11-1992

Gully Evolution in the Upper Delaware River Basin Northeastern Kansas

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GULLY EVOLUTION IN THE UPPER DELAWARE RIVER BASIN
NORTHEASTERN KANSAS

A Thesis

Presented to the
Department of Geography/Geology
and the
Faculty of the Graduate College
University of Nebraska

In Partial Fulfillment
of the Requirments for the Degree
Master of Arts
University of Nebraska at Omaha

by
Iona L. Meyer

November 1992

THESIS ACCEPTANCE

Accepted for the faculty of the Graduate College, University of Nebraska, in partial fullfillment of the requirements for the degree Master of Arts, University of Nebraska at Omaha.

Committee

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November 17, 1992
Date

ACKNOWLEDGEMENTS

Of the many people who contributed their services to this project, I would like to thank foremost, the members of my thesis committee, Drs. Rolfe Mandel, Jeffrey Peake, and Joseph Benak for their support, guidance and patience during the course of this project.

The U.S. Department of Agriculture's Soil Conservation Service played an integral role in site selection, financial support and field assistance. District Conservationists Matt Sprick, Bruce Yonke and Eldon Schwant of Brown County, Jackson County and Nemaha County, respectively, provided site selection services. Robert Drees initiated funding by the SCS, and also provided valuable field assistance. Cecil Palmer offered on site soil coring and soil description services, and Steve Myers, conducted the biomass survey.

Larry Kramer and his associates at the Deep Loess Research Station furnished a rain gauge for the project, and also provided research results from the erosion studies at Treynor, Iowa. Art Bettis, of the Iowa Department of Natural Resources, is to be thanked for his field assistance and our numerous discussions on erosion processes. Additional field assistance by Melissa Milner, Riley Jacobs and Randy Settje is greatly appreciated. I would also like to thank Jean Raemer, of the Corp of Engineers, for helping with aerial photo interpretations. Dr. Michel Ransom, of Kansas State University, provided soil laboratory analysis.

Special thanks go to Eldon Sudback, who volunteered his property for my study site, and to Martha Fritz, who diligently gathered rain data at the site during the monitoring period. Finally, I wish to thank my husband, Jerry, for developing the computer program for my project, and for his moral support. Supplemental funding was provided by the University of Nebraska's Committee on Research.

ABSTRACT

A small gully network developed across a pasture in the Dissected Till Plain of northeastern Kansas was monitored for one year to assess gully evolution in non-loessial materials. The objectives of this investigation were to identify stable and unstable drainage elements within the gully network; identify zones of net erosion and deposition; estimate the volume of sediment removed or deposited during the monitoring period; determine rates of headcut advancement; determine processes that advance and widen gullies, and to determine the historic development of the gully network.

Portions of the gully network were measured after every rain event exceeding 1.5 cm in a 24 hour period. A series of reference points and/or transects were established at selected gully elements to determine headcut advancement rates and detect changes in gully volume. Historic growth rates were determined by examining aerial photographs.

Results of this investigation indicate that the upper reach was a zone of net erosion, whereas the lower and middle reaches were zones of net sedimentation. Although considerable erosion occurred during the monitoring period, with sidewalls accounting for 92.0% of all erosion, sedimentation was the dominant process, resulting in a net decrease in gully volume of about 2.77m^3. It is likely that a portion of the sediment was contributed by adjacent slopes that are experiencing sheet and rill erosion.

Gully headcut advance ranged from 4 to 69 cm/yr, with advancement apparently controlled by surface deposits and soils. Headcuts migrated fairly rapidly when advancing into former gullies that are filled with sediment. The gully fills are marked by permeable, low strength silt. However, headcuts advancing into the in-situ glacial till had slower advancement rates due to till having a higher clay content, thereby imparting greater resistance to erosion.

Headcuts migrating into gully fills were subject to advancement by failure at the toe of headwalls, and by toppling, whereas headcuts migrating into the till-derived soils advanced primarily by rill enlargement. Gully widening resulted from sidewall failure, which was largely controlled by soil moisture conditions, undercutting, and cattle.

Examination of aerial photographs suggest that portions of the gully network have rejuvenated and infilled since 1937. This evidence is supported by the existence of late-Holocene gully fills at the study site. Cut-and-fill cycles play an important role in river basin evolution, and appear to be an important factor of gully evolution at the study site. Headcuts migrating into gully fills can be expected to advance quickly. Hence, soils and terrain analysis may be used to locate gully fills, allowing land managers to isolate areas prone to rapid gully development.

TABLE OF CONTENTS

Chapter

LIST OF ILLUSTRATIONS

Figure

LIST OF TABLES

CHAPTER ONE

INTRODUCTION

Statement of the Problem

Gullying is a major problem in agricultural areas throughout most of North America. It not only destroys farmland by dissecting fields, but also increases sediment load and reduces water quality in streams. It is important, therefore, to understand gully processes in order to develop land management strategies for areas affected by gullying. This study examines short term gully evolution in the Upper Delaware River Basin of northeastern Kansas (Figure 1). The primary objective of this study is to identify stable and unstable drainage elements within a selected gully network. Additional objectives are to: (1) identify zones of net erosion and sedimentation within the gully network, (2) estimate the volume of sediment removed or deposited during the monitoring period, (3) determine rates of headcut advancement, (4) determine predominate processes that widen and deepen gullies, and (5) examine the historic development of the gully network.

The present study is significant for several reasons. First, it provides information on gully evolution in a major agricultural region of the United States. Second, it contributes new information on gully evolution in non-loessial materials. Although numerous studies of gully

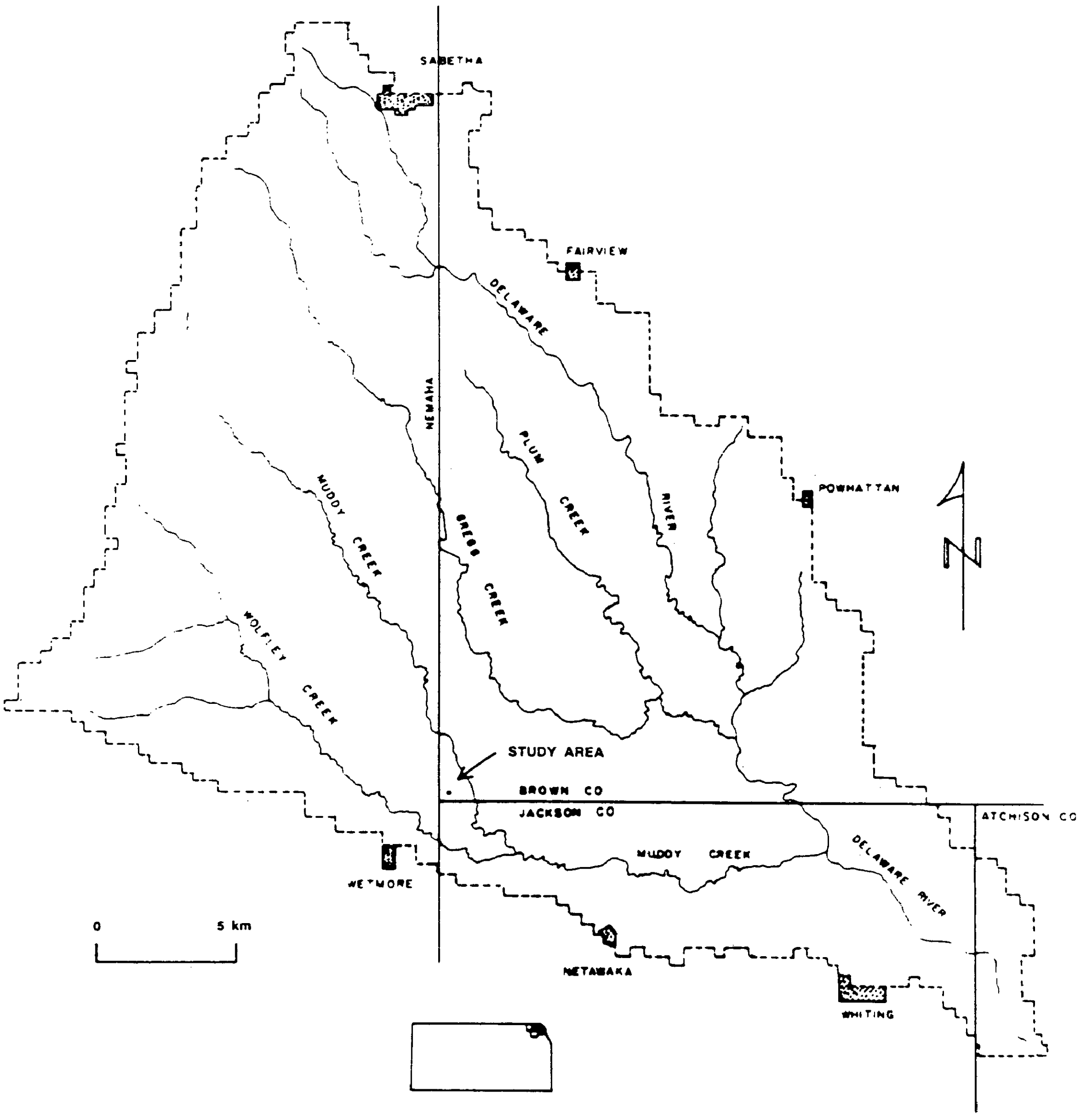


Figure 1. Upper Delaware River Basin (Mandel et al. 1991).

development have been conducted in the Midwest (e.g., Brice 1966; Daniels and Jordan 1966; Bariss 1971; Bradford and Piest 1977; Bettis 1983), they all focused on gully development in loess and/or loess-derived alluvium. Little is known about gully development in till-derived soils, and although portions of northeastern Kansas are mantled with loess, many of the gullies are cut into surface deposits of glacial drift. Third, it furnishes new information on gully erosion rates and sediment yields in a moist-subhumid climate of the Midwest. Finally, it enables one to assess watershed conditions for potential gully development.

Origin of Problem

Research on gully development in North America was initiated in response to reactivation of gully systems in the late nineteenth century (Heede 1974:262). Gullying during early historic times is attributed to land clearance associated with Euro-American settlement (Palmer 1965:6; Heede 1974:262). It was not until the 1930's however, that major gully research began.

Early studies focused on conditions that affect gully development, such as climate, soil, topography, vegetation, and landuse (e.g., Ireland et al. 1939:44; Palmer 1965). Also, there was emphasis on stages of gully development and cycles of cutting and filling (e.g., Schumm and Hadley 1957:172; Daniels and Jordan 1966).

Research since 1960 has gone in two directions: (1)

identifying specific conditions or processes that influence gully-wall stability (e.g., Piest et al. 1975; Bradford and Piest 1977; Bradford et al. 1978; Roloff et al. 1981), and (2) attempting to quantify gully processes in order to predict gully development and rates of advancement (e.g., Beer and Johnson 1963; Thompson 1964; Soil Conservation Service 1966; Seginer 1966; Patton and Schumm 1975; Stocking 1980).

Some studies (e.g., Bradford and Piest 1977:115; Roloff et al. 1981:13) have suggested that increased moisture content of gully walls reduces soil shear strength, thereby inducing gully-wall failure. Bradford and others (1978:326) supported this hypothesis. They suggested that the depth and position of the water table in relation to gully banks is a significant factor in wall stability. Piest and others (1975:67) also contended that increased subsurface water can lower the shear strength of erodible channel banks by increasing internal stresses (pore pressure and load) within soil masses. Although there is a a general consensus that saturation of soils is a major factor in gully-wall failure, there are other variables, such as soil properties, vegetation, topography and climate, that influence wall stability. Consequently, it is difficult to predict gully-wall failure due to complex interactions of these variables.

Previous studies have attempted to monitor gully development through direct measurement of channels (e.g., Leopold et al. 1966; Mandel et al. 1985), or through the use of aerial photographs (e.g., Beer and Johnson 1963; Jones and Keech 1966:189; Seginer 1966:237; Patton and Schumm 1975). Expected rates of gully development were based on records of past growth. However, as factors influencing gully development became better understood, attempts were made to quantify these factors and develop models. Most models attempted to predict rates of gully-head advancement (e.g., Thompson 1964; Seginer 1966; Soil Conservation Service 1966; Stocking 1980) or increases in aerial extent of gully channels (e.g., Beer and Johnson 1963; Soil Conservation Service 1966). Patton and Schumm (1975), however, attempted to identify valley floors that were prone to gullying. Analytical studies generally suggested that the most significant factors controlling gully development and advancement are: (1) drainage basin area, (2) precipitation data, and (3) slope. Although these studies have merit, they are not without problems. First, many studies have limited applications because they were conducted under specific environmental conditions and time constraints. If they are to be adapted to other locations, they would have to be adjusted due to regional differences in topography, soils, precipitation and gully-stage development. Second, models assume a constant growth rate for gullies, and do not account for changes in factors, such as climate and vegetation through time. Third, causative processes are inadequately defined. Although the significant variables are identified in each model, the associated processes, such as slumping or rilling, are not considered. Fourth, gully processes are extremely complex, thereby making prediction difficult. Finally, none of the analytical studies considered vegetation a significant variable in retarding erosion. There is strong evidence that vegetation plays a significant role in gully stabilization, thereby affecting rates of gully development (see Saxton and Spomer 1968; Barnes 1973:5-8; Kirkby and Morgan 1980:290; Heede 1981:257). Vegetation should, therefore, be considered a variable in models.

Although these models lack precision due to the problems listed above, they have shed light on important variables influencing gully growth. However, only when models becomes process orientated will they become more accurate. It is the intent of this study, therefore, to associate erosion processes with gully morphology, with morphology being an indicator of stage of development.

CHAPTER TWO

ENVIRONMENTAL SETTING

Physiographic Setting

The study area is located in southwestern Brown County, Kansas (Figure 1). This area is within Fenneman's (1931) Dissected Till Plain of central North America (Figure 2). The Dissected Till Plain is characterized by deeply incised valleys separated by smooth, rolling hills. Steep, convex slopes occur where the Delaware River and its tributaries have dissected the landscape, and gullies are advancing headward into the uplands. However, local relief in the Upper Delaware River valley does not exceed 45 m (Mandel et al. 1991).

The study site is located approximately 3 km northeast of Wetmore, Kansas (Figure 3). The site is situated on a ridgetop with 2-3% slopes. A gully network with numerous drainage elements has developed across the site (Figures 4 and 5). This network drains an area of approximately 28,000 m^2.

Bedrock Geology

Northeastern Kansas is underlain by Upper Pennsylvanian and Lower Permian shale, limestone, and sandstone (Merriam 1963). Throughout most of Brown County, Upper Pennsylvanian bedrock is exposed along steep, north-facing slopes adjacent to major rivers. (Eikleberry and Templin 1960:25). This bedrock is composed of thin units of limestone separated by

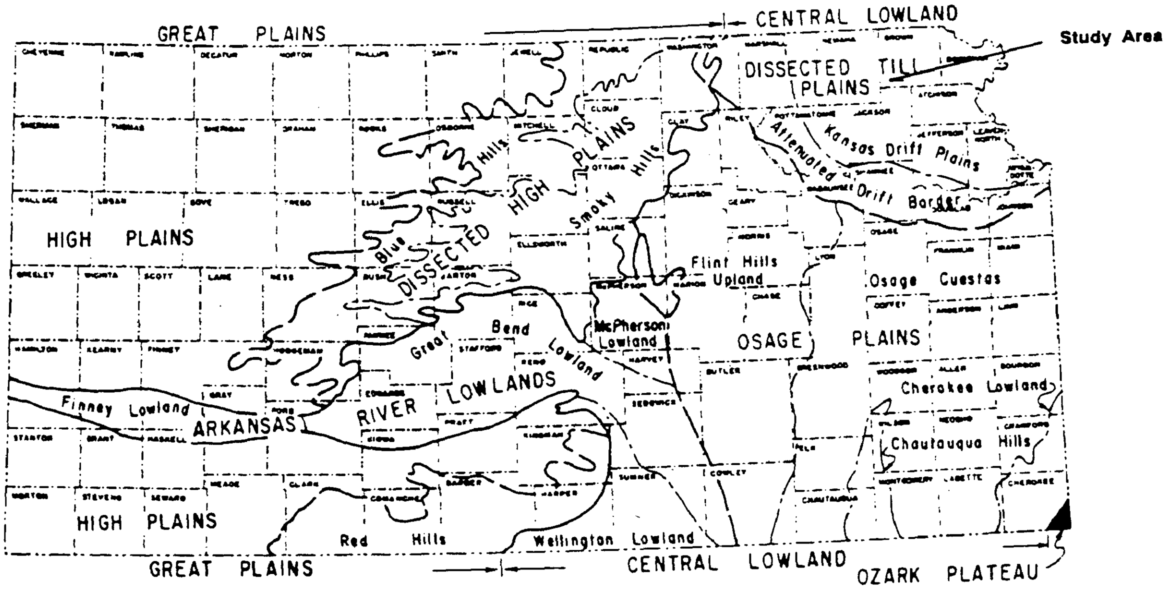


Figure 2. Location of study area in Dissected Till Plain (Fenneman 1931).

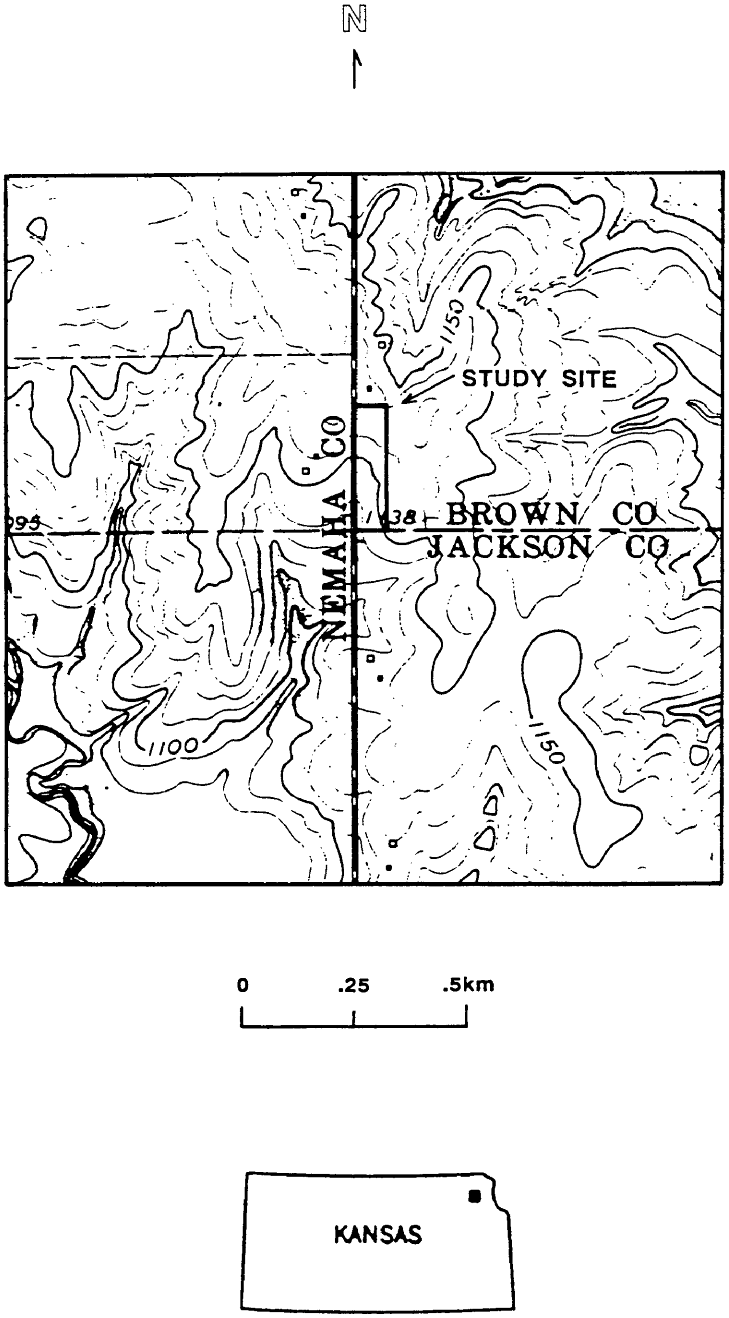


Figure 3. Study site location.

Figure 4. Photo of study site.

Figure 5. Photo of portion of gully network.

thick units of shale. Limestone and shale of the Council Grove Group (Permian) are exposed in southwestern Brown County (Merriam 1963).

Surface Geology

During the early Pleistocene, continental glaciers advanced into northeast Kansas on several occasions (Bayne 1968; Aber 1978; Dort 1985). As these glaciers advanced and retreated, glacial drift was deposited over the Pennsylvanian and Permiam bedrock. According to Dort (1985), the drift includes several till deposits. These deposits range in age from approximately 0.6-2.0 years B.P. (Boellstorf 1978; Hallberg and Boellstorf 1978), and are collectively referred to as Pre-Illinoian till (Hallberg et al. 1980). The Pre-Illinoian till deposits at the study site are a mixed matrix of coarse and fine-grained calcareous and siliceous sediments.

Some upland areas of Pre-Illinoian till are mantled with Loveland and/or Peorian loess. Fry and Leonard (1949:896-897) suggested that these loesses are Illinoian and Wisconsinan in age, respectively. In Brown County, loess deposits decrease in thickness west of the Missouri River, with 6 feet of loess occurring in the southwestern portion of the county (Eikleberry and Templin 1960).

Valley bottoms are filled with Holocene and late Pleistocene alluvium (Mandel et al. 1991). Streams and gullies were filled with upland derived sediments, and were later trenched. Numerous postglacial gully cut-and-fill cycles have been identified in western Iowa, and the alluvial fills are collectively called the DeForest Formation (Daniels et al. 1963).

Climate

Temperatures vary widely, both daily and annually in the study area. The mean daily temperatures for January and July at Holton, Kansas during the period 1960-1990 are -3.1° C and 25.8° C., respectively (Kansas State University Cooperative Extension Service 1991) (Table 1). The mean annual yearly precipitation at Holton for the same period is 938.5 mm (Table 1). Most of the annual precipitation falls in April through September due primarily to frontal activity. Maritime polar and continental polar air masses flowing into eastern Kansas during the spring and summer often converge with warm, moist tropical air flowing north from the Gulf of Mexico. This convergence of air masses often produces intense rainfalls of short duration along the convergence zone. Convectional thunderstorms in the summer months also may produce heavy rainfalls (Mandel 1987). Although most precipitation occurs in the summer months, it is not uncommon to have prolonged dry periods during this season.

Table 1. Temperature and Precipitation Summary From Holton, Kansas 1960-1990. (Kansas State University Cooperative Extension Service 1991).

	TEMPERATURE (°C)			PRECIP. (mm)	NOTE
Month	Average Monthly Max.	Average Monthly Min.	Average Monthly Mean	Average Monthly	
January	3.7	-9.1	-3.1	24.1	
February	5.9	-6.5	-0.3	23.9	
March	12.5	-0.9	5.8	60.2	1,3
April	19.8	5.7	12.8	79.3	1,3,6
May	24.8	11.3	18.1	115.8	1,2,3
June	29.4	16.5	22.9	150.4	1,2,3
July	32.4	19.1	25.8	89.9	3
August	31.3	17.2	24.5	112.0	
September	26.8	12.9	19.9	121.9	4
October	20.9	6.6	13.8	79.5	
November	12.3	-0.1	6.1	47.2	
December	4.8	-6.6	-0.9	34.3	5
Year	18.7	5.5	12.1	938.5	

Note: Missing data for above chart.

1. 1968 and 1979 (Temperature).
2. 1968 (Precipitation)
3. 1979 (Precipitation)
4. 1984 and 1987 (Precipitation).
5. 1985 (Precipitation).
6. 1986 (Precipitation).

Vegetation

Kuchler (1969:163) described the natural vegetation of northeastern Kansas as a mosaic of oak-hickory forest and tall grass prairie. Typically, the tall grass prairie is found on level upland areas, whereas the oak-hickory forests occur on steep hillslopes and in ravines. Also, riparian forests occur along streams. Grasses commonly found in the tall grass prairie are big bluestem (*Andropogon gerardi*), little bluestem (*Andropogon scoparius*), switchgrass (*Panicum virgatum*), and Indiangrass (*Soghastrum nutans*). Arboreal species common to the oak-hickory forest are white oak (*Quercus alba*), red oak (*Quercus borealis*), and bitternut hickory (*Carya cordiformis*). The understory is composed largely of rosebud (*Ceris canadensis*) and hawthorn (*Crateagus viridis*). Riparian forests are dominated by cottonwood (*Populus deltoides*), willow (*Salix*), and elm (*Ulmus*).

Although smooth brome grass (*Bromis inermis*) was seeded at the site in 1969 (Sudback 1991, personal communication), Kentucky bluegrass (*Poa pratenis*), yellow Indiangrass (*Sorghastrum nutans*), big bluestem (*Andropogon gerardi*), sideoats grama (*Bouteloaa curtipendula*), and clover (*Trifolium repens*) have been identified (Myers 1991, personal communication). The non-brome grasses were introduced through time to the site by wind, cattle, birds and human actions. It can be reasonable to expect, therefore, that this pasture will continue to evolve.

Soils

The soils at the study site are Mollisols with thick mollic epipedons, and cambic or argillic horizons. Two soil series identified within the study area are: the Pawnee and Burchard clay loam (Eikleberry and Templin 1960: sheet 8) (Figure 6).

Pawnee soils are developed in calcareous glacial till, and occur on ridges within the upper portions of the drainage network. These soils are moderately well drained, but have rapid surface runoff due to slow water and air infiltration. The Pawnee soils are Aquic Argiudolls characterized by A-Bt-BC horizonation (Table 2). These soils have a mixed mineralogy dominated by montmorillonite.

Burchard soils also are developed in calcareous glacial till, but occur along sideslopes. These soils are well drained, and have moderately slow permeability. The Burchard soils are Typic Argiudolls characterized by A-Bt-B horizonation (Campbell et al. 1975:39). They also have a mixed mineralogy dominated by montmorillonite. The A horizon is 8-10 inches thick, dark brown or brown, and may have enough sand or gravel to make it coarser than clay loam. The soil becomes lighter colored and coarser textured with depth (Eikleberry and Templin 1960).

A third unnamed soil was identified in linear depressions that extend upslope. These depressions mark

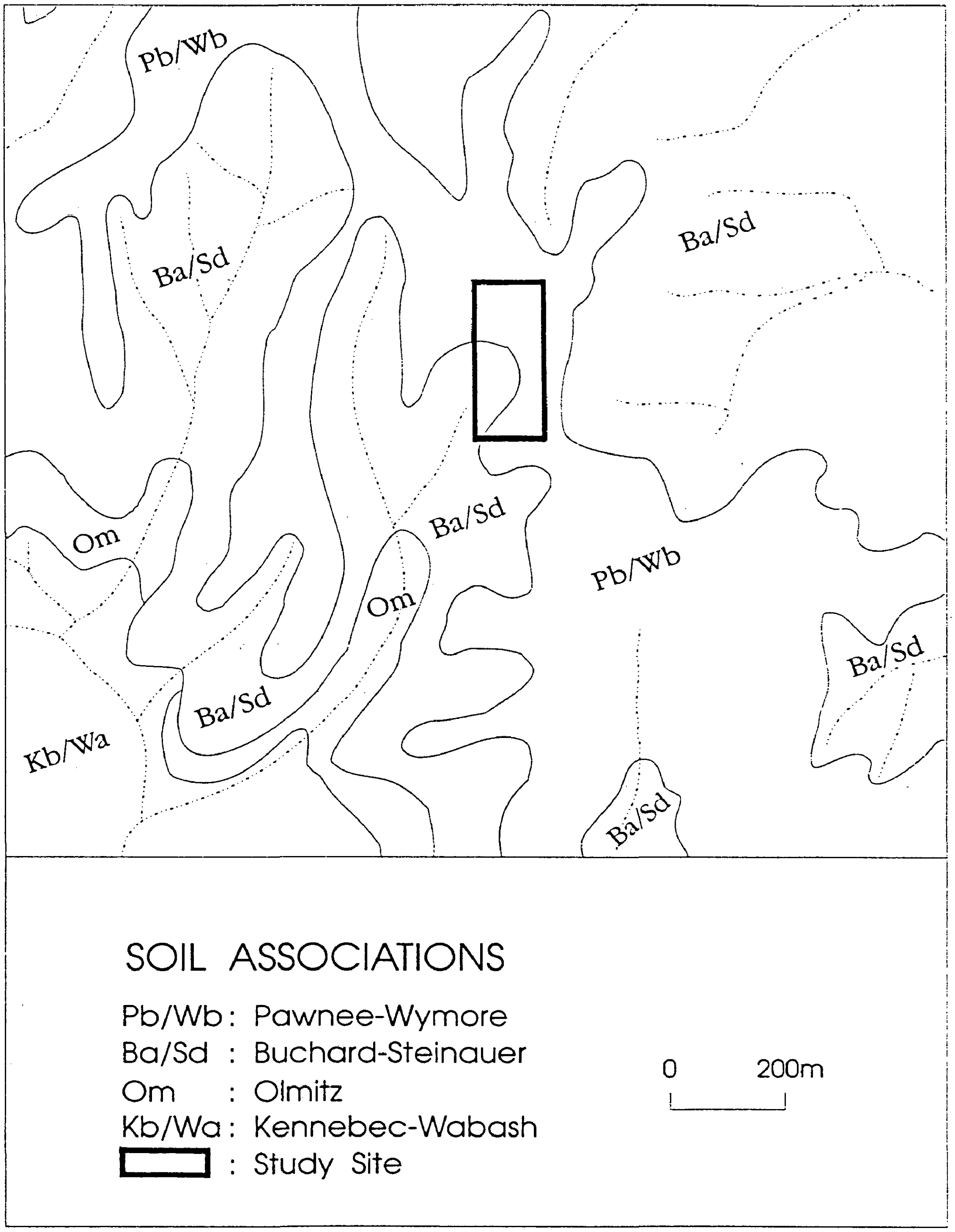


Figure 6. Soil Associations at study site.

Table 2. Pawnee Series Soil Description

Soil Series: Pawnee
Legal Description: S.W. 1/4, S.W. 1/4, Section 31, Township 4 South, Range 15 East
Slope: 3-4%
Vegetation: Pasture
Described By: Cecil Palmer and Rolfe Mandel

Depth (cm)	Horizon	Description
0-19	Ap	Dark grayish brown (10YR 4/2) clay loam, very dark grayish brown (10YR 3/2) moist; moderate medium granular structure; slightly hard, friable; many fine and very fine roots; few small erratics (pebbles and cobbles); noneffervescent; clear smooth boundary.
19-44	Bt1	Yellowish brown (10YR 5/6) clay, yellowish brown (10YR 5/4) moist, common dark yellowish brown (10YR 3/4) root infillings 1-10 mm wide; moderate fine subangular blocky structure; very hard, firm; few erratics (pebbles and cobbles); common fine and very fine roots; noneffervescent; gradual smooth boundary.
44-73	Bt2	Yellowish brown (10YR 5/8) clay, yellowish brown (10YR 5/6) moist; common fine distinct (7.5YR 3/0) and few fine distinct grayish brown (2.5Y 5/2) mottles; moderate fine blocky structure; hard, firm; noneffervescent; gradual smooth boundary.
73-113	BC	Yellowish brown (10YR 5/6) clay loam, dark yellowish brown (10YR 4/4) moist; common distinct medium and coarse grayish brown (2.5Y 5/2) and common fine distinct very dark gray (7.5YR 3/0) mottles; moderate medium blocky structure; hard, firm; common erratics (pebbles and cobbles); few fine and medium roots; few fine hard Fe-Mn concretions; noneffervescent; smooth gradual boundary.
113-133+	C	Yellowish brown (10YR 5/6) loam, dark yellowish brown (10YR 4/4) moist; common distinct medium and coarse light brownish gray (2.5Y 6/2) and common fine distinct dark gray (7.5 YR 4/0) mottles; weak medium blocky structure; hard, firm; common erratics (pebbles and cobbles); few carbonate lithoclasts, 1-1.5 cm in diamter; matrix noneffervescent.

Table 3. Unknown Soil Series Description

Soil Series: Unknown (Similar to Judson)
Legal Description: S.W. 1/4, S.W. 1/4, Section 31, Township 4 South, Range 15 East
Slope: 3-4%
Vegetation: Pasture
Described By: Cecil Palmer and Rolfe Mandel

Depth (cm)	Horizon	Description
0-15	Ap	Dark gray (10YR 4/1) silt loam, very dark gray (10YR 3/1) moist; weak fine granular structure; slightly hard, friable; many fine and very fine roots; noneffervescent; clear smooth boundary.
15-45	A	Very dark grayish brown (10YR 3/2) silt loam, very dark gray (10YR 3/1) moist; moderate fine subangular blocky parting to coarse granular structure; hard, friable; many fine and very fine roots; common worm casts; noneffervescent; gradual smooth boundary.
45-61	AB	Dark brown (10YR 4/3) light silty clay loam, dark brown (10YR 3/3) moist; weak fine subangular blocky structure; hard, friable; common fine and very fine roots; noneffervescent; gradual smooth boundary.
61-98	Bw	Brown (10YR 5/3) light silty clay loam, dark brown (10YR 3/3) moist; few fine faint yellowish brown (10YR 5/4) mottles; weak fine subangular blocky structure; hard, friable; few rounded to subrounded carbonate clasts 2-3% by volume; few very fine roots; few worm casts; moderate effervescent; gradual smooth boundary.
98-119	BC	Brown (10YR 5/3) loam, grayish brown (10YR 5/2) moist; common fine faint yellowish brown (10YR 5/6) and few very fine distinct strong brown (7.5YR 4/6) mottles; weak fine subangular blocky structure; hard, friable; few very fine roots; few fine hard ferro-manganese nodules; noneffervescent; gradual smooth boundary.
119-140+	C	Brown (10YR 5/3) loam, brown (10YR 5/3) moist; common fine faint yellowish brown (10YR 5/6) mottles, few very fine distinct strong brown (7.5YR 4/6) mottles; weak fine blocky structure; hard, friable; common fine hard ferro-manganese nodules; noneffervescent.

positions of paleo-gullies that have filled almost entirely with sediment (Meyer and Mandel 1991). This soil description has an A-Bw profile similar to the Judson silt loam (Table 3), but is too coarse for that series.

CHAPTER THREE

METHODOLOGY

The methodology for this study was composed of two parts. The first part involved examining aerial photographs, topographic maps, and county soil surveys of the study area. Historic growth rates of the gully network were determined by examining 1:20,000 and 1:40,000 scale aerial photographs provided by the U.S. Department of Agriculture ASCS Office. Photographs were available for the years 1937, 1954, 1959, 1966, 1972 and 1981. In addition, a combined topographic and soils map was produced using 1:20,000 scale county soil survey maps, and the 1:24,000 scale Wetmore Quadrangle (U.S. Geological Survey 1961).

The second part of this study involved field investigations. These investigations were conducted between May 11, 1990 and May 6, 1991, and involved qualitative and quantitative analyses of the gully network.

Qualitative assessments included recording changes in gully morphology, and taking photographs at selected reference points. Analyses were made after every rain event exceeding 1.5 cm in a 24 hour period.

