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Studies of tractive force models on degrading streams.

by

Bradley Alan Levich

A Thesis Submitted to the

Graduate Faculty in Partial Fullfillment of the

Requirements for the Degree of

MASTER OF SCIENCE

Department: Civil and Construction Engineering
Major: Civil Engineering
(Geotechnical Engineering)

Signatures have been redacted for privacy

Iowa State University
Ames, Iowa

1994

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INTRODUCTION

Stream degradation in western Iowa has caused problems since the early part of this century. As streams erode deeper, the channel banks become unstable and landslides occur. Western Iowa is especially vulnerable to degradation because of the easily erodible loess soil in this area. The deepening and widening of channels have placed pipelines, bridges and other utility crossings at risk. As the streams degrade, piling beneath bridges is exposed and the integrity of the substructure is diminished. Channel bank instability often requires approach spans to be added to bridges. One bridge has required 10 new spans because the stream has widened (Lohnes et al., 1980). This stream erosion has caused public agencies and industries to spend millions of dollars in remediation. Another effect of widening is loss of agricultural land.

A well accepted solution to stream degradation is construction of grade stabilization structures in the channel to act as barriers to further erosion. A grade stabilization structure is an artificial overfall that dissipates the energy of the water downstream and causes aggradation upstream.

The cost of reinforced concrete structures in the last decade has been on the order of $300,000 (Hanson et al., 1985). Research has shown that simpler, less costly

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structures constructed of steel sheet piling, H-pile, or of gabions can provide adequate protection from the channel degradation; however, no consistent strategy exists for deciding which type of structure will be most effective and economical for a stream of given size, grade, and discharge (Hanson et al., 1985). A simple method of predicting how deep and how wide these streams will become is needed to plan and design channel stabilization facilities. Lack of channel cross sections and site specific soil characteristics on these streams make this task difficult; therefore, the method must employ all the tools available to an engineer including field observations of channel condition, longitudinal profiles, and location of knickpoints. These tools provide a method of estimating how deep and wide the stream will become. Prior studies have provided methods of prediction of degradation. However, some of these methods were developed for specific streams not the general area and other methods were developed and tested in streams in different geological setting. For example Massoudi (1981) developed a Tractive Force method for Willow Creek in western Iowa, while Hack (1957) developed his model on streams in Virginia and Maryland.

The objective of this study is to use historical and geological data to define a practical procedure for predicting stable longitudinal profiles and identifying reaches of the

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streams that are in need of protection. Quantitative and qualitative data will be used in achieving this goal.

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STUDY AREA

The degradation problem in western Iowa appears to have started on tributaries to the Missouri River. This study includes six streams, two streams that are direct tributaries to the Missouri River and four other streams located further up in the basin (Figure 1). The stream characteristics are shown in Table 1. These streams have drainage basin areas that range from 742 square miles to 19 square miles (Larimer, 1957). The six streams have average stream gradients from 21.6 to 4.33 feet per mile and average sinuosity ratios from 1.02 to 1.18. The longest stream is the Maple River 89.9 miles while the shortest stream is McElhaney Creek 9.25 miles. The study area is located within a 22 county area shown in Figure 2.

The surfacial soils of the study area are thick deposits of loess which is wind-blown silt thought to have originated from the Missouri River floodplain. The thickness of the loess cover is shown in Figure 3 as reported in Dahl et al. (1958) and ranges from 10 feet to over 100 feet in the area. This loess is of Wisconsin age and was deposited from 29,000 to 14,000 years ago (Ruhe, 1969). The loess and underlying Pre-Illinonian tills are separated by the Sangamon paleosol. Figure 4 shows the western Iowa stratigraphic column as reported by Bettis (1990).

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Table 1. General stream characteristics.

Stream	Drainage Basin Area (mi^2)	Length of main stream (mi)	Maximum Relief (ft)	Average Stream Gradient (ft/mi)	Average Sinuosity
Indian Creek	68	30.3	245	8.08	1.12
Keg Creek	190	63.6	384	6.05	1.10
Maple River	742	89.9	390	4.33	1.18
McElhaney Creek	19	9.25	200	21.63	1.02
Walnut Creek	223	64.3	379	5.89	1.05
Willow Creek	146	43.9	384	8.73	1.02

The alluvium in the larger streams is derived from loess. The streams in western Iowa flow through the DeForest Formation alluvium. The DeForest Formation consists of four members Camp Creek, Roberts Creek, Corrington, and Gunder (Bettis, 1990). These members are mainly field classified by color. Camp Creek is very dark gray to brown that sometimes appears to have a reddish tint. While Roberts Creek is very dark gray to dark grayish brown that appears almost black in the field. Corrington member is not visible in the streams that have been observed in this study but it is described as very dark brown to yellowish brown. Gunder member is greenish gray to olive brown. The Gunder member usually outcrops in areas of steep slopes or where knickpoints are present. Keg

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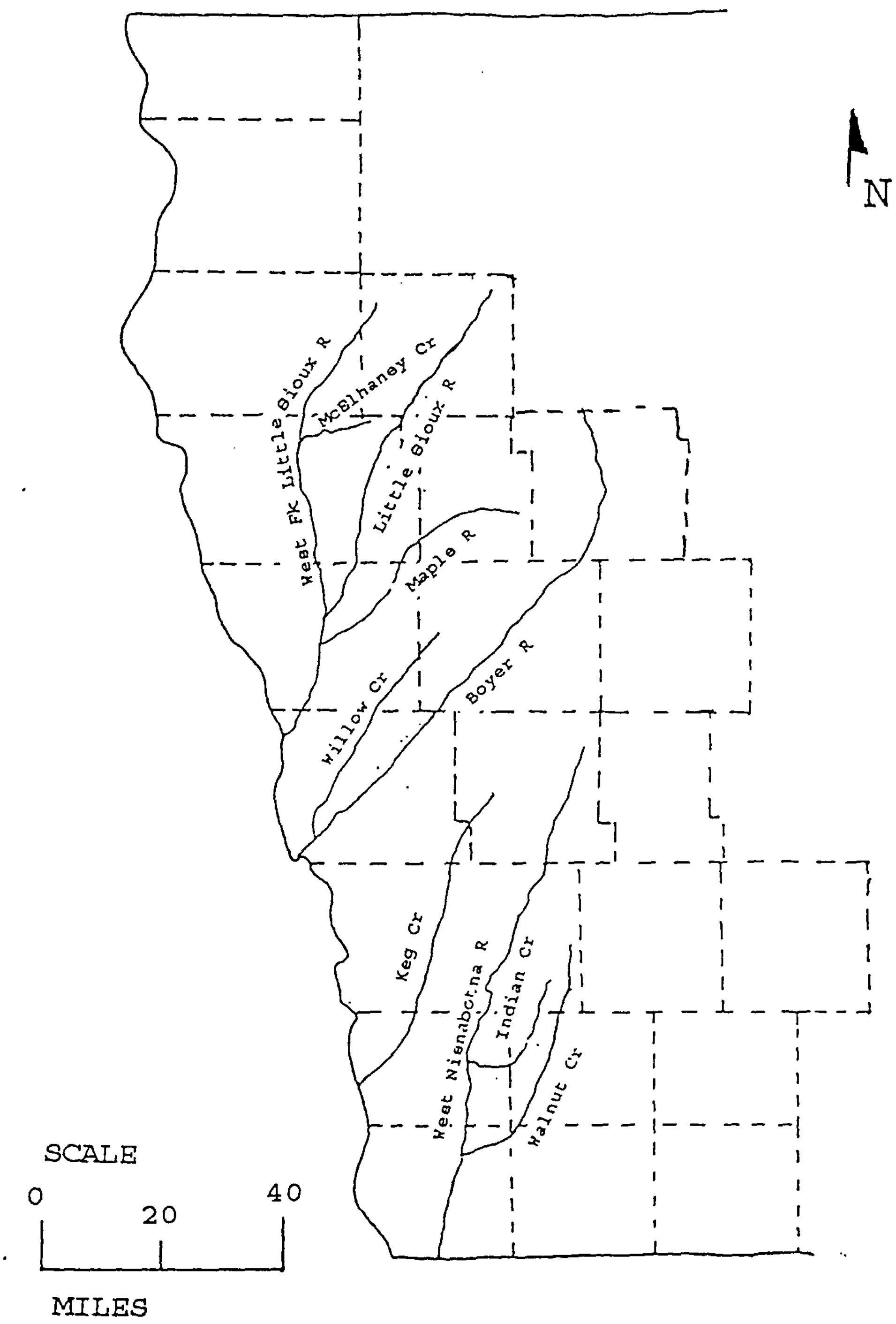

Figure 1. Streams in study area. Modified from Dirks (1981).

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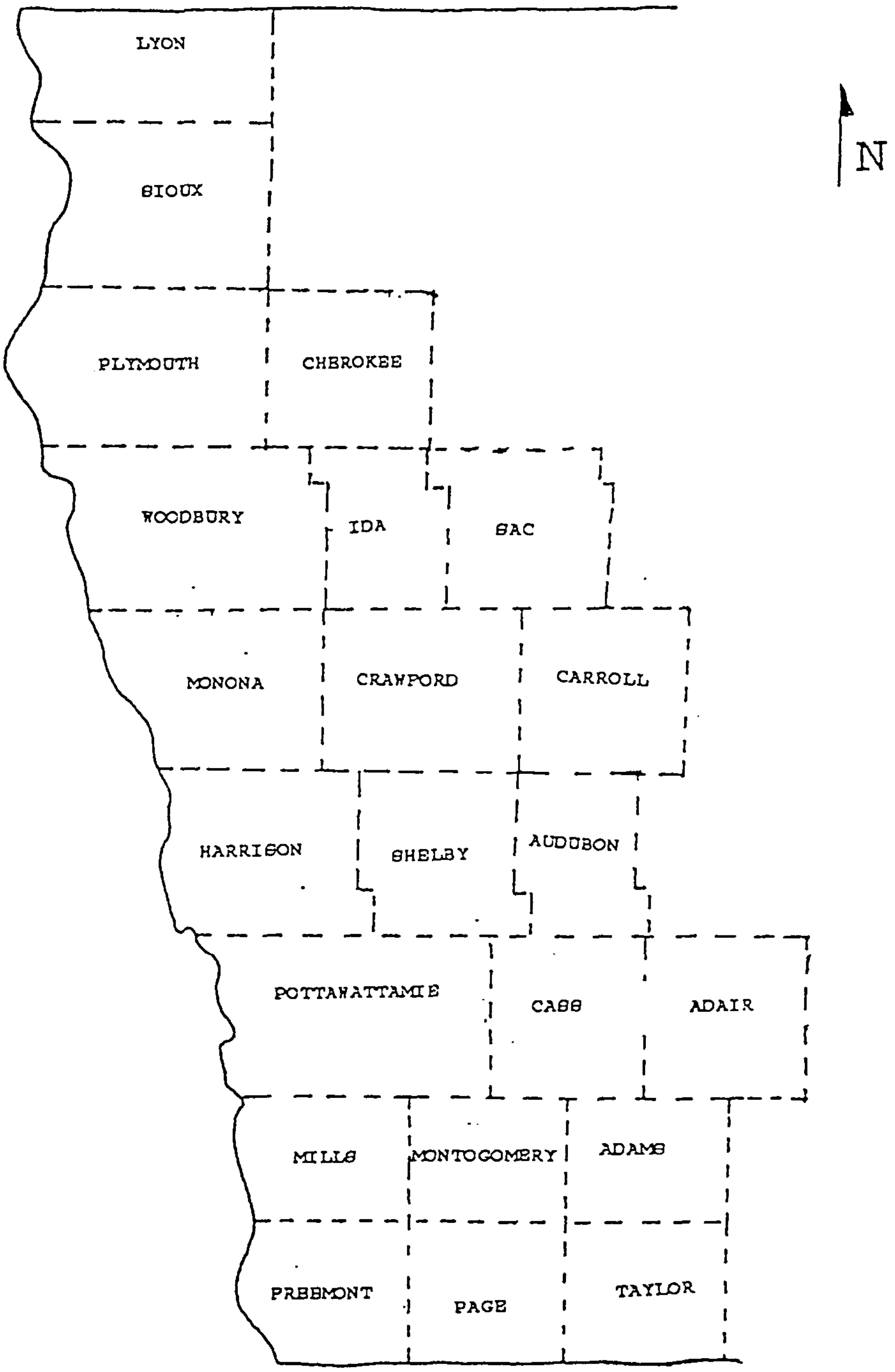

Figure 2. Counties in study area.

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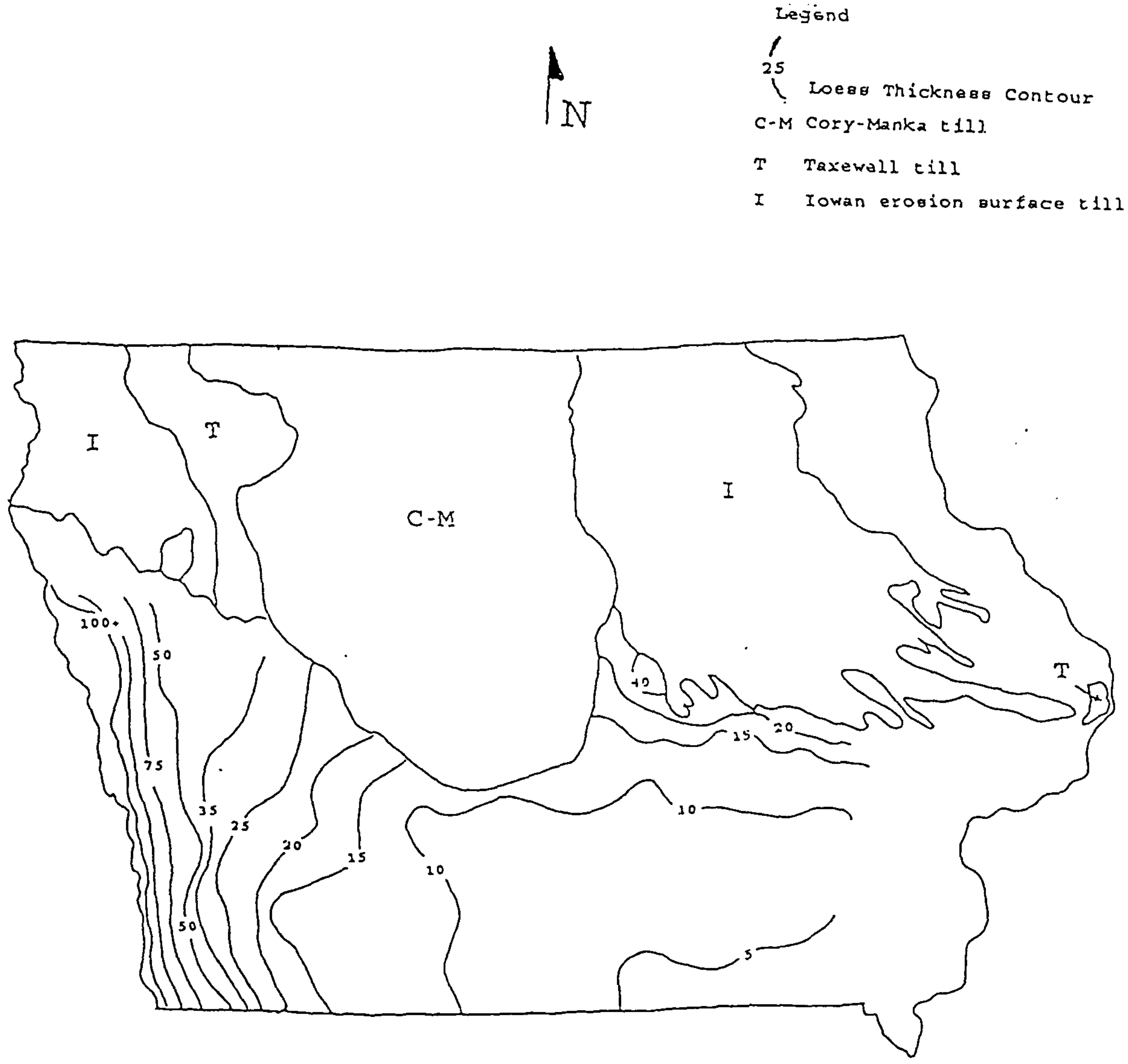

Figure 3. Wisconsin loess thickness in southern Iowa. Modified from Dahl (1958).

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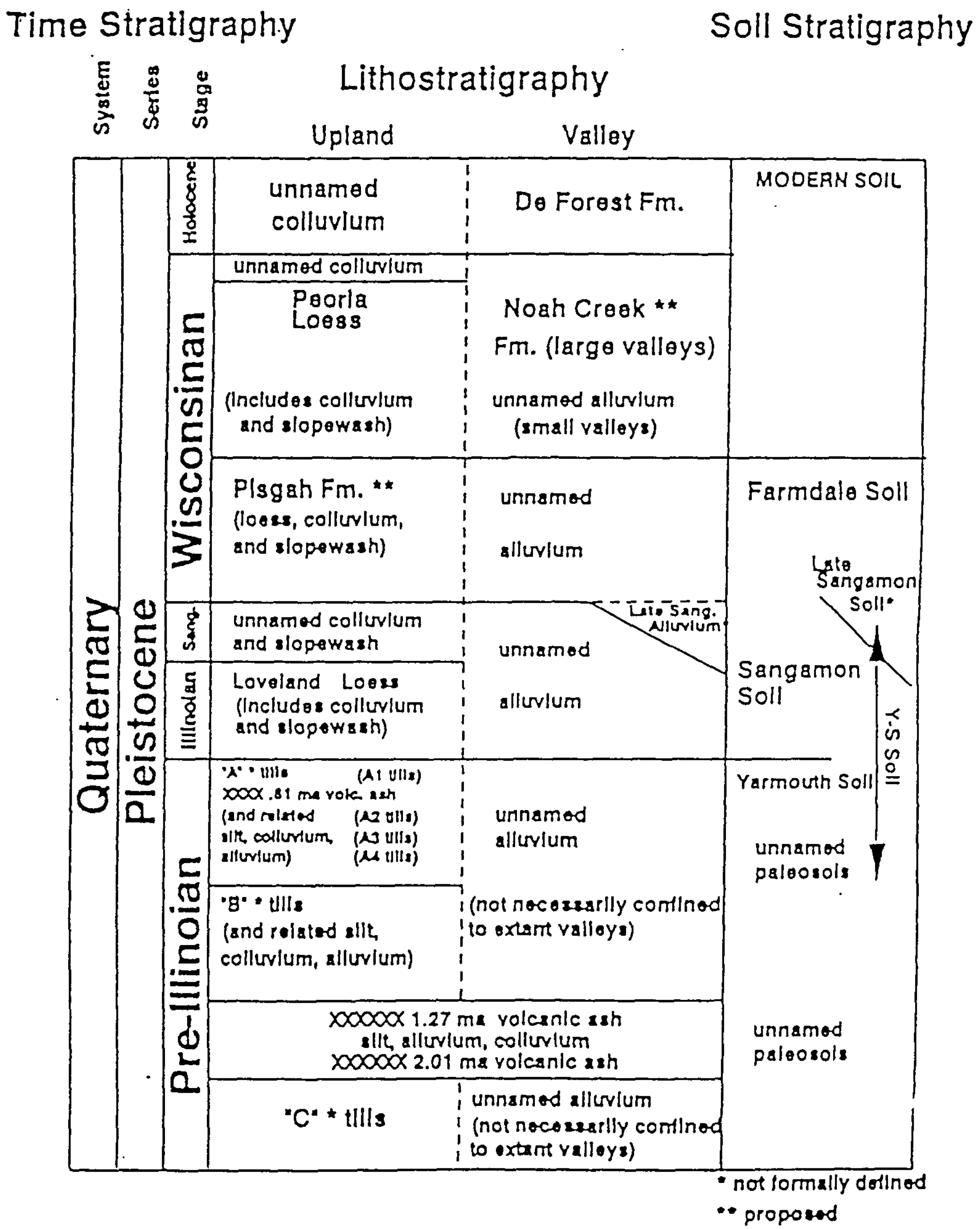

Figure 4. Western Iowa Stratigraphic column for the Pleistocene Series. From Bettis (1990).

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Creek and Walnut Creek both expose the Gunder member near knickpoints. Table 2 states the lithologic characteristics of the DeForest Formation members in western Iowa (Bettis, 1990).

Stream channel degradation is present in many other parts The country. Scientists and geologists in Tennessee, Mississippi, and Louisiana have studied stream degradation, and other states in which problems are reported include Kansas, Missouri, and Nebraska. A common factor in all these areas of degradation is the presence of loess deposits.

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Table 2. Lithologic properties of the DeForest Formation. From Bettis (1990).

MEMBER	BED	LITHOLOGIC PROPERTIES
Camp Creek		stratified silt loam to clay loam (texture varies according to local source material); calcareous to noncalcareous; very dark gray to brown (10YR 3/1-5/3); no surface soil to very poorly expressed surface soil developed in upper part of unit.
Roberts Creek	Turton	stratified silty clay loam to loam; calcareous to noncalcareous in upper part; very dark gray to dark grayish brown (10YR 3/1-4/2); thin dark colored surface soils developed in upper part.
	Mullenix	stratified silt loam and clay loam with thin lenticular sand and gravel bodies in lower part; noncalcareous grading downward to calcareous, very dark gray to dark grayish brown (10YR 3/1-4/2); coarse columnar structural units evident on weathered sections; thick dark-colored surface soils in upper part.
Corrington		stratified to massive; calcareous to noncalcareous; loam to clay loam with lenses of sand and gravel; very dark brown to yellowish brown (10YR 2/2-5/4); several buried soils; thick well horizonated surface soils with brown B horizons developed in upper part; found in alluvial fans in large valleys.
Gunder	Hatcher	massive (to planar bedded in its lower part), calcareous to noncalcareous silt loam; brown to yellowish brown (10YR 4/3-5/4); prominent coarse columnar structural units evident on weathered sections; thick, moderately well horizonated surface soils with brown B horizons developed in upper part.
	Watkins	stratified, calcareous silt loam with sandy and loamy interbeds; dark greenish gray (5GY 4/1) to olive brown (2.5 Y4/4); often exhibits 7.5YR hue secondary accumulation of iron oxides; deeply buried.

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PROCESS OF DEGRADATION

Degradation moves upstream in the form of an overfall or knickpoint that indicates where active degradation of the stream bed is occurring. Knickpoints are defined as a "short, oversteepened segment of the longitudinal profile" (Ritter, 1986). A typical knickpoint is shown in Figure 5. As a knickpoint moves upstream the stream cuts vertically into the channel leaving a new, lower stream bed below. Knickpoints can vary in height from a little ripple to a 20 foot overfall (Dirks, 1981).

Three different kinds of knickpoints were recognized by Holland and Pickup (1976): rotating knickpoints, stepped knickpoints, and minor erosional knickpoints. Rotating knickpoints die out as their faces rotate backward and lengthen. Stepped knickpoints maintain a vertical face as they retreat upstream. Minor erosional knickpoints are the little riffles on the stream bottom. The most commonly observed knickpoint in western Iowa is the stepped knickpoint (Dirks, 1981).

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Figure 5. An example of a knickpoint eroding upstream in Jims Branch at Highway 59.

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CAUSES OF DEGRADATION

Stream straightening

Several hypotheses have been suggested to explain the cause of stream degradation. One is that stream straightening from 1870 to 1960 caused an increase in the stream gradient thereby increasing the stream flow velocity (Massoudi, 1981). This velocity increase caused the stream to adjust to a new equilibrium profile. A massive amount of down cutting and widening occurred to restore the stream to an equilibrium gradient. This adjustment was shown in several studies on Willow Creek in Harrison County. Daniels (1960) showed that straightening of the Willow Creek channel was associated with a shortening of this portion from 26.3 to about 20 miles. Also the average slope of the channel increased from 5.16 ft/mile to 7.66 ft/mile and from 7.50 ft/mile to 8.48 ft/mile. Daniels stated that the new ditches with smooth straight sides and increased velocity were responsible for the degradation of the Willow Creek (1960). Massoudi (1981) also stated that the straightening of Willow Creek caused steeper slopes which in turn caused an increase in velocity, boundary shear, and tractive force which led to a higher rate of erosion of the bed and banks. Another erosive effect that Massoudi (1981) suggested was that smoother perimeters of newly dredged

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channels had less friction than the older meandering channels. The lower friction caused an increase in velocity.

Landuse

Another possible cause for degradation is the change from prairie to row crops that resulted in greater runoff into stream channels. Piest et al. (1976 and 1977) estimated that surface runoff increased 2 to 3 times by rowcropping and the peak discharge was increased as much as 50 times. Another study by Leopold et al. (1964) estimated an increase as high as 80 times the original peak for prairie regions converted into row crops.

Change in base level of Missouri

A third possibility is that the streams are degrading from the natural degradation of the Missouri which has lowered the base level of its tributaries. Dahl (1961) stated that the Missouri River underwent a change from a meandering stream to a braided or semi-braided stream between 1804 and the late 1800s. During this time period the Missouri experienced 10-12 feet of down cutting (Lohnes et al., 1977). Hallberg (1979) suggested that the transformation to a semi-braided stream was caused by frequent recurrence of high-flood flows which were

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related to climatic conditions in the 1880s and 1890s. The river adjusted to this transformation by decreasing in length and increasing in channel area inverse proportionally (Hallberg et al., 1979).

The lowering of the river base could have caused the degradation of the tributaries; however, Lohnes et al. (1977) indicate that the Missouri River from Sioux City, Iowa to Omaha, Nebraska had vertical stability between 1879 and 1952. Between the mid 1930s and 1976 the Missouri River channel was constructed from a broad semi-braided stream to a narrow single smooth channel with a series of gentle bends and well stabilized banks. By the early 1950's the dams upstream of Gavins Point were closed and the flows in the Missouri regulated. The channel was shortened by 18 miles and the channel area was reduced by 62,000 acres in Iowa. The riverwas not allowed to adjust naturally, as it had when it changed from a natural meandering stream to a semi-braided stream. This channelization, regulation, and possibly the clear water discharge from the dams lead to a second degradation stage. This second cycle lead to approximately 8 feet of degradation at Sioux City to almost zero at Omaha (Sayre and Kennedy, 1978). Most of the degrading streams enter the Missouri River near Omaha. This evidence suggests that the present degradation problem is not caused by the lowering of the Missouri River base.

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Natural Phenomenon

Another hypothesis is that the streams may be experiencing a natural cycle. These streams may cycle through degradation and aggradation stages throughout the history of the stream. The natural cycle may have been altered by the hydrologic or climatic changes which caused the channels to adjust. Hallberg et al. (1979) showed that a period of high flows caused the Missouri River to change from a meandering to a semi-braided stream. In the process of adjusting the slope and cross sectional area of the channel, the Missouri River degraded.

The natural cycle of the streams will depend on the surfacial geology and the flow characteristics of the streams. The stream may downcut until it reaches an erosion resistant material then begin to meander.

Meandering streams continually adjust by making cutoffs and oxbow lakes. The straightened western Iowa channels adjust by degrading and widening. Eventually they will reach an equilibrium and may even start to aggrade.

