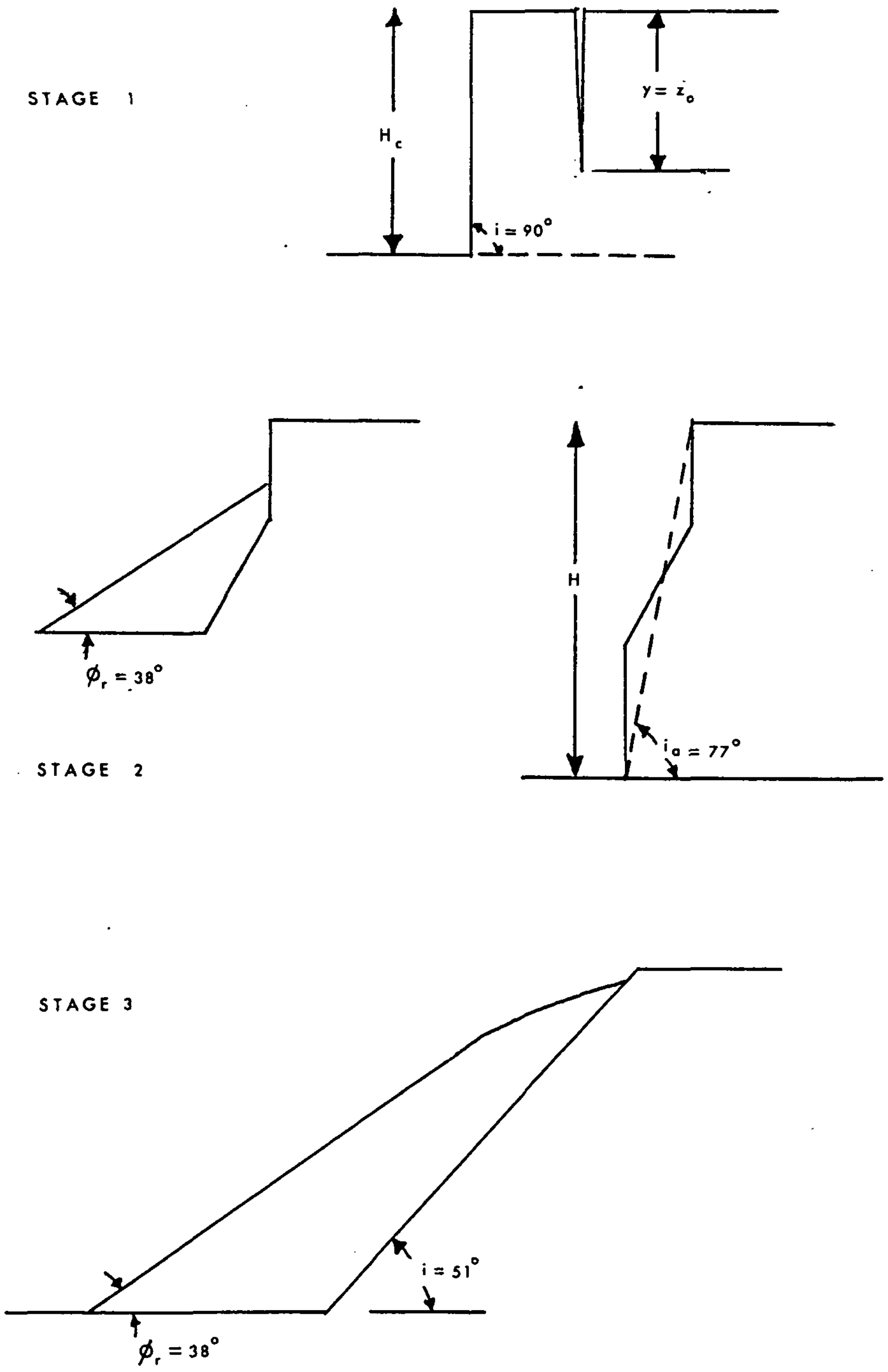

Figure 37. Hypothetical sequence of loess slope failures caused by adjacent downcutting. After Lohnes and Handy (1968)

When H_c is reached cleavage failure will occur, initiating stage 2. The slope would then suffer further degradation and removal of talus materials to a maximum depth H, dependent on the apparent slope angle i_a (theoretically 77° for the Wisconsin loess). Stage 3 represents a third period of failure leaving a slope of 51°, which in most cases will be covered by talus material resting at the angle of repose.

Because the properties of the Tazewell-Cary alluvium are similar to the upland loess, it is logical that an approach like the one used by Lohnes and Handy (1968) should also apply to slope stability analysis for the streambanks of Western Iowa. A similar approach will be made here assuming an undrained loading condition, so that the $\phi = 0$ concept applies. In using this method, the pore pressure is taken as zero along any failure surface where the undrained strength is used. Lambe and Whitman (1979) point out that this does not mean that pore pressures are actually zero; rather, it is used to be consistent with the assumption that undrained strength is independent of the effective stress at failure.

Assuming that all slope components with an angle greater than 75° represent a shearing face in the alluvium, the critical height as predicted by the Culmann analysis should be a measure of the maximum stable height that these steep components of the streambanks can obtain. In Figure 38, predicted values of H_c are plotted against observed heights of these steep components. It appears that all of the slope segments observed are stable (the line drawn at 45° represents the boundary between stable and unstable slopes). As predicted for a vertical slope in the Tazewell-Cary alluvium, H_c is between 30 and 40 feet (depending on the value of cohesion and unit weight), but slump blocks have been observed in conjunction with slopes less than 15 feet in height. If a $c - \phi$ analysis is made assuming a ϕ angle of 25^o, predicted bank heights are over 100 feet.

The presence of unstable slopes with height less than that predicted by the Culmann analysis is evidence that long term stability is not always controlled by the conditions assumed in performing the stability analysis. Changes in natural groundwater levels can introduce pore pressures and additional driving forces into the system. Bishop and Bjerrum (1960) concluded that a $\phi = 0$ analysis is not an appropriate approach for long-term slope stability predictions, and that $c - \phi$ methods should be used.

The analysis presented in Figure 38 can be modified so that observed slope heights of the steep streambank components are plotted against the depth of tension cracking as predicted by the Terzaghi equation. Since ϕ is assumed to be zero, the cracking depth Z_o is estimated by $2c/\gamma$. Figure 39 shows this approach. The proximity of most of the data points to the line drawn at 45^o suggests that the vertical and near-vertical slope components are the result of tension cracks at the top of the streambanks, not shearing failures as previously analyzed for. Again, divergence of points from a straight line in Figure 38 may be related to the method in which the strength of the alluvium was determined.

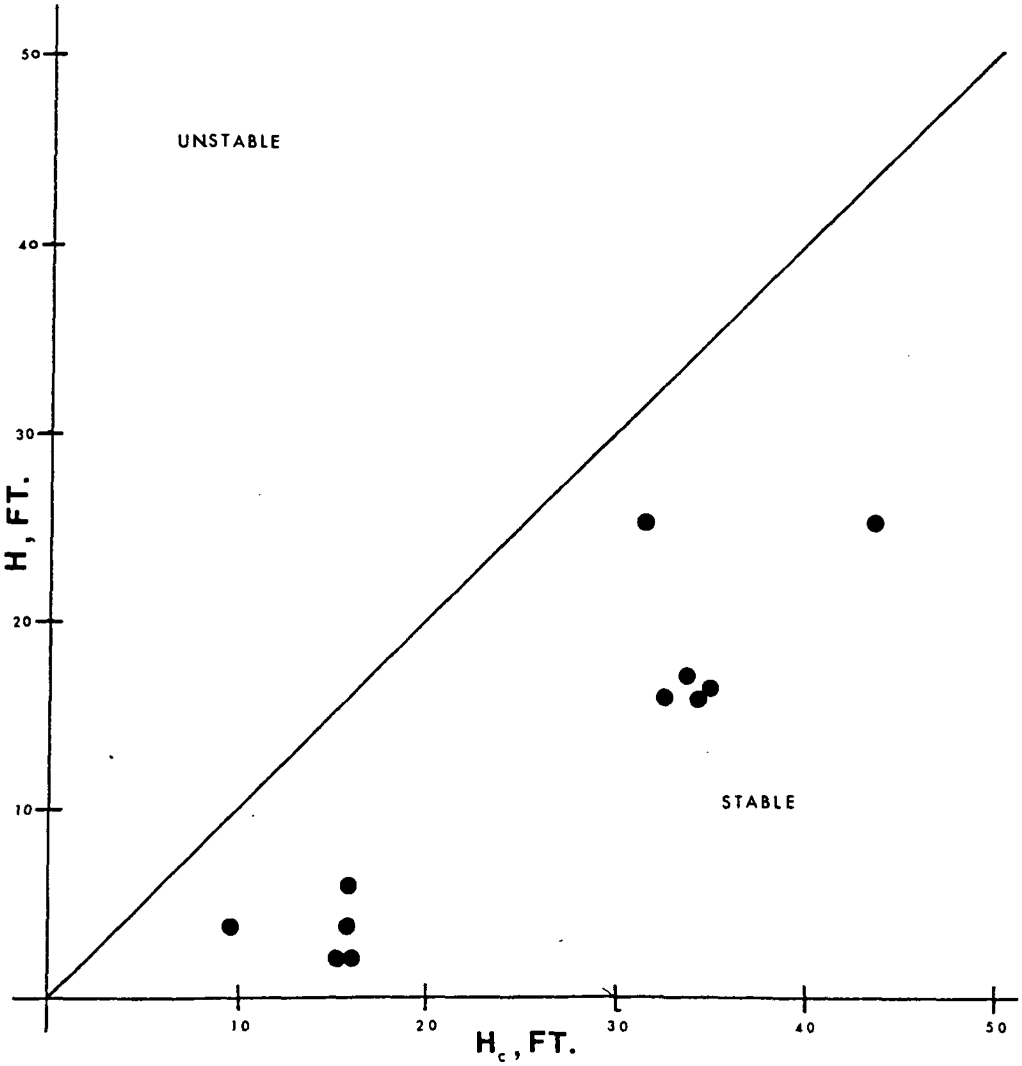

Figure 38. Calculated versus observed heights of steep slope components for eleven streambanks