The site was surveyed using a pocket transit and Dumpy level to create a plan view of the gully network. A series of reference points and/or transects were established at the mouth, midpoint and headcut (HC) of selected gully elements (Figure 7). Headcut reference points were located 2 m

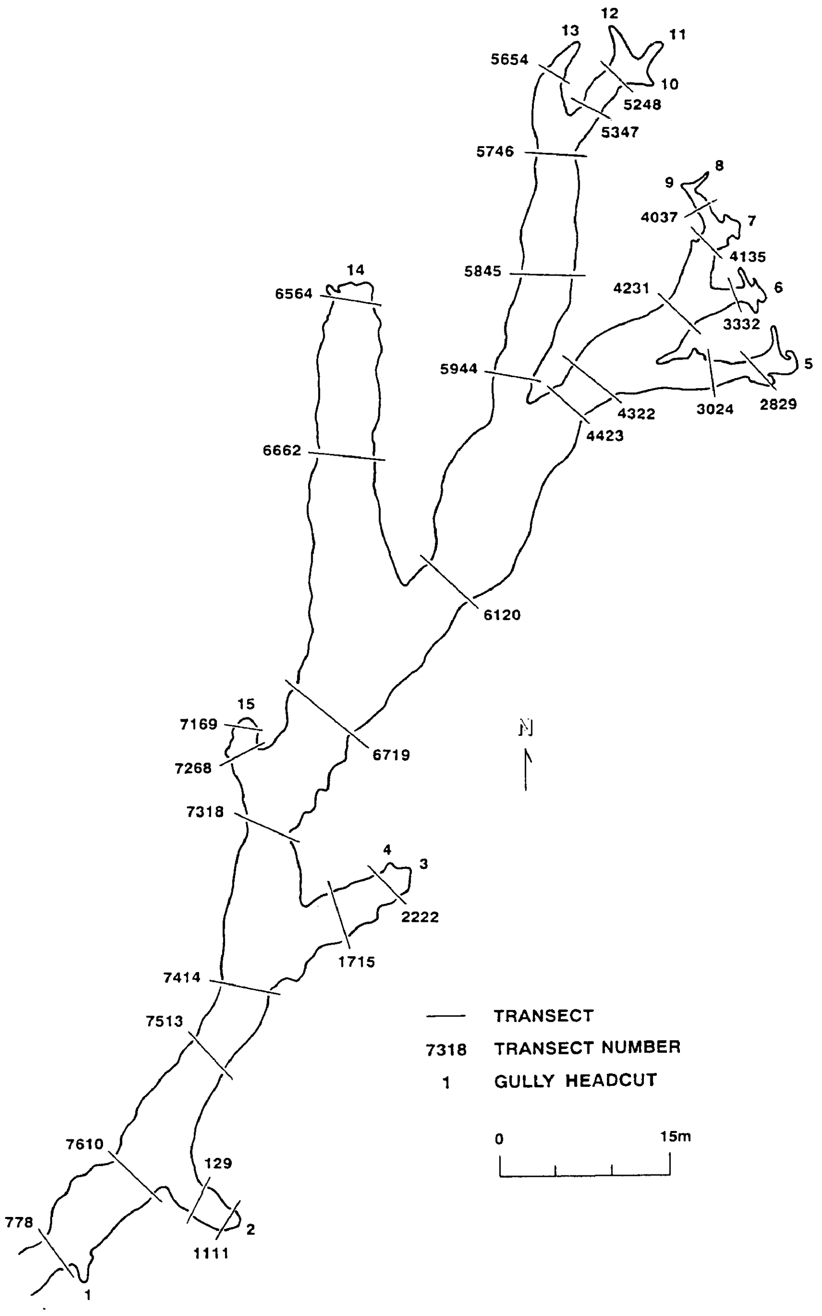


Figure 7. Plan view of gully showing headcut and transect locations.

upslope from each headcut, with the exception of reference point 14. It was located 3 m above the headcut because of the anticipated migration beyond 2 m. With the exception of five reference points, the balance of reference points were offset 1 m. Points 19, 29, 68, and 69 were offset 2.0 m, 2.0 m, 0.5 m, and 0.5 m, respectively, for two reasons. First, points 19 and 29 were expected to retreat past 1 m, and second, the location of points 68 and 69 relative to the adjacent channel did not permit 1m offsets. Elevations were taken with a Dumpy level and stadia rod at every transect and headcut in order to determine slope gradients and produce longitudinal profiles of gully segments.

Measurements were taken along the 29 cross-channel transects after every rain event exceeding 1.5 cm in a 24 hour period in order to determine changes in gully volume and create cross-sectional profiles. Volume changes indicate the amount of sediment deposited or removed during the monitoring period, and cross-sectional profiles show changes in gully geometry through time.

Although numerous methods exist for measuring soil erosion and deposition within gullies (Loughran 1989), a modified version of Toy's (1983) Linear Erosion Measurement Instrument (LEMI) was used. The LEMI allows one to determine changes in the elevation of the land surface without affecting erosional/depositional processes. Measurements were taken by laying a stadia rod across the

Figure 8. Photo of meter stick and stadia rod.

gully at each transect. A meter stick was lowered from the stadia rod to the ground surface at the quarter and midpoints of each transect (Figure 8).

Gully widening was determined by measuring the change in distance from reference points at each transect to the gully lip. Headcut advancement was determined by taking measurements from fixed reference points to each headcut.

Area and Volume Calculations

Data gathered with the modified LEMI were used to determine changes in gully morphology. The formula to calculate changes in channel area per quarter transect (Figure 9) is based on the area of a trapezoid, and is expressed as follows:

$$Qtr(A) = (AC + BD) /2 \ (EF)$$

where $Qtr(A)$ = the area of the cross section ABCD, AC and BD are section heights, and EF is the section width. The total cross-sectional area per transect is the sum of quarter areas. Thus,

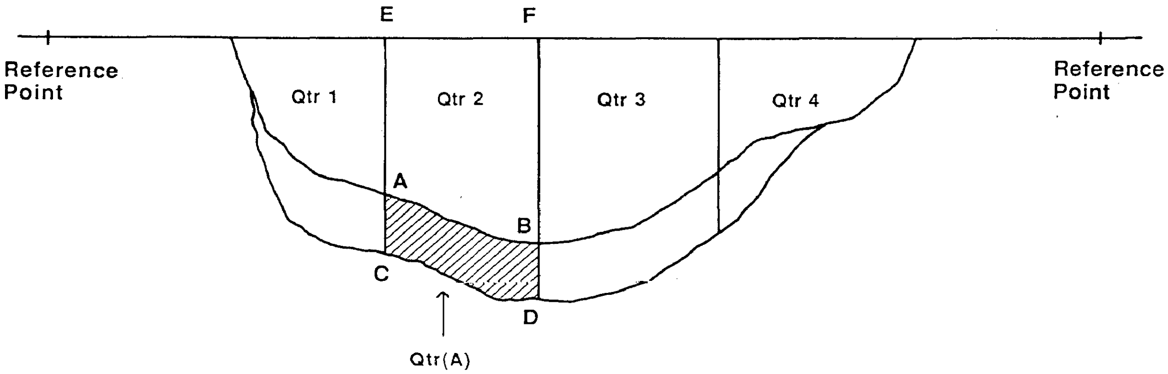
$$A = Qtr(A1) + Qtr(A2) + Qtr(A3) + Qtr(A4)$$

This procedure was repeated at every transect.

The formula used to calculate the volume of sediment removed or deposited between cross-section areas (Figure 10) is:

$$V = D \ (A + a)/2$$

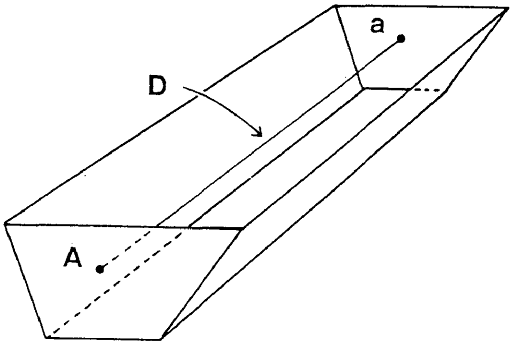
where V is the volume between channel transects, D is the distance between transects, A is the cross-section area per



NOMENCLATURE

AC = Height of segment side
BD = Height of segment side
EF = Width of segment
Qtr (A) = Area of cross-section ABCD
Qtr = Transect quarter

Figure 9. Generalized cross-section of a gully channel.



NOMENCLATURE

A = Cross-sectional area per transect
a = Cross sectional area of next transect
D = Distance between transects

Figure 10. Generalized channel segment of a gully (Mandel et al. 1985)

transect, and a is the cross-section area of the next transect. Change in gully volume per quarter transect is expressed as cubic meters of sediment removed or deposited within that quarter. Summing these values yields the total change in gully volume per gully segment.

Rain Data Collection

An automated recording rain gauge was installed at the site to measure precipitation during the monitoring period. The gauge indicated time, duration, and amount of rainfall per week in minimum time increments of one hour, and minimum volume increments of 2.5 mm. This information is useful in determining the effects of rainfall frequency and intensity on erosion. In addition, 31 years (1960-1990) of precipitation data recorded at Holton, Kansas, were provided by the Kansas State University Cooperative Extension Service (1991). Holton is located approximately 25 km south of the study site. The data include annual precipitation, and rain events that exceeded 50.8 mm in a 24 hour period. This information is useful in comparing gully growth with years and/or days of high precipitation.

Soil Survey

In addition to observing and measuring the gully network, two soil cores were taken with a Giddings hydraulic probe. The first core was taken 4.8 m west of reference point 65 to determine the width of a gully fill. The second core was taken approximately 16.5 m north of headcut 14 to determine the extent of the gully fill upslope.

Soil profiles were described and soil samples were collected from gully sidewalls at reference points 43 and 65. Representative profiles of the Pawnee soil series and Judson-like soil are exposed at points 43 and 65, respectively. Sidewalls were cleaned off with a shovel, and soil samples were collected from each horizon. Soil profiles were described using standard U.S.D.A. terminology and procedures (Tables 2 and 3). The samples were analyzed for particle size distribution and total carbon content at the Kansas State University Soil Laboratory.

A modified pipette method formulated by Kilmer and Alexander (1949) and the Soil Survey Staff (1982) was used to determine particle size distribution. Total carbon content was determined using the combustion method according to Tabatabai and Bremner (1970). Bulk density of soil samples was determined at the UNO Civil Engineering laboratory using a paraffin clod method. This procedure is a modification of the method described by Bowles (1992).

Biomass Survey

A biomass survey was conducted May 9, 1991 at the site to determine forage production, vegetation type, and vegetation density. Each determination was a multi-step process, and the double-sampling method was used (U.S.D.A. 1976:604).

A 30 m transect was established upslope from HC 3,

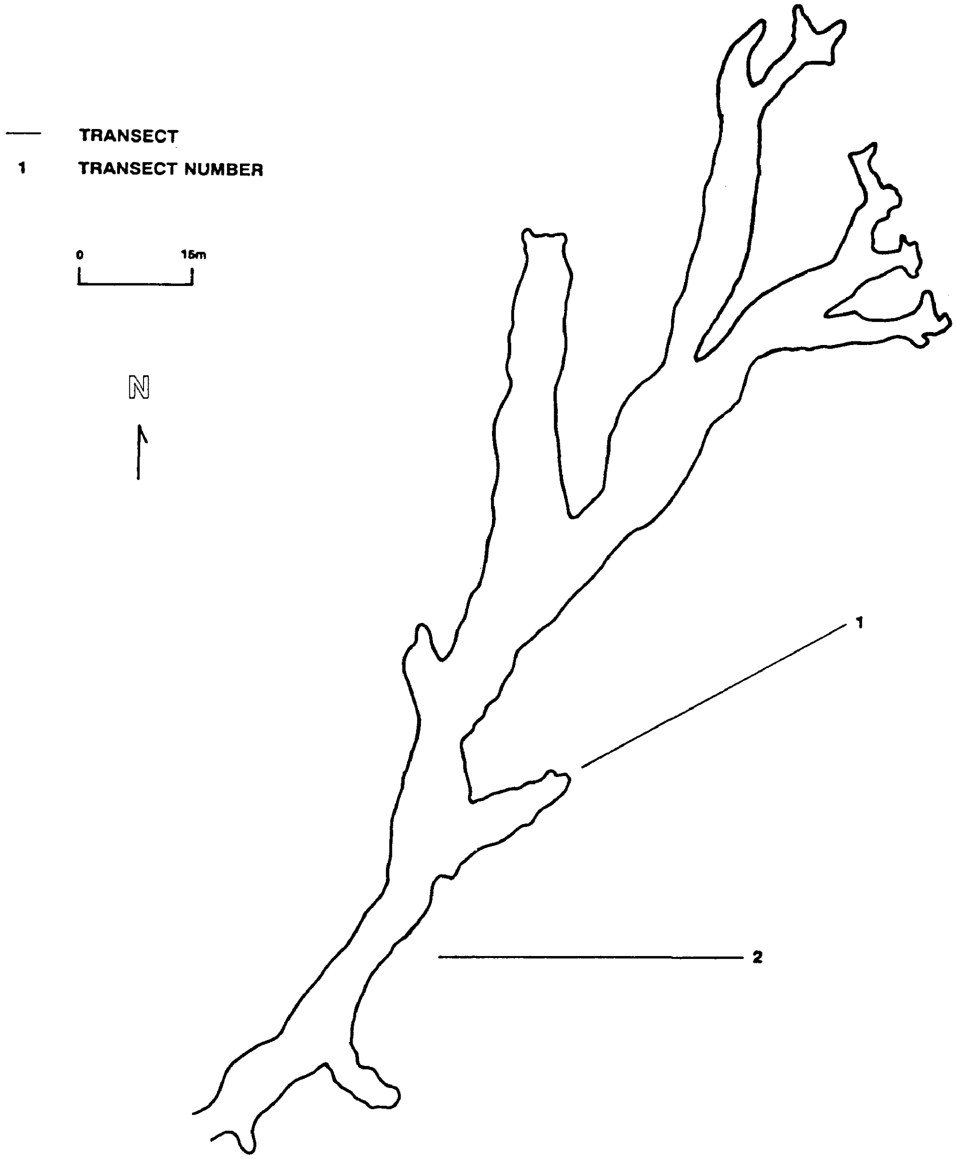


Figure 11. Plan view of gully showing location of biomass transects.

and another 30 m transect was established between HC 2 and HC 3 (Figure 11). An 0.18 m^2 metal frame was randomly placed at three locations along the transect line. All plant species within the frame were clipped, bagged, air dried for two weeks, and then weighed. The total production was added and divided by three to determine the average production per transect.

The same transects were used to determine vegetation type and density. A pencil was placed vertical to the ground at every foot along the transect. If the pencil touched a plant, the plant type was recorded. Otherwise, it was noted whether the pencil touched plant litter or bare ground. Percentage of area covered by each vegetation type, litter or bare ground was then calculated.

Sediment Yield Calculations

To determine a sediment budget for the gully's drainage area, the sediment yield and sediment delivery ratio were calculated. Sediment yield is the total soil loss delivered to a specific point. It includes sediment produced by sheet, rill and gully erosion, minus deposition occurring within the watershed. Sediment delivery ratio is the ratio of annual sediment yield to total erosion at a specific measuring point within a watershed, and is often expressed as a percentage of the total upstream erosion (Roehl 1962:202).

Sediment yield for the watershed was estimated from gross erosion, the sediment delivery ratio, and sediment storage. Sediment yield is estimated by the formula:

$$Y = E(DR)$$

where Y = annual sediment yield (tonnes/unit area)
E = annual gross erosion (tonnes/unit area)
DR = sediment delivery ratio (<1).

Gross erosion includes all water erosion occurring in the watershed, including sheet, rill and gully erosion. Sheet and rill erosion were estimated by the USLE equation:

$$A = RKLSCP$$

where A = the calculated annual soil loss in tons/acre
R = the rainfall factor
K = the soil erodibility factor
L = the slope length factor
S = the slope gradient factor
C = the cropping management factor
P = the erosion control practice factor

The SCS provided data for the R, K, C and P factors. L and S factors were determined by measuring slope gradients and slope lengths.

Gully erosion and sediment storage were determined by changes in net gully volume. Once gross erosion and sediment storage had been determined, the sediment yield was calculated by subtracting deposition from gross erosion. Tonnes/hectare were based on the bulk density value of the

Ap horizon of the gully fill soil (Table 4). This value was reduced 25% assuming that redeposited soil is less compact. The bulk density value for the Ap horizon representing the Pawnee soil was not used, due to its probable error (Table 5).

Sediment delivery ratio was calculated using the equation:

$$DR = Y/\text{gross erosion}$$

where DR = sediment delivery ratio

Y = sediment yield.

Table 4. Properties of Soil Developed in Gully Fill.

		PARTICLE SIZE DISTRIBUTION (% < 2 mm)								
Depth (cm)	Hor.	Total Sand	Coarse Silt	Medium Silt	Fine Silt	Total Silt	Total Clay	Texture Class	Total Carbon	Bulk Density
0-15	Ap	22.7	20.3	17.5	4.1	41.9	35.4	CL	1.95	1.48
15-45	A	11.3	19.8	21.3	13.9	55.1	33.6	SiCL	0.65	1.75
45-61	AB	8.7	23.2	25.1	5.3	53.6	37.8	SiCL	0.33	1.70
61-98	Bw	8.4	25.2	25.1	6.0	56.2	35.4	SiCL	0.25	1.67
98-119	BC	6.6	23.2	27.3	0.6	51.1	42.2	SiCL	0.18	1.64
119-140+	C	7.7	21.0	26.2	7.1	54.3	38.0	SiCL	0.17	1.64

Table 5. Properties of Soil Developed in Glacial Till.

		PARTICLE SIZE DISTRIBUTION (% < 2 mm)								
Depth (cm)	Hor.	Total Sand	Coarse Silt	Medium Silt	Fine Silt	Total Silt	Total Clay	Texture Class	Total Carbon	Bulk Density
0-19	Ap	22.1	13.4	17.3	4.5	35.3	42.6	C	1.14	1.04
19-44	Bt1	18.7	16.5	17.3	3.7	37.5	43.8	C	0.58	1.79
44-73	Bt2	25.6	13.6	15.0	5.3	33.9	40.5	C	0.16	1.81
73-113	BC	31.2	13.9	15.3	5.5	34.7	34.1	CL	0.05	1.78
113-133+	C	32.2	18.2	13.6	5.1	36.9	30.9	CL	0.04	1.89

CHAPTER FOUR

GULLY EVOLUTION

Gully evolution is dependent upon a series of complex processes, and not all gullies undergo the same processes. It is this lack of uniformity between gullies that makes it difficult to predict their growth.

Although gullies evolve by various growth mechanisms, they all begin when a geomorphic threshold has been exceeded; either due to an increase in shear stress, such as increased runoff erosivity, or to a decrease in soil strength. Schumm (1973) suggested that gullies evolve when geomorphic thresholds are exceeded. Extrinsic factors such as climate or landuse, may induce a geomorph system to change. For example, land use changes may increase surface runoff or alter drainage patterns. An intrinsic threshold would operate, if for example, sediment stored within a fluvial system became unstable at critical threshold slopes, leading to accelerated erosional events (Chorley et al. 1984:11). Regardless though of how thresholds are exceeded, most gullies evolve as a result of increased surface runoff and/or concentrated flow in rills (Imeson and Kwaad (1980:432). Once this runoff becomes channelized, a headcut is formed, and a gully develops.

Growth Processes

Gullies evolve through time by headcut advancement and lateral enlargement. In addition, the processes responsible for growth are numerous and complex. Although most gullies may be unique in their evolutionary histories, they do in some cases, share common growth processes. Furthermore, the processes for advancement and enlargement may also be the same. The following discussion summarizes various growth processes.

Two conditions necessary for gully growth are (1) a source of soil debris, and (2) enough runoff to transport the debris through the gully system (Piest et al. 1975:74). Soil debris is often produced by gully-wall failure. Wall failure infers bank instability, and instability is based on numerous factors, such as soil and soil moisture conditions, slope angle, bank height, and the amount of debris at slope bases. When soil strength is exceeded by driving forces, banks will fail, and the gully system will advance and enlarge (Bradford and Piest 1980:84).

Headward extension occurs for numerous reasons, but the one most often cited is undercutting of the headwall (see Ireland et al. 1939; Peterson 1950; Blong 1970; Heede 1970; Bettis 1983). Undercutting occurs by differential erosion within a soil profile, and/or by base saturation of the headwall. A weaker horizon capped by a more resistant horizon erodes quicker, and the headwall collapses or topples, thereby advancing the gully. There are, however, various reasons why erosion is concentrated at the base of headwalls.

According to Leopold et al. (1964) and Higgins et al. (1990), the process of sapping at the base of headcuts by seepage erosion is an important headward extension mechanism. Higgins summarized numerous gully studies, and pointed out that sapping is common to them all. Sapping involves removal of soil particles at the base of headcuts due to emergence of subsurface flow and/or base saturation. Examples of subsurface flow are: (1) intersection of headcuts with water tables (Dunne (1980), (2) paleosols restricting water movement and forcing throughflow to converge with headwalls (Roloff et al. 1981), (3) water flowing through tension cracks to form seep caves (Ireland et al. 1939), and (4) variations of the above (see Piest et al. 1975; and Swanson et al. 1989).

Ireland et al.(1939:48) and Brice (1966:333) noted that saturation at the base of headwalls is an important headward extension process. Base saturation often occurs in response to the effects of plungepools and waterfalls. Brice suggested that gullies cutting into loess-derived soils advance in response to plungepool action. Plungepools are potholes at the base of a headcut scoured out by water flowing over the headcut (Figure 12). Water in the pool aids in saturating the basewall, and loess erodes easily. In addition, water flowing over headcuts produce spray, which often wets headwall bases.

A variety of processes influence lateral enlargement,

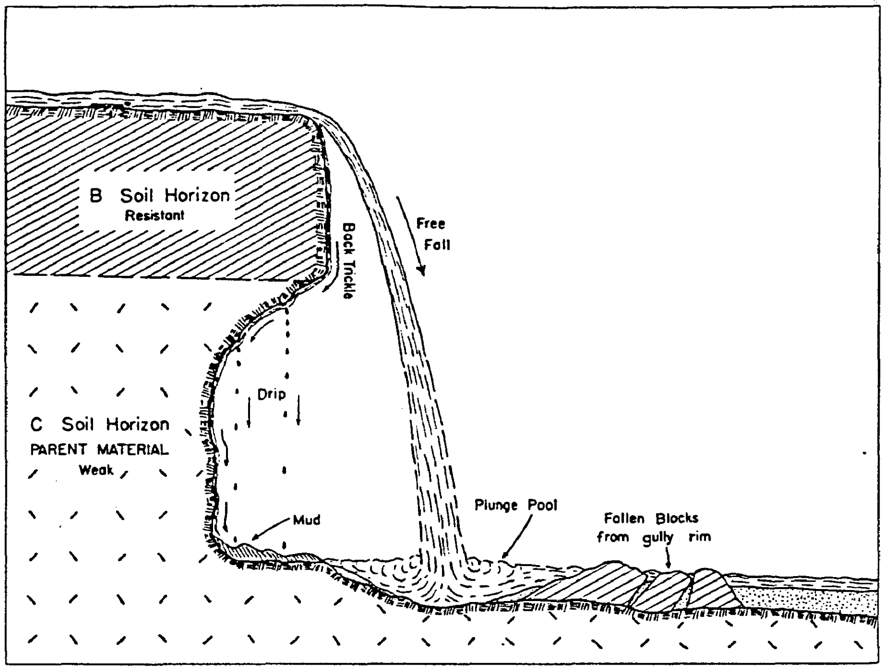


Figure 12. Gully plungepool (Ireland et al. 1939).

but most are related to mass wasting of gully walls. Mass wasting is the downslope movement of soil under the influence of gravity, although water may accelerate this process by reducing soil particle cohesion. According to Bettis (1990), slope failure by mass wasting most often occurs after snowmelt and heavy rains. The extra moisture induces failure by increasing shear stress (load) and pore pressure in the gully bank, thereby decreasing soil shear strength. Common forms of mass wasting contributing to gully widening, such as slumping, toppling, and soil creep, are discussed below.

Slumping involves a back rotational movement of a mass of unconsolidated material along a curved failure plane. The material does not advance far or very quickly. Slumping occurs in response to slope oversteepening and/or when a slope is over loaded. Daniels and Jordan (1966:74) noted that gullies extending up slopes in western Iowa widen mainly by slumping after repetitive freeze/thaw cycles in early spring during snowmelt. Bradford and Piest (1977) indicated similar results. They determined that gullies cutting into loess-derived alluvial soils widen by slumping. Also, they suggested that slumping is dependent on the structural characteristics of loess, and on changing soil moisture content. Bettis (1983) concurred. He stated that the combination of sidewall undercutting and groundwater movement towards gullies induce deep rotational slumps.

Similarly, Crouch and Blong (1989) stressed that slumping (circular slip) is a major slope failure process associated with gullies cutting into alluvial/colluvial sediments in eastern Australia.

Toppling is similar to slumping in that both processes generally involve movement of large masses of soil. Toppling occurs when fractures develop at gully rims and extend down through a soil mass. According to Bradford and Piest (1977:116), fractures or vertical tension cracks may develop along natural cleavage planes along a slope's surface. The cracks may reduce slope stability by decreasing soil cohesion and increasing pore water pressure on the crack surface, due to water infiltration. Thompson and Bettis (1980) concurred. Cracks near the gully rim intercept water, thereby adding weight to the soil mass, as well as decreasing shear strength along the failure plane. In slope stability tests, Bradford et al. (1973) determined that the maximum tension zone depth can be calculated, and also suggested that tension-crack depth and width can be affected by clay shrinkage and frost action. In the Piedmont region of South Carolina, gullies widened by the development of tension cracks parallel to gully rims (Ireland et al. 1939). Cracks develop at various distances from the rim, and as they widen, the soil mass separates from the gully rim, and eventually slides or topples into the gully. Debris often accumulates at footslopes. Bettis

(1983) noted that toppling occurred after periods of freeze/thaw cycles, and after heavy spring rains, whereas Blong (1985) suggested that toppling occasionally occurs in response to lateral undercutting of banks.

Soil creep is another form of mass wasting that aids in gully widening. This process involves the slow movement of surface soil a short distance downslope under the influence of gravity. The alternating cycles of expansion and contraction of soil particles is the principal cause of creep. Two similar weathering processes that cause creep are freeze/thaw and wet/dry cycles. Freezing and wetting raise soil particles at right angles to slopes, while thawing and drying moves the particles downslope as they fall back to lower levels. Creep increases the supply of soil debris to gullies by decreasing aggregate stability. Small soil particles are produced as aggregates disintegrate. These particles are readily transported by water.

In the freeze/thaw cycle, disruption of the soil matrix occurs as ice crystals expand in pores between soil particles, forcing them apart. Repetition of this cycle over time reduces particle bond strength, thereby breaking aggregates into smaller particles. Foster (1986:102) suggested that thawing soils are susceptible to erosion in late winter by runoff due to reduced critical shear stresses of soils. Blong (1970) pointed out that the development of interstitial ice in vertical gully walls is an effective means of prying soil particles from the walls. Palmer (1965) discovered that significant erosion occurred during spring thaw on south facing slopes. Excessive moisture is released by thawing, and the sidewalls readily slough. He also suggested that freezing and thawing creates cracks at slope tops, thereby exposing more soil to surface runoff and erosion. In their studies at Treynor, Iowa, Piest et al. (1975:172) also determined that freeze/thaw cycles contribute to lateral enlargement, especially in the spring.

Equally important, wetting and drying processes exert considerable stress upon soil structure. In particular, the clay mineral montmorillonite has the ability to adsorb water and swell, thereby reducing bond strengths that bind soil particles together. Consequently, as moisture content increases, aggregate stability is reduced, especially after numerous wetting and drying cycles.

Another process that widens and extends gullies is piping. Piping refers to subsurface erosion by water flowing through tunnels or holes in the ground. Pipes often emerge at headwalls and\or gully sidewalls. As pipes enlarge, they often collapse, thereby extending and widening a gully system. Heede (1971) studied piping processes in the Alkalai Creek watershed in northwestern Colorado. He proposed that soils with high sodium content increases soil dispersion, thereby inducing piping. Pipes develop along soil cracks, and as water moves through them, sodium in the soil promotes soil dispersion, thereby enlarging the pipes. Stocking (1981) investigated gully advancement in Zimbabwe and discovered a high correlation between gully advancement and piping. He reported that piping in sodium rich soils extends gullies by subsurface enlargement and collapse, while gullies induce piping by increasing the hydraulic gradient. Leopold et al. (1964) also stated the importance of piping in the extension of discontinuous gullies. They noted that pipes may extend several hundred feet into ungullied alluvium, and once they collapse, they form tributary gully heads by coalescence.

Very little information is available concerning erosional processes acting on gully channels, or the importance of these processes in gully growth. Crouch (1987:536) noted that gully floors at his study site did not experience net lowering, but experienced cycles of erosion and deposition. However, Daniels and Jordan (1966:65-69) stressed the relationship between knickpoint migration and channel entrenchment. They suggested that deepening of small ephemeral streams occurs in response to channel scour as knickpoints migrate upslope. Roloff et al. (1981) suggested that stratigraphy influences channel erosion. Gullies incising loess-mantled till cease to downcut when erosion resistant till is reached, and rates of channel widening subsequently increase.

Stages of Development

Although there has been a substantial amount of research addressing various aspects of gully evolution, few studies have focused on the stages of gully development (e.g., Ireland et al. 1939; Blong 1970; Bariss 1971 and Heede 1974:1976). Results of these studies suggest that each stage is a product of different growth mechanisms, thereby producing distinctive morphology. The following discussion summarizes previous studies of gully evolution, and provides a model of gully development based on those studies.

The earliest work on stages of gully evolution was conducted by Ireland et al. (1939) in the sandy Piedmont region of South Carolina. They suggested that all gullies in their study area pass through four stages of development. The first stage is a period of channel erosion by downward scour. Small rills and channels develop from accelerated runoff. The loamy or sandy A horizons are easily removed by erosion in cultivated areas, exposing a clayey B horizon. Channels cut into the B horizon are typically narrow and V-shaped.

The second stage is a period of headward cutting and rapid enlargement. Growth in this stage is dependent on the advancement of headcuts, bank failure, and the removal of sediment from the channel. The B horizon overlies a weak C horizon composed of weathered sandstone. Once the B horizon was removed, the C horizon eroded quickly. Waterfalls developed where lateral tributaries eroding through the B horizon entered overdeepened gully channels. Under low flow conditions, most of the water flows outward from the headcut, although there may be some back trickle (Figure 12). Under high flow conditions, the backdrip may be a continuous cover of sheet flow over the headwall. In addition, the development of plungepools below waterfalls produce splash. Both conditions promote headcut retreat by wetting the weaker C horizon. The more resistant B horizon overhangs and eventually topples. This cycle may be repeated many times in Stage 2 (Figure 13). Gully widening occurred mainly through slumping and caving processes. Once this material is removed from the gully walls, they are less stable and subject to renewed slumping and caving.

Stage 3 is denoted as a time of healing and re-adjustment. They suggested the gully is in a graded condition, and headcuts are near the drainage divide. Accordingly, less downcutting and widening are occurring, resulting in low-angle side walls. Plungepools are converted into sloping headwalls. The reduced slopes favor the establishment of vegetation, thereby reducing erosion.

The final stage is gully stabilization. The channel approximates local base level, the gully walls are at their angle of repose, and there is sufficient vegetation established to anchor the soil. They contended that a

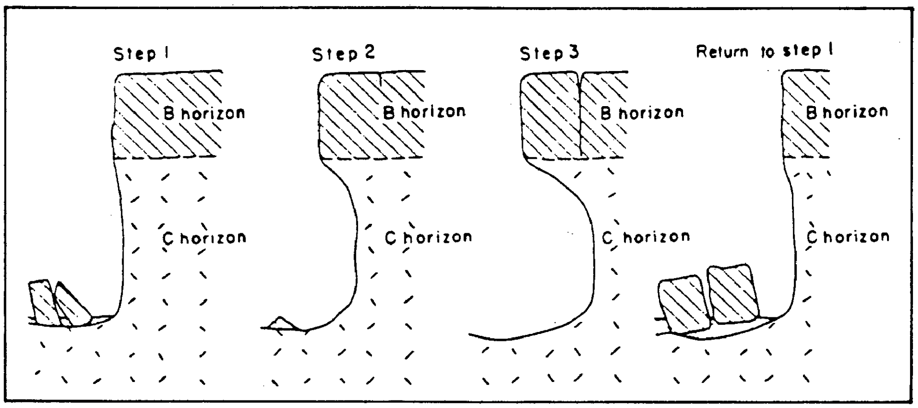


Figure 13. Steps in headcut retreat by gully-head caving (Ireland et.al 1939).

stabilized gully should resist a normal flow of water through the system, but at any point in time, the gully may rejuvenate.

Blong's (1970) results are very similar to those of Ireland et al. (1939), but he devised a sequence of six stages for gully development. He looked at gullies cutting into relatively flat pumice valley floors in New Zealand. His generalized sequence of gully development is as follows.

Stage 1: Development of knickpoints or small scarplets during occasional surface flow.
Stage 2: Headcut advancement and gully deepening by plungepool action and undermining. Headcuts are vertical. A fan may form at the gully mouth, which may become oversteepened.
Stage 3: Extension of gully downvalley across the fan. Discontinuous gullies may coalesce to form a gully network. In addition, new knickpoints and trenches may develop due to variations in discharge, and the gully floor then regrades. These stages may be repeated numerous times.
Stage 4: Gully widening in response to high discharge levels. Gully walls are vertical and smooth. Abandoned gullies, however, have sidewall development by blockfall movement and/or talus formation.
Stage 5: An increase in gully floor gradient after subsequent lower discharges.
Stage 6: Potential repetition of the above stages. Blong noted that pumice deposits are unstable, implying they are prone to erosion.

The presence of paleochannels (now filled) in gully-wall exposures indicates that numerous gully cycles have occurred since pumice deposition in 130 A.D.

Bariss (1971) researched gully formation on the loess-mantled terrain of central Nebraska. After investigating seven active gullies, Bariss suggested that gullies developing in loess pass through three stages of development, and are strongly controlled by their topographic position. A summary of his developmental theory follows.

Stage 1:	Gully initiation at heads of small valleys or at stabilized gullies encroaching tableland rims. Headcuts are advancing.
Stage 2:	Rapid gully deepening along entire network until local base level is reached. Sidewalls are vertical and channel floor is ungraded. This unstable phase is short lived.
Stage 3:	Channel widening by sapping, and wall retreat by scaling, caving and slumping. Bariss noted that as sidewalls retreat, they become longer and less steep; therefore, more stable. Decreased slope values also imply the beginning of gully stability. He associated stabilized and vegetated slopes with smooth gully floors, and suggested this stage represents the end of gully formation, with the gully being transformed into a valley. Bariss concluded that gully formation is a natural process, and that one could expect a continuation of this cycle.

Heede (1974; 1976) attempted to correlate stages of gully development to channel morphology by comparing the hydraulic geometry of ephemeral gullies in the Rocky Mountains of Colorado to rivers. He also suggested that gully development should be considered part of landscape evolution, passing from youthful to mature stages, and that each stage has different levels of equilibrium. A summary of his developmental theory follows.

Youthful Stage:	Initiation of a discontinuous gully along breaks in gradients on hillslopes. This stage is

associated with extension of headcuts in response to piping and plungepools, considerable downcutting of the channel, and potential high sediment yields. Lateral widening is also occurring in response to sloughing and shearing of vertical walls. Furthermore, a small fan may develop at the gully toe. He also contended that this stage is proceeding towards dynamic equilibrium.

Early Mature Stage: The fusion of discontinuous gullies to form a continuous gully network, characterized by numerous knickpoints in the channel floor. This stage has not yet attained equilibrium.

Although Heede identified only two stages of gully development in the Alkali Creek watershed, he suggested that gullies can attain full maturity. He theorized that mature gullies are in dynamic equilibrium, and are characterized by certain features, such as dense vegetative cover. Finally, Heede supported Ireland et al. (1939) and Blong's (1970) view that gullies do not always develop in an orderly sequence of events.

Analysis of the previous studies indicates that researchers share common ideas about gully evolution. A generalized model of gully development can be proposed, therefore, based on those commonalities. The model includes four stages of development, and each stage indicates different phases of erosion. In addition, each stage may occur at any point along the gully network. Following is a brief summary of the four stages.

Stage 1: Channel incision. Small, narrow channels incise into the surface soil. Headcuts develop at small knickpoints within the channel.
Stage 2: Gully enlargement. Headcut extension and lateral enlargement by wall failure promote rapid growth of the gully system.
Stage 3: Healing. At this stage, the gully has minimal growth, and vegetation begins to retard erosion.
Stage 4: Stabilization. Gully walls have gentle slopes, and vegetation is well established.

Cut-and-Fill Cycles

Cut and fill cycles are considered an important component of gully development, and may be considered a part of natural landscape evolution (Daniels and Jordan 1966). In a study of small, loess mantled valleys in western Iowa, Daniels and Jordan (1966) documented at least five periods of alluviation and erosion during the past 15,000 years. They noted that once streams reach grade, alluviation may occur, followed by entrenchment and/or stability. Finally, they suggested that gullies are drainage system extensions, thereby reflecting processes occurring in valleys, and that modern gullies are likely to continue cut-and-fill cycles.

Bettis (1983) also studied small valleys in the Loess Hills of Iowa, and determined there were multiple episodes of cutting and filling during the Holocene. He suggested that streams reoccupied former gully channels, and through time, filled with sediment derived from gully walls and valley slopes. These deposits are retrenched in response to gullies migrating up valley. Radiocarbon ages confirm the presence of at least six distinct Holocene-age alluvial fills in the loess region. He also contended that gullies have shaped the modern landscape in this region by cut-and-fill cycles, and may be considered a natural process in landscape evolution.

Analogous to the research conducted in Iowa are several studies undertaken in the southwestern United States on arroyos and the semi-arid cycle of erosion (e.g., Antevs 1952; Schumm and Hadley 1957). Although these studies indicate that arroyos proceed through stages of erosion and sedimentation, not all researchers agree on how the erosion cycles begin. A review of their works follows.

Antevs (1952) summarized much of the earliest work concerning cut-and-fill cycles in the arid Southwest. He noted that most arroyo cutting began in the late 1880's after people settled into that area. Excerpts from diaries of early explorers and military personnel document that prior to settlement, southeastern Arizona and southwestern New Mexico had a nearly continuous vegetative cover. Small valleys had wet meadows, tall grasses, infrequent floods, and streams had ill-defined channels.

Although the Spanish occupied this area before the 1880's, it wasn't until 1870, when cattle were re-introduced, that major vegetative destruction began. With plentiful grass and water, and much of the country being public domain, cattle numbers increased dramatically, altering the landscape within a short time. Vegetation was severely reduced, thereby increasing runoff, and valley floors became deeply incised.