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FIELD INVESTIGATION

In 1993 field surveys of five streams were completed to build a data base of longitudinal profiles. The streams that were chosen for these surveys were: Willow Creek, Keg Creek, Indian Creek, Walnut Creek, and McElhaney Creek (Figure 1). These streams were chosen because they are geographically scattered and varied in size. The drainage area of these streams ranged from 19 square miles to 223 square miles. Each stream had reaches that were straightened; and the degradational activity varied from very active to stable for the streams.

The field survey consisted of measuring stream depths at bridge locations. The bridge deck elevation was determined either from bridge plans or by traversing a level from a United States Geological Survey (USGS) bench mark. To determine the distance from the bridge deck to the stream bed a 12 pound weight was lowered from the bridge using a poly rope marked at every foot. A tape measure and a straight edge were used to measure the height to the nearest inch from the bridge deck to the stream bed. Two measurements were made at each bridge, to locate the lowest elevation point. These measurements were recorded in field books and then transferred to a spreadsheet. Along with the measurements, notes of the stream condition, bridge type, and any anomalies were also

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recorded. After transfer to a spreadsheet, the bridge decks that were tied to USGS elevation were recorded along with the source of the measurement. The longitudinal profile was plotted and compared to other data including previous field surveys and USGS topographical maps at a scale of 1:24,000. A more detailed profile of points of interest was prevented because of high currents caused by the high water of 1993.

A survey of a small reach of Keg Creek was completed in 1994 with the help of the Soil Conservation Service (SCS). This survey was a detailed stream bed survey near the gabion grade control structure. The survey was extended one bridge downstream and two bridges upstream from the gabion structure. A total station was used to complete this survey giving both elevation data and location along the stream.

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ANALYSIS OF EXISTING PROFILES

The 1993 profiles were compared to data that were obtained from past records or profiles made from county bridge data to determine the state of the stream. The study determines the effectiveness of existing structures and if more structures may be required.

Willow Creek

Five longitudinal profiles of Willow Creek are available for analysis (Figure 6 and 6a). The 1958, 1966, 1971, and 1980 profiles were obtained from Massoudi (1981) data. The 1993 data were surveyed as part of this study. Starting from the mouth, the longitudinal profiles for the five different years were examined. From 40 miles from the headwater to 29.9 miles from the headwater the 1993, 1980, 1966, and 1958 longitudinal profiles coincide. No data exists for the 1971 survey in this section of Willow Creek. At mile 29.9 there is a grade stabilization structure that was placed on the stream circa 1970. Therefore, the 1980 and 1993 profiles rise in elevation from 1057.7 to 1072 feet within a short distance at this flume. The 1966 and 1958 data fall along the same longitudinal profile in this reach. This suggests that this section of the stream was stable in 1966 and the structure

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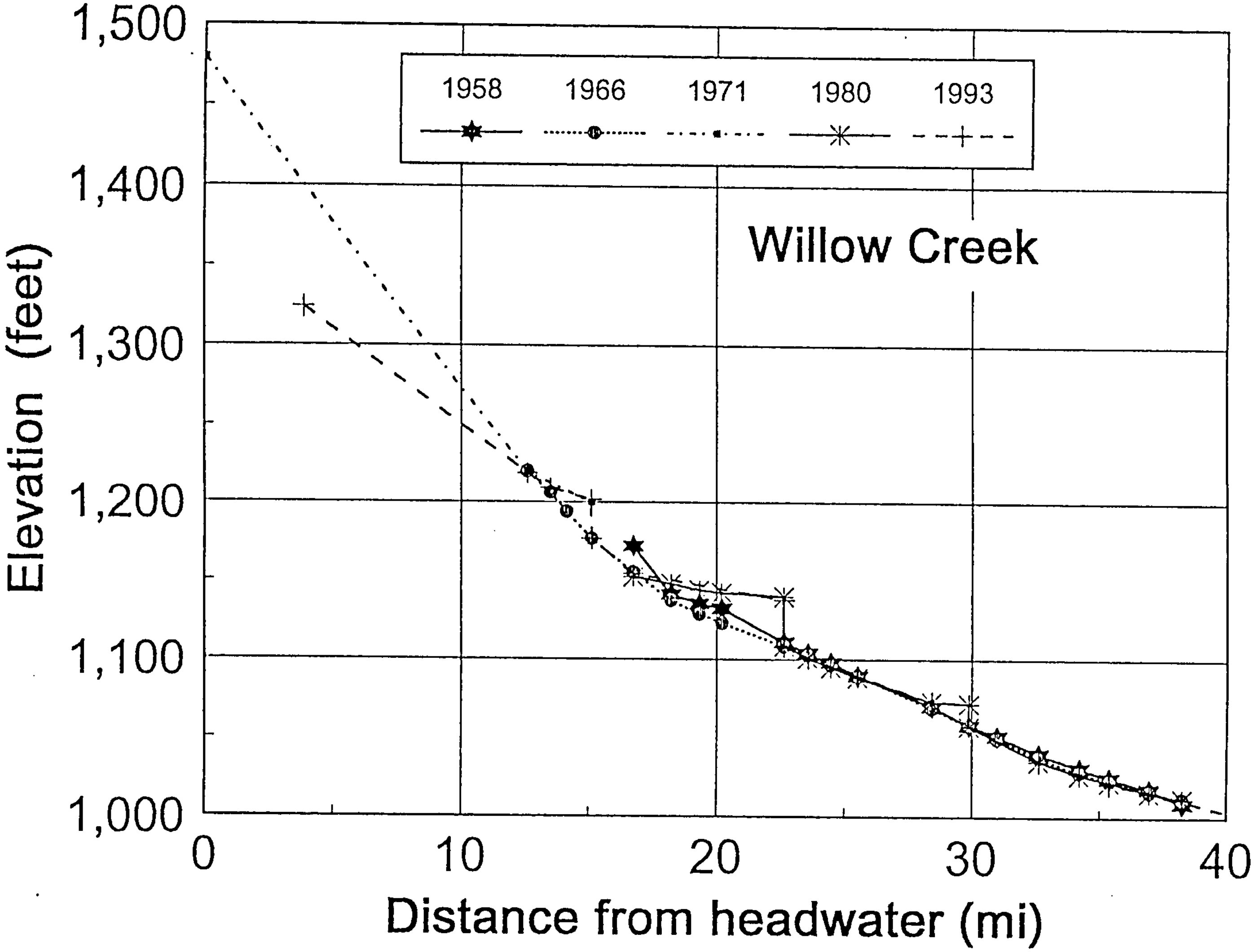

Figure 6. Willow Creek longitudinal profile for 1958, 1966, 1971, 1980 and 1993.

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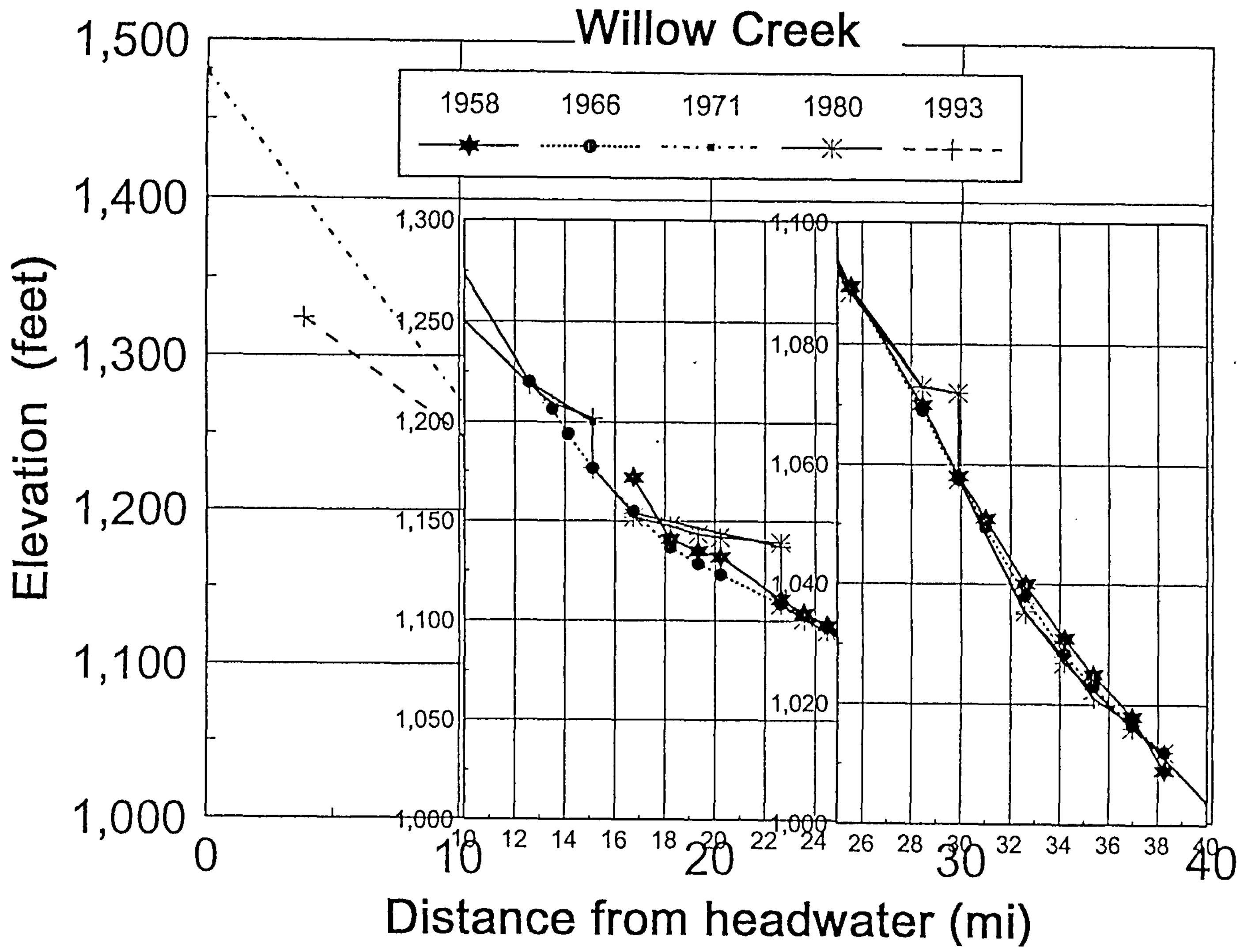

Figure 6a. Willow Creek detailed longitudinal profile for 1958, 1966, 1971, 1980 and 1993.

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that was placed here was unnecessary. The 1993 and 1980 profiles intersect and follow the 1958 and 1966 profiles at mile 28.4. These profiles coincide up to mile 22.6 where the second grade control structure is located. This 40 foot flume was placed on the Willow Creek circa 1970. Here the 1993 and 1980 profiles rise in elevation from 1108.5 to 1139.5 feet. The 1966 and 1958 profiles diverge above mile 22.6. This suggests that the flume was necessary. The 1958 and 1980 data end at mile 16.7. The 1993 profile shows the third and final grade control structure on Willow Creek at mile 15.1. The profile at this flume jumps from 1176.5 to 1201.9 feet. The 1971 data begin at the flume and the 1971 and 1993 data intersect the 1966 profile at mile 12.6. At mile 12.6 the 1966 profile ends and there is insufficient data above this point to analyze.

From these profiles, a few general statements can be made. First, the furthest downstream structure was not necessary because the stream was stable in 1966. Second, the grade stabilization structure at mile 22.6 was probably not placed in the most economical location since the knickpoint had probably past this point because the 1966 and 1958 profiles do not separate until they pass the structure. Finally the 1971, 1980 and 1993 profiles show that Willow Creek has been stabilized with the grade control structure. However, the tributaries and Willow Creek most upstream

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reaches may still be degrading.

Keg Creek

Five different longitudinal profiles were available on Keg Creek: 1993, 1980, 1976, 1972, and 1954 (Figure 7 and 7a). The 1980, 1976, 1972, and 1954 data were obtained from Dirks (1981). The 1993 data were surveyed as part of this research. All stream length measurements were made from the headwater of the stream. The 1993 and 1980 profiles show that from mile 64 to 51 the stream has not degraded. However, the 1972 profile shows that the stream had eroded approximately three feet from 1972 to 1980. The 1993, 1980, and 1972 profiles show up to three feet of aggradation from mile 51 to 40. From mile 40 to 36 aggradation occurred between 1972 and 1980. However, this reach was stable between 1980 and 1993. The 1954 data were plotted only from mile 41 to mile 32. Keg Creek had degraded 3 to 10 feet from 1954 to 1972. At mile 36 the stream has down cut only 1.5 feet since 1980 and 3.5 feet between 1972 and 1980. However, at mile 35 Keg Creek entrenched four feet from 1980 to 1993 while it degraded only one foot from 1972 to 1980. This degradation increase is probably due to the placement of a grade control structure at mile 34.61 in 1980. The entrenchment was caused by dissipation of the stream energy just down stream of the structure. From mile 36 to

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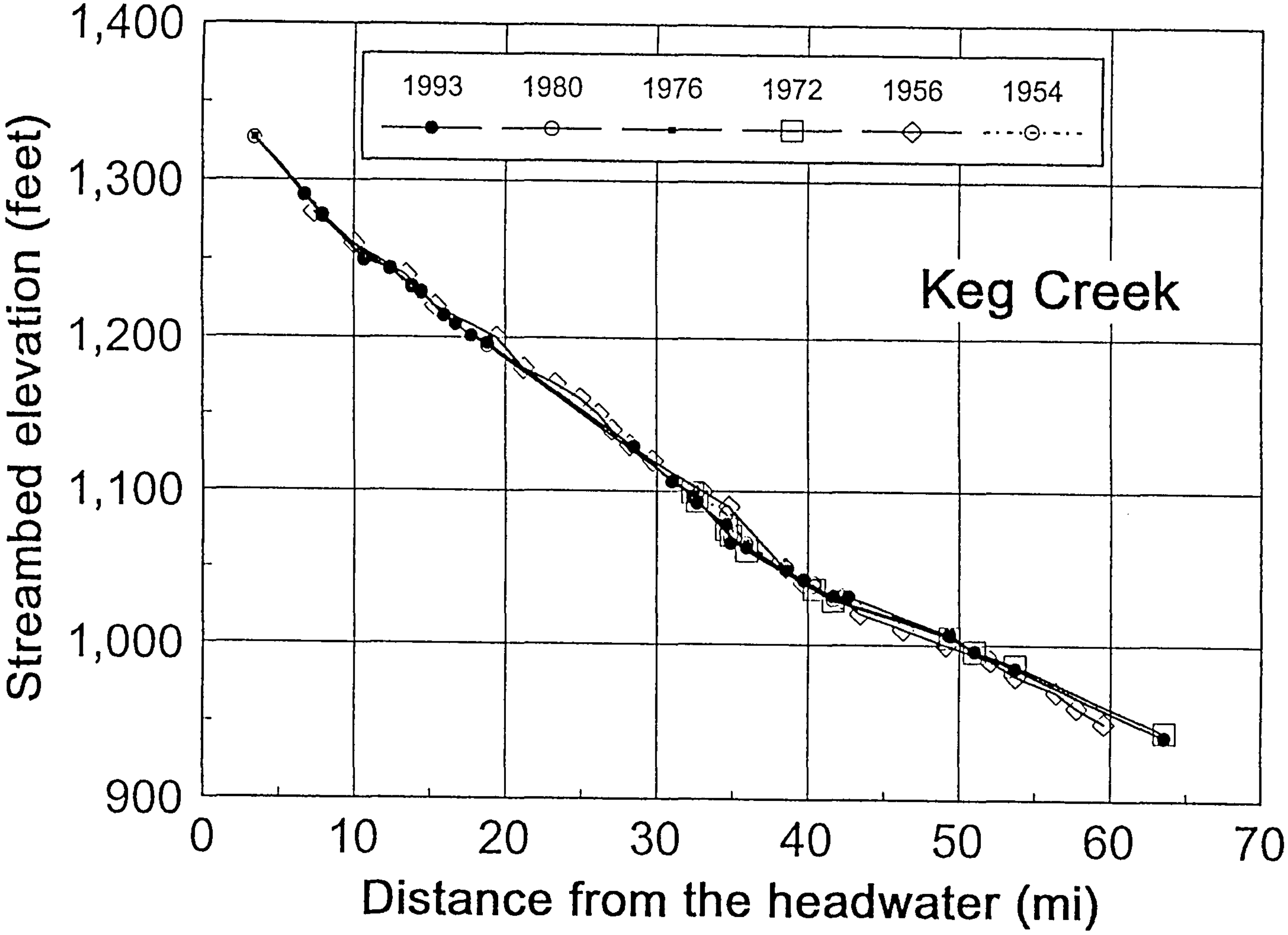

Figure 7. Keg Creek longitudinal profile 1954, 1956, 1972, 1976, 1980, and 1993.

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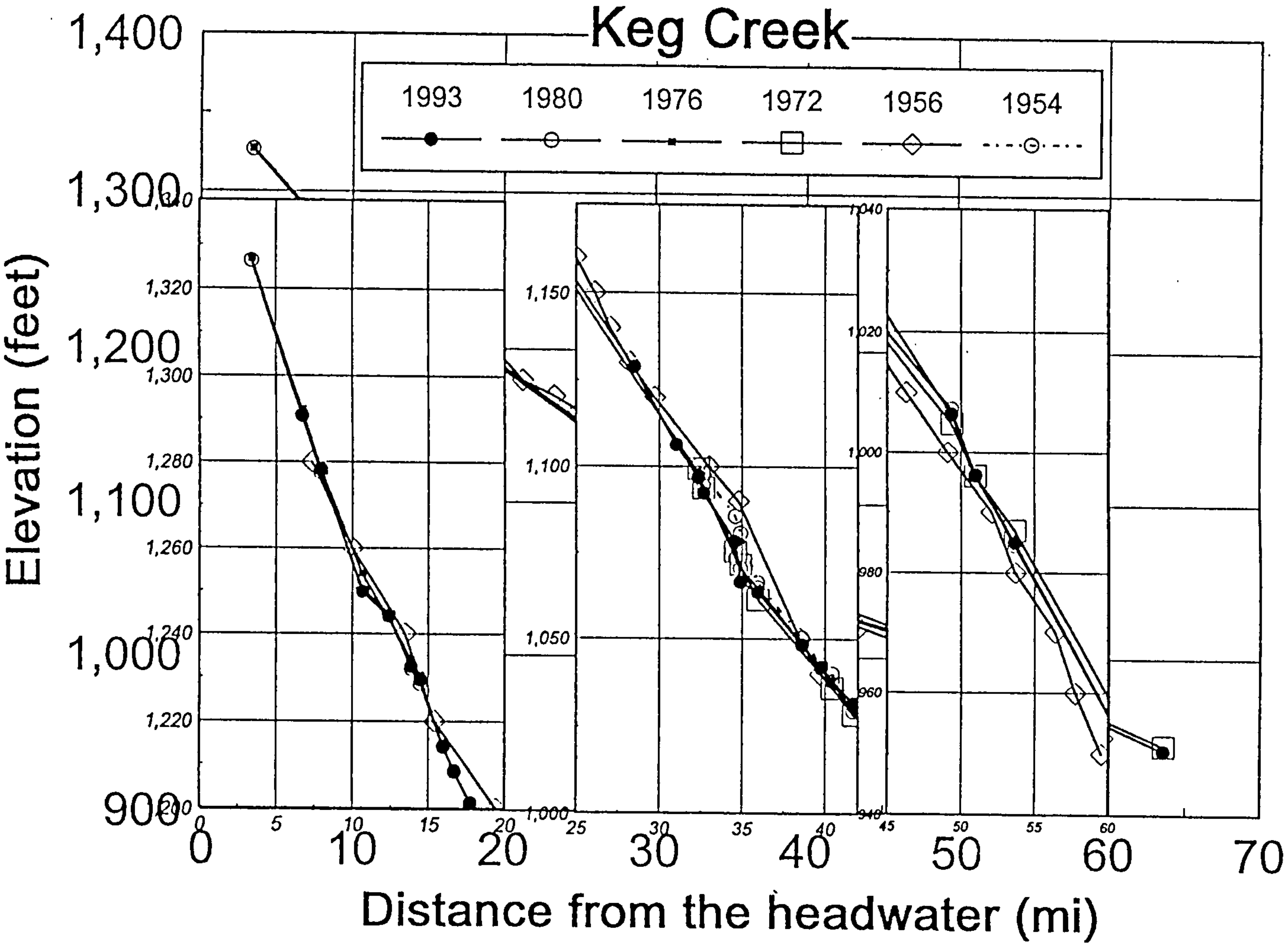

Figure 7a. Keg Creek detailed longitudinal profile 1954, 1956, 1972, 1976, 1980, and 1993.

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mile 64 no degradation has occurred since 1980. The 1980 profile was surveyed before the structure was built. This grade control structure takes out approximately 10 feet of drop. Since 1980 the stream has aggraded five feet above the structure. However, the stream has not aggraded to the 1954 profile elevation which is ten feet above the 1980 profile. At the structure location the 1972 and 1980 data show that the stream was still degrading (approximately 2 feet) when the structure was placed. However, the 1954 and 1972 profiles show that most of the degradation (approximately 10 feet) had already occurred prior to placement of the structure. From mile 34.61 to 32.38 the 1954 and 1972 profiles show approximately four feet of degradation. From 1972 to 1980 the stream aggraded at mile 32.7 and degraded at mile 32.4. While from 1980 to 1993, the stream has degraded approximately two feet. No analysis was possible from mile 32.4 to mile 19.85 because only two 1993 data points existed and no data points for 1980. The 1972 profile ends at mile 32.4. From mile 19.85 to mile 3 Keg Creek has not degraded since 1980. The 1976 data were plotted only from mile 14.5 to mile 3. In this reach Keg Creek had eroded a maximum of four feet from 1976 to 1980.

In summary Keg Creek is stable from the mouth up to the gabion grade control structure. It is still degrading from mile 30 to 32 but is stable above this section. Keg Creek has

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a knickpoint located around mile 32, but this knickpoint has not advanced upstream much in the last 13 years. This could be due to the grade control structure raising the base level enough to slow movement but not enough to drown out the knickpoint. Keg Creek will probably degrade above the grade control structure but this degradation probably will be less than approximately 2 additional feet unless the flood flows of 1993 have reactivated the knickpoint movement.

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ANALYSIS OF STREAM GEOMETRY

The stream characteristics of Maple River, Walnut Creek, Willow Creek, Mosquito Creek, McElhaney Creek, and Keg Creek were studied. The streams' widths were measured from aerial photographs, by the Soil Conservation Service, using a computer digitizer. The SCS measurements were not the top width, but the width located down in the channel where exposed earth was visible. These SCS widths were compared to trends found by Daniels and Jordan (1966). Daniels and Jordan found that the Willow Creek's gradient decreased on the Missouri River floodplain. Daniels and Jordan (1966) stated that the decrease in gradient caused the stream to adjust by decreasing in width five feet above the channel while increasing in depth of flow (Figure 8). The SCS data displayed the trend of increasing width from the headwater than a decreasing trend as the streams neared the mouth of the stream on Willow Creek, Keg Creek, and Maple River (Figure 9 and 10). However, these stream width measurements showed much more scatter than that of the Daniel measurements. The other three streams (Mosquito Creek, Indian Creek and McElhaney Creek) showed an increasing trend from headwater to mouth (Figure 10 and 11). They did not display the decrease or constant stream width near the mouth of the stream.

Calhoun-Burns and Associates completed a survey on a 6

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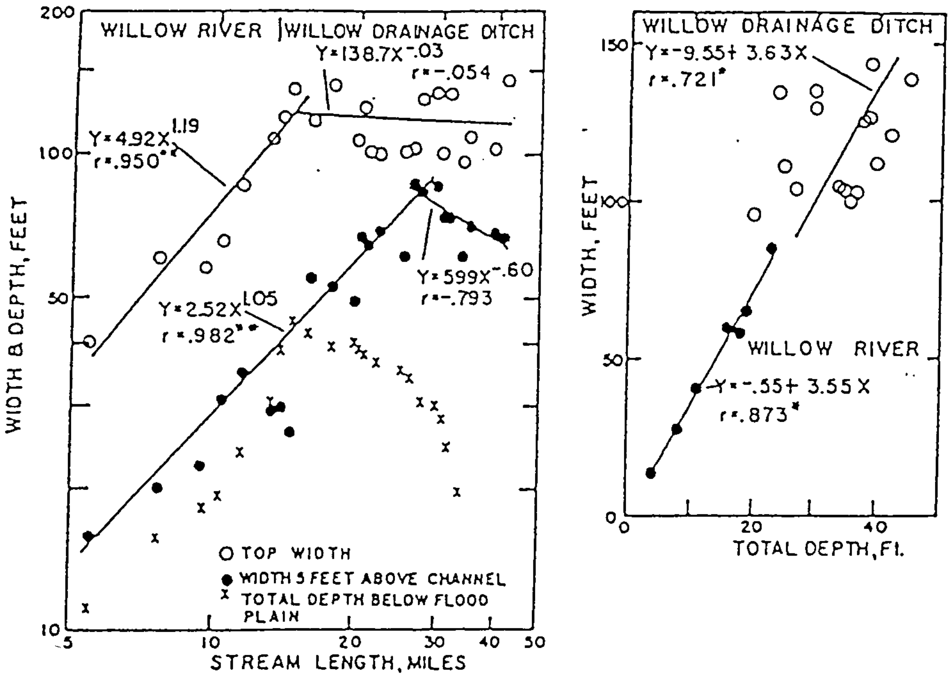

Figure 8. Relation of top width, width 5 feet above channel bottom, and depth of channel bottom below flood plain to stream length for Willow River. From Daniels and Jordan (1966).

