THE UNIVERSITY OF MANITOBA

SOME MORPHOMETRIC PROPERTIES AND EROSION RATES OF GULLIES ALONG A PORTION OF THE MANITOBA ESCARPMENT

by

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ABSTRACT

Continuous gullies located on steep slopes along the Manitoba Escarpment were classified; the gully morphology was analyzed, and rates of gully erosion were calculated. Four of the gullies are classified as Stage 2 of gully development, and two gullies are classified as Stage 3. Five of the gullies are linear, and one gully is classified as parallel. The gully heads are classified as inclined-pointed, although one gully head could conceivably be classified as inclined-rounded. The gullies are in a youthful stage of development.

Morphometric analysis revealed the gullies to be wider than they are deep, the north facing gully side is steeper than the south facing gully side, and the gully cross-sections are rectangular in shape. Gully cross-sections are rectangular in shape. Gully width and gully depth are related to the percentage of silt-clay within the surface material. The percentage of silt-clay is regarded as an indicator of the surface material's susceptibility to gully erosion. Much of the available energy for gully erosion was used to deepen rather than to widen the gully channel.

Summer rainfall removed 23.8 times more material from the gullies than snowmelt runoff. Infrequent intense summer precipitation is identified as the major gully eroding agent. Soil freeze-thaw processes and the gully drainage basin snowmelt runoff had a tendency to add sediment to the gully channels during the 1974 spring snowmelt period.

Those areas along the portion of the Manitoba Escarpment studied which are most susceptible to gully erosion are characterized as having steep slopes, large drainage basins, and containing surface materials having high percentages of silt-clay. It is recommended that

revegetation and gully segregation methods be implemented to reduce and eventually stabilize gully erosion.

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INTRODUCTION

The clearing and cultivation of agricultural land on some of the steep slopes along the Manitoba Escarpment has resulted in severe water erosion. This process of erosion is particularly evident by the extent of well-developed, numerous gully systems found along portions of these steep slopes. If left unchecked, the incidence of gullying would certainly increase, resulting in flooding of the better agricultural land at the base of the Manitoba Escarpment and silting up of ditches and natural drainageways.

The aim of this thesis is to explain the morphology of these erosional features, measure the rates of gully erosion, and to identify those human and environmental factors contributing to gully development. With a better understanding of gully erosion within one particular portion of the Manitoba Escarpment, it is hoped that soil conservation and water management methods could be effectively employed to improve present land utilization within other similar areas along the Manitoba Escarpment.

CHAPTER I

The Field Area

1. Location of Field Area

A total of 6 gullies were selected for this study. The gullies are located 12 miles northwest of Neepawa within the Municipality of Rosedale. Five of the gullies are located 5 miles west of the Town of Eden, while the remaining gully is located 7 miles west of Eden. The gullies are accessible from Provincial Highway 5, via the use of Provincial Road 265 (see Figure 1.1).

Names were assigned to each gully as follows: Roadside Gully; Eden Farm Gully 1; Eden Farm Gully 2; Rosedale Gully 1; and Rosedale Gully 2 (all are located in Section 23, Township 16, West of Principal Meridian). The remaining gully, the Polonia Gully, is located in Section 21, Township 16, Range 16, West of Principal Meridian.

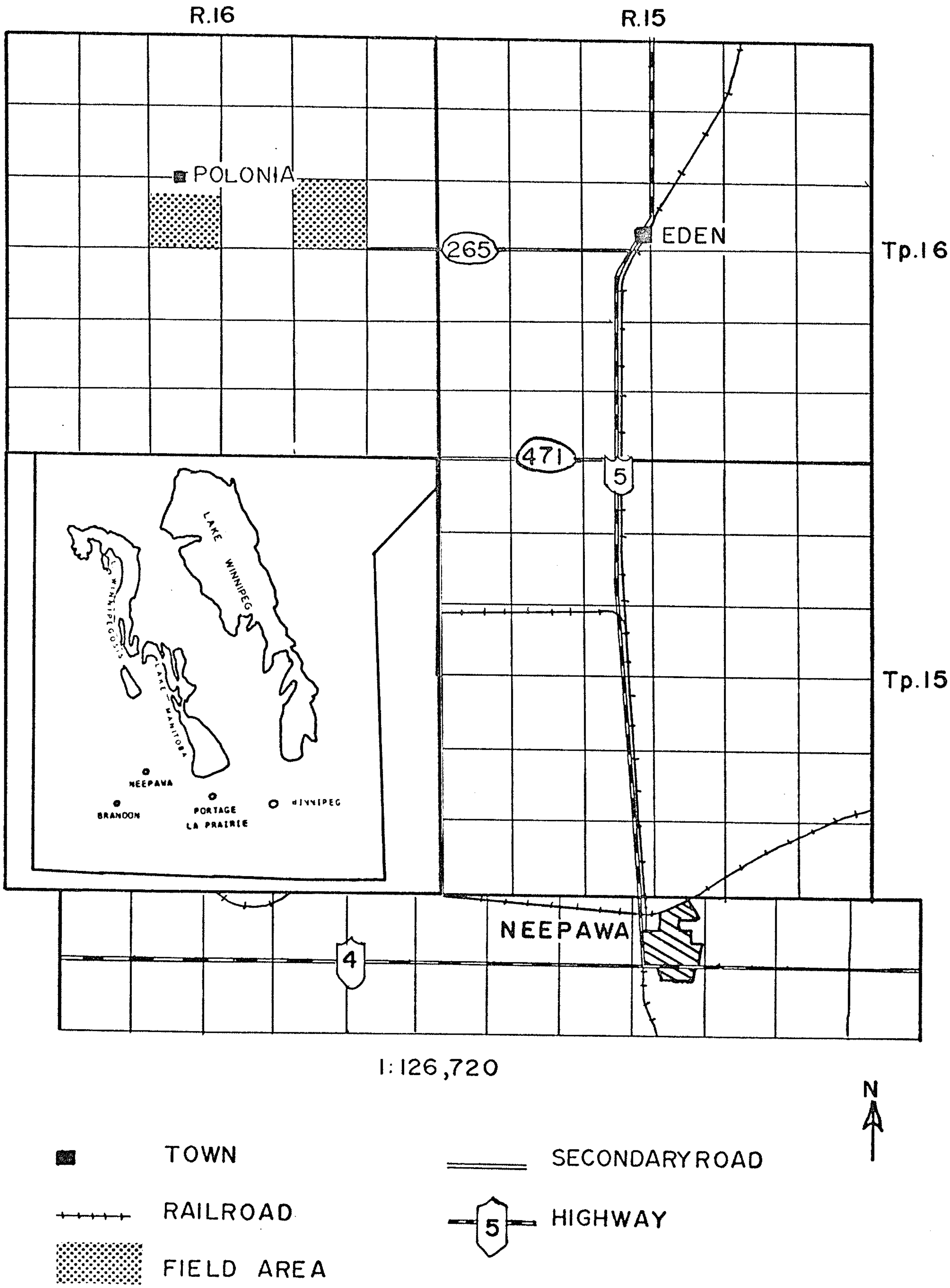
The elevation of the field area ranges from 1875 feet A.S.L. to 2125 feet A.S.L. The elevation of each gully, defined by the contour line through which each gully crosses, is as follows: Eden Farm Gully 1 and Eden Farm Gully 2 are 1875 feet A.S.L.; the Roadside Gully is 1900 feet A.S.L.; Rosedale Gully 1 and Rosedale Gully 2 are 1975 feet A.S.L.; and the Polonia Gully is 2125 feet A.S.L.

2. The Bedrock Geology of the Field Area

The Manitoba Escarpment is comprised of shales of the Riding Mountain Formation. These Cretaceous Period shales are overlain by both glacial and postglacial deposits. The shales are often found close to the surface along intermittent streams, deeply incised valleys, and roadcuts.

The Riding Mountain Formation is composed of two main shale

FIGURE 1.1


R.16
R.15
POLONIA
EDEN
265
Tp.16
471
5
LAKE WINNIPEG
WINNIPEGOSIS
LAKE MANITOBA
NEEPAWA
BRANDON
PORTAGE LA PRAIRIE
WINNIPEG
Tp.15
NEEPAWA
4
1:126,720
N
TOWN
SECONDARY ROAD
RAILROAD
5
HIGHWAY
FIELD AREA

members. The upper member is the hard, grey, siliceous, Odanah Shales. The lower member is the soft, greenish brown, bentonitic, Millwood Shales. The entire field area is underlain by the Odanah Shale Member. This shale occurs as thin, horizontal fissile beds and tends to break with a characteristic subconchoidal fracture.

3. Pleistocene Geology

During the Wisconsinan glaciation, there were two regional centers of ice accumulation for the ice sheets which covered Manitoba. The Keewatin ice sheet was centered in the Northwest Territories, west of Hudson Bay from which the ice flowed south, and the Patrician ice sheet was centered southwest of James Bay from which the ice spread towards the southwest. From these two centers the ice advanced across Manitoba.

The Keewatin ice sheet spread south along the west coast of Hudson Bay as far as Churchill, swung southwest towards The Pas, and then advanced southeast along the base of and on top of the Manitoba Escarpment (Davies, et al. 1962, p. 151). The Patrician ice sheet moved in a southwestward direction covering the area between the Nelson River and the International Boundary, and extended as far west as Lake Winnipeg. During the maximum advance, the Keewatin ice sheet extended into Iowa, and the Patrician ice sheet covered an area between the Great Lakes, Lake Winnipeg, and Hudson Bay. It is thought that the Assiniboine sublobe of the Keewatin ice sheet retreated from the Riding Mountain area 13,000 years ago (MacKay, 1970, p. 7) or 14,000 years ago (Klassen, 1972, p. 553).

The Manitoba Escarpment is underlain by various shales, sandstones, and evaporites, of the Cretaceous and Jurassic periods. To the north and east of the Escarpment are limestones and dolostones of the Devonian, Silurian, and Ordovician periods, as well as Precambrian granitic rocks. As the Keewatin ice sheet moved in its southerly direction, all these bedrock formations contributed materials to the present surface deposits.

When the Assiniboine sublobe of the Keewatin ice sheet downwasted, an ice-stagnation landform known as the Newdale Till Plain covered the Manitoba Escarpment. The Newdale Till Plain is composed predominantly of ground moraine deposits, although there are areas of end moraines, glacial outwash, and occasional eskers on the Escarpment.

The field area is located on a vast end moraine deposit (Klassen, 1972) and is described by Ehrlich, et al. (1958) as boulder till. It is a medium textured till of shale, limestone, and granitic rocks. The texture is predominantly unsorted fine sand to clay loam with moderate amounts of gravels and boulders. The topography of this end moraine deposit is characterized by low knolls and depressions.

4. Climate

In accordance with the Köppen-Geiger system of climatic classification, the field area has a "Dfb type" of climate, defined as a humid continental, cool summer climate. This climate designates the field area as having sufficient heat and sufficient precipitation for the growth of high-trunked trees; sufficient precipitation in all months; the warmest month with mean temperatures under 71.6^{o}F; and with at least four months having mean temperatures over 50^{o}F (Strahler, 1965, Plate 2).

Ehrlich, et al. (1958) designate the field area as subhumid with a definite summer maximum of precipitation. Approximately 80 per cent of the yearly precipitation falls as summer rainfall, while the remainder is accounted for by winter snowfall. The mean annual precipitation based upon 26 years of observations from the Neepawa Weather Station is 19.43 inches, with a standard deviation of 3.85 inches. Because the Neepawa Weather Station is the closest weather station, only 12 miles south of the field area, the Neepawa precipitation data is used as being representative of the precipitation falling upon the field area.

The mean monthly temperature of 33.9°F was taken from 69 years of observations from the Minnedosa Weather Station (Ehrlich, et al. 1958 p. 25). The Minnedosa Weather Station is the second closest weather station, being 15 miles southwest of the field area. The mean monthly temperature of 33.9°F is considered to be representative of the true mean monthly temperatures of the field area.

The potential evapotranspiration for the field area is approximately 21.65 inches per year (Weir, 1960, p. 19). The average moisture deficit, defined as the difference between water need and precipitation for those months having a deficit for an average year, ranges from 2.95 inches to 3.94 inches per year (Weir, 1960, p. 19). The frost free period for the field area ranges from 90-100 days per year, and the vegetation growing season is within the range of 170-180 days per year (Ehrlich, et al. 1958, p. 24).

5. Soils

The present day soils have developed upon the ground moraine deposits of the Newdale Till Plain. The field area is located on the medium textured tills in which the dominant soil is a grey wooded soil. Three soil associations: the Granville; the Clarksville; and the Wapus associations cover the field area.

The Polonia Gully is situated in medium textured till and is part of the Granville Soil Association. The Granville Association is a very fine sandy loam to clay loam soil, developed on ground moraine consisting of mixed limestone, shale, and granitic rock. These soils have a moderate degree of natural fertility. Because of the sloping topography within the Granville Association, erosion by water is a serious problem.

The Eden Farm Gullies 1 and 2, and the Roadside Gully, are situated in soils of the Clarksville Association. The Clarksville Association has developed upon a till with a texture of fine sandy loam to loam, that is predominantly of shale origin. The topography of the Clarksville Association is irregular gently sloping to hilly, with an overall slope to the east.

Rosedale Gullies 1 and 2 are situated in the Wapus Association, a soil which has developed on thin shale drift deposits over shale bedrock. This soil is described as fine sandy loam and silt loam. The Wapus Association soils have a low natural fertility, and are very susceptible to wind and water erosion, especially on the steeper slopes.

All the gullies in this study have developed on sandy loam soils. The 1958 soils survey by Ehrlich, et al. (1958) recommends that the clearing and cultivation of these soils should be discouraged. The soil survey states that clearing and cultivation of these soils results in severe water erosion on the steeper slopes, eventually resulting in an increased flood potential on the better agricultural land at the base of the Manitoba Escarpment.

A more detailed analysis of the surface deposits associated with each of the gullies is presented in Table 1.1. This data was compiled by the author after field collection and laboratory analysis of

TABLE 1.1

SOIL ANALYSIS

Gully	Per Cent Gravel	Per Cent Sand	Per Cent Silt-Clay	Color Based on Munsell Color Chart	Description
Polonia	6	82	12	2.5Y6/4 light yellowish brown	carbonate rich till, non compact, friable when dry
Roadside	22	69	8	10YR6/3 pale brown	shale rich till, non compact, friable when dry
Rosedale					
Gully 1 and Gully 2	42	57	1	10YR5/4 yellowish brown	shale and carbonate till, non compact, friable when dry
Eden Farm					
Gully 1	38	58	4	10YR7/2 light grey	shale rich till, non compact, friable when dry
Gully 2	20	72	8	10YR7/2 light grey	shale rich till, non compact, friable when dry

the soil samples.

6. Vegetation

The native vegetation found within the field area is predominantly aspen, with undergrowths of hazel, wild rose, saskatoon and chokecherry. This native vegetation is restricted to deep ravines, swampy land, and shelterbelts around the farmsteads.

All of the gullies have developed on farmland, which may be described as improved pasture. Agricultural land which is too steep to allow cultivation has been retained in natural grasses and used as improved pasture. The two Rosedale Gullies are the only gullies presently not located upon improved pasture. Since 1946 and until 1967 the land on which the Rosedale Gullies are located had been improved pasture. In 1967, the Water Resources Branch of the Department of Mines and Natural Resources purchased the northeast, northwest, and southwest quarter sections of Section 23, Township 16, Range 16, West of Principal Meridian. The rapid movement of water across these quarter sections of land had resulted in a loss of topsoil, low productivity, and the devaluation of the farmland. The Manitoba Government's aim in purchasing this land was to plant trees and forage crops to retard future erosion, and to demonstrate to local farmers some of the advantages to be gained from proper land utilization.

Reforestation of the quarter sections was begun in 1967 and completed in 1973. A total of 188,800 trees of various species have been planted to date. The two Rosedale Gullies are located in an area of Jack Pine planted in 1968. The Jack Pine have a density of 1740 per acre, planted in rows having a 5 foot by 5 foot spacing. (1)

The two Rosedale Gullies appear on the 1964 aerial photographs and thus the gullies were present prior to the reforestation project.

7. History of Settlement

Pioneer agricultural settlement began in this western portion of Manitoba in the late nineteenth century. Settlement proceeded northward from Portage La Prairie via the North or Ellice Trail, with the best agricultural land being settled adjacent to this trail. By 1877 the towns of Neepawa and Eden had their beginning as the Ellice Trail extended farther northward.

When the railway reached Neepawa in 1883, only the marginal land along the eastern slopes of the Manitoba Escarpment remained unsettled, new homesteads were started at the base of the Escarpment.

All of Section 23, Township 16, Range 16, West was first settled in 1893. Thus the Eden Farm Gullies, the Rosedale Gullies, and the Roadside Gully, are situated on land first settled in 1893. The site of the Polonia Gully was settled in 1881. (2)

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CHAPTER II

The Process of Gullying

1. Definition and Classification of Gullies

Gullying may be regarded as an advanced and destructive form of soil erosion. Furthermore, in some watersheds it is an important source of sediment in river catchments resulting in impaired water quality. Peterson (1950, p.407) defines gullies as "any erosion channel so deep that it cannot be crossed by a wheeled vehicle or eliminated by plowing". Peterson further states that gullying has usually been considered as "culturally accelerated erosion", that is, man induced erosion features through some form of land misuse. Butzer (1974, p.61) emphasizes the headward advance characteristic of some gullies, and defines gullying as "the rapid and catastrophic erosion of all soil horizons by deep channels that eat back from permanent drainage lines. Gullies deepen, widen and cut headward after each rainstorm, mainly in unconsolidated parent materials. Headward erosion in silts may be aided by subsurface piping." Prehistoric gullies have been identified by Tuan (1966) resulting in a shift of attention to possible past climatic causes of gullies.

Rills are often identified as gullies. A single rill may become a gully, or, by a coalescence of rills, larger flows may come into existence and result in gully erosion. Lueder (1959) differentiates these two erosion features in terms of their visibility on aerial photographs and are important erosion features.

Whatever the cause, man induced or climatic, gullying is an advanced and destructive form of soil erosion. This author accepts the definition of a gully as an erosional channel large enough in scale to

Gully erosion penetrates the weak C horizon. This

be visible on aerial photographs, and deep enough to constitute a hindrance to land cultivation.