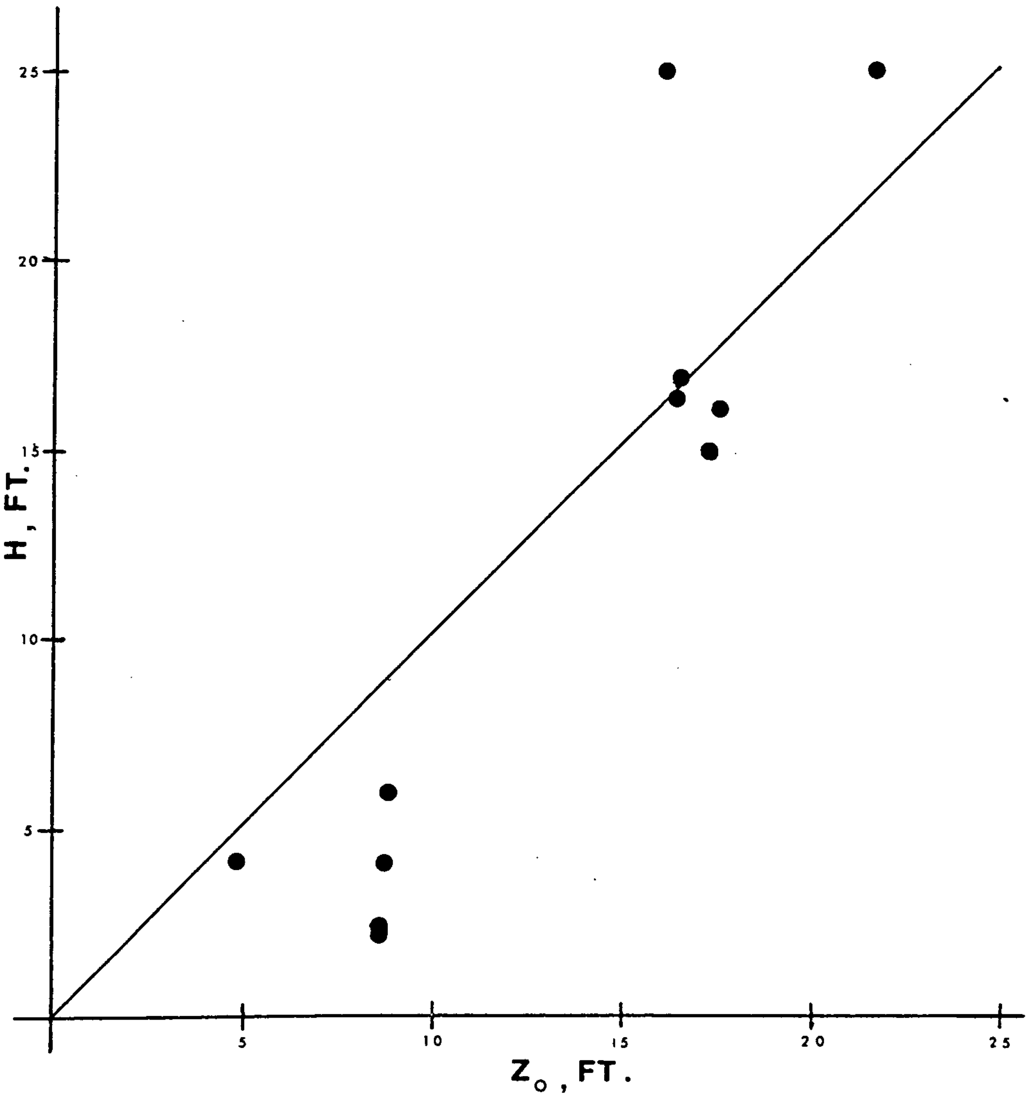

Figure 39. Calculated depth of tension cracking versus observed heights of steep slope components, eleven streambanks

Based on the evidence presented in this section, it is concluded that the stable height of slopes within the Tazewell-Cary alluvium is affected by the depth of tension cracking in the soil. Movement of groundwater in the vicinity of any free-standing slab of alluvium will probably initiate failure and subsequent slumping, which explains the presence of slump blocks adjacent to slopes that are judged to be stable by conventional methods such as the Culmann analysis. Tension cracks can be expected behind any streambank in cohesive material with a steep slope component near the top, as long as the material in that segment is above the permanent water table. Slope failure as described in this section should be a common feature of degrading streams.

CONCLUSIONS

Publications prior to this study have provided a description of the degradation that has occurred on several Western Iowa streams. Also, studies at Iowa State University have provided in-depth descriptions of the Quaternary history and alluvial morphology of several of the major rivers in Western Iowa (Dahl, 1961; Pedersen, 1962; Knochenmus, 1963). This thesis has attempted to describe and define some of the mechanisms associated with the degradation of Western Iowa streams, as well as suggest some methods for predicting the amount and rate of degradation, by focusing on the changes that have taken place in the Keg and Willow Creek drainage basins.

One of the problems encountered during this study has been the difficulty in obtaining precise data on the changes that have occurred in Western Iowa streams within the past century. Searches for historical literature and records are tedious and often unrewarding, especially in regard to specific changes in the slope, width and depth of stream channels at some given point in time. On the other hand, the time span of interest is short geologically, too short to allow much valuable data to be gained from studies of alluvial morphology.

Of the three causes suggested for the degradation observed since the turn of the century, straightening of the stream channels holds the most supporting evidence. There is not conclusive evidence to support the theory of Piest et al. (1976) that increased runoff has caused the problem, and while it appears that the channel of the Missouri River underwent natural degradation prior to 1879, the magnitude of that degradation (10-15 feet) was not enough to explain the entrenchment observed along Keg and Willow Creeks. In addition, geomorphic evidence indicates that the channel of the Missouri in the vicinity of Omaha has been essentially stable since 1879.

Movement of knickpoints headward through the stream channels of Western Iowa plays an important role in the degradational process. Degradation is prominent in the vicinity of the knickpoint and for some distance upstream, but takes place for only short distances downstream from the overfall. Increases in channel slope, streamflow velocity, depth of flow and friction head appear to accompany the movement of a knickpoint into a specific reach of channel. Downstream of a knickpoint velocity of flow decreases with time, and asymtotically approaches a limiting value.

Daniels (1960) has suggested that Hack's (1957) equation can be used to estimate the ultimate amount of degradation that will occur in an unstable reach of stream, provided that the longitudinal profile in a stable reach downstream is known. Verification of his predictions on the entrenchment of the upper 13 miles of the Willow Creek channel indicate that this approach is plausible, although problems were encountered in trying to apply it to predicting further degradation of the Keg Creek Channel.

Lohnes et al. (1980) suggested a rational approach backed by historical evidence to describe the rate of entrenchment of a stream system. It was hypothesized that the equation:

$$\ln(h_1/h_o) = -k' t$$

can be used to predict the time it would take for a given point on the stream to reach equilibrium in the face of vertical degradation. The value of the degradational constant k' appears to be related to the drainage area and thus discharge of the basin above the point in question.

Natural processes of erosion, both by water flowing in the channel and sheet wash, have helped to shape the streambanks observed. However, the rate of widening of the Willow drainage ditch has been constant with time (Ruhe and Daniels, 1965). Since this stream has rarely if ever filled its banks more than half full since straightening, mass movement of the Tazewell-Cary alluvium has undoubtedly played a role in the widening process. The slump blocks that are a common feature within the channel are further evidence for this argument.

Application of soil mechanics provides a rational approach for describing the slopes encountered in nature. There is evidence that tension cracks, common features at the top of the streambanks along Keg and Willow Creeks, control the height of the steep (above 75^o) slope components observed. This realization is important for the engineer involved with the problem of rapidly widening stream channels, because it suggests that once entrenchment of the stream ceases, widening can be curtailed by controlling the stability of the streambanks.

SUGGESTIONS FOR FURTHER STUDY

As noted previously, many of the conclusions made during this study are tenative because of the lack of a broad data base, particularly with respect to changes that have taken place in the stream channels of Western Iowa since straightening. There is a need to expand the present knowledge of the degradational history of a few streams to many streams, so that the trends observed in this thesis can be verified or disproved. Particularly useful would be a statistical analysis of some or all of these trends, and the development of empirical equations to describe them.

Future in-depth studies of the stratigraphy and properties of the alluvium are suggested, in light of the fact that the formation of knickpoints appears to be related to the presence of erosion-resistant layers such as paleosols present within the alluvium. Also, verification of the premise that the alluvium of the Keg Creek basin (as well as other basins within the study area) is contemporaneous with the Tazewell-Cary alluvium of the Willow Creek basin would be worthwhile in continuing to update the Pleistocene History of the region.

Finally, it would be desirable for a future study to advance the rational approach on predicting the rate of degradation that has been followed by Lohnes et al. (1980) and this author. This could be accomplished by experimentation, particularly in flume studies on the hydraulics of knickpoints, to gain a better understanding of the factors that control channel degradation.

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LITERATURE CITED

Antosch, L. and J. Jones. "Iowa's lowhead dams; their past, present and future roles." Iowa State Water Resources Research Institute, No. 96, Special Report, 1979.

Beer, C. E. "Relationship of factors contributing to gully development in loess soils of western Iowa." Ph.D. Dissertation, Iowa State University, Ames, Iowa, 1962.

Bishop, A. W. and L. Bjerrum. "The relevance of the triaxial test to the solution of stability problems." Proc. ASCE Research Conf. on Shear Strength of Cohesive Soils, Boulder, Colorado, 1960, 437-501.

Bloom, A. L. Geomorphology: A Systematic Analysis of Late Cenozoic Landforms. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1978.

Dahl, A. R. "Missouri River studies: alluvial morphology and Quaternary history." Ph.D. Dissertation, Iowa State University, Ames, Iowa, 1961.

Dahl, A. R., R. L. Handy, and D. T. Davidson. "Variation of loess thickness and clay content in southern Iowa." Iowa Academy of Science Proceedings, No. 64 (1958), 393-399.

Daniels, R. B. "Entrenchment of the Willow drainage ditch, Harrison County, Iowa." Am. Jour. Sci., 258 (Mar. 1960), 161-176.

Daniels, R. B. and R. H. Jordan. "Physiographic history and the soils, entrenched stream systems and gullies, Harrison County, Iowa." U.S. Department of Agriculture Technical Bulletin 1348, September, 1966.

Daugherty, R. L. and A. C. Ingersoll. Fluid Mechanics with Engineering Applications. New York: McGraw-Hill, 1954.

Davidson, D. T. and R. L. Handy. "Property variations in the Peorian (Wisconsin) loess of southwestern Iowa." Iowa Academy of Science Proceedings, No. 59 (1952), 248-265.

Hack, J. T. "Studies of longitudinal stream profiles in Virginia and Maryland." U.S. Geological Survey Professional Paper 294-B (1957), 45-97.

Hallberg, G. R. "Wind-aligned drainage in loess in Iowa." Iowa Academy of Science Proceedings, No. 86 (1979), 4-9.

Hallberg, G. R., J. M. Harbaugh and P. M. Witinok. "Changes in the channel area of the Missouri River in Iowa, 1879-1976." Iowa Geological Survey Special Report Series No. 1, 1979.

Handy, R. L. "Collapsible loess in Iowa." Soil Science Society of America Proceedings, 37, No. 2 (Mar.-Apr. 1973), 281-284.

Hansen, J. A., A. R. Dahl and D. T. Davidson. "Further studies of loess in Iowa: thickness, clay content, and engineering classification." *Iowa Academy of Science Proceedings*, No. 65 (1959), 317-322.

Holland, W. N. and G. Pickup. "Flume study of Knickpoint development in stratified sediment." *Geol. Soc. Am. Bull.* No. 83 (1976), 76-82.

Horton, R. E. "Erosional development of streams and their drainage basins, hydrophysical approach to quantitative morphology." *Geol. Soc. Am. Bull.* No. 56 (1945), 275-370.