Antevs suggested that vegetative cover is the controlling factor of arroyo cutting and filling in the semi-arid Southwest. He further stated that arroyo cutting is amplified during drought because reduced precipitation thins an already reduced vegetative cover. In addition, during intense rain events, accelerated runoff becomes channelized and floods could easily occur, causing extensive channel incisement. Sediment is then carried through the arroyo. He suggested that filling occurs during climatic transitions. Transition stages would have fair to sparse vegetation on uplands, and fairly good cover in the valleys. The increased vegetative cover would not reduce all erosion from upland areas; hence, sediments would be deposited in gully channels. He also suggested that filling may occur under reduced stream flow in response to the presence of vegetation in the channel floor, or when stream flow is absorbed into the channel bed. However, he considered this scenario a temporary condition. Under relatively moist conditions, he suggested that neither cutting or filling occurred. Instead, soil formation dominates the landscape. This cycle would then repeat itself depending on climatic conditions. Antevs stressed that during arroyo inception of the 1800's, had the vegetative cover remained unaltered by man's activities, the vegetation could have survived periods of drought. Therefore, arroyo cutting had to occur in response to vegetation depletion initiated by causes other than climate. He supports this concept by suggesting that the droughts of 1900 and 1950 in Arizona may not have been severe enough to deplete vegetation; hence channel incision should not have occurred. However, because there was significant arroyo development during both years, he suggested it was in response to overgrazing by cattle.

Schumm and Hadley (1957) investigated arroyo development in small drainage basins in eastern Wyoming and northern New Mexico, and concluded that arroyo development is related to erosional thresholds rather than climate changes. Specifically, they determined the origin and location of discontinuous gullies in small valleys, and explained how drainage basin characteristics influence gully formation. Each valley contained modern alluvial fills, and because alluviation steepens a valley's gradient, they suggested that a critical gradient would be reached, thereby inducing incision. Valley filling, they suggested, is related to discharge. Sediment loads increase downstream when much of the flow is absorbed into channel beds, and most runoff does not reach a master stream (Culler 1956).

Another characteristic of semi-arid drainage networks is that many tributaries are not in accordance with the master stream. An example is when a tributary is graded to a terrace of the master stream. Infilling of the lower tributary valleys causes sediment and water to spread over terrace surfaces, with the terrace acting as a buffer to accordance.

Based on these two drainage basin characteristics, Schumm and Hadley formulated an erosion cycle model for semi-arid climates. A brief summary of the model follows.

Stage 1: Alluviated tributaries join a master stream by trenching their fills. Headcuts migrate upslope.
Stage 2: As headcuts continue to migrate upslope, they rejuvenate other tributaries.
Stage 3: Rejuvenated tributaries increase runoff and sediment load. Sediment deposits increase at lower portions of master channel in response to lower gradient and channel widening. Alluviation continues until channel fills, and deposition moves upstream into tributaries. Alluviation eventually decreases due to a reduced sediment source upslope.
Stage 4: The tributary fills become oversteepened, and discontinuous gullies form at these steepened reaches. As gullies continue to incise, sediment is moved down valley, and is deposited as fans at the tributary mouth. This fan becomes oversteepened, and incisement occurs, thereby joining the tributary with the master stream. The cycle then repeats.

Schumm and Hadley concluded that cutting and filling occurs on localized oversteepened valley fills, and that high intensity rain events may trigger incision of the fills. In addition, each tributary may have their own cut-and-fill histories independent of other tributaries and/or the master stream.

CHAPTER FIVE

RESULTS AND DISCUSSION

The purpose of this chapter is to present and discuss the results of short-term gully evolution in the Dissected Till Plain of northeastern Kansas. Initially, changes in gully volume at the first and second half of the monitoring period are analyzed, and factors affecting those changes are discussed. Zones of net erosion and sedimentation are identified and erosion results are compared to those of other studies. Headcut advancement rates are presented and factors affecting those rates are analyzed. Then, sediment yield data for the study site are presented. This is followed by an analysis of changes in gully geometry through time and space. Cross-sectional and longitudinal profiles are evaluated, and the results are incorporated into a model for gully development. The model describes and identifies stable areas within the gully network. Headcut advancement and gully widening processes are then identified and discussed. Data from the biomass survey are also presented, and the results are used to show relationships between cattle grazing and gully erosion. Finally, the historical growth of the modern gully network between 1937 to 1991 is discussed.

Volume Change

There were 16 days where rainfall amounts exceeded 1.5 cm/24 hours during the twelve-month monitoring period.

Measurements were made along cross-channel transects and at headcuts after each of these rain events to detect changes in gully volume and geometry. Location of gully transects and segments are shown in Figures 7 and 14 respectively. Table 6 summarizes changes in volume during the monitoring period.

The first half of the monitoring period (5/90 - 11/90) was dominated by sedimentation and concomitant decreases in gully volume in the middle and lower reaches. Erosion in the upper reach increased gully volume.

The second half of the monitoring period (11/90 - 5/91) was dominated by erosion in the middle and upper reaches, resulting in a net volume increase. Although considerable erosion occurred, it was insufficient to remove all sediment that accumulated in the middle reach during the first period. Sedimentation was the dominant process in the lower reach, but to a lesser degree than in the first half of the monitoring period.

Several explanations account for sedimentation dominating the lower and middle reaches during the period 5/90 - 11/90. First, sediment produced during this period would normally be flushed through the system due to greater frequency and intensity of precipitation. Although 74% of the recorded precipitation fell during this period (Table 7), the total recorded precipitation was below Holton's annual average of 938.28 mm (Kansas State University

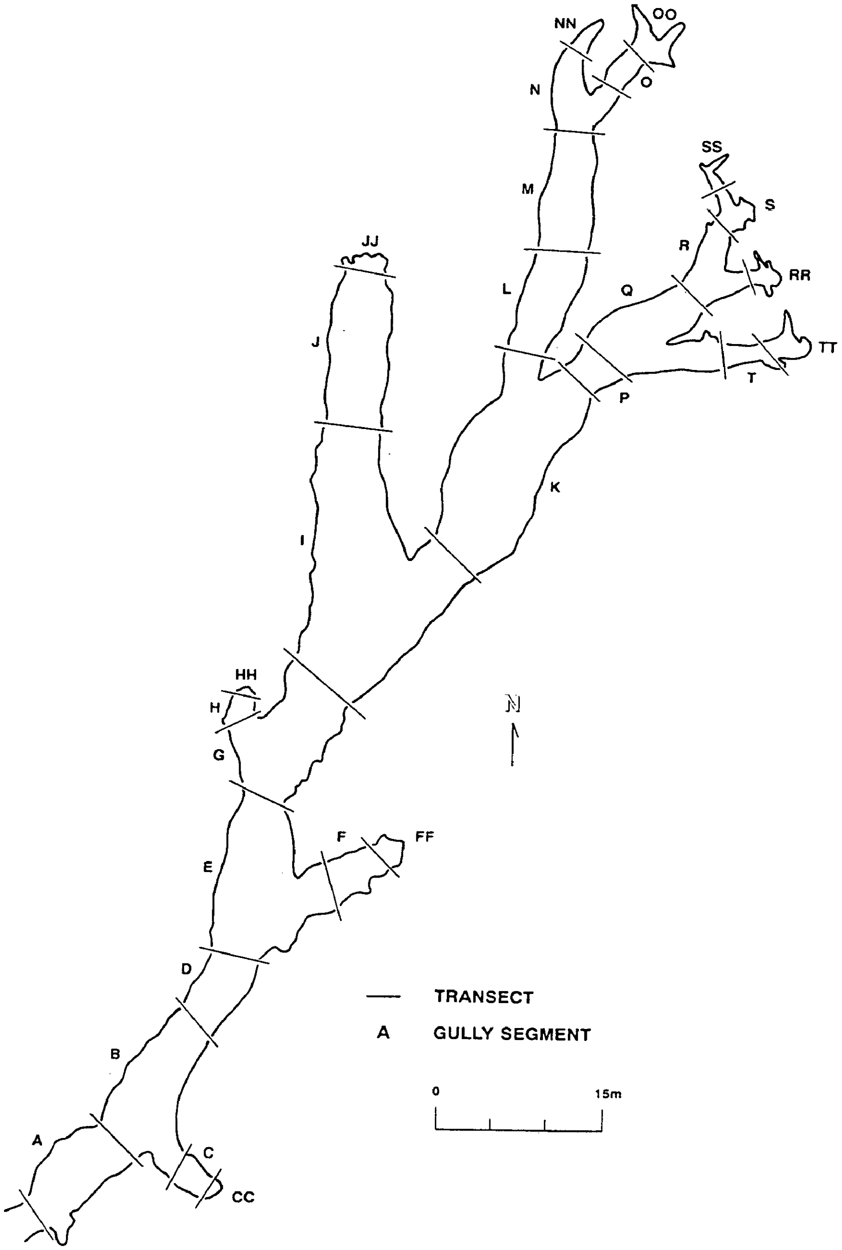


Figure 14. Plan view of gully showing gully segments.

Table 6. Summary of Increases (+) and Decreases (-) in Gully Volume.

	Total Volume Change (m^3)			Volume Change/Meter (m^3)		
	Monitoring Period					
	5/90-11/90	11/90-5/91	5/90-5/91	5/90-11/90	11/90-5/91	5/90-5/91
Lower Reach						
Segment A	-1.69	-0.98	-2.67	-0.17	-0.10	-0.27
B	-2.13	-1.18	-3.31	-0.11	-0.07	-0.18
C	-0.08	-0.03	-0.11	-0.03	-0.01	-0.04
CC	+0.08	0.00	+0.08	+0.06	0.00	+0.06
D	-0.39	-0.09	-0.48	-0.06	-0.01	-0.07
E	-2.26	+0.48	-1.78	-0.09	+0.02	-0.07
F	-0.26	-0.06	-0.32	-0.06	-0.01	-0.07
FF	+0.20	-0.04	+0.16	+0.08	-0.02	+0.06
Sub-Total	-6.53	-1.90	-8.43			
Mean Change				-0.05	-0.03	-0.08
Middle Reach						
Segment G	-3.23	+0.12	-3.11	-0.18	+0.01	-0.17
H	+0.10	0.00	+0.10	+0.04	0.00	+0.04
HH	+0.08	0.00	+0.08	+0.06	0.00	+0.06
I	-10.98	+1.46	-9.52	-0.27	+0.03	-0.24
J	-1.31	+0.72	-0.59	-0.09	+0.05	-0.04
JJ	+0.45	+0.27	+0.72	+0.23	+0.12	+0.35
K	+7.50	+3.14	+10.64	+0.19	+0.08	+0.27
Sub-Total	-7.39	+5.71	-1.68			
Mean Change				0.00	+0.04	+0.04
Upper Reach						
Segment L	+2.38	+0.69	+3.07	+0.24	+0.06	+0.30
M	+0.33	+0.67	+1.00	+0.03	+0.06	+0.09
N	+0.22	+0.63	+0.85	+0.02	+0.05	+0.07
NN	+0.12	+0.06	+0.18	+0.03	+0.01	+0.04
O	-0.01	+0.24	+0.23	0.00	+0.06	+0.06
OO	+0.13	+0.07	+0.20	+0.03	+0.01	+0.04
P	+0.72	+0.19	+0.91	+0.22	+0.06	+0.28
Q	-1.40	+0.97	-0.43	-0.06	+0.05	-0.01
R	-0.06	+0.60	+0.54	-0.01	+0.05	+0.04
RR	+0.07	0.00	+0.07	+0.02	0.00	+0.02
S	+0.09	+0.20	+0.29	+0.02	+0.05	+0.07
SS	+0.01	+0.05	+0.06	+0.01	+0.01	+0.02
T	+0.01	+0.13	+0.14	0.00	+0.03	+0.03
TT	+0.16	+0.07	+0.23	+0.04	+0.02	+0.06
Sub-Total	+2.77	+4.57	+7.34			
Mean Change				+0.04	+0.04	+0.08
Total Change	-11.15	+8.38	-2.77			

Table 7. Recorded Rain Events At Study Site During The Period May 9, 1990 Through May 5, 1991.

Date	Amount(mm)	Duration(hr)	Rate(mm/hr)
05:09:90	19.55	2.75	7.11
05:10:90	5.84	3.00	1.95
05:11:90	16.51	6.50	2.54
05:14:90	20.30	2.00	10.15
05:15:90	25.40	2.00	12.70
05:18:90	3.81	3.50	1.09
05:19:90	2.54	1.00	2.54
05:24:90	7.62	0.50	15.24
05:24:90	12.70	3.00	4.23
05:24:90	1.27	1.00	1.27
May Total	115.54		
06:06:90	27.94	1.00	27.94
06:13:90	5.08	0.50	10.16
06:14:90	5.08	0.50	10.16
06:14:90	8.89	3.00	2.96
06:14:90	7.62	0.50	15.24
06:15:90	19.05	3.00	6.35
06:18:90	17.78	0.50	35.56
06:19:90	7.62	0.50	15.24
06:30:90	1.27	0.25	5.08
June Total	100.33		
07:09:90	3.81	1.00	3.81
07:09:90	1.27	1.00	1.27
07:21:90	76.20	4.00	31.75
07:21:90	5.08	4.00	1.27
07:25:90	5.08	2.00	2.54
07:25:90	5.08	4.00	1.27
07:27:90	11.43	0.50	22.86
July Total	107.95		
08:02:90	5.08	0.50	10.16
08:02:90	2.54	3.50	0.73
08:03:90	5.08	3.00	1.69
08:03:90	2.54	0.50	5.08
08:03:90	11.43	1.00	11.43
08:11:90	10.16	1.00	10.16
08:12:90	5.08	2.00	2.54
08:12:90	6.35	2.00	3.18
08:16:90	7.62	1.50	5.08
08:16:90	13.97	2.00	6.99
08:16:90	2.54	0.50	5.08
08:19:90	15.24	0.25	60.96
08:19:90	5.08	0.50	10.16
August Total	92.71		

Table 7. Continued.

Date	Amount(mm)	Duration(hr)	Rate(mm/hr)
09:18:90	5.08	0.50	10.16
09:18:90	2.54	0.50	5.08
09:20:90	2.54	0.50	5.08
09:20:90	1.27	0.50	2.54
Sept Total	11.43		
10:02:90	3.81	2.00	1.91
10:02:90	1.27	2.00	0.64
10:03:90	10.16	1.00	10.16
10:03:90	5.08	3.00	1.69
10:08:90	7.62	9.00	0.85
10:20:90*	8.12	1.00	8.12
October Total	36.06		
11:03:90*	45.47	12.00	3.79
11:08:90**	5.08	1.00	5.08
Nov Total	50.55		
03:12:91	2.54	2.00	1.27
03:13:91	1.27	1.00	1.27
03:16:91*	26.67	3.00	8.89
03:27:91	5.72	2.00	2.86
March Total	36.20		
04:02:91	2.54	4.00	0.64
04:08:91	2.54	3.00	0.85
04:12:91	20.32	4.50	4.52
04:13:91	11.43	5.50	2.08
04:17:91	19.05	15.50	1.23
04:21:91	2.54	2.00	1.27
04:22:91	2.54	1.00	2.54
04:24:91	2.54	2.00	1.27
04:26:91	33.56	1.50	23.71
04:26:91	12.70	0.75	16.93
04:28:91	7.62	15.00	0.51
April Total	117.38		
05:03:91	2.54	12.00	0.21
05:04:91	11.43	0.75	15.24
05:04:91	6.35	2.00	3.18
05:05:91	2.54	0.50	5.08
May Total	22.86		
Total Recorded Precipitation	691.01		

* Estimated duration.

**Estimated date of precipitation.

Cooperative Extension Service 1991). During the monitoring period, 691.01 mm of precipitation was recorded (precipitation was not recorded between 11/9/90 and 3/10/91 due to rain gauge's inability to operate during cold weather). Equally important, only one rain event during that period exceeded 50.8 mm within 24 hours. It is likely that reduced runoff, due to fewer rain events and/or fewer intense storms, had little energy to transport sediment. Under these conditions, sediment was more likely to aggrade in gully channels, decreasing gully volume. Second, channel gradient decreases significantly at and below transect 6719 (Figure 15). As channel gradient and flow velocities decrease, runoff loses its transport capacity, promoting aggradation. According to Schumm et al. (1984), as channel depth decreases and channel width increases, sediment storage increases. Hence, once aggradation begins, it promotes additional aggradation. Third, vegetation on gully walls, toe slopes, and channels act as sediment traps, and probably accounted for some sedimentation (Figures 16 and 17).

Although erosion dominated the upper reach during the period 5/90 - 11/90, the change in gully volume was small. One factor controlling erosion is soil moisture conditions and storm intensity. High summer temperatures reduced soil moisture. As soil moisture decreases, soil strength increases, especially among soils that contain the clay

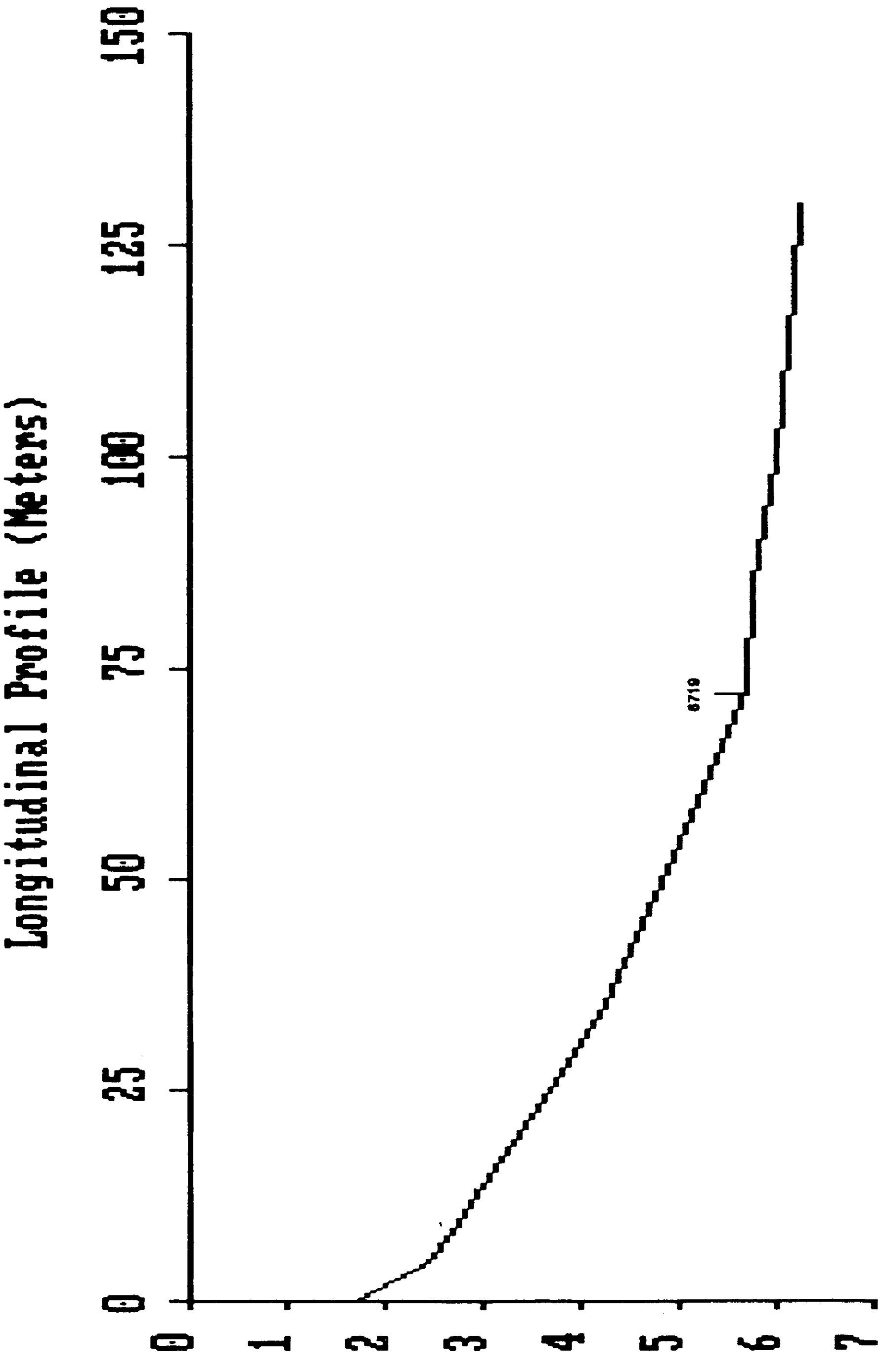


Figure 15. Decreased channel gradient at transect 6719.

Figure 16. Photo of vegetation along toeslopes, sidewalls and floor north of transect 6120.

Figure 17. Photo of vegetation along channel floor in gully element 3.

mineral montmorillonite. It is also likely that the upper reach had reduced amounts of runoff entering the reach due to decreased average annual precipitation, and few high intensity storm events. Less raindrop energy is available to detach soil particles, thereby decreasing erosion rates. Furthermore, as temperatures increased, and rainfall decreased, soil cracks formed, allowing water to infiltrate, thereby decreasing erosion rates.

Soil moisture conditions and storm intensity are similarly responsible for erosion dominating the middle and upper reach during the period 11/90 - 5/91. Although this period had only one-fourth the annual precipitation (Table 7) nearly three-fourths of all erosion occurred during this period. Moist soil conditions during winter months due to thawing action probably accelerated erosion. Although the soil froze during the winter months, on numerous occasions air temperatures were above freezing, and the A horizons of the surface soil thawed. Foster (1986:102) noted that thawing soils are less cohesive. Shear strength is apparently reduced in thawing soils which are thereby subject to erosion from late winter runoff. For example, saturated A horizons of surface soils were observed throughout the gully network on February 3, 1991, due to snowmelt. However, frozen subsurface horizons reduced infiltration, producing large volumes of interflow and surface runoff. Saturated soils tend to experience sidewall and headwall failure, and runoff produced by snowmelt transports loose soil debris through the gully system. This phenomenon probably occurred numerous times during the winter months.

Late winter thaws followed by spring rains is another condition affecting erosion. Soils remained fairly moist from March through May of 1991 due to frequent rain events (Table 7). Once the soil was moistened, intense rain events, such as those on April 26, 1991, and May 4, 1991, produced greater runoff. Increased runoff has greater scour and transport capabilities, thereby enlarging the gully. Furthermore, cooler temperatures during this time period maintained high soil moisture by reducing evaporation rates. This, in turn, maintained erodible soil conditions.

Based on the results of their investigation at the Treynor Experiment Station in southwestern Iowa, Piest et al. (1975:79) also determined that most gully erosion occurred during early spring, although this period experienced approximately one-third the annual precipitation. They noted that most soil debris is produced during winter and early spring, and is transported through the system during the first spring rainstorms. Subsequent rain events, therefore, transported less sediment.

Sedimentation in the lower reach during the period 11/90 - 5/91 occurred in response to insufficient runoff to transport all the sediment produced in the middle and upper reaches. Although most sediment was transported through the gully network, it is likely that the heavier soil particles remained in the lower reach.

Although significant erosion occurred during the twelve month period, sedimentation was the dominant process, resulting in a 2.77m^3 decrease in gully volume. Sidewalls experienced the greatest amount of erosion, and was probably the greatest sediment source. However, it is likely that a portion of the sediment was derived from adjacent slopes. Based on estimates derived from the Universal Soil Loss Equation, approximately 2.1 tonnes/hectare of sediment is shed from the slopes every year. The upper reach experienced the greatest amount of erosion, whereas the lower reach had the greatest amount of sedimentation.

Although net volume changes denote the quantity of erosion and sedimentation, the volume change/meter provides a more accurate picture by indicating where the greatest rates of erosion or sedimentation are occurring (Table 6). Mean rates of erosion and sedimentation were calculated for gully segments.

The mean values for volume changes within the upper reach for the time periods 5/90 - 11/90 and 11/90 - 5/91 are identical, whereas the mean values for the lower reach of the same time periods are similar, indicating similar rates of infilling. The mean values for the middle reach vary considerably between the time periods 5/90 -11/90 and 11/90

- 5/91.

It is also important to note that the mean values for gully segments K, L and P are significantly higher during the period 5/90 - 11/90 than the following time period. The sidewalls at transects 5944 and 4423 (Figure 7) receded considerably due to cattle walking across that area. No cattle were present during the second time period.

Zones of net erosion within gully segments were detected by locating quarter sections of cross-channel transects that experience net increases in volume during the monitoring period (Table 8). The position of quarter sections are illustrated in Figure 9. The first and fourth-quarter sections typically encompass gully sidewalls and a small portion of channel floor. However, a greater proportion of the channel floor is included in sections where sidewalls are vertical or nearly vertical. The second- and third-quarter sections encompass the bulk of the channel floor.

Data shown in Table 8 indicate that all reaches of the gully network experienced the greatest net erosion within the area of the first and fourth-quarter sections, (sidewalls), accounting for 91.2% of the erosion detected during the monitoring period. Headcut advancement accounts for 6.7% of the erosion, and channel floor erosion accounts for 2.1% (Table 8). The 2.1% figure does not include channel floors of headcut segments e.g., segment CC, FF etc.

Table 8. Summary of Increases in Gully Volume (+) For The Period 5-12-90 Through 5-7-91.

		Quarter Sections of Cross-Channel Transects				
		1st	2nd	3rd (m³)	4th	Total
Lower Reach						
Segment	A	0.00	0.00	0.00	0.00	0.00
	B	+0.10	0.00	0.00	0.00	+0.10
	C	+0.01	0.00	0.00	+0.02	+0.03
	CC	+0.03	+0.02	+0.01	+0.02	+0.08
	D	+0.06	0.00	0.00	+0.24	+0.30
	E	0.00	0.00	0.00	+0.87	+0.87
	F	0.00	0.00	0.00	+0.11	+0.11
	FF	+0.03	+0.02	+0.02	+0.09	+0.16
Sub-Total		+0.23	+0.04	+0.03	+1.35	+1.65
Middle Reach						
Segment	G	+0.02	0.00	0.00	+0.10	+0.12
	H	+0.05	0.00	0.00	+0.09	+0.14
	HH	+0.03	+0.01	+0.01	+0.03	+0.08
	I	+0.77	0.00	0.00	0.00	+0.77
	J	+0.44	+0.13	0.00	0.00	+0.57
	JJ	+0.20	+0.23	+0.21	+0.08	+0.72
	K	+9.50	0.00	0.00	+4.10	+13.60
Sub-Total		+11.09	+0.37	+0.22	+4.40	+16.00
Upper Reach						
Segment	L	+1.21	0.00	0.00	+2.25	+3.46
	M	+0.62	0.00	0.00	+0.53	+1.15
	N	+0.29	+0.08	+0.03	+0.51	+0.91
	NN	+0.04	+0.05	+0.04	+0.05	+0.18
	O	+0.15	0.00	0.00	0.09	+0.24
	OO	+0.16	+0.02	0.00	+0.04	+0.22
	P	+1.07	+0.04	0.00	0.00	+1.11
	Q	+0.62	0.00	0.00	0.00	+0.62
	R	+0.51	+0.01	0.00	+0.17	+0.69
	RR	+0.02	+0.02	0.00	+0.03	+0.07
	S	+0.05	+0.08	+0.08	+0.08	+0.29
	SS	0.00	+0.01	+0.03	+0.02	+0.06
	T	+0.01	+0.03	+0.08	+0.02	+0.14
	TT	+0.03	+0.08	+0.09	+0.03	+0.23
Sub-Total		+4.78	+0.42	+0.35	+3.82	+9.37
Total Erosion		+16.02	+0.83	+0.60	+9.57	+27.02

Veness (1980) and Crouch (1987) reported findings similar to these. Veness's research in New South Wales revealed that fluted sidewalls generated about 90% of the sediment in gully networks, and the ratio of downcutting to sidewall erosion was 1:8 at 41 survey stations. Likewise, Crouch demonstrated that sidewalls were a significant sediment source. Bradford and Piest (1980), however, determined that gullies cutting into deep, loess-derived soils experienced greater erosion at headwalls.

Headcut Advancement

Headcut advancement ranged from 5 to 69 cm/yr within the gully network (Table 9). Based on field observations, this rate is strongly controlled by surface geology and soils. The most rapid advancement rates occurred where headcuts are migrating upslope into late-Holocene gully fills, including headcuts 2, 3, 4, 14 and possibly 15 (Figure 7). Linear depressions mark the position of paleo-gullies that are almost entirely filled with sediment. The presence of Cumulic Hapludolls (Mollisols) with weakly expressed A-Bw profiles developed at the top of these gully fills suggests that they are late-Holocene in age. Radiocarbon ages determined on materials from gully fills at other localities in the Upper Delaware River Basin support this interpretation (Mandel 1991). The relatively low clay content (Table 4) and high permeability of gully fill promotes headcut advancement. Toy (1987:23) suggested that

Table 9. Headcut Advancement From 5/12/90 Through 5/07/91.

Headcut Number	Advancement (cm)
1	14
2	26
3	37
4	26
5	19
6	13
8	6
9	4
12	5
13	21
14	69
15	25

the most significant soil property affecting soil erosion is shear strength, which is a function of cohesion and pore water pressures.

Shear strength is the maximum resistance of soil particles to shear stresses, and cohesion is the property by which soil particles cling together (U.S.D.A. 1967). Cohesive forces are attributable to the colloidal fraction in soils. Due to its greater surface area/mass and greater physiochemical activity than sand or silt, clay dominates soil behavior (Hough 1969 and Hillel 1982). Clay and colloidal size particles act as binding agents, and soils without these fine grained particles will have single grained structures (Foth and Turk 1972). For example, the sand fraction is composed of single grained particles dominated by quartz. They are chemically inactive, and generally do not form aggregates, resulting in cohesionless particles that are easy to detach. The sand fraction, therefore, acts as a weakening and loosening agent on soils (Troeh et. al 1991).

Silt particles possess a clay film, resulting in some cohesion, plasticity and adsorption, but relatively much less than clay particles (Brady 1974). Silty soils may also be well aggregated, but are prone to rapid breakdown when wetted (Troeh et al. 1991). Silty soils are also more permeable than clay soils due to larger pore spaces, whereas clayey soils are considered relatively impermeable due to a preponderance of micropores. Furthermore, soil generally becomes more erodible with increasing silt content (Wischmeier and Smith 1978).

Increased clay fractions, however, promote large, stable, aggregates that are less easy to detach (Troeh et al. 1991). Soils with high clay content, and small proportions of silt, such as the till-derived soils, should be less erodible. Furthermore, soils that have been disturbed or reworked, such as the soils formed in the gully fills, have reduced bulk densities (Robert Drees 1991, personal communication). Lower bulk densities increase water infiltration (Toy 1987). It is likely that greater infiltration capacities may facilitate erosion by increasing weight and pore pressure of the soil mass, thereby decreasing soil shear strength. Tables 4 and 5 reveal that the gully fill soils have lower bulk densities than soils developed in glacial till. The Ap horizon of the till-derived soil is, however, an exception.

Slower rates of headcut advancement are associated with gullies cutting into till and till-derived soils, including headcuts 5 through 13 (Figure 7). The till-derived soils are classified as Argiudolls (Mollisol) with thick, clay-rich Bt horizons. Headcut advancement into the till-derived soil is limited due to its high clay content (Table 5) and lower permeability.

Overall, the rates of headcut advancement documented at the study site are low compared to those in thick loessial areas of the Midwest. For example, Daniels and Jordan (1966) reported that a 130 to 180 mm rainfall within a 12 hr. period across a 1 ha watershed of western Iowa opened a small drainageway and formed a gully that advanced 21.9 m in several hours. Brice (1966) also documented fairly fast advancement rates in the loess plains of central Nebraska. During a 15 year period, numerous gullies advanced nearly 0.8 km. Despite the comparatively low rates of advancement at the study site, they should not be considered insignificant. For example, headcut 14 will migrate 7 m over the next ten years if it maintains its present rate of advancement.

Channel Floor Erosion

Few studies discuss or quantify channel floor erosion. Peterson (1950) summarized gully growth in valleys of the western U.S., and suggested that channel deepening is a function of valley slope, sediment properties, and runoff, but gave no information on the significance of channel erosion as a sediment source. Crouch (1987) studied gullies in Australia, and determined that gully floors deepened by knickpoint migration. Knickpoints formed when collapsed sidewall material accumulated on channel floors, temporarily damming channel flow. He noted, however, that no real channel floor lowering occurred, but rather the floor exhibited a cyclical behavior of erosion and redeposition as the knickpoints moved upstream.

The only knickpoint observed at the Wetmore site was in the lower portion of gully element 2. Sediment is accumulating directly below the knickpoint (Figure 18). The knickpoint probably generated a portion of that sediment, but the amount was insignificant. If the knickpoint continues to migrate, however, it may eventually remove the fill in gully element 2 (Figure 19).

The largest erosion values for channel floors occurred at or immediately below headcuts. However, most of those values were small compared to those for sidewall erosion. Bradford, et al. (1978) suggested that parent materials strongly influenced incision of gully channels in the thick

Figure 18. Photo of knickpoint in gully element 2.

Figure 19. Photo of knickpoint in gully element 2.

loessial region of western Iowa. Downcutting slowed considerably once gully floors reached glacial till. They noted that the till has a higher strength, higher clay content, and lower permeability compared to the overlying loess-derived alluvium. Although the till and till-derived soils may retard channel incision at the Wetmore site, downcutting is ultimately controlled by a culvert located about 150 m south of the gully mouth. The culvert is the local base level for the gully's drainage area; hence, the gully should cut no deeper than that level.

Volume changes are also affected by variations in rain events. Changes associated with the last significant rainfall episode (>13 mm/24 hrs) for each month are presented in Table 10. The summary of increases and decreases in gully volume reveals a pattern. Most channel segments within the upper reach are zones of net erosion (gully volume increased), whereas nearly all segments within the lower reach were zones of net sedimentation (gully volume decreased). Only segment CC showed no change.

Most of the channel segments in the middle reach were zones of net erosion. However, it is important to note that no channel segment within the gully network was consistently a zone of erosion, sedimentation, or stability from one rainfall episode to the next. Instead, cycles of erosion and deposition were documented in every segment.

As expected, intense rainfalls had greater effects on

Table 10. Summary Of Increases (+) And Decreases (-) In Gully Volume Recorded During The Period 5-12-90 Through 5-7-91.

	May 24~ 7.62~~(.5)* 12.70(3.0) 1.30(1.0)	June 18 17.8(.5)	July 21 76.2(4.0) 5.1(4.0)	August 19 15.2(.25) 5.1(.50)	October 3 10.2(1.0) 5.1(3.0)	November 3 45.5(12.0)**	March 16 26.7(3.0)**	April 26 35.6(1.50) 12.7(0.75)	May 4 11.4(0.75) 6.4(2.00)	Total
LOWER REACH										
SEGMENT A	+0.59	+0.23	-0.54	-0.23	-0.01	+0.04	+0.10	-1.13	+0.04	-0.91
B	+1.16	+0.28	-1.16	-0.14	-0.72	+0.26	+0.39	-1.60	-0.08	-1.69
C	-0.05	+0.03	-0.04	+0.01	-0.08	-0.03	+0.01	0.00	-0.02	-0.17
CC	-0.01	-0.01	+0.03	0.00	-0.01	0.00	+0.01	0.00	-0.01	0.00
D	+0.40	+0.09	-0.21	+0.03	-0.42	+0.01	+0.24	-0.55	+0.18	-0.23
E	+0.08	+0.23	-0.50	+0.08	-1.44	+0.13	+0.59	-1.01	+0.97	-0.87
F	+0.12	-0.06	-0.11	+0.03	-0.17	-0.01	-0.08	-0.02	-0.02	-0.32
FF	-0.07	0.00	+0.10	+0.02	+0.02	0.00	-0.05	0.00	0.00	+0.02
MIDDLE REACH										
SEGMENT G	***	+0.47	-0.79	-0.43	-0.13	-0.02	+0.12	-0.05	+0.36	-0.47
H	***	+0.03	-0.08	+0.03	+0.01	0.00	-0.06	+0.04	+0.01	-0.02
HH	+0.06	0.00	-0.02	0.00	+0.02	+0.01	-0.04	+0.04	0.00	+0.07
I	+4.45	+2.39	-2.62	-1.84	-1.33	-1.45	+1.55	+1.02	+0.33	+2.50
J	+0.10	+1.04	-0.48	+0.60	+0.35	-0.10	+0.37	+0.01	+0.08	+1.97
JJ	+0.16	+0.04	+0.08	+0.07	+0.05	+0.02	+0.26	-0.05	0.00	+0.63
K	+0.51	+0.69	-3.08	+0.33	-1.88	+0.11	+1.17	+0.88	+0.85	-0.42
UPPER REACH										
SEGMENT L	+0.03	+0.31	-0.84	+0.49	-0.44	+0.25	+0.11	-0.07	+0.24	+0.08
M	+0.06	-0.16	-0.72	+0.81	-0.47	+0.14	+0.23	-0.03	+0.11	-0.03
N	-0.19	-0.22	-0.38	+0.39	-0.51	+0.17	+0.21	+0.48	-0.11	-0.16
NN	0.00	+0.36	-0.04	+0.04	-0.04	0.00	+0.01	+0.04	+0.01	+0.38
O	-0.04	-0.02	-0.06	+0.02	-0.05	-0.06	+0.01	+0.23	0.00	+0.03
OO	-0.06	-0.01	-0.05	+0.03	-0.01	-0.04	-0.02	+0.09	0.00	-0.07
P	+0.09	+0.12	-0.13	+0.35	-0.12	-0.13	-0.08	+0.22	+0.10	+0.42
Q	-1.22	+0.61	+0.04	+1.41	-0.76	-0.68	-0.47	+1.15	+0.36	+0.44
R	+0.11	+0.02	-0.25	-0.03	+0.08	-0.09	-0.08	+0.70	+0.01	+0.47
RR	+0.02	0.00	-0.02	+0.03	0.00	+0.01	-0.01	+0.01	0.00	+0.04
S	+0.08	-0.07	+0.05	-0.02	+0.03	-0.07	+0.08	+0.11	+0.06	+0.25
SS	0.00	-0.01	+0.01	+0.01	-0.01	-0.01	+0.02	+0.01	+0.02	+0.04
T	+0.03	0.00	+0.11	+0.11	-0.17	-0.06	-0.01	+0.07	+0.05	+0.13
TT	+0.10	-0.02	+0.01	+0.05	+0.02	-0.01	0.00	+0.05	+0.02	+0.22

~ Date of rain event
~~ Amount of rain (mm)

* Duration of rain event in hours
** Estimated duration of rain event
*** Missing data

Note: No significant rainfall was recorded during September and December of 1990, or January and February of 1991.