Gullies have been classified as being continuous or discontinuous (Heede, 1974, and Leopold, et al. 1964). Continuous gullies begin their downstream course as many small rills. The continuous gully starts well up on the hillside and the channel continues down to the main valley. The discontinuous gully starts with an abrupt headcut, with the headcut located at any position on the hillslope. The gully depth rapidly decreases downslope developing a bottom gradient much gentler than that of the original valley floor. The discontinuous gully is characterized by pronounced changes in the channel slope, or knickpoints. Mosley (1972) has described in detail the evolution of the discontinuous gully from an initial break in the vegetation cover.

Heede (1974) and Leopold, et al. (1964) believe the discontinuous gully represents a youthful stage of gully development. Changes in headward extension, gully width, and thalweg slope, result in the fusion of the discontinuous gully into a continuous gully, designated as the early mature stage. The disappearance of the knickpoints indicates that the gully has obtained its equilibrium slope, although this stage may include other aspects of stability such as channel vegetation.

Lueder (1959) attempted to predict those probable characteristics that are associated with young gullies based upon the soil characteristics of the surface material. It is the author's opinion that the Lueder classification is inadequate because it is too general and too variable. A more detailed classification is presented by Ireland, et al. (1939) who described 4 stages of gully development in South Carolina. As specified by these authors, the 4 stages of gully development are as follows:

Stage 1: The first stage involves a channel cut through the upper portion of the B horizon.

Stage 2: Stage 2 is the most violent stage of gully growth. Gully erosion penetrates the weak C horizon. This stage is characterized by upslope migration of the overhanging gully head, rapid deepening of the gully channel, and active caving of the gully head.

Stage 3: This is a period of gully readjustment. Weathering, slope wash, and mass movement, tends to remodel the gully side slope into more gentle slopes with talus accumulations at the base.

Stage 4: The last stage in gully development is characterized by the establishment of vegetation, with the attainment of gully stabilization.

Ireland, et al. (1939) point out that in large or old gullies all 4 of the above stages may simultaneously be present in different parts of the gully.

Ireland, et al. (1939) also classified the form of the gully, suggesting that the terms used are morphologically descriptive of the system. The following is their classification of gully form as summarized by Bertrand, and Woodburn (1964, p. 174):

A	Linear:	long and narrow.
B	Bulbous:	broad and spatualte at the upper end, but may be linear in the downstream portion.
C	Dendritic:	formed of many branching tributaries.
D	Trellis:	tributary gullies or branches enter the main channels at angles approaching 90 degrees.
E	Parallel:	composed of two or more parallel tributaries that empty into a main stem.
F	Compound:	combinations of any two or more gully forms.

According to the vertical profile and the rim outline, Ireland, et al. (1939, p.57) also classified the form of the gully heads. This classification is presented in Figure 2.1.

The Ireland, et al. (1939) gully classification system is the most detailed, morphologically descriptive, and most often used classification. The gullies in this thesis shall be classified in accordance with their classification, and the stage of gully development will also be identified.

2. Environmental and Human Factors

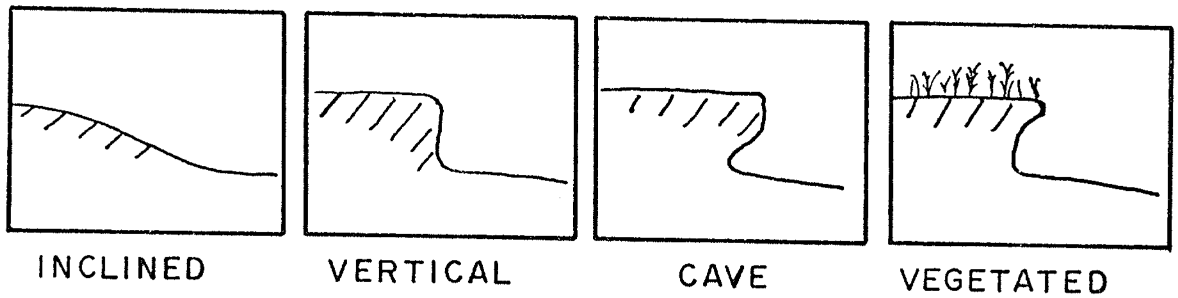
Both environmental and human factors are responsible for the initiation and development of gullies. The causes of gullying are variable, and there is no one cause which is applicable to all gullies. This section shall be brief and mention only those major causes of gullying.

Daniels and Jordan (1966) examined gullies in Iowa and found that approximately 50 per cent of the gullies are located along field boundaries, farm lanes, fence rows, and cattle trails; and 50 per cent are in channels of valley-slope drainageways. From their example, it is clear that both man and natural conditions are comparably responsible for the development of gullies in Iowa.

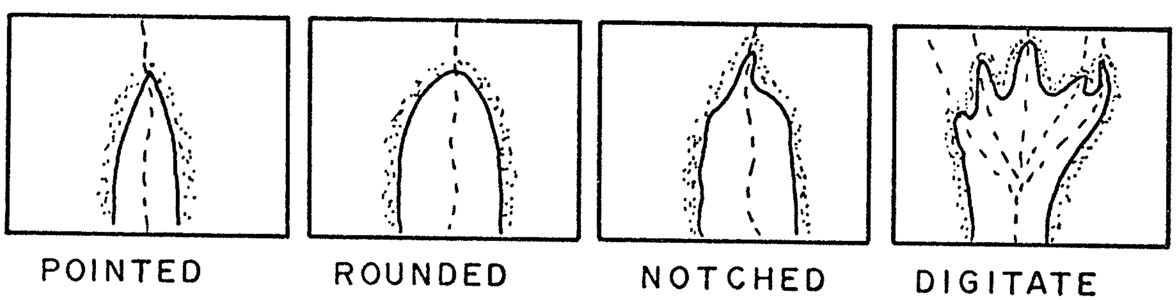
Whenever the natural protection of the land is destroyed, the soil is made more vulnerable to erosion. Whether the vegetative cover is destroyed by man or by natural conditions, the underlying soil is subject to those environmental conditions responsible for soil erosion. Mosley (1972) illustrates how incipient erosion begins from the initial break in vegetation. Once a small depression from an initial break in the vegetation has formed, both wind and water act to extend the depression. In the early stages of gully development, overland flow lifts

FIGURE 2.1

VERTICAL GULLY HEAD PROFILE



GULLY HEAD RIM OUTLINE



IRELAND, ET AL. (1939, p.57)

and carries out sediment from the depression during periods of intense runoff. As the depression develops, material is removed by overland flow from around the edges of the depression, and steep headwalls are formed. The material removed from this incipient basin is redeposited in the center of the basin where the overland flow has been ponded and loses velocity. This fine redeposited material is now susceptible to deflation once the surface has dried, and is removed by frequent strong winds. Runoff from occasional heavy rainstorms causes headward migration by erosion and slumping of the vertical headwalls, and deflation continues to deepen the basin. As the basins extend headward, they coalesce and form discontinuous gullies. Flowing water then becomes the predominant erosive agent as water flows throughout the gully system.

Ireland, et al. (1939) state several climatic causes of gullying. The range of temperature, the intensity and seasonal distribution of precipitation, the variations in humidity and wind, all control: the operation and effectiveness of rock disintegration; the rate of surface runoff; the regime of streams; frost and ice action; and the rate and extent of mass movement of the soils. These climatic induced factors in association with steep slopes and different soil types are conducive to gullying.

Man's activities are the most easily recognized causes of gullying. The clearing of land for cultivation removes the protective canopy of vegetation. Associated with land clearing is the raising of livestock, frequently compounded by overgrazing, making the land more vulnerable to erosion by reducing the quantity and quality of the vegetative cover. The result is a sparse plant cover poorly adapted to absorbing rainfall and slowing the runoff.

Man-made changes in the natural drainage of lands produce unwise concentrations of flowing water. Livestock trails, farm tracks and roads, plow furrows, or poorly sited and designed drains, all tend to concentrate channel flow as well as increase runoff from bare surfaces. The cultivation of steep slopes has a tendency to increase the rate of runoff and increase soil erosion.

Generally, improper land use practices together with overgrazing have been responsible for the initiation of gullies. Mosley (1972, p.658) notes that a change in rainfall intensities and overgrazing are accepted as being responsible for gully erosion in the west and southwest of the United States. Man's activities are usually responsible for gully initiation, while climatic or other environmental factors are responsible for the growth of gullies.

3. Gully Morphology

Heede (1970, p.79) expressed the importance of gully morphology, "Understanding the morphology of gullies is the first step in evaluating gully processes. Such an evaluation, in turn, makes projections of future gully behavior possible since gully morphology can be interpreted as the product of gully processes." Thus gully morphology may aid land managers in evaluating past, present, and possible future gully developments. Unfortunately, past studies of gullies have been primarily concerned with erosion rates of gullies rather than the investigation of gully morphology.

In a study of Colorado gullies in 1970, Heede used regression analysis on gully morphometric properties. In this study Heede found that the discontinuous and continuous gullies are really not two different gully types, but rather they are only stages in gully development. His evidence based upon gully morphology was not, however, entirely conclusive.

Heede (1970) used the gully shape factor to express the stage of gully development. The shape factor relates the maximum to the mean gully depth, and this ratio expresses the channel shape. Heede (1970, p. 86) defines the gully shape factor as the maximum gully depth divided by the mean gully depth, where the mean gully depth is the gully cross-sectional area divided by the bankful gully channel width. If the shape is considered as a geometric figure, a triangular channel has a shape factor of 2, a parabolic channel has a shape factor of 1.5, and a rectangular channel has a shape factor of 1.0. Of all the geometric figures, the semi-circular shape would constitute the channel with the most efficient cross-section because for a given cross-section it has the smallest wetted perimeter. Hence such a gully would discharge more water than any other gully shape. The semicircular shape does not occur in nature. The parabolic shape is the shape most resembling the semicircular shape as it is found in nature. Heede studied a total of 15 gullies and the lowest shape factor was 1.7 for only one gully. For his study, it meant that nearly all the gullies had relatively inefficient cross-sections, and that this may have been an expression of the youthful stage of the channel.

Two studies in particular, have related watershed variables to the rate of gully erosion. Beer and Johnson (1965) found a logarithmic relationship between gully processes and morphometric properties. They found that the change in gully surface area (erosion) was due to the deviation of precipitation from the normal, an index of surface runoff, the area of the watershed, the gully length, and the length from the gully to the watershed divide. Similarly, Thompson (1964) found the rate of gully head advancement was dependent upon drainage area, precipitation, and the soil clay content. Ireland, et al. (1939) found that the drainage area alone does not control the rate of gully erosion. In their view the slope of the drainage basin is a vital factor which controls the rate of erosion.

Heginbottom (1967) used a total of 16 variables of gully morphometry and with the use of correlational analysis attempted to differentiate "Upland and Lowland" gullies found on different soil types north of Montreal. Based on gully morphology, he found no real evidence that more than one population of gullies was involved.

Few studies have dealt with gully morphology. By understanding gully morphology, insight into gully processes may be gained. The stage of gully evolution may be related to the gully shape factor. Beer and Johnson (1965) and Thompson (1964) agree that the gully erosion rate is a function of precipitation and drainage basin area, while Ireland, et al. (1939) believe the slope of the drainage basin to be more important than the drainage basin area. Thompson (1964) showed gully erosion to be dependent upon the soil factor, but Heginbottom (1967) could not differentiate gully types on different soils. It is apparent that considerably more research is required on gully morphology as it relates to those factors responsible for gully erosion.

4. Summary

Gullying is defined as an advanced and destructive form of soil erosion. The form of this erosion is a gully or ephemeral channel.

Gullies are caused by climatic conditions conducive to soil erosion and usually in connection with land misuse. Gullies have been classified as either continuous or discontinuous gullies, while the more advanced form of gully erosion is characterized by continuous gullies. The stage of gully development may also be expressed by the gully shape factor.

Studies of gully morphology are few. Those studies relating gully morphology to gully processes were found to be contradictory in nature. More research combining gully morphology with gully processes is required for a better understanding of the problem of gullying.

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CHAPTER III

The Gullies Along The Manitoba Escarpment

1. Field Methods

A total of 6 gullies were selected for this study. The gullies selected were chosen on the basis of their size, the vegetation and soil types around the gully, and their accessibility. The Roadside Gully was selected because the gully is long and well-developed, as well as being located on improved pasture. Located at the base of the Roadside Gully is an alluvial fan, and it was hoped that the amount of sediment deposited on the alluvial fan could be measured. The Eden Farm Gully 1 is a moderate length gully located on improved pasture. This gully has developed as a result of a cattle path intercepting downslope runoff. The Eden Farm Gully 2 is also a moderate length gully located on improved pasture, and it is a tributary gully to a larger gully which has developed as a result of a farm access road channelizing runoff. The two Rosedale Gullies were selected because they are both located on a revegetated slope, with the vegetation possibly having an effect upon the rate of gully erosion. The Polonia Gully is a moderate length gully with the gully drainage basin located on a cultivated grain crop field, and the gully channel is located on a field of improved pasture. The Polonia Gully is the only gully located on a westward facing slope. (The remaining 5 gullies are located on eastward facing slopes.) The Roadside Gully and the Eden Farm Gullies are located on the Clarksville Soil Association, the Rosedale Gullies are located on the Wapus Soil Association, and the Polonia Gully is located on the Granville Soil Association.

The method used to measure the gully cross-sections restricted the choice of gully sizes to those gullies which had a gully depth less than 5 feet, with no restrictions placed upon the gully width. The gullies selected in May 1973, had mean gully depths ranging from 1.3 - 3.3 feet. The restrictions placed upon the gully size are justified in the event that during the period of this study, if gully erosion was severe, then the gully depths would increase to a degree where the gully cross-sectional measurements could not be taken.

Field work commenced in May 1973. Wooden stakes were driven into the ground on both sides of the gully. The placement of these stakes represented the location of the gully cross-sections. The gully cross-section stakes were placed at approximately equal intervals along the entire length of the gully, with the number of cross-sections dependent upon the length of the gully. The approximate placement interval of each gully channel cross-section is as follows: Polonia and Roadside - 15 feet; Rosedale Gully 1 and Rosedale Gully 2 - 10 feet; Eden Farm Gully 1 - 11 feet; and Eden Farm Gully 2 - 30 feet. The following is the number of cross-sections for each gully: Polonia - 7; Roadside - 14; Rosedale Gully 1 - 6; Rosedale Gully 2 - 5; Eden Farm Gully 1 -5; and Eden Farm Gully 2 - 3.

To obtain the cross-sectional measurements, the following method was used. A survey measuring tape was extended and attached between the two cross-section stakes. The distance between the cross-section stakes was recorded. At given recorded lengths along the survey tape, a plumb line attached to a measuring tape was dropped from the survey tape and the distance from the survey tape to the gully was recorded. This procedure was repeated every 4-6 inches along the survey tape. Depending upon the width of the gully, from 12 to 25 measurements were taken at each gully cross-section. The use of the plumb line allowed cross-section measurements to be made with an accuracy of 1/16 of an inch. An illustration of this method is presented in Plates 3.1 and 3.2.

The cross-sectional data was plotted on graphs at a scale of one inch to one foot. One graph was used to represent each cross-section. This procedure was begun in May 1973, and repeated in October 1973, May 1974, and October 1974. Each time the cross-section measurements were taken, the exact same position along the gully cross-section was measured. Each gully cross-section over time was plotted on the same graph and any change in gully form was evident from the graphs. A total of 40 graphs each containing 4 cross-sections measured over time was thus obtained.

Since the gully cross-sections were drawn to a scale of one inch equals one foot, all necessary gully cross-sectional measurements were made directly from the graphs. Gully width and gully depth were read directly from the graphs. The gully side slope angles were measured directly from the graphs using a protractor. In order to calculate area changes in the gully cross-sections, a Hewlett-Packard 9100A Calculator with Digitizer board was used. This calculator measured areas to an accuracy of 0.02 square inches. The changes in gully cross-sectional areas was noted, and from this data it was possible to calculate erosion or deposition rates of the gullies as reflected in the changes in the gully cross-sections.

Any change in the gully cross-sections between May and October was due to the effect of summer rainfall. Changes due to spring snowmelt were evident in the October-May measurement period. Thus, the study covered two summer rainfall periods and one spring snowmelt period.

Each gully and its associated drainage basin was mapped by plane table. The Hewlett-Packard calculator was used to calculate the

Plate 3.1

Plate 3.2

Gully cross-sectional measurements taken using surveyor's tape and plumb line drainage basin area, as well as the Roadside Gully alluvial fan. The gullies, drainage basins, and the Roadside alluvial fan are presented in Figures 1 to 6, Appendix I. Because the depth of the Roadside Gully alluvial fan was measured, it was possible to calculate the volume of sediment deposited at the base of the Roadside Gully from May 1973 to October 1973. The maps of the drainage basins allowed for the calculation of the elongation ratios for each basin. The entire gully thalweg was also surveyed for each gully, and the thalweg profiles are presented in Figures 1 to 6, Appendix II. The slope angles of the hillslopes on which the gullies are situated was also surveyed.

To calculate the volume of eroded material for a given amount of precipitation, on May 24, 1973, sediment traps were placed in the Roadside Gully and the Eden Farm Gully 2. The sediment traps were examined one week later and the precipitation and volume of sediment in the traps was noted. Upon return to the field area in September 1973, the sediment traps had been damaged beyond use and no further studies involving sediment traps were pursued.

Another method was attempted to measure rates of erosion and deposition. Metal pins 18 inches long were driven into the sides and bottom of the gullies, and their lengths measured using a ruler. Erosion or deposition would show as changes in the exposure of the pins. It was found that some of the pins located in the gully thalwegs had washed away, while many of the pins located in the gully sides had been disturbed by cattle. Because of this loss of pins and disturbance, this method was also discontinued.

Till samples were taken from the site of each gully. The till samples were sieved and the percentages of gravel, sand, and silt-clay were recorded. A verbal description of each till sample was also made.

The data generated from this analysis is presented in Tables 1 to 20, Appendix III.

2. Environmental and Human Factors Contributing to Gully Erosion

Aerial photographic coverage of the entire field area includes the years 1946, 1958, 1964, and 1972. This aerial photographic coverage makes it possible to examine past land uses as well as to examine rates of gully growth. From the aerial photographic coverage and the visits to the field area, it is possible to identify those environmental and human factors responsible for the initiation and development of the gullies studied.

The 1946 aerial photographs show that the Polonia Gully was present in 1946. From 1946 until the present, the drainage basin of the Polonia Gully has been under grain cultivation. The natural vegetation has been removed and replaced with grain crops. The cultivated drainage basin has a slope of 16.40 per cent. Ireland et al. (1939) recommended that in South Carolina the steepest slope suitable for cultivation for most soils was 12 per cent. A contributing cause of the Polonia Gully may be the cultivation of this steep slope.