Iowa Geological Survey. "Surface water resources of Iowa." Water-supply Bulls. No. 3, 6 and 9, 1953, 1956 and 1958.

Iowa State Planning Board. *Water Resources of Iowa, 1873-1932*. Detroit, Mich.: College Press Division, Copifyer Corp., 1933.

Knochenmus, D. "Alluvial morphology of the Nishnabotna River." M.S. Thesis, Iowa State University, Ames, Iowa, 1963.

Lambe, T. W. and R. V. Whitman. *Soil Mechanics, SI Version*. New York: John Wiley and Sons, 1979.

Lara, O. G. "Annual and seasonal low-flow characteristics of Iowa Streams." U.S. Geological Survey Open-File Report 79-555, Iowa City, Iowa, 1979.

Larimer, O. J. *Drainage Areas of Iowa Streams*. U.S. Geological Survey Water Resources Division, 1974.

Lees, J. "Geology of Crawford County, Iowa." Iowa Geological Survey Annual Report 21, 1912.

Leopold, L. B., M. G. Wolman and J. P. Miller. *Fluvial Processes in Geomorphology*. San Francisco: W. H. Freeman and Co., 1964.

Lohnes, R. A., M. D. Dougal, M. Johnson and R. Bachmann. "Water management, water quality and alluvial morphology of oxbow lakes, Final Report, Phase I."Engineering Research Institute Project 1279, Iowa State University, Ames, Iowa, 1977.

Lohnes, R. A. and R. L. Handy. "Slope angles in friable loess." *Journal of Geology*, 76, No. 3 (1968), 247-258.

Lohnes, R. A. and R. C. Joshi. "Quantitative variations in loess topography." *Iowa Academy of Science Proceedings* No. 74 (1967), 160-167.

Lohnes, R. A., F. W. Klaiber and M. D. Dougal. "Alternate methods of stabilizing degrading stream channels in western Iowa." Dept. of Civil Engineering, Engineering Research Institute, Iowa State University, Ames, Iowa, ISU-ERI-Ames-81047, 1980.

Miller, V. C. "A quantitative geomorphic study of drainage basin characteristics in the Clinch Mountain Area, Virginia and Tennessee. U.S. Office of Naval Research Project NR389-042, Technical Report 3, 1953.

Pedersen, D. "Alluvial morphology of the Little Sioux River." M.S. Thesis, Iowa State University, Ames, Iowa, 1962.

Piest, R. F., C. E. Beer and R. C. Spomer. "Entrenchment of drainage systems in Western Iowa and Northwestern Missouri." *Proceedings of the 3rd Federal Inter-Agency Sedimentation Conference*, 1976, 5-48 to 5-60.

Piest, R. F., L. S. Elliot and R. C. Spomer. "Erosion of the Tarkio drainage system, 1845-1976." *Trans. Am. Soc. Ag. Eng*. No. 20 (1977), 485-488.

Ruhe, R. V. *Quaternary Landscapes in Iowa*. Ames, Iowa: Iowa State University Press, 1969.

Ruhe, R. V. and R. B. Daniels. "Landscape erosion - geologic and historic." *Journal Soil and Water Conservation* No. 20 (1965), 52-57.

Sayre, W. W. and J. E. Kennedy, Eds. "Degradation and aggredation of the Missouri River, Proceedings of a Workshop in Omaha, Nebraska." Iowa Institute of Hydraulics Research Report, University of Iowa, Iowa City, Iowa, No. 215, January, 1978.

Shimek, B. "Geology of Harrison and Monona Counties." Iowa Geological Survey Annual Report 20, 1909.

Simonson, R. W., F. F. Riecken and G. D. Smith. *Understanding Iowa Soils*. Dubuque, Iowa: Wm. C. Brown Co., 1952.

Smith, J. H. *History of Harrison County, Iowa*. Des Moines: Iowa Printing Co., 1888.

Terzaghi, K. *Theoretical Soil Mechanics*. New York: John Wiley and Sons, 1943.

Udden, J. A. "Geology of Mills County, Iowa." Iowa Geological Survey Annual Report 13, 1903.

U.S. Department of Agriculture, Statistical Reporting Service. "Number and Size of Farms; Geographic Patterns in Iowa." Iowa Crop and Livestock Reporting Service, Des Moines, Iowa 1920-1976.

U.S. Geological Survey. *Water Resources Investigations in Iowa*. Iowa City, Iowa: U.S. Geological Survey, 1978.

White, C. A. *First and Second Annual Report of Progress by the State Geologist and the Assistant and Chemist on the Geological Survey of the State of Iowa*. Des Moines: F. W. Palmer, State Printer, 1868.

APPENDIX I

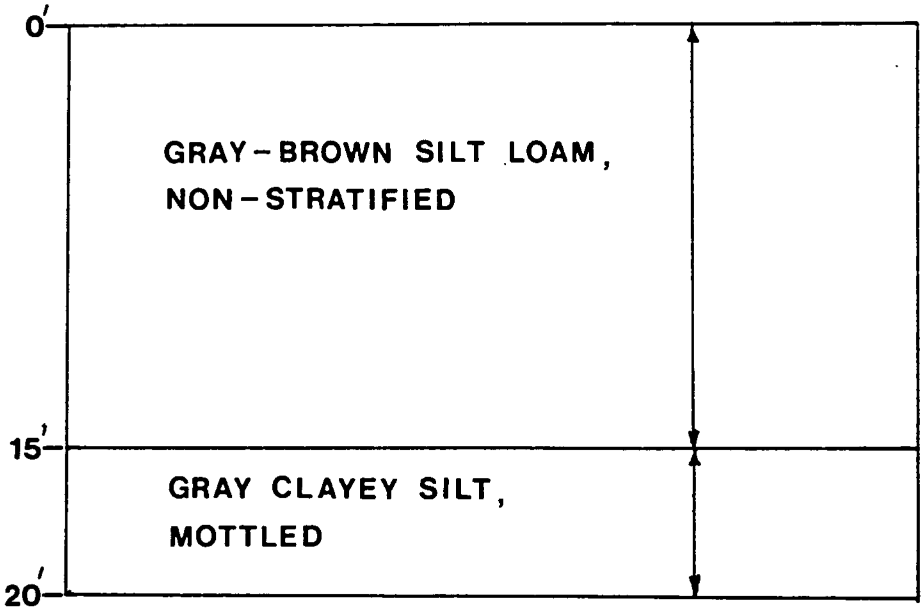


Figure 40. Stratigraphy of alluvium observed on Keg Creek, Sec. 6, R40W, T78N, Shelby County

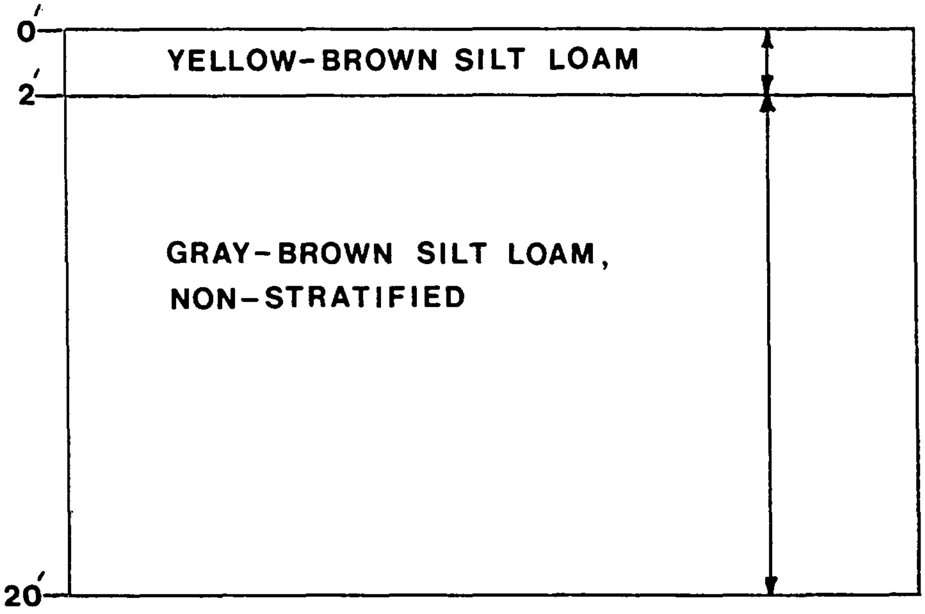


Figure 41. Stratigraphy of alluvium observed on Keg Creek, Secs. 14 and 15, R41W, T77N, Pottawattamie County

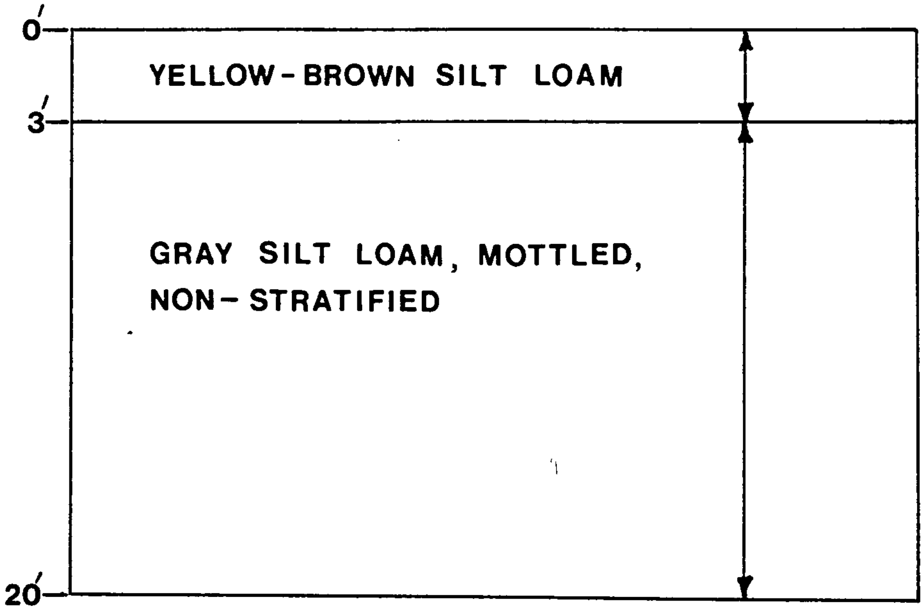


Figure 42. Stratigraphy of alluvium observed on Keg Creek, Secs. 33 and 34, R41W, T76 and 77N, Pottawattamie County