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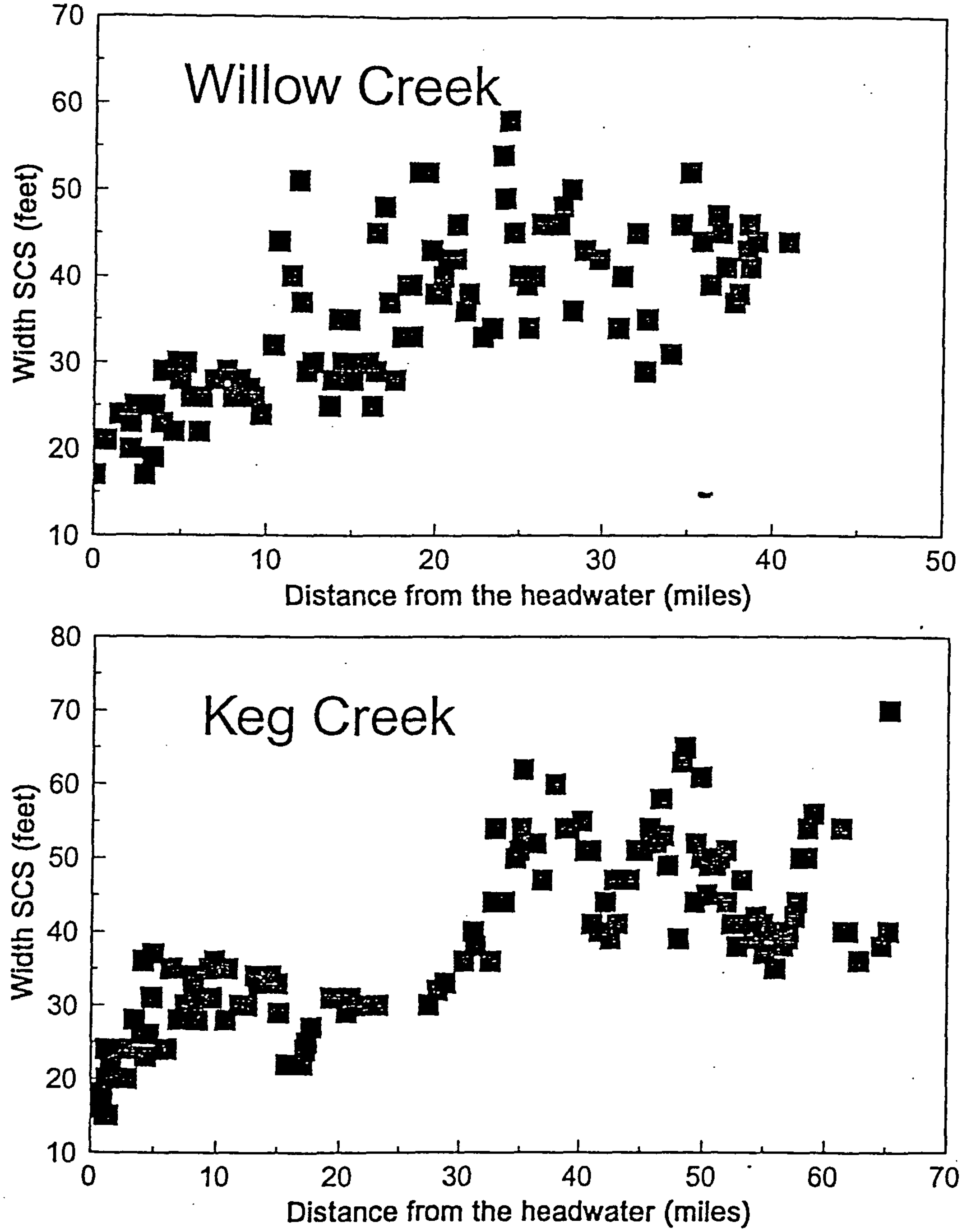

Figure 9. SCS width measurements for Willow Creek and Keg Creek.

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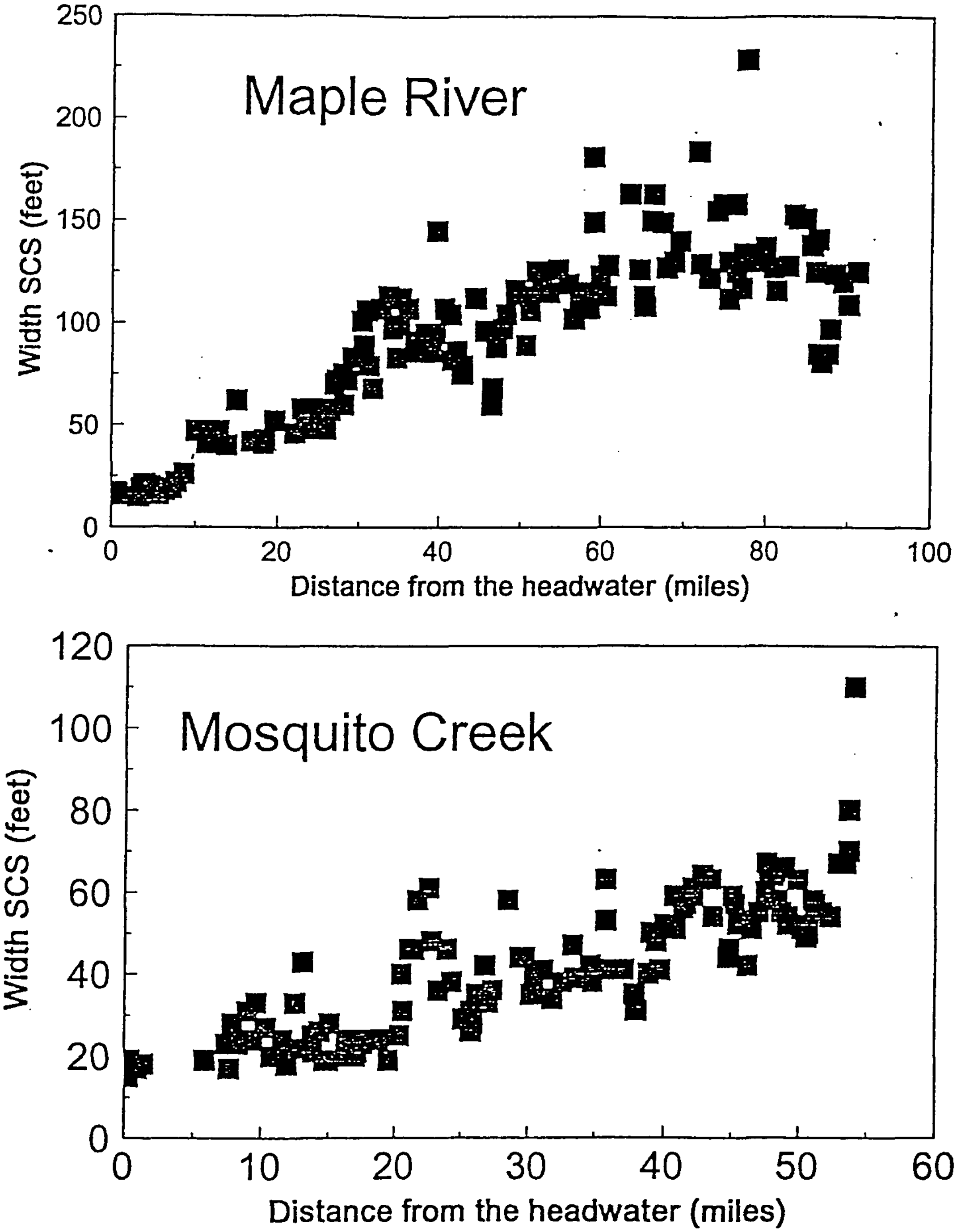

Figure 10. SCS width measurements for Maple River and Mosquito Creek.

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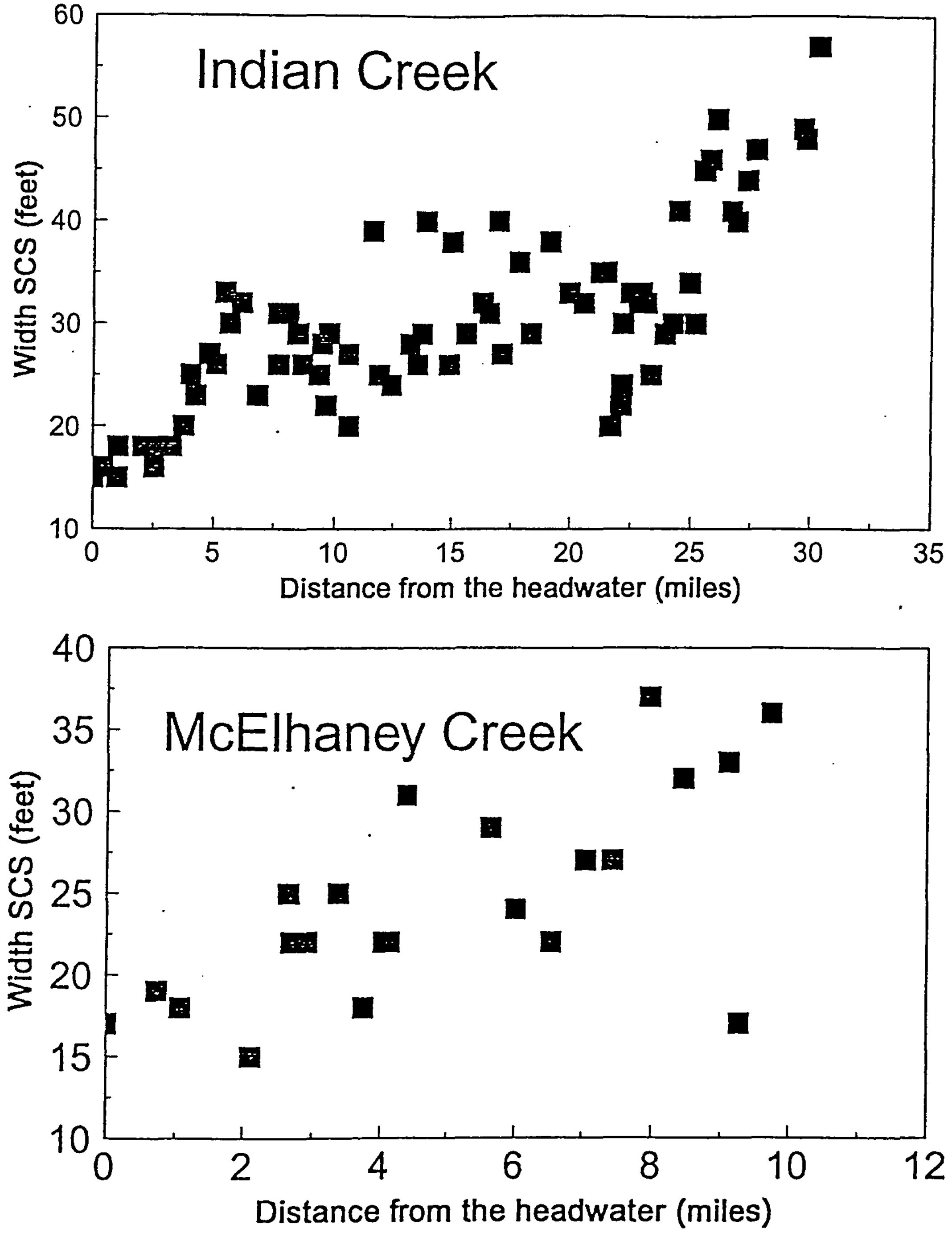

Figure 11. SCS width measurements for Indian Creek and McElhaney Creek.

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mile section of Walnut creek in 1992. These data are shown in Table 3. The width to depth ratio did not show any trend when plotted versus distance from headwater (Figure 12). Depth plotted versus distance from headwater showed an increasing trend in the downstream direction (Figure 12). Top width showed no trend when plotted versus distance from headwater (Figure 13). Bottom width was almost a constant value with some scatter (Figure 13). These survey data agree with the SCS data that there is no trend in top width downstream. The width to depth ratio was also plotted for Daniels (1960) data for Willow Creek. No trend was found in this data (Figure 14).

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Table 3. Walnut Creek 1992 survey data from Calhoun-Burns and Associates.

Distance from headwater (miles)	Top width (feet)	Bottom width (feet)	Depth (feet)	Top width to depth ratio
19.25	79	18	29.7	2.66
18.49	66	18	18.1	3.65
18.05	88	17	28.3	3.11
17.93	70	20	27.5	2.55
17.78	118	18	25.55	4.62
17.59	53	25	25.3	2.09
17.35	82.5	23.5	22.5	3.67
17.3	153	31	25.5	6
17.18	108	16	26.1	4.14
17.08	97	16	27.95	3.47
16.85	75	24	26.6	2.82
16.58	89	17	19.7	4.52
16.33	111	18	25.7	4.32
16.26	116	24	27	4.30
16.07	89	20	23.35	3.81
15.85	119	18	21.75	5.47
15.72	113	21	22.3	5.07
15.44	90	19	23.4	3.85
15.17	80	20	27.1	2.95
14.91	96	17	22.8	4.21
14.51	61	21	17.45	3.50

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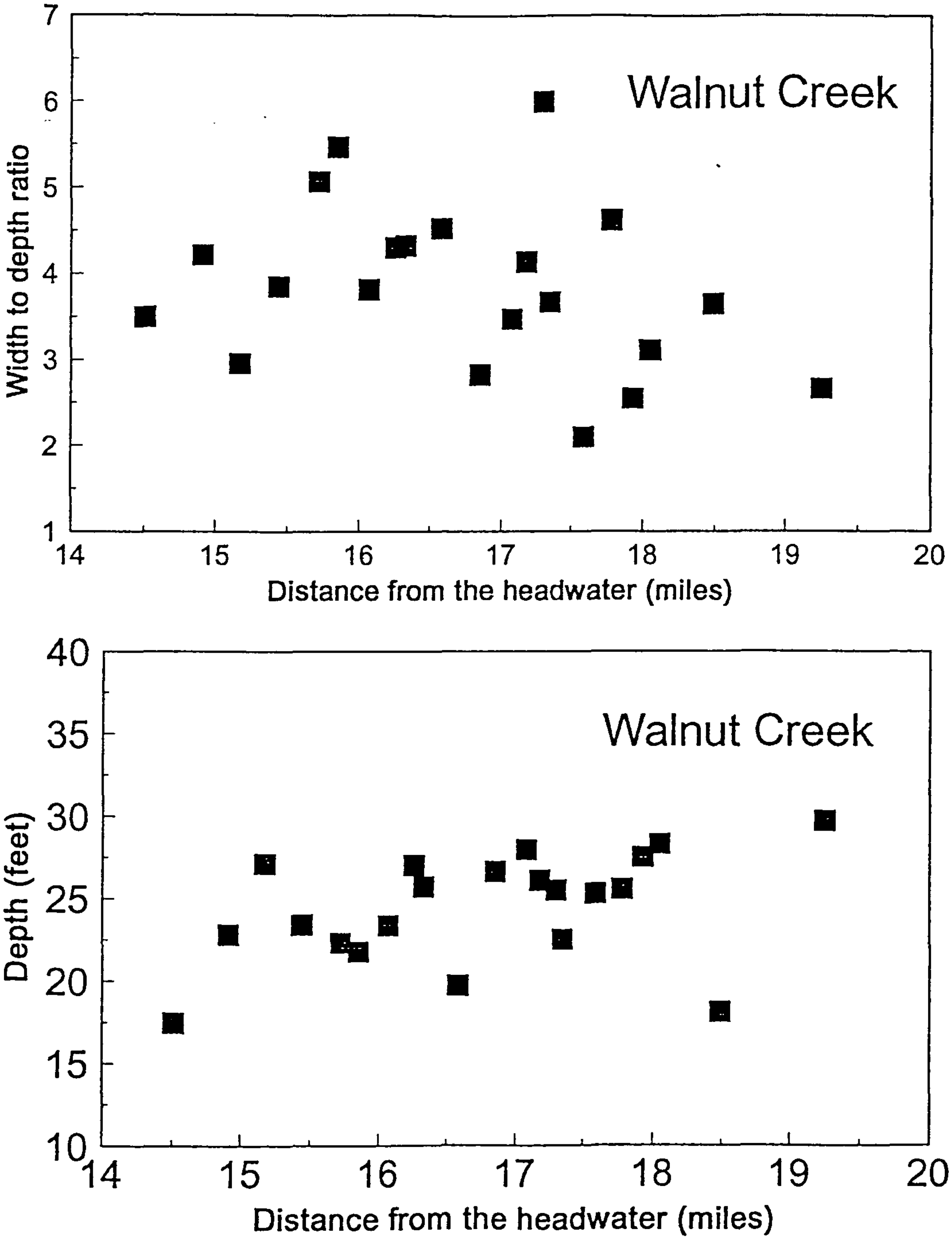

Figure 12. Walnut Creek 1992 width to depth ratio and depth plotted versus distance from headwater.

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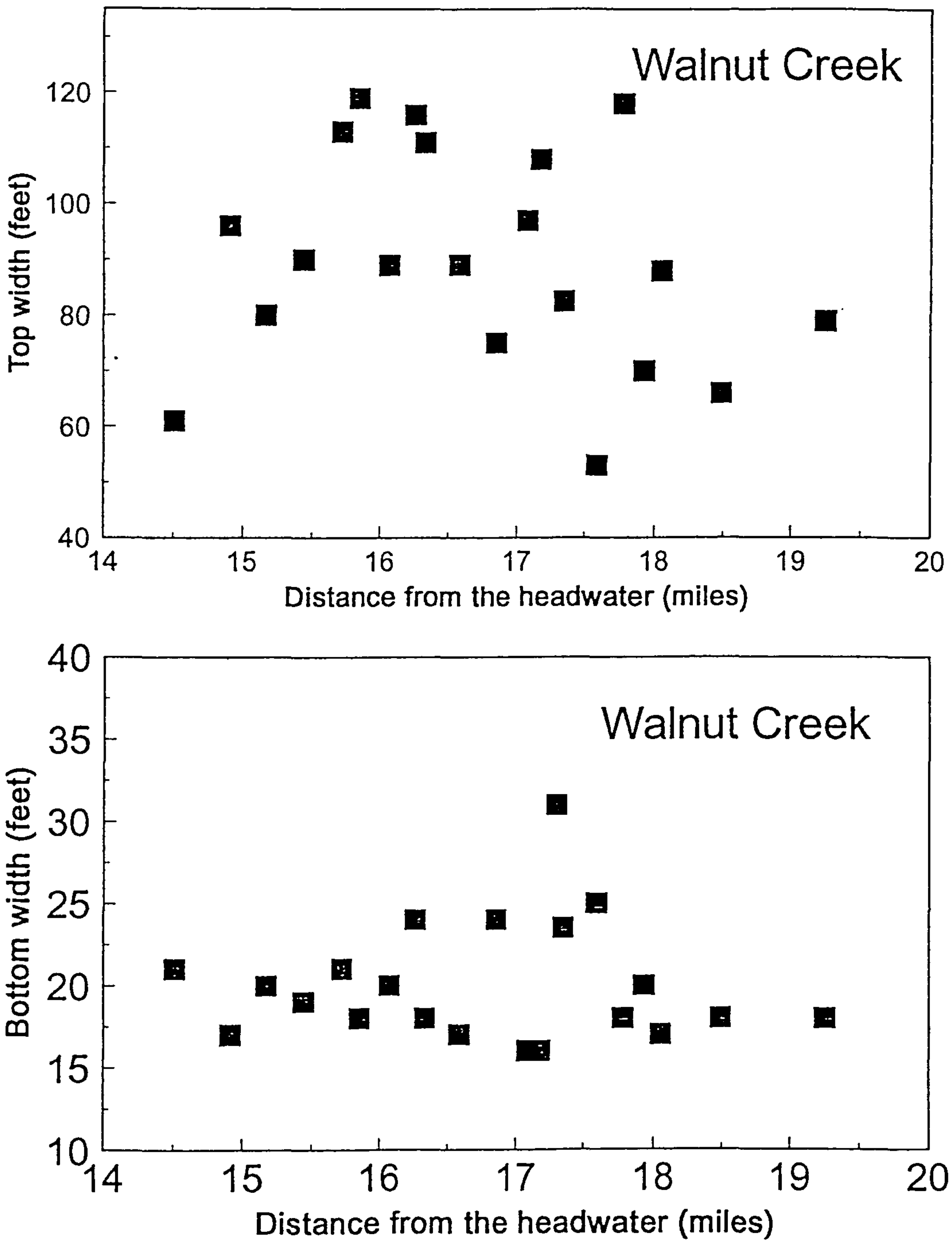

Figure 13. Walnut Creek 1992 top width and bottom width plotted versus headwater.

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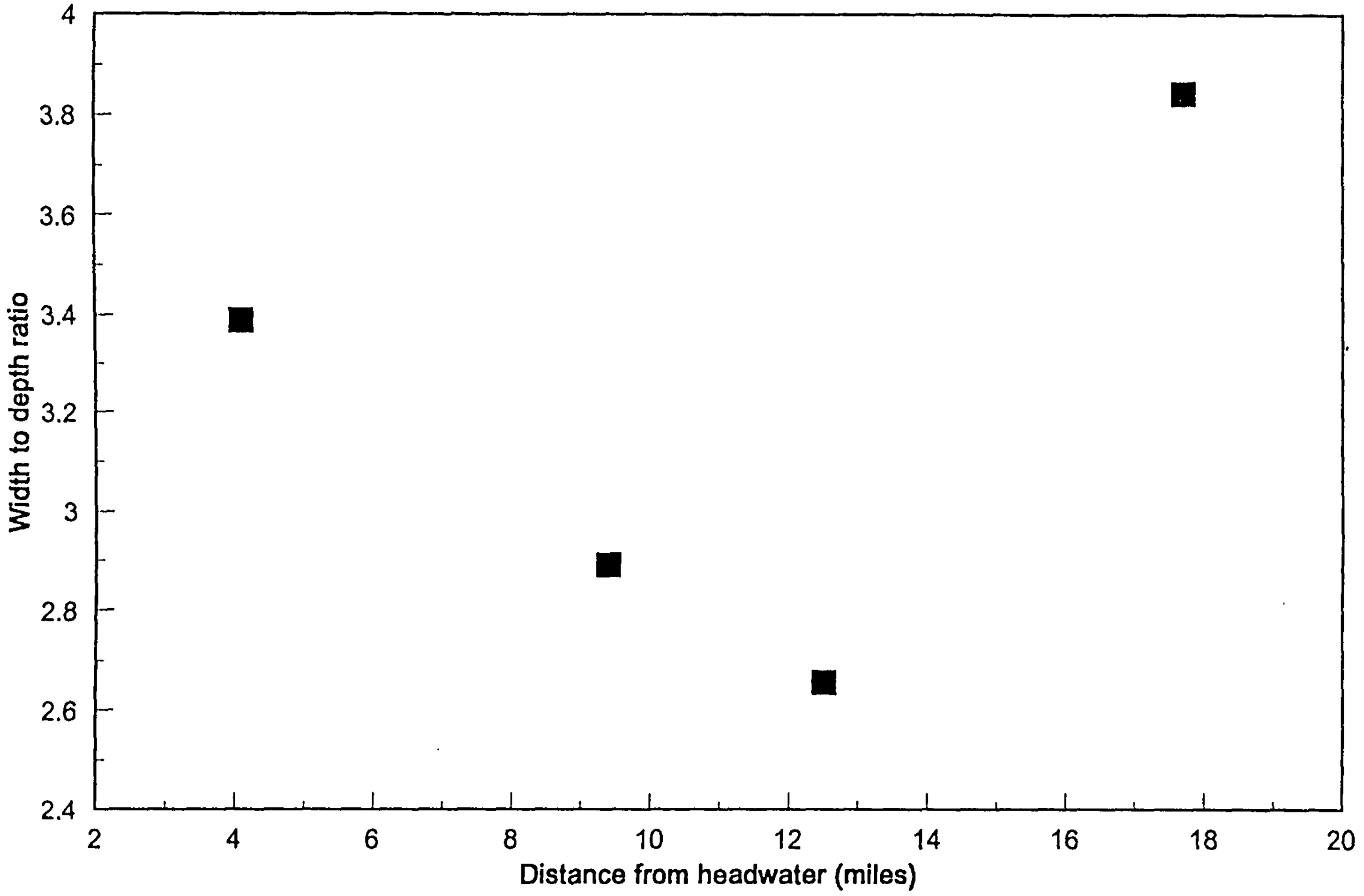

Figure 14. Willow Creek width to depth ratio versus the distance from the headwater. From Daniels (1960).

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STREAM CLASSIFICATION

Streams in the deep loess regions have been observed to go through certain stages throughout the stream's history. Simon (1989) developed a six stage process to describe stream degradation (Figure 15).

Stage I - "Premodified" The stream is not modified and has densely vegetated banks and a meandering channel with some lateral erosion. With regard to channel bank slope stability, this stage has mean factors of safety of 3.6 and 2.4 for planar and rotational failure respectively. These values are well above the critical level.

Stage II - "Constructed" This stage is a constructed trapezoidal channel with sides designed with a factor of safety of 1.5.

Stage III - "Degradation" In this stage the stream is degrading because of increased channel gradients and stream power downstream. The channel bank heights increase and bank slopes steepened due to stream downcutting and popout failures at the bank toe. The mean factor of safety of this stage decreases to 3.0 and 1.8 for planar and rotational failure respectively.

Stage IV - "Threshold" This stage occurs when degradation begins to slow down. The stream banks are in a failure condition and the stream is widening at a rate of 3 to

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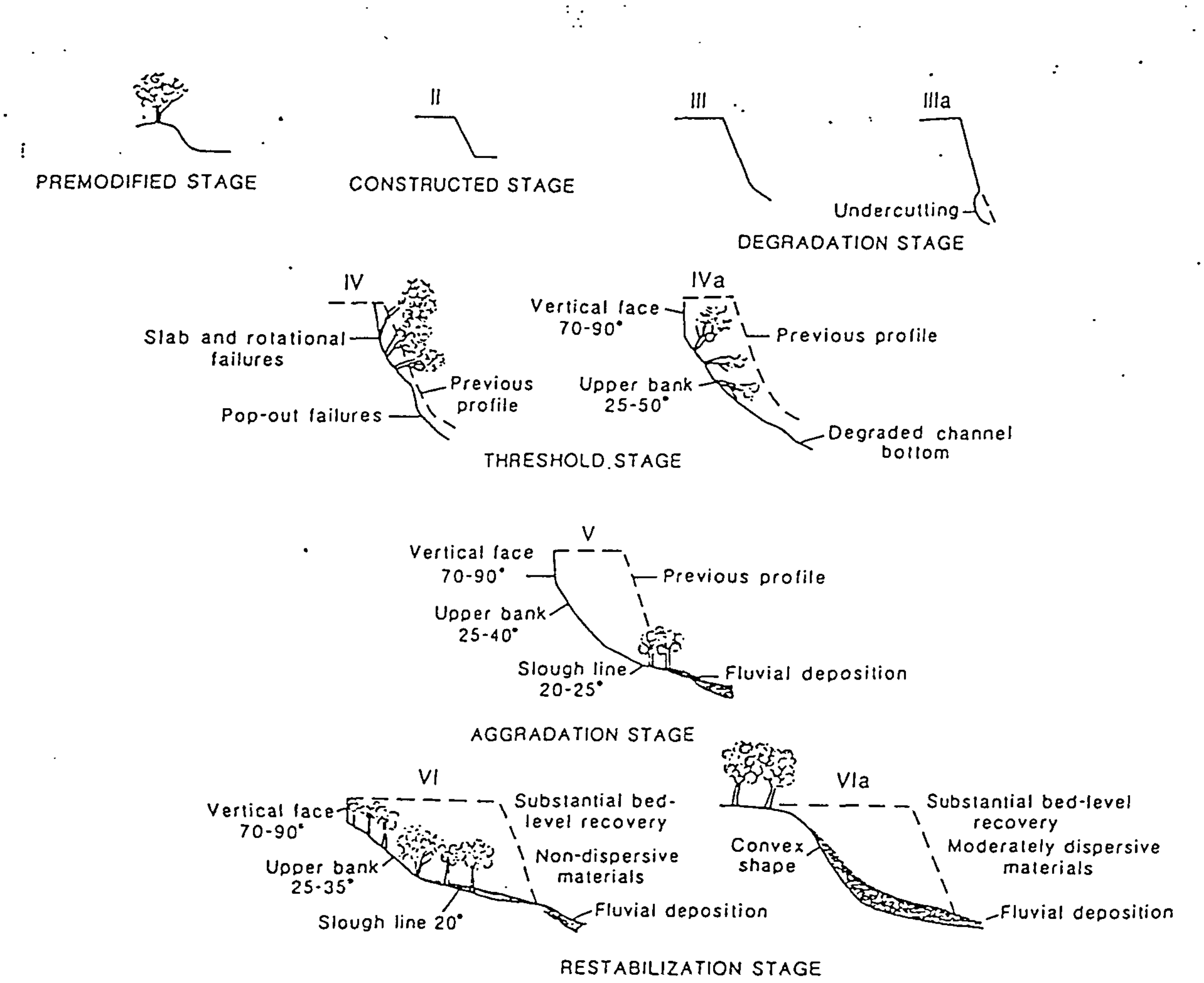

Note: Scale is relative.