The Roadside Gully was also present on the 1946 aerial photographs. The aerial photographs show that from 1946 until 1958 the Roadside Gully drainage basin was planted in grain crops. From 1958 until the present, the drainage basin has been used as improved pasture. Although the hillslope is much gentler than that of all the other gullies (6.7 per cent), the replacement of natural vegetation with grain crops may have been a contributing factor in the development of the Roadside Gully.

The Rosedale Gully 1 and Rosedale Gully 2 are present on the

1958 aerial photographs, but they are not present on the 1946 aerial photographs. From 1958 until 1967 the Rosedale Gully sites were situated on improved pasture. Because of the steep slopes, shallow topsoil, and overgrazing by cattle, this land had reached exceedingly low productivity. In 1967 the Manitoba Provincial Government purchased this land and revegetated it with grasses and trees, with hopes of returning the badly eroded terrain to its natural condition. Because of the land misuse prior to 1967, the Rosedale Gullies developed upon what was once improved pasture.

The Eden Farm Gullies show most clearly the effects of man's activities upon the initiation of gullies. The 1946 aerial photographs show the Eden Farm Gully 1 as a small shallow gully located on improved pasture. The Eden Farm Gully 2 first appears on the 1958 aerial photographs, while the Eden Farm Gully 1 is already well-developed by 1958. In 1946 the site of the gullies contained a field access road and cattle paths. By 1958 the field access road had turned into a large deep gully, and the Eden Farm Gully 2 is a tributary gully to what was once a field access road. In 1946 a cattle path had developed along a fence row and by 1958 this cattle path had turned into a deeply incised gully. The field access road channelized flow down the ruts of the road with the end result being a gully. The cattle path alongside the fence row intercepted natural downslope runoff, channelized the flow down the cattle path, resulting in the development of a gully.

Illustrations of all the gullies in this study are found in Plates 3.3 to 3.7. Examples of gullies developing alongside a fence row and a field access row are presented in Plates 3.8 to 3.11.

Plate 3.3
Eden Farm Gully 1 looking east

Plate 3.4
Eden Farm Gully 2 looking south-east

Plate 3.5

Polonia Gully looking west

Plate 3.6

Rosedale Gully 1 looking west. The Rosedale Gully 2 is alongside but not visible. Note vegetation growing within the gully channel.

Plate 3.7

Roadside Gully looking south

Plate 3.8

This gully, located at the Eden Farm Gully 2 site, has developed since 1946. What is now the gully was once a field access road leading from the farmhouse. Continued use of this road has resulted in severe erosion .

Plate 3.9

A closer view of the gully in Plate 3.8
The marker stake is approximately 2 feet long.

Plate 3.10

A cattle path developing parallel to a boundary fence at the Eden Farm Gully 2 site. The cattle path intercepts downslope runoff. In time the cattle path may develop into a gully.

Plate 3.11

A fully developed gully running parallel to an abandoned boundary fence at the Eden Farm Gully 2 site. Parallel to this abandoned fence was once a cattle path similar to the cattle path in Plate 3.10.

3. Gully Classification

According to the Ireland, et al. (1939) gully classification system, 4 of the gullies in this study are in the second stage of gully development. The Polonia, Roadside, and the two Eden Farm Gullies are in a stage of active gully erosion. These gullies have cut their channels through the topsoil and B horizon (stage 1), but they have not yet reached stage 3 which is characterized by gully readjustment having gentle side slopes and talus accumulations at the base. The 4 gullies are actively eroding, and are characterized by the penetration of the gully channels through the C horizon, deepening of the gully channel, and upslope migration of the gully heads (particularly evident by Roadside Gully bifurcated gully head). The gully sides are very steep with no accumulated talus at the base of the gully sides. The remaining two Rosedale Gullies are classified as stage 3 gullies. Although these two gullies are characterized by modest plant colonization along the gully sides and gully channel (note Plate 3.6), the establishment of the vegetation was the result of a vegetation project by the Manitoba Provincial Government, and not by the attainment of natural vegetation through gully stabilization. The Rosedale Gullies are characterized as having gentle side slopes with some talus accumulation along the base of the gully sides, and are therefore classified as stage 3 gullies.

The form of 5 of the gullies are of the linear type, as evident from Figures 1-5, Appendix I. The form of the Roadside Gully is classified as parallel due to the bifurcated gully head. The gully heads are classified as inclined - pointed, although the Eden Farm Gully 1 could conceivably be classified as inclined - rounded. The thalweg profiles (Figures 1-6, Appendix II) illustrate that all the gullies are of the continuous gully type as described by Heede (1974) and Leopold, et al. (1964).

4. Summary

The field work for this study was begun in May 1973 and completed in October 1974. During this time period, gully cross-sectional measurements were taken after two summer rainfall periods and one spring snowmelt period. This allowed for a comparison of erosion rates resulting from rainfall and snowmelt.

The advantage of the method used in gully cross-section measurements was that repeated measurements could be taken at the exact same locations along the gully profile. When the cross-section profiles were placed on graphs, erosion rates and morphometric properties could easily be read directly from the graphs.

The 6 gullies studied along the Manitoba Escarpment are all man-induced erosional features. Overgrazing of pasture by cattle, the replacement of native vegetation with cultivated grain crops on steep slopes, cattle paths intercepting downslope runoff, and the improper placement of farm access roads, have all contributed to the problem of gullying.

Of the 6 gullies in this study, 4 are classified as stage 2 gullies, and 2 are classified as stage 3 gullies. The form of the gullies are of the linear type, except the Roadside Gully which is classified as parallel. The Eden Farm Gully 1 head is classified as inclined-rounded, and the remaining gully heads are classified as inclined-pointed.

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CHAPTER IV

Analysis of Data

1. Introduction

The purpose of this chapter is to identify which gully morphometric variables are exerting the most influence upon gully development. By analyzing the gully morphometric variables, it is hoped that a better understanding of gully evolution and geomorphic processes acting upon the gullies may be gained.

2. Procedure

In this study 6 gullies were selected for analysis. The gullies were selected as being representative of a larger population of gullies found along this portion of the Manitoba Escarpment. The small sample size of 6 gullies necessitated the use of the 0.10 level of significance, or better, as being indicative of a statistically significant relationship. In this analysis there is a 10 per cent probability that a relationship between gully variables may be due to chance alone.

A total of 19 morphometric properties were derived from each of the gullies. The morphometric properties chosen are those which are the most characteristic of the gully form. The definition of each morphometric property is found in Table 1, Appendix III, and the morphometric data for each of the gullies is found in Tables 2-19, Appendix III.

From the 19 morphometric properties, 4 were selected as dependent variables. The 4 dependent variables selected were: gully width, gully depth, mean gully side-slope angle, and gully fall. The dependent variables selected are those variables directly responsive to erosional processes occurring within the gullies. It is hoped that the dependent variables would illustrate cause and effect relationships operating within the gullies.

For the purpose of numerical analysis, each of the dependent variables was paired against each of the remaining 18 independent variables, and the data was analyzed for possible cause and effect relationships. The procedure of pairing each dependent variable against each independent variable was carried out twice. The first procedure involved pairing the original data for the dependent and the independent variables, and the second procedure involved pairing the common logarithms of the dependent variable against the common logarithms of the independent variable. It is common geomorphological practice to transform data to logarithmic values, as the logarithmic data is more apt to plot as a straight line on logarithmic paper (Strahler, 1954).

The method of analysis used in this study was devised by Strahler (1954). The regression line between each dependent and each independent variable was calculated using a Olivetti Underwood Programma 101. For each set of paired variables, the program calculated the Y (dependent variable) on X (independent variable) regression equation, as well as the correlation coefficient between paired variables. This part of the analysis was performed on the original data as well as the logarithm transformed data. From these calculations the significance level between the dependent variables was computed.

The formulae on which these calculations are based, and a discussion of this analysis is presented as Appendix IV. The "t" values used and their corresponding significance levels are presented as Table 1, Appendix V. The regression "t" values, significance levels, correlation coefficients, and the constants which determine the specific linear and power equations for paired variables, are presented as Tables 2-17, Appendix V. Plots and power function equations between significant paired variables are presented as Figures 1-11, Appendix VI.

3. Discussion of Gully Morphology

Regression analysis was used between pair-wise relationships among gully morphometric variables, and the significance of the relationship was computed. This type of analysis presents problems when the nature of the process-response relationship between variables is not precisely known.

Doornkamp and King (1971, p.71) discuss some of the problems involved using regression analysis between morphometric variables. It is often difficult to identify which is the "response" and which is the "process" variable. This results from the fact that most geomorphological relationships are part of a complex system of interrelationships. Because 2 variables are related, this does not mean that they illustrate a cause and effect relationship. It may be that both variables are responding in a similar manner to another process variable, which may or may not be known.

In this study regression analysis is used as a searching procedure by which possible geomorphological relationships may be identified. The terms dependent and independent variables will only be used with reference to the regression equation, as regression analysis requires one variable to be defined as the independent variable, and the other variable to be defined as the dependent variable. It is the responsibility of the geomorphologist to consider and examine the implications of each regression analysis. Because of the problems involved with the use of regression analysis, the variables gully width, gully depth, mean gully side-slope angle, and gully fall, shall be discussed in terms of their implications with each paired variable, rather than their dependence upon each paired variable.

Gully Width Relationships

Increased gully width is a response to erosional processes acting upon a gully over a time period. The same erosional processes and time period are also responsible for other morphometric properties of the gullies. Consequently, some of the significant relationships between gully width and other gully morphometric properties may be explained in this way. In response to erosional processes acting upon the gullies over time, the gully fall, gully length, and volume of eroded material per foot of gully length, are shown to increase proportionately to the increase in gully width. The variable volume of eroded material per foot of gully length, is an expression of the amount of eroded material proportionate to the size of the gully.

Gully width is inversely proportional to the percentage of gravel and directly proportional to the percentage of sand and the percentage of silt-clay found within the surface material. Since gully width is a response to erosional processes acting upon the gullies over time, the susceptibility of the surface material to erosion can be expressed by the gully width. The finer grained the surface material is, the more susceptible that deposit is to erosion. Wider gullies would consequently tend to develop on surface materials containing low percentages of gravel, and high percentages of fines.

Gully width is also related to the gully drainage basin area.[1] The larger the gully drainage basin area, the more area is contributing available runoff towards the gully channel, with the result being an increase in erosion rates reflected by the increased widths of the gullies.

It is concluded that those significant relationships found between gully width and: gully fall; gully length; and volume of eroded material per foot of gully length, are all responses to erosional processes acting upon the gullies over time. Wider gullies would be expected to develop upon fine grained surface materials with large contributing gully drainage basin areas. This is evident from the relationship between gully width and the percentage of fines, and the relationship between gully width and the drainage basin area.

Gully Depth Relationships

Like gully width, gully depth is a response to erosional processes acting upon the gullies over time. The relationship between gully depth to the volume of eroded material per foot of gully length is thus a response to erosional processes, and this relationship was expected.

Gully depth is related to the mean gully side-slope angle. This relationship implies that as the gully channel downcuts, this process will determine the mean gully side-slope angle, or, as the gully deepens, the gully sides become steeper. This relationship may appear as obvious, but the relationship should be viewed in relation to the erosional processes acting upon the gullies. If the gully sides became steeper independently of the gully depth, it may signify that the gullies have attained some

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1. Significant at the 0.01 level.

equilibrium stage where erosional forces are concentrated upon widening rather than deepening the gully floor. For this to take place, a process transition from vertical to lateral erosion of the gully channel floor would have to occur. Because this stage has not been reached, it indicates that the gullies in this study have not attained equilibrium conditions, and the gullies are in a youthful stage of gully development. This hypothesis is in agreement with the gully shape factor data (Table 20, Appendix III), which shows the gullies to have inefficient cross-sectional shapes, indicative of a youthful channel cross-section. Leopold and Miller (1956, p.36) described stages of gully development as, "The early stage of a discontinuous gully is considered to represent the narrow, deep condition, and at a later stage, lateral cutting and slumping of the arroyo walls lead to widening, with a consequent shallowing of the cross-section of flowing water at a particular discharge." The gullies studied along the Manitoba Escarpment are continuous gullies where the gullies are wider than they are deep (Table 4, Appendix III), but there has been no measured lateral cutting or slumping of the gully walls (Table 2, Appendix III), as compared to the increase of gully depths (Table 3, Appendix III). The absence of lateral cutting but the increasing gully depth would indicate that the gullies along the Manitoba Escarpment are in the early stage of gully development as defined by Leopold and Miller (1956).

Similar to the gully width, the gully depth is related to the percentage of silt-clay in the surface material. The higher the percentage of silt-clay, the deeper the gully, and like gully width, this relationship expresses the susceptibility of the surface material to erosion.

In summary, gully depth is a response to erosional processes acting upon the gullies over time. As the gully deepens, the gully sides hillslope angles of the slopes along the Manitoba Escarpment increase in magnitude, the drainage basins become more elongated in shape, and the gully fall would incœrease as a result of the increased hillslope angle.

In summary, gully fall varies in proportion to the rate of gully erosion as evident by the relationships between gully fall and: gully volume; the volume of eroded material per foot gully length; and the ratio of mean gully side-slope angle to thalweg slope angle. Gully fall is also related to the size and shape (degree of elongation) of the gully drainage basin.

4. Summary of Morphometric Properties

Gully width, gully depth, and gully fall, were shown to be responsive to erosional processes acting upon the gullies over time. Deeper and wider gullies would tend to develop on surface materials containing high percentages of silts and clays, with the wider gullies also having a tendency to develop in areas with large drainage basins. As the gully channels deepened, the gully sides became steeper. It was also shown that the gully fall is related to large elongated shaped drainage basins.

From a review of Appendix III, a number of morphometric properties of the gullies are evident. The drainage basins of all the gullies showed a definite elongated shape resulting from the steep slopes on which the basins are located. The gullies are wider than they are deep. The gully shape factors show the gully cross-sections to be rectangular. The north facing side-slope of the gully is steeper than the south facing side-slope.[2] Palmer (1965) found in a study of New Hampshire gullies the north

2. Significantly different at the 0.005 level of significance based upon 24 observations.

facing gully side is shaded, and as the air temperature rises, the north facing gully side has a lower temperature than the south facing gully side. The south facing gully side warms rapidly during thaw periods and excess moisture is released by thawing and flows out of the soil, resulting in soil creep occurring on the frost weakened slope. In Palmer's (1965) study, the south facing gully side-slope would have a tendency to erode more, reducing the south facing gully side-slope angle. The gullies along the Manitoba Escarpment showed no observed preferred orientation of rainfall or snowmelt erosion, or soil freeze-thaw processes, to account for the north facing gully side being steeper than the south facing gully side.

There are effectively many relationships which may have been expected but which did not appear. There is no relationship between gully width and gully depth. It is conceivable that a relationship between gully width and gully depth may exist only at certain stages of gully development. The Leopold and Miller (1956, p. 31) study found that the early stage of gully development is characterized by a deep and narrow channel, the next stage is characterized by widening of the gully, and the last stage, defined as the "stage of coalescence", is characterized by lengthening and deepening of the gully. Although the gullies along the Manitoba Escarpment are wider than they are deep (Table 3, Appendix III), there is no evidence of gully widening, and these gullies may be defined as being in the early stage of gully development. There was also no relationship between gully depth and gully fall, the only true vertical properties of the gullies. Heginbottom (1967), who examined gullies north of Montreal, found no correlation between these two properties.

Schumm (1960) found a high inverse correlation of -0.91 between the logarithm width-depth ratio to the logarithm of the percentage silt-clay. This author correlated his logarithm width-depth ratio data to the logarithm percentage silt-clay data and found a correlation coefficient of -0.2756. Even though the gully width and the gully depth showed a significant relation to the percentage of silt-clay, the width-depth ratio to percentage silt-clay showed no significant relationship. Schumm concluded that the percentage silt-clay serves as a parameter representative of the resistance to erosion in a stream channel. Schumm found that as the percentage of silt-clay increased, the width-depth ratio decreased. Therefore, in fine grained sediments the channel will be relatively deep and narrow, whereas in sediments containing less silt-clay, the channel will be wide and shallow. It is this author's opinion that the gully width and the gully depth of those gullies studied along the Manitoba Escarpment are related to the percentage of silt-clay within the surface material, with the percentage of silt-clay being a strong indicator of the surface material's susceptibility to erosion. Contradictory results were reported by Knighton (1974) who found the silt-clay fraction acted as a binding agent, maintaining steep angles of repose for stream channels. Knighton showed that as the silt-clay content increased, the stream bank angle also increased, and this he believed was a morphological expression of bank cohesiveness. The gullies along the Manitoba Escarpment had some very steep side-slope angles, some up to 70 and 80 degrees. Although the relationship between mean gully side-slope angle and the percentage of silt-clay was close to being significant, the relationship between the percentage of silt-clay with gully depth and gully width appears to be more an indicator of the surface material's susceptibility to erosion rather than an expression of cohesiveness.

Leopold and Maddock (1953) found stream width and depth increased downstream along the stream channel. Leopold and Miller (1956) found the width of discontinuous gullies increased downstream, and they attributed this increase in gully width to the increased velocity of flowing water within the gully channel, and an increase of gully slope down the gully channel. The width and depth data for those gullies studied along the Manitoba Escarpment showed no downstream trends, nor did the gully channel width increase with an increase in channel slope. The gullies studied by Leopold and Miller were long discontinuous gullies with large drainage basins and large gully falls. Leopold and Maddock studied streams having a continuous discharge. The gullies along the Manitoba Escarpment did not exhibit morphometric properties which are similar in nature to streams or large discontinuous gullies, rather the gullies are short ephermal channels with small drainage basins and having a small gully fall.

The absence of clearly-defined hydraulic downstream relations may suggest that the gullies are in a youthful stage of evolution, and the mechanics of gully development have not developed to a stage of adjusting to hydraulic factors acting upon the gullies. As discussed in the previous chapter, the gullies along the Manitoba Escarpment are classified as being in Stage 2 and Stage 3 of gully development (youthful stages). The gully shape factors and the absence of lateral gully floor erosion, indicate that the gullies are also in a youthful stage of development. The absence of downstream morphometric relations in this study is another indicator of the stage of gully development.