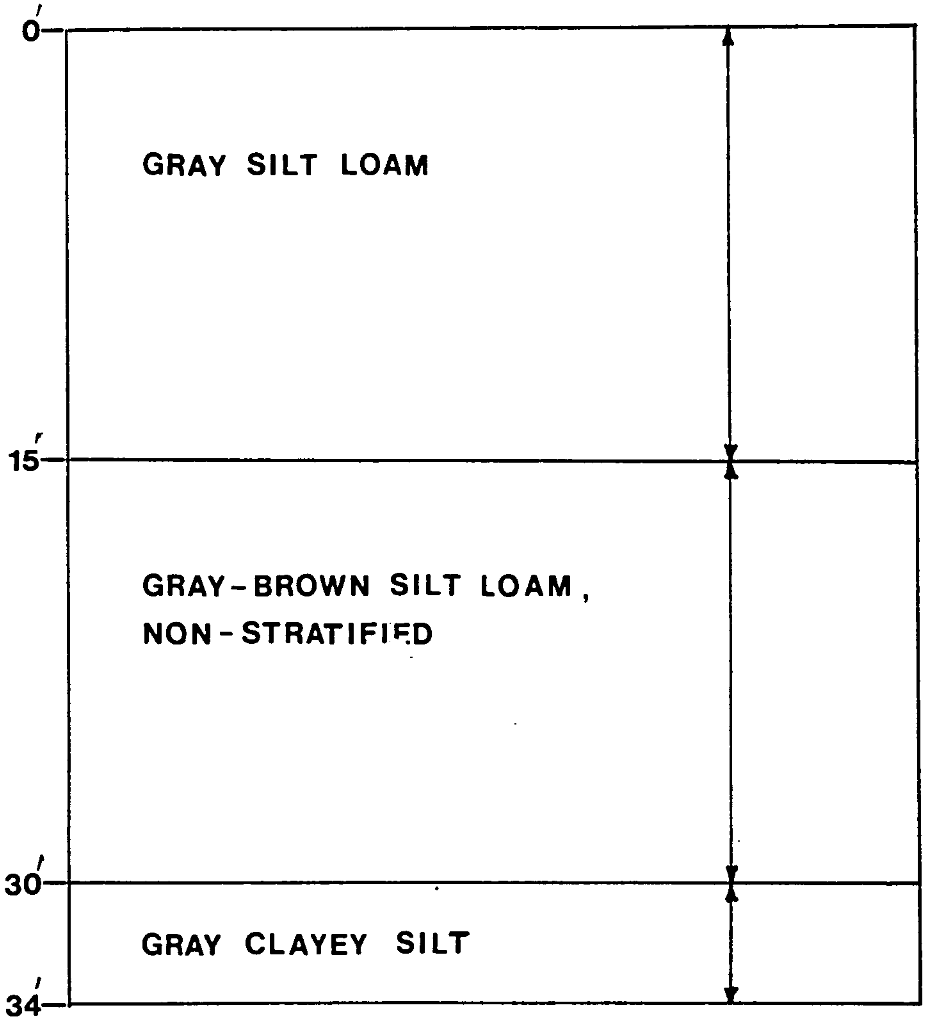


Figure 43. Stratigraphy of alluvium observed on Keg Creek, Secs. 15 and 22, R42W, T75N, Pottawattamie County

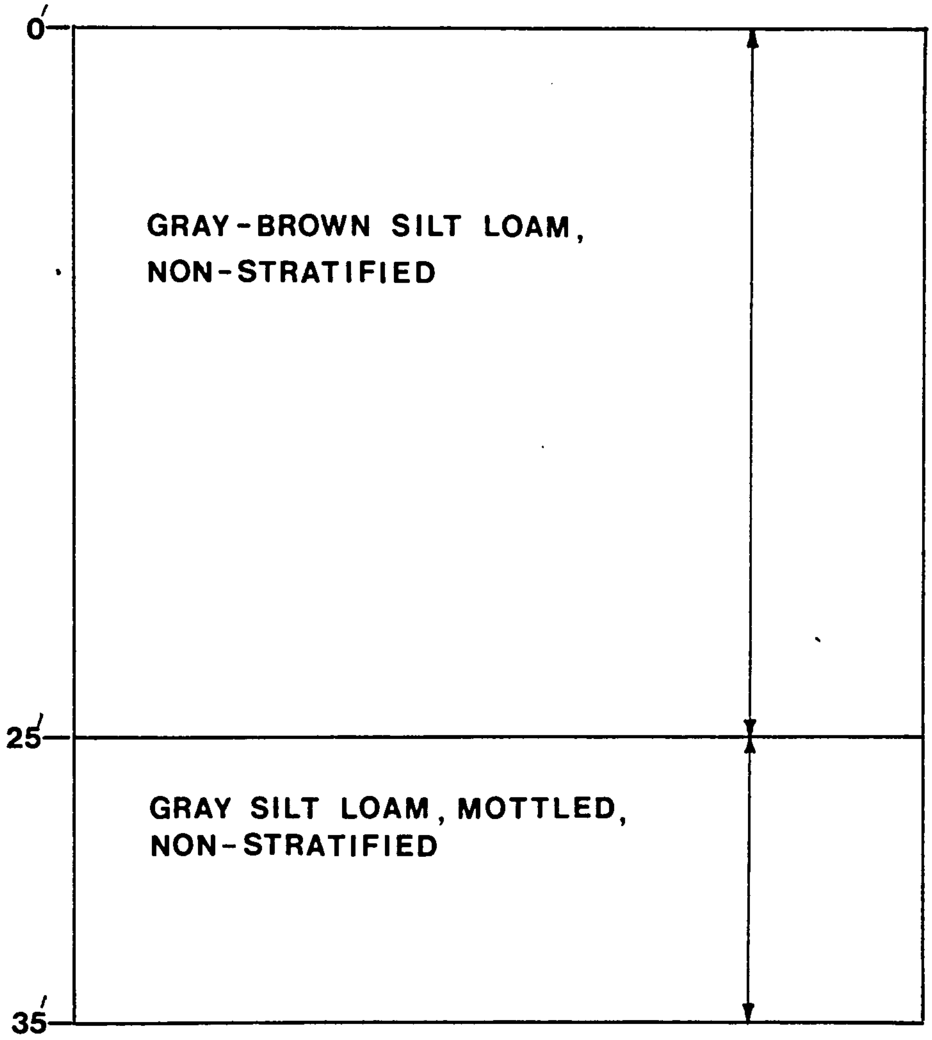


Figure 44. Stratigraphy of alluvium observed on Keg Creek, Secs. 1, 2, 35, 36, R42W, T75N, Pottawattamie County

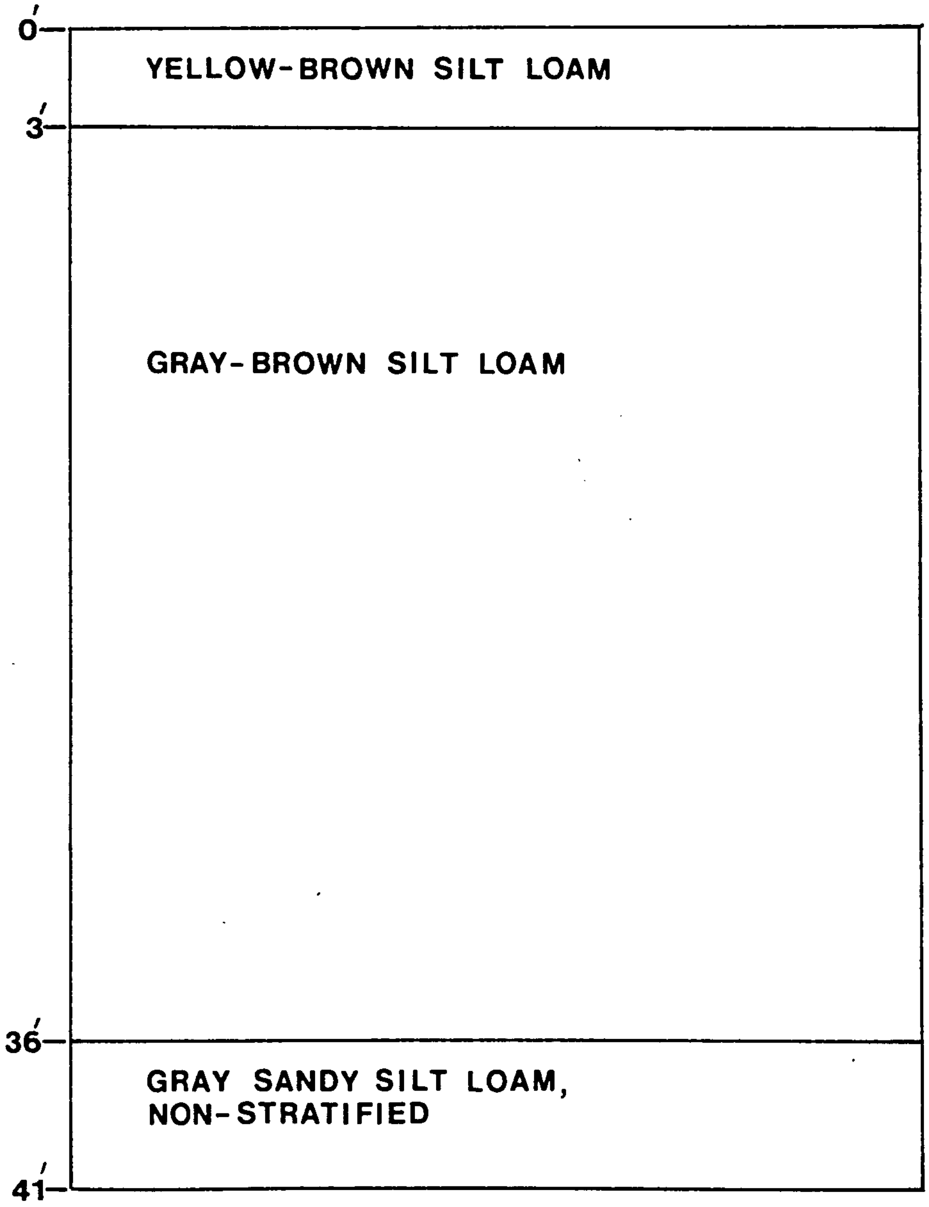


Figure 45. Stratigraphy of alluvium observed on Keg Creek, Secs. 4 and 9, R42W, T74N, Pottawattamie County