Figure 15. Six-stage model of bank slope development in disturbed channels. From Simon (1989).

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13 feet per year. The channel is shaped by the mass wasting process. Both rotational and planar failures exist because the mean factor of safety decreases to near one. Banks exhibit rotational failure scars.

Stage V - "Aggradation" The stream begins to stabilize and aggrade. The mean factor of safety of the side slopes increase to 2.0 for planar and 1.9 for rotational failure. The banks become stable and start to produce vegetation.

Stage VI - "Restabilization" The final stage is the stage at which the stream has stabilized and woody vegetation begins to occupy the channel. The bank heights and angles have decreased to a stable level.

For application to western Iowa, these stages are difficult to identify in the field and lead to confusion and different interpretations of the channel stability. The idea of using a factor of safety is appealing to me as a geotechnical engineer; however it requires site specific soil characteristics that are difficult to obtain. The modifications of Simon's (1989) model uses field observations and longitudinal profiles as the main criteria for classification. The field observations include cross sectional geometry, vegetation cover, knickpoint location, and slope failure type.

Stage I - "Natural Meandering Channel" is before the stream system has been disturbed and is rare in western Iowa.

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The channel consists of stable banks with woody vegetation down to the water line. The plan and cross sectional view of this stage is shown in Figure 16.

Stage II - "Incipient condition" is before impending degradation has started. This stage is characterized by uniform side slopes and may show a shallow (less than 3 feet) vertical cut below channelized slopes. These slopes may have woody vegetation close to the water line. At this stage the channel shows no evidence of side slope failures and is probably located more than 1500 feet upstream of a knickpoint (Figure 16). The channel bottom will have an elevation greater than 20 feet above the upstream projection of the longitudinal profile of the stable reach.

Stage III - "Active condition" is the stage during active degradation. The channel bottom is at an elevation about 15 feet above the upstream projection of the stable longitudinal profile. During this stage the activity is usually located within 1500 feet of a knickpoint. The downstream portion of the channel will likely experience less than an additional 10 feet of degradation while the upstream portion may have 15 feet or more of additional degradation. On the channel side slopes slab or planar failures are evident and no woody vegetation exists in the bottom half of the channel. The side slopes of the channel may be a composite of two or three nearly linear segments with average slope angles greater than

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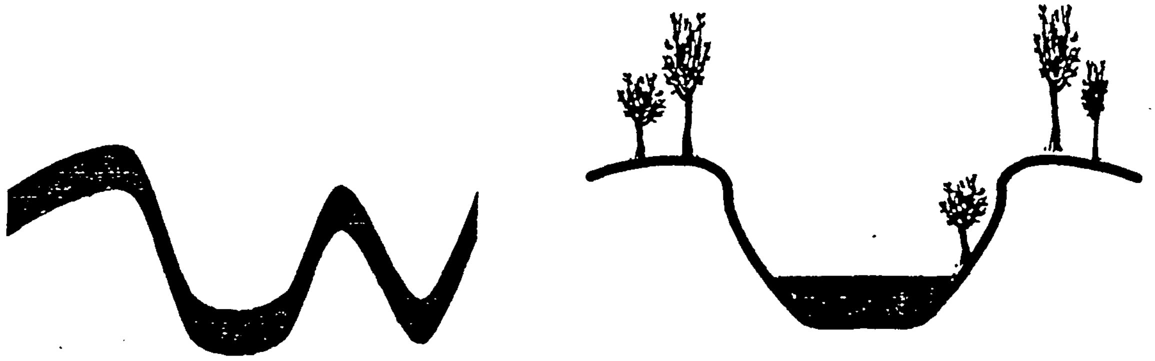

Stage I Plan View

Stage I Typical cross section

Stage II Plan View

Stage II Typical cross section

Figure 16. Stage I "Natural Meandering condition" and Stage II "Incipient condition" plan and cross sectional views.

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60 degrees (Figure 17).

Stage IV - "Stable condition" exists where no further degradation is likely. The longitudinal profile has not changed in 10 years. A stream reach in this stage is located greater than 1500 feet downstream from a knickpoint. The woody vegetation has grown to the average flow line and the channel sides have vertical banks of less than two feet in height. The side slopes are complex slopes with failure scars and average slope angles less than 45 degrees. The slope failures appear as deep-seated rotational failures (Figure 17).

These stages are suggested as guidelines to identify the activity of the channel and not all the criteria for a stage may be evident at a stream cross section. Table 4 outlines the stages. The quantitative data are tentative and based upon observation of the degradational history of Willow and Keg creeks and some soil mechanics considerations.

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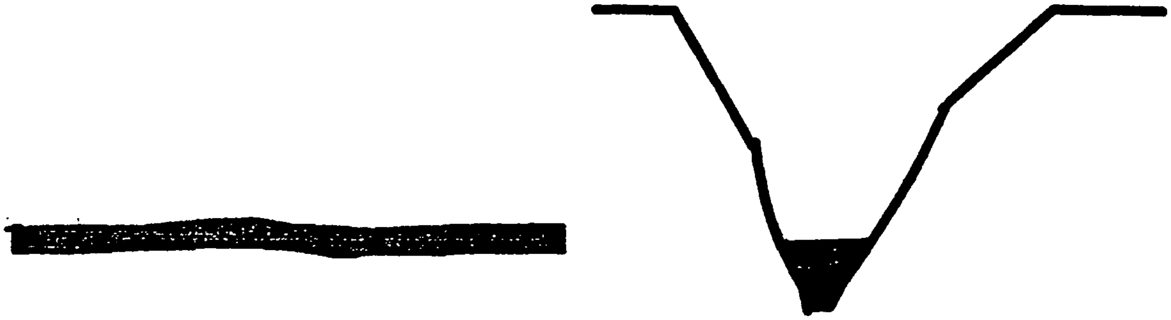
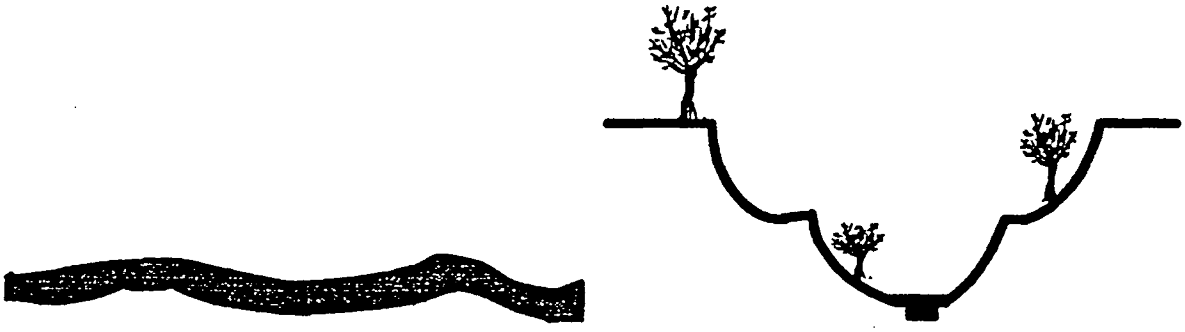


Stage III Plan View Stage III Typical cross section



Stage IV Plan View Stage IV Typical cross section

Figure 17. Stage III "Active condition" and Stage VI "Stable condition" plan and cross sectional views.

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Table 4. Stream stage characteristics.

Stage	Plan form	Knickpoint Location	Channel bottom longitudinal profile	Side Slope Geometry
I	Meandering	None	Stable	Stable
II	Straight	Greater than 1500 ft. upstream	Greater than 20 ft above upstream stable projection	Vertical cuts less than 3 ft.
III	Straight	Within 1500 feet	Less than 15 ft. above upstream stable projection	Composite of 2 or 3 nearly linear segments Average slope angle > 60°
IV	Straight-Meandering	Greater than 1500 ft. downstream	Stable	Complex with failure scars and average slope angle < 45°

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PREDICTION METHODS

The prediction of a stable stream profile in western Iowa is difficult because of the lack of historic data on the streams' longitudinal profiles and cross sections. Few longitudinal profiles are available from the Soil Conservation Service and past research reports; however these profiles can be used to evaluate predictive methods in order to determine which method is most applicable to western Iowa streams.

Some methods have been suggested for predicting degradation downstream of reservoirs, but these methods do not apply to streams carrying a high sediment load. Simons (1976) derived a mathematical model that predicts degradation below reservoirs on large coarse bed streams. While Schumm (1960) derived equations to predict width to depth ratios of streams based on the type of material in the channel bed. This equation predicts that a stream with an uniform percentage of silt-clay in the channel will have a constant width to depth ratio throughout the stream. However, Massoudi (1981) showed that the width to depth ratio varied downstream and is not a constant. This variation could be caused by variable geology, but more detailed surveys need to be completed to verify the geology change. Two methods defined as the Tractive Force model (Massoudi, 1981) and the Hack method (Hack, 1957) are evaluated in this report.

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Hack Method

Hack (1957) studied streams in seven areas of Virginia and Maryland with varying stream profiles and geological terrain but none included thick loess deposits. The streams had drainage areas from 0.12 to 375 square miles and stream slopes from 500 ft/mile with boulders to gentle slopes with fine gravels. The average size of bed material varied from a few millimeters to over 600 millimeters. Several different stream characteristics were studied: stream length, drainage area, channel slope, channel cross section, and size of material on the stream bed. Hack (1957) did not include discharge in the stream characteristics studied, even though he considered the discharge as the most important factor controlling slope. However, he did assume that drainage area is proportional to average annual discharge.

Hack (1957) discovered that the channel slope is inversely proportional to a power function of the drainage area for a given bed material and also the channel slope is inversely proportional to channel length for a given bed material. In the streams studied the width to depth ratio decreased along the downstream length.

Using the relationship between the variables studied Hack found that streams may be expressed by two simple equations. One equation is for a stream with uniform size bed load.

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$$H = k\log_e L + C$$

where H = fall from the drainage divide, L = length from the drainage divide, and k, C = constants. This equation is a straight line on a semilogarithmic plot.

The second equation is for streams with stream bed particle size changing systematically in a downstream direction.

$$H = \frac{k}{n+1} L^{(n+1)} + C$$

where n does not = -1, H = fall from the drainage divide, L = length from the drainage divide, and k, n, C = constants. When C = 0 this equation reduces to a simple power equation that will plot a straight line on logarithmic graph paper(Hack, 1957).

Hack (1957) concluded that stream profiles adjust to carry erosion products of their basins. The channel geometry will adjust and come to equilibrium with the relief, age, and geology of the basins. This adjustment was shown in the different stream profiles that existed on the Middle River and its tributary East Dry Branch (Hack, 1957). The stream slopes changed at a major geologic contact (Figure 18).

Application of the Hack model requires the stream profiles to be plotted on semi-log paper with equilibrium profiles of streams flowing through uniform geology producing straight lines. From this plot an equation for the stable

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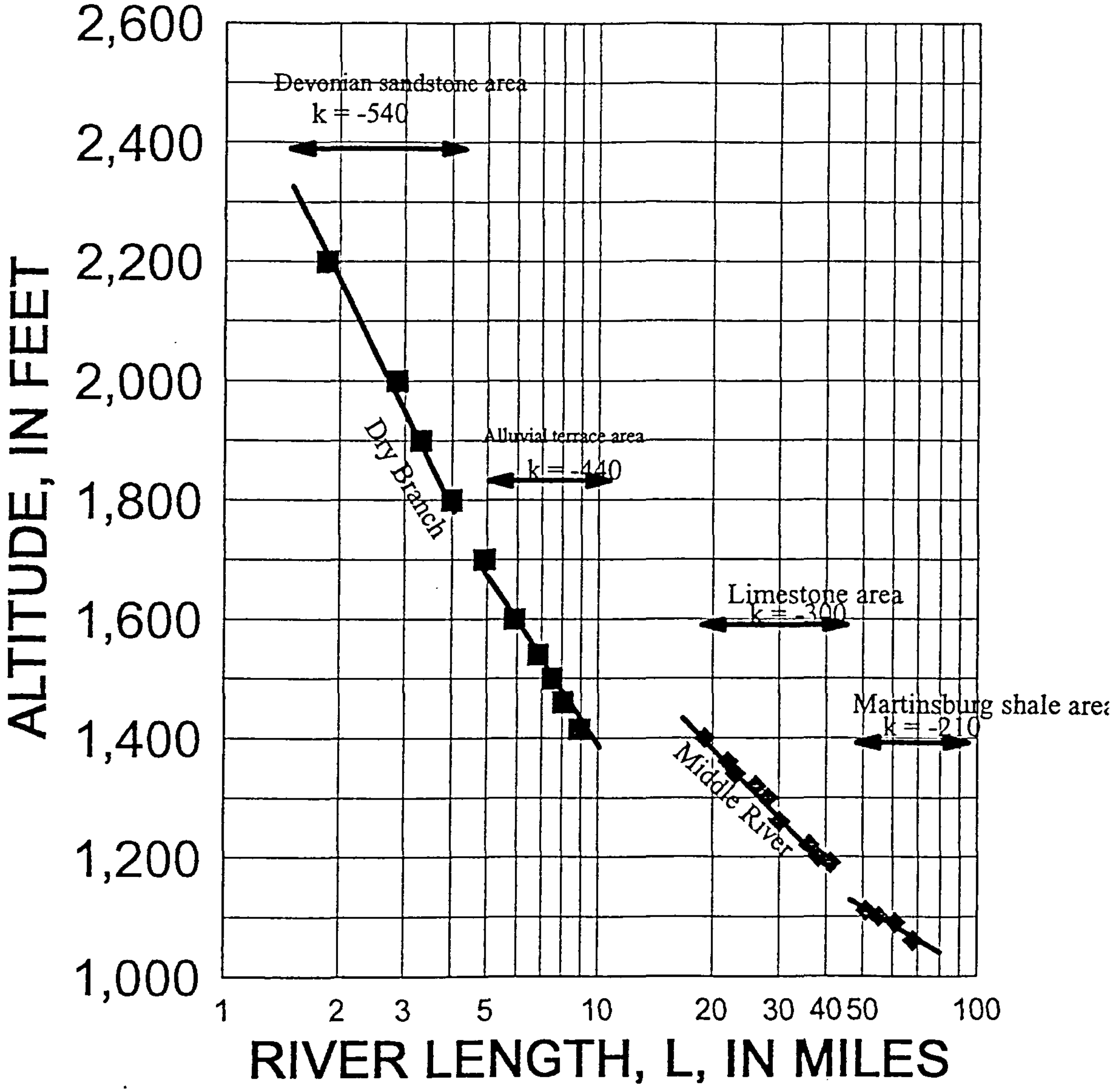

Figure 18. Longitudinal profiles of East Dry Branch and Middle River drawn on a semilogarithmic plot. Modified from Hack (1957).

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profile can be developed:

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

E = bottom elevation, C and k = constants, and L = length of river in miles.

A degrading stream can be plotted to produce a straight stable downstream section that when projected upstream will be lower than the actual stream profile (Figure 19). Daniels (1960) suggested that the Hack stable projection could be used to predict degradation upstream of a knickpoint. Lohnes et. al. (1980) applied this principle successfully to a reach of Willow Creek (Figure 20). However, as shown in Figures 21 and 22 the Keg Creek, Walnut Creek, Indian Creek, and Maple River longitudinal profiles plot concave down on the semilog plot. Daniels and Jordan (1966) reported a similar trend for Thompson Creek and a longer reach of Willow River. Daniels and Jordan (1966) suggested that these streams will follow the same slope as the defining geologic member. For example as shown in Figure 23 the Willow River follows the slope of the Mullenix alluvium while Thompson Creek follows the Turton alluvium. If there is a defining geologic member then one geologic member must be stronger than another. Lohnes (1991) obtained strength values from the SCS for the five beds of the DeForest Formation (Table 5). The shear strength of each member was calculated using the following equation:

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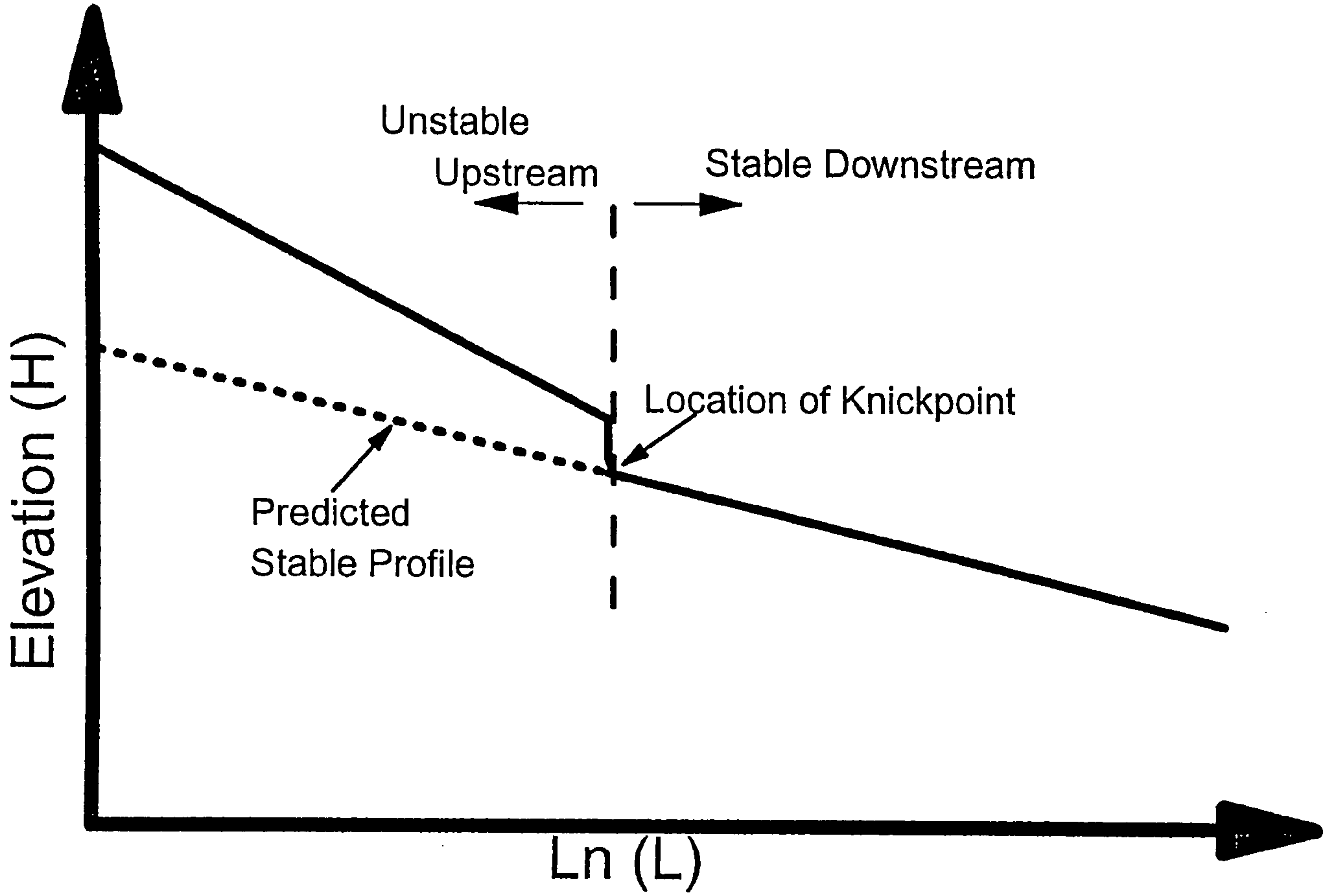

Figure 19. Ideal application of the Hack model. From Lohnes (1991).

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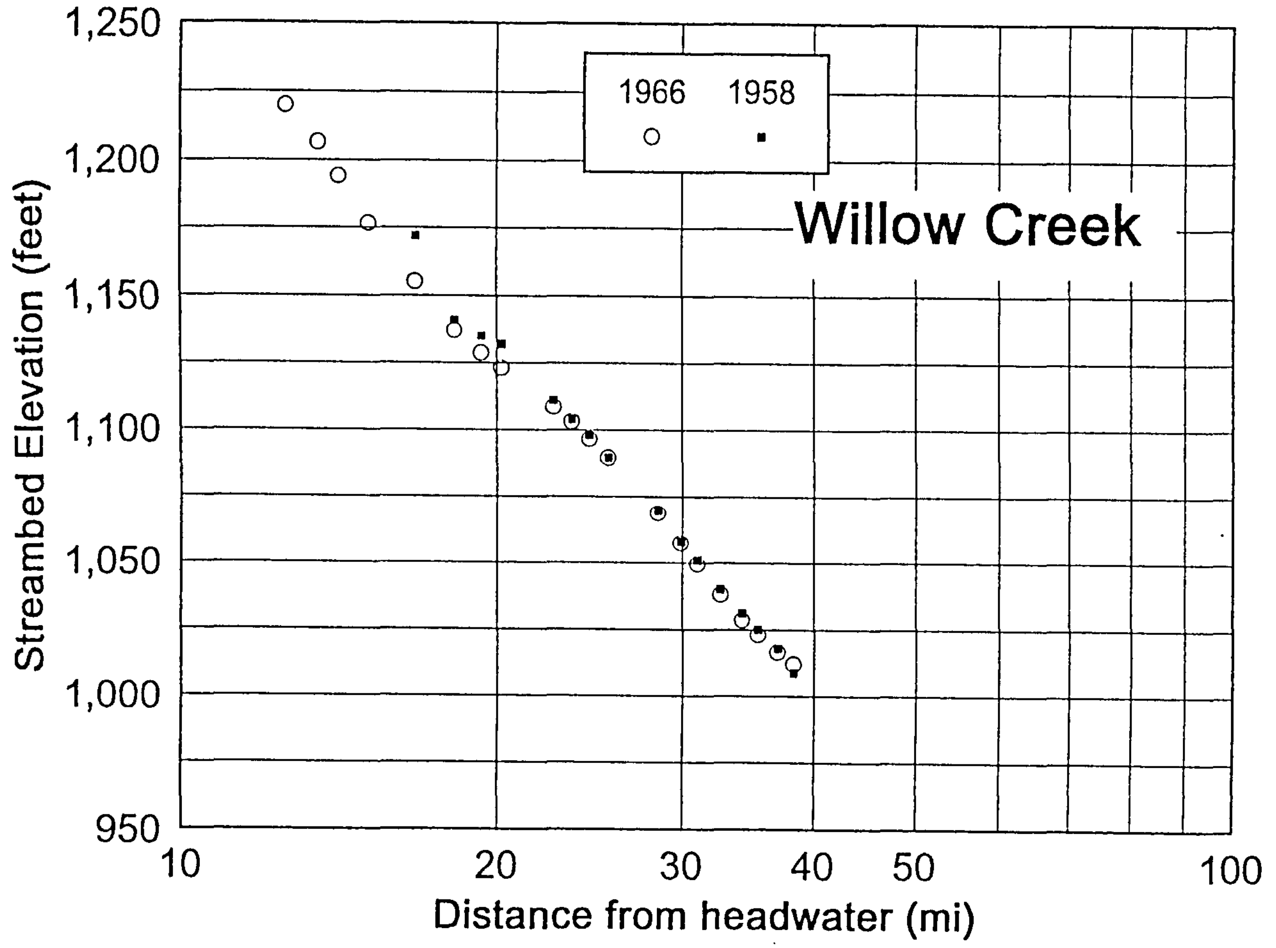

Figure 20. A reach of Willow Creek plotted on logarithmic paper. Modified from Lohnes (1980).

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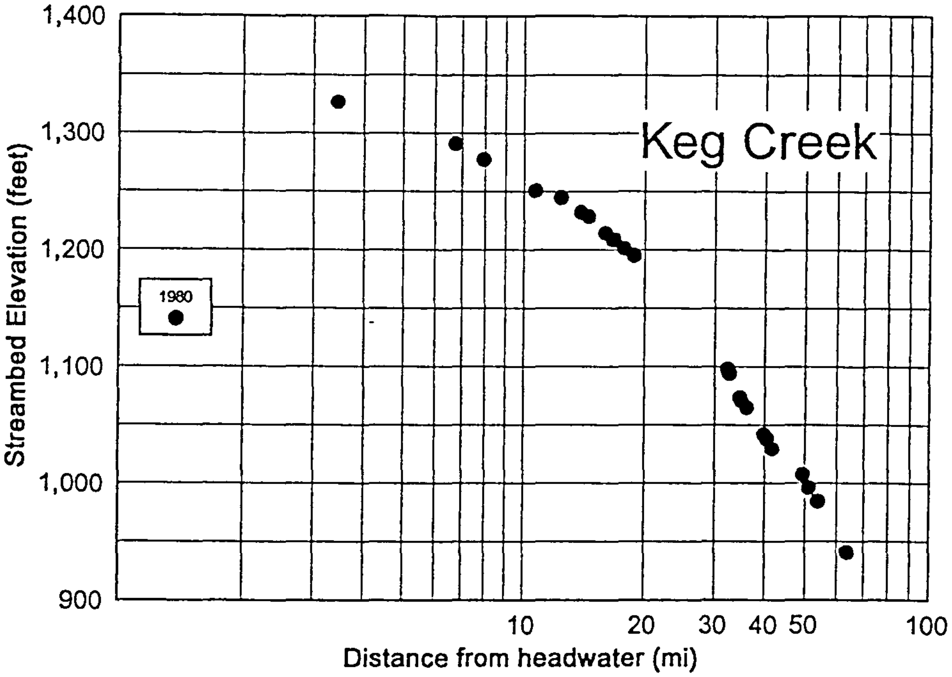

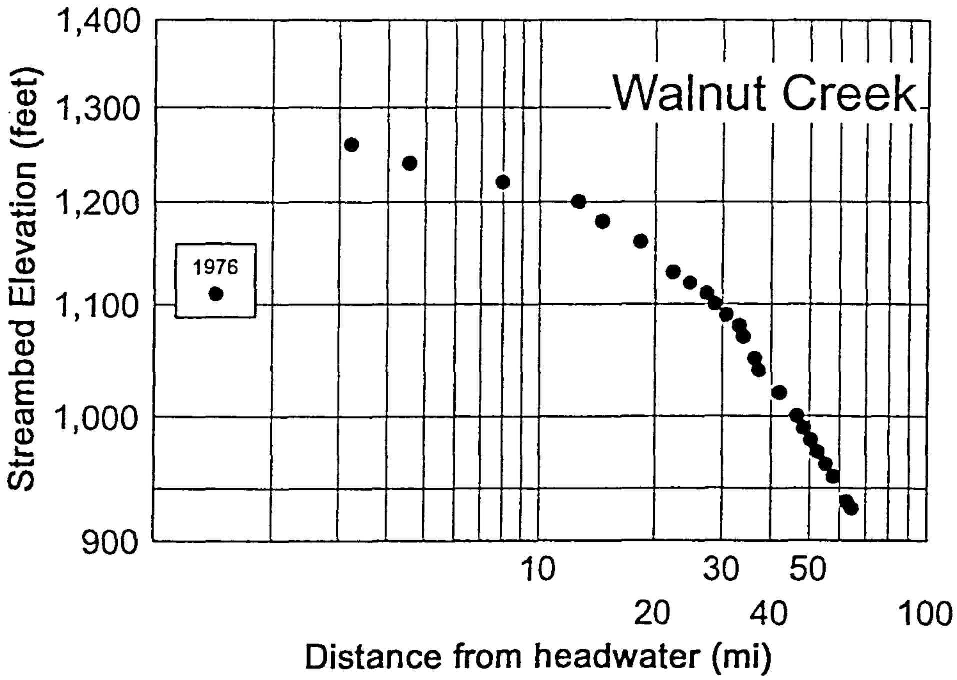

Figure 21. Keg Creek and Walnut Creek longitudinal profiles plotted on logarithmic scale.