5. The Relationship Between Gully Morphology and Erosion Processes

By relating the morphometric properties of the gullies from the previous sections to erosion processes, the following is hypothesized.

The larger the drainage basin area, the more runoff from snowmelt and rainfall is funnelled towards the gully channel. This runoff results in gully erosion with increases in the width and depth of the gullies. As the gully erodes headward, the gully fall is increased giving a greater head to the runoff, and increasing the erosive capability of the gully channel flow. The wider and deeper gullies will tend to develop in areas which have large drainage basins contributing the available runoff.

The capacity for a gully to erode was shown to be related to the percentage of fines, especially the silt-clay content within the surface material. The gully width and gully depth increased in proportion to the percentage of fines. Therefore, areas along this portion of the Manitoba Escarpment having steep slopes, large drainage basins, and containing surface materials with high percentages of silts and clays, are those areas most susceptible to gully erosion.

The north facing side of the gullies are steeper than the south facing gully sides. Some mechanism, possibly the heating of the gully sides has resulted in differential freeze-thaw cycles along the gully sides, resulting in greater erosion along the south facing sides of the gullies, reducing the south facing side-slope angle.

It was shown that as the gully depth increases, the gully sides become steeper. Gully depth was not related to gully width. This implies that as the gully deepens, the corresponding increase of the gully side-slope angle is not related to an increase of gully width. This suggests that the erosional forces acting upon the gullies are most active along the bottom portions of the gully channel and sides, and are less active along the upper portions of the gully. Consequently, the gully depth and side-slopes increase independently and faster than gully width.

The gullies in this study may be considered as being in a youthful stage of gully development. The relatively small size of the gullies, the inefficient gully cross-sections (shape factor), the absence of downstream morphometric trends, and the concentration of erosional forces upon deepening the gully thalweg rather than widening the thalweg, all suggest that the gullies have not developed to a stage of adjusting to hydraulic factors which are eroding the gullies.

Summary

Pair-wise relationships were established between the dependent variables of gully width, gully depth, gully side-slope angle, and gully fall, with 18 independent gully morphometric variables. Those relationships that were of significance have led to the conclusion that areas most susceptible to gully erosion are characterized as having steep slopes, large drainage basins, and containing surface materials having high percentages of silts and clays.

The gullies studied along this portion of the Manitoba Escarpment are characterized as having rectangular shaped gully cross-sections, the north facing side of the gully is steeper than the south facing gully side, the gullies are wider than they are deep, and there were no observed morphometric trends downstream along the gully. The gullies are presently considered as being in a youthful stage of evolution.

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CHAPTER V

Discussion of Gully Erosion

1. Introduction

The detailed measurement of the gully cross-sections afforded the opportunity for calculating the rate of erosion of each gully. As each gully aggraded or degraded, the change would appear in the cross-sectional measurements.

Gully cross-sectional measurements were taken a total of 4 times: May 12-13, 1973; October 20-21, 1973; May 13-14, 1974; and October 5-6, 1974. Each time, two consecutive days were required to take the cross-sectional measurements at the sites of the 6 gullies. The May-October interval is representative of the summer rainfall period, where any change of gully dimension is due to the effects of rainfall. The October-May interval represents the spring snowmelt period. There is no gully erosion during winter when the ground surface is covered in snow and remains in a frozen state. The rates of gully erosion were based upon two summer rainfall periods and one snowmelt period.

The Neepawa Weather Station records provided values of the total amount of precipitation in the form of snowfall and rainfall. The same station also recorded the number of summer thunderstorms, and the amount of precipitation contributed by each thunderstorm. It was therefore possible to categorize the precipitation in terms of snowfall, precipitation due to thunderstorm activity, and precipitation due to non-thunderstorm activity. The amounts of precipitation falling upon the field area by these categories are summarized in Table 5.1.

Rainfall intensity data was obtained from the Wilson Creek Experimental Watershed, located 27 miles north of the field area. The rainfall intensity data was used to estimate the effect of rainfall intensity

TABLE 5.1

PRECIPITATION DATA

Based Upon the Neepawa Weather Station

	May 12, 1973 to October 20, 1973	October 20, 1973 to May 13, 1974	May 13, 1974 to October 5, 1974
Total Precipitation	18.27 inches	8.76 inches	6.69 inches
Number of Thunderstorms	10		6
Thunderstorm Precipitation	5.46 inches		1.71 inches
Non-Thunderstorm Precipitation	12.81 inches		4.98 inches

upon gully erosion rates. By comparing precipitation data between the Neepawa Weather Station and the Wilson Creek Experimental Watershed, it was noted that the two stations have close agreement of daily precipitation totals. This close agreement of precipitation totals is due to the fact that both stations are under the influence of the same frontal precipitation systems.[1]

The Neepawa Weather Station reports precipitation totals at 8 A.M. and 5 P.M. daily, but the Wilson Creek Experimental Watershed precipitation data is recorded on a recording precipitation gauge. The recording precipitation gauge is more representative of rainfall intensity and total precipitation than the data reported at the Neepawa Weather Station. Although thunderstorm precipitation is more localized than frontal precipitation, the rainfall intensity data from the Wilson Creek Experimental Watershed is used as being representative of thunderstorm intensities falling upon this portion of the Manitoba Escarpment. Therefore, the rainfall intensity data from the Wilson Creek Experimental Watershed was used in this study.

2. Rates of Gully Erosion

The volume of eroded material contributed by each gully is summarized in Table 5.2. Because the gullies are of different dimensions, a much more representative erosion rate is presented in Table 5.3, which gives the mean gully erosion rate in terms of square feet of eroded material contributed by any one gully cross-section. From this table it is evident that all the gullies eroded during the summer of 1973. During the 1974 spring snowmelt period, only the Polonia Gully and

1. Pers. Comm. Mr. J. Thomlinson, Wilson Creek Experimental Watershed Manitoba

TABLE 5.2

TOTAL VOLUME OF ERODED MATERIAL - CUBIC FEET

Gully	May 1973 to October 1973	October 1973 to May 1974	May 1974 to October 1974
Polonia	- 108.90	- 33.00	+ 4.40
Roadside	-1432.60	0.00	+179.80
Rosedale			
Gully 1	- 47.80	+ 32.44	- 2.28
Gully 2	- 40.50	+ 34.00	- 8.00
Eden Farm			
Gully 1	- 74.72	+ 00.57	- 21.51
Gully 2	- 147.98	- 17.64	- 46.06

(+) indicates aggradation

(-) indicates degradation

Calculated from the value derived from the mean volume of eroded material per gully cross-section times the gully length.

TABLE 5.3

VOLUME OF ERODED MATERIAL PER FOOT OF GULLY LENGTH - V/L

(Cubic feet/foot)

Gully	May 1973 to October 1973	October 1973 to May 1974	May 1974 to October 1974
Polonia	- 0.99	- 0.30	+ 0.04
Roadside	- 2.47	0.00	+ 0.31
Rosedale			
Gully 1	- 0.84	+ 0.57	- 0.04
Gully 2	- 0.81	+ 0.68	- 0.16
Eden Farm			
Gully 1	- 1.32	+ 0.01	- 0.38
Gully 2	- 1.51	- 0.18	- 0.47

(+) indicates aggradation

(-) indicates degradation

Calculated from the total volume of eroded material divided by the gully length.

the Eden Farm Gully 2 showed evidence of erosion. One gully showed no change, and 3 gullies showed a tendency towards aggradation. During the 1974 summer rainfall period, only the Polonia Gully and the Roadside Gully showed evidence of aggradation, while the other gullies degraded.

For all the gullies, the total volume of material eroded or deposited per inch of precipitation was calculated to be the following:

summer 1973: - 101.32 cubic feet/inch of rainfall
summer 1974: + 15.98 cubic feet/inch of rainfall
spring 1974: + 1.79 cubic feet/inch of snowfall precipitation

(+) indicates aggradation
(-) indicates degradation

The value of +15.98 cubic feet of material deposited per inch of rainfall precipitation during the 1974 summer rainfall period was due to the influence of the high aggradation value of +179.80 cubic feet of sediment contributed by the Roadside Gully. If this high aggradation value was not included with the remaining 5 gullies, then a value of -73.45 cubic feet of eroded material for the total 1974 summer precipitation period is obtained. By dividing this value by the total 1974 summer precipitation, -10.97 cubic feet of material was removed per inch of summer precipitation. Even with the inclusion of the high aggradation value, and based upon the 1973-1974 average, summer rainfall activity was 23.83 times more effective as an eroding agent than snowmelt runoff. The most meaningful erosion rates per inch of summer precipitation was the 1973 summer precipitation period. When comparing the 1974 spring snowmelt aggradation rate to the 1973 summer precipitation erosion rate, the 1973 summer precipitation period was 56.60 times more effective as an eroding agent than snowmelt runoff, while the 1974 summer precipitation period was 8.92 times more effective as an aggradation agent compared to snowmelt runoff of that same year.

Snowmelt runoff and non-intense precipitation are not considered to be significant gully eroding agents. Heede (1967) in a Colorado study of gullies of similar size to this study found the available snowpack and rate of melt insufficient to cause gully stream flow and gully erosion. During his 7 year study period only 5 summer storms produced gully stream flows, and these 5 storms were responsible for gully erosion.

Figures 5.1 to 5.3 are plots of the rainfall intensities occurring within the field area. Figure 5.1 illustrates the one hour rainfall intensities of the 2 year, 5 year, 10 year, and 25 year return period intensities based upon Bruce (1968). Also shown is the infiltration rate for gravelly sandy loams similar to those in the field area.[2] Rainfall occurring below the infiltration rate percolates into the ground, and rainfall intensity above the infiltration rate is converted into available runoff. Figure 5.2 illustrates the rainfall intensity of the August 18, 1973 thunderstorm, the most intense thunderstorm which occurred during the summer rainfall periods (the rainfall intensity data for this thunderstorm are presented in Table 5.4), and the intensity of the rainfall that occurred during the sediment trap observation period (May 21 and May 22, 1973). Figure 5.3 illustrates the 1973 and 1974 mean summer rainfall intensities. Figures 5.2 and 5.3 are based upon the Wilson Creek Experimental Watershed precipitation intensity data. From an examination of these plots, a comparison of rainfall intensities with

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2. Interpolated from Foster (1948) and Free et al. (1940).

FIGURE 5.1

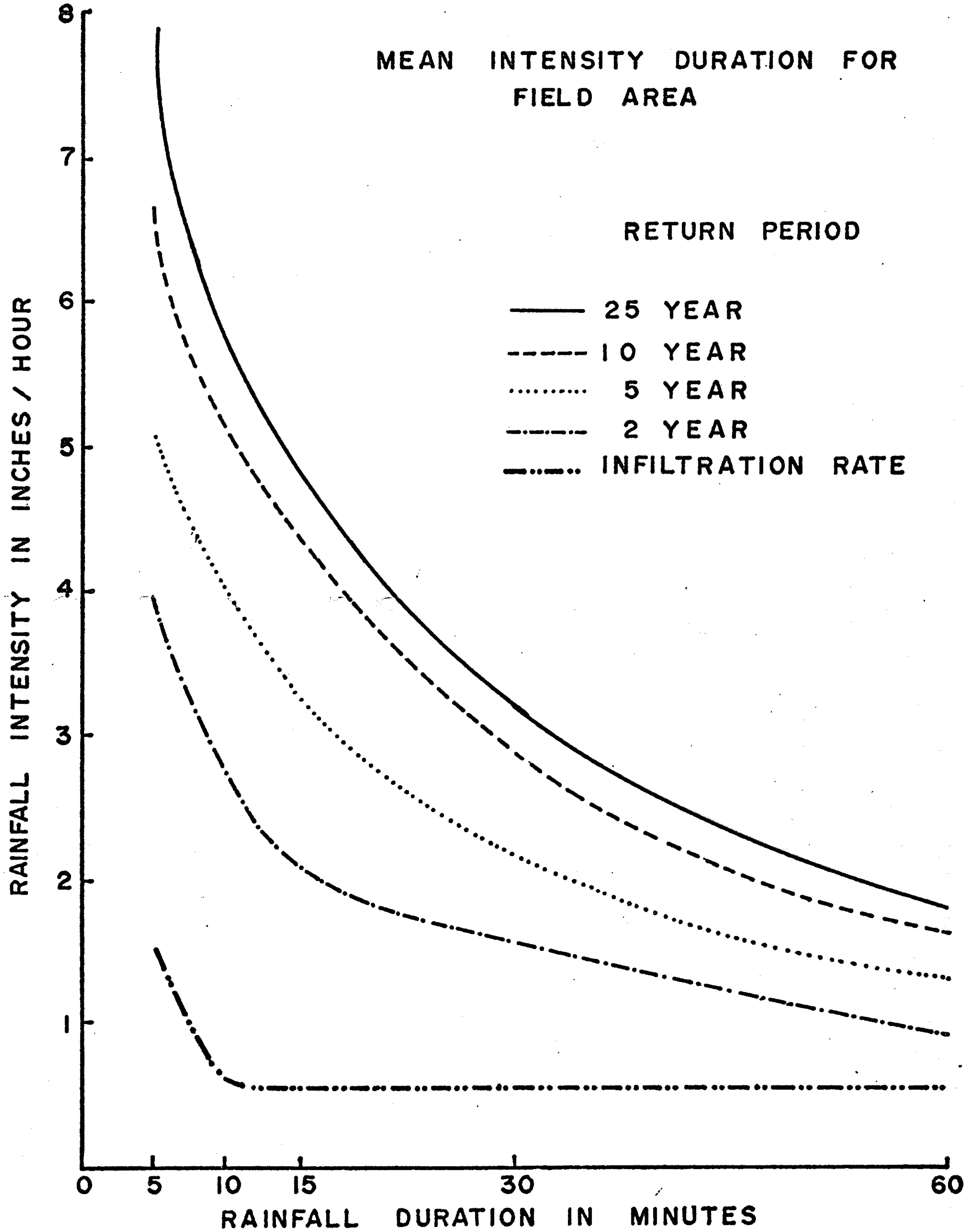
MEAN INTENSITY DURATION FOR FIELD AREA
RETURN PERIOD
25 YEAR
10 YEAR
5 YEAR
2 YEAR
INFILTRATION RATE
RAINFALL INTENSITY IN INCHES / HOUR
RAINFALL DURATION IN MINUTES
8
7
6
5
4
3
2
1
0
5
10
15
30
60

FIGURE 5.2

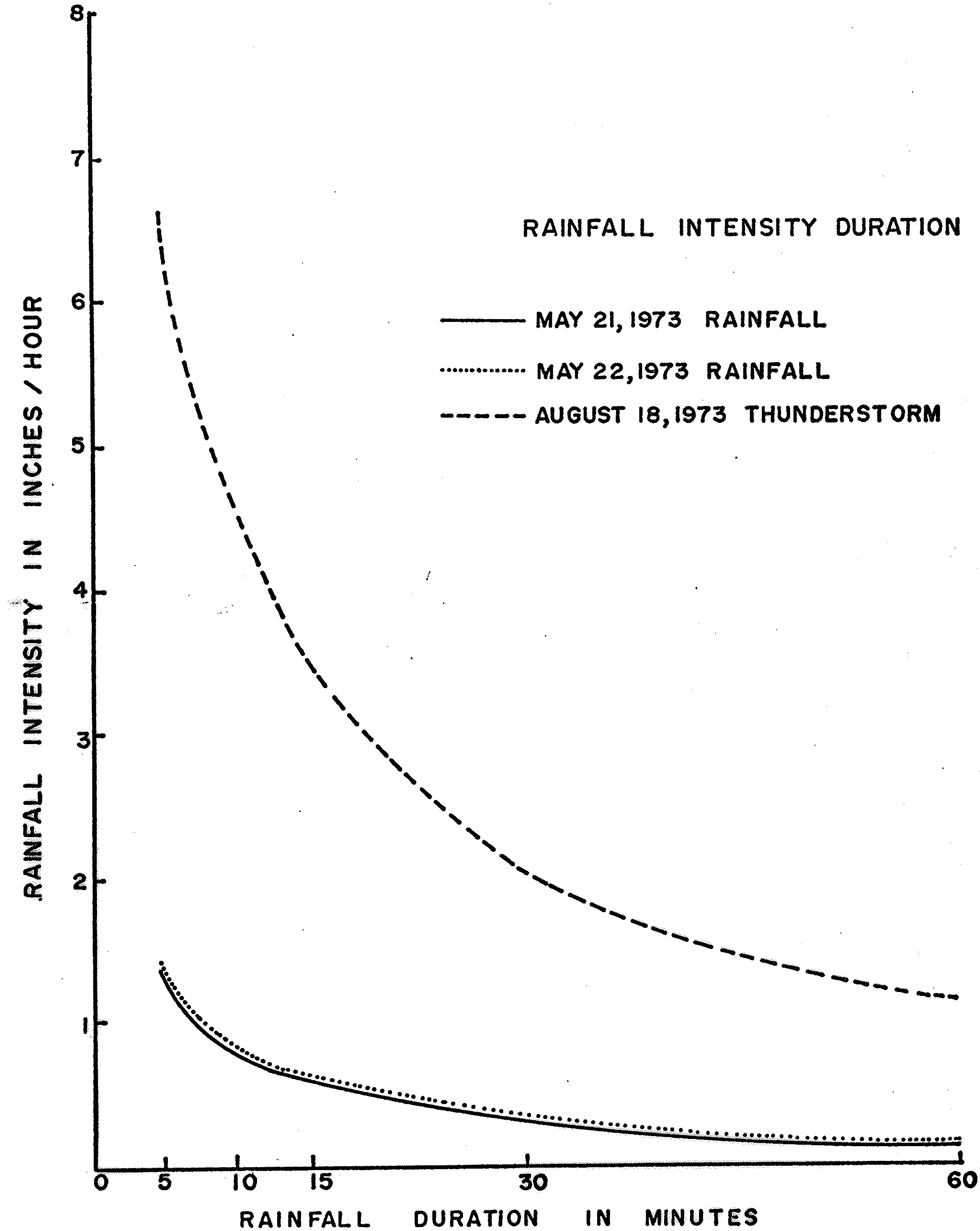
RAINFALL INTENSITY DURATION
MAY 21, 1973 RAINFALL
MAY 22, 1973 RAINFALL
AUGUST 18, 1973 THUNDERSTORM
RAINFALL INTENSITY IN INCHES / HOUR
RAINFALL DURATION IN MINUTES
0
5
10
15
30
60
1
2
3
4
5
6
7
8