APPENDIX II

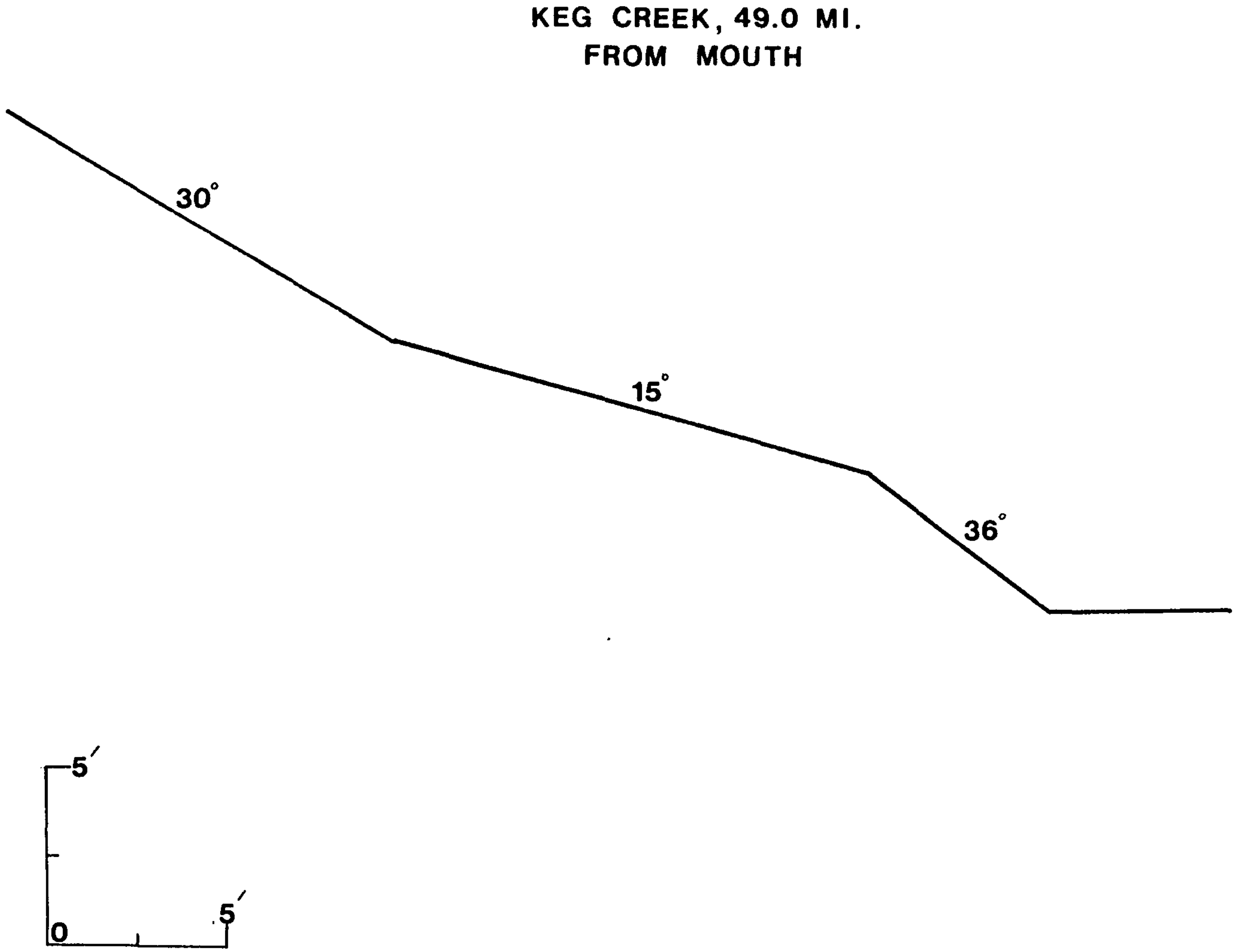


Figure 46. Streambank geometry observed at mile 49.0, Keg Creek

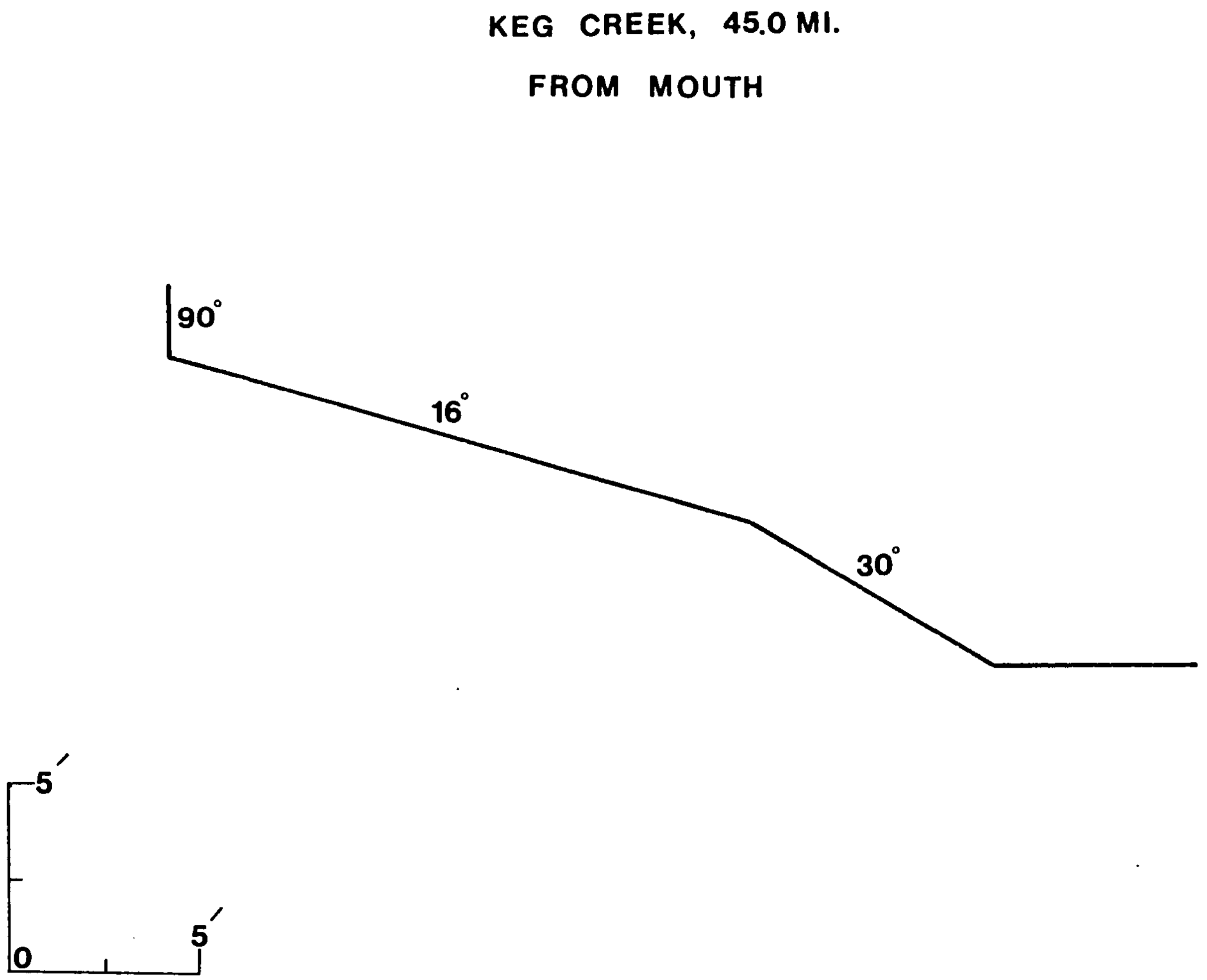
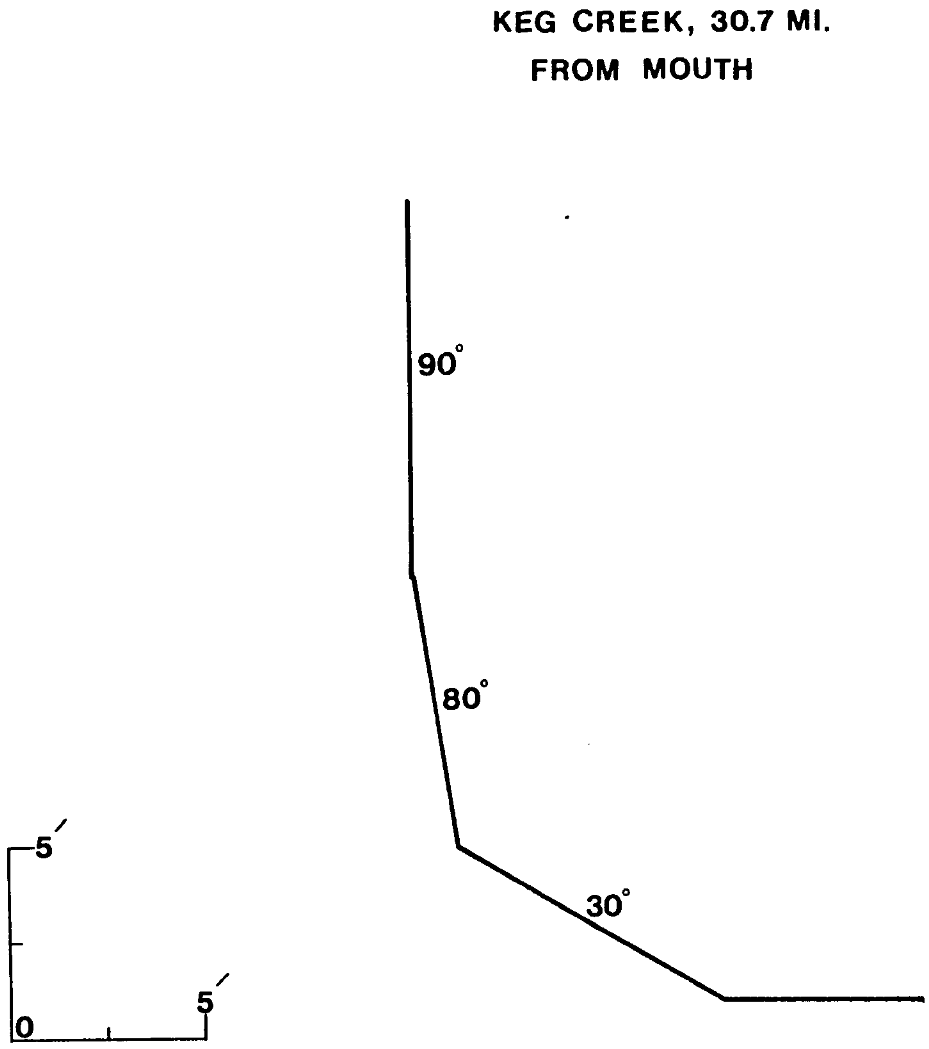