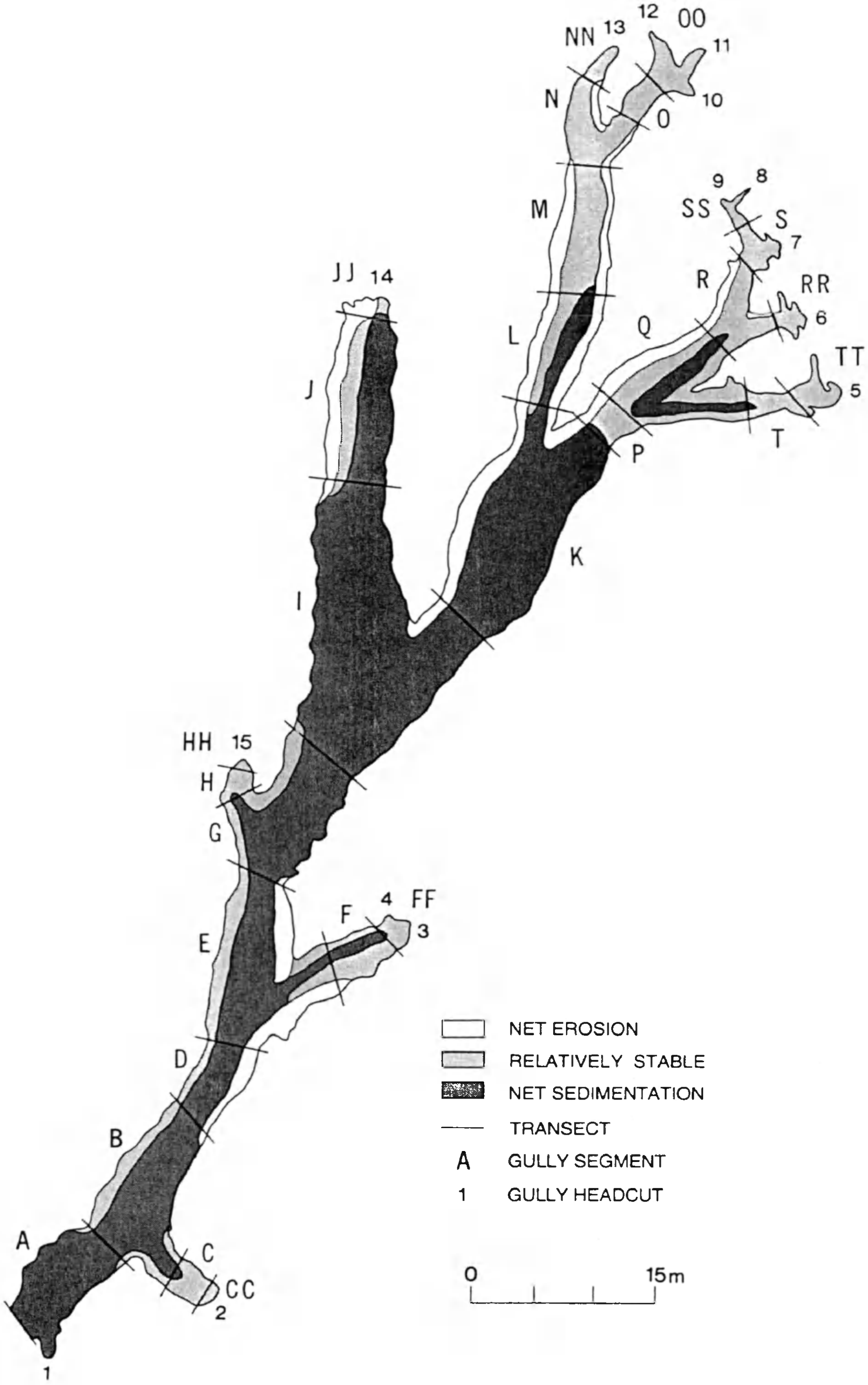


Figure 20. Gully network indicating zones of erosion, sedimentation and relative stability during the period May 12, 1990 to May 7, 1991.

channel geometry than some of greater magnitude. For example, the 35.6 mm rainfall that occurred in 1.5 hours on April 26, 1991, caused extensive erosion in the upper and middle reaches, and considerable deposition in the lower reach. However, a 45.5 mm rainfall that occurred over a 12 hour period on November 3, 1990 had comparatively minor effects on the volumes of most gully segments (Table 10).

Figure 20 identifies areas of net erosion, net sedimentation and relative stability within the entire gully network for a period of one year. Relative stability is defined as those areas which experienced volume changes between -0.20 and +0.20 cubic meters. Three patterns stand out: (1) most erosion occurred along sidewalls within the upper reaches of the gully network, (2) the network was dominated by sedimentation, and (3) although all headcuts advanced during the monitoring period, the advances were, with the exception of headcut 14, minor. Zones of erosion, sedimentation and relative stability changed very little from the first half of the monitoring period, 5/90 - 11/90. The only significant difference occurred in segments N,R, D and E. Those segments did not experience sidewall erosion.

Sediment Yield

The sediment yield and sediment delivery ratio of the watershed were 5.7 tonnes and 16.4%, respectively. Gross erosion was 34.7 tonnes, of which 5.9 tonnes and 28.8 tonnes were accounted by sheet-rill and gully erosion, respectively. Subtracting 29.0 tonnes of sediment deposited within the watershed from the gross erosion, results in a sediment yield of 5.7 tonnes. These figures suggest that after one year, 16.4% of the soil eroded from the watershed was transported out of the drainage basin, representing 5.7 tonnes of sediment. These figures are only an approximation, however, because sediment yield varies as precipitation, cover and land use patterns change through time (Soil Conservation Service 1983). Piest and Spomer (1968) determined that the annual sediment yield from both gully and sheet erosion from a grassed watershed was one ton or less/acre (2.2 tonnes/hectare). Furthermore, they proposed that although sediment yields can be highly variable, sheet and gully erosion probably account for about 80 and 20% of the yield in loessial regions, respectively. Roehl (1962) reported similar results. He analyzed 44 small watersheds in southeastern United States, and determined that sheet erosion usually was the predominant sediment source. In a study of watersheds across the U.S., Glymph (1957) also determined that sheet erosion is a major sediment source. He analyzed 113 watersheds ranging from 0.1 to 1132 km^2 in size. His results indicated that sheet erosion usually was the major sediment source, though its contribution to individual watersheds ranged between 11 and 100%. Hence, each watershed should be analyzed individually.

A number of researchers (e.g., Anderson 1957; Langbein and Schumm 1958; Heede 1974) have noted that many factors affect sediment yield. Anderson (1957) noted that sediment yield is a function of land use, vegetative condition, topography, storm type, and method of analysis. Langbein and Schumm (1958) suggested fluctuations in sediment yield are due to weather patterns. Changes in rainfall intensity, seasonal and areal distributions of rainfall, number of storms, and temperature will affect sediment production. Piest and Spomer (1968) reported that sediment yields at locations downstream are related to the quantities of sediment produced upstream and transport efficiency. Heede (1974), however, claimed that sediment yield is related to the stability of a gully during stream flow, and the stage of gully development. His research suggested that youthful gullies are generally less stable and generate greater sediment than mature gullies.

Gully Geometry

Many factors influence gully geometry. For example, in his study of arroyos in the southwestern U.S., Graf (1979) determined that form is controlled by mass movement processes acting on arroyo walls, and by fluvial forces acting on arroyo floors. Crouch and Blong (1989:294-295) agree with Graf, but noted that sidewall formation is a function of numerous processes acting on gully walls, such as fluting, toppling, caving, undercutting, and circular slips. Similarly, Bradford, et al. (1978) suggested that form is controlled by soil morphology, type of processes acting on gully walls, and transport capacity of runoff.

Examination of cross-section and longitudinal profiles revealed that the gully network changed very little in form after the monitoring period. The cross-section profiles show how the gully changed through time (Appendix 1). In each profile, 'A' represents channel geometry at the beginning of the study, and 'B' represents the geometry at the end of the monitoring period. Three patterns are noted: (1) all transects retained their original form, regardless of infilling or erosion, (2) the lower and middle reach is dominated by infilling, and (3) the upper reach is dominated by erosion, although infilling occurred at transects 5944, 4231 and 3024.

The cross-section profile at each transect also show how gully form changes through space. As one moves upslope, channels become narrower and deeper (Appendix 1). The lower reach has a fairly wide, shallow channel. Channels within the middle of the drainage network are moderately deep and wide, whereas those within the upper reach tend to be very narrow and deep.

The shape of gullies appears to be largely controlled by parent materials. Gullies advancing into the late-Holocene fills have wide, U-shaped channels with vertical headwalls (Figure 17), whereas gullies cutting into the

Figure 21. Photo of V-shaped channel cutting into till-derived soil.

glacial till and till-derived soils have deeper, V-shaped channels with no headwalls (Figure 21).

Analysis of width/depth ratios revealed changes in form through time and space (Appendix 2). Two patterns stand out. First, as one moves upslope, width/depth ratios decrease. Second, all transects, with the exceptions of 5654, 4037 and 2829, experienced increased width/depth ratios through time. As one moves upslope, the gully network is younger and has deeper, narrower channels, resulting in smaller width/depth ratios. Increased ratios through time suggests that channel depths are decreasing while channel widths remain constant or are increasing. The increased ratios also reflect the overall net decrease in flow velocity and increase in sedimentation in the gully network. Furthermore, the increased ratios suggest that the channels are evolving into more mature stages.

Transects 5654, 4037 and 2829 show decreased width/depth ratios through time. The decreases suggest that channel depths are increasing and/or widths are increasing. Based on field observations, the channels are actively eroding at those transects.

Because form changes with time as gullies go through stages of development, a model of gully development based on channel form can be developed. During the first stage, channels typically have various forms. For example, channels cutting into till-derived soil have deep, narrow

Figure 22. Photo of shallow, U-shaped channel along gully element 9.

V-shaped channels (Figure 21), or shallow, U-shaped channels (Figure 22). Extensions into gully fills, however, have wide, U-shaped channels with rounded headrims (Figure 17).

Development of steep headwalls in conjunction with channel widening and deepening is the second stage of gully development. This stage is characterized by production of large volumes of sediment. The upper reach experienced the greatest widening and deepening (Table 6).

The third stage of development is characterized by (1) the presence of vegetation along sidewalls and/or channel floors, (2) reduced sidewall slopes, and (3) increased sedimentation. Slope calculations indicate that most sidewalls experienced a decrease in gradient through time (Appendix 2), facilitating the establishment of vegetation. Slope increases occurred, however, most often near headwalls in the upper reach. Volume calculations indicate sedimentation was the dominant process in the middle and lower reaches. Cross-channel profiles of gullies approaching the third stage show a flattening of channel floors.

The fourth and final stage of gully development is characterized by wide, stable channels filled with sediment and covered with vegetation (Figure 23). Filled channels were detected immediately above headcuts 2, 3 and 14, and appear as slight depressions in the landscape. Stability may be interrupted by renewed trenching, resulting in a new

Figure 23. Photo of stabilized gully fill above headcut 3.

Figure 24. Photo of gully fill beginning to retrench above headcut 14.

cycle of growth. The gully fill above headcut 14 is starting to retrench and appears to be progressing from stage 4 to stage 1 (Figure 24).

Gully development does not always evolve sequentially through the four stages, nor is every gully element in the same stage. Furthermore, there may be no sharp distinctions between stages due to gradational changes. For example, gully elements 3 and 4 are in stage 3, whereas gully element 15 is in stage 2. Similarly, the gully network is not necessarily younger as one moves upslope. For example, while gully element 14 is grading from stage 2 to stage 3, immediately above the headcut is stage 4, which is beginning to evolve towards stage 1. Equally important, retrenching does not always occur after a channel is stabilized. For example, although the lower reach is in stage 3, a knickpoint migrating from the road ditch towards the lower reach may rejuvenate that reach if it continues to migrate. If that happens, the main channel of the lower reach may evolve into stage 2, and the other gully elements will adjust accordingly.

Sidewall Form

Gully walls varied in form, but three profiles predominate: vertical, sloping, and vertical/sloping (Figure 25). Vertical profiles are common in the lower reach, and the sidewalls are relatively short in height (Figure 26). Sloping profiles frequently occur in the middle and upper

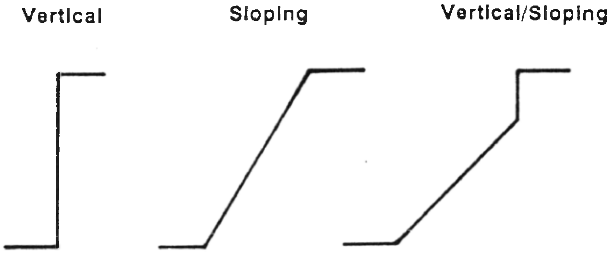


Figure 25. Predominate sidewall forms.

Figure 26. Photo of vertical sidewalls in lower reach of gully network.

Figure 27. Photo of sloping sidewalls in upper reach.

Figure 28. Photo of vertical/sloping sidewalls.

Figure 29. Photo of irregular shaped sidewalls in gully element 14.

reaches, and have various inclinations. The sidewalls may be partially vegetated (Figure 27). The vertical/sloping profiles also occur in the middle and upper reaches. They are characterized by a vertical face extending approximately 10 - 20 cm below the gully rim (Figure 28). Some walls are very irregularly shaped, and appear scalloped (Figure 29). Daniels and Jordan (1966) noted irregularly shaped gully walls in southwestern Iowa, and attributed them to runoff flowing over sidewalls. It is unclear why numerous sidewalls at the Wetmore site are scalloped, but in some cases the scallops appear to be rill extensions. Regardless of sidewall form, they changed little during the monitoring period.

Longitudinal Profile

The longitudinal profile reveals the shape of a gully's gradient. Figure 15 typifies the longitudinal profile found throughout the gully network at the Wetmore site. Profiles are not static, however, and may occasionally adjust. For example, gradient increases occur at points of incompetency. If runoff cannot transport its load below a certain point, sediment is deposited and the channel bed aggrades. Gradients increase below that point, and decrease above that point (Morisawa 1968:101). As deposition continues, the channel bed may oversteepen, renewing incision (Schumm and Hadley (1957). However, if runoff has excess energy to carry its load, scouring may occur. Below the scour point, gradients decrease, whereas above that point, gradients increase, and erosion moves upslope.

During the monitoring period, the longitudinal profile of every gully element changed 0.2% or less. This is an approximation, however, because measurements were not always made in the deepest portion of the channel. All gully elements measured experienced a decrease in slope, except element 3, which showed an increase (Table 11). Gully elements 1, 4, 7, 8, 10 and 11 were not measured due to time constraints. Gradient reductions probably resulted from an increase in sediment storage throughout most the gully network. It is unlikely, however, to expect significant changes in gradient during a period of one year. Furthermore, gullies cutting into till-derived soils probably have relatively stable channel floors.

Table 11. Slope Gradients, and Gradient Changes During the Period May 12, 1990 to May 7, 1991 Per Gully Element.

Gully Element	Initial Slope 5-12-90	Change	Final Slope 5-7-91
2	-0.166	-0.243	-0.409
3	0.363	0.042	0.405
5	2.757	-0.217	2.539
6	3.135	-0.131	3.004
9	3.045	-0.223	2.821
12	2.538	-0.062	2.476
13	2.660	-0.125	2.535
14	0.699	-0.164	0.535
15	0.943	-0.108	0.835

Headcut Advancement Processes in Gully Fills

Field observations indicate that toppling is the principal extension process for headcuts advancing into gully fills. Toppling occurs in response to the formation of shrinkage cracks near and/or at headcuts, and to saturation of headwall bases.

Shrinkage cracks are common throughout the study site. The presence of clay minerals with high shrink/swell capacities, such as montmorillonite and smectite, is largely responsible for the development of these cracks. As the soil dries, weak oxygen bonds between crystal units of these clay minerals allow them to readily collapse and shrink, producing soil cracks. The magnitude of cracking is dependent upon soil moisture conditions and the proportion of expandable clay minerals in the soil. Shrinkage cracks typically extend down headwalls from gully rims, and often develop at the center of headwalls (Figure 30). These cracks may radiate away from headcuts (Figure 31), and always intercept runoff. As soil moisture content increases, weight is added to the soil mass, and soil particle cohesion decreases. These conditions induce headwall failure, and the soil block eventually breaks away from the gully rim. The material may topple into the channel, or slide down the headwall a short distance (Figure 32).

In some cases, shrinkage cracks may extend to the base

Figure 30. Photo of vertical shrinkage cracks extending down headwalls 3 and 4.

Figure 31. Photo of shrinkage crack extending away from headcut 13.

Figure 32. Photo of material toppling at headcut 14.

Figure 33. Photo of shrinkage crack extending to base of headcut 3.

of headwalls (Figure 33). During rain events, the cracks act as water conduits and direct moisture vertically to the base, aiding in headwall saturation. Wetted fronts adjacent to cracks were noted in the field. This process may be particularly active at headcuts 2, 3, and 4 because headcut heights are short. It is likely that more moisture will reach these headwall bases because of their short headwall heights.

Saturation of headwall bases also promotes headcut advancement, especially where headcuts occupy low positions in the landscape and/or cut into low-strength gully fills. Headcuts occupying low-gradient positions will retain runoff for longer periods of time, allowing water to infiltrate deep into the subsoil. Once basewalls are saturated, they undercut quickly, and the upper soil mass topples down. Where toppling occurs in response to undercutting, a steep headwall is produced. This headwall is then subjected to renewed undercutting. As this cycle continues, headcuts migrate uplsope.

Saturation of headwalls also may be facilitated by the accumulation of rainfall and snowmelt in plungepools. Rainfall ponding in a small plungepool at the base of headcut 2 was observed numerous times during the monitoring period. Accumulated snow and ice near headcuts were also observed (Figure 34). Both conditions promote headwall failure by saturating headwall bases.

Figure 34. Photo of snow accumulating at the base of the headwall in gully element 2.

Headcut Advancement Process In Till-Derived Soils

Few steep headwalls have developed in till at the study site. Instead, graded channels typically extend upslope from the main gully channel into the till-derived soils (Figure 35). This phenomenon is occurring at gully elements 5, 6, 7, 8, 9, 10 and 11. These elements are in the first stage of development because of their graded headwalls and narrow, shallow channels. Only elements 12 and 13 have steep headwalls. However, these two elements are in the second stage of development. Before vertical headwalls develop in till, upslope migration of the channel appears to advance by rill enlargement. Meyer et al. (1975) suggested that headcuts may develop along rills, and rills often progress into headcuts. Through time, the rills enlarge and extend upslope. Foster (1986) argued that slope lengths shorten and steepen as gullies gradually incise the landscape. This process lowers the base level of adjacent slopes, increasing rill erosion.

Widening of Gully Channels

Field observations indicate a variety of processes influencing gully widening. These processes are described in the following discussion.

Based on field observations, wet/dry cycles contributed to slope failure during late spring and early summer. Slope failure occurred along horizontal shrinkage cracks that developed 10 to 22 cm below the surface along sidewalls

Figure 35. Photo of gully element 6 grading into main gully channel.

(Figure 36). Cracks as large as 1 cm wide and 18 cm deep extended diagonally into gully walls. It is likely that these shrinkage cracks accelerate slope failure in gully walls in the same manner as they do in headcut advancement. As water infiltrates through the cracks, weight is added to the soil mass, decreasing shearing resistance. Once instability is attained, the soil mass slides downslope, similar to slumping. As moisture conditions change, the cycle is repeated.

Failure of gully walls also occurred where vertical shrinkage cracks developed along gully rims. Some of these cracks are more than 0.5 m deep (Figure 37). As they enlarge, the soil mass breaks away from the rim and slides or topples downslope (Figure 38).

Examples of gully-wall failure related to moisture conditions were observed at reference points 44 and 47 (Figures 39 and 40). These failures occurred following a 48.26 mm rain event preceeded by several days of light rainfall in mid-spring. Slope failures caused by excess moisture also occurred during the winter. Surface horizons of soils became saturated by snowmelt, causing soil masses to slide over frozen soil.

Wet/dry cycles also enhance gully widening. As the face of the wall dries after a rain event, it develops polygonal-shaped platelets (Figure 41). The platelets easily spall from sidewalls, and once detached, the material

Figure 36. Photo of horizontal cracks along gully walls.

Figure 37. Photo of shrinkage crack 63 cm deep along sidewall near reference point 44.

Figure 38. Photo of enlarged shrinkage crack separating soil mass from gully rim near reference point 65.

Figure 39. Photo of wall failure near reference point 44.

Figure 40. Photo of wall failure near reference point 47.

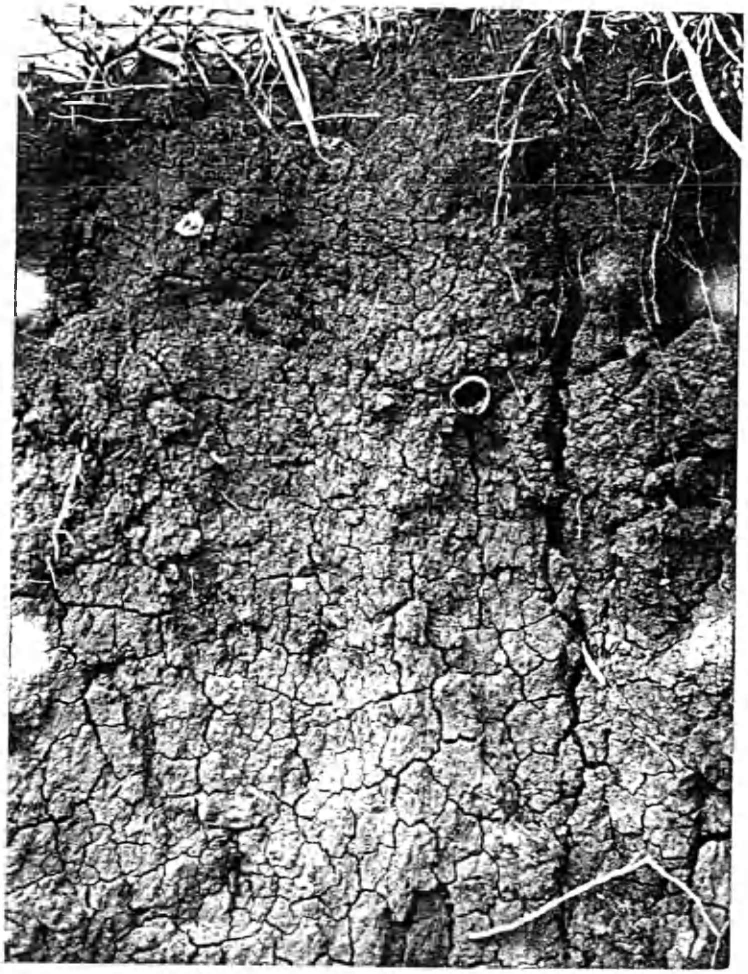


Figure 41. Photo of polygonal-shaped platelets on sidewall.

moves downslope. A new moisture front is then exposed to drying, and the cycle is repeated.

When temperatures were at or below freezing, freeze/thaw processes probably caused slope failure along gully walls. Although no freeze/thaw processes were observed, evidence of frost heave was noted. Many reference tags rose 4 to 8 cm in late winter (Figure 42). As temperatures decreased, moisture within the soil formed ice crystals and expanded. Freeze/thaw cycles disrupt soil aggregates, producing fine soil particles which break away from gully walls and accumulate at or near footslopes (Figure 43). The particles are subsequently removed by deflation or fluvial action.

The gully walls were relatively dry during much of the winter, causing shrinkage cracks to develop. As the cracks enlarged, portions of the sidewalls protruded and developed irregular shaped surfaces (Figure 44). Gully widening occurred when the protrusions separated from sidewalls.

Another process observed in sediment production was rilling. As rills dissected sidewalls, they produced soil debris and assisted in sidewall retreat (Figures 45 and 46). Rilling occurred throughout the site, but was more common on west-and north-facing slopes. Solar insolation is fairly intense on west-facing slopes, causing a reduction in vegetative cover. Reduced cover, in turn, enhances rilling. Also, since most summer storms track west to east across the

Figure 42. Photo of a reference tag elevated by frost heave in late winter.

Figure 43. Photo of sediment from gully wall accumulating on toeslope during winter months.

Figure 44. Photo of protrusions on sidewall due to soil drying.

Figure 45. Dissection of sidewalls by rilling in upper reach.

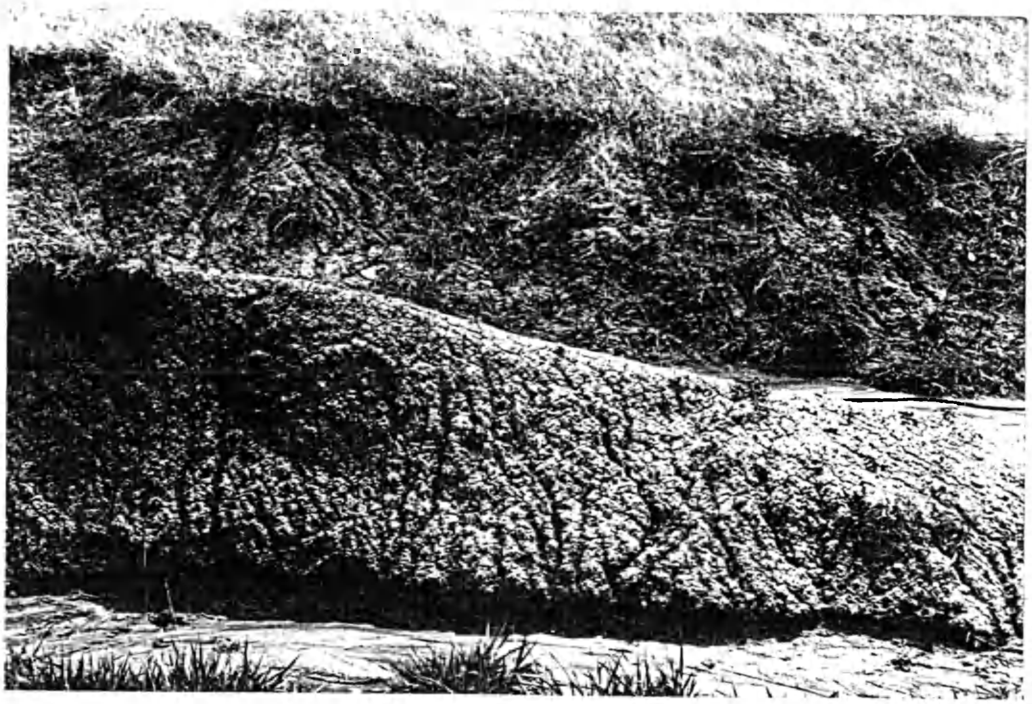


Figure 46. Photo of rilling and undercutting processes eroding sidewall in middle reach.

region, west-facing slopes have greater exposure to direct raindrop impact, increasing the likelihood of rilling on these slopes. Based on field observations, vertical shrinkage cracks in the sidewalls promote rill development. Rills extending below the shrinkage cracks were observed at several localities in the gully network (Figure 47). Rills occasionally coalesced below the sod along the gully rim, funneling runoff to the base of the gully wall (Figure 48). This concentration of runoff tends to undercut the wall and cause slope retreat.

An equally important factor contributing to gully widening at the study site is cattle grazing. Cattle grazing accelerated gully growth directly and indirectly.

Cattle directly affected the gully network by disturbing sidewalls as they moved across and through the gully network. As they descended and ascended sidewalls, they dislodged soil particles, accelerating sidewall retreat and sediment production (Figure 49). Furthermore, when grazing at the rim, they often dislodged soil clods. This displacement may initiate new gully elements.

Headcut extension probably is encouraged by the formation of cattle trails. Several headcuts, including 9, 10 and 12, are advancing up what appear to be cattle trails. Cattle are noted for travelling along the same path; hence, cattle trails are often well developed, and are prime locations for channel development.

Figure 47. Photo of rills occurring below shrinkage crack.

Figure 48. Photo showing coalescence of rills below sod.

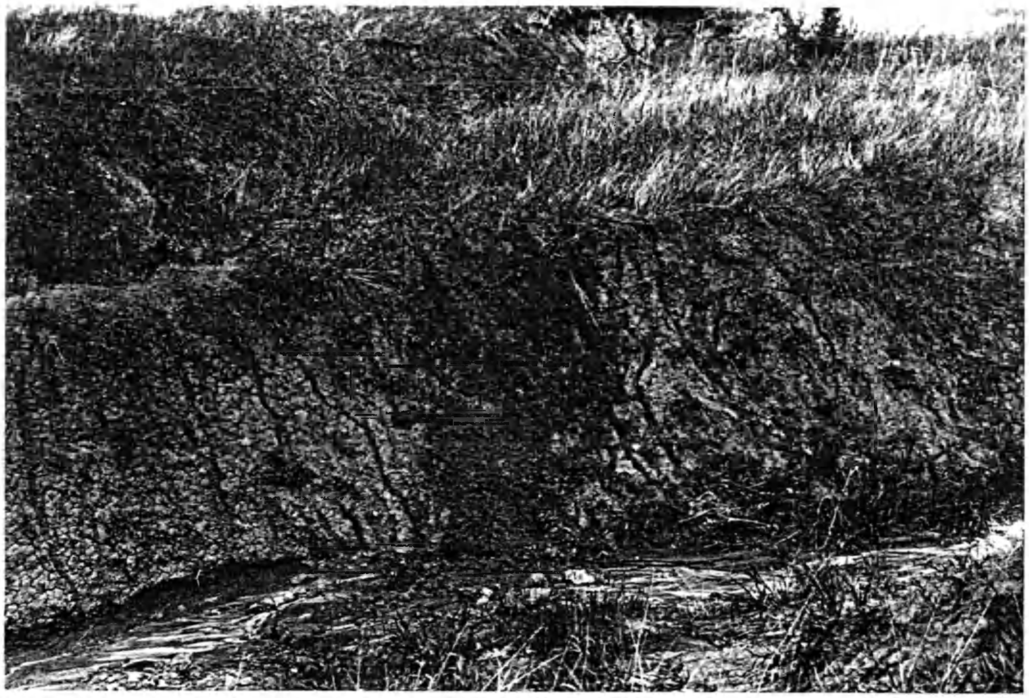


Figure 49. Photo of soil debris (center) brought downslope by cattle.

Cattle indirectly affected gully growth by increasing overland flow in portions of the study site. Overland flow probably increased in response to overgrazing and soil compaction. The cattle grazed preferentially near gully rims and upslope from headcuts 2, 3, and 14 (Figure 17). As summer progressed, these areas had decreased vegetative cover. Reduced vegetative cover exposes more bare soil to raindrop impact, and promotes decreased soil moisture and littler incorporation. Litter incorporation reduces runoff by increasing soil permeability. In addition, cattle trampling compacts soil and reduces infiltration rates, and also affects aggregate stability. Warren et al. (1986) studied the effects of trampling on silty-clay soils under moist and dry conditions. They determined that trampling under wet conditions deformed existing aggregates, creating a flat and comparatively impermeable surface of dense, unstable clods. Under dry conditions, aggregates were reduced in size due to mechanical disintegration of aggregates by compactive and abrasive forces of cattle. Both conditions reduce infiltration rates and increase runoff and sediment production. Although it is unknown if overland flow increased or aggregate stability decreased at the study site, it is reasonable to expect they both influenced runoff rates and sediment production.

The last major process responsible for sidewall retreat was undercutting by channel flow. Undercutting was most dramatic in the lower reaches during late winter. The near vertical walls collapsed as increased runoff flowed against walls that were already saturated due to thawing and late-winter rains. Conversely, undercutting was a minor process during the summer due to reduced precipitation and runoff. Figure 46 demonstrates the insignificance of undercutting, especially in the middle reach.

Other factors influencing sidewall retreat include the formation of calcium carbonate nodules with the C horizon of the Pawnee soil series, and burrowing animals. As the calcium nodules enlarge, they exert pressure on the surrounding soil matrix, displacing soil particles (Mandel 1991, personal communication). Also, numerous animal burrows were seen in sidewalls about 15 cm below the gully rim. Burrowing disturbs gully walls, and the burrows probably increase infiltration of water into the sidewalls.

Biomass Survey

The results of the biomass survey suggest that current landuse practices may affect erosion rates at the study site. These results are divided into two parts: (1) forage production, and (2) vegetation density and type.

The forage production survey was conducted to determine carrying capacity of the pasture. Table 12 summarizes forage production in kg/hectare/growing season for the study site. Figures are for two sampling locations assessed during the beginning of the 180 day growing season.

Transect 1 extends upslope from headcut 3, and transect 2 extends upslope between headcuts 2 and 3 (Figure 11). Based on an average for the two transects, forage production at the study site is 1,342 kg/hectare/growing season.

Table 12. Forage Production In Kg/Hectare/Growing Season (Myers 1991, personal communication).

	TRANSECTS	
Transect	1	2
Species		
Smooth Bromegrass	652	936
Kentucky bluegrass	375	616
Sedge	8	97
Total	1035	1649

During the period May, 1990 through October, 1990, 40-45 yearlings grazed at the study site. Each yearling requires approximately 9 kg of forage/day (Myers 1991, personal communication). Hence, the study site has the capacity to support only 2.4 yearlings during the growing season. The study site, however, is a small portion of approximately an 80 hectare pasture, and overgrazing should not be a problem. Nevertheless, portions of the site appeared to be overgrazed, especially transect 1. The cattle grazed preferentially along transect 1 (Figure 11), keeping this portion of the pasture grazed fairly close to the ground. Cattle prefer tender, new plant growth in lieu of older tougher grasses, and will return to recently grazed areas. If an area is continuously grazed, it is reasonable to expect a deterioration in vegetative cover, with increased runoff and sedimentation in the watershed.

The survey of vegetation type and density was conducted to determine pasture condition, with the premise that greater plant density reduces rill and sheet erosion. Plants reduce erosion in numerous ways: (1) they decrease runoff velocity by diverting water around stems, thereby reducing runoff entrainment capacity, (2) they absorb raindrop energy, reducing soil splash, (3) their roots increase shear strength of soil, (4) they increase infiltration capacity by reducing soil moisture through transpiration, and (5) they produce organic matter which aids in absorption of water and increases soil permeability. Table 13 summarizes vegetation type and density for the same two transects used in the forage production survey.

Results from the survey suggest that heavier grazed areas are prone to degraded vegetative cover. Such is the case at transect 1. Almost 50% of that area is bare ground.

The study site is classified as improved pasture, which is defined as native prairie that has been disturbed by plowing, with grasses being re-introduced at a later time. It was converted from cropland to pasture in 1969. Although the field was seeded with Smooth bromegrass, which is considered an excellent pasture grass with high erosion

Table 13. Vegetation Type And Density Along Transects 1 And 2 (Myers 1991, personal communication).

Transect 1	% of Transect Area
Kentucky bluegrass, *Poa pratenis*, L.	11.0
Yellow Indiangrass, *Sorghastrum nutans*, L.	1.0
Big bluestem, *Andropogon gerardi*, Vitman	2.0
Sideoats grama, *Bouteloaa curtipendula*, Terr	1.0
Smooth Bromegrass, *Bromis inermis*, Leyss	17.0
Clover, *Trifolium repens*, L.	14.0
dead plant litter from previous years growth	12.0
rock	1.0
bare ground	41.0
	=====
	100.0%

Transect 2	% of Transect Area
Kentucky bluegrass, *Poa pratenis*, L.	32.0
Yellow Indiangrass, *Sorghastrum nutans*, L.	1.0
Sideoats grama, *Bouteloaa curtipendula*, Terr	1.0
Smooth Bromegrass, *Bromis inermis*, Leyss	28.0
Clover, *Trifolium repens*, L.	10.0
dead plant litter from previous years growth	19.0
bare ground	9.0
	=====
	100.0%

resistance (Archer and Bunch 1953), it constitutes a small percentage of all grasses present today. The reduction in bromegrass can be accounted for in several ways. First, other seed type may have been brought into the area by people, animals and wind. Second, the bromegrass seed probably was not 100% pure. Third, changes in land use may affect growing conditions for some plant species. For example, Kentucky bluegrass, which is a non-native grass, thrives in overgrazed pastures and is considered an indicator of declining range conditions (Myers 1991, personal communication). Furthermore, it is an invader species capable of persisting under harsh growing conditions (Myers 1991, personal communication). Kentucky bluegrass is establishing a foot hold within transects 1 and 2, (Table 13), suggesting that the pasture is degrading. Native grasses that are indicators of healthy pasture, such as Yellow Indiangrass, big bluestem, and sideoats grama, are rare at the study site.