FIGURE 5.3

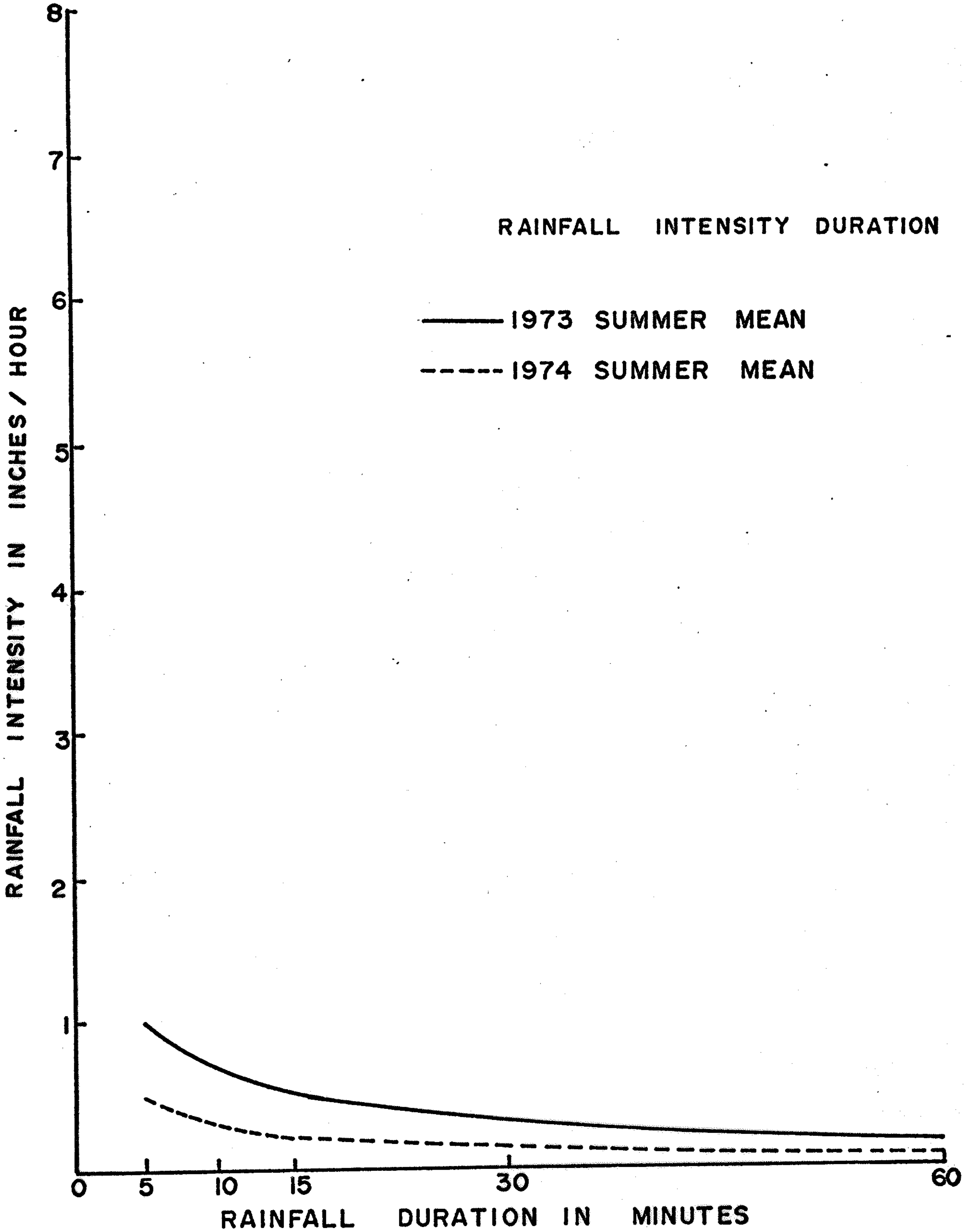
8
7
6
5
4
3
2
1
RAINFALL INTENSITY IN INCHES / HOUR
RAINFALL INTENSITY DURATION
1973 SUMMER MEAN
1974 SUMMER MEAN
0
5
10
15
30
60
RAINFALL DURATION IN MINUTES

TABLE 5.4

AUGUST 18, 1973, THUNDERSTORM INTENSITY DATA FROM WILSON CREEK EXPERIMENTAL WATERSHED

Rainfall Duration	Rainfall Intensity (inches)
5 minute	0.54
10 minute	0.76
15 minute	0.87
60 minute	0.97
120 minute	1.01
6 hour	1.09
12 hour	1.12

erosion rates could be made.

The 1973 and 1974 mean summer rainfall intensities are below the 2 year intensity return period, and this rainfall may be considered as "average" intensity summer rainfall. The 1973 and 1974 mean summer rainfall is also below the infiltration rate for the gully soil types. Therefore, the mean summer precipitation may be considered to be capable of infiltrating into the ground with little or no available runoff to cause gully erosion.

On May 24, 1973, the two sediment traps placed within the Roadside Gully and the Eden Farm Gully 2 on May 12, 1973, were examined. From the time of placement of the two sediment traps until the time of examination, 0.27 inches of precipitation fell upon the two gullies. This precipitation resulted in 0.051 cubic feet of deposited sediment in the Eden Farm Gully 2 sediment trap, and 0.053 cubic feet of deposited sediment in the Roadside Gully sediment trap. For one inch of precipitation, this represents a rate of erosion of 0.18 cubic feet of eroded sediment from the Eden Farm Gully 2, and 0.19 cubic feet of eroded sediment from the Roadside Gully. Figure 5.2 illustrates the rainfall intensities of the May 21 and May 22, 1973, rainfalls which were responsible for contributing the sediment to the sediment traps. The May 21 and May 22 rainfalls were recorded as non-thunderstorm precipitation, and only a small portion of this rainfall was above the infiltration rate. This rainfall is regarded as non-intense rainfall because no portion of the rainfall was above the two year return period. This rainfall was recorded as non-thunderstorm precipitation with an intensity approximately equal to the 1973 summer mean intensity duration.

If the erosion rate of approximately 0.2 cubic feet of sediment eroded per inch of non-intense precipitation is representative, then a comparison could be made between erosion rates resulting from intense and non-intense precipitation. By multiplying the non-intense precipitation erosion rate with the amount of non-intense precipitation falling upon the gullies, a value representing the volume of eroded material removed due to non-intense precipitation is obtained. Subtracting this value from the total volume of eroded material from each gully will give the volume of eroded material removed from each gully as a result of intense precipitation. During the summer of 1973, a total of 18.21 inches of non-intense precipitation and 5.46 inches of intense precipitation fell on the field area (Table 5.1). This non-intense precipitation falling upon the Eden Farm Gully 2 would erode 2.30 cubic feet of material and the intense precipitation would erode 145.68 cubic feet of material from the gully. The same amount of non-intense precipitation would erode 2.43 cubic feet of material from the Roadside Gully, and 1430.17 cubic feet of material would be eroded as a result of the intense precipitation falling upon the gully. Intense precipitation is therefore capable of removing 588.5 times more material from the Roadside Gully than non-intense precipitation. From the Eden Farm Gully 2, 63.3 times more material would be removed from the gully as a result of intense precipitation compared to non-intense precipitation.

Infrequent intense summer precipitation, exceeding the infiltration rate, is considered to be the major gully eroding agent. During the 1974 summer rainfall period, the precipitation intensities did not exceed the infiltration rate of the field area soils. Only one intense thunderstorm, occurring on August 18, 1973 (Figure 5.2 and Table 5.4) was recorded as having an intensity above the infiltration rate. This thunderstorm had a rainfall intensity approximately equal to the intensity of the 10 year return period. It is probable that this one intense thunderstorm was responsible for the majority of the erosion attributed to the 1973 summer rainfall period.

The differences of erosion rates between the 1973 and 1974 summer rainfall periods (Table 5.3) are explained in terms of the duration factor of intense precipitation and the production of runoff water. For thunderstorm activity, Bruce and Clark (1966) showed that on a sandy loam soil, similar to the sandy loam soils within the field area, the runoff exceeds the infiltration rate at approximately the 30 minute duration of a thunderstorm. Wischemeir and Smith (1958) showed that the kinetic energy of a thunderstorm at the 30 minute duration is highly correlated with soil loss. Also, Musgrave (1955) reported that the minimum infiltration rate of sands and silts of moderate depth is 0.05 inches per 30 minute duration. The depressional storage for the mean slope of the field area of 14.8 per cent on pasture is between 0.02 and 0.07 inches, Chow (1964). Assuming that after a 30 minute duration of intense precipitation, with a minimum rainfall intensity of 0.05 inches, and a mean depressional storage of 0.05 inches, runoff conditions would occur after 0.10 inches of intense precipitation. For the summer of 1973, a total of 7.33 inches of intense precipitation was available as runoff, while only 3.43 inches of intense rainfall was available as runoff during the summer of 1974. The summer of 1973 experienced greater erosion rates than the summer of 1974. This difference is explained in terms of more intense precipitation occurring during the summer of 1973, and because there was more available runoff to cause gully erosion.

An example of summer rainfall erosion is found at the Roadside

Gully site. At the base of the Roadside Gully is an alluvial fan (Figure 6, Appendix I). The alluvial fan was surveyed in May, 1973, and again surveyed in October, 1973; prior to and after the summer rainfall period. After the summer of 1973, it was calculated that a total of 8,449 cubic feet of sediment had been deposited on the alluvial fan. From the gully cross-sectional measurements, it was calculated that 1432.6 cubic feet of material had eroded from the gully. The difference of 7016.4 cubic feet of sediment could only have been supplied by the Roadside Gully drainage basin. By dividing the amount of sediment removed from the drainage basin by the drainage basin area, it was found that the drainage basin had eroded by 0.04 feet during the summer of 1973.

It is concluded that a total summer precipitation of 18.27 inches, of which 7.33 inches of precipitation was available as runoff, was sufficient precipitation to erode 1432.6 cubic feet of sediment from the Roadside Gully, and to lower the associated drainage basin by 0.04 feet. At the end of the 1974 summer rainfall period, the Roadside Gully alluvial fan showed no gain in sediment. Apparently the 1974 snowmelt runoff and the total summer precipitation, of which 3.43 inches of the total summer precipitation was available as runoff, were insufficient to carry sediment down the length of the gully to add to the alluvial fan.

Only the Polonia Gully and the Eden Farm Gully 2 showed evidence of erosion after the 1974 snowmelt period. The Roadside Gully showed no change, while the two Rosedale Gullies and the Eden Farm Gully 1 had sediment added to these gullies after the snowmelt period. Although 3 of the 6 gullies tended towards aggradation, snowmelt water samples taken from the gullies showed exceedingly high concentrations of suspended sediment (see Table 5.5). Stickling (1973, p.65) examined the

TABLE 5.5

SUSPENDED SEDIMENT FROM SNOWMELT

Gully	Suspended Sediment Grams/Liter
Polonia	6.04
Roadside	0.23
Eden Farm	
Gully 1	3.17
Gully 2	15.97
Rosedale	
Gully 1 and Gully 2	All runoff infiltrated into the ground

suspended sediment concentrations in Canadian rivers and found the highest concentration of suspended sediment exceeded 1 gram per liter. Of the gullies in which snowmelt runoff was present, the suspended sediment concentrations were exceptionally high. The one exception was the Roadside Gully where the suspended sediment concentration was only moderate. The maximum snowmelt flow observed from any of the gullies was less than 1 inch deep and approximately 1 foot wide, with a very slow velocity.

The high suspended sediment concentrations and the fact that 3 of the 6 gullies aggraded, suggests that snowmelt processes were capable of both gully aggradation as well as gully degradation. As the snow within the gully channel melted from late April to early May, 1973, it was observed that the contact zone between the snow in the snow filled gully and the gully sides were generally damp. The snow filled gully channel may act as a site for initiating soil freeze-thaw processes. Alternate freezing and thawing of the snow-gully contact zone would cause a loosening and shattering of the soil fragments, yielding a supply of fine sediment. Since the snow was observed to remain in the gullies well into late spring (see Plate 5.1), the presence of lingering snow would increase the number of soil freeze-thaw cycles, even though the air temperature would be above freezing.[3]

The number of soil freeze-thaw cycles received by the field area during the fall and spring of 1972-1973 was 41 cycles, Environment Canada (1973). The soil temperature data, from which the number of soil freeze-thaw cycles is calculated, for the spring of 1974, has not yet been

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3. The field area receives an annual mean of 42 soil freeze-thaw cycles, Fraser (1959).

Plate 5.1

Snow remains in the Roadside Gully long after the snow has melted from the drainage basin. The picture was taken April 21, 1974, and the snow in the gully had melted by May 13, 1974.

published. If the number of soil freeze-thaw cycles for the 1973-1974 snowmelt period is close to the annual mean value, then the erosion rates calculated from this study may represent average soil freeze-thaw erosion rates of the gullies.

Snowmelt runoff processes in conjunction with soil freeze-thaw processes could explain the addition of sediment to the gullies as well as the high suspended sediment concentrations measured from snowmelt runoff. As the snow within the gully drainage basins melted, the meltwater could transport fine grained sediment to the gullies by the system of rills which lead towards the gullies. Because of the steep slopes, sparse vegetation of those drainage basins located on overgrazed pasture, and the susceptability of the surface material to erosion, well-defined systems of rills are present in each gully drainage basin. The observed meltwater flowing from the snow filled gully channels was clearly unable to erode or scour the gully channels. The meltwater flowing down the gully channels merely transported sediment which had been loosened by other agents.

Soil freeze-thaw activity and meltwater transported sediment could therefore account for the sediment which was added to those gullies which showed aggradation, and accounts for the high suspended sediment concentrations measured from the gully meltwaters.

All meltwater runoff infiltrated into the ground in the two Rosedale Gullies. This meltwater runoff was not capable of removing the sediments produced by the soil freeze-thaw processes and the drainage basin meltwaters, and consequently the two Rosedale Gullies showed evidence of aggradation. The Roadside Gully and the Eden Farm Gully 1 showed no substantial change after the snowmelt period, even though these two gullies had moderate suspended sediment concentrations. The fine suspended sediment produced by soil freeze-thaw processes and the drainage basin meltwaters was small enough to be within the magnitude of the gully measurement error, and consequently would not be measured as degradation. This may indicate that the gully channel snowmelt runoff was just sufficient to transport the fine suspended sediments produced by soil freeze-thaw processes and the drainage basin meltwaters supplied to the gullies during the snowmelt season. Gully channel snowmelt runoff was apparently sufficient to transport all the sediment produced by the soil freeze-thaw processes and drainage basin meltwaters from the Polonia Gully and the Eden Farm Gully 2. This would account for the exceedingly high suspended sediment concentrations measured from these gullies during the spring snowmelt period.

From field observations during the spring snowmelt period, it is this author's opinion that the 1974 spring snowmelt runoff was not capable of initiating gully erosion. Some other mechanisms, such as soil freeze-thaw processes, were responsible for the measured erosion rates during this period. The gully channel snowmelt runoff was merely a transporting agent of previously eroded sediments.

The exact role of snow lingering within gullies upon erosional processes does not appear to have been investigated. The literature concerning this problem deals primarily with nivation hollows found in northern environments where nivation processes are most active during longer periods of time. A number of questions concerning future research of the problem may be raised. How many additional soil freeze-thaw cycles are added to the annual mean number of soil freeze-thaw cycles from the action of snow lingering within the gullies? How does the intensity of the soil freeze-thaw activity play a role in altering the gully side and bottom material? What chemical alterations, if any, of gully material takes place due to the presence of snow? If these questions could be investigated, a more complete understanding of all aspects of gully erosional processes in southern Manitoba could be obtained.

There were no morphological changes observed or measured within the gullies from the snowmelt period to the beginning of the rainfall period of 1974. There was no change in gully width. The gully depth either remained constant or showed a very slight depth increase. There was no change in gully cross-sectional shape. Sediment was added in equal quantities to the sides and bottoms of those gullies which aggraded. Only the two Rosedale Gullies showed any significant change in the mean gully side-slope angle. This was expected as the gullies had sediment added to the gully sides, decreasing the mean gully side-slope angle by approximately 5 degrees.

Summary

During the summer rainfall period of 1973, all the gullies eroded. During this period the Roadside Gully drainage basin eroded by an estimated 0.04 feet.

Spring snowmelt runoff does not appear to have the capacity of initiating or maintaining gully erosion. Snowmelt runoff was shown to be merely a transporting agent of previously eroded sediments. Soil freeze-thaw processes are identified as the agents most probably responsible for all spring gully erosion. The deposition of sediment within the gullies is most probably due to soil freeze-thaw processes and the drainage basin meltwaters carrying suspended sediments to the gullies. Further research into the erosive effect of snow lingering within the gullies into late spring is recommended.

The summer rainfall period of 1974 had 2.73 times less precipitation and fewer thunderstorms than the previous summer. The 1974 precipitation was capable of continuing gully erosion within the smaller gullies, but was unable to erode the larger gullies. The 1974 precipitation was capable of removing sediment from the drainage basins and depositing the sediment within those larger gullies. Either the total amount, the intensity, or the available runoff of the 1974 summer precipitation period, was not capable of removing sediment from the larger gullies or continuing gully erosion.

Intense summer precipitation is the major agent responsible for gully erosion. If the data gathered from the sediment traps is representative of the erosion rate of non-intense precipitation, then intense summer precipitation is the most active eroding agent acting upon the gullies along this portion of the Manitoba Escarpment.

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CHAPTER VI

Conclusions

1. Gully Retardation Proposals

Gullying is a sign of wasting soil resources and misuse of farmland. The effects of the gullies along this portion of the Manitoba Escarpment are felt in many ways. Gullies decrease the resale value of farmland. They make access to parts of the farm difficult, and are often a danger to livestock. Cultivation is difficult in parts of the paddock left between gullies. If the paddocks are inaccessible, the amount of productive land is reduced. Gullies may undermine dams, buildings, or roads. Even if nothing obvious is threatened, a gully drains the soil moisture on either side of channel, leaving less soil moisture reserves for crop cultivation.

The 6 gullies studied were shown to be actively eroding, but methods of control could easily be initiated. The methods of gully control proposed for this area may be divided into three general groups:

(a) Gully Segregation
(b) Revegetation
(c) Structures

(a) Gully Segregation

Gully segregation is the enclosement of a gully by a fence or other means to prevent access to the gully by livestock. Two of the causes of gullying reported in this study are the overgrazing of pastures by livestock and the interception of downslope runoff by livestock paths. If a gully is revegetated with grasses or trees, the young plants must be protected from livestock. When the ground surface around a gully is saturated with water after snowmelt or heavy rainfall, concentrations of livestock can easily trample and destroy any existing vegetation alongside the gullies. Hoofprints can often penetrate deeply into the saturated soil removing the vegetative cover and exposing the underlying soil to erosion.