Figure 47. Streambank geometry observed at mile 45.0, Keg Creek



KEG CREEK, 30.7 MI.
FROM MOUTH

Figure 48. Streambank geometry observed at mile 30.7, Keg Creek

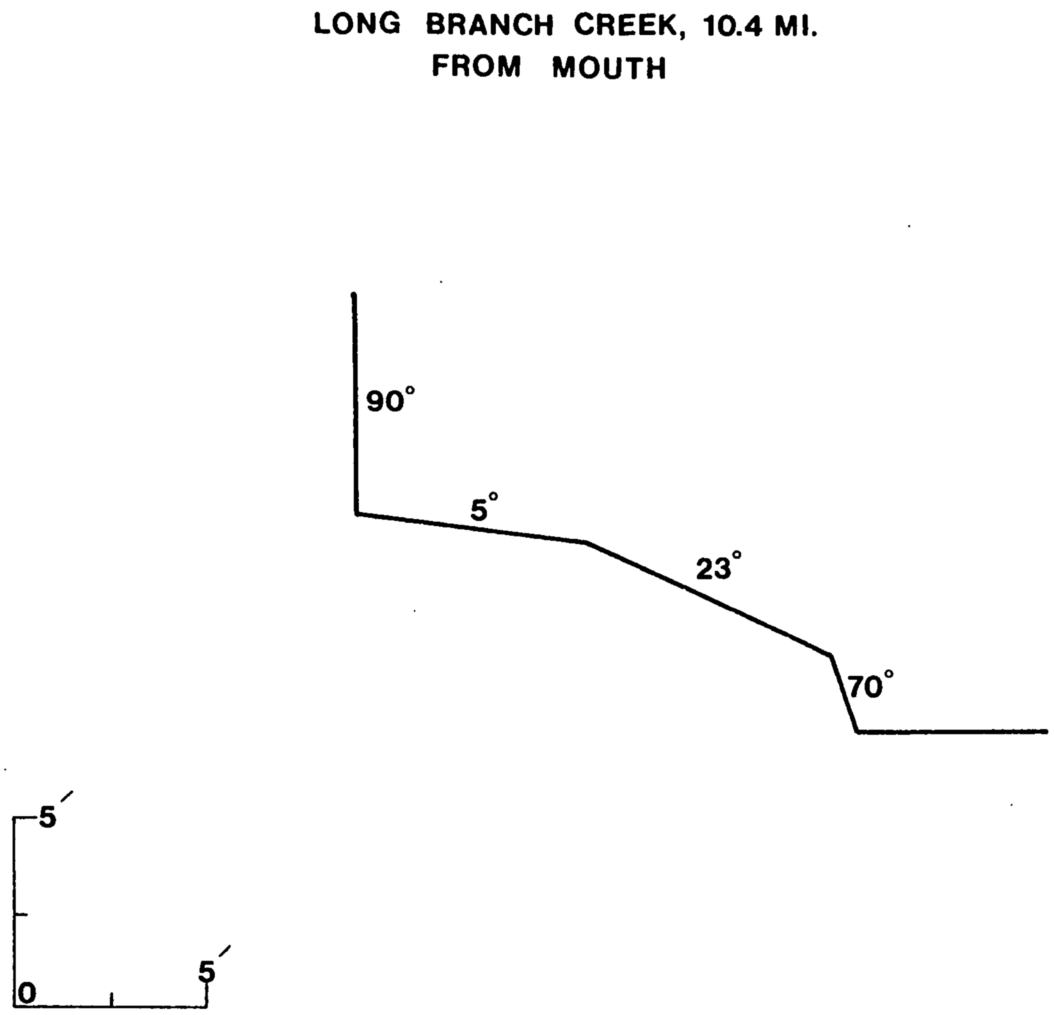


Figure 49. Streambank geometry observed at mile 10.4, Long Branch Creek .