Historical Development

Based on an interview with the current landowner of the study site (Eldon Sudback 1991, personal communication), and examination of aerial photographs taken in 1937, 1954, 1959, 1966, 1972 and 1981, portions of the current gully network occupy former gullies. The modern gully network is not visible on the earliest photograph, but portions of a former gully system are apparent. Some of the paleo-gullies have remained stable, while others have rejuvenated. How the gully network evolved from 1937 to the present is briefly summarized in the following discussion.

In 1937, the study site was farmland. Two interesting phenomena stand out on the aerial photograph for that year. First, a very faint north/south orientated depression extends up the hillside. It appears to be channel fill, but is difficult to resolve due to lack of relief on the photograph. Intersecting this depression is a well-defined forked channel trending east/west. High color contrast between this forked channel and the surrounding area suggests that it is either bare soil or a poorly vegetated channel (Jean Raemer 1992, personal communication). The forked channel is located directly upslope from headcut 3 (Figure 51). It is approximately 45m long and its distal end is approximately 23m from the upland divide. Several other irregularly shaped, devegetated areas also are visible, and one appears to correspond to headcut 2.

The 1954 photograph shows continued farming activity at the study site. The forked channel is still visible, but reduced color contrast between the forked and adjacent areas suggest that it is infilling with sediment and revegetating (Jean Raemer 1992, personal communication). The channel perimeters, however, appear raw, and the headcut has not migrated further upslope. A new channel, corresponding to the current main channel, has developed, and is connected to

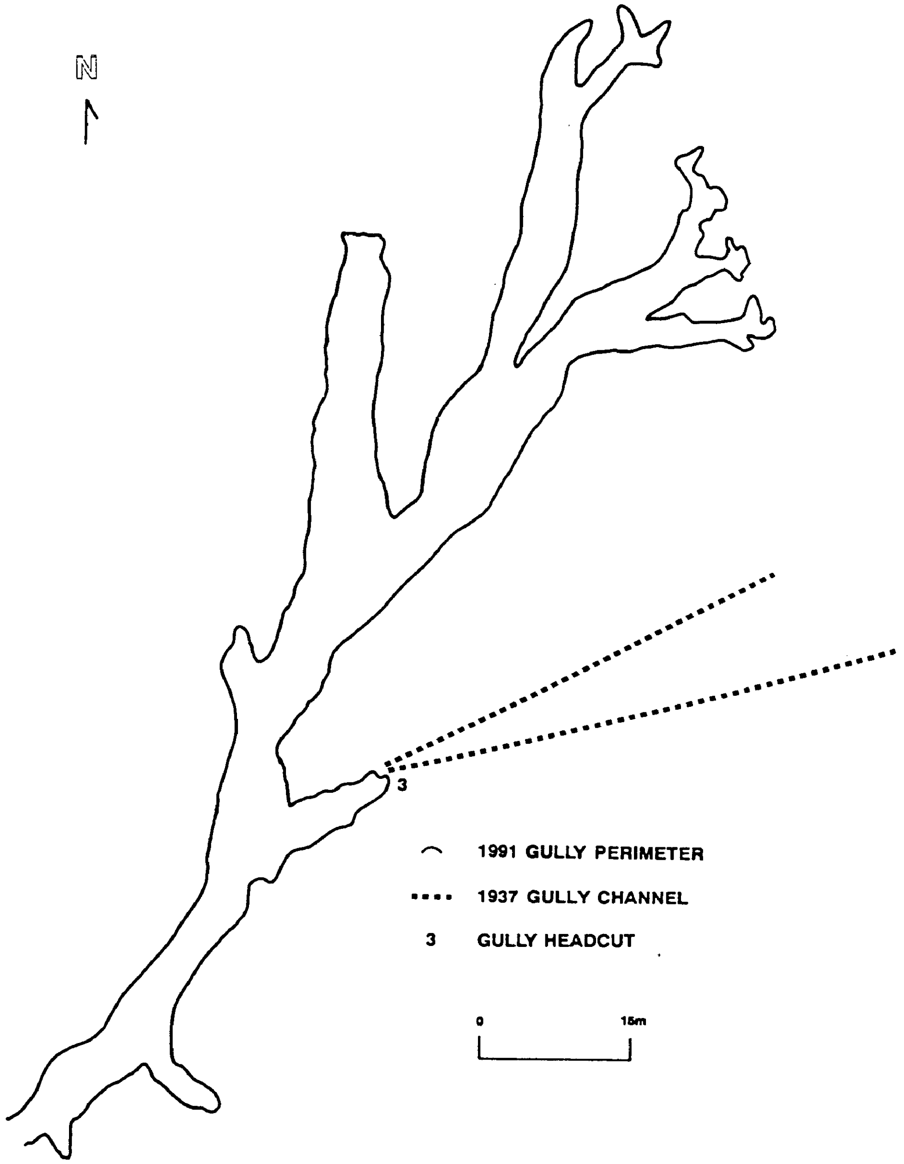


Figure 50. Plan view of gully development in 1937.

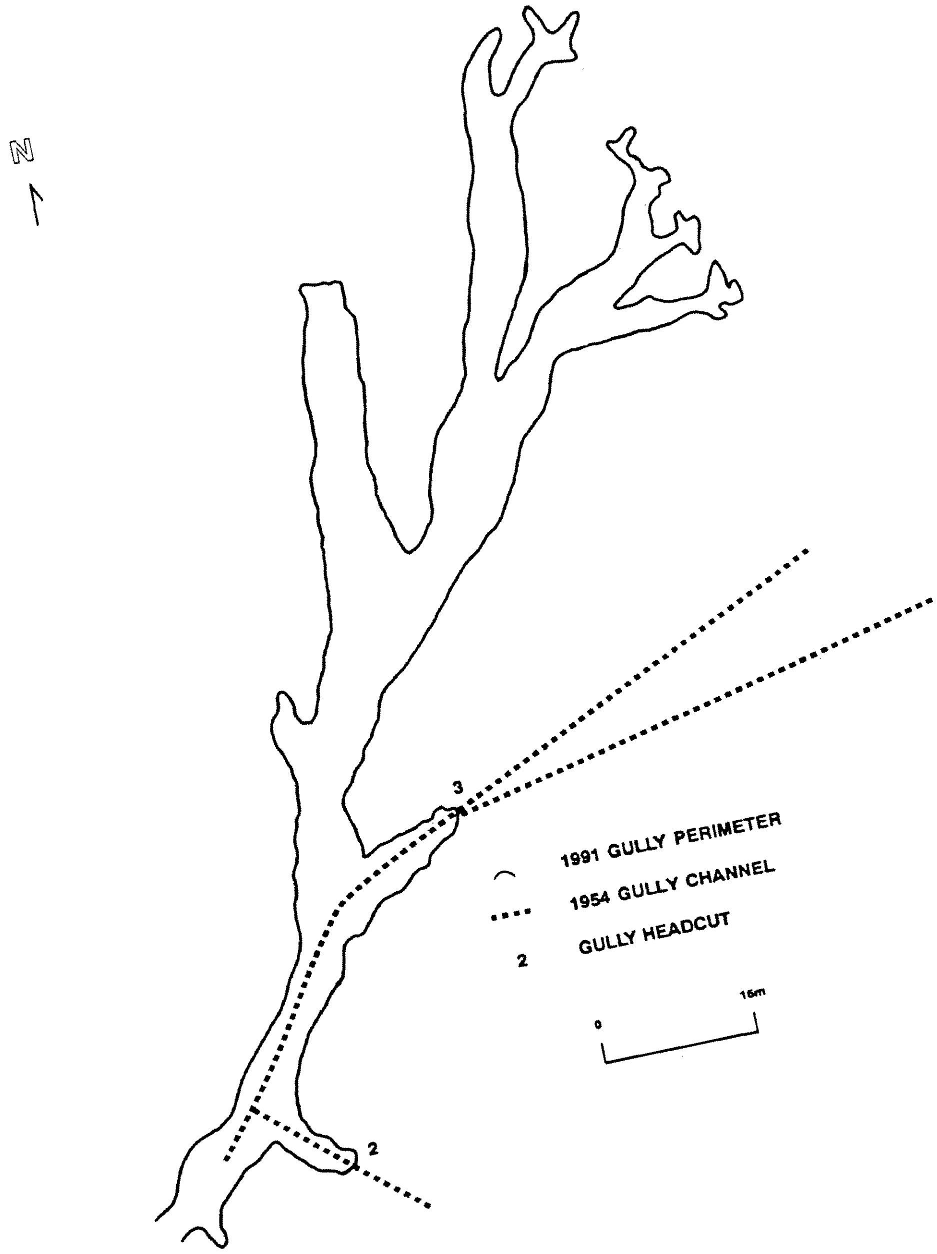


Figure 51. Plan view of gully development in 1954.

the forked channel (Figure 52). The connecting channel is approximately 40m long. A northeast-trending ill-defined depression is visible north of the forked channel. This depression is about 20m long, but does not connect with the main gully channel. A northwest trending channel or depression approximately 20m long is visible that extends up and beyond gully element 2 (Figure 52).

The 1959 photograph was difficult to interpret due to its poor quality. However, extremely faint depressions suggest that drainage channels may have existed.

By 1966, the main gully channel had migrated upslope past gully element 3 (Figure 53). Extending directly upslope from this well-defined channel are very faint depressions that closely correspond to portions of the modern gully network. The forked channel above headcut 3 appears as a depression, and is probably continuing to infill. Equally important, the 1954 paleochannel corresponding to headcut 2 is no longer visible (Figure 53).

In 1966, the current landowner purchased the property as cropland. According to Mr. Sudback (1991, personal communication), at that time the current gully network had not developed, but small depressions in the landscape were visible. Location of depressions he described correspond to the depressions visible on the 1966 aerial photograph. Mr. Sudback contended that he was able to till across the entire study area with no difficulties. He grew milo for three

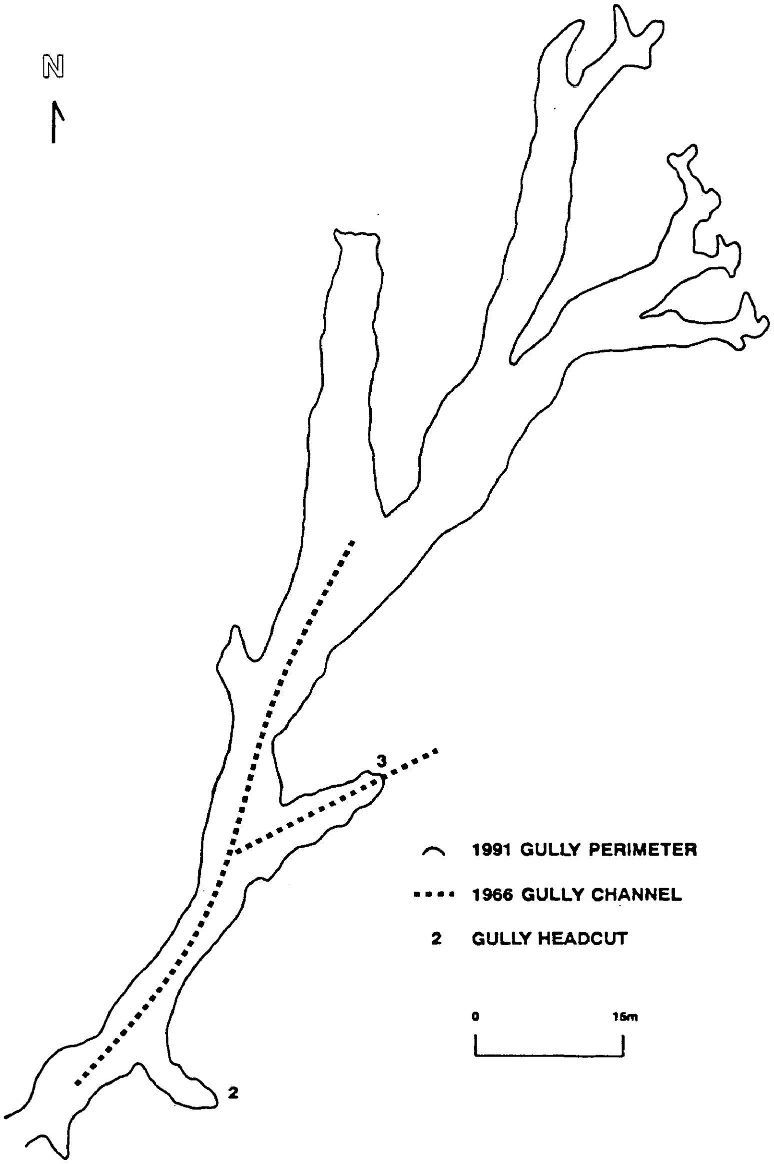


Figure 52. Plan view of gully development in 1966.

years, and in 1969, the land was converted to brome pasture. The grass matured for one year, and in 1970, 40-45 yearlings were placed on the site. In his best estimate, gullies began to develop across the site approximately 1 to 3 years after the cattle were introduced.

Details are difficult to see in the 1972 photograph due to a change in scale. Although the photograph shows a fairly uniform surface, very slight depressions are visible that correspond to former drainage patterns. This evidence suggests that vegetative cover was fairly well established on the site, and former channels appear to be filled in and vegetated.

The modern gully network probably started to develop in the summer of 1973 in response to four factors: (1) changed landuse activity, (2) oversteepening of infilled channels, (3) small depression scoured by runoff,and (4) above normal precipitation.

Cattle had recently been introduced, and it is reasonable to conclude they broke the sod cover in numerous places, encouraging erosion. The 1972 photograph suggests that nearly all channels had infilled and were probably stable. However, it is likely that portions of the infilled channels were oversteepened, increasing the gradient beyond a geomorphic threshold. Once the threshold had been exceeded, (i.e., by storm events or land use changes) channel trenching began. The channel then undergoes a complex response in which it attempts to seek a new equilibrium within the drainage network. As the channel trenches, deposition follows. Renewed trenching, which is often episodic, may then continue this sequence. Schumm (1973) argued that landscape evolution cannot be explained by progressive erosion alone, but that the landscape experiences interruptions of periodic adjustments when geomorphic thresholds are exceeded.

It is also likely that not all channels filled completely with sediment, thereby leaving small depressions on the landscape. Brice (1966:295) suggested that valley-bottom gullies may start as small, scoured depressions that are likely to develop scarps on their upslope side. Once initiated, the scarps then migrate upslope.

Lastly, it is likely that precipitation was the external variable that triggered a response, i.e., downcutting, within the gully network. On October 11, 1973, a 213 mm rain event occurred at Holton, Kansas (Kansas State Cooperative Extension Service 1991). Not only was that a very intense rain event, but 1973 was a very wet year (Figure 54). According to Mr. Sudback, once gully development began, its growth was fairly constant.

The 1981 photograph reveals well-defined channels that correspond to gully elements 6, 11, and 14 (Figure 55). They are approximately 20, 40, and 20m in length,

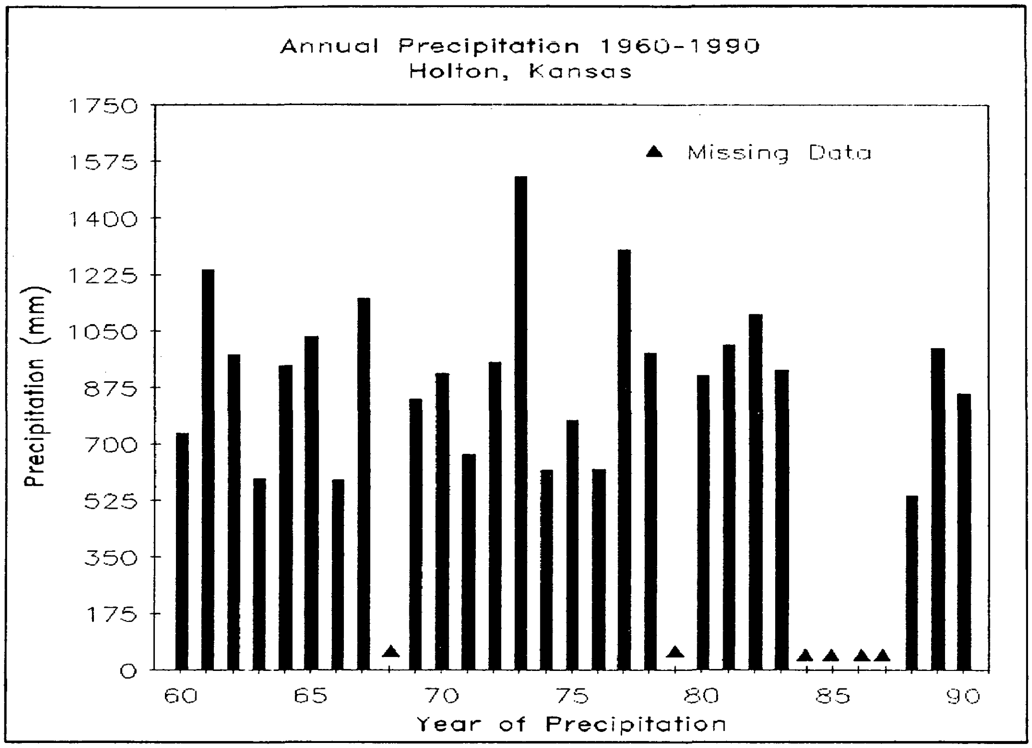


Figure 53. Annual precipitation for Holton, Kansas, between 1960-1990 (Kansas State University Cooperative Extension Service 1991).

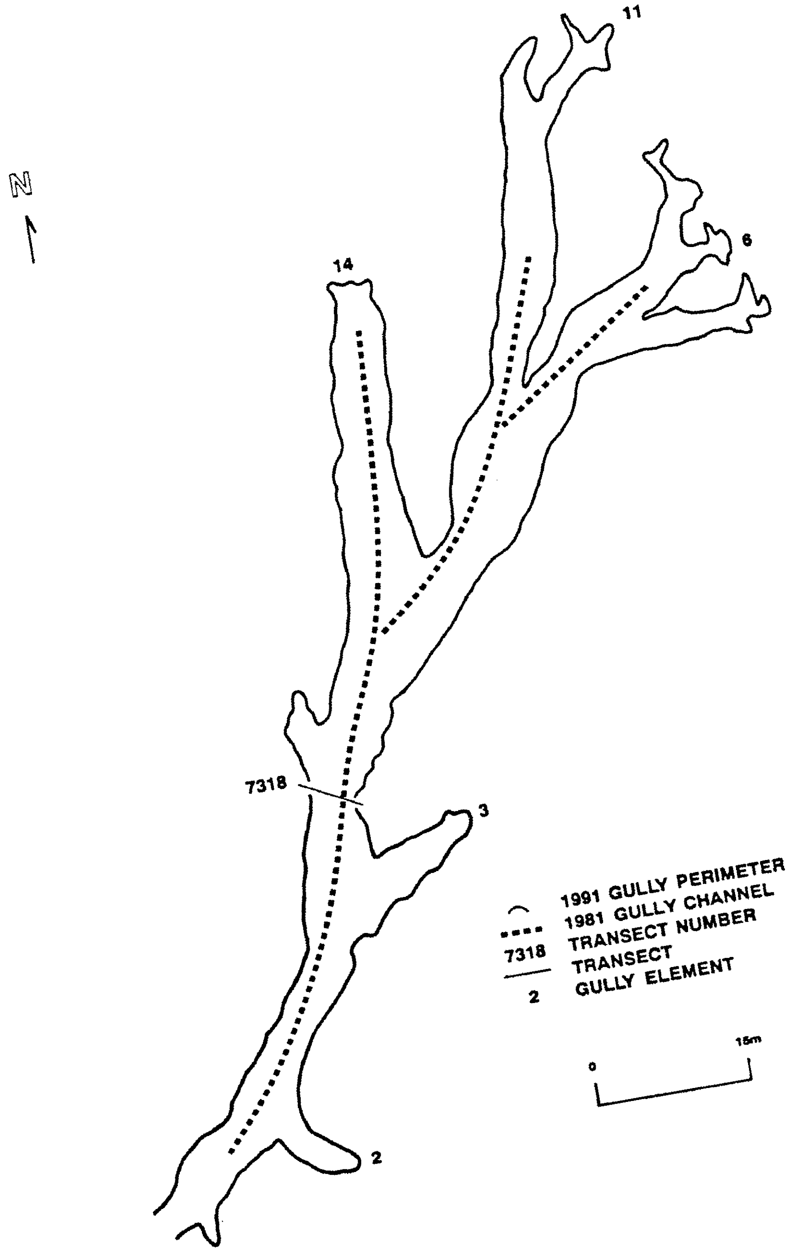


Figure 54. Plan view of gully development in 1981.

respectively. The main channel downslope from transect 7318 is less well-defined and appears to discontinue near the road. Gully element 2 is not visible, and only a slight impression of gully element 3 is visible, suggesting these elements have infilled and stabilized.

CHAPTER 6

SUMMARY AND CONCLUSION

A single gully network on a pasture in the Dissected Till Plain of northeastern Kansas was monitored for one year to assess gully evolution in non-loessial materials. Emphasis was placed on (1) identifying stable and unstable drainage elements within the gully network, (2) identifying zones of net erosion and net sedimentation, (3) estimating the volume of sediment eroded or deposited, (4) determining rates of headcut advancement, (5) determining the predominant processes that void gullies, and (6) reconstructing the historic development of the gully network.

Changes in gully volume during the monitoring period were used to identify zones of net erosion, sedimentation, and relative stability, as well as estimating the volume of soil eroded and deposited. Results of this investigation indicate that sedimentation was the dominant process in the gully network (Table 6). Although significant erosion occurred during the monitoring period, the network experienced a net decrease in volume of about 2.77m^3 (Table 6). The greatest sediment sources were gully sidewalls, and adjacent slopes experiencing sheet and rill erosion. Sediment yield and sediment delivery ratio calculations suggest that approximately 16.4% of the soil eroded from the watershed exited the drainage basin, representing about 5.7

tonnes of sediment. The upper reach of the gully network was a zone of net erosion (volume increase), with sidewalls accounting for 92.0% of all erosion, whereas headwall and floor erosion were insignificant (Table 8). The lower and middle reaches were zones of net sedimentation (volume decrease). Most of the relatively stable zones were along east-facing sidewalls in the lower reach and at headcuts (Figure 20). Although all headcuts migrated upslope, their advances were insignificant and most were classified as relatively stable areas. Moreover, every gully segment experienced cycles of erosion and sedimentation from one rainfall event to the next (Table 10). Equally important, intense rain events had greater effects on gully volume than some gradual rainfalls of greater magnitude (Table 10).

Gully headcut advance ranged from 4 to 69 cm/yr within the gully network. This rate of advancement is low compared to gullies cutting into loess-derived soils elsewhere in the region, and appears to be controlled by the characteristics of surface deposits and soils. Specifically, headcuts migrate faster when advancing into silty, late-Holocene gully fills than they do when migrating into till-derived soils. The low strength, high silt content, and high permeability of a gully fill promotes headcut advancement, whereas the greater strength, high clay content, and low permeability of the till and till-derived soil limit headcut advancement. Headcut advancement into gully fills was primarily due to failure at the toe of headwalls and to toppling, whereas gullies cutting into the glacial till advanced primarily by rill enlargement.

Sidewall failure led to lateral enlargement of the gully network. Field observations suggest that gully-wall failure was largely controlled by soil moisture conditions. Increased moisture levels increase shear stress and pore pressure to the sidewalls, thereby decreasing shear strength. Shrinkage cracks near gully rims intercepted moisture and facilitated slope failure by adding weight to the soil mass. Other factors influencing sidewall retreat include rilling, undercutting, and cattle moving through and across the gully network.

During the monitoring period, every transect experienced cross-section areal changes. Gully geometry, however, changed very little. After the 12 month monitoring period, each transect retained its original cross-section form, and changes in longitudinal profiles were negligible. Channel form changed, however, through space. As one moves upslope, channels are deeper and narrower. Channel form also varies according to stage of gully development. The model of gully development for the study site suggests that one can identify stages of development based on channel form. Applying the model to the study site reveals that in general, as one moves upslope, the gully network is younger, with the exception of gully elements 2, 3, 4, and 14, all which have stabilized gully fills (stage 4) above their headcuts.

Results of this study suggest that one cannot associate erosion processes with gully morphology. Although four stages of gully development were identified within the gully network, some processes were not unique to a particular stage. For example, while toppling, rilling and undercutting are more likely to occur during stage two, they were also observed in gullies that advanced to stage three. Furthermore, transitional stages compound the problem of associating a distinctive form with a specific process. The principal of equifinality suggests that a specific form may be produced by different processes (Von Bertalanffy 1968:86-87). Young (1972:86-87) asserted that models should not be used to determine process from observed form, due to equifinality. Accordingly, one should have several working hypotheses to account for erosional phenomena. Lastly, the monitoring period was too short to detect gully segments evolving into different stages, or to determine whether a particular form results from unique processes.

It is feasible to predict with some degree of accuracy future gully development at the study site. First, assuming climate, topography, landuse, vegetation, and soils remain constant, headcuts 2, 3, 4 and 14 are likely to reach the interfluve before the others. These four headcuts should continue to advance through the late-Holocene gully fills at their current rates. The extent of the fills, however, are unknown. Once the headcuts migrate beyond the fills, their advancement rates should be similar to the rates of gullies currently advancing into the till-derived soils. When headcuts reach the interfluve, gully growth is likely to decelerate due to little runoff entering the gully system. However, as Miller et al. (1962) noted, once gullies reach a drainage divide, they continued to develop by direct raindrop impact and other weathering forces.

Second, the maximum depth of gully incision can be estimated. Currently, the base level of the gully network is controlled by a culvert located about 150 m below the gully mouth. Knickpoints can continue to develop above the culvert and migrate upslope to the highest point in the gully network. However, the gully system cannot cut deeper than the local base level, which is approximately 11 meters below the highest point.

More difficult to predict, however, is long-term gully evolution. Using the ergodic hypothesis one can theorize how the gully network will evolve based on form. The ergodic hypothesis suggests that one can substitute space for time for long-term evolutionary studies (Chorley et al. 1984). By recognizing differences in landscape form through time, and realizing that different stages of landform development can occupy the same space, one can predict how the landform should evolve at a different point in time and space. For instance, gullies evolve through a general sequence of stages, and each stage is distinctive in form. Moreover, as one moves upslope, the gully network is generally younger. One can assume, therefore, that the portion of the gully network in the lowest position of the landscape was at one time the location of an active headcut. Similarly, the current headcuts will migrate further upslope, and through time, the channels will become wider and shallower, simulating the lowest point of the modern gully network. The stages may not be sequential, but given past evolutionary form, it is reasonable to predict how the gully will appear in the future.

Although one can predict to some degree future gully growth, it is difficult to determine whether human intervention can effectively stop or control a process that may be an inherent part of natural landscape evolution. The record of the gully network suggests that it has experienced cut-and-fill cycles, and aerial photographs clearly show portions of the gully network that have rejuvenated and infilled since 1937. This evidence is supported by the existence of late-Holocene gully fills at the Wetmore site.

Cut-and-fill cycles appear to be an important component of gully development at the Wetmore site, and are likely to to continue in the future. It is unknown, however, how the modern gully system was rejuvenated, or how long it will continue to develop upslope. Although the gully network experienced net sedimentation during the monitoring period, the sediment stored in the system may be removed by knickpoint migration. A knickpoint migrated approximately 30 cm upslope from the road ditch towards the gully mouth during the 12 month period. If the knickpoint continues to migrate upslope, it could rejuvenate a new cutting episode, and quickly remove the sediment stored from the previous year.

To increase our understanding of gully evolution in non-loessial areas, future research should (1) expand the study regionally in order to compare results from different gully networks, (2) maintain long-term monitoring programs in gully networks, such as the one at Treynor, Iowa, to assess changes through time, and (3) conduct intensive studies of soil properties within and between gully networks in order to assess their role in gully evolution.

Results of this study study suggest that much of the gully erosion in upland areas of the Dissected Till Plain may be predicted from soils-geomorphic data. Cycles of cutting and filling are endemic to landscape evolution in the region, and rapid headcut advancement can be expected where they are moving into gully fills. Soils and terrain analysis may be used to locate these fills, thereby allowing land managers to isolate areas that are susceptible to rapid gully development.

The sequence and causes of headcut advance must be better understood before we can thoroughly explore methods to control gully erosion. Although conservation systems and reduced grazing intensities may inhibit the initiation of gully processes on rangeland, the control of further advancement of existing gullies depends on reduced runoff and reduced gully-wall failure. Terraces have been shown to limit gully erosion by reducing runoff on cropland; however, there is also a need to develop lower cost land management techniques that stabilize gullies on rangeland.

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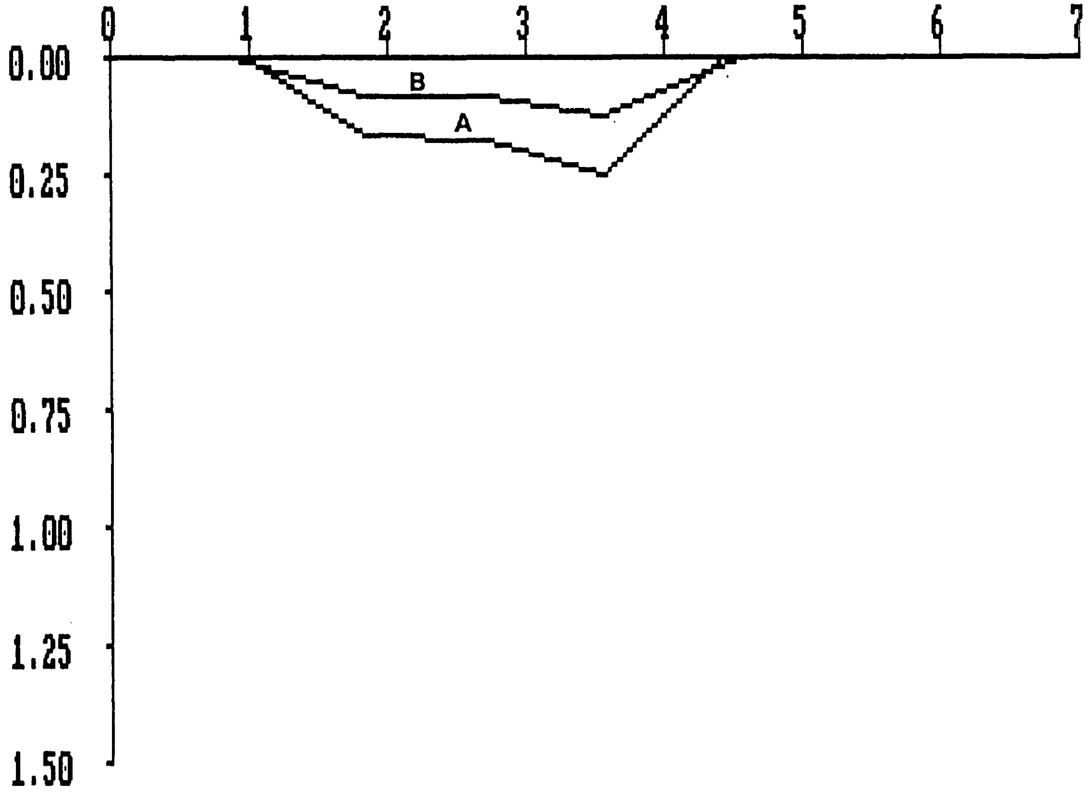
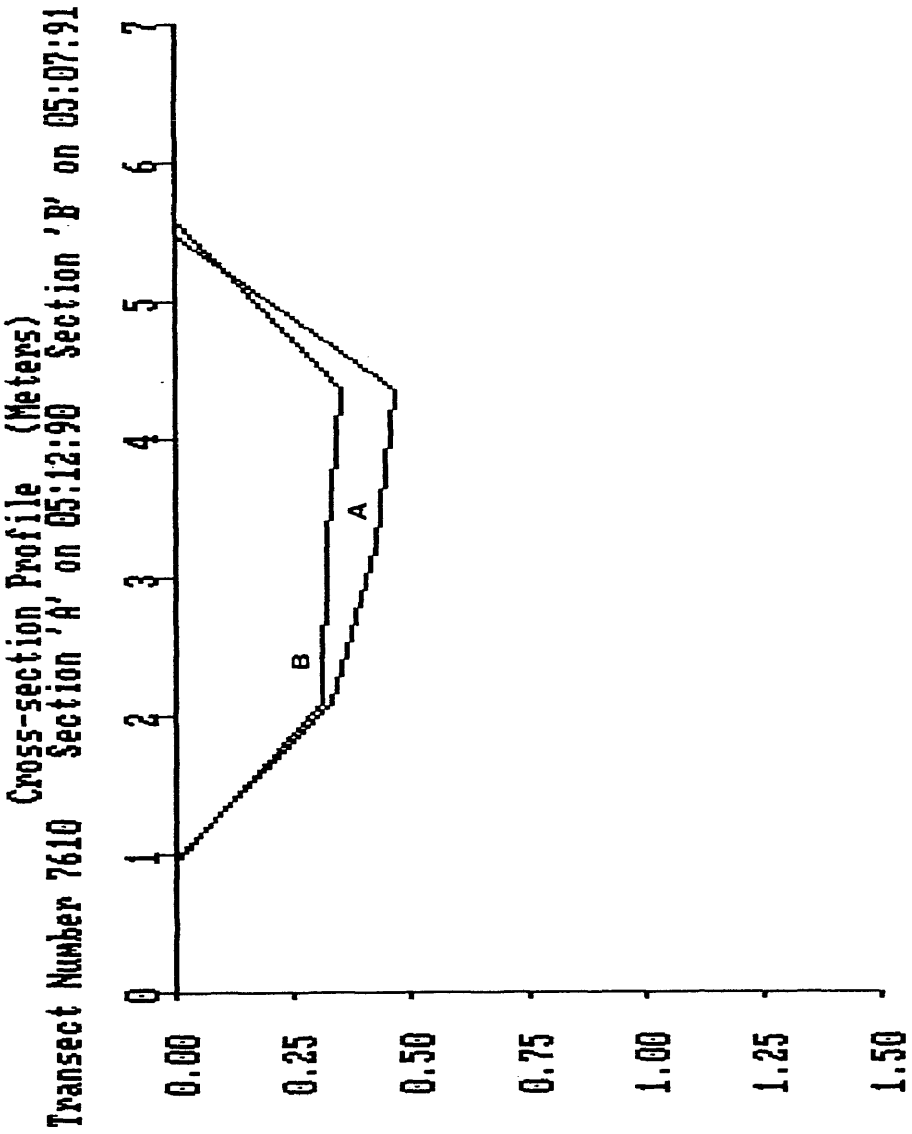
APPENDIX 1: CROSS-SECTION PROFILES/TRANSECT

Cross-section Profile (Meters)
Transect Number 778 Section 'A' on 05:12:90 Section 'B' on 05:07:91