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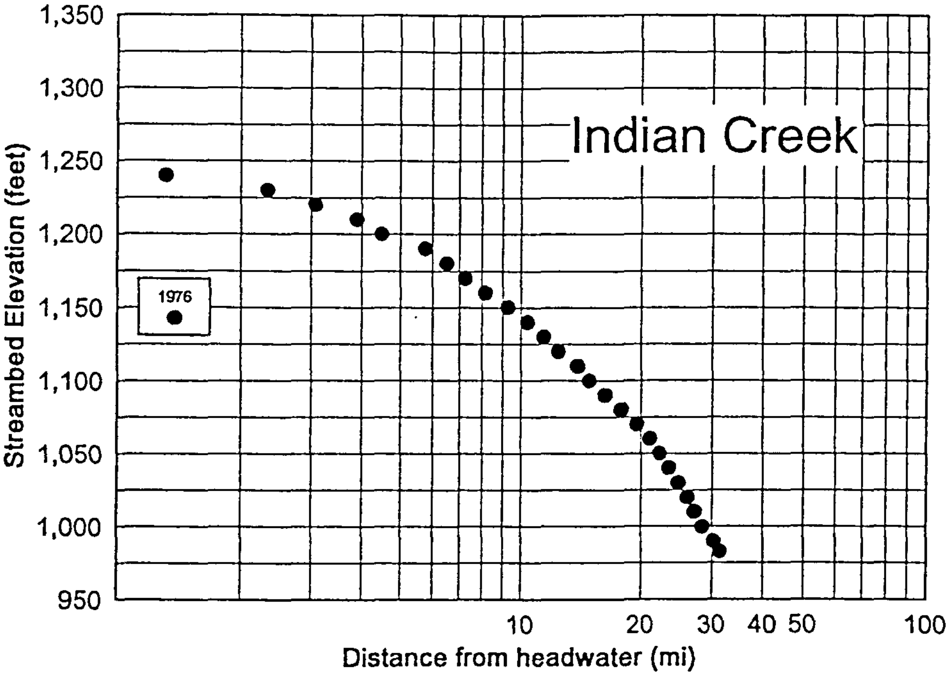

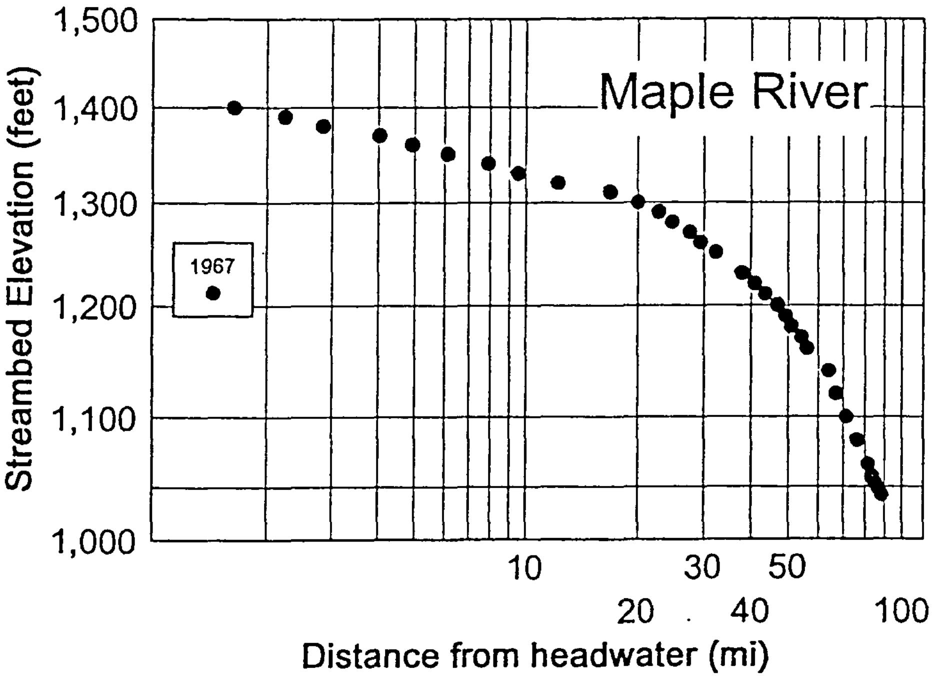

Figure 22. Indian Creek and Maple River longitudinal profiles plotted on logarithmic paper.

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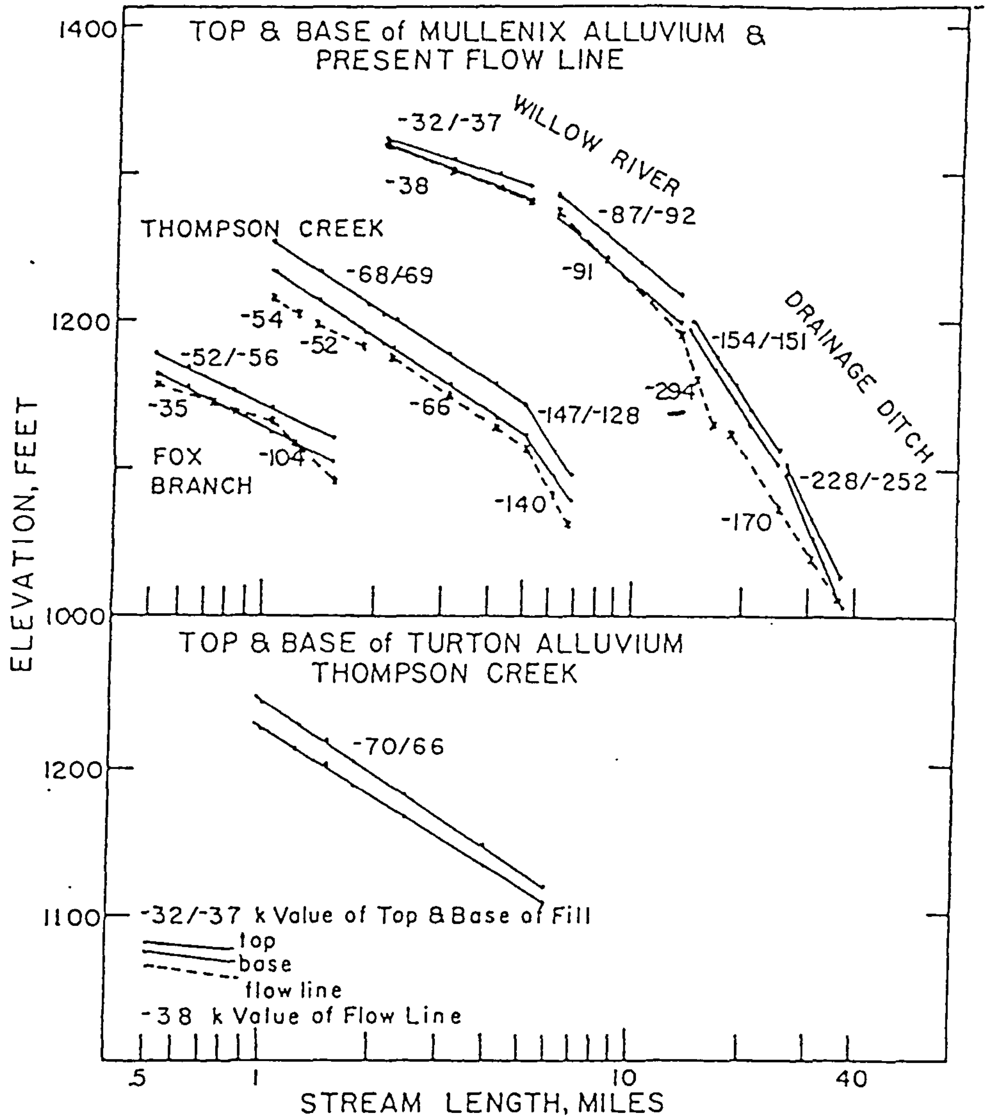

Figure 23. The k values of the base of the Mullenix and Turton fills and of the present stream channels in the Willow River and Thompson Creek valleys. From Daniels and Jordan(1966).

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$$S_r = c + \sigma\tan\phi$$

where $\sigma = 0.1(\gamma_b)$, c = mean cohesion (psf), ϕ = mean friction angle (deg.), σ = shear stress (psf), γ_b = buoyant unit weight (pcf), and S_r = shear strength (psf). Assuming the mean unit weight was the dry unit weight and the specific gravity of the soil was 2.71 then the saturated unit weight could be calculated from the dry unit weight. The results of the calculated shear strength for each member is shown in Table 5.

Table 5. Strength data of the DeForest Formation data. From Lohnes (1991).

Unit	Mean c (psf)	std. dev.	Mean phi (deg.)	std. dev.	Mean unit weight (pcf)	Mean sat. unit weight (pcf)	std. dev.	Sr (psf)
Post Settl.	139	144	29	5	82.8	114.65	5.1	141.90
Turton	163	131	29	4	89.5	118.87	5.8	166.13
Mullenix	221	164	27	4	88.9	118.50	6.0	223.86
Hatcher	190	131	28	4	93.3	121.27	6.2	193.13
Watkins	210	150	30	6	90.5	119.51	8.9	213.30

The members do not show a trend of increasing strength from youngest to oldest probably because the data that was used had a high standard deviation. These data do not support the idea that one member will control the depth of the stream degradation. Therefore, Daniels prediction that the stream slope will follow one controlling member is not supported by the strength data. However, field observations in 1994 have

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shown that the geologic members do have some control over the stream profile. The Gunder member was present in the steep gradient portion of Keg Creek and all observed knickpoints on Keg and Walnut creeks were formed in the Gunder Member.

Another possible cause for irregularity of the profile of Maple River is that it has unusual thickness of alluvial sediment. The thickness does not decrease from the mouth to the headwater, but decreases then increases and then decreases again, as shown in Figure 24. However, Keg Creek limited alluvial thickness data does not show an unusual pattern. Therefore the alluvial thickness variation on the Maple River cannot be the only cause of the irregularity of the profile.

The irregularity of the profile could stem from a change in the stream reach, from a meandering to a straight reach. However the break in slope was not related to straight or meandering reaches, because even in a stream of mostly straight reaches there was a break in slope (Appendix A).

Tractive Force Model

The second method studied is an analytical method developed by Massoudi (1981) who used Willow Creek as the model stream. Five basic assumptions underlie this model. The first assumption is a constant width to depth ratio at a given location regardless of the depth of degradation. This

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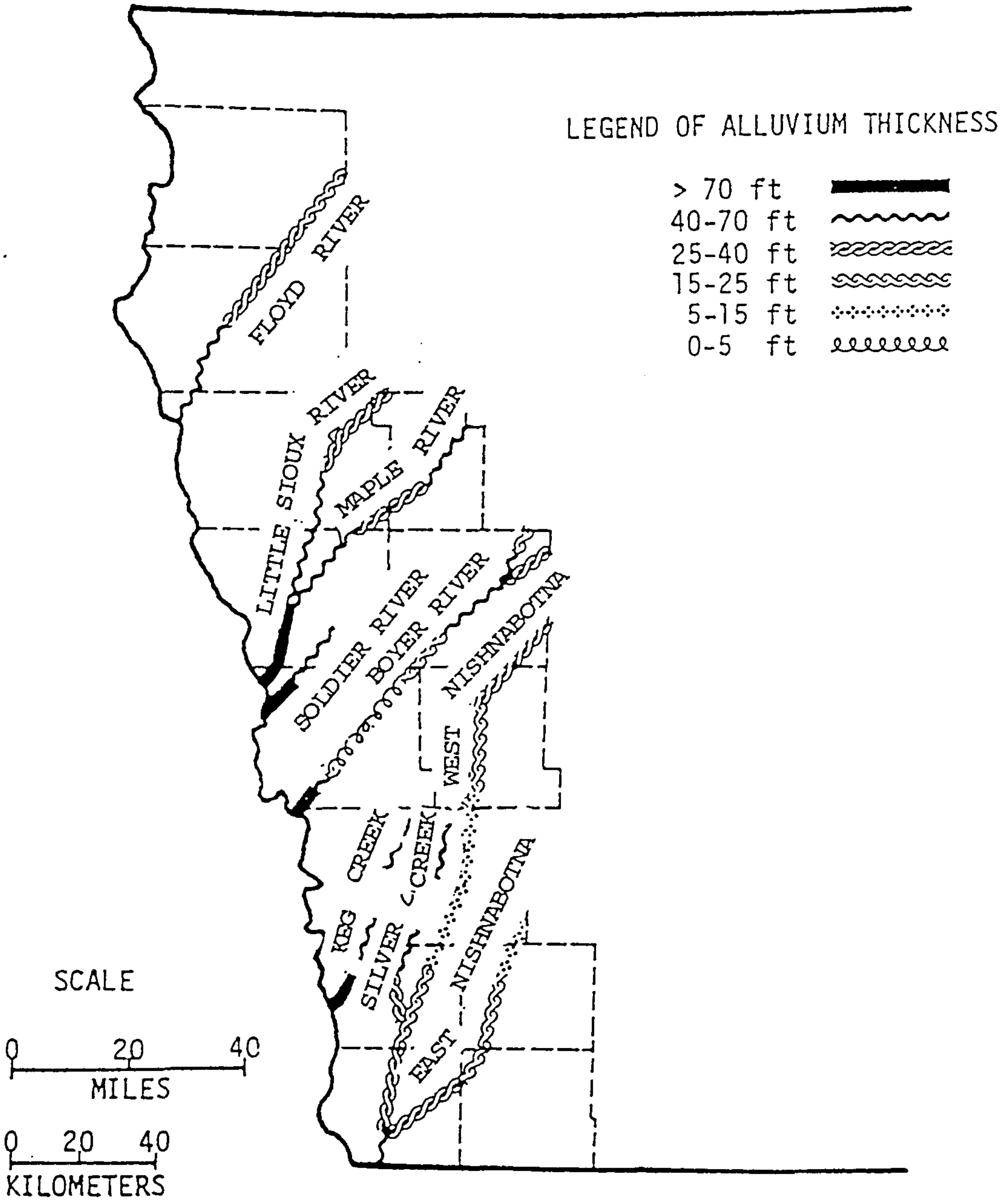

Figure 24. Thickness of alluvium beneath channel bottom. Modified from Lohnes et al. (1980).

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ratio is calculated by the following equation:

$$\frac{W}{D}=0.077X+5.23$$

where X = distance from the headwater in miles and W/D = the width to depth ratio. A second assumption is that the channel is trapezoidal and the bottom width is:

$$B=1.67X+12.79$$

where B = the bottom width of a trapezoidal channel with one to one side slopes and X = the distance from the headwater in miles. The third major assumption is that the Manning roughness coefficient = 0.035. Fourth, shear stress on the channel bed, τ, is assumed to be:

$$\tau=\gamma DS$$

where γ = the unit weight of water, D = the depth of the water in the channel, and S = slope of the channel. The final assumption is that the erosion resistance (critical shear stress) can be calculated from the channel geometry of the stable reach of the Willow. This erosion resistance was obtained from the original, stable channel cross section prior to straightening in 1916, in a reach of the river that appeared to be in vertical equilibrium. The section was determined to be in vertical equilibrium because it was aggrading downstream of the section. From the Willow survey, a uniform slope of 0.12 percent and a uniform cross section

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was estimated (Figure 25). Assuming bankfull capacity for the original stream, the erosion resistance and flow rate was determined to be 0.85 psf and 2700 cfs respectively.

The depth of the cross section and the slope is used to calculate the erosion resistance. The erosion resistance is assumed to be the shear stress for the stable channel.

Manning's equation is used to calculate the flow rate of the cross section:

$$Q=\frac{1.49}{n}AR^{\frac{2}{3}}S^{\frac{1}{2}}$$

where Q = flow rate (cfs), n = Manning roughness coefficient, A = area of the cross section (ft^2), R = hydraulic radius = wetted area/ wetted perimeter (ft), and S = slope of the channel. This flow rate (2700 cfs) is used to back calculate a recurrence interval, RI, of two years for the following discharge equation.

$$Q=422.58(LF)(RI)^{0.301}(D_a)^{0.504}$$

where LF = land use factor = 0.80, D_a = drainage area (sq mi), and Q in cfs.

The general steps used to calculate a stable stream bed elevation are as follows: First, a longitudinal profile of the present stream is plotted. Then, using the stream classification system, the stable portion of the stream is

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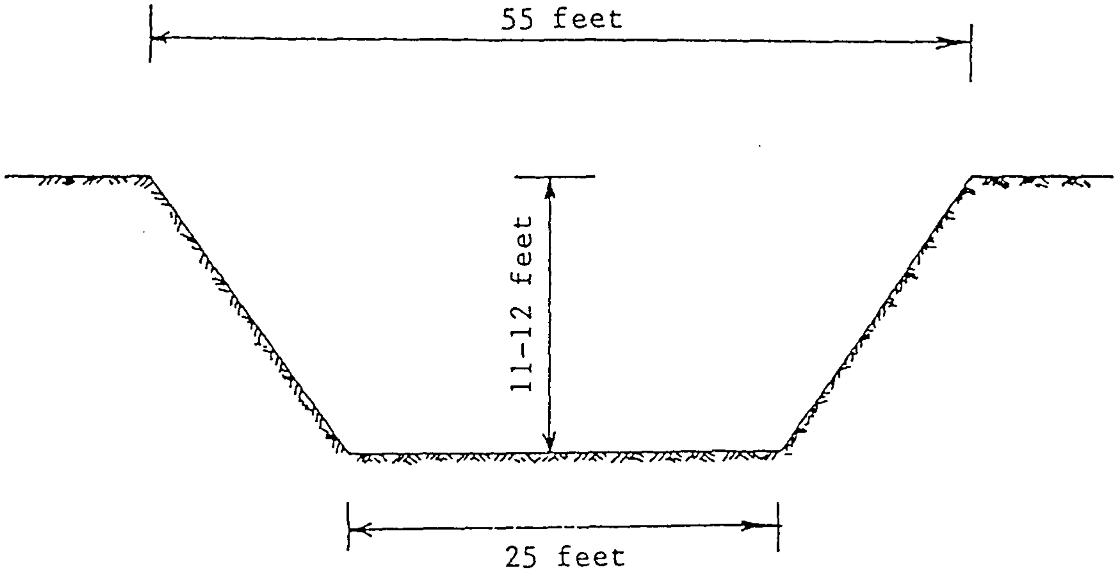

Figure 25. Approximate average cross section of the original Willow Creek. From Massoudi (1981).

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identified. The upstream end of the stable section is used as the starting point. The upstream unstable channel cross sections are divided into equal segments. For each section, the stream bed elevation, drainage area, and distance from theheadwater is recorded. The next step is to use the discharge equation assuming a land factor and a recurrence interval to calculate the discharge at each cross section. The land factor and recurrence interval that were assumed in the trial run were 0.80 and 2 respectively. Then, start the calculations of shear stress from the stable section and compare the next section's shear stress to the erosion resistance (critical shear stress). If the erosion resistance is less than the calculated shear stress the section is lowered by an increment of 0.25 inches and the shear stress recalculated. The section is lowered until the calculated shear stress is less than or equal to the erosion resistance. The channel will degrade until the shear stress equals the erosion resistance. Using the width to depth ratio and bottom width equations, the channel cross sectional geometry can be calculated assuming one to one side slopes of a trapezoidal channel.

Equations of the Tractive Force Model

Given the information of elevation of the stream bed, drainage area, and distance from the headwater; the flow and

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cross sectional geometry are calculated using the assumptions and flow equation. From the flow and cross sectional geometry at the trial locations, a depth of flow can be calculated by trial and error using the Manning and continuity equations.

$$V=\frac{1.49}{n}\frac{(BD+D^2)^{\frac{2}{3}}}{(B+2D\sqrt{2})^{\frac{2}{3}}}S^{\frac{1}{2}}$$

$$Q=VA=V(BD+D^2)$$

where V = Mannings velocity (ft/sec), n = Mannings roughness coefficient = 0.035, B = channel bottom width (ft), D = depth of flow (ft), and S = slope of the channel section (ft/ft). Once the flow depth is determined, the shear stress is calculated using $\tau = \gamma DS$ and compared to the erosion resistance of 0.85. If the calculated shear stress is greater than the erosion resistance, then the depth of the cross section is lowered by an increment of 0.25 feet and the change in cross section is calculated by

$$B=B_i+\Delta D(\frac{W}{D}-2)$$

$$S=S_{1+i}-\frac{\Delta D}{\Delta L}$$

where B = new bottom width (ft), B_i = bottom width prior to lowering (ft), ΔD = change in depth (ft), W/D = constant width to depth ratio, S = new slope, S_{i+1}= slope before lowering, and ΔL = length between sections (ft). The section is lowered

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until the erosion resistance is greater than the calculated shear stress (Massoudi, 1981).

Massoudi did his calculation on a mainframe computer which is not available to many county engineers. A Quick Basic computer program was written to do this repetitive process. This program can be run on any personal computer but preferably an IBM compatible 386 or 486. A copy of the program and output is shown in Appendix B. This program was run on Willow Creek, Keg Creek, McElhaney Creek, Indian Creek, and Walnut Creek. All predictions were based on Massoudi's (1981) assumptions. The Willow Creek 1966 profile was shown to be stable in the lower reaches but did degrade above the second grade control structure a maximum 11 feet below the original stream bed elevation (Figure 26 and 26a). Keg Creek was predicted to degrade a maximum of 5.5 feet since 1954 by the Tractive Force model (Figure 27 and 27a). Walnut Creek stable profile was predicted to degrade a maximum of 2.0 feet since 1976 (Figure 28). The Walnut Creek profile was plotted from USGS map contours. Indian Creek profile was plotted from 1976 USGS map contours and was predicted to downcut only 0.25 feet in scattered areas (Figure 29). McElhaney Creek stable profile was a maximum of 11.75 feet below the 1965 profile from USGS maps (Figure 30). The degradation for each stream is shown in Table 6.

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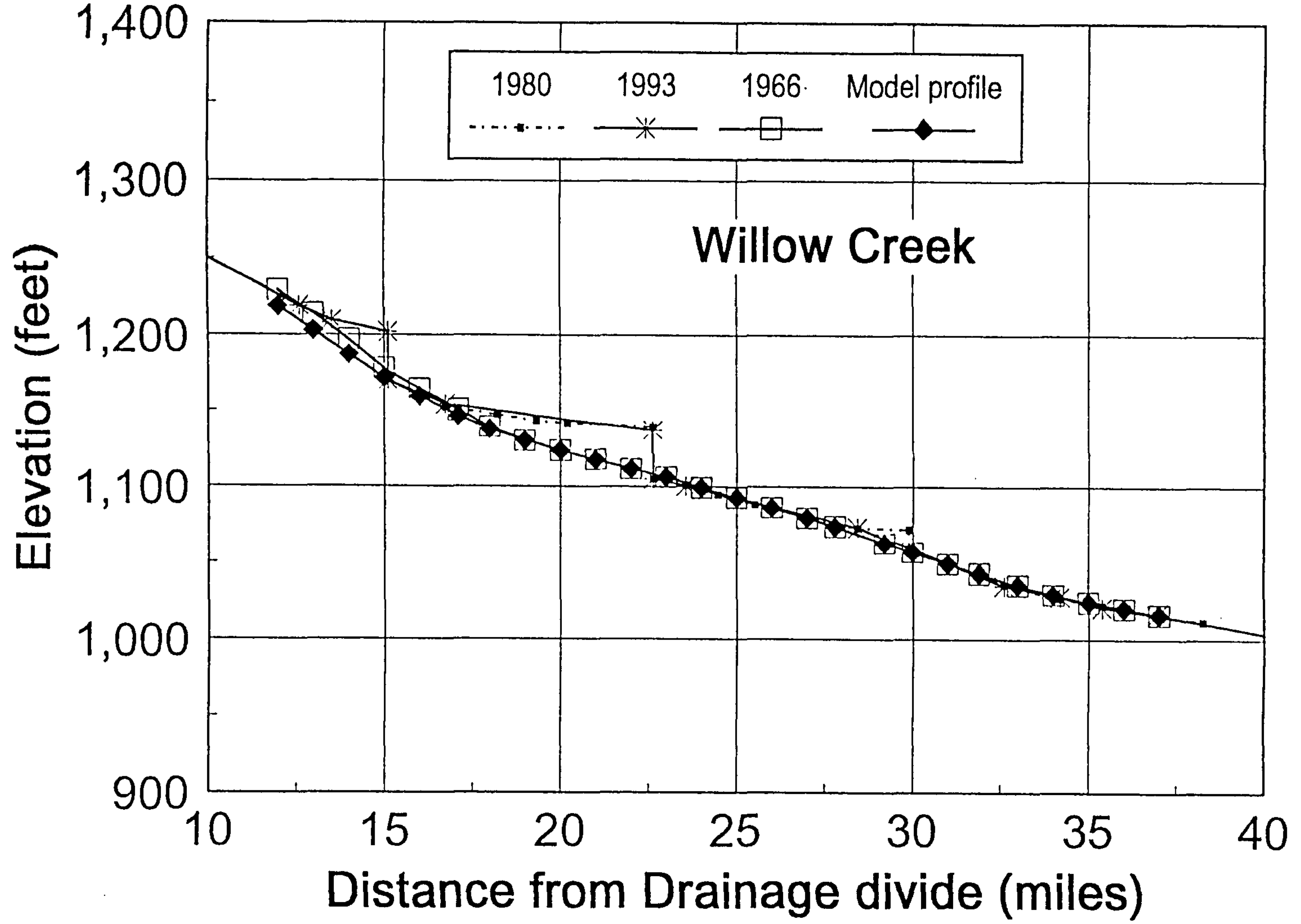

Figure 26. Willow Creek predicted stable longitudinal profile.