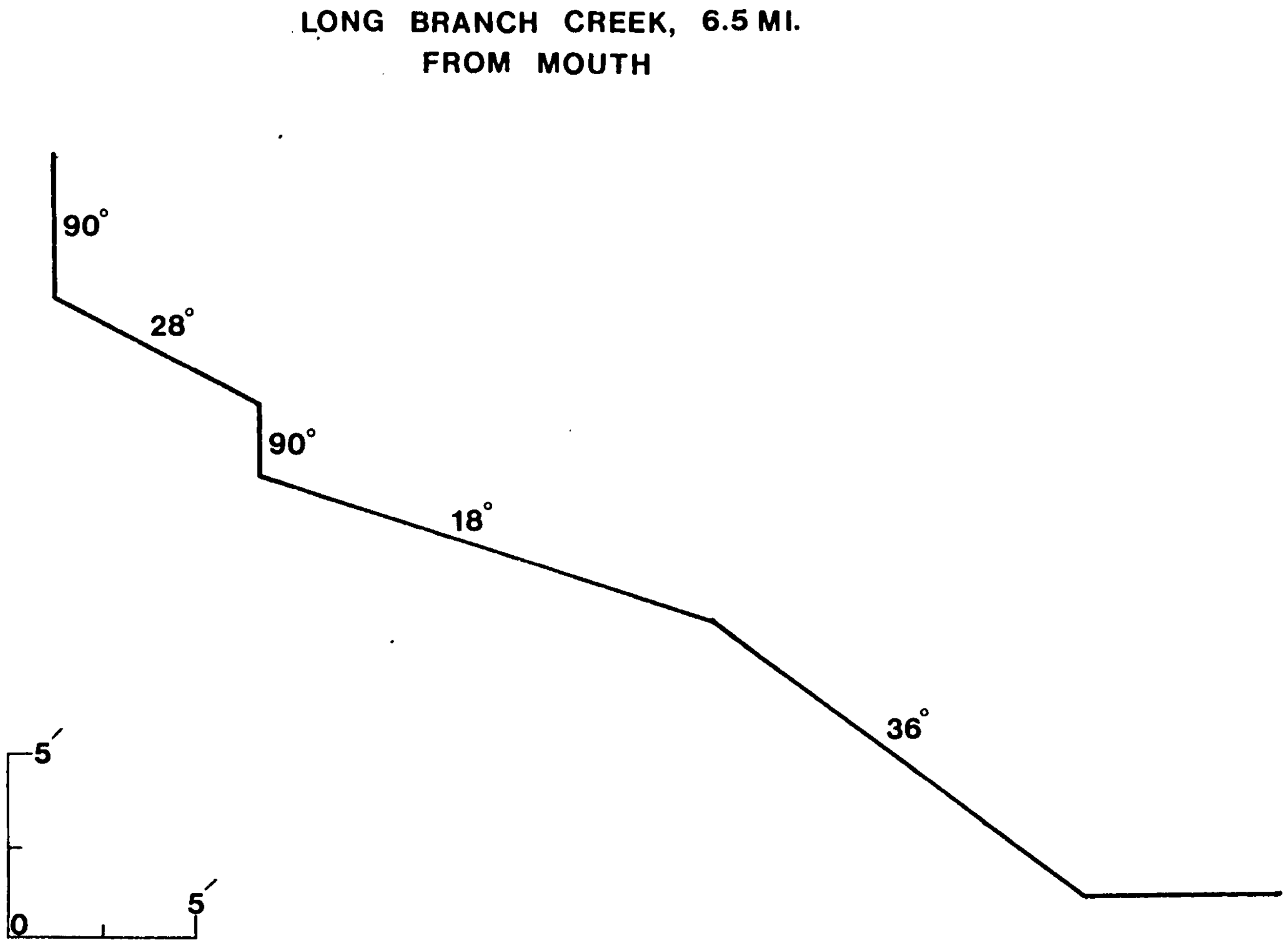


Figure 50. Streambank geometry observed at mile 6.5, Long Branch Creek

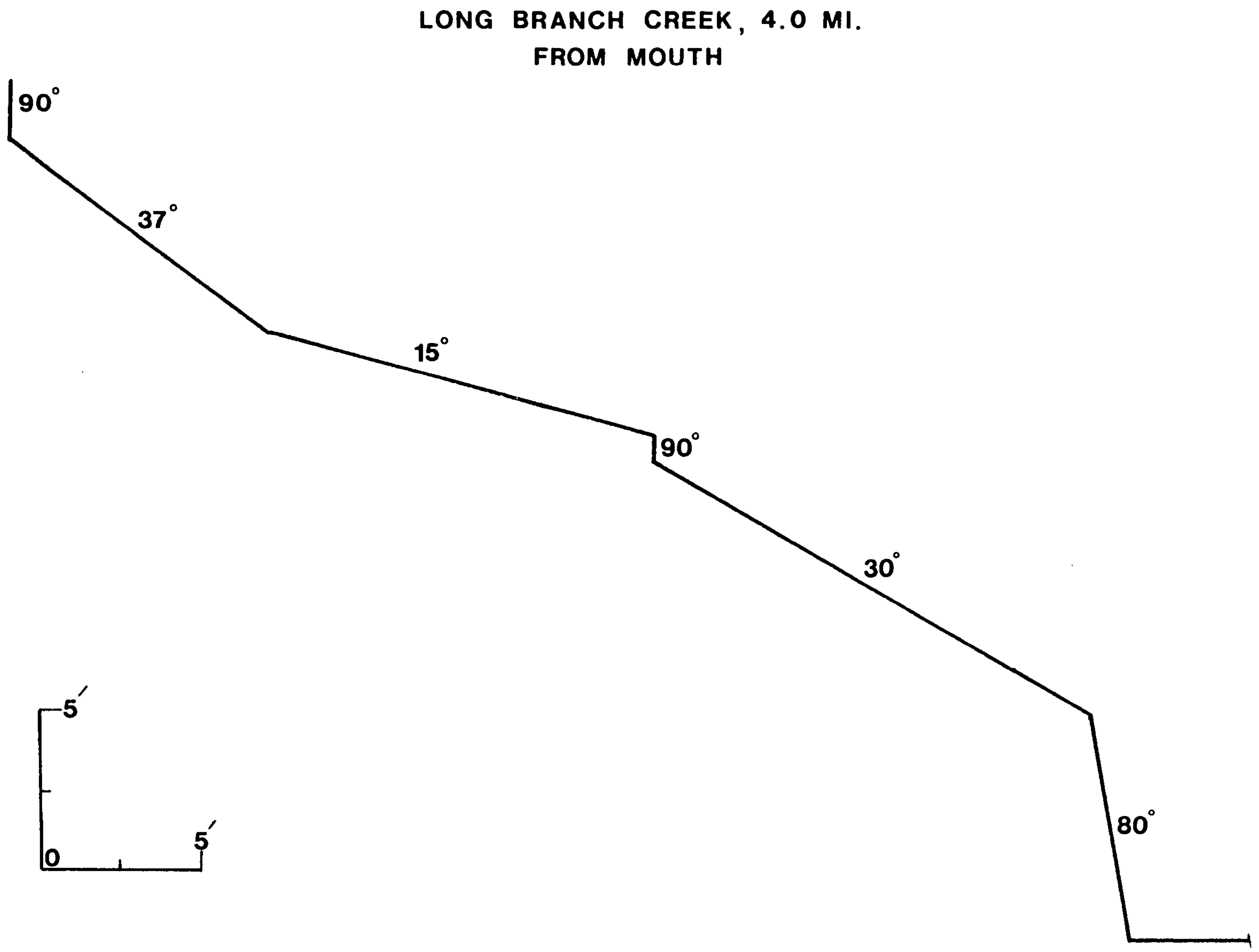


Figure 51. Streambank geometry observed at mile 4.0, Long Branch Creek

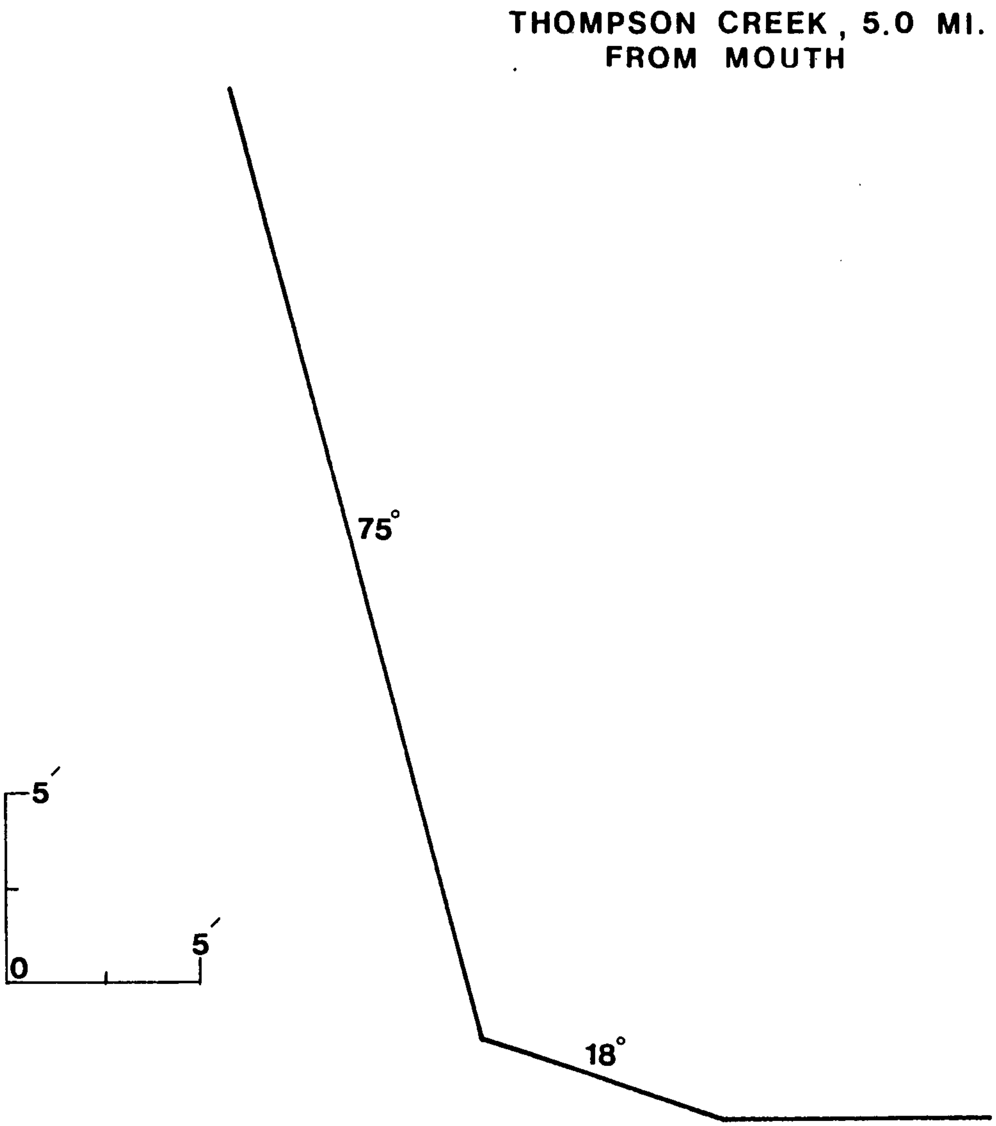


Figure 55. Streambank geometry observed at mile 5.0, Thompson Creek

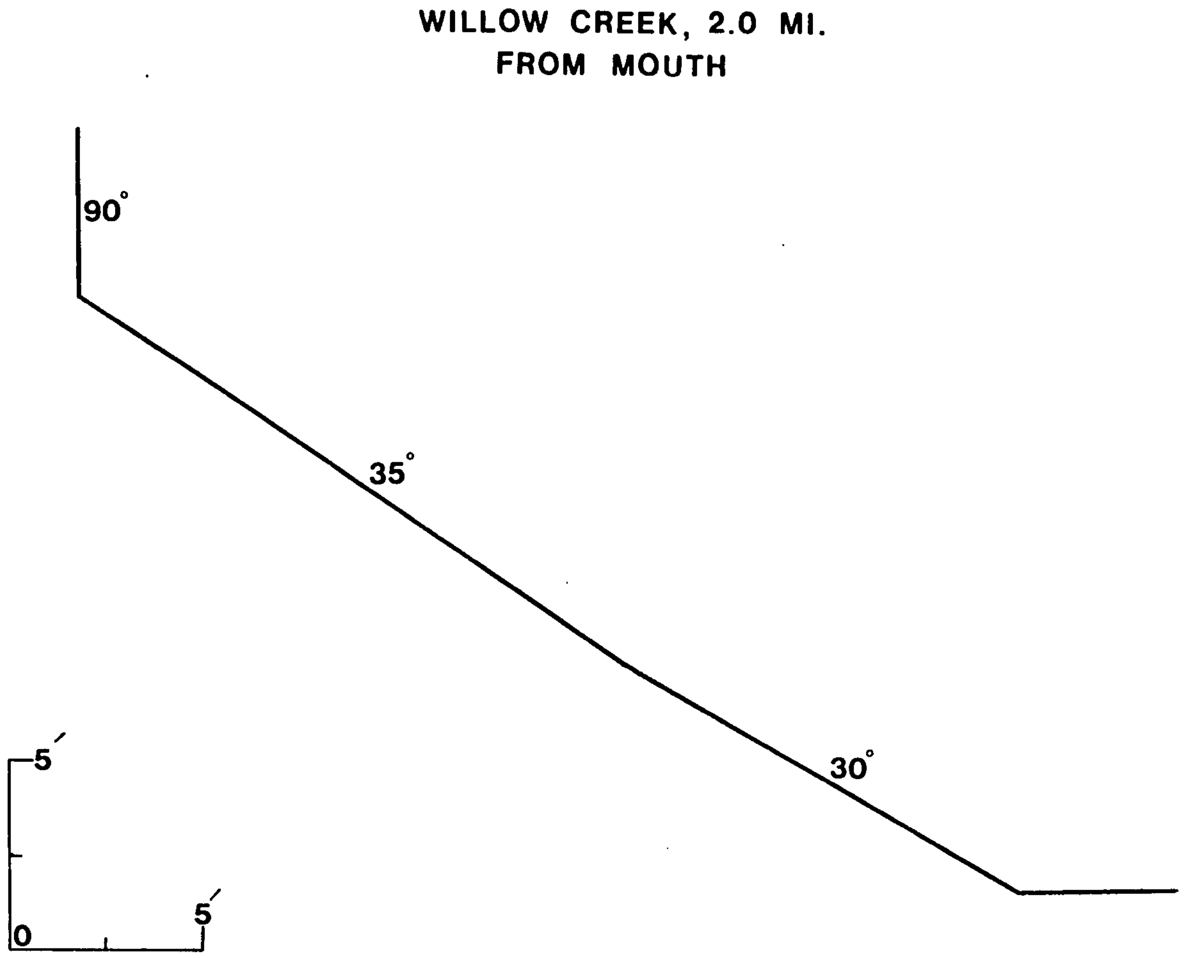


Figure 53. Streambank geometry observed at mile 2.0, Willow Creek