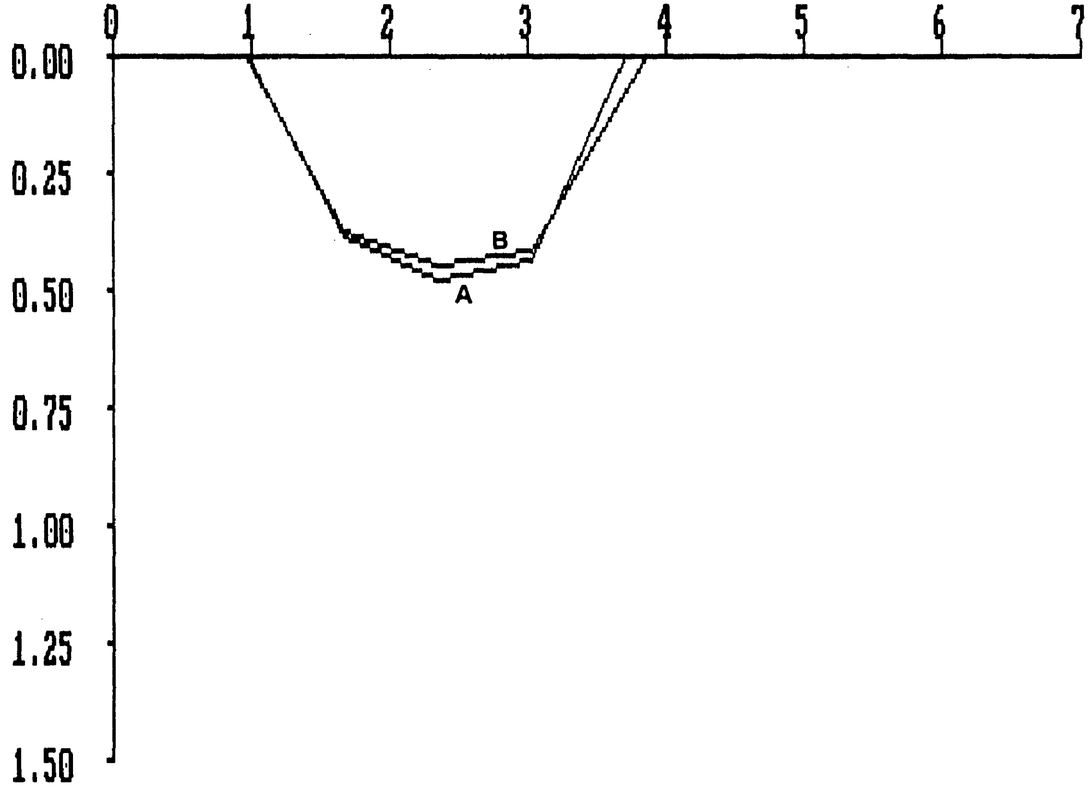


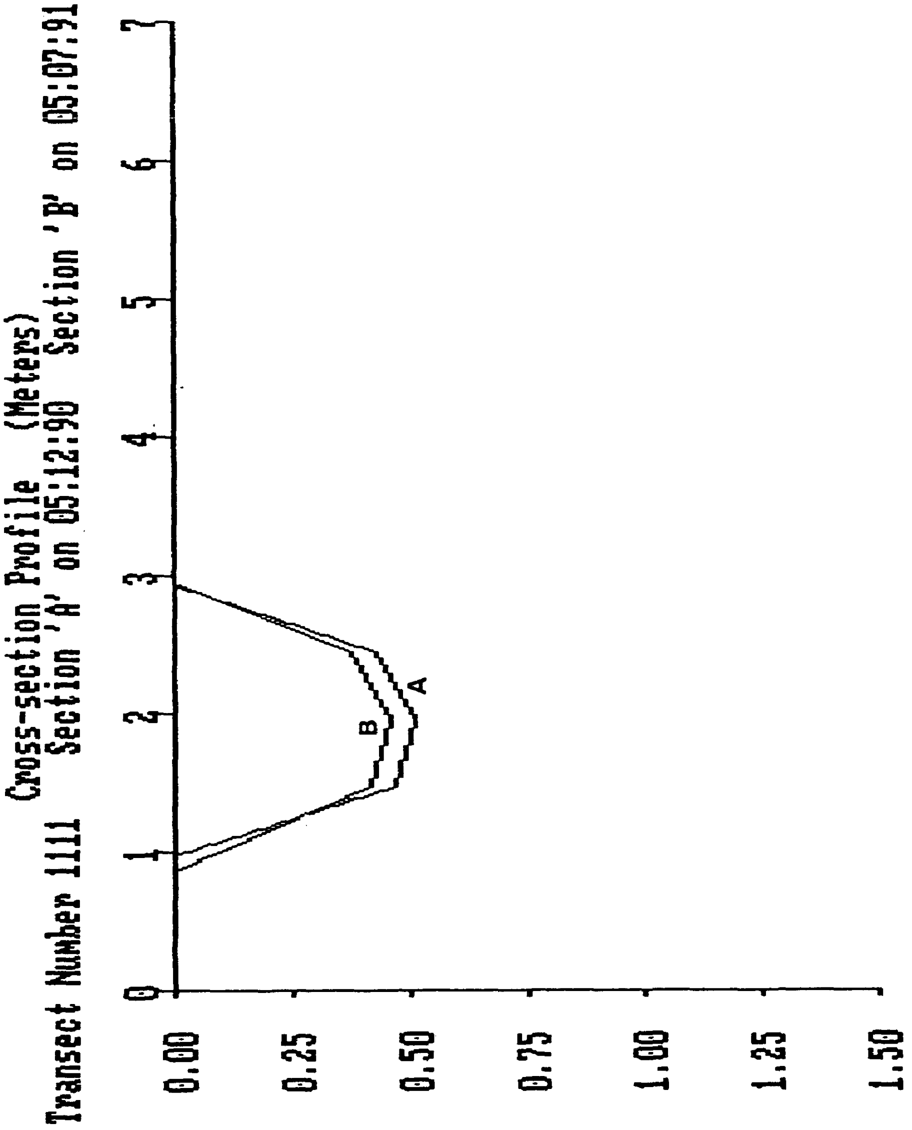


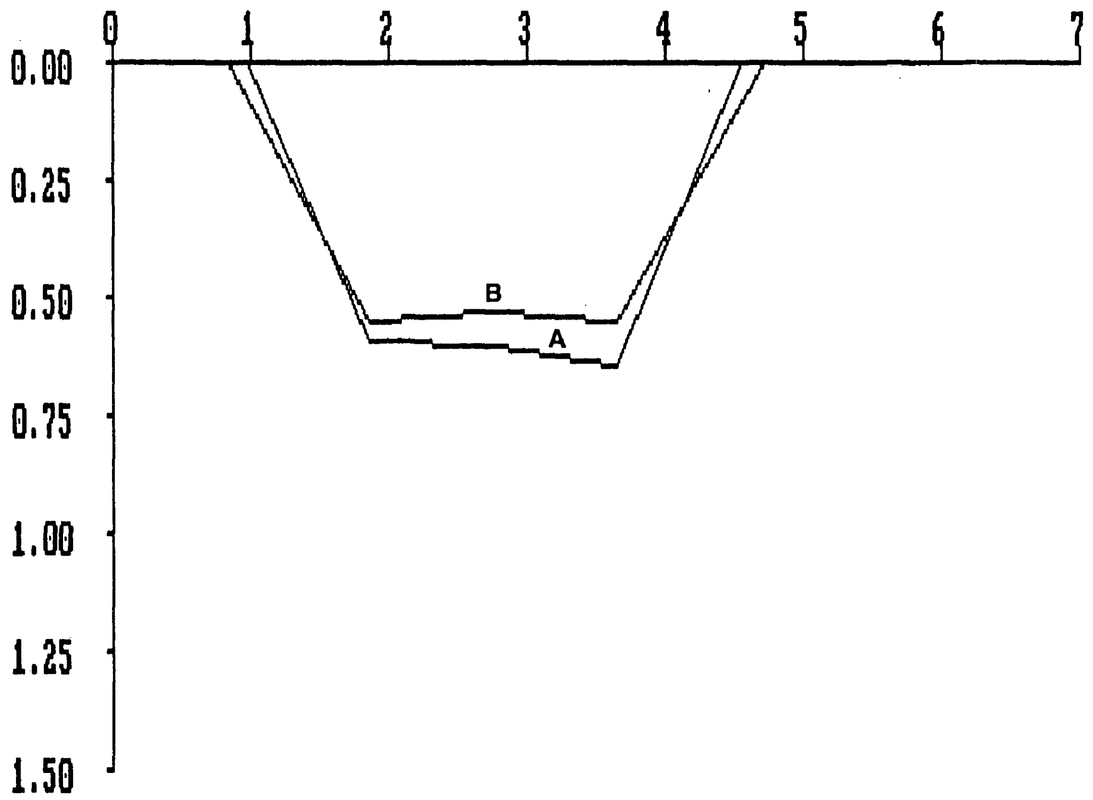
Cross-section Profile (Meters)

Transect Number 7610 Section 'A' on 05:12:90 Section 'B' on 05:07:91

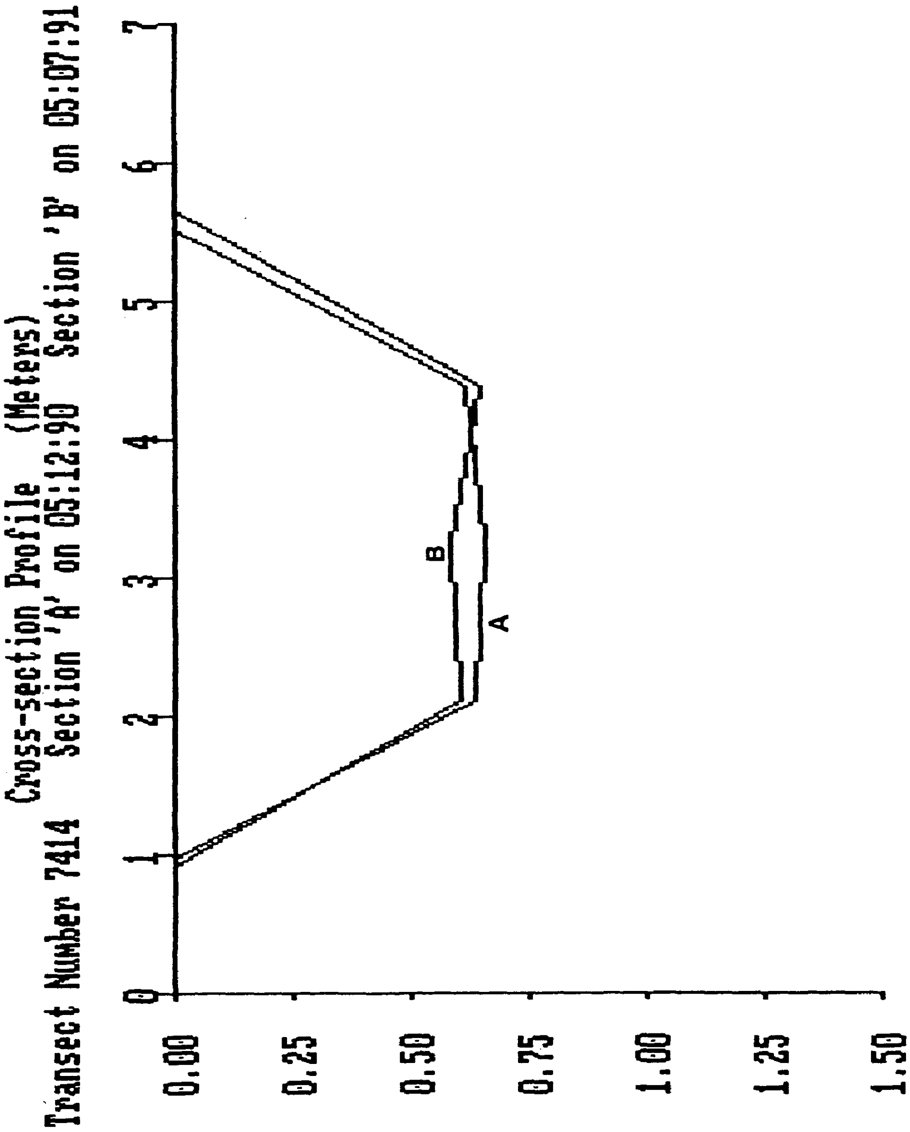
Cross-section Profile (Meters)
Transect Number 129 Section 'A' on 05:12:90 Section 'B' on 05:07:91

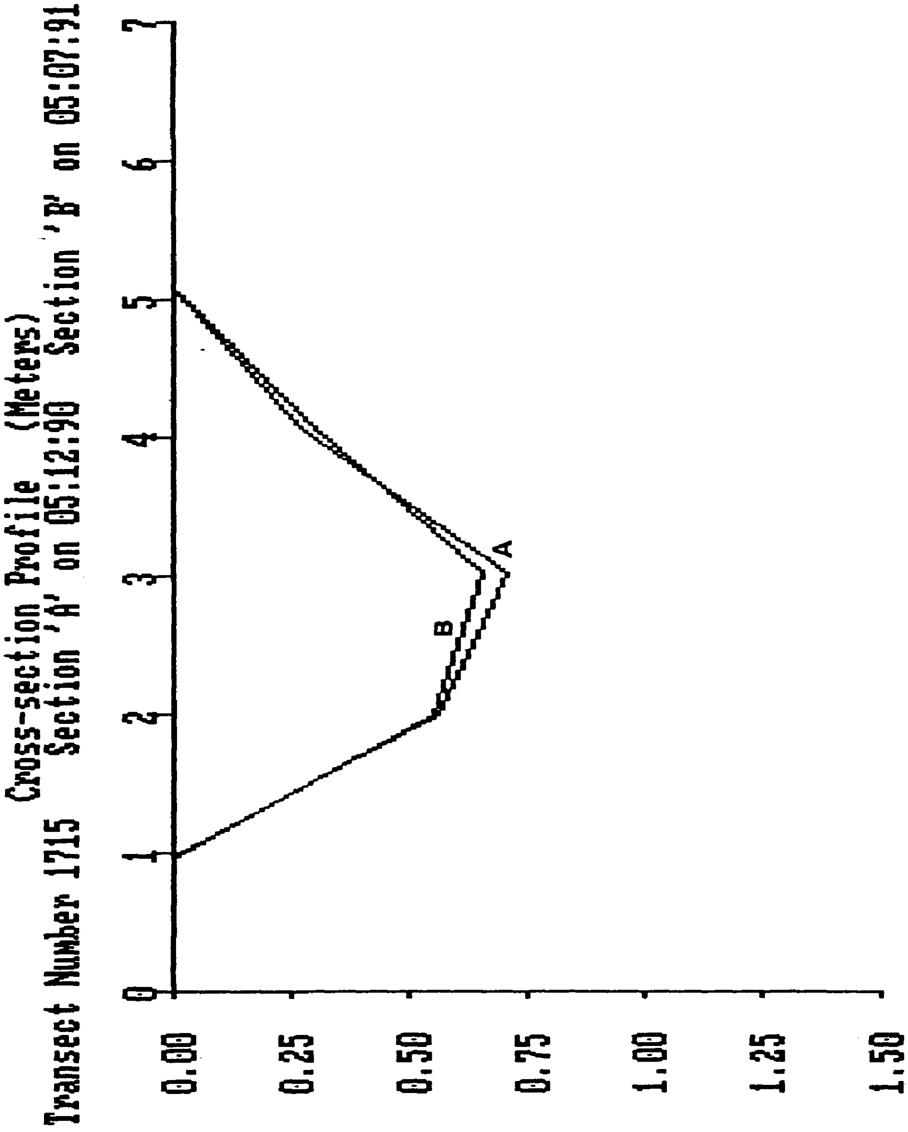



Cross-section Profile (Meters)
Transect Number 1111 Section 'A' on 05:12:90 Section 'B' on 05:07:91
0
1
2
3
4
5
6
7
0.00
0.25
0.50
0.75
1.00
1.25
1.50
A
B



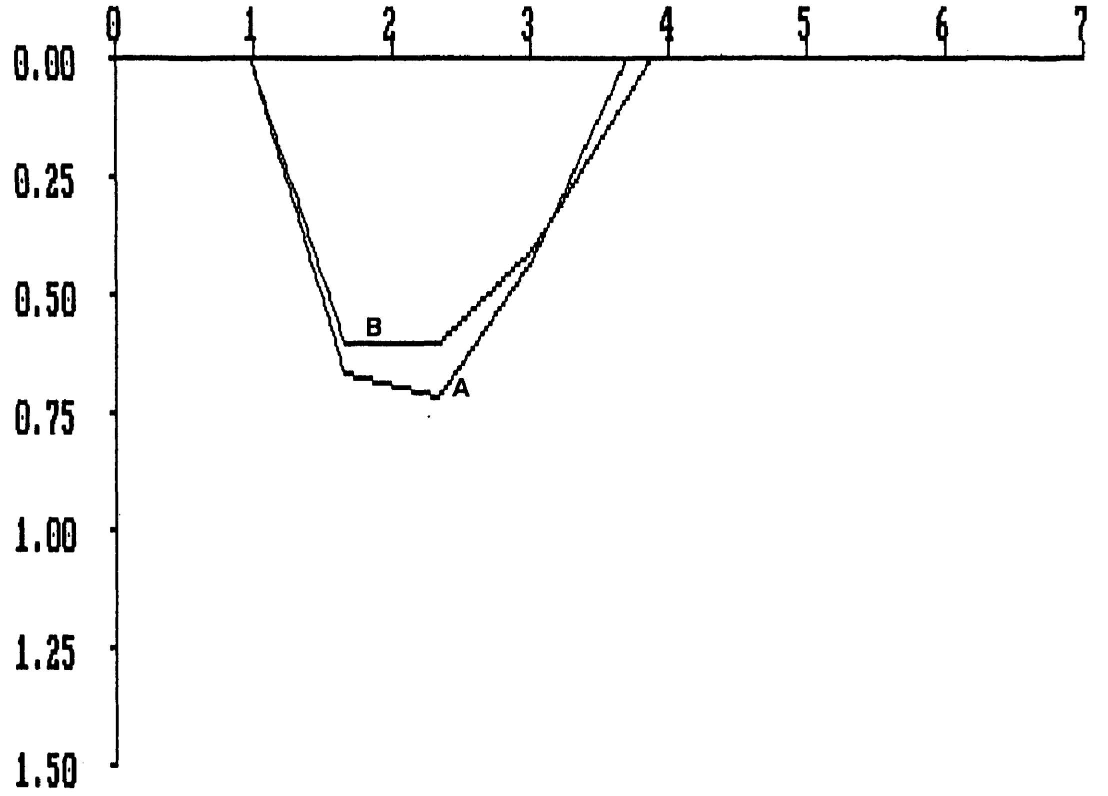
Cross-section Profile (Meters)
Transect Number 7513 Section 'A' on 05:12:90 Section 'B' on 05:07:91


Cross-section Profile (Meters)
Transect Number 7414 Section 'A' on 05:12:90 Section 'B' on 05:07:91
0
1
2
3
4
5
6
7
0.00
0.25
0.50
0.75
1.00
1.25
1.50
A
B

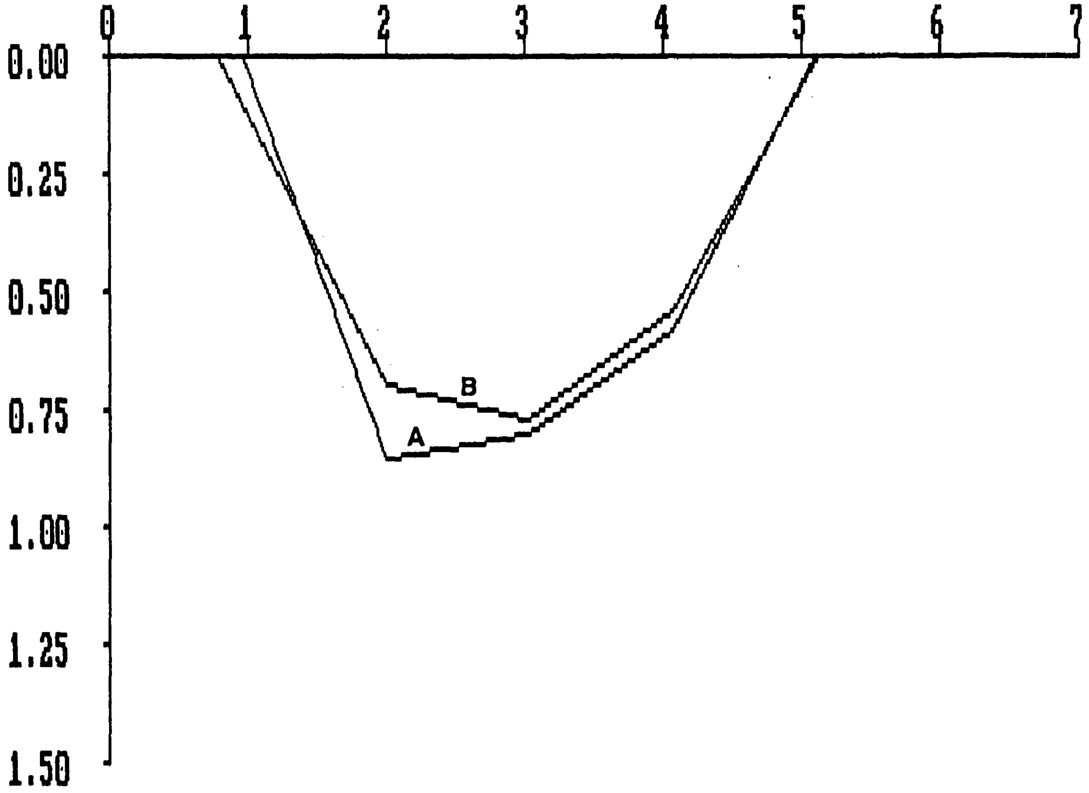


Cross-section Profile (Meters)

Transect Number 1715 Section 'A' on 05:12:90 Section 'B' on 05:07:91

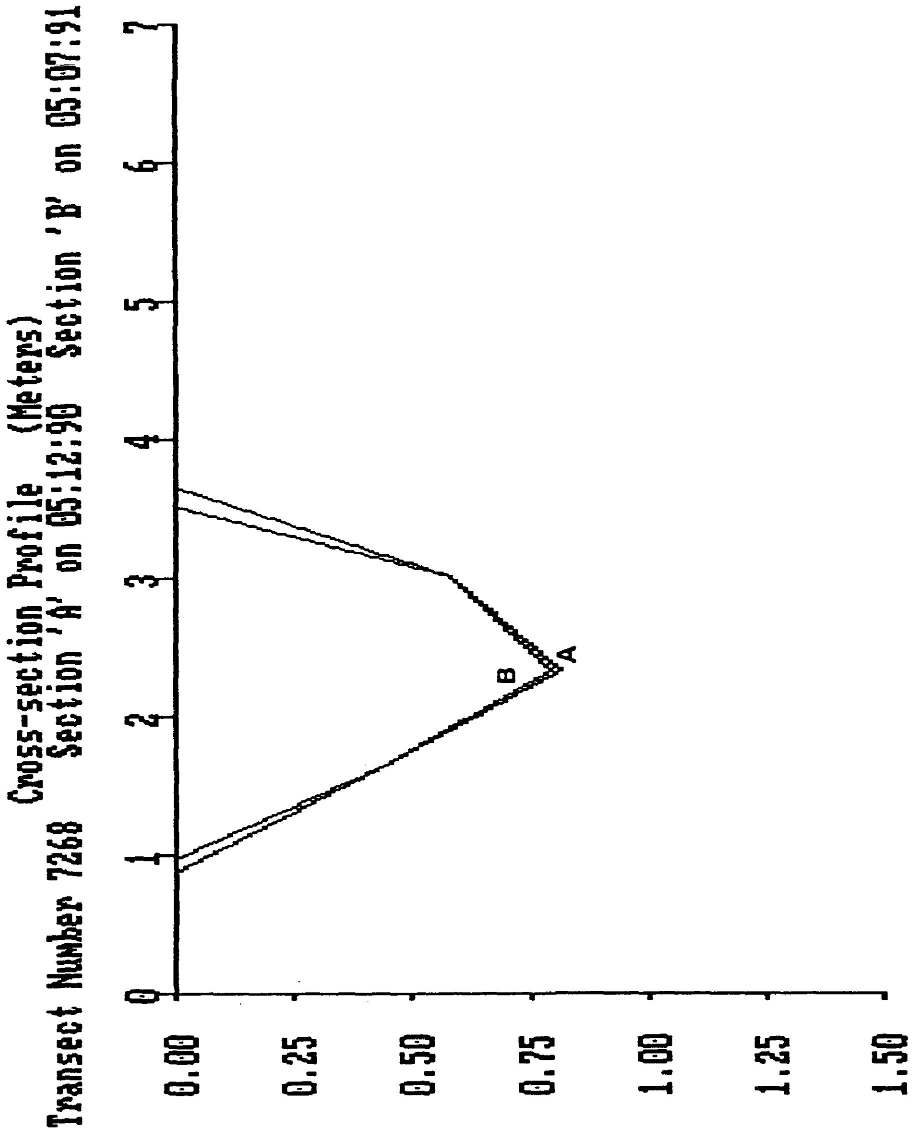


Cross-section Profile (Meters)
Transect Number 2222 Section 'A' on 05:12:90 Section 'B' on 05:07:91



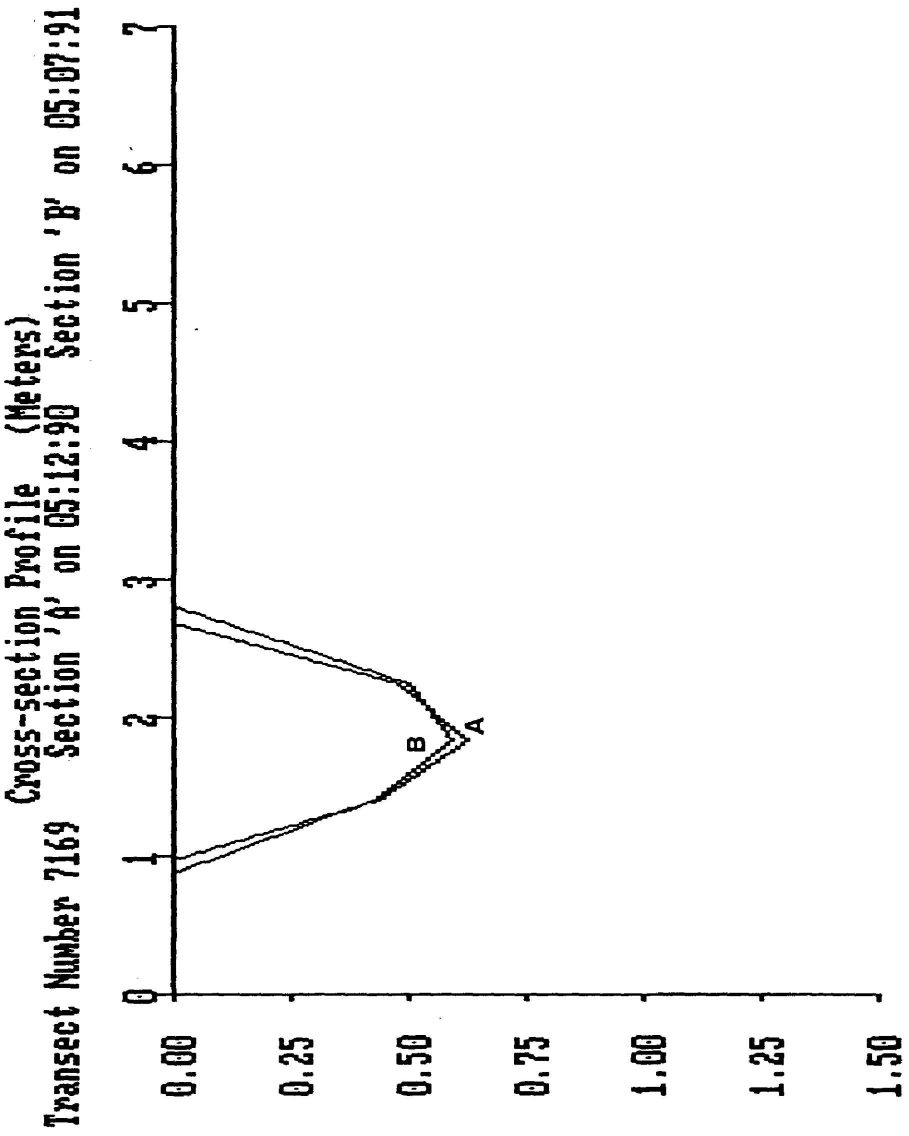
Cross-section Profile (Meters)

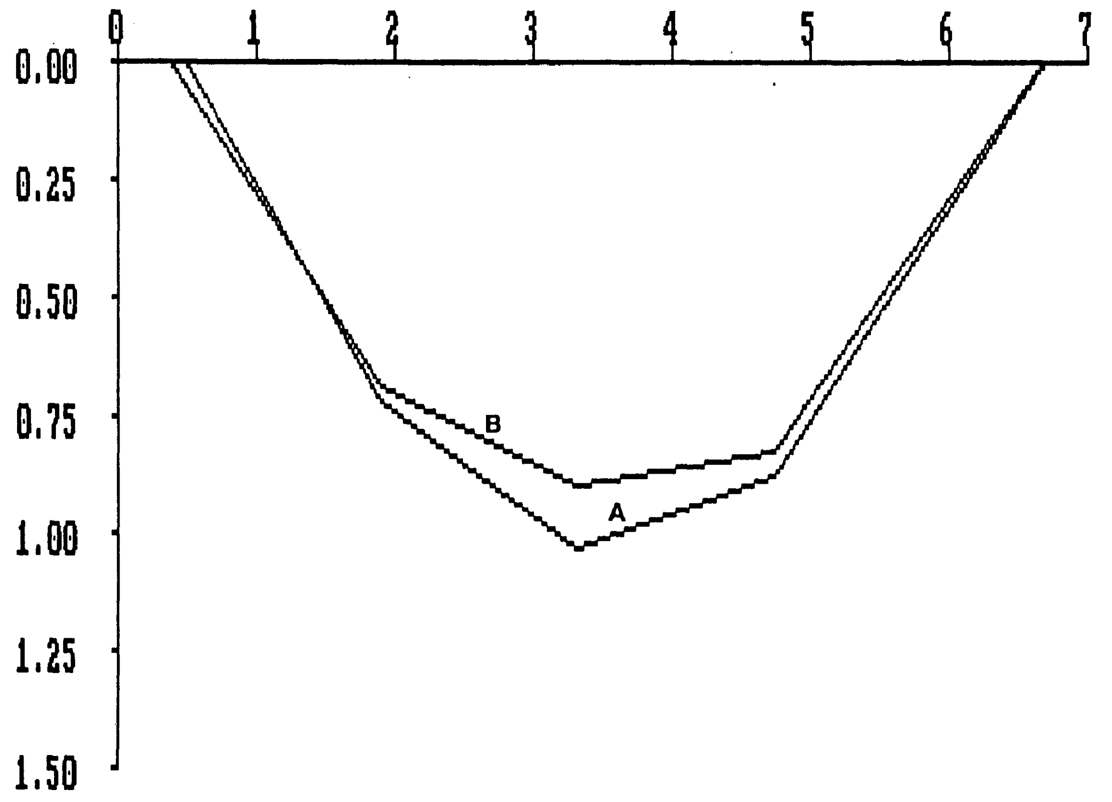
Transect Number 7318 Section 'A' on 05:12:90 Section 'B' on 05:07:91



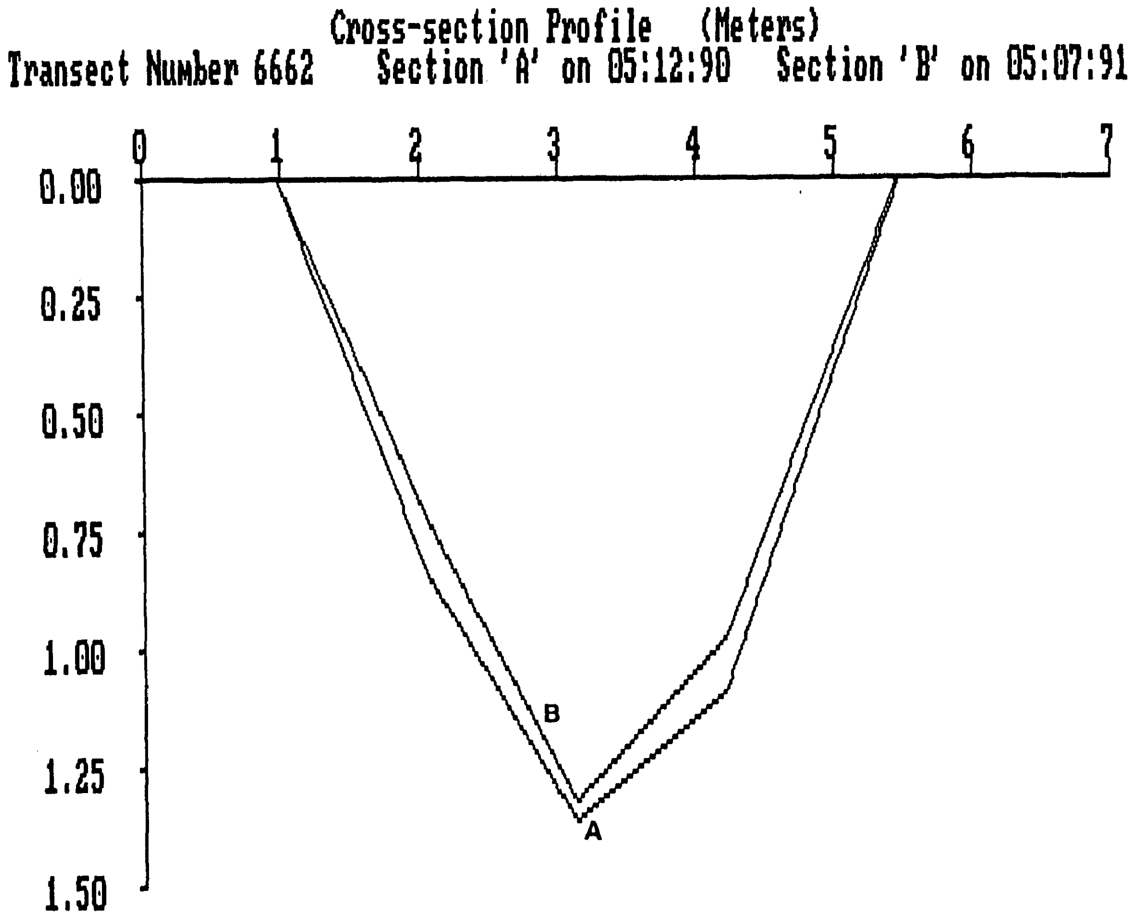
Cross-section Profile (Meters)

Transect Number 7268 Section 'A' on 05:12:90 Section 'B' on 05:07:91

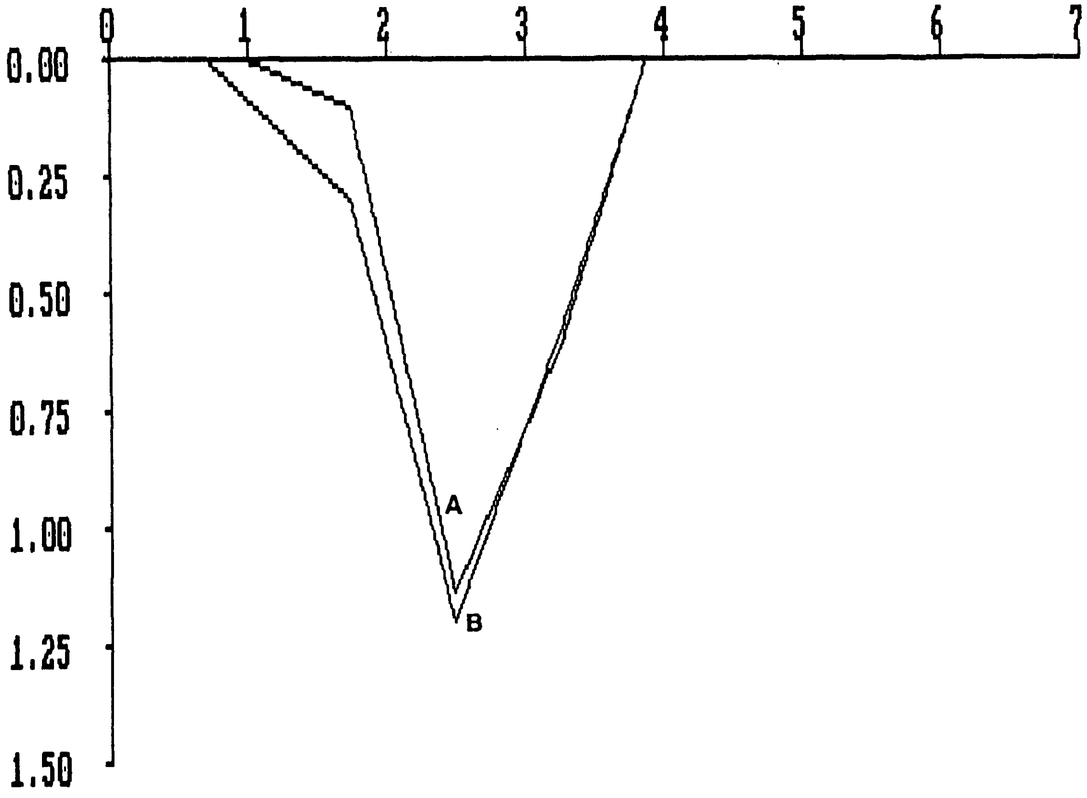

Cross-section Profile (Meters)
Transect Number 7169 Section 'A' on 05:12:90 Section 'B' on 05:07:91
0
1
2
3
4
5
6
7
0.00
0.25
0.50
0.75
1.00
1.25
1.50
A
B



Cross-section Profile (Meters)
Transect Number 6719 Section 'A' on 05:12:90 Section 'B' on 05:07:91