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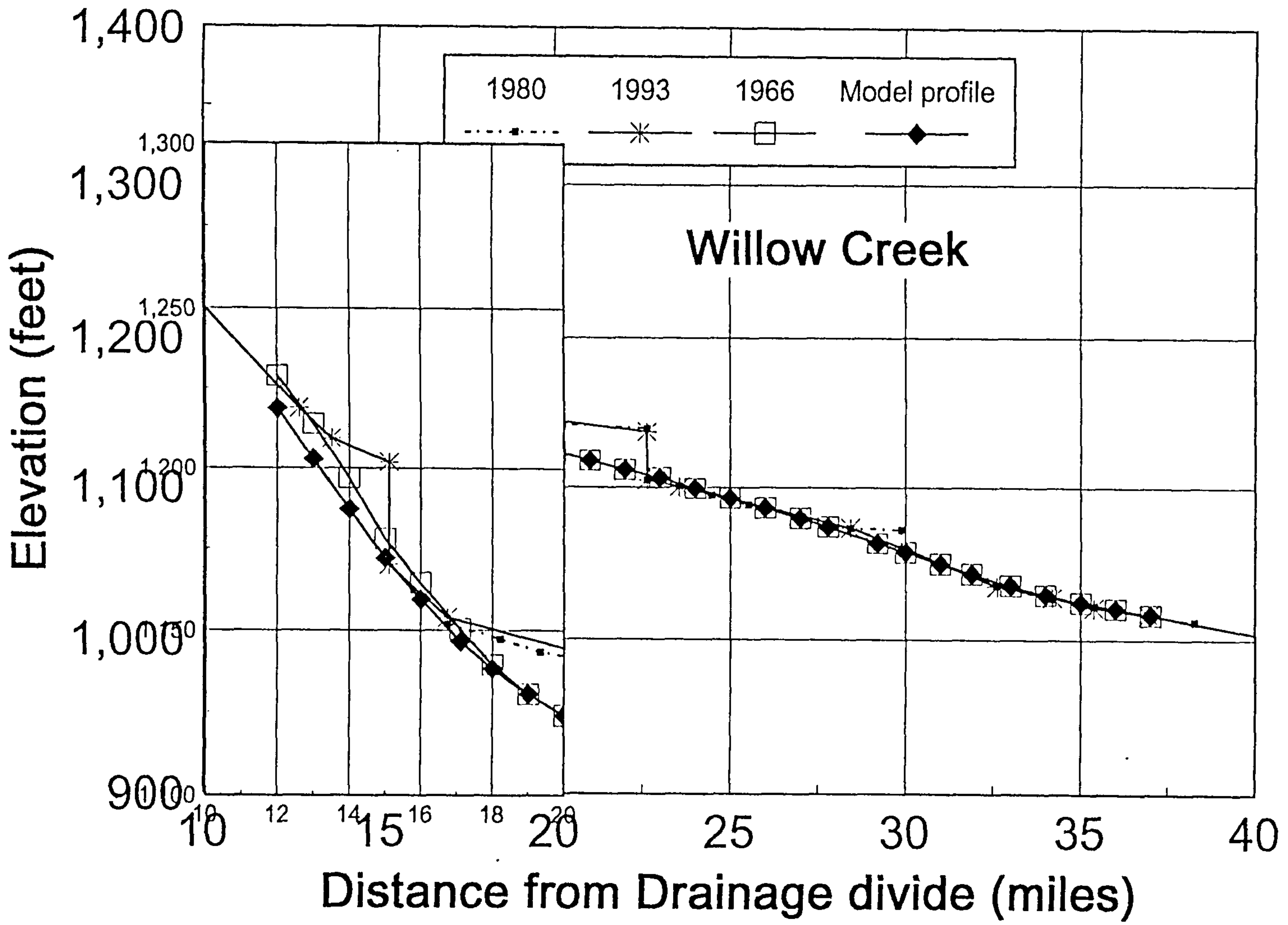

Figure 26a. Willow Creek detailed predicted stable longitudinal profile.

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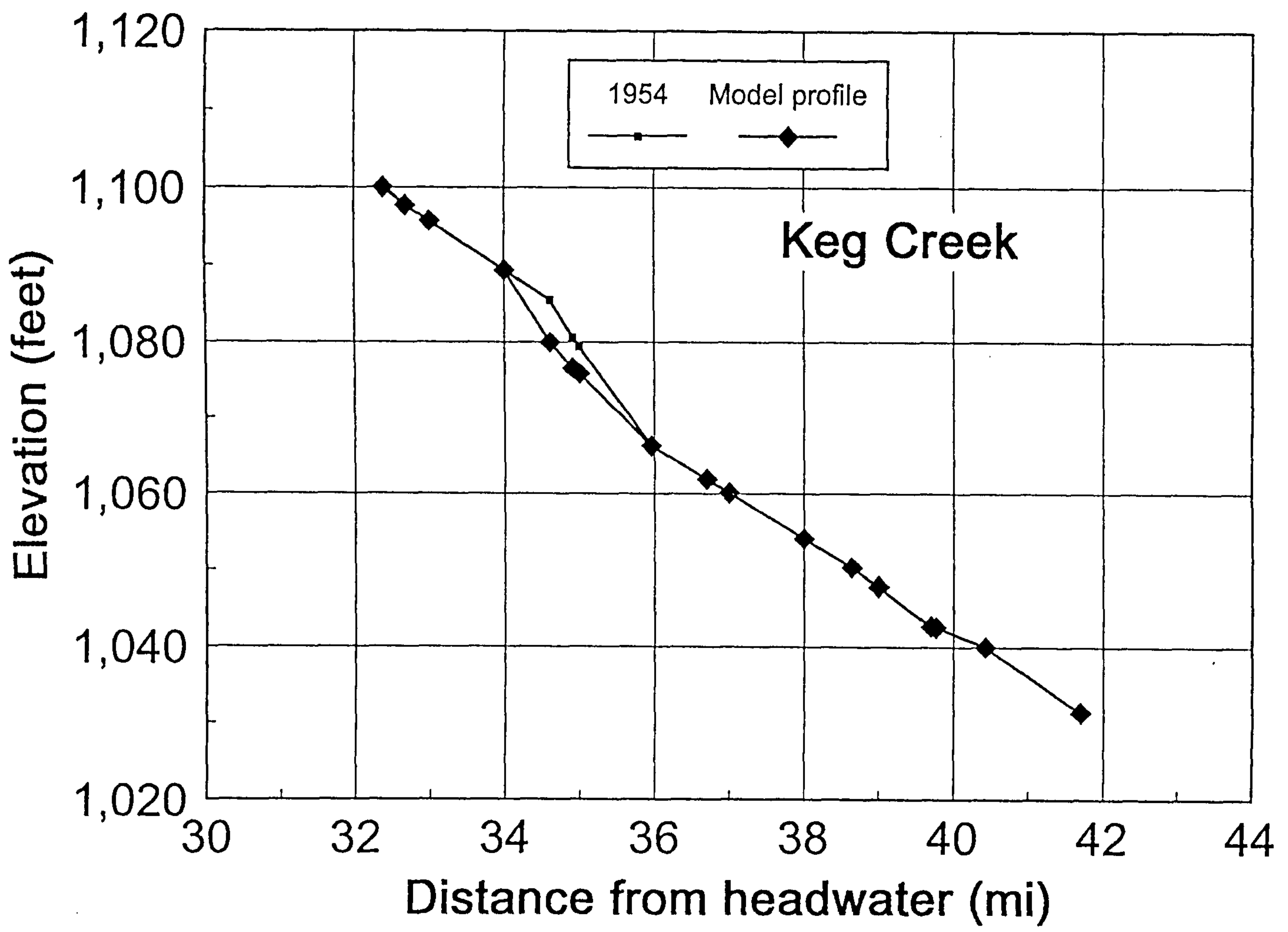

Figure 27. Keg Creek predicted longitudinal profile.

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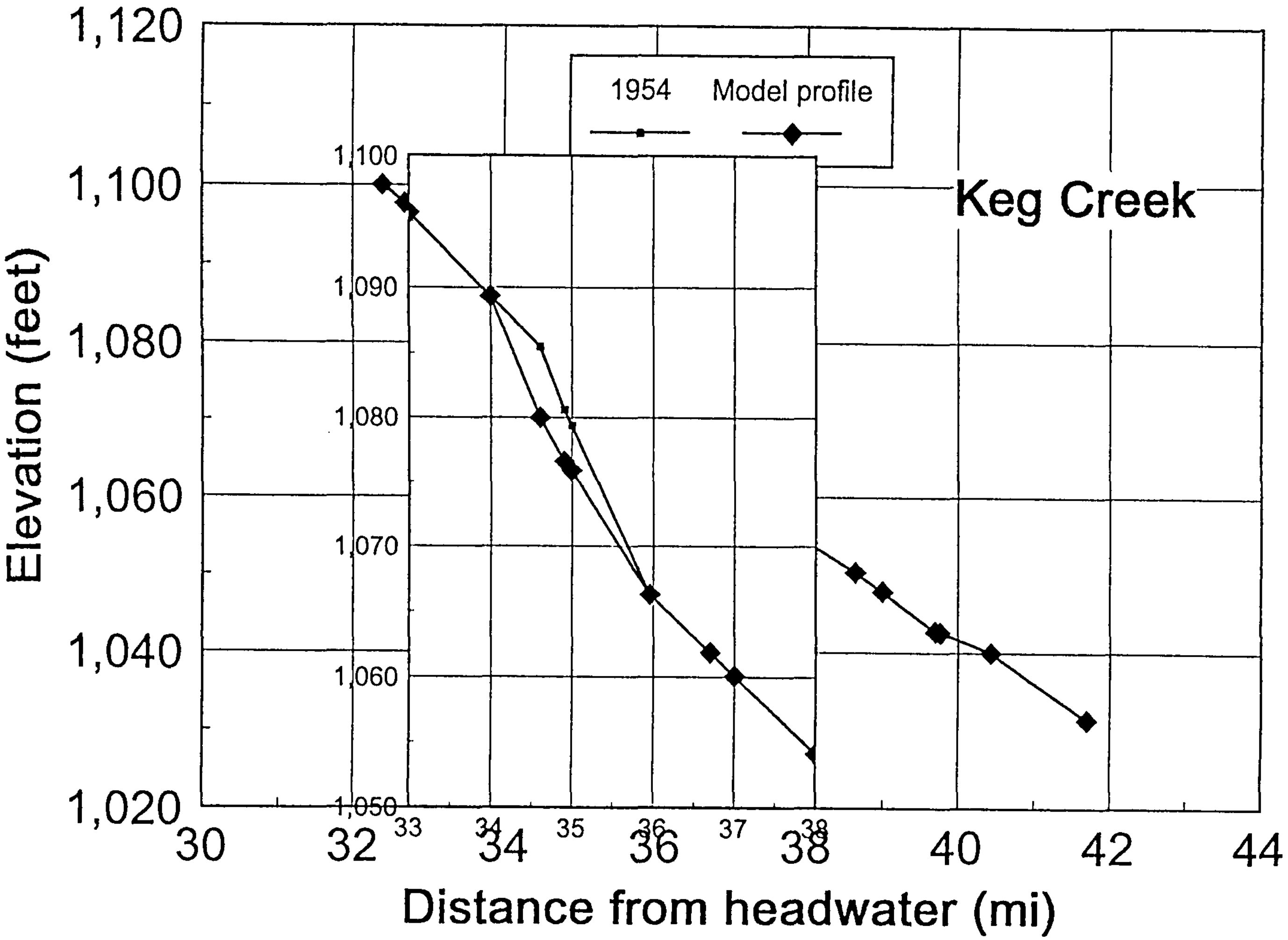

Figure 27a. Keg Creek detailed predicted longitudinal profile.

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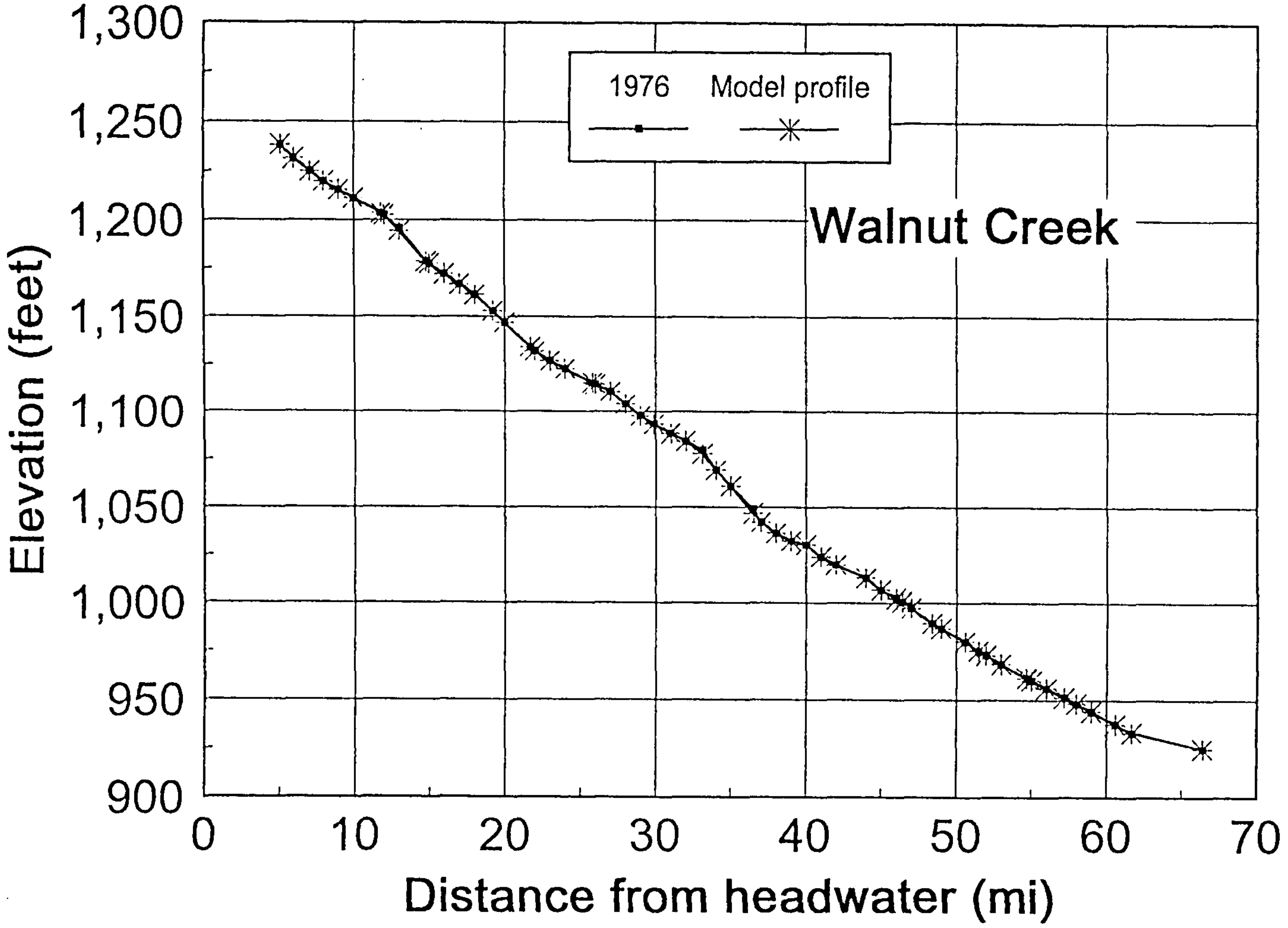

Figure 28. Walnut Creek predicted longitudinal profile.

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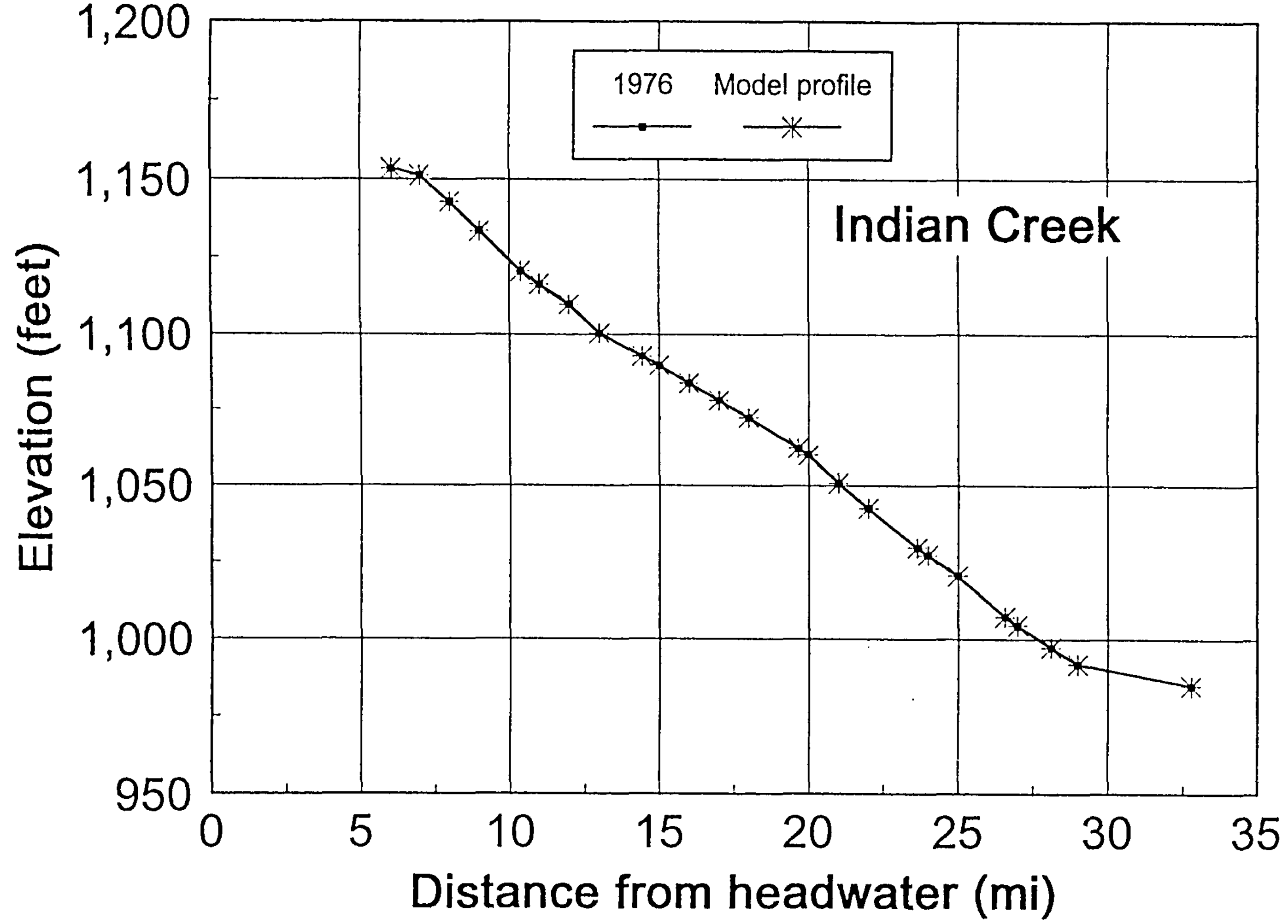

Figure 29. Indian Creek predicted longitudinal profile.

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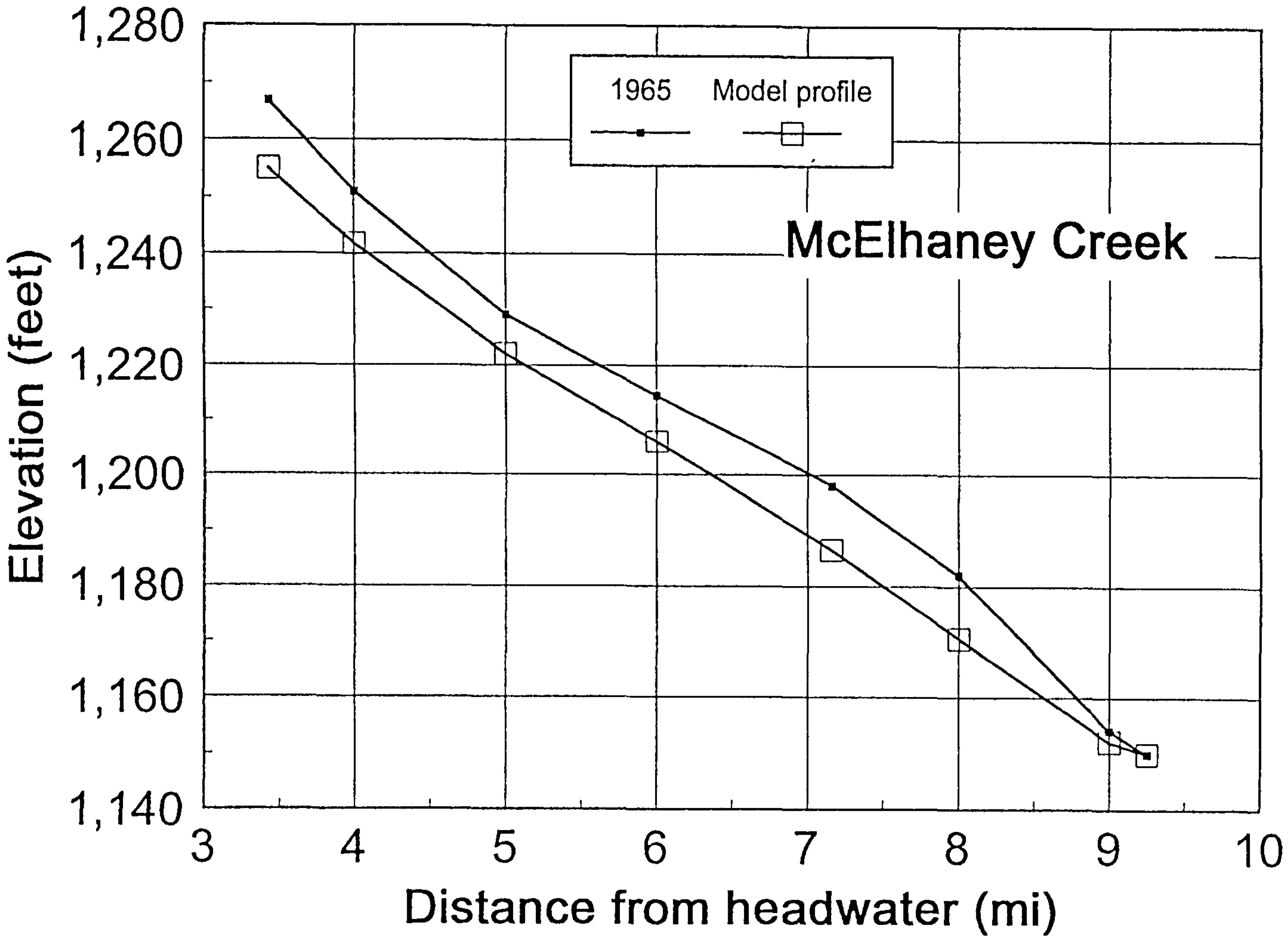

Figure 30. McElhaney Creek predicted longitudinal profile.

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Table 6. Summary of predicted degradation.

Stream	Year from which the degradation is calculated	Maximum Future Degradation (feet)	Distance from headwater (mile)
Willow Creek	1966	11	13.0
Keg Creek	1954	5.5	34.61
Walnut Creek	1976	2.0	33.1
Indian Creek	1976	0.25	20.0
McElhaney Creek	1965	11.75	3.43

Geological

The numerous gullies in the hills of western Iowa display the highly erodible nature of loess soil. Davidson and Handy (1952) indicate that loess has a low shearing strength. This low shearing strength may be related to its low resistance to erosion. The loess also has smaller particle sizes that could lead to its erodibilty.

A stream may degrade until it reaches a geological layer resistant enough to prevent future erosion. Bettis (Communication, 1993) states that the Gunder and Roberts Creek members of the DeForest Formation have higher erosion resistances than the Camp Creek member. The Roberts Creek member and the Gunder member are equally resistant to water tractive forces (Bettis Communication, 1993). Therefore, if the streams were controlled by the most erosion resistant member, the streams would follow the Roberts Creek or Gunder member. This agrees with the Daniels and Jordan (1966)

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interpretation that the Willow and Thompson Creeks follow the slope of the Roberts Creek member. However, the SCS strength data exhibit no statistical difference between the strengths of the three members of the DeForest Formation (Lohnes, 1991). It is possible that the strength measurements are not a good indication of erosion resistance of cohesive soils. The geologic member that a stream follows will also depend on the presence of the various members within the stream system.

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GRADE CONTROL STRUCTURE LOCATION

The process of determining if a stream is degrading and how far it will degrade is outlined in the flowchart in Figure 31. The first step is to determine the condition of the stream at the location of interest. The information needed for this step is the stream cross sectional geometry, vegetation cover on side slope, longitudinal profile and knickpoint location, and slope failure type. This information can be used to determine whether the stream is in the Meandering channel stage, Incipient condition, Active condition, or Stable condition. The criteria are based on field observations and historic information at the site. These stages were described in the stream classification section. If the stream is a natural meandering stream or stage I then a grade control structure is not recommended for the short term. However, if this stream system is disturbed the stream may begin to degrade until it reaches a new equilibrium then a grade control structure may be needed to protect bridges and other structures. For a stage II "Incipient condition" stream, the predictive model must be run. If the stream is predicted to degrade more than 5 feet then a grade control structure is recommended. However, if the model predicts less than 5 feet of additional degradation then a grade control structure is not recommended. This is

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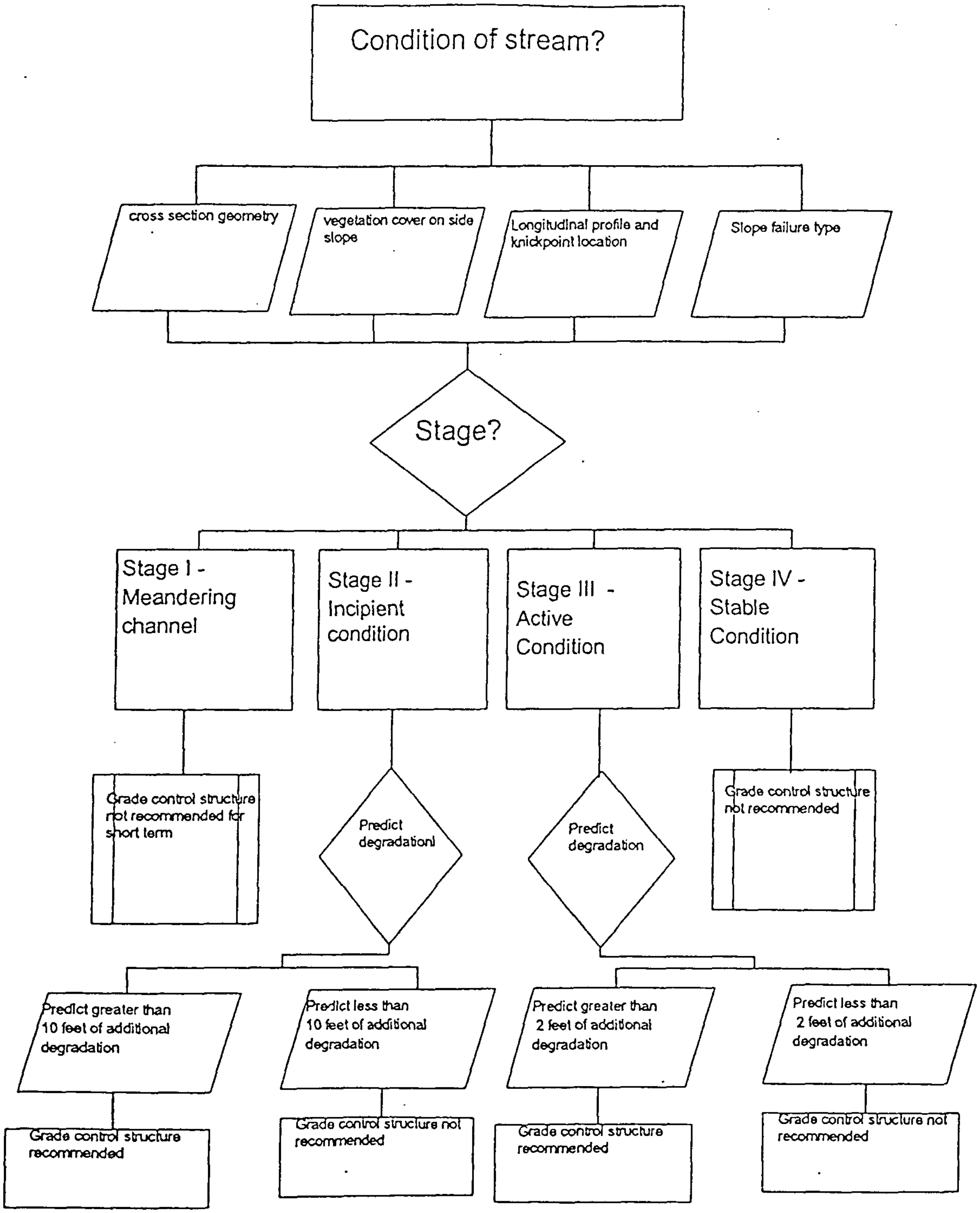

Figure 31. Flow chart of logic path used to determine if a grade control structure is required.