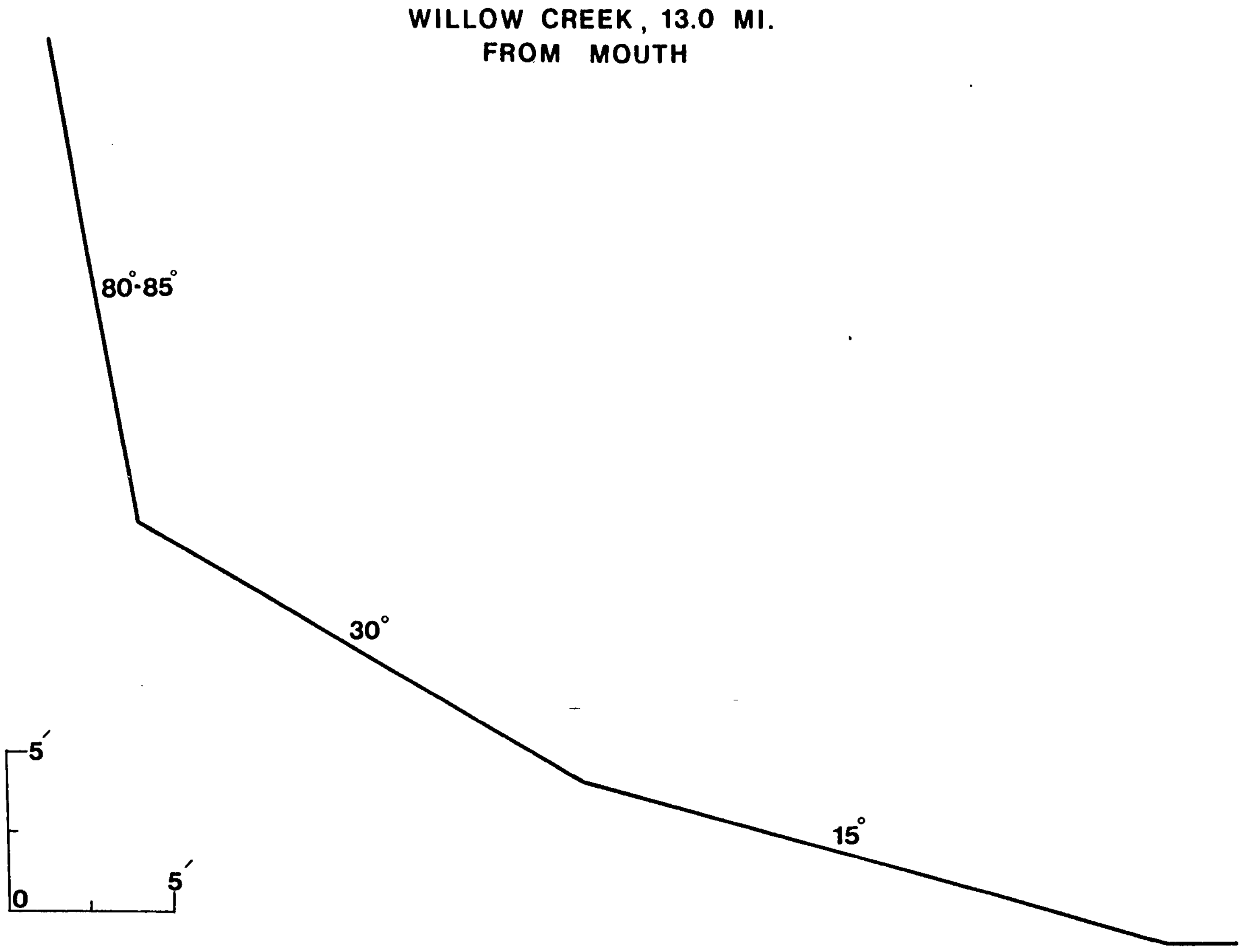


Figure 54. Streambank geometry observed at mile 13.0, Willow Creek

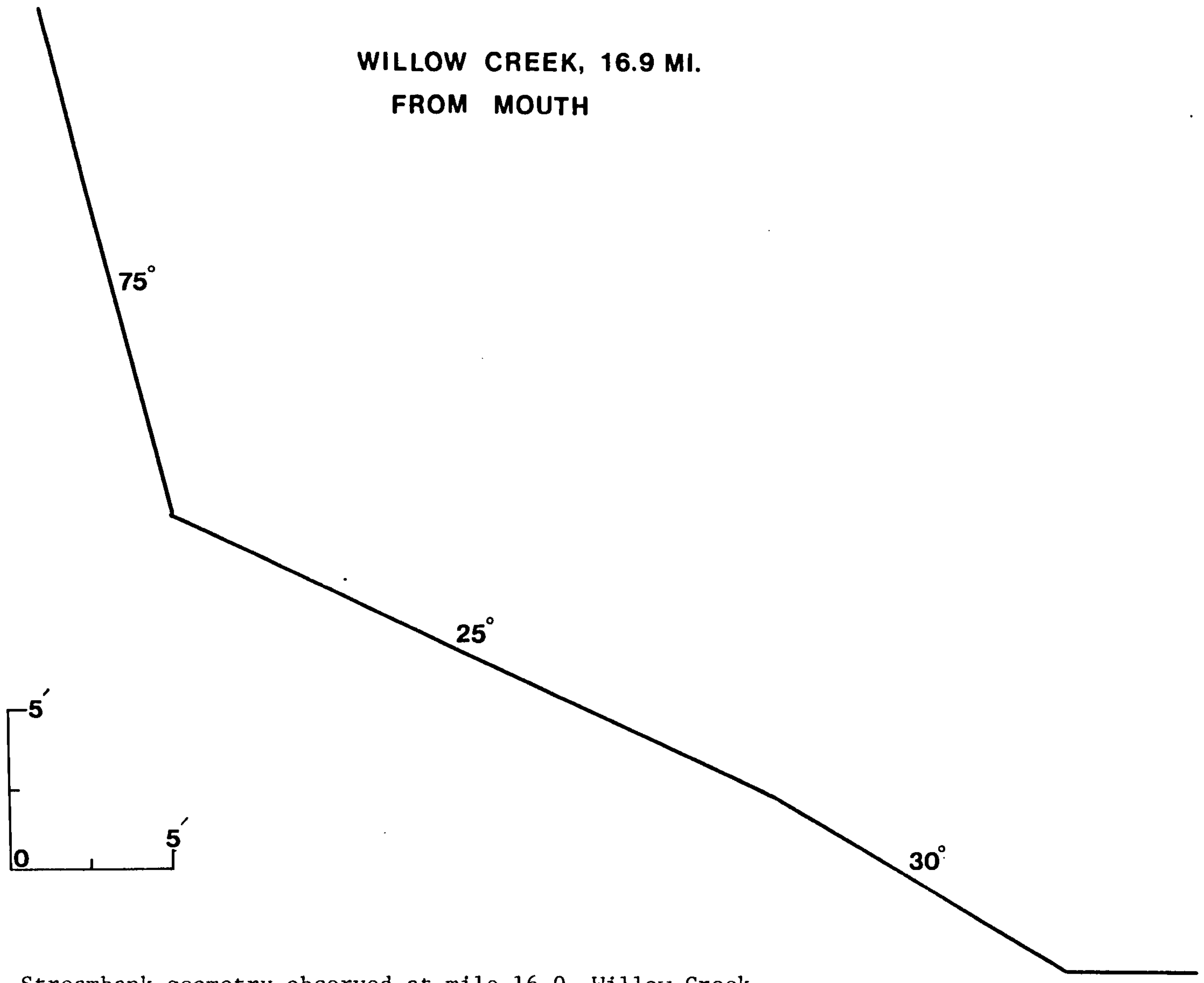


Figure 55. Streambank geometry observed at mile 16.0, Willow Creek

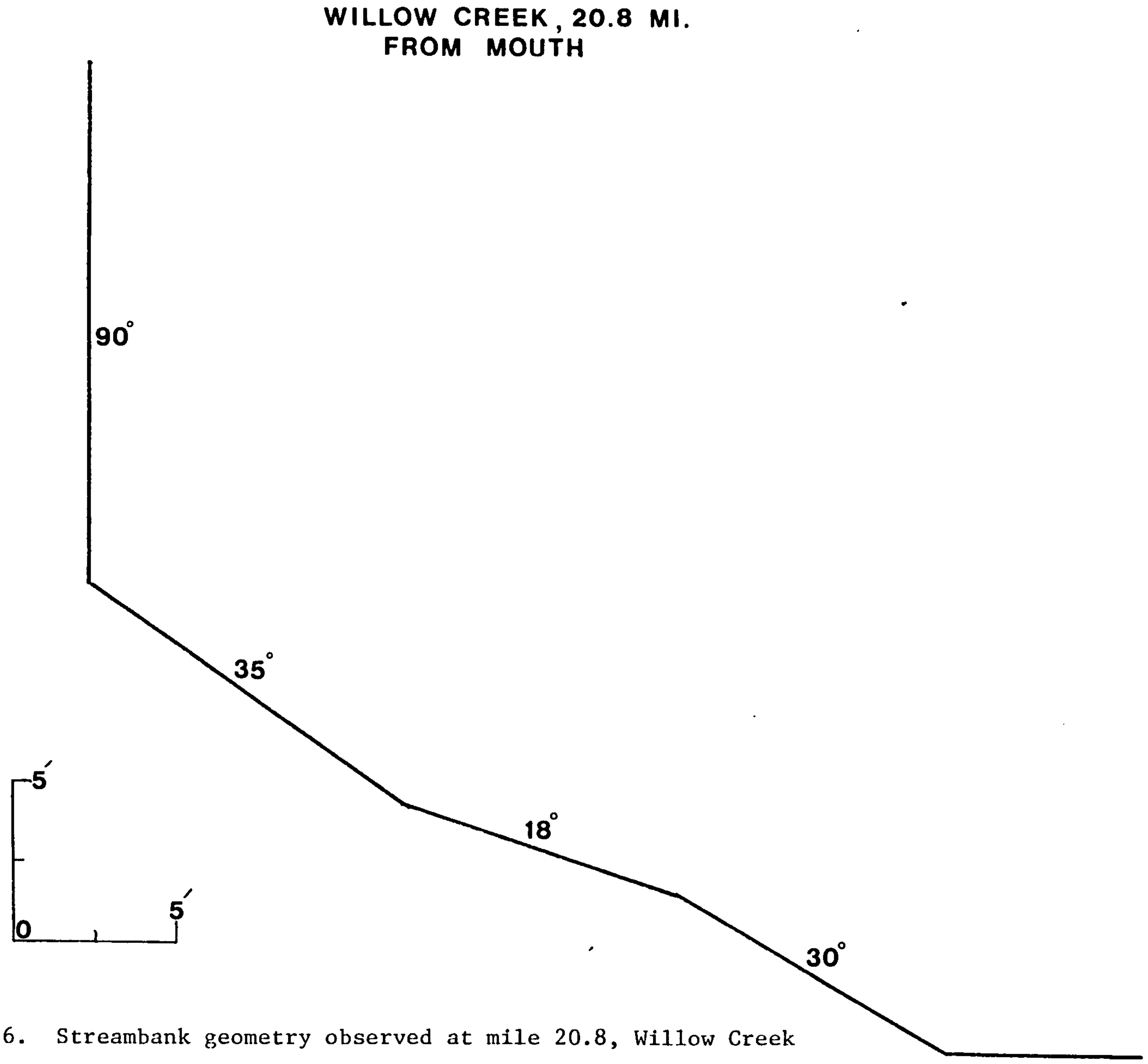


Figure 56. Streambank geometry observed at mile 20.8, Willow Creek

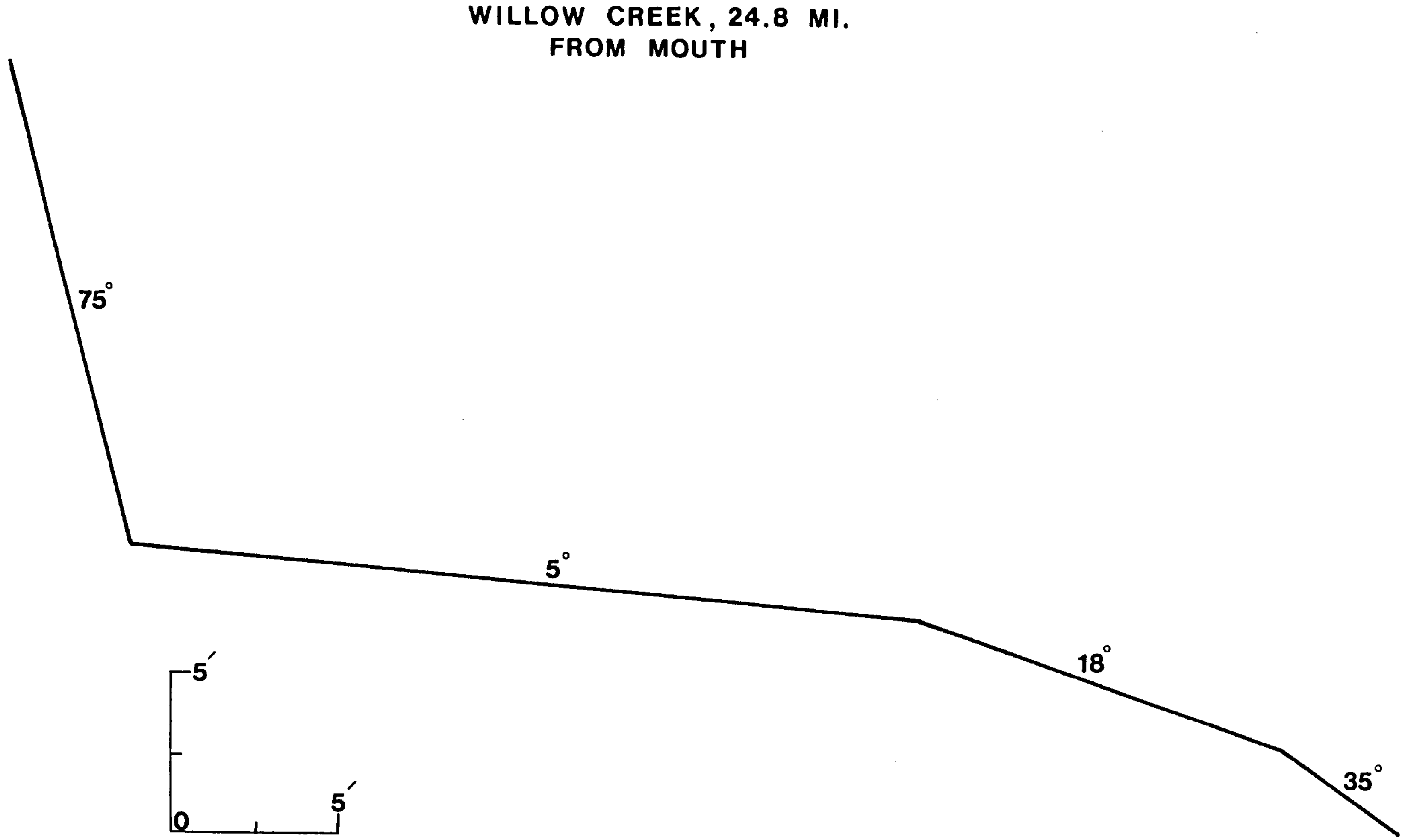


Figure 57. Streambank geometry observed at mile 24.8, Willow Creek