Gullies may also be segregated by placing livestock feeds and water troughs away from gullied areas. This would help to redirect livestock paths to new locations allowing existing livestock paths to revegetate. In the case of unnatural concentrations of flows due to man made tracks and field access roads, the use of alternate roads would reduce the incidence of gullying resulting from the development of ruts within the road.

Gully segregation isolates the gullies, and where applicable, allows natural stabilization process to occur within the gullies. The advantage of gully segregation is that it is inexpensive. The construction of temporary fences or the relocation of feeds and water troughs requires little expense and manpower.

(b) Revegetation

The revegetation of the gully drainage basins is recommended. Revegetation with natural grasses or trees is recommended as the grasses could later be used as livestock feed. Increasing the vegetative cover would reduce splash erosion and also reduce the velocity of overland flow. Erosion of the gully channel can be controlled by placing strips of sod-forming grasses down the thalweg of the gully, and where the gradient permits, the planting of grasses across the gully. The grasses act as silt traps. As the floor of the gully is slowly built up with silt, the grasses would spread up and down the gully channel.

The most important gully eroding agent identified in this study was intense summer precipitation. Because of the relatively infrequent occurrence of exceedingly intense thunderstorms, the planting of grasses or trees would have sufficient growing time to become established between the intense thunderstorm return periods, and not have the young sprouts washed away by surface runoff.

Revegetation with trees, as evident from the Rosedale Soil and Water Conservation Project, along severely eroded hillslopes, has been successful in preventing further gully and hillslope erosion. Trees with a mass of fibrous roots should be planted in trenches along the side of the gully. In this position the trees send out their roots laterally and protect the sides of the gullies. Edwards (1958) recommends that trees should never be planted in the gully channel or at the foot of the gully sides. In this position trees would only increase scour by causing flow to swirl around the roots during periods of high runoff.

Revegetation of the gully channel and its drainage basin produces the best erosion retardation results and is the most economical means of gully control. The revegetated slopes would retard soil and gully erosion, improve pastures, and make more feed available to livestock. Although the two Rosedale Gullies showed evidence of erosion, the revegetation project by the Provincial Government has resulted in vegetation growing along the length of the gully channel. As this vegetation becomes increasingly established, it would be expected that the rates of gully erosion will decrease.

(d) Structures

Man made structures are expensive alternatives and should only be considered where revegetation and gully segregation attempts fail, or where water erosion due to gullying is so severe that property is threatened. This author found no justification for the construction of structures within those gullies studied. On visits to the field area and surrounding areas, various gully retardation structures were observed and it is felt that some of these structures used are more of a hindrance than they are a benefit.

Gully control structures range from the simple and inexpensive to the elaborate and expensive. Simple control structures consist of rock debris or log check dams reinforced with rock. Heede(1960) has presented a well illustrated variety of simple control structures. Edwards(1958) and Minshall(1953) discuss a diversity of gully control structures of elaborate design. Their gully control structures are designed for very large and potentially destructive gullies.

Because the gullies studied along the Manitoba Escarpment are relatively small and located on small marginal farms, any gully control structures must be inexpensive and used only where other gully retardation attempts have failed. The best type of structure recommended is a log or rock check dam. The check dams reduce channel flow in times of severe runoff and allows silt build up behind the dams. The silt build up reduces the channel gradient and flow velocity. Best results could be obtained from using a series of check dams along the entire length of the gully channel.

The advantage of check dams is their cost. If constructed of rock debris, rocks removed from cultivated fields could be put to use in the construction of the check dams. Rock debris or hay should not be used to fill or cover the entire length of the gully. Rock debris or hay prevents the establishment of vegetation in the gully. Erosion will still continue, although at a slower rate, as flowing water percolates through the cover and undermines the hay or rock debris.

The 6 gullies studied were shown to be in active stages of erosion. If gully controls are required to stabilize gully erosion along this portion of the Manitoba Escarpment, the most economical means suggested is revegetation. The Rosedale Soil and Water Conservation Project, conducted by the Provincial Government, was proven to be a successful revegetation project. At the site of the 2 Rosedale Gullies, natural vegetation was established on the gully floor and along the gully sides. The result of this revegetation project was a stabilization of slopes and a much improved pasture. If similar revegetation attempts were applied to the remaining gullies in this study, the result would be a reduction of gully erosion with eventual gully stabilization.

2. Conclusions

In accordance with the Ireland, et al. (1939) gully classification system, 4 of the gullies in this study are classified as Stage 2 of gully development, and 2 gullies are classified as being in Stage 3. The form of 5 of the gullies are of the linear type, and one gully is classified as parallel. The gully heads are classified as inclined-pointed, although one gully could conceivably be regarded as inclined-rounded. The thalweg profiles illustrate that all the gullies are of the continuous gully type.

The drainage basins of all the gullies are elongated in shape due to their location on steep slopes. Each gully channel is characterized as having a rectangular shaped cross-section, the north facing side of the gully is steeper than the south facing gully side, and the gullies are wider than they are deep. There was no clearly-defined downstream morphometric trends along the gully channel.

Erosional forces are most active along the bottom portions of the gully channel and sides, and less active along the upper portions of the gully channel. This implies that the gully depth and side-slopes increase independently and at a faster rate than increases of gully width.

The morphometric characteristics of the gullies have led to the conclusion that the gullies are in a youthful stage of gully development. The small size of the gullies, the inefficient gully cross-sections (shape factor), the absence of downstream morphometric trends, and the concentration of vertical rather than lateral erosion along the gully thalweg, all suggest that the gullies have not developed to a stage of adjusting to hydraulic factors which are eroding the gullies.

The capacity for a gully to erode was shown to be dependent upon the percentage of silt-clay found within the surface material. Those areas along this portion of the Manitoba Escarpment which are most susceptible to gully erosion are characterized as having steep slopes, large drainage basins, and having surface materials containing high percentages of silt-clay.

During the period of this study, summer rainfall was identified as the principal gully eroding agent, while snowmelt runoff showed a tendency to add sediment to the gully channel. Based upon the 1973-1974 average, summer rainfall activity was 23.83 times more effective as an eroding agent than snowmelt runoff. Spring snowmelt runoff did not appear to have the capacity for initiating or maintaining gully erosion. Spring snowmelt runoff is merely a transporting agent of previously eroded sediments. Gully aggradation values attributed to the spring snowmelt period are most likely due to soil freeze-thaw processes operating along the gully channel, and drainage basin meltwaters carrying suspended sediments to the gully channel.

During the 1973 summer rainfall period, all the gullies eroded, and the Roadside Gully drainage basin was eroded by an estimated 0.04 feet. The 1974 summer rainfall was capable of continuing gully erosion within the smaller gullies, but was unable to erode the larger sized gullies. Either the total amount, the intensity, or the available run-off was not sufficient for removing sediment from the larger gullies or continuing gully erosion during the 1974 summer rainfall period.

Infrequent intense summer precipitation, exceeding the infiltration rate, is the major gully eroding agent. For 2 gullies studied during 1973, intense summer precipitation removed 588.5 and 63.3 times more material from the gullies and drainage basins than non-intense precipitation. It is suggested that the volume of eroded material removed from the gullies and drainage basins is related to the intensity duration and return period of the intense summer precipitation.

Water erosion by the process of gullying poses a definite threat to the agricultural productivity along the Manitoba Escarpment. Gullying is identified as an intermittent erosional phenomenon most active during intense summer precipitation periods and was found to be the major soil erosion process active in this area. If left unchecked, the incidence of gullying would certainly increase, resulting in flooding of the better agricultural land at the base of the Manitoba Escarpment, and silting up of ditches and natural drainageways. An overall program of soil conservation and water management is required to alleviate this problem.

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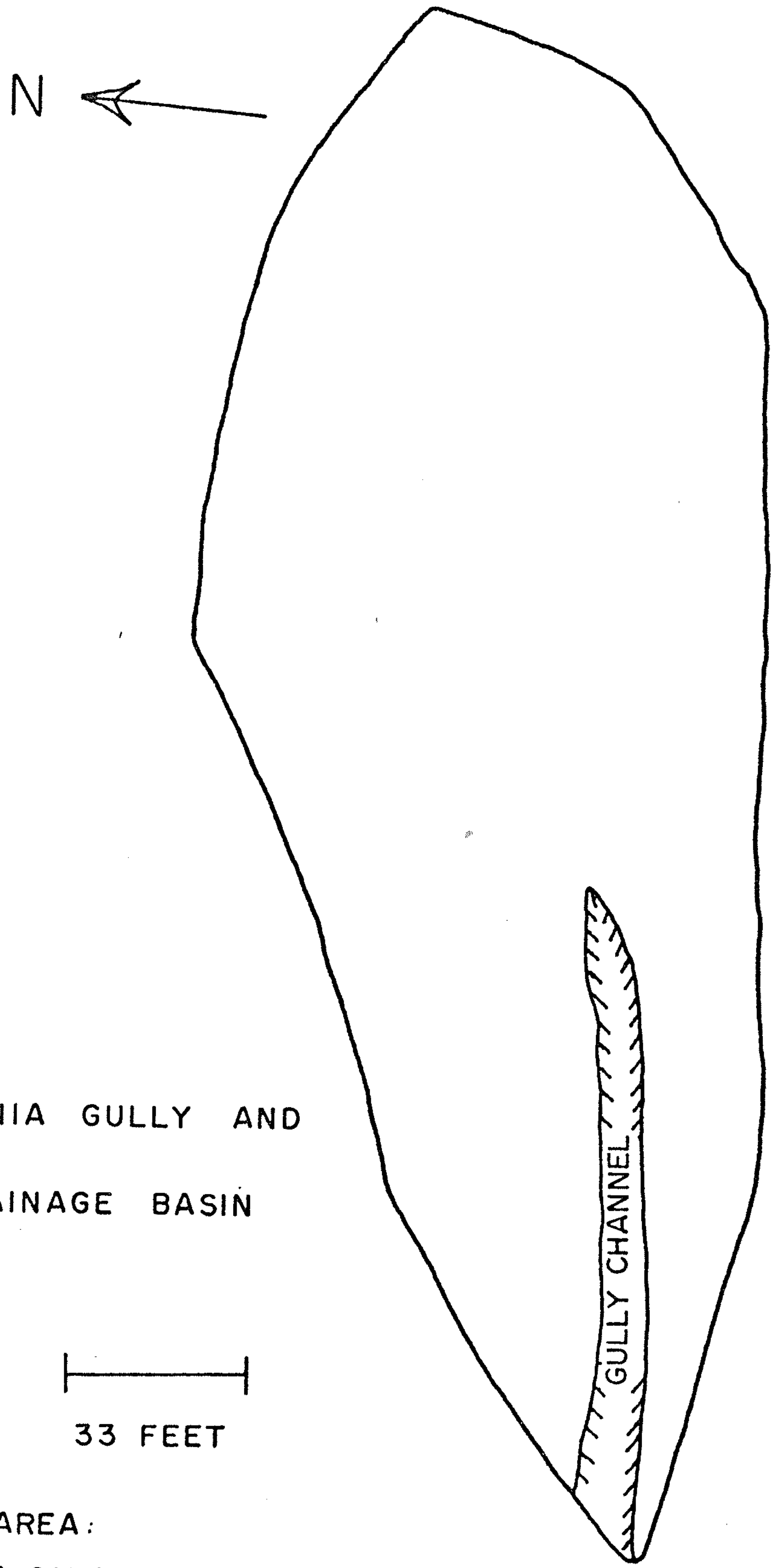
APPENDIX I

GULLY CHANNELS AND DRAINAGE BASINS

FIGURE I

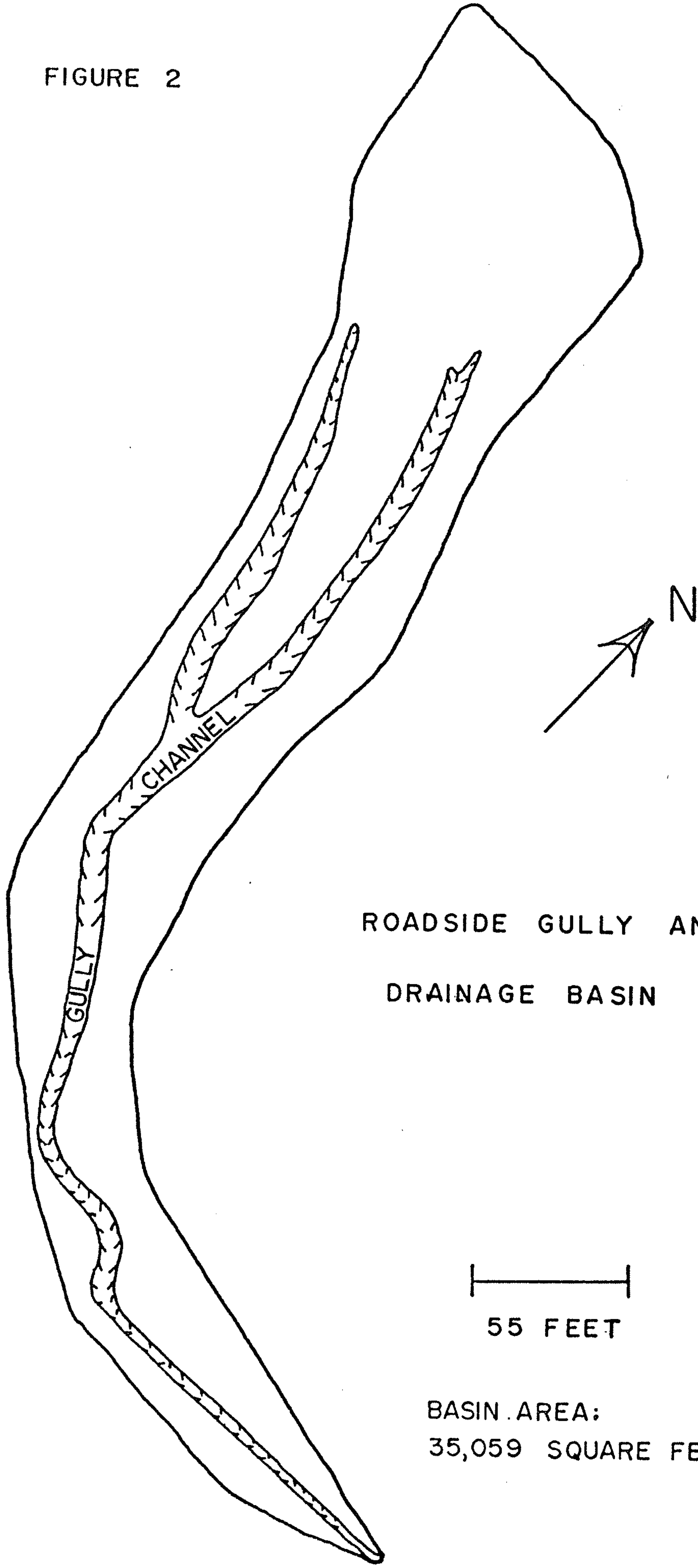


POLONIA GULLY AND DRAINAGE BASIN

33 FEET

BASIN AREA:
20,027 SQUARE FEET

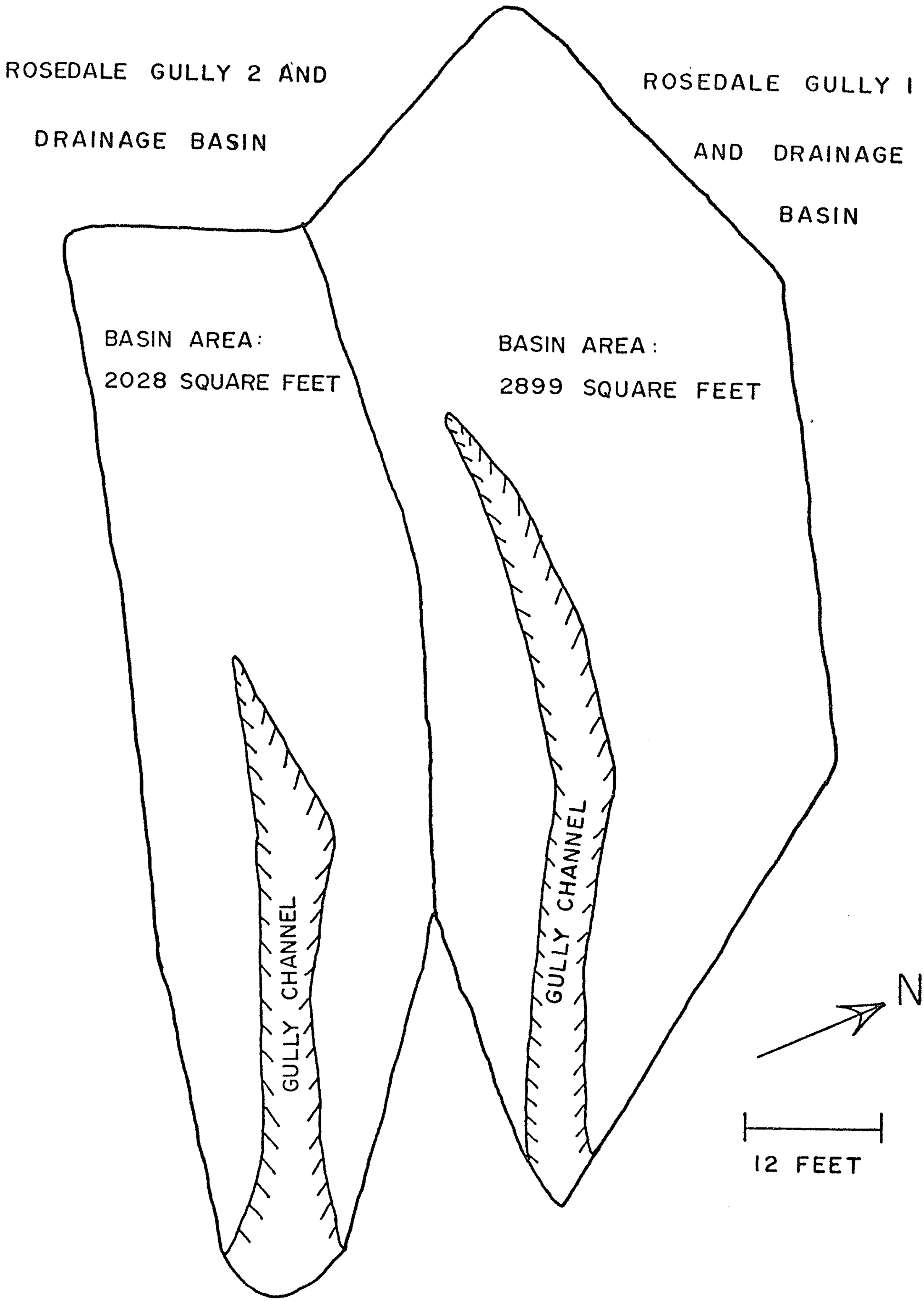
FIGURE 2



ROADSIDE GULLY AND DRAINAGE BASIN

BASIN AREA:
35,059 SQUARE FEET

FIGURE 3



ROSEDALE GULLY 2 AND DRAINAGE BASIN
ROSEDALE GULLY I AND DRAINAGE BASIN
BASIN AREA: 2028 SQUARE FEET
BASIN AREA: 2899 SQUARE FEET
GULLY CHANNEL
GULLY CHANNEL
N
12 FEET