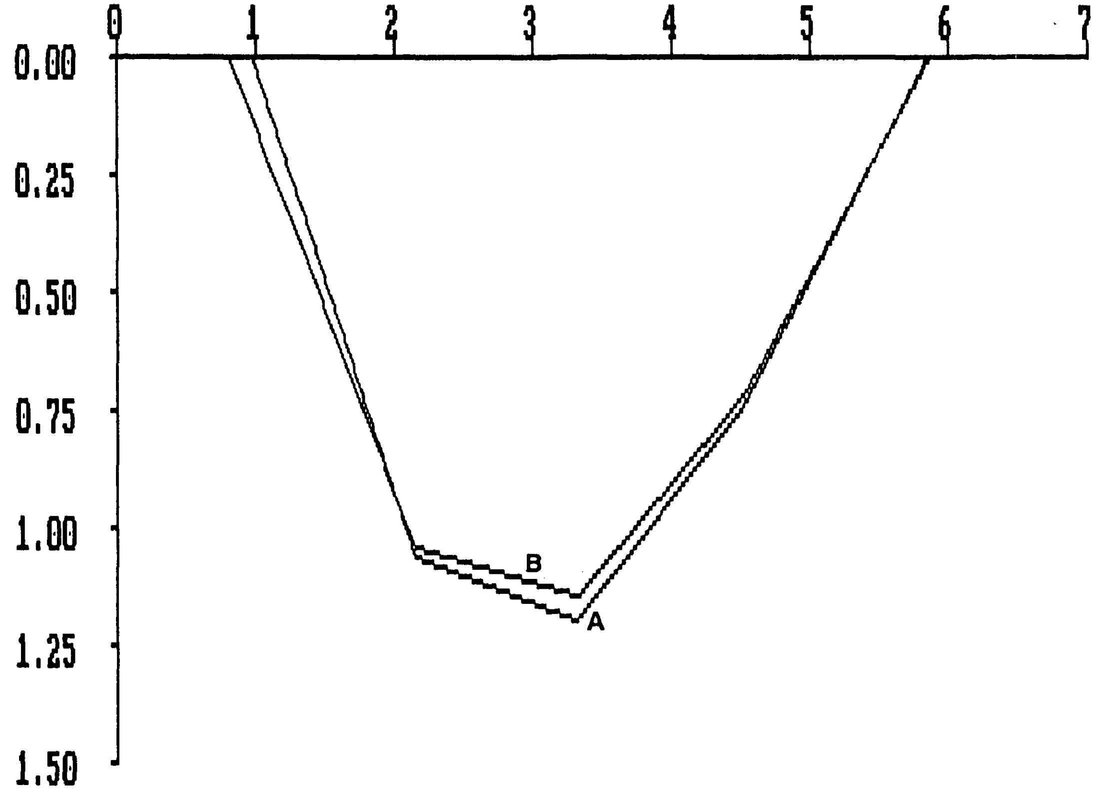
Cross-section Profile (Meters)
Transect Number 6662 Section 'A' on 05:12:90 Section 'B' on 05:07:91

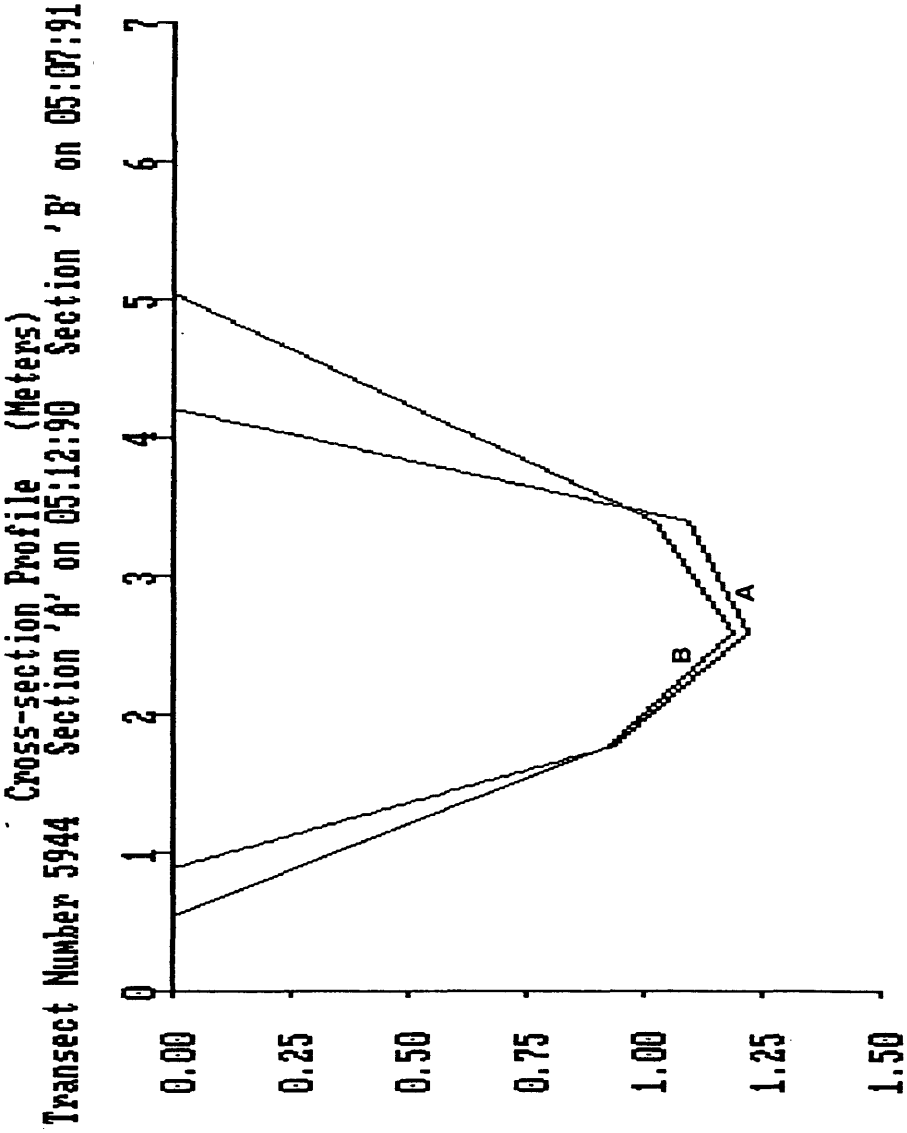


Cross-section Profile (Meters)

Transect Number 6564 Section 'A' on 05:12:90 Section 'B' on 05:07:91

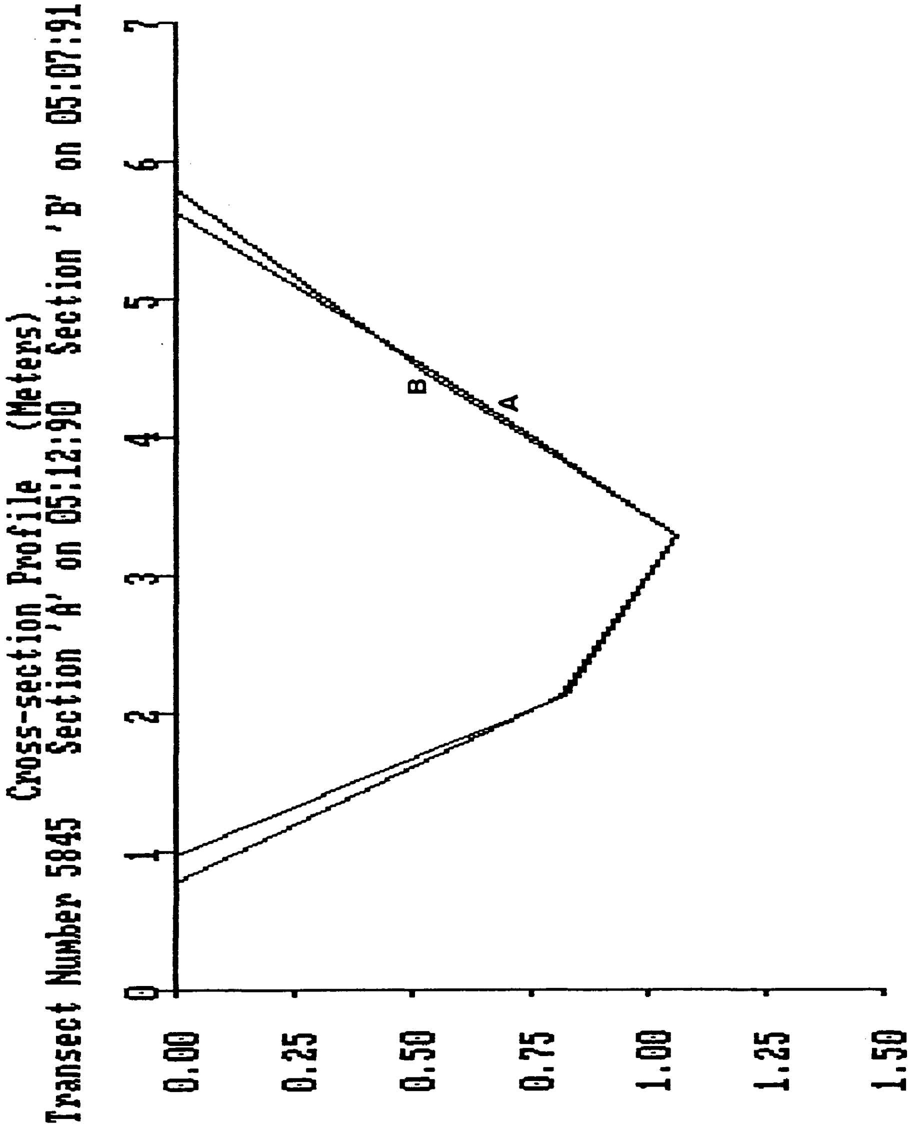
Cross-section Profile (Meters)
Transect Number 6120 Section 'A' on 05:12:90 Section 'B' on 05:07:91

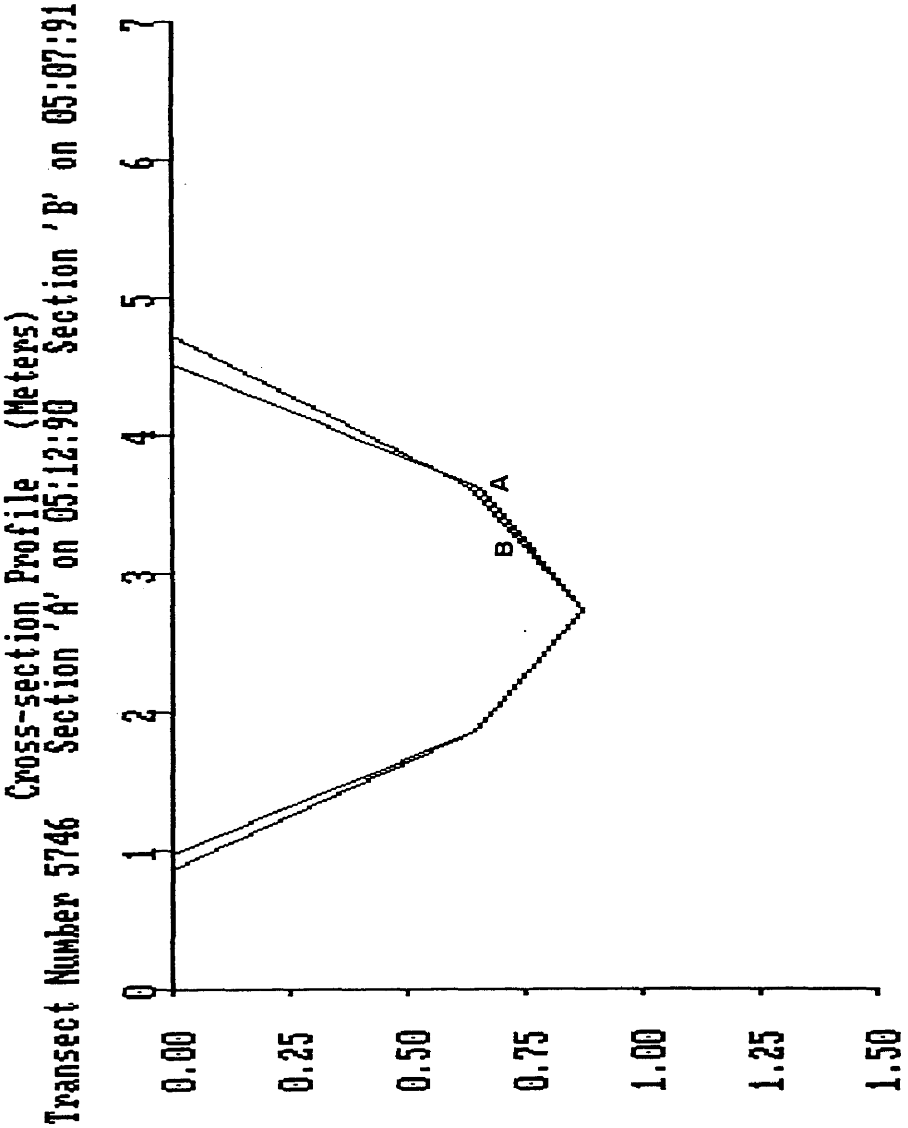


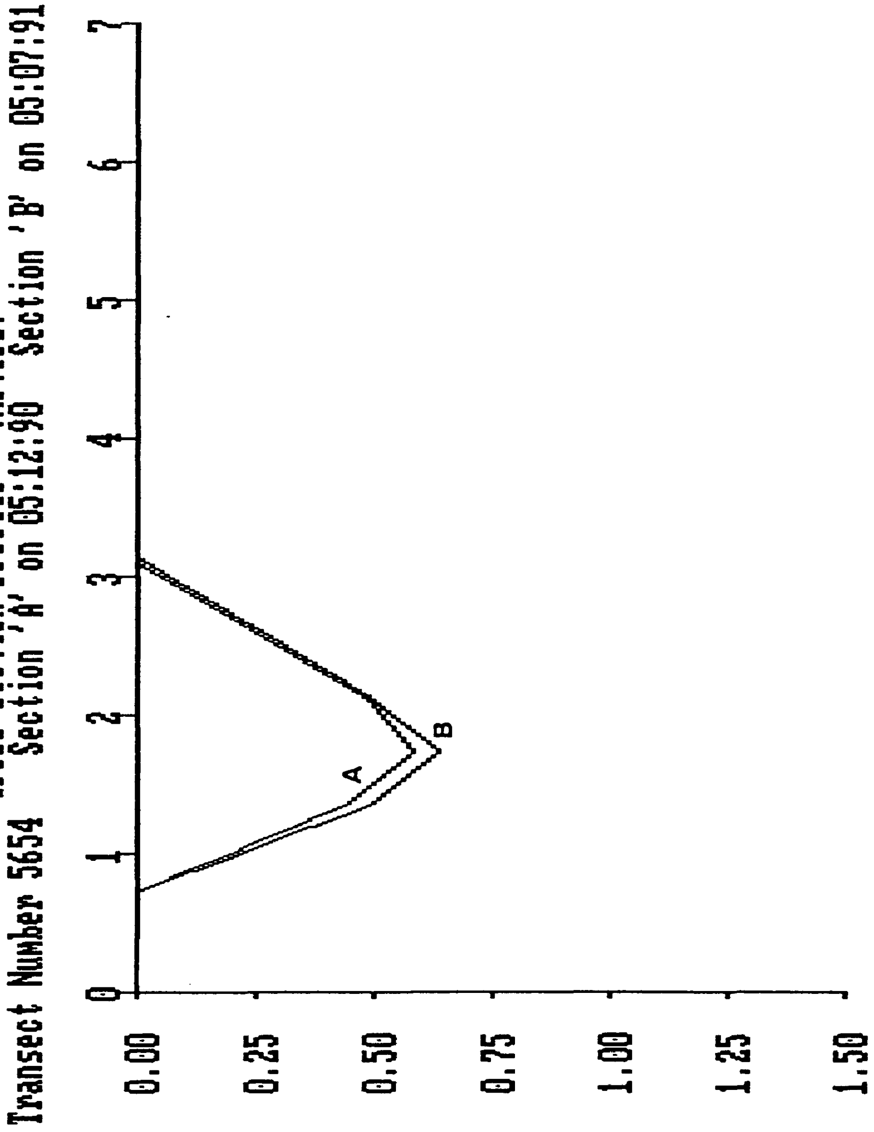


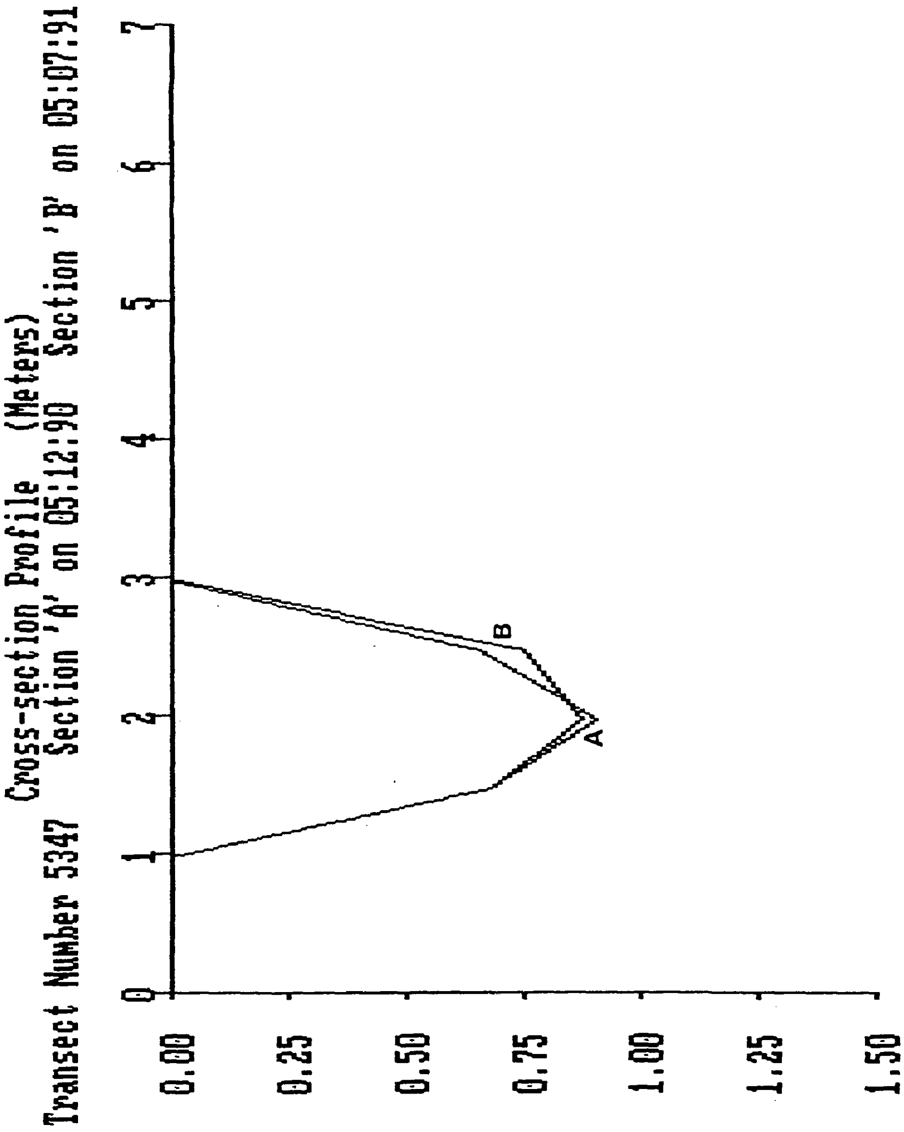
Cross-section Profile (Meters)

Transect Number 5944 Section 'A' on 05:12:90 Section 'B' on 05:07:91

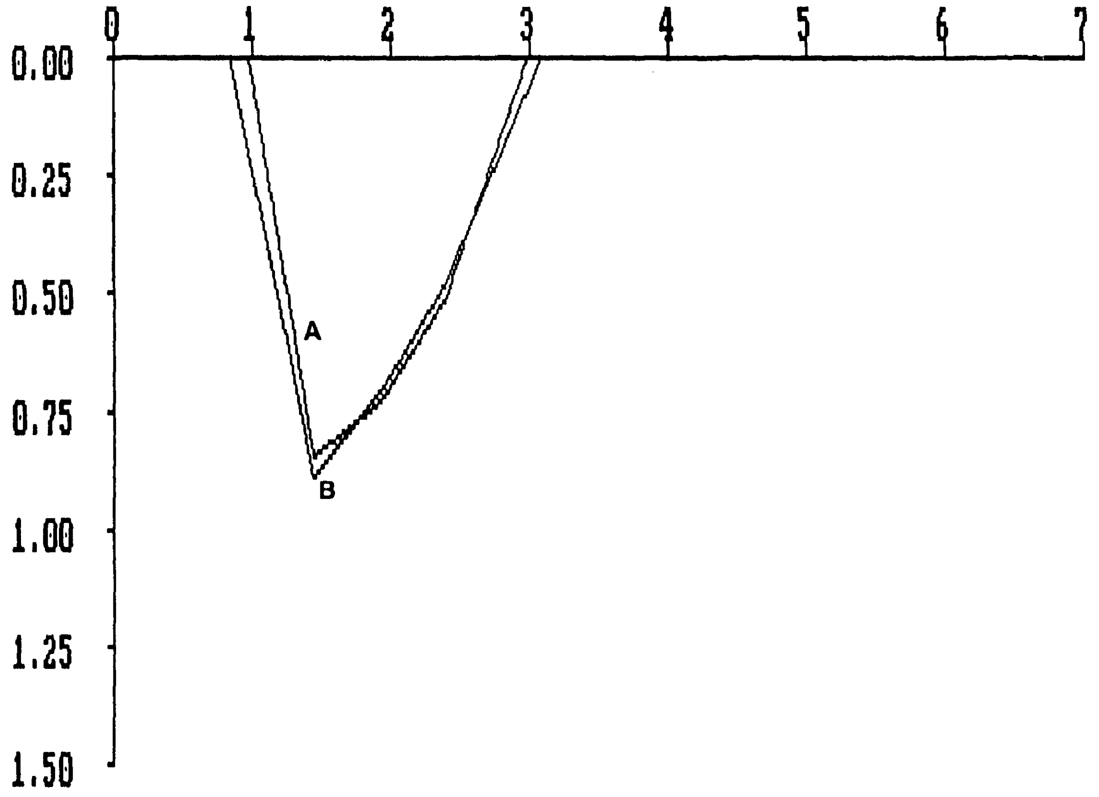

Cross-section Profile (Meters)
Transect Number 5845 Section 'A' on 05:12:90 Section 'B' on 05:07:91
0
1
2
3
4
5
6
7
0.00
0.25
0.50
0.75
1.00
1.25
1.50
A
B

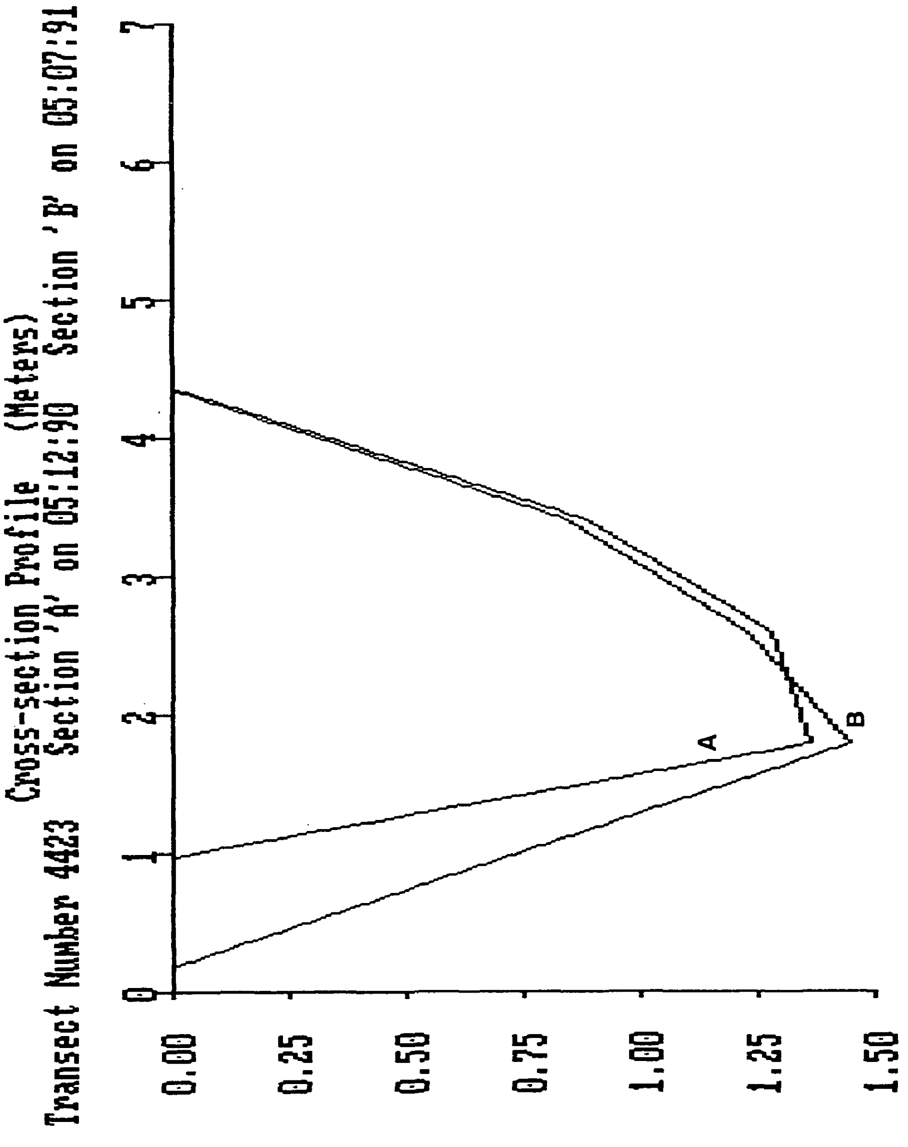

Cross-section Profile (Meters)
Transect Number 5746 Section 'A' on 05:12:90 Section 'B' on 05:07:91
0
1
2
3
4
5
6
7
0.00
0.25
0.50
0.75
1.00
1.25
1.50
A
B

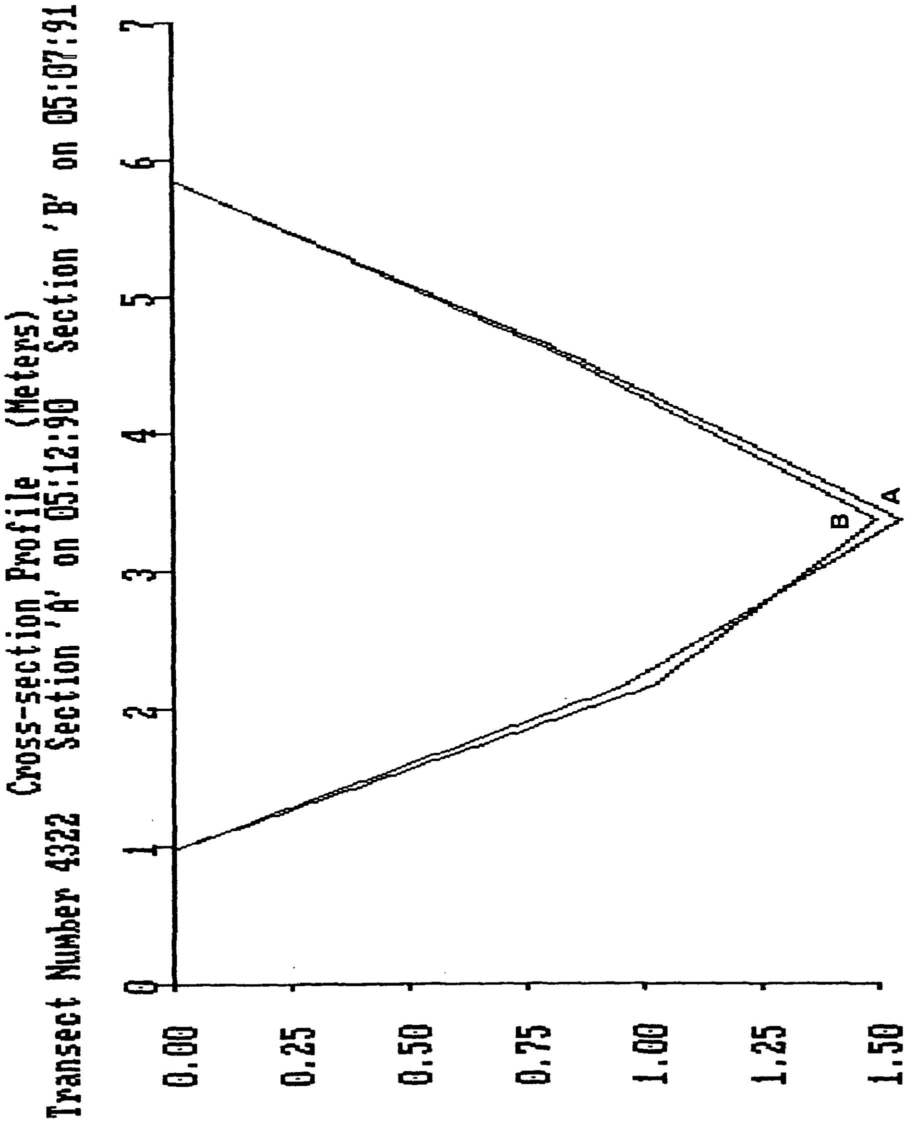

Cross-section Profile (Meters)
Transect Number 5654 Section 'A' on 05:12:90 Section 'B' on 05:07:91
0
1
2
3
4
5
6
7
0.00
0.25
0.50
0.75
1.00
1.25
1.50
A
B

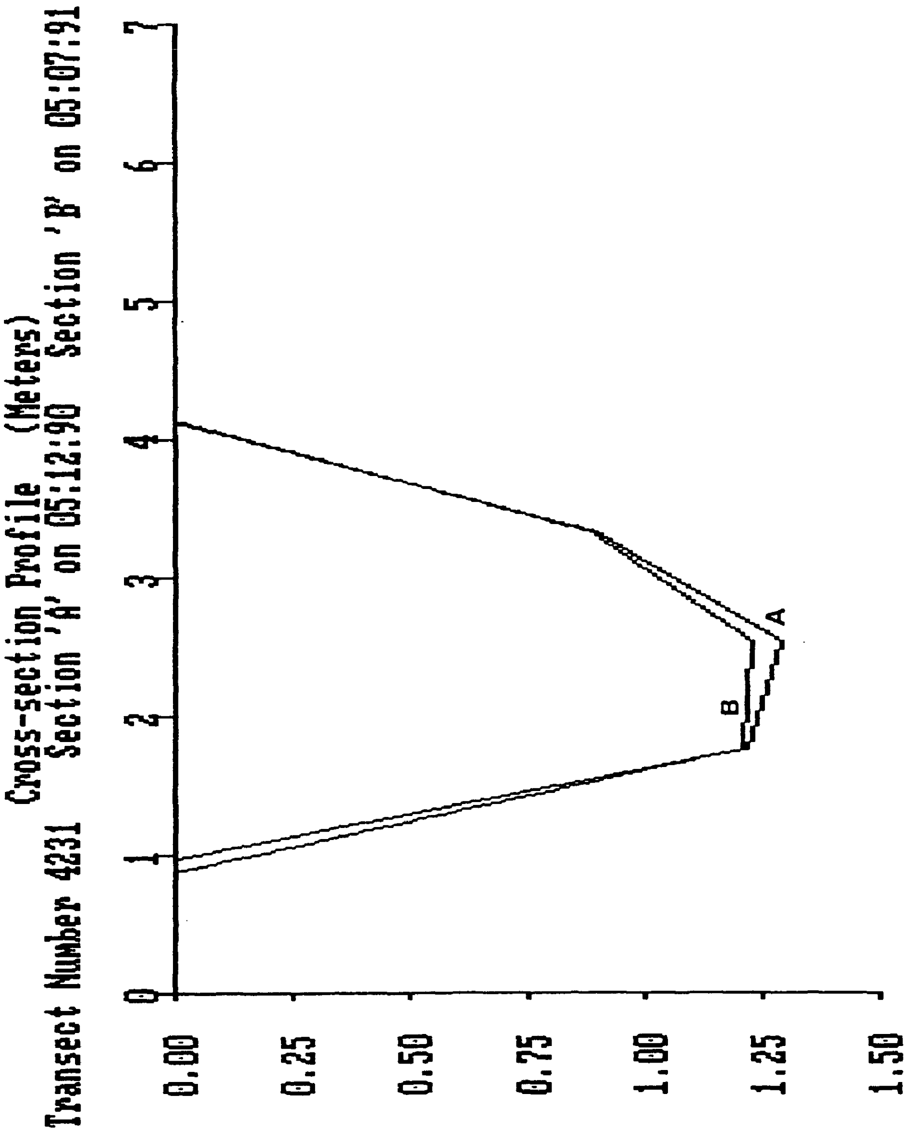

Cross-section Profile (Meters)
Transect Number 5347 Section 'A' on 05:12:90 Section 'B' on 05:07:91
0
1
2
3
4
5
6
7
0.00
0.25
0.50
0.75
1.00
1.25
1.50
A
B

Cross-section Profile (Meters)
Transect Number 5248 Section 'A' on 05:12:90 Section 'B' on 05:07:91



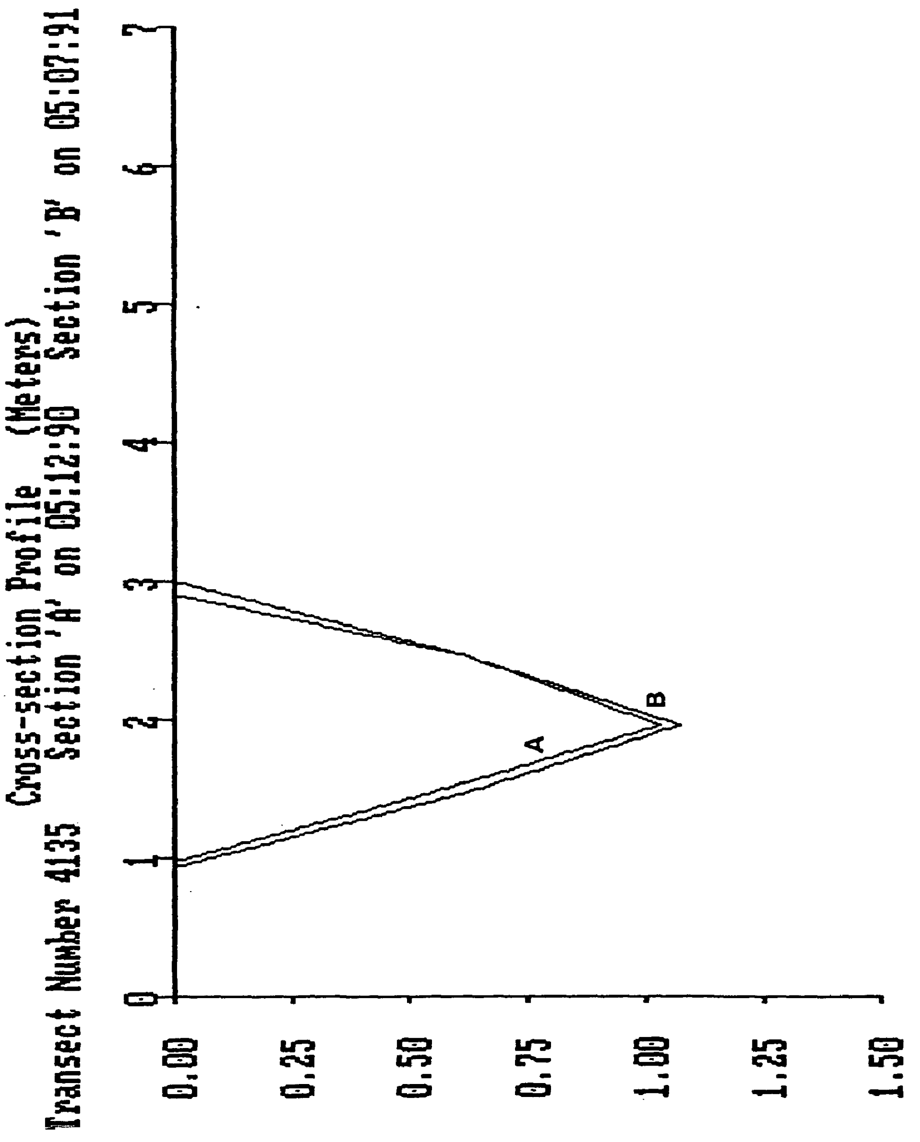

Cross-section Profile (Meters)
Transect Number 4423 Section 'A' on 05:12:90 Section 'B' on 05:07:91
0
1
2
3
4
5
6
7
0.00
0.25
0.50
0.75
1.00
1.25
1.50
A
B