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assuming that existing bridges and pipelines can withstand less than 5 feet of degradation. Stage III streams are actively degrading therefore, the predictive model should be run. If the output of the model predicts that the stream will degrade greater than an additional 2 feet then a grade control structure is required to stabilize the stream. This two feet or more of degradation will endanger structures that have already been wekened by the degradation. If less than two feet of degradation is predicted then a grade control structure is not recommended. The equilibrium or stage IV "Stable Condition" does not require any grade control structures. A stream can be forced back to stage II if the equilibrium is disturbed by straightening the stream or lowering the base level.

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TRACTIVE FORCE PREDICTIONS

A Tractive Force model, derived by Massoudi (1981) was used to predict the stable profile of Willow Creek. The model is based on the assumption that erosion resistance controls the depth of degradation in a stream. The erosion resistance is compared to the calculated tractive shear stress of channel cross sections upstream of a stable reach to determine if the channel will degrade. The channel cross section degrades until the erosion resistance is greater than the calculated shear stress.

The erosion resistance is dependent on flow depth and channel slope. Massoudi calculated an erosion resistance of 0.85 psf for Willow Creek using a stable cross section from the prestraightened Willow channel. This erosion resistance was calculated assuming bankfull flow.

To calculate the erosion resistance, a channel forming discharge must be determined. Massoudi (1981) assumed that the channel forming discharge equaled the bankfull flow in the original prestraightened channel and was found to equal the two year recurrence interval for Willow Creek. Pickup and Warner (1976) determined the 1.58 year flood to be the most effective discharge; therefore, the two year flow is a reasonable estimate of the channel forming discharge.

The previous section of the report showed that when

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stream longitudinal profiles are plotted on semilog paper a profile consisting of two linear segments with the upstream segment having a flatter slope develops. This suggests that erosion resistance is variable within a single stream. Daniels and Jordan (1966) determined that different geologic members control the slopes of different streams. Therefore the erosion resistance does not only vary within one stream but also varies from stream to stream.

For this study, the erosion resistance was calculated for Keg Creek, Walnut Creek, Indian Creek, and McElhaney Creek at the furthest available cross section downstream that was assumed to be stable. This approach does not accommodate the variation of erosion resistance within a stream. The stable cross sections were developed from field measurements of bottom width and top width, and from calculating the channel depth assuming one-to-one channel side slopes. The calculated erosion resistance is used to compare calculated and observed degradation for streams with profiles at two different years. A Quick Basic program of the Tractive Force model was written to compute the new profiles. All profiles were based on estimated cross section data and calculated erosion resistance that does not vary along the stream.

Massoudi (1981) assumed that the width to depth ratio and the bottom width varied linearly downstream, and that the channel side slopes would remain at 45 degrees. These

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assumptions are not valid for all western Iowa streams; however because cross section data are unavailable for every stream, the assumptions were used to simplify calculations in the Tractive Force model.

Keg Creek Erosion Resistance Variation

The erosion resistance of Keg Creek was calculated using a stable cross section located near the Mills and Pottawattamie county border. This section of Keg Creek was located in Mills county with a top width of 85.0 feet, a bottom width of 32.0 feet, assuming one to one side slopes (Figure 32). The Drainage area for this section was approximately 137 square miles, which gives a two year flow of 4971.83 cfs from Massoudi's (1981) flow equation. The erosion resistance was determined to be approximately 0.89 psf for a stable stream gradient of 4.4 feet/mile and the two year flow. Table 7 shows the predicted degradation for an erosion resistance of 0.89 psf.

This erosion resistance underestimates the degradation by a factor of at least two. The erosion resistance could change in the upstream reaches due to a change in soil composition. Also, the width to depth ratio and the bottom width assumptions may not be valid for Keg Creek. Another possible reason for underestimating the degradation is the assumed

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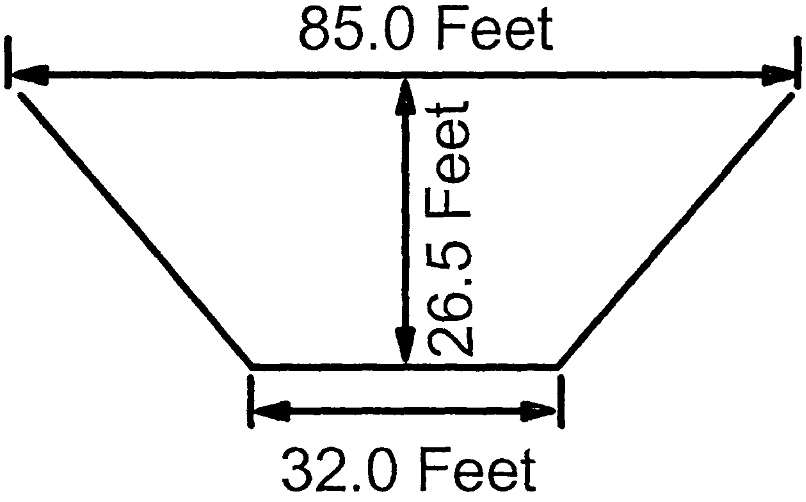

Figure 32. Keg Creek cross section located in Mills county that was used to calculate erosion resistance.

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Table 7. Degradation predicted on Keg Creek using calculated stable erosion resistance.

Distance from the headwater (miles)	Actual Degr. 1954-1972 (feet)	$\tau_c = 0.89$ Predicted Degr. (feet)	Slope (ft/mi)
32.38	1	0.00	8.67
32.68	4	0.00	6.31
33	5	0.00	6.32
34	8.11	0.00	6.33
34.61	10	4.75	16.33
34.91	9	3.25	13.67
35	8.67	3.00	13.61
35.96	5	0.00	5.97
36.7	4.78	0.00	5.97
37	4.69	0.00	5.97
38	4.32	0.00	5.97
38.64	4.17	0.00	6.86
39.0	3.73	0.00	7.33
39.7	2.6	0.00	1.67
39.76	2.8	0.00	3.88
40.43	4	0.00	6.77
41.7	3	0.00	

downstream stable reach may not have been stable. If this downstream reach was unstable, the reach would degrade, causing more degradation to occur upstream.

Comparison of Erosion Resistances

The erosion resistance of Walnut Creek, Indian Creek, and McElhaney Creek was calculated using the same procedure as conducted on Keg Creek: assuming a two year channel forming discharge, assuming one to one channel side slopes, and calculating the stable channel gradient near the assumed stable cross section. The channel cross section used to

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calculate the erosion resistance was located near the mouth of the stream, or where the channel was assumed to be in vertical equilibrium. The erosion resistances for Keg Creek, Walnut Creek, Indian Creek, McElhaney Creek and Willow Creek are shown in Table 8.

The calculated difference in erosion resistance between streams might be related to clay content, loess thickness, or slope of stable section.

The clay content of the upland loess from Handy's (1973) clay content variation within Iowa loess deposits is shown in Figure 33. The approximate clay contents and loess thicknesses for each stream cross section are listed in Table 8.

Table 8. Calculated erosion resistance.

Stream	Calc. Erosion Res.	Drainage Area (sq. mi)	Distance from headwater (mi)	Channel slope (ft/mile)	Clay	Loess Thick. (feet)
Willow Creek	0.85	34.7	16.74	6.34	28	75
Keg Creek	0.89	137	43.7	4.40	22	75
Walnut Creek	0.89	52.6	19.2	4.54	35	23
Indian Creek	0.40	67.72	32.28	1.85	26	35
McElhaney Creek	1.23	17.32	8.61	16.68	27	<10

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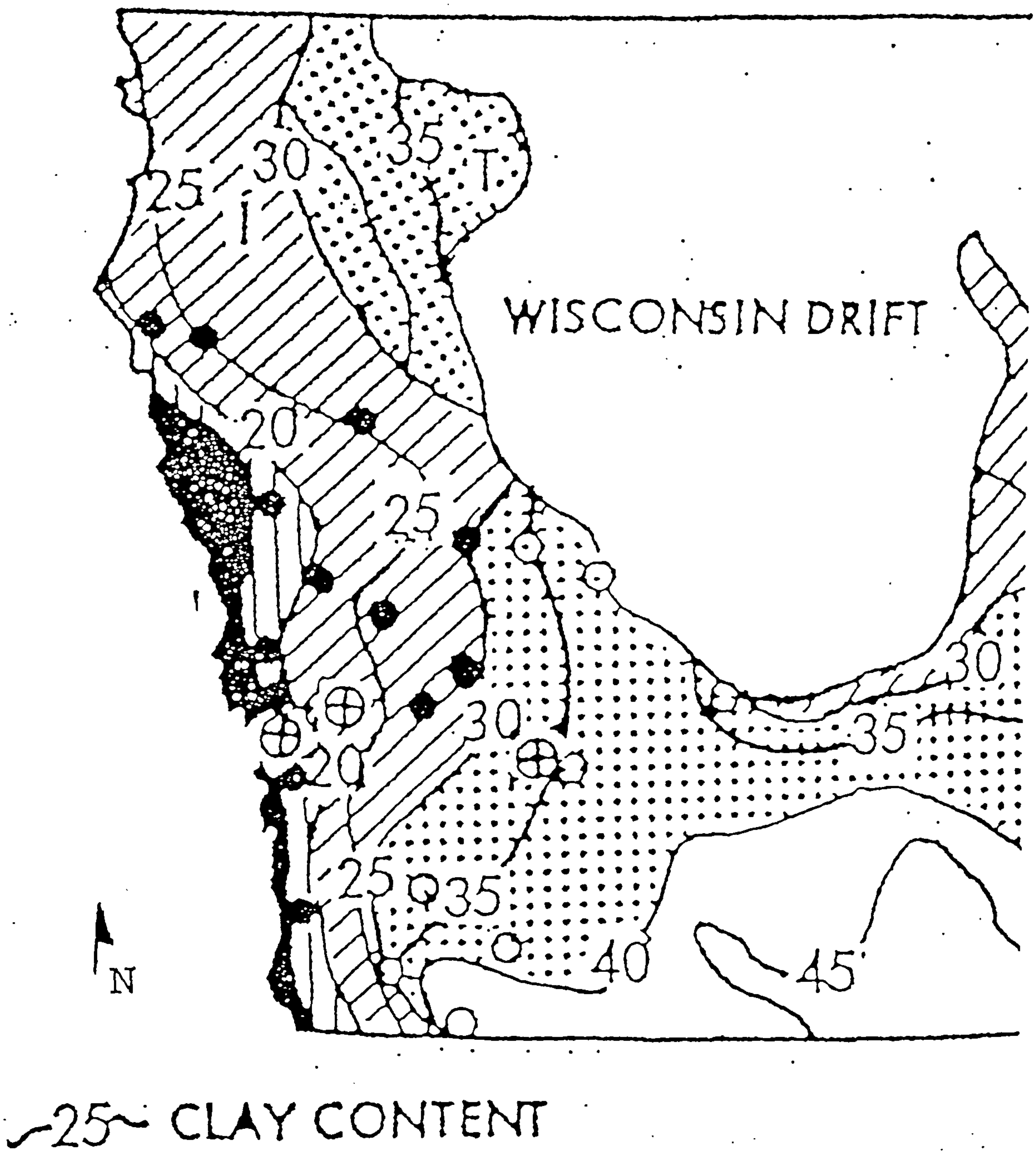

Figure 33. Clay content percent in Western Iowa Loess. Modified from Handy (1973).

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No correlation exists between erosion resistance and either clay content or loess thickness. The erosion resistance increases with slope, but this trend has scatter (Figure 34). Slope is a critical variable in the Tractive Force model. As shown in Table 7, the predicted stream degradation also depends on the slope of the existing channel. Slope is not only related to erosion resistance but also is related to the amount of calculated degradation.

The Tractive Force model was used to calculate the future degradation based on the calculated erosion resistance for each stream. Data for the initial and calculated stream profiles for Keg Creek, Walnut Creek, Indian Creek, and McElhaney Creek are in Appendix C. Their respective predicted stable profiles are shown in Figures 35 and 36.

The predicted maximum degradation varied from 16.25 feet on Indian Creek to 1.75 feet on Walnut Creek. Maximum predicted degradations for Keg Creek, Walnut Creek, Indian Creek and McElhaney Creek are shown in Table 9.

Table 9. Maximum predicted degradation.

Stream	Calculated Erosion Resistance (psf)	Maximum Predicted Degradation (feet)	Distance from headwater (mile)	Percent of Stream Length
Keg Creek	0.89	4.75	34.61	54.4
Walnut Creek	0.89	1.75	33.1	51.5
Indian Creek	0.40	16.25	20.0	65.9
McElhaney Creek	1.23	5.75	8.0	37.1

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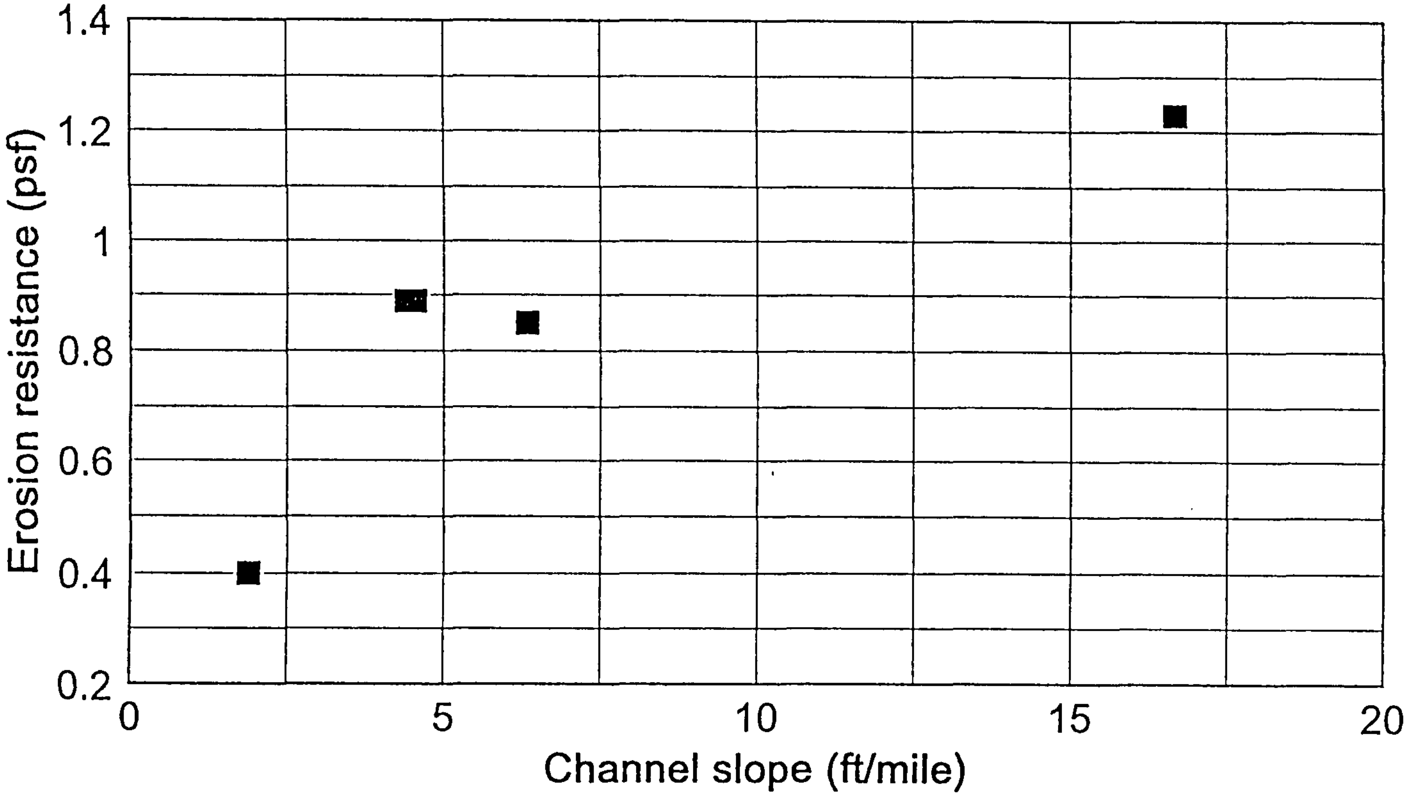

Figure 34. Relationship between erosion resistance and slope of the stable channel.

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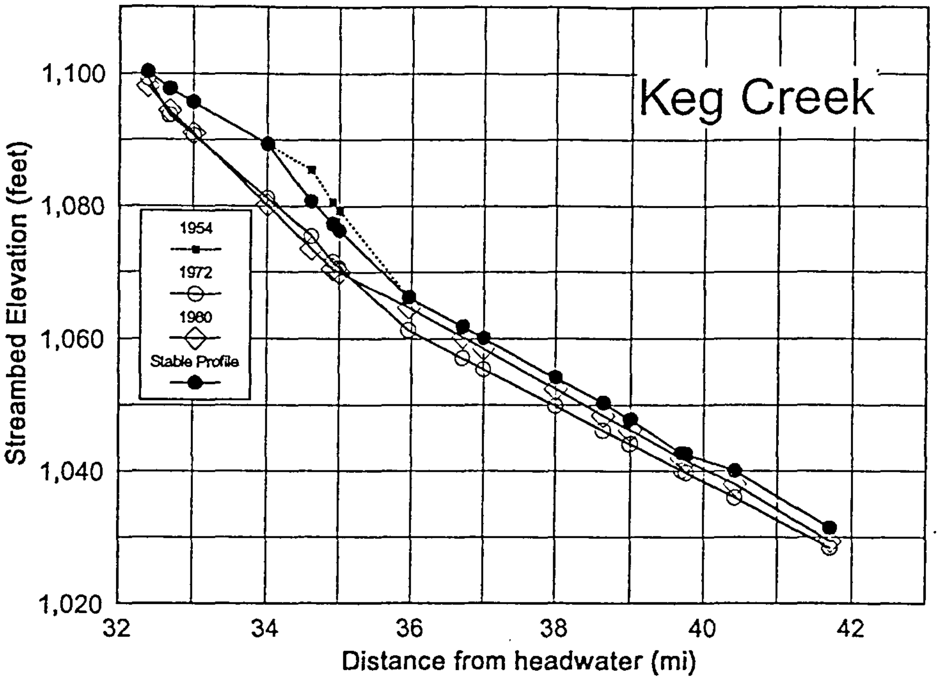

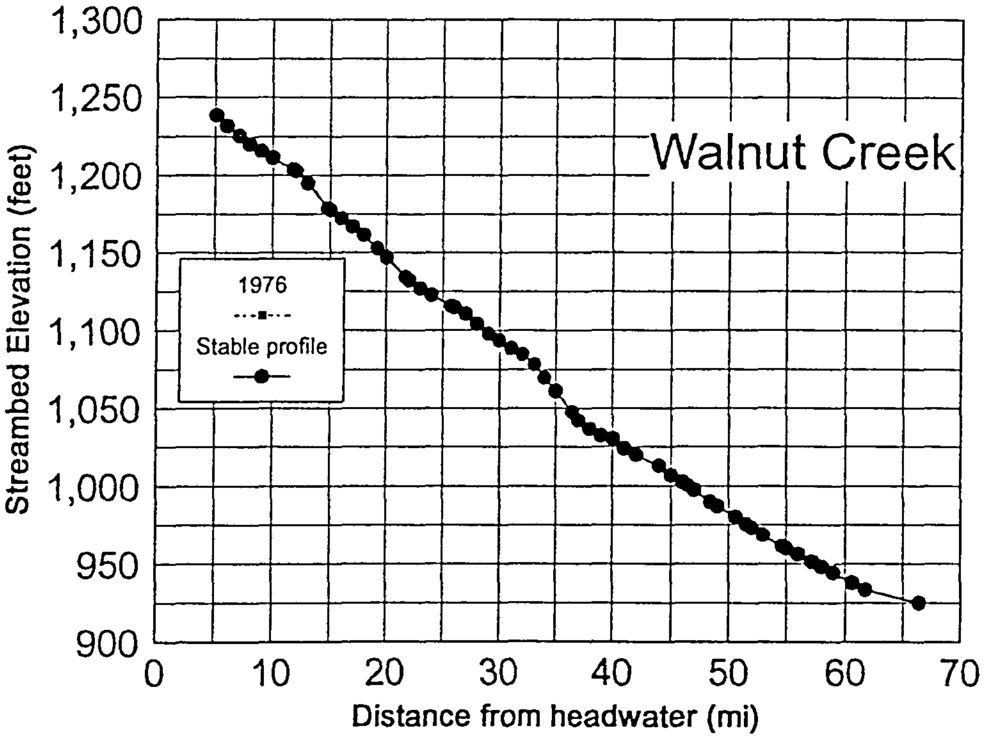

Figure 35. Keg Creek and Walnut Creek predicted stable profiles using calculated erosion resistances.

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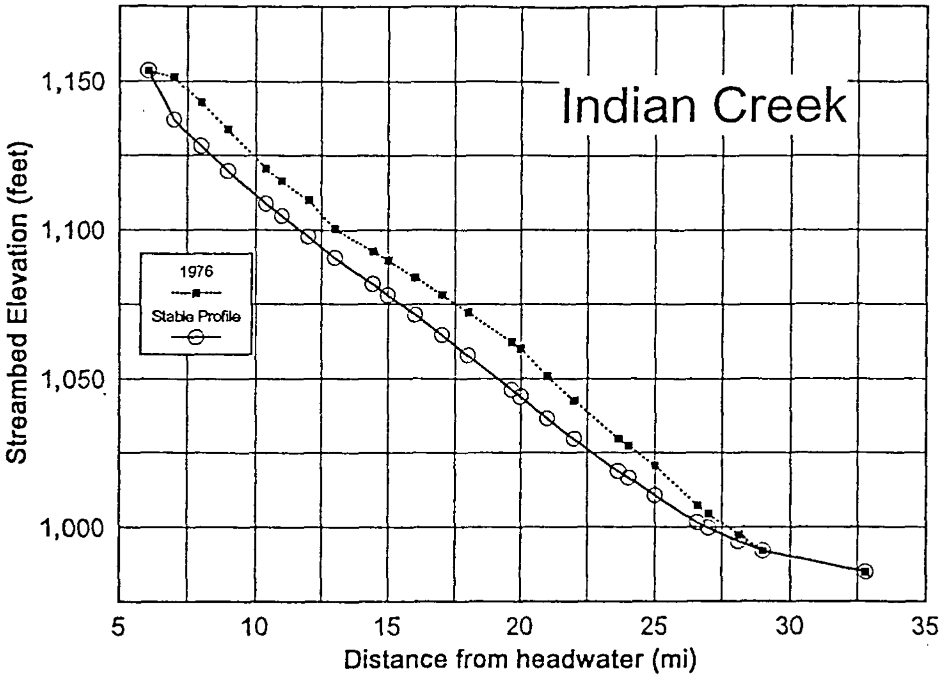

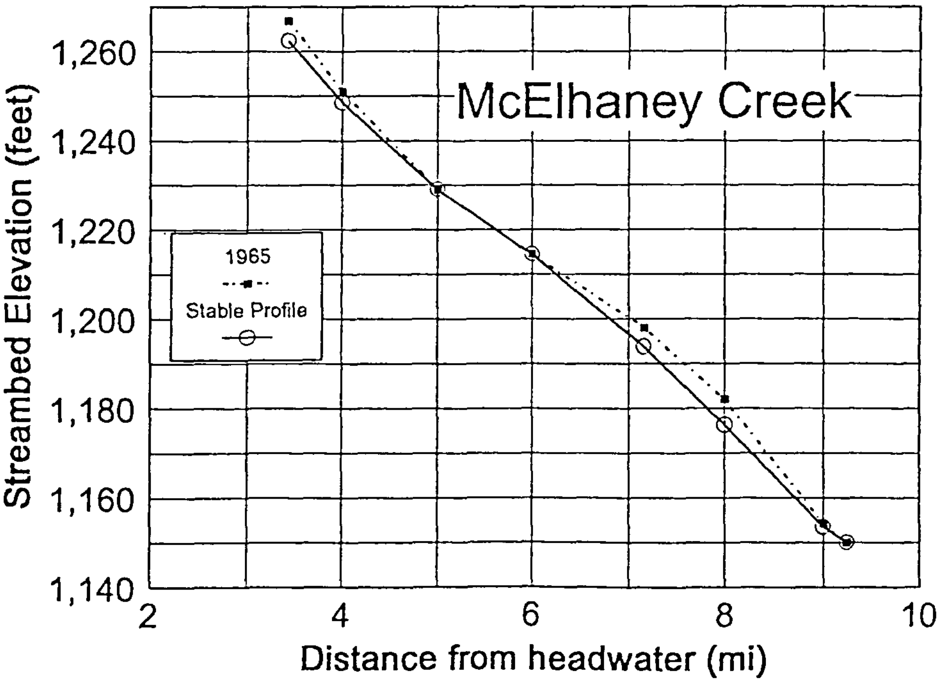

Figure 36. Indian Creek and McElhaney Creek predicted stable profile using calculated erosion resistances.

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Profiles of different years were unavailable for Walnut Creek, Indian Creek, and McElhaney Creek. Therefore the predicted degradation could not be compared with actual degradation. The degradation predictions may be higher or lower than the actual degradation. If erosion resistance was calculated in an unstable portion of the stream, the predicted degradation would be less than the actual degradation due to overestimating the erosion resistance. The erosion resistance may vary along the stream because of changing geology. This causes the predicted degradation to vary. The assumed downstream stable reach may not have been stable. If this downstream reach was unstable, the reach would be lowered, causing an underestimation of the actual degradation. The erosion resistance was calculated from cross section data with assumed one-to-one side slopes and an assumed average stable slope which may not be valid.