FIGURE 4

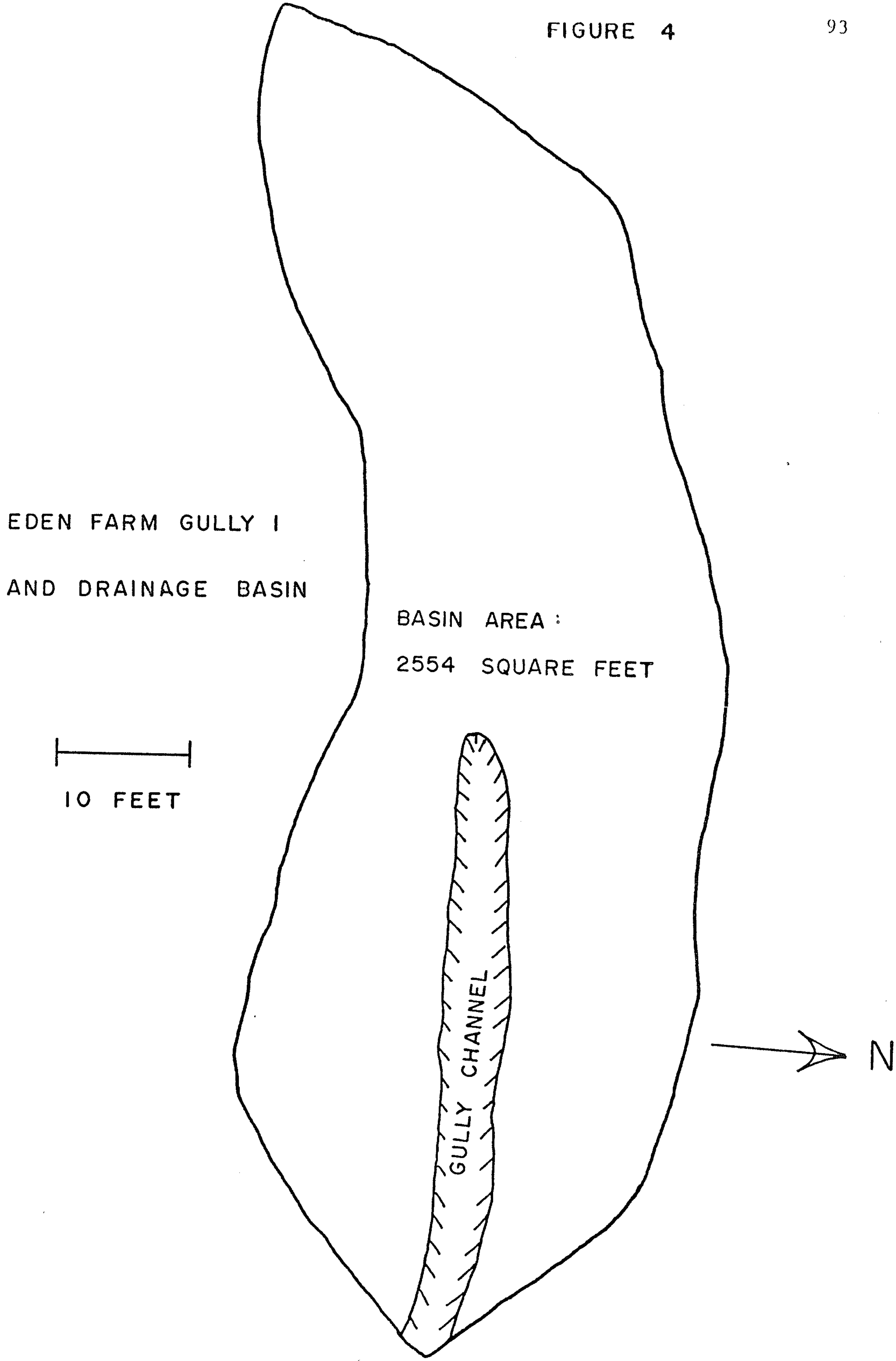
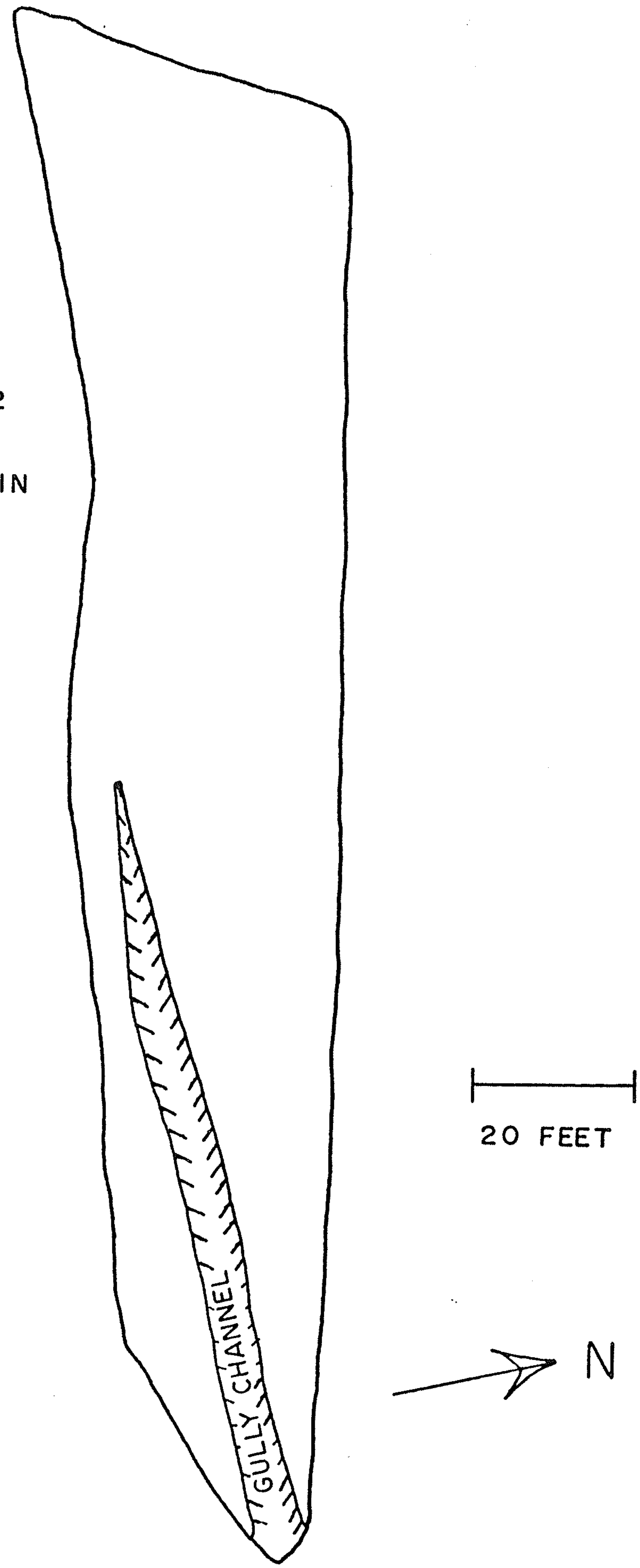

EDEN FARM GULLY I
AND DRAINAGE BASIN
BASIN AREA:
2554 SQUARE FEET
10 FEET
GULLY CHANNEL
N

FIGURE 5

EDEN FARM GULLY 2

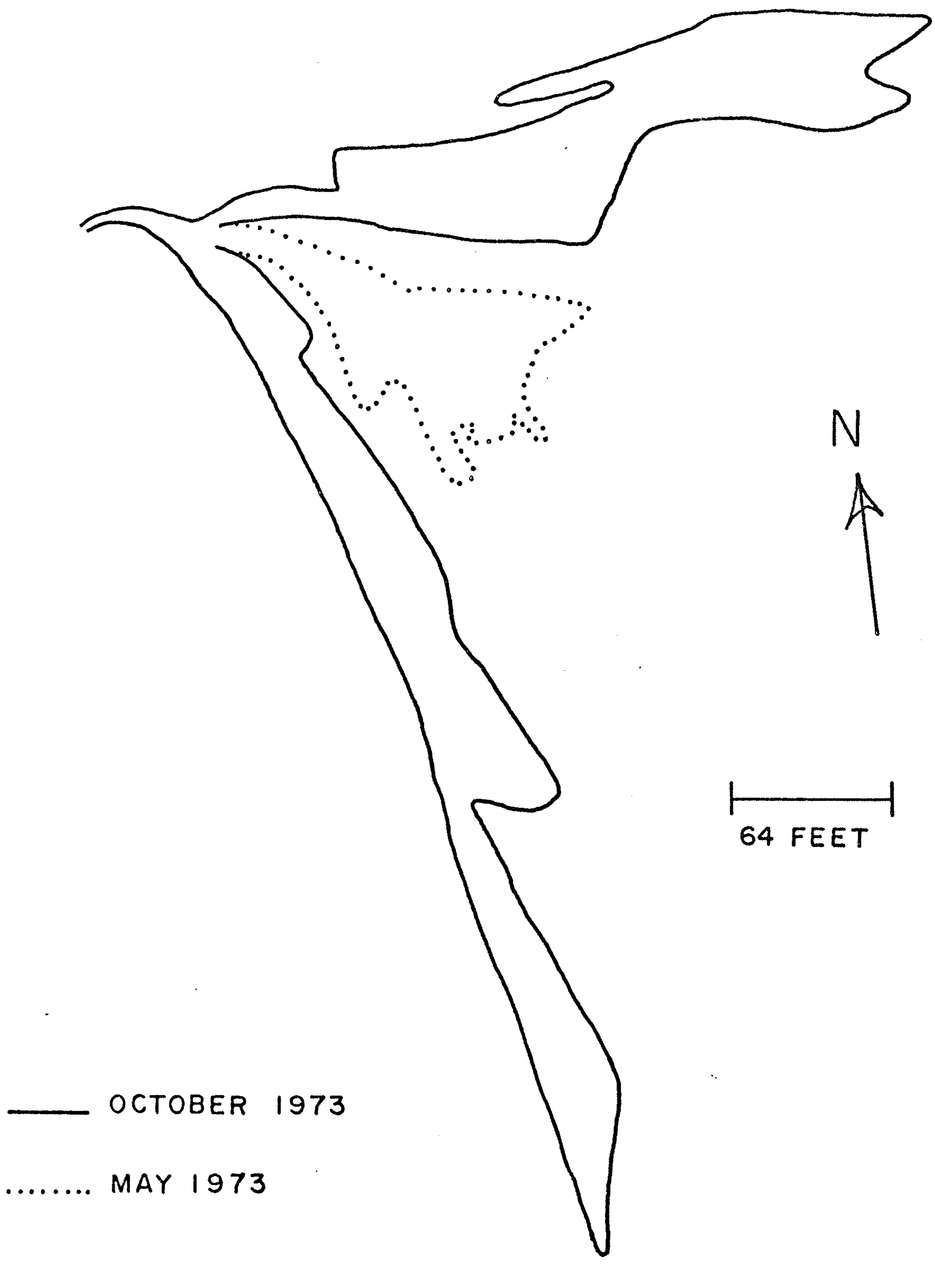
AND DRAINAGE BASIN



BASIN AREA:
5552 SQUARE FEET

FIGURE 6

ROADSIDE ALLUVIAL FAN



APPENDIX II

GULLY THALWEG PROFILES

FIGURE 1

POLONIA GULLY THALWEG PROFILE

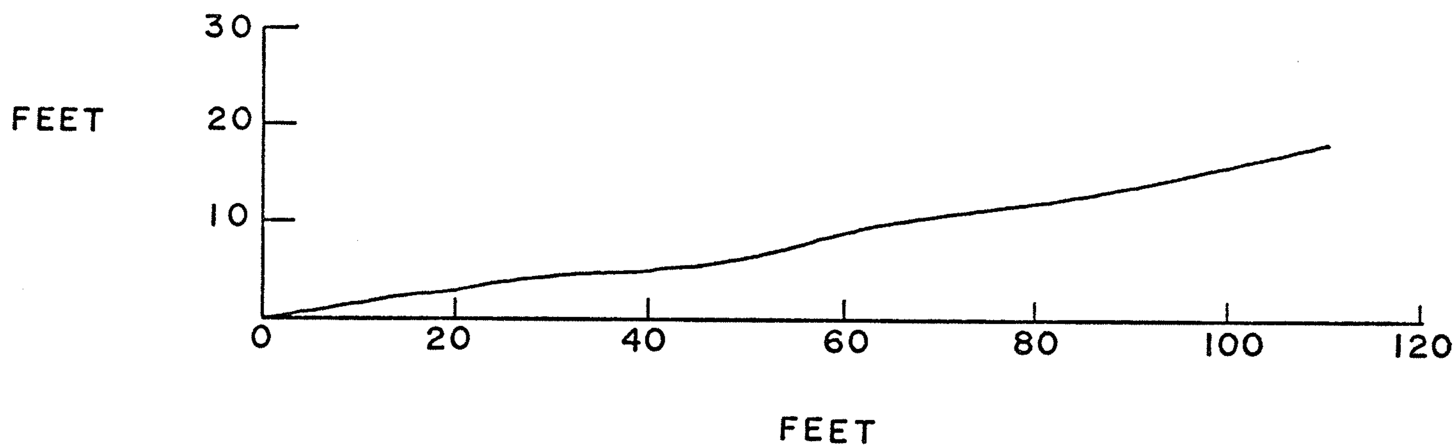


FIGURE 2

ROADSIDE GULLY THALWEG PROFILE

The gully thalweg profile is representative of both the bifurcated gully head channels, as both the gully head channels are at the same elevation.