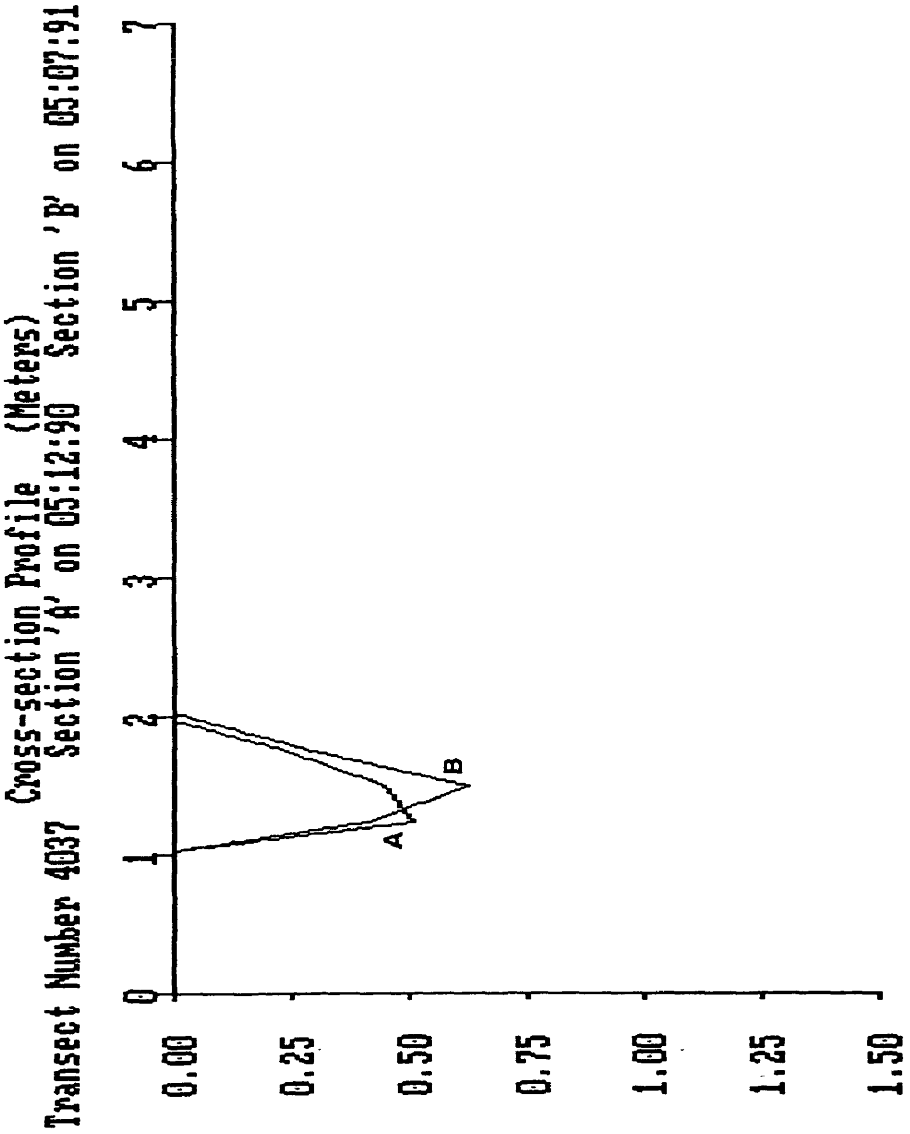

Transect Number 4322
Cross-section Profile (Meters)
Section 'A' on 05:12:90 Section 'B' on 05:07:91
0
1
2
3
4
5
6
7
0.00
0.25
0.50
0.75
1.00
1.25
1.50
A
B

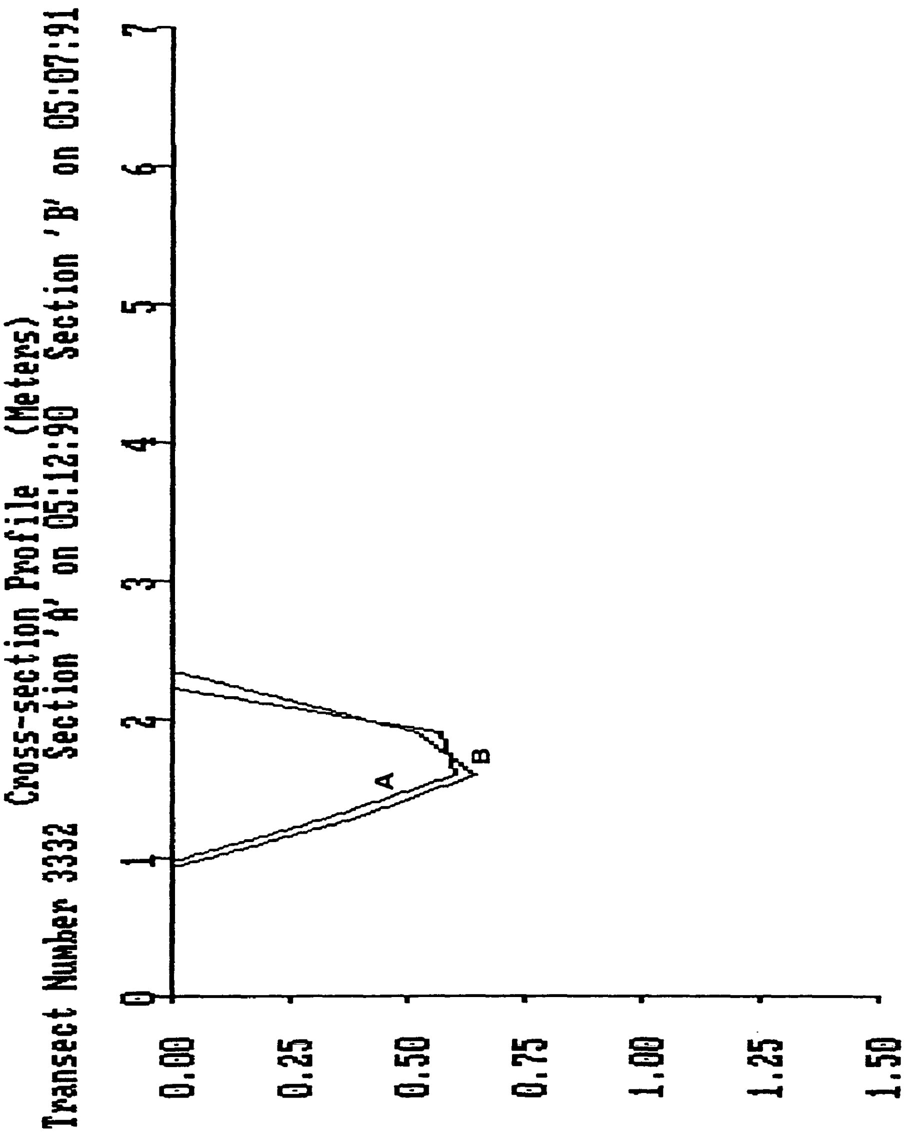


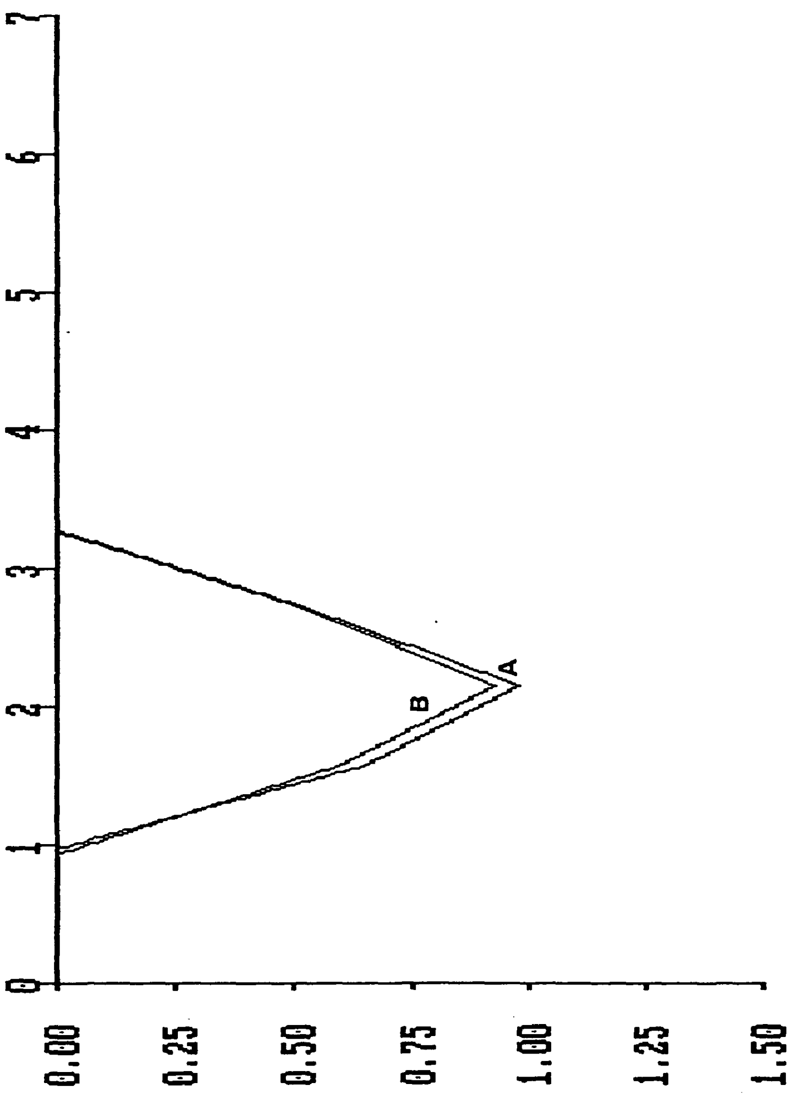
Cross-section Profile (Meters)

Transect Number 4231 Section 'A' on 05:12:90 Section 'B' on 05:07:91


Transect Number 4135
Cross-section Profile (Meters)
Section 'A' on 05:12:90
Section 'B' on 05:07:91
0
1
2
3
4
5
6
7
0.00
0.25
0.50
0.75
1.00
1.25
1.50
A
B


Cross-section Profile (Meters)
Transect Number 4037 Section 'A' on 05:12:90 Section 'B' on 05:07:91
0
1
2
3
4
5
6
7
0.00
0.25
0.50
0.75
1.00
1.25
1.50
A
B

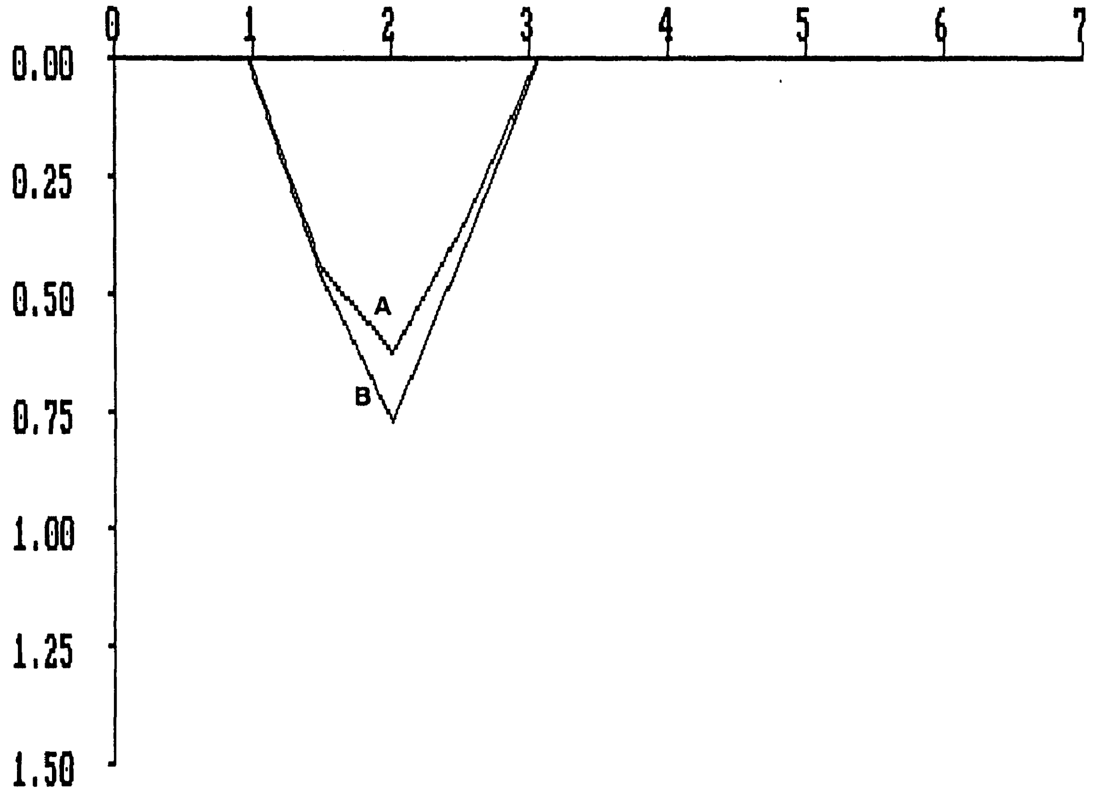

Cross-section Profile (Meters)
Transect Number 3332 Section 'A' on 05:12:90 Section 'B' on 05:07:91
0
1
2
3
4
5
6
7
0.00
0.25
0.50
0.75
1.00
1.25
1.50
A
B



Cross-section Profile (Meters)

Transect Number 3024 Section 'A' on 05:12:90 Section 'B' on 05:07:91

Cross-section Profile (Meters)
Transect Number 2829 Section 'A' on 05:12:90 Section 'B' on 05:07:91



APPENDIX 2: WIDTH/DEPTH RATIOS AND BANK SLOPE/TRANSECT

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 778

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	19.78	10.81	15.69
05:21:90	21.53	8.47	10.84
06:03:90	19.74	7.48	12.09
06:07:90	25.93	8.94	11.20
06:12:90	19.42	10.81	11.09
06:18:90	33.55	8.31	10.55
06:24:90	29.15	6.91	11.63
07:27:90	29.15	6.91	10.55
08:06:90	31.67	6.28	10.01
08:21:90	37.90	6.28	9.55
10:06:90	31.67	6.16	10.76
11:09:90	31.75	6.16	9.55
02:28:91	29.31	6.16	9.55
03:10:91	27.07	6.84	10.11
03:19:91	31.58	6.28	9.55
04:16:91	31.58	6.28	10.11
04:21:91	31.58	6.28	9.55
04:28:91	47.38	4.00	6.78
05:07:91	47.38	4.57	6.78

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 7610

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	10.77	15.88	22.23
05:21:90	12.51	15.88	20.50
06:03:90	11.37	15.50	21.37
06:07:90	11.70	15.50	20.61
06:12:90	11.37	15.88	20.87
06:18:90	11.95	15.88	20.02
06:24:90	11.65	15.88	20.02
07:27:90	12.65	14.96	18.43
08:06:90	12.68	15.30	18.43
08:21:90	13.08	15.17	17.86
10:06:90	13.60	14.15	16.91
11:09:90	13.28	14.15	17.07
02:28:91	12.89	14.72	17.07
03:10:91	13.57	14.72	17.33
03:19:91	12.89	14.60	17.20
04:16:91	13.25	14.60	17.20
04:21:91	12.89	14.60	17.20
04:28:91	15.39	14.60	15.95
05:07:91	14.91	14.60	15.52

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 129

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	5.88	28.78	32.15
05:21:90	5.76	28.78	32.74
06:03:90	5.88	28.44	30.40
06:07:90	6.04	28.44	31.20
06:12:90	5.92	28.44	31.20
06:18:90	5.88	28.44	30.40
06:24:90	5.98	28.72	29.12
07:27:90	6.23	28.11	26.83
08:06:90	6.21	27.79	27.39
08:21:90	6.16	28.39	26.30
10:06:90	6.33	26.57	25.23
11:09:90	6.40	26.57	26.02
02:28:91	6.34	27.18	26.29
03:10:91	6.59	27.18	25.51
03:19:91	6.57	27.18	25.77
04:16:91	6.50	26.88	26.29
04:21:91	6.50	26.88	26.29
04:28:91	6.50	26.88	26.29
05:07:91	6.64	26.88	26.29

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 1111

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	3.96	42.66	40.70
05:21:90	3.94	43.92	39.35
06:03:90	4.06	44.43	33.21
06:07:90	4.06	43.88	38.66
06:12:90	4.06	43.30	38.66
06:18:90	4.06	43.30	37.23
06:24:90	4.14	43.30	37.95
07:27:90	4.14	42.71	37.23
08:06:90	4.14	40.60	37.23
08:21:90	4.22	40.01	37.23
10:06:90	4.12	41.42	37.23
11:09:90	4.14	41.42	35.96
02:28:91	4.37	35.97	36.69
03:10:91	4.55	35.97	35.96
03:19:91	4.76	35.36	36.69
04:16:91	4.76	35.36	36.69
04:21:91	4.76	35.36	36.69
04:28:91	4.65	34.74	36.69
05:07:91	4.65	34.11	36.69

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 7513

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	6.13	32.67	35.24
05:21:90	6.63	29.49	33.97
06:03:90	6.35	30.88	33.02
06:07:90	6.42	29.87	32.62
06:12:90	6.53	29.87	32.62
06:18:90	6.42	29.87	32.21
06:24:90	6.43	29.87	31.95
07:27:90	6.93	29.01	29.01
08:06:90	6.93	29.01	28.61
08:21:90	6.81	29.01	28.21
10:06:90	7.05	28.57	27.80
11:09:90	7.07	28.33	27.80
02:28:91	7.02	27.85	28.61
03:10:91	7.02	27.20	28.83
03:19:91	7.04	27.20	27.80
04:16:91	6.91	27.20	27.80
04:21:91	6.95	27.19	27.80
04:28:91	7.60	26.77	26.57
05:07:91	7.55	27.20	26.77

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 7414

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	7.08	28.68	27.74
05:21:90	7.25	28.68	27.70
06:03:90	7.04	26.75	27.70
06:07:90	7.12	26.01	28.10
06:12:90	7.12	25.64	28.10
06:18:90	7.45	26.38	28.47
06:24:90	7.34	26.38	28.85
07:27:90	7.47	26.19	28.44
08:06:90	7.59	26.57	28.44
08:21:90	7.82	26.57	29.74
10:06:90	7.82	25.45	28.27
11:09:90	7.82	25.45	28.27
02:28:91	7.68	25.63	28.64
03:10:91	7.68	25.63	28.27
03:19:91	7.68	26.00	29.01
04:16:91	7.56	25.63	28.27
04:21:91	7.56	26.00	28.27
04:28:91	8.21	25.63	28.27
05:07:91	8.40	26.00	26.57

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 1715

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	5.96	27.85	14.42
05:21:90	6.04	28.27	14.42
06:03:90	5.77	26.57	14.41
06:07:90	5.97	26.35	14.42
06:12:90	5.97	28.04	14.42
06:18:90	5.89	26.78	14.93
06:24:90	6.06	27.20	14.93
07:27:90	6.14	27.20	15.44
08:06:90	6.09	26.35	16.95
08:21:90	6.17	26.35	17.94
10:06:90	6.25	27.41	14.42
11:09:90	6.25	27.41	13.91
02:28:91	6.63	24.61	11.31
03:10:91	6.24	27.63	14.93
03:19:91	6.24	27.63	14.42
04:16:91	6.25	26.99	15.44
04:21:91	6.25	26.99	15.44
04:28:91	6.44	26.99	15.95
05:07:91	6.44	26.99	15.95

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 2222

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	3.89	43.75	31.56
05:21:90	4.24	41.19	24.09
06:03:90	4.21	43.32	25.20
06:07:90	4.21	43.32	26.29
06:12:90	4.21	43.32	26.29
06:18:90	4.20	43.75	24.98
06:24:90	4.26	43.32	24.98
07:27:90	4.46	42.44	23.66
08:06:90	4.82	42.88	23.66
08:21:90	4.82	42.44	24.20
10:06:90	4.85	41.99	23.73
11:09:90	4.76	41.99	23.96
02:28:91	5.00	41.53	23.43
03:10:91	4.98	41.07	23.66
03:19:91	5.00	41.07	23.43
04:16:91	4.98	41.53	24.20
04:21:91	4.98	41.53	24.20
04:28:91	4.98	41.07	24.73
05:07:91	4.98	40.60	24.73

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 7318

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	5.33	38.20	28.69
05:21:90	5.41	32.05	27.85
06:03:90	5.42	30.75	25.69
06:07:90	5.42	31.47	24.81
06:12:90	5.42	31.47	28.27
06:18:90	5.42	31.47	27.42
06:24:90	5.42	31.47	27.42
07:27:90	5.49	31.11	27.00
08:06:90	5.49	30.75	27.00
08:21:90	5.62	30.75	25.73
10:06:90	5.83	29.13	26.35
11:09:90	5.81	28.71	25.93
02:28:91	5.83	29.09	25.92
03:10:91	5.88	28.71	26.35
03:19:91	5.81	28.71	25.93
04:16:91	5.81	28.71	26.35
04:21:91	5.88	28.71	26.35
04:28:91	5.88	28.71	25.93
05:07:91	5.81	29.05	26.35

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 7268

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	3.23	32.74	48.12
05:21:90	3.31	32.74	45.00
06:03:90	3.40	31.65	43.09
06:07:90	3.43	31.65	41.74
06:12:90	3.37	30.96	44.10
06:18:90	3.41	30.40	41.25
06:24:90	3.41	31.52	41.25
07:27:90	3.59	30.96	41.25
08:06:90	3.59	30.40	41.25
08:21:90	3.57	29.74	41.25
10:06:90	3.59	29.74	41.37
11:09:90	3.64	29.98	41.31
02:28:91	3.71	29.90	40.82
03:10:91	3.71	28.81	40.82
03:19:91	3.71	28.81	40.82
04:16:91	3.67	29.36	40.82
04:21:91	3.71	29.36	40.82
04:28:91	3.67	28.81	41.31
05:07:91	3.62	29.36	41.31

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 7169

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	2.79	45.00	47.49
05:21:90	2.78	45.64	46.22
06:03:90	3.11	39.70	44.47
06:07:90	3.00	42.05	43.42
06:12:90	3.13	39.70	43.42
06:18:90	3.13	40.96	43.96
06:24:90	3.03	40.96	44.48
07:27:90	3.25	39.81	42.32
08:06:90	3.33	39.70	40.84
08:21:90	3.39	39.70	41.93
10:06:90	3.39	39.05	40.84
11:09:90	3.45	39.05	41.39
02:28:91	3.38	38.93	41.19
03:10:91	3.38	38.93	41.19
03:19:91	3.38	38.93	41.19
04:16:91	3.38	39.59	41.19
04:21:91	3.44	39.59	40.60
04:28:91	3.30	38.53	41.76
05:07:91	3.36	38.53	41.76

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 6719

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	6.19	26.25	23.51
05:21:90	6.38	24.97	22.29
06:03:90	6.01	26.41	23.75
06:07:90	6.37	25.77	23.03
06:12:90	6.50	25.77	23.51
06:18:90	6.25	25.77	23.03
06:24:90	6.25	26.25	23.51
07:27:90	6.39	26.10	23.03
08:06:90	6.58	25.93	23.03
08:21:90	6.73	25.78	22.54
10:06:90	7.03	24.00	22.78
11:09:90	6.88	23.69	22.05
02:28:91	6.95	24.30	23.13
03:10:91	7.10	24.30	22.64
03:19:91	6.88	23.86	22.39
04:16:91	6.97	24.03	22.15
04:21:91	7.12	23.73	22.15
04:28:91	7.28	24.03	22.39
05:07:91	7.20	23.73	22.39

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 6662

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	3.40	37.12	39.98
05:21:90	3.43	32.24	39.98
06:03:90	3.43	32.60	39.19
06:07:90	3.48	33.33	39.46
06:12:90	3.48	32.60	38.66
06:18:90	3.48	31.87	37.84
06:24:90	3.48	33.33	38.93
07:27:90	3.53	32.24	38.66
08:06:90	3.53	32.24	38.39
08:21:90	3.59	32.60	37.84
10:06:90	3.51	32.97	37.37
11:09:90	3.54	32.24	37.09
02:28:91	3.58	32.60	37.22
03:10:91	3.58	32.97	35.79
03:19:91	3.58	32.97	36.94
04:16:91	3.64	32.60	36.94
04:21:91	3.64	32.60	36.94
04:28:91	3.53	33.33	37.22
05:07:91	3.50	33.33	37.22

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 6564

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	2.62	7.31	43.18
05:21:90	2.41	7.31	42.71
06:03:90	2.32	7.31	42.71
06:07:90	2.27	7.31	42.71
06:12:90	2.21	7.31	42.71
06:18:90	2.23	7.31	41.74
06:24:90	2.30	6.54	41.74
07:27:90	2.32	6.34	41.74
08:06:90	2.86	7.13	42.23
08:21:90	2.51	7.20	42.23
10:06:90	2.66	16.98	41.25
11:09:90	2.60	18.25	41.25
02:28:91	2.66	17.76	41.25
03:10:91	2.59	18.27	41.25
03:19:91	2.72	18.27	40.75
04:16:91	2.59	18.77	41.74
04:21:91	2.59	18.77	41.74
04:28:91	2.73	15.66	41.74
05:07:91	2.73	15.66	41.74

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 6120

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	4.19	40.99	28.20
05:21:90	4.23	39.85	28.84
06:03:90	4.36	39.08	27.55
06:07:90	4.32	38.29	26.90
06:12:90	4.32	37.49	27.88
06:18:90	4.29	38.08	28.20
06:24:90	4.34	38.14	27.88
07:27:90	4.43	38.02	27.88
08:06:90	4.43	38.29	27.55
08:21:90	4.47	38.02	27.55
10:06:90	4.55	37.76	27.23
11:09:90	4.54	37.69	27.23
02:28:91	4.55	36.80	27.06
03:10:91	4.59	36.27	27.40
03:19:91	4.53	36.27	27.06
04:16:91	4.57	36.54	27.06
04:21:91	4.53	36.54	27.06
04:28:91	4.57	36.80	27.06
05:07:91	4.53	36.80	27.38

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 5944

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	2.80	45.62	52.71
05:21:90	3.37	45.62	35.39
06:03:90	3.52	45.00	33.27
06:07:90	3.74	38.24	33.02
06:12:90	3.79	36.87	32.52
06:18:90	3.79	36.65	32.94
06:24:90	3.76	36.94	33.69
07:27:90	3.87	36.43	32.52
08:06:90	3.92	36.00	32.77
08:21:90	3.86	36.29	32.26
10:06:90	3.99	35.92	31.85
11:09:90	3.89	36.21	32.36
02:28:91	3.82	36.43	31.94
03:10:91	3.79	36.43	32.20
03:19:91	3.87	35.71	32.20
04:16:91	3.87	36.00	31.47
04:21:91	3.87	36.00	31.47
04:28:91	3.92	36.00	31.26
05:07:91	3.89	36.00	31.26

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 5845

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	4.51	34.57	24.84
05:21:90	4.59	32.35	24.30
06:03:90	4.50	32.56	25.07
06:07:90	4.50	32.05	23.75
06:12:90	4.58	32.71	22.59
06:18:90	4.52	32.71	22.65
06:24:90	4.58	32.38	21.58
07:27:90	4.73	31.63	20.09
08:06:90	4.83	31.76	22.10
08:21:90	4.79	30.10	21.88
10:06:90	4.89	29.26	21.21
11:09:90	4.93	29.26	21.21
02:28:91	4.83	29.61	20.70
03:10:91	4.90	29.61	20.42
03:19:91	4.90	29.61	20.65
04:16:91	4.90	29.92	21.01
04:21:91	4.85	30.23	21.51
04:28:91	4.91	29.92	20.87
05:07:91	4.87	30.23	21.23

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 5746

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	4.14	35.54	35.95
05:21:90	4.20	33.95	36.77
06:03:90	4.19	34.91	36.77
06:07:90	4.12	34.25	35.95
06:12:90	4.17	32.11	37.96
06:18:90	4.20	32.51	36.28
06:24:90	4.26	32.25	35.07
07:27:90	4.36	31.86	34.66
08:06:90	4.36	31.86	34.66
08:21:90	4.49	31.45	30.58
10:06:90	4.38	31.61	33.55
11:09:90	4.55	31.86	29.19
02:28:91	4.48	32.51	30.72
03:10:91	4.53	32.11	29.01
03:19:91	4.49	31.86	30.19
04:16:91	4.55	32.11	29.36
04:21:91	4.50	32.11	29.74
04:28:91	4.45	32.51	30.13
05:07:91	4.50	32.51	29.74

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 5654

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	4.22	34.09	25.66
05:21:90	3.95	37.01	25.66
06:03:90	4.02	37.01	25.66
06:07:90	3.83	35.87	23.81
06:12:90	3.89	37.01	25.20
06:18:90	3.89	36.44	25.66
06:24:90	3.92	35.87	24.78
07:27:90	4.02	34.70	25.20
08:06:90	3.83	35.87	23.91
08:21:90	3.66	37.01	23.91
10:06:90	3.83	35.87	23.46
11:09:90	3.83	35.29	23.46
02:28:91	3.89	34.70	24.36
03:10:91	3.89	35.87	24.81
03:19:91	3.89	35.29	24.36
04:16:91	3.95	35.29	24.36
04:21:91	3.95	35.29	24.36
04:28:91	3.89	37.01	24.81
05:07:91	3.89	37.01	25.25

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 5347

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	2.25	53.13	52.31
05:21:90	2.23	53.53	51.01
06:03:90	2.23	53.92	51.88
06:07:90	2.33	53.13	50.56
06:12:90	2.36	53.53	50.56
06:18:90	2.30	53.53	51.01
06:24:90	2.25	53.13	50.56
07:27:90	2.37	53.53	49.09
08:06:90	2.42	53.13	48.95
08:21:90	2.36	52.72	48.48
10:06:90	2.44	52.72	47.45
11:09:90	2.38	52.72	50.10
02:28:91	2.30	53.13	50.10
03:10:91	2.30	52.31	50.10
03:19:91	2.35	52.31	48.54
04:16:91	2.38	52.72	48.54
04:21:91	2.38	53.13	49.01
04:28:91	2.35	53.13	54.75
05:07:91	2.38	53.13	54.75

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 5248

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	2.84	59.74	40.36
05:21:90	2.81	60.04	38.55
06:03:90	2.92	55.11	37.57
06:07:90	2.81	61.43	39.90
06:12:90	2.85	58.83	38.35
06:18:90	2.85	61.70	37.28
06:24:90	2.93	61.43	37.28
07:27:90	2.84	59.74	36.47
08:06:90	3.01	53.81	35.69
08:21:90	3.11	53.46	35.93
10:06:90	3.11	52.13	35.93
11:09:90	3.11	51.43	35.38
02:28:91	3.09	52.47	35.78
03:10:91	3.14	52.22	35.38
03:19:91	3.19	51.78	35.38
04:16:91	3.18	52.22	34.82
04:21:91	3.19	52.22	34.99
04:28:91	3.27	54.28	34.44
05:07:91	3.27	54.28	34.44

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 4423

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	2.72	58.30	42.54
05:21:90	3.26	42.29	42.86
06:03:90	3.20	44.20	42.21
06:07:90	3.27	44.20	42.54
06:12:90	3.27	43.24	42.21
06:18:90	3.38	41.24	42.21
06:24:90	3.38	41.63	42.21
07:27:90	3.44	40.43	42.21
08:06:90	3.46	40.22	41.89
08:21:90	3.46	41.81	41.89
10:06:90	3.46	41.61	41.56
11:09:90	3.48	41.61	41.23
02:28:91	3.50	41.77	42.21
03:10:91	3.48	41.59	41.56
03:19:91	3.47	41.59	41.86
04:16:91	3.45	41.21	41.86
04:21:91	3.43	41.36	41.86
04:28:91	3.45	42.01	41.52
05:07:91	3.49	41.14	41.19

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 4322

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	3.23	37.97	32.98
05:21:90	3.25	37.68	33.89
06:03:90	3.30	37.68	32.67
06:07:90	3.30	37.68	32.67
06:12:90	3.27	37.68	33.28
06:18:90	3.30	39.39	32.36
06:24:90	3.23	39.39	32.67
07:27:90	3.38	39.81	32.98
08:06:90	3.38	35.84	33.59
08:21:90	3.38	39.54	32.98
10:06:90	3.34	38.94	31.85
11:09:90	3.41	39.39	31.85
02:28:91	3.46	39.67	31.09
03:10:91	3.46	39.67	32.36
03:19:91	3.44	39.11	31.53
04:16:91	3.44	39.11	31.53
04:21:91	3.41	38.83	31.22
04:28:91	3.32	38.83	31.85
05:07:91	3.35	39.67	32.16

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 4231

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	2.51	56.42	48.01
05:21:90	2.54	55.65	46.33
06:03:90	2.53	55.20	47.34
06:07:90	2.56	54.46	47.00
06:12:90	2.56	54.46	47.00
06:18:90	2.56	54.00	47.00
06:24:90	2.59	54.46	46.66
07:27:90	2.61	53.45	46.01
08:06:90	2.63	53.45	46.35
08:21:90	2.67	53.68	46.67
10:06:90	2.68	53.13	47.00
11:09:90	2.67	53.68	46.67
02:28:91	2.62	55.11	46.67
03:10:91	2.60	55.11	46.67
03:19:91	2.61	54.98	47.02
04:16:91	2.59	54.74	47.34
04:21:91	2.61	54.98	47.34
04:28:91	2.66	52.59	47.34
05:07:91	2.72	53.05	47.34

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 4135

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	1.93	47.16	53.43
05:21:90	1.99	48.18	53.86
06:03:90	2.06	48.95	55.53
06:07:90	2.03	49.01	55.12
06:12:90	1.97	49.47	55.12
06:18:90	1.97	49.93	55.12
06:24:90	2.07	49.93	55.12
07:27:90	1.98	49.40	54.71
08:06:90	1.94	48.95	54.71
08:21:90	1.92	48.48	52.98
10:06:90	1.97	48.88	52.25
11:09:90	2.03	48.42	51.80
02:28:91	2.12	49.33	50.10
03:10:91	2.16	48.42	47.49
03:19:91	2.08	47.96	47.96
04:16:91	2.08	48.42	47.96
04:21:91	2.19	47.96	47.96
04:28:91	2.00	48.42	47.96
05:07:91	1.98	48.88	48.42

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 4037

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	2.18	66.67	46.27
05:21:90	2.09	66.25	46.27
06:03:90	2.09	65.82	46.27
06:07:90	2.00	66.25	47.49
06:12:90	1.92	66.25	47.49
06:18:90	1.85	64.44	48.65
06:24:90	1.92	63.43	47.49
07:27:90	1.89	62.90	42.51
08:06:90	1.82	62.35	41.50
08:21:90	1.86	58.24	41.50
10:06:90	1.95	58.84	40.43
11:09:90	1.87	62.35	41.63
02:28:91	1.78	62.90	39.17
03:10:91	1.84	61.19	46.04
03:19:91	1.78	62.90	43.92
04:16:91	1.78	62.90	43.92
04:21:91	1.78	61.78	46.04
04:28:91	1.69	61.19	45.00
05:07:91	1.66	62.35	46.04

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 3332

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	2.13	45.00	60.69
05:21:90	2.17	46.74	60.26
06:03:90	2.06	45.00	60.26
06:07:90	2.10	45.00	60.26
06:12:90	2.26	45.83	53.13
06:18:90	2.32	45.00	50.71
06:24:90	2.30	45.78	50.19
07:27:90	2.56	42.58	50.19
08:06:90	2.43	43.41	50.19
08:21:90	2.35	41.91	50.19
10:06:90	2.37	44.22	49.04
11:09:90	2.47	47.23	47.89
02:28:91	2.39	46.55	49.04
03:10:91	2.45	43.41	48.50
03:19:91	2.45	45.76	48.50
04:16:91	2.45	43.41	48.50
04:21:91	2.45	44.22	48.50
04:28:91	2.30	47.23	48.50
05:07:91	2.26	46.51	48.50

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 3024

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	2.42	46.82	42.84
05:21:90	2.44	46.82	43.94
06:03:90	2.66	45.92	42.27
06:07:90	2.63	45.47	42.84
06:12:90	2.66	45.47	44.47
06:18:90	2.69	45.00	42.84
06:24:90	2.73	45.00	41.82
07:27:90	2.42	45.00	44.45
08:06:90	2.44	45.92	42.27
08:21:90	2.39	45.47	42.84
10:06:90	2.68	42.32	43.33
11:09:90	2.67	42.27	42.75
02:28:91	2.70	42.27	42.75
03:10:91	2.68	41.85	42.75
03:19:91	2.66	42.71	42.75
04:16:91	2.57	42.23	42.75
04:21:91	2.57	41.74	42.75
04:28:91	2.66	43.65	42.75
05:07:91	2.57	42.23	43.33

WIDTH/DEPTH RATIO AND BANK SLOPE OF TRANSECT NUMBER 2829

DATE	W/D RATIO	WEST SLOPE (DEG.)	EAST SLOPE (DEG.)
05:12:90	3.45	39.81	32.68
05:21:90	3.45	39.81	35.64
06:03:90	3.06	43.92	37.04
06:07:90	3.15	41.04	36.35
06:12:90	3.10	42.22	39.05
06:18:90	3.09	39.91	37.87
06:24:90	3.04	39.29	35.84
07:27:90	2.97	38.78	35.84
08:06:90	3.10	39.40	35.84
08:21:90	2.82	39.40	35.84
10:06:90	3.01	39.40	35.84
11:09:90	3.06	38.78	35.84
02:28:91	3.09	40.52	36.53
03:10:91	3.09	39.40	36.35
03:19:91	3.10	39.40	35.84
04:16:91	3.10	39.40	35.13
04:21:91	3.10	39.40	36.53
04:28:91	2.86	40.01	35.13
05:07:91	2.82	40.01	36.53