Comparison of constant erosion resistance with calculated

The predicted degradations for Keg Creek, Walnut Creek, Indian Creek, and McElhaney Creek were calculated using the erosion resistance of 0.85 psf calculated for Willow Creek and a calculated erosion resistance from Table 8. The maximum degradations predicted with the different erosion resistances were located at the same reach in each stream except McElhaney

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Creek (Table 6 and 9). The maximum degradation increased when the erosion resistance decreased. Indian Creek's maximum degradation increased from 0.25 feet to 16.25 feet using a calculated erosion resistance that was less than one-half the erosion resistance calculated for Willow Creek. Keg Creek and Walnut Creek calculated erosion resistances were approximately 1.05 times the erosion resistance of Willow Creek. This caused a decrease from 5.5 to 4.75 feet and 2.0 to 1.75 feet of maximum degradation. Increasing the erosion resistance on McElhaney Creek from 0.85 to 1.23 psf caused the maximum predicted degradation to be decreased by a factor of two.

There is no clear way of determining whether the Willow Creek erosion resistance for every stream or a stream specific erosion resistance is more accurate without comparing more profiles of expected versus predicted degradation. However, calculating the erosion resistance for each stream is intuitively a more pleasing method of determining the predicted degradation because alluvium characteristics vary from one location to another.

Discussion of the Tractive Force Model

Massoudi (1981) developed the Tractive Force model on geohydraulic principles of stream channel erosion. This model depends on determining an erosion resistance of the stream.

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Massoudi ingeniously back calculated erosion resistance from a stable reach of Willow Creek. Also Massoudi's assumptions on channel geometry made the Tractive Force model programmable.

However, to apply this model, a stable reach of the stream must be identified, detailed cross sectional data must be obtained, and the erosion resistance must be calculated. If the stream geology changes the erosion resistance may change, requiring a new stable cross section to be surveyed in this reach. The stream's cross sectional geometry must either be assumed from Massoudi's assumption or measured in the field. Therefore, the Tractive Force model requires a large amount of field work that makes it difficult to apply.

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CONCLUSIONS

The streams in western Iowa have entrenched deeply into the thick loess deposits. The cause of this entrenchment is not clear, but a combination of man made changes and climatic changes are possible. It is obvious that the degradation of these streams has damaged many bridges and utilities. The degradation problem can be controlled by the installation of grade control structures, however, the optimum design and placement of these structures requires an estimation of the final stable profile.

Two predictive models were analyzed. The Hack model can be applied to short reaches of a stream where the geology does not change. The Hack model is simple and easy to apply; however, for longer reach predictions where streams have flatter slopes in the upstream reaches it is impossible to apply. Therefore, the Tractive Force model may be more useful in predicting stable profiles for longer reaches of the streams provided the erosion resistance of the various reaches can be determined.

The Tractive Force model requires field work which consists of locating a stable section, measuring the cross sectional geometry, and calculating the erosion resistance at that section. The predicted stable channel depends on Massoudi's assumptions of channel geometry, channel forming

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flow, and a constant erosion resistance. A more accurate determination of a final stable profile requires measuring the channel geometry and determining changes in the geology of the stream. The Tractive force method is limited by geology because if the geology changes the erosion resistance will change. Therefore both the Hack and the Tractive Force models require detailed information on the stream's geology.

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RECOMMENDATIONS

The Hack model and Tractive Force model both require knowledge of the stream's geology. A thorough mapping of the geologic members in the streams is recommended. Also, strength data should be obtained for the DeForest Formation members. The strength measurements might be related to the erosion resistance of each member.

More research is necessary to study the effects of geology on erosion resistance and to study the effects of the 1993 floods. The 1993 floods may have reactivated degradation or mass movement on streams that are currently considered stable.

A useful modification of the Tractive Force model would be to vary the erosion resistance within each stream. The erosion resistance would be calculated at a stable cross section in every reach of the stream where the geology changed. If the geology changed systematically downstream a function could be developed for the erosion resistance versus distance from headwater.

Upon review of all the different options available to predict stream degradation, the most practical method may be to develop longitudinal profiles for degrading streams at various dates. These profiles could be compared to determine whether degradation rate is increasing or decreasing from year

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to year. This would require field surveys of streams to be completed. The most practical approach would be to develop a standard bridge inspection report that would measure channel cross section changes with respect to degradation.

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APPENDIX A.

STREAM REACH TYPE, STRAIGHT OR MEANDERING

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Table 1A. Keg Creek, Walnut Creek, and Indian Creek reaches.

Stream	distance from headwater (miles)	k now	Channel description
Keg Creek	0 - 23.26		straight (9.10 floodplain)
	23.26 - 24.01		meandering
	24.01 - 24.46		straight
	24.46 - 26.51		meandering
	26.51 - 27.10		straight
	27.1 - 34.41	-532.1	meandering
	34.41 - 36	-532.1	straight
	36-62.56	-538.5	straight (58.08 bluffline)
Walnut Creek	0 - 3.58		straight
	3.58 - 3.85		meandering
	3.85 - 13.39	-95.4	straight (6.48 floodplain)
	13.39 - 14.4	-285.3	meandering
	14.44 - 21.1	-285.3	straight
	21.15 - 21.82	-285.3	meandering
	21.82 - 30	-285.3	straight
	30 - 49	-532.4	straight
	49.00 - 49.8	-532.4	meandering
	49.89 - 51.68	-532.4	straight
	51.68 - 52.65	-532.4	meandering
	52.65 - 64.28	-532.4	straight
Indian Creek	0 - 13.57	-196.2	straight (6.41 floodplain)
	13.57 - 14.23	-196.2	meandering
	14.23 - 14.82	-196.2	straight
	14.82 - 18.85	-196.2	meandering
	18.85 - 19.22	-196.2	straight
	19.22 - 20.0	-196.2	meandering - straight
	20 - 20.16	-416.3	meandering - straight
	20.16 -20.34	-416.3	straight (bridge)
	20.34 - 21.39	-416.3	meandering-straight
	21.39 - 22.88	-416.3	straight
	22.88 - 23.32	-416.3	meandering
	23.32 - 24.00	-416.3	straight
	24.00 -24.33	-416.3	meandering
	24.33 - 24.93	-416.3	straight
	24.93 - 26.27	-416.3	straight-meandering
	26.27 - 26.42	-416.3	straight (railroad)
	26.42 - 27.13	-416.3	meandering
	27.13 - 27.95	-416.3	straight
	27.95 - 29.59	-416.3	meandering
	29.59 -30.33	-416.3	straight

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Table 2A. McElhaney Creek, Willow Creek, and Maple River reaches.

Stream	headwater (miles)	k now	Channel description
McElhaney Creek	0-3.25		meandering
	3.28-4.06	-211.3	straight (3.43 floodplain)
	4.06 - 5.85	-211.3	meandering
	5.85 - 6.30	-211.3	straight
	6.30 - 6.60	-211.3	meandering
	6.60 - 7.00	-211.3	straight
	7.00 - 9.25	-439	straight
Willow Creek	0 - 4.03	-175.5	meandering-straight
	4.03 - 5.22	-175.5	meandering
	5.22 - 6.08	-175.5	meandering (6.08 Floodplain)
	6.08 - 6.79	-175.5	straight
	6.79 - 12.38	-175.5	meandering-straight
	12.38 - 12.68	-391.4	straight (road)
	12.68 - 14.62	-391.4	meandering
	14.62 - 23.94	-391.4	straight
	23.94 - 25.43	-391.4	meandering
	25.43 - 36.76	-391.4	straight (36.76 bluffline)
	36.76 - 43.92	-391.4	straight
Maple River	0 - 3.6	-103.4	straight - meandering
	3.6 - 4.5	-103.4	meandering
	4.5 - 6.6	-103.4	straight
	6.6 - 8.9	-103.4	straight - meandering (8.5 floodp
	8.9 - 12.2	-103.4	straight
	12.2 - 14.5	-103.4	meandering
	14.5 - 16.9	-103.4	straight
	16.9 - 22.0	-103.4	meandering
	22.0 - 22.4	-103.4	straight
	22.4 - 25.3	-103.4	meandering
	25.3 - 34.5	-532.9	straight
	34.5 - 35.8	-532.9	straight - meandering
	35.8 - 36.9	-532.9	straight
	36.9 - 38.4	-532.9	straight - meandering
	38.4 - 40.7	-532.9	meandering
	40.7 - 41.2	-532.9	straight
	41.2 - 43.3	-532.9	meandering
	43.3 - 44.1	-532.9	straight
	44.1 - 48.8	-532.9	meandering
	48.8 - 49.8	-532.9	straight
	49.8 - 54.1	-532.9	meandering
	54.1 - 58.0	-532.9	straight - meandering
	58.0 - 64.5	-532.9	meandering
	64.5 - 70.8	-532.9	straight - meandering
	70.8 - 83.5	-532.9	meandering
	83.5 - 89.4	-532.9	straight

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APPENDIX B.

TRACTIVE FORCE PROGRAM

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TRACTIVE FORCE PROGRAM

```
DECLARE SUB LOWER (N!, ELEVATION!(), WD!(), TAU!(),
                 DISTANCE!(), SLOPE!(), BOTTOM!(), TAUC!,
                 FLOW!(), NUM!)
DECLARE SUB DEPTH (FLOW!(), SLOPE!(), BOTTOM!(), Y!,
                   FLOWDEPTH!(), TQ!())
DECLARE SUB CRITICAL (ELEVATION!(), D!, WD!(), TAU!(),
                      DISTANCE!(), SLOPE!(), FLOW!(),
                      BOTTOM!(), NUM!, TAUC!)
COMMON SHARED Y, TQ(), MAN(), Q, N
COMMON SHARED FLOW(), SLOPE(), BOTTOM(), FLOWDEPTH()
CLS
INPUT "NUMBER OF SECTIONS       ", NUM
DIM SHARED DISTANCE(NUM)
DIM SHARED FLOW(NUM)
DIM SHARED BOTTOM(NUM)
DIM SHARED SLOPE(NUM + 1)
DIM SHARED WD(NUM)
DIM SHARED TAU(NUM + 1)
DIM SHARED ELEVATION(NUM)
DIM SHARED DRAINAGE(NUM)
INPUT "LAND USE FACTOR  ", LF
INPUT "RECURRENCE INTERVAL      ", RI
INPUT "EROSION RESISTANCE (CRITICAL SHEAR STRESS)", TAUC

REM THE DATA MUST BE PLACED IN STARTING AT AN STABLE REACH
    AND GOING UPSTREAM TO THE HEADWATER

PRINT "START FROM FIXED SECTION AND WORK UPSTREAM"
FOR N = 1 TO NUM
INPUT "ENTER DISTANCE FROM DRAINAGE DIVIDE IN MILES OF THE
       SECTION      ", DISTANCE(N)
INPUT "ENTER ELEVATION OF SECTION IN FEET        ",
       ELEVATION(N)
INPUT "ENTER THE DRAINAGE AREA  ", DRAINAGE(N)
NEXT N
CLS
N = 1

REM Calculate width to depth ratio and bottom width and flow
    condition
REM WD is width to depth ratio
REM BOTTOM is the bottom width in feet
REM FLOW is the flow in cfs

FOR N = 2 TO NUM
WD(N) = .077 * DISTANCE(N) + 5.23
BOTTOM(N) = 1.67 * DISTANCE(N) + 12.79
```

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```
FLOW(N) = 422.58 * LF * ((RI) ^ .301) * DRAINAGE(N) ^ .504
NEXT N


REM calculate the slope of the stream from the upstream
    section to the downstream section

N = 2

FOR N = 2 TO NUM
SLOPE(N) = (ELEVATION(N) - ELEVATION(N - 1)) / ((DISTANCE(N
            - 1) - DISTANCE(N)) * 5280)
NEXT N

N = 1
LPRINT " THE INTIAL INPUT DATA"
LPRINT " ELEVATION,DISTANCE FROM DRAINAGE DIVIDE,
       DRAINAGE AREA, SLOPE"
FOR N = 1 TO NUM
LPRINT USING "#######.#####,"; ELEVATION(N); DISTANCE(N);
                              DRAINAGE(N); SLOPE(N)
NEXT N

REM DIMENSION THE ARRAYS

DIM SHARED FLOWDEPTH(NUM)
DIM SHARED TQ(NUM)
DIM SHARED MAN(NUM)
DIM SHARED V(NUM)
DIM SHARED C(NUM)


REM CALCULATE DEPTH OF FLOW BY TRIAL AND ERROR
REM CALCULATE SHEAR STRESS AND COMPARE TO CRITICAL SHEAR
    STRESS

Z = 2
FOR Y = Z TO NUM

REM USE A SUBROUTINE DEPTH TO CALCULATE THE DEPTH OF FLOW IN
        A TRAPEZOIDAL CHANNEL

CALL DEPTH(FLOW(), SLOPE(), BOTTOM(), Y, FLOWDEPTH(), TQ())

REM CALCULATE THE SHEAR STRESS WITHIN THE CHANNEL SECTION

TAU(Y) = FLOWDEPTH(Y) * 62.4 * SLOPE(Y)

REM PRINT OUT THE CALCULATED FLOW AND ACTUAL FLOW FOR EACH
    SECTION
```

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```
LPRINT " CALCULATED FLOW,  ACTUAL FLOW, NUMBER OF SECTION"
LPRINT USING "######.####,"; TQ(Y); FLOW(Y); Y
LPRINT " PREDICTED SHEAR STRESS, CRITICAL SHEAR STRESS,
        DEPTH OF FLOW, NUMBER OF SECTION"
LPRINT USING "#####.#####,"; TAU(Y); TAUC; FLOWDEPTH(Y); Y

REM IF THE SHEAR STRESS IS GREATER THAN THE CRITICAL SHEAR
    EXIT THE LOOP

IF TAUC < TAU(Y) THEN EXIT FOR
NEXT Y

IF Y > NUM THEN
LPRINT " ELEVATION, DISTANCE FROM DRAINAGE DIVIDE, DRAINAGE
       AREA, SLOPE"
FOR N = 1 TO NUM
LPRINT USING "#######.##########,"; ELEVATION(N);
             DISTANCE(N);DRAINAGE(N); SLOPE(N)
NEXT N
END IF
IF Y > NUM THEN END

N = Y

REM LOWER THE DEPTH OF THE SECTION BY AN INCREMENT OF 0.25
    AND CALCULATE THE NEW CROSS SECTION

CALL LOWER(N, ELEVATION(), WD(), TAU(), DISTANCE(), SLOPE(),
         BOTTOM(), TAUC, FLOW(), NUM)
DO UNTIL Y = NUM

D = Y

REM USE THE SUBROUTINE CRITICAL THE DETERMINE IF THE SECTION
    IS LESS THAN THE CRITICAL SHEAR STRESS
REM LOWER THE SECTIONS THAT DO NOT PASS THE CRITICAL SHEAR
    STRESS

CALL CRITICAL(ELEVATION(), D, WD(), TAU(), DISTANCE(),
            SLOPE(), FLOW(), BOTTOM(), NUM, TAUC)

LOOP
REM THE SUBROTINE LOWER DOES THE ITERATION UNTIL ALL THE
    SECTIONS PASS THE CRITIRIA


LPRINT " FINAL ELEVATION, DISTANCE FROM DRAINAGE DIVIDE,
       DRAINAGE AREA, SLOPE"
FOR N = 1 TO NUM
LPRINT USING "#######.##########,"; ELEVATION(N);
```

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```
             DISTANCE(N); DRAINAGE(N); SLOPE(N)
NEXT N
END

SUB CRITICAL (ELEVATION(), D, WD(), TAU(), DISTANCE(),
            SLOPE(), FLOW(), BOTTOM(), NUM, TAUC)

FOR Y = D TO NUM

REM CALL THE SUBROUTINE DEPTH TO CALCULATE THE FLOWDEPTH

CALL DEPTH(FLOW(), SLOPE(), BOTTOM(), Y, FLOWDEPTH(), TQ())

REM CALCULATE THE SHEAR STRESS USING THE FLOWDEPTH

TAU(Y) = FLOWDEPTH(Y) * 62.4 * SLOPE(Y)

REM COMPARE THE CALCULATED SHEAR WITH THE INPUTED EROSION
    RESISTANCE

IF TAUC < TAU(Y) THEN EXIT FOR
NEXT Y



N = Y
IF Y > NUM THEN
LPRINT " ELEVATION, DISTANCE FROM DRAINAGE DIVIDE, DRAINAGE
       AREA, SLOPE"
FOR N = 1 TO NUM
LPRINT USING "#######.##########,"; ELEVATION(N);
             DISTANCE(N); DRAINAGE(N); SLOPE(N)
NEXT N
END IF
IF Y > NUM THEN END

REM CALL THE SUBROUTINE LOWER IF THE CRITICAL SHEAR STRESS
    IS LESS THAN THE CALCULATED SHEAR STRESS

REM LOWER WILL LOWER THE ELEVATION BY 0.25 FEET UNTIL THE
    CRITICAL SHEAR STRESS IS GREATER THAN THE CALCULATED
    SHEAR STRESS

CALL LOWER(N, ELEVATION(), WD(), TAU(), DISTANCE(), SLOPE(),
         BOTTOM(), TAUC, FLOW(), NUM)
END SUB

SUB DEPTH (FLOW(), SLOPE(), BOTTOM(), Y, FLOWDEPTH(), TQ())
FLOWDEPTH(Y) = .5
TQ(Y) = 0
```

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```
DO UNTIL FLOW(Y) < TQ(Y)

REM INCREASE THE FLOW DEPTH BY AN SMALL INCREMENT

FLOWDEPTH(Y) = .05 + FLOWDEPTH(Y)

REM MAN(Y) AND C(Y) ARE MANNINGS EQUATION FOR FLOW WITHIN A
    TRAPEZOIDAL CHANNEL

MAN(Y) = (1.49 / .035) * (SLOPE(Y) ^ .5) * ((BOTTOM(Y) *
        FLOWDEPTH(Y)) + FLOWDEPTH(Y) ^ 2) ^ (2 / 3)

C(Y) = 1 / (BOTTOM(Y) + 2 * FLOWDEPTH(Y) * SQR(2)) ^ (2 / 3)

V(Y) = MAN(Y) * C(Y)

REM TQ IS THE TOTAL FLOW CALCULATED USING A TRAIL FLOW DEPTH

TQ(Y) = V(Y) * (BOTTOM(Y) * FLOWDEPTH(Y) + FLOWDEPTH(Y) ^ 2)

LOOP
END SUB

SUB LOWER (N, ELEVATION(), WD(), TAU(), DISTANCE(), SLOPE(),
          BOTTOM(), TAUC, FLOW(), NUM)

REM LOWER WILL KEEP LOWERING THE STREAMBED ELEVATION UNTIL
    THE SHEAR STRESS IS LESS THAN THE CRITICAL SHEAR STRESS

DO UNTIL TAU(N) < TAUC

ELEVATION(N) = ELEVATION(N) - .25

REM BOTTOM IS THE WIDTH OF THE STREAM AT THE BOTTOM OF THE
    CHANNEL

BOTTOM(N) = BOTTOM(N) + .25 * (WD(N) - 2)

REM CALCULATE A NEW SLOPE BASED ON THE LOWER ELEVATION

SLOPE(N) = (ELEVATION(N) - ELEVATION(N - 1)) / ((DISTANCE(N
            - 1) - DISTANCE(N)) * 5280)
Y = N

REM CALL THE DEPTH SUB TO CALCULATE THE DEPTH OF WATER IN
    THE CHANNEL AT THE GIVEN FLOW RATE

CALL DEPTH(FLOW(), SLOPE(), BOTTOM(), Y, FLOWDEPTH(), TQ())

REM CALCULATE THE SHEAR STRESS IN THE CHANNEL AT THE
```

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```
    FLOWDEPTH

TAU(N) = FLOWDEPTH(Y) * 62.4 * SLOPE(Y)
LOOP
END SUB
```

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APPENDIX C.

TABLES OF STREAM PREDICTIONS

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Table 1C. Keg Creek predicted stable profile

Distance from the headwater (miles)	Drainage area sq mi	Elevation of streambed (1954)	Elevation of streambed (1972)	Elevation of Stream bed (1980)	STABLE PROFILE Erosion Resistance = 0.89 and Q2	1954-1970 Actual Degradation (feet)	1954-1980 Actual Degradation (feet)	Predicted Degradation (feet)	Slope (ft/mile)
32.1	91.4								
32.38	92.59	1100.3	1099.3	1098.1	1100.3	1	2.2	0	8.67
32.68	93.87	1097.7	1093.7	1094.4	1097.7	4	3.3	0	6.31
33	95.23	1095.68	1090.68	1091	1095.68	5	4.68	0	6.32
34	99.5	1089.36	1081.25	1080.2	1089.36	8.11	9.16	0	6.33
34.61	102.1	1085.5	1075.5	1073.6	1080.75	10	11.9	4.75	16.33
34.91	103.37	1080.6	1071.6	1070.5	1077.35	9	10.1	3.25	13.67
35	103.76	1079.37	1070.7	1070	1076.37	8.67	9.37	3	13.61
35.96	107.85	1066.3	1061.3	1064.8	1066.3	5	1.5	0	5.97
36.7	111	1061.88	1057.1	1060.3	1061.88	4.78	1.58	0	5.97
37	112.1	1060.09	1055.4	1058.5	1060.09	4.69	1.59	0	5.97
38	115.77	1054.12	1049.8	1052.4	1054.12	4.32	1.72	0	5.97
38.64	118.11	1050.3	1046.13	1048.4	1050.3	4.17	1.9	0	6.86
39	119.43	1047.83	1044.1	1046.24	1047.83	3.73	1.59	0	7.33
39.7	122	1042.7	1040.1	1042	1042.7	2.6	0.7	0	1.67
39.76	122.27	1042.6	1039.8	1041.6	1042.6	2.8	1	0	3.88
40.43	125.29	1040	1036	1038	1040	4	2	0	6.77
41.7	131	1031.4	1028.4	1029.4	1031.4	3	2	0	

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Table 2C. Walnut Creek predicted stable profile.

Distance from drainage divide (miles)	Drainage Area (sq miles)	1976 Elevation (feet)	PROFILE for erosion resistance = 0.89 and Q2 (feet)	Predicted Degradation (feet)	Slope (ft/mile)
5.1	7.68	1238.4	1238.4	0	7.61
6	12.5	1231.55	1231.55	0	5.84
7.1	18.4	1225.13	1225.13	0	5.80
8	20.14	1219.91	1219.91	0	4.33
9	22.08	1215.58	1215.58	0	4.32
10	24.02	1211.26	1211.26	0	4.33
11.8	27.5	1203.46	1203.46	0	4.30
12	28.16	1202.6	1202.6	0	6.72
13	31.46	1195.88	1194.63	1.25	9.59
14.8	37.4	1178.61	1178.61	0	5.40
15	38.09	1177.53	1177.53	0	5.36
16	41.55	1172.17	1172.17	0	5.36
17	45	1166.81	1166.81	0	5.36
18	48.46	1161.45	1161.45	0	6.99
19.2	52.6	1153.06	1153.06	0	7.43
20	55.35	1147.12	1147.12	0	7.48
21.7	61.2	1134.4	1134.4	0	7.23
22	61.87	1132.23	1132.23	0	5.17
23	64.12	1127.06	1127.06	0	4.20
24	66.36	1122.86	1122.86	0	4.04
25.8	70.4	1115.59	1115.59	0	3.95
26	70.99	1114.8	1114.8	0	3.93
27	73.91	1110.87	1110.87	0	6.69
28	76.84	1104.18	1104.18	0	6.28
29	79.77	1097.9	1097.9	0	4.79
29.9	82.4	1093.59	1093.59	0	4.55
31	85.84	1088.58	1088.58	0	4.07
32	88.96	1084.51	1084.51	0	4.10
33.1	92.4	1080	1078.25	1.75	11.77
34	94.68	1069.41	1069.41	0	8.40
35	97.21	1061.01	1061.01	0	8.05
36.5	101	1048.94	1047.44	1.5	13.22
37	102	1042.33	1042.33	0	5.64
38	104	1036.69	1036.69	0	4.19
39	106	1032.5	1032.5	0	2.02
40	108	1030.48	1030.48	0	6.37
41	113.5	1024.11	1024.11	0	4.20
42	119	1019.91	1019.91	0	3.51
44	130	1012.88	1012.88	0	6.15
45	134.17	1006.73	1006.73	0	4.40
46	138.33	1002.33	1002.33	0	4.40
46.4	140	1000.57	1000.57	0	5.33
47	141.8	997.37	997.37	0	5.52
48.4	146	989.64	989.64	0	4.47
49	149.55	986.96	986.96	0	4.24
50.6	159	980.18	980.18	0	5.22
51.5	161	975.48	975.48	0	4.80
52	162.41	973.08	973.08	0	4.59
53	165.22	968.49	968.49	0	4.18
54.7	170	961.38	961.38	0	4.17
55	170.84	960.13	960.13	0	3.96
56	173.64	956.17	956.17	0	3.96
57.2	177	951.42	951.42	0	3.97
58	183.83	948.24	948.24	0	4.00
59	192.35	944.24	944.24	0	4.00
60.6	206	937.84	937.84	0	4.00
61.7	215	933.44	933.44	0	1.80
66.4	223	925	925	0	

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Table 3C. Indian Creek predicted stable profile.

Distance From drainage divide (miles)	Drainage Area (sq. miles)	1976 Elevation (feet)	STABLE PROFILE erosion resistance =0.4 and Q2 (feet)	Predicted Degradation (feet)	Slope (ft/mile)
6.06	6.74	1153.4	1153.4	0	2.30
7	8.54	1151.24	1136.99	14.25	8.38
8	10.45	1142.86	1128.11	14.75	9.17
9	12.36	1133.69	1119.69	14	9.56
10.38	15	1120.5	1108.75	11.75	6.66
11	15.74	1116.37	1104.62	11.75	6.37
12	16.92	1110	1097.75	12.25	9.61
13	18.1	1100.39	1090.64	9.75	5.31
14.43	19.8	1092.8	1081.8	11	5.32
15	21.24	1089.77	1078.02	11.75	5.82
16	23.76	1083.95	1071.45	12.5	5.82
17	26.29	1078.13	1064.63	13.5	5.85
18	28.81	1072.28	1057.78	14.5	6.01
19.66	33	1062.3	1046.3	16	6.24
20	33.38	1060.18	1043.93	16.25	9.42
21	34.48	1050.76	1036.51	14.25	8.07
22	35.59	1042.69	1029.69	13	7.86
23.64	37.4	1029.8	1018.8	11	6.72
24	38.94	1027.38	1016.63	10.75	6.71
25	43.21	1020.67	1010.67	10	8.44
26.59	50	1007.25	1001.5	5.75	6.71
27	53.08	1004.5	999.75	4.75	6.40
28.11	61.4	997.4	995.15	2.25	6.02
29	62.65	992.04	992.04	0	1.85
32.8	68	985	985	0	

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Table 4C. McElhaney Creek predicted stable profile.

Distance From drainage divide	Drainage Area	1965 Elevation	STABLE PROFILE Erosion Resistance = 1.23 and Q2	Predicted Degradation	Slope
(miles)	(sq. miles)	(feet)	(feet)	(feet)	(ft/mile)
3.43	6.55	1266.82	1262.32	4.5	27.75
4	7.61	1251	1248.5	2.5	21.95
5	9.48	1229.05	1229.05	0	14.55
6	11.34	1214.5	1214.5	0	14.22
7.16	13.5	1198	1193.75	4.25	19.05
8	15.71	1182	1176.25	5.75	27.83
9	18.34	1154.17	1153.42	0.75	16.68
9.25	19	1150	1150	0	

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