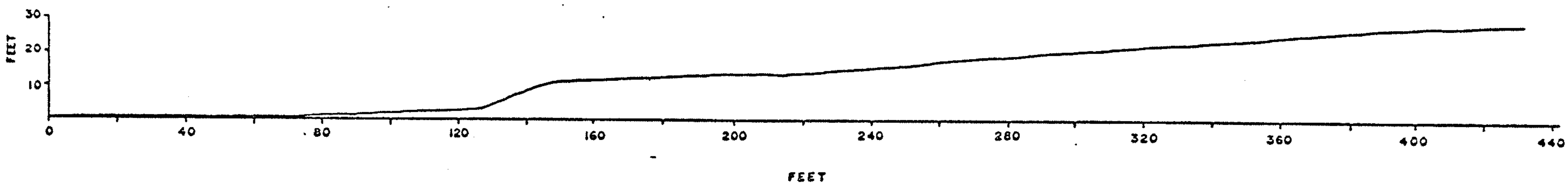


FIGURE 3

ROSEDALE GULLY I
THALWEG PROFILE

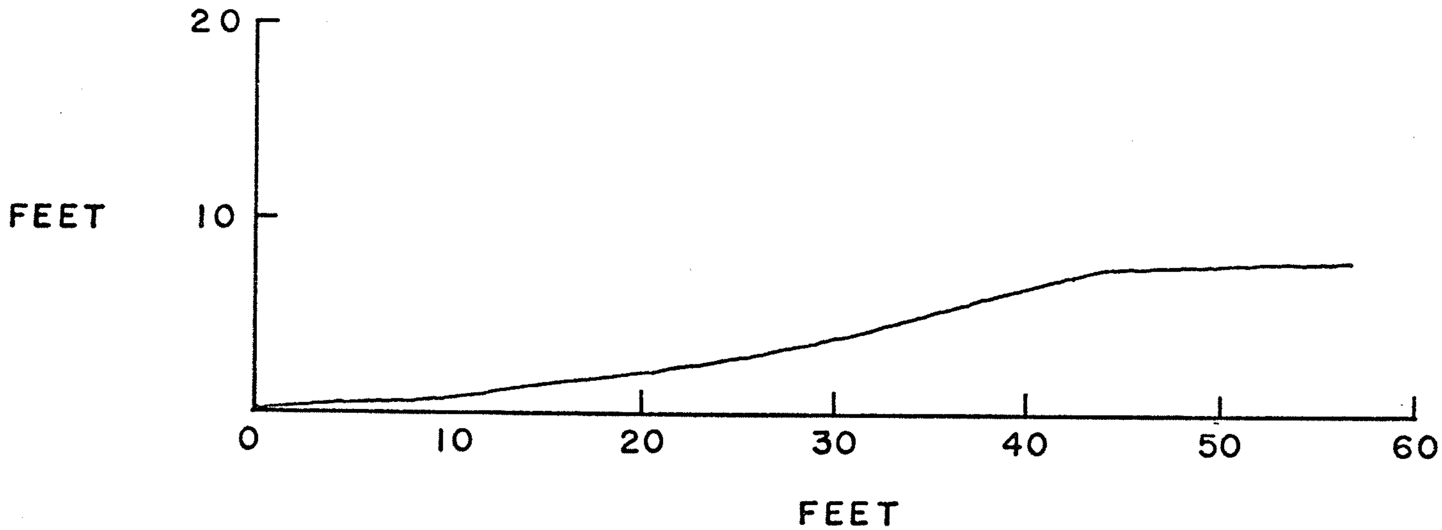


FIGURE 4

ROSEDALE GULLY 2
THALWEG PROFILE

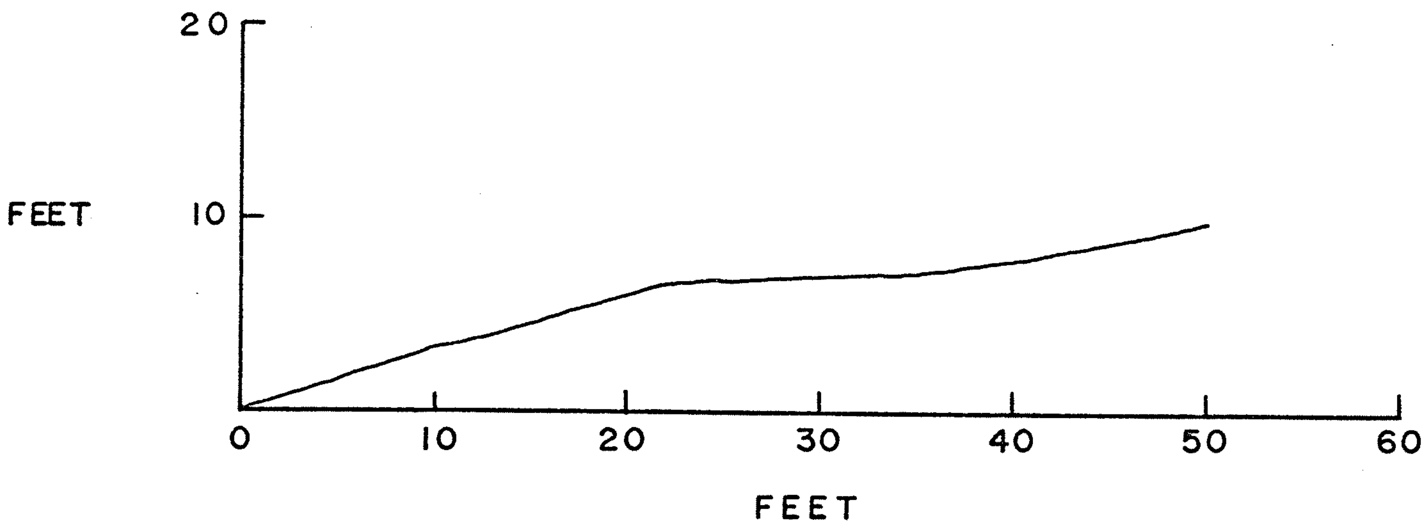


FIGURE 5

EDEN FARM GULLY I
THALWEG PROFILE

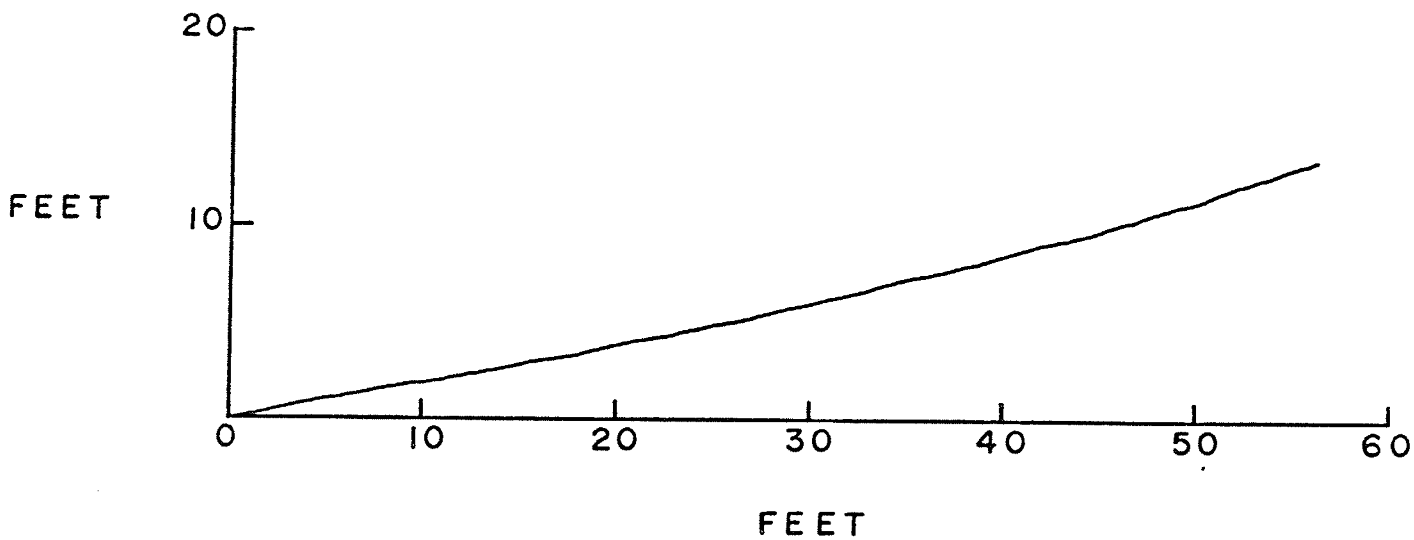
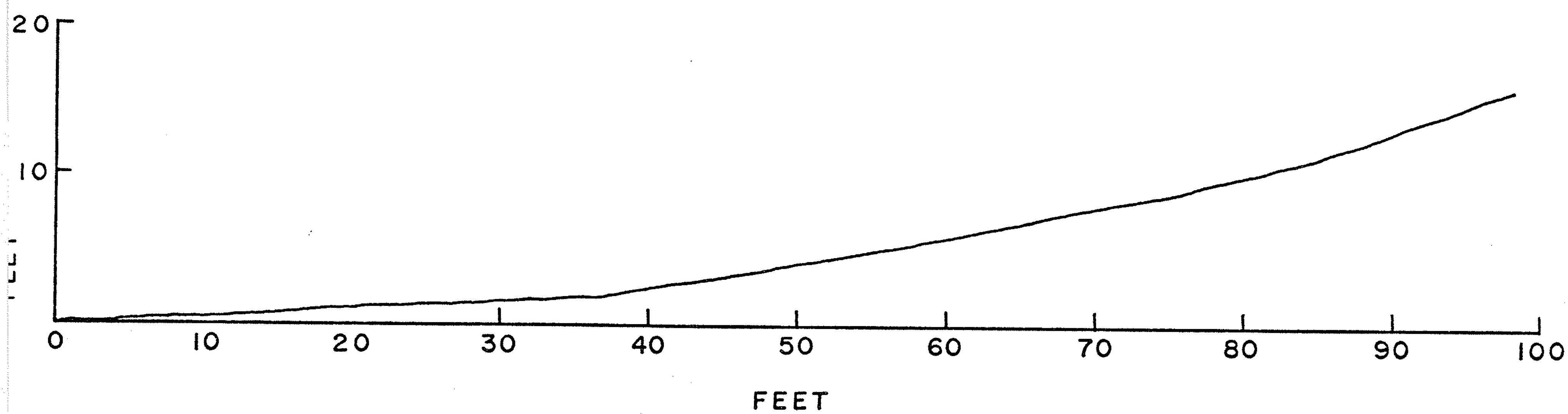


FIGURE 6

EDEN FARM GULLY 2
THALWEG PROFILE



APPENDIX III

GULLY MORPHOMETRIC DATA

TABLE 1

GULLY MORPHOMETRIC PROPERTIES

Symbol	Definition
W	Mean Gully Width
D	Mean Gully Depth
W/D	Ratio of Mean Gully Width to Mean Gully Depth
θ	Mean Gully Side Slope Angle
θN	Mean Gully North Facing Slope Angle
θS	Mean Gully South Facing Slope Angle
θT	Thalweg Slope Angle Defined as Rise Over Run
F	Total Gully Fall Defined as the Difference in Elevation Between the Gully Head and the Terminus of the Gully Channel
L	Gully Length
A	Gully Drainage Basin Area
a	Mean Gully Cross Sectional Area
v	Mean Gully Volume Defined as Gully Length Times Mean Gully Cross-Sectional Area
V/L	Volume of Eroded Material Per Foot of Gully Length
$\theta/\theta T$	Ratio of Mean Gully Side Slope Angle to Thalweg Slope Angle
E	Elongation Ratio Defined as (Schumm 1956, p. 612)

$$E = \frac{2\sqrt{\frac{A}{\pi}}}{L}$$

where: A = Area of Drainage basin in square feet

π = 3.14

L = The maximum length of the drainage basin measured parallel to the major channel

TABLE 1 Cont'd

Symbol	Definition
% G	Per Cent Gravel Within the Surface Material
% S	Per Cent Sand Within the Surface Material
% S-C	Per Cent Silt-Clay Within the Surface Material
α	Hillslope Angle Defined as Per Cent Slope

TABLE 2

MEAN GULLY WIDTH - W (feet)

Gully	May 1973	October 1973	May 1974	October 1974
Polonia	7.2	7.2	7.2	7.1
Roadside	7.6	7.7	7.7	7.6
Rosedale				
Gully 1	3.9	3.9	3.9	3.9
Gully 2	4.1	4.1	4.1	4.1
Eden Farm				
Gully 1	4.9	4.9	4.9	5.0
Gully 2	6.8	6.8	6.8	6.8

TABLE 3

MEAN GULLY DEPTH - D (feet)

Gully	May 1973	October 1973	May 1974	October 1974
Polonia	2.4	2.3	2.4	2.4
Roadside	2.6	3.1	3.1	2.9
Rosedale				
Gully 1	1.5	1.6	1.4	1.4
Gully 2	1.3	1.4	1.2	1.3
Eden Farm				
Gully 1	2.5	3.1	3.1	3.0
Gully 2	3.3	3.8	3.7	3.7

TABLE 4

RATIO OF MEAN GULLY WIDTH TO MEAN GULLY DEPTH - $W/_D$ (feet)

Gully	May 1973	October 1973	May 1974	October 1974
Polonia	3.0	3.0	3.0	2.9
Roadside	2.8	2.5	2.5	2.7
Rosedale				
Gully 1	2.6	2.5	2.8	2.7
Gully 2	3.2	2.9	3.4	3.1
Eden Farm				
Gully 1	1.9	1.6	1.6	1.6
Gully 2	2.0	1.8	1.8	1.8

TABLE 5

MEAN GULLY SIDE SLOPE ANGLE - θ (degrees)

Gully	May 1973	October 1974	May 1974	October 1974
Polonia	39.53	39.95	38.07	37.85
Roadside	33.90	38.45	38.30	34.65
Rosedale				
Gully 1	36.75	34.45	30.05	32.50
Gully 2	39.70	36.62	31.74	33.15
Eden Farm				
Gully 1	39.59	48.59	49.63	43.85
Gully 2	43.20	47.35	49.65	46.35

TABLE 6

MEAN GULLY NORTH FACING SLOPE ANGLE - θN
(degrees)

Gully	May 1973	October 1973	May 1974	October 1974
Polonia	43.87	42.86	40.50	38.10
Roadside	35.40	43.60	41.10	36.70
Rosedale				
Gully 1	42.00	33.00	31.80	32.60
Gully 2	43.70	40.00	32.04	33.60
Eden Farm				
Gully 1	39.53	52.06	53.86	48.50
Gully 2	43.90	55.40	54.80	48.80

TABLE 7

MEAN GULLY SOUTH FACING SLOPE ANGLE - θS
(degrees)

Gully	May 1973	October 1973	May 1974	October 1974
Polonia	35.20	37.54	35.65	37.60
Roadside	32.40	33.30	35.50	32.60
Rosedale				
Gully 1	31.50	35.90	28.30	32.40
Gully 2	35.70	33.24	31.44	32.70
Eden Farm				
Gully 1	39.66	45.13	45.40	39.20
Gully 2	42.50	39.30	44.50	43.90

TABLE 8

THALWEG SLOPE ANGLE DEFINED AS RISE OVER RUN - θT (feet)

Gully	θT
Polonia	0.16
Roadside	0.07
Rosedale	
Gully 1	0.13
Gully 2	0.19
Eden Farm	
Gully 1	0.26
Gully 2	0.16

TABLE 9

TOTAL GULLY FALL - F (feet)

Gully	F
Polonia	18.00
Roadside	30.20
Rosedale	
Gully 1	7.57
Gully 2	9.95
Eden Farm	
Gully 1	14.57
Gully 2	16.00

TABLE 10

GULLY LENGTH - L (feet)

Gully	L
Polonia	110
Roadside	580
Rosedale	
Gully 1	56.9
Gully 2	50
Eden Farm	
Gully 1	56.6
Gully 2	98

TABLE 11

GULLY DRAINAGE BASIN AREA - A
(square feet)

Gully	A
Polonia	20027
Roadside	35059
Rosedale	
Gully 1	2899
Gully 2	2028
Eden Farm	
Gully 1	2554
Gully 2	5552

TABLE 12

MEAN GULLY CROSS SECTIONAL AREA - a
(square feet)

Gully	May 1973	October 1973	May 1974	October 1974
Polonia	8.52	9.51	9.81	9.77
Roadside	11.27	13.74	13.74	13.43
Rosedale				
Gully 1	2.71	3.55	2.98	3.02
Gully 2	2.35	3.16	2.48	2.64
Eden Farm				
Gully 1	6.34	7.66	7.65	8.03
Gully 2	9.40	10.91	11.09	11.56

TABLE 13

MEAN GULLY VOLUME - v (cubic feet)

Gully	May 1973	October 1973	May 1974	October 1974
Polonia	937.20	1046.10	1079.10	1074.70
Roadside	6536.60	7969.20	7969.20	7789.40
Rosedale				
Gully 1	154.20	202	169.56	171.84
Gully 2	117.50	158	124	132
Eden Farm				
Gully 1	358.84	433.56	432.99	454.50
Gully 2	921.20	1069.18	1086.82	1132.88

TABLE 14

VOLUME OF ERODED MATERIAL PER FOOT OF GULLY LENGTH - V/L

(cubic feet/foot)

Gully	May 1973 to October 1973	October 1973 to May 1974	May 1974 to October 1974
Polonia	- 0.99	- 0.30	+ 0.04
Roadside	- 2.47	0.00	+ 0.31
Rosedale			
Gully 1	- 0.84	+ 0.57	- 0.04
Gully 2	- 0.81	+ 0.68	- 0.16
Eden Farm			
Gully 1	- 1.32	+ 0.01	- 0.38
Gully 2	- 1.51	- 0.18	- 0.47

(+) indicates aggradation

(-) indicates degradation

TABLE 15

RATIO OF MEAN GULLY SIDE SLOPE ANGLE TO THALWEG SLOPE ANGLE - $\theta/\theta T$ (degrees)

Gully	$\theta/\theta T$
Polonia	3.48
Roadside	9.08
Rosedale	
Gully 1	4.44
Gully 2	3.20
Eden Farm	
Gully 1	3.24
Gully 2	5.18

TABLE 16

ELONGATION RATIO - E (dimensionless)

Gully	E
Polonia	0.28
Roadside	0.18
Rosedale	
Gully 1	0.29
Gully 2	0.27
Eden Farm	
Gully 1	0.27
Gully 2	0.21

TABLE 17

PER CENT GRAVEL, SAND, AND SILT-CLAY

Gully	Per Cent Gravel	Per Cent Sand	Per Cent Silt-Clay
Polonia	6	82	12
Roadside	22	69	8
Rosedale			
Gully 1	42	57	1
Gully 2	42	57	1
Eden Farm			
Gully 1	38	58	4
Gully 2	20	72	8

TABLE 18

HILLSLOPE ANGLE DEFINED AS PER CENT SLOPE

Gully	α
Polonia	16.4
Roadside	6.7
Rosedale	
Gully 1	13.8
Gully 2	13.4
Eden Farm	
Gully 1	25.2
Gully 2	13.5

TABLE 19

MEAN NORTH FACING SIDE OF GULLY MINUS MEAN SOUTH FACING SIDE OF GULLY - $\theta N - \theta S$ (degrees)

Gully	May 1973	October 1973	May 1974	October 1974
Polonia	8.67	4.82	4.85	0.5
Roadside	3	10.3	5.6	4.1
Rosedale				
Gully 1	10.5	- 2.9	3.5	0.2
Gully 2	8	6.76	0.6	0.9
Eden Farm				
Gully 1	- 0.13	6.93	8.46	9.3
Gully 2	1.40	16.10	10.30	4.90

TABLE 20

GULLY SHAPE FACTOR

Defined as the mean value of each gully cross-sectional shape factor

Gully	Shape Factor
Polonia	1.20
Roadside	1.16
Rosedale	
Gully 1	1.36
Gully 2	1.28
Eden Farm	
Gully 1	1.50
Gully 2	1.21

APPENDIX IV

STATISTICAL ANALYSIS

Statistical Analysis

X = Independent Variable

Y = Dependent Variable

$x = (X - \bar{X})$

$y = (Y - \bar{Y})$

$\bar{X} = \Sigma X / N$

$\bar{Y} = \Sigma Y / N$

$$\Sigma x^2 = \Sigma X^2 - \bar{X} \Sigma X = \Sigma (X - \bar{X})^2$$

$$\Sigma y^2 = \Sigma Y^2 - N \bar{X} \bar{Y} = \Sigma (Y - \bar{Y})^2$$

$$\Sigma xy = \Sigma X Y - \bar{X} \Sigma Y = \Sigma (X - \bar{X}) (Y - \bar{Y})$$

Central Moments About the Mean

$$r^2 = \frac{(x y)^2}{\Sigma x^2 \Sigma y^2}$$ Coefficient of Determination

$$r = \sqrt{r^2}$$ Pearsons Correlation Coefficient

$$b = \Sigma x y / \Sigma x^2$$ Slope of Regression Line

$$a = \bar{Y} - b \bar{X}$$ The Y - Intercept of the Regression Line

The standard error of estimate is an estimate of the scatter of Y - values about the regression line, and is expressed as follows:

$$S_B = \frac{\sqrt{\frac{\Sigma(y - Y)^2}{n-2}}}{\sqrt{\Sigma x_i^2}}$$ (Wonnacott and Wonnacott, 1970)

If the scatter is small, the observed trend is not likely to be due to chance, but a large scatter of points suggests that the trend may be due to chance. Also, if the regression line has a very small slope (being nearly parallel to the X - axis) the trend is very weak and may be due to chance. Thus the significance of a regression may be calculated by a statistic which varies directly with the slope of the regression line, and varies inversely as the amount of scatter decreases.

The significance level of the regression is found by the relationship of the regression slope to the estimated scatter of Y - values about the slope of the regression line in the form of:

$$t = \frac{b}{S_B}$$ (Wonnacott and Wonnacott, 1970)

where: b = the regression line slope; and

S_B = the estimate of the scatter of the Y - values about the regression line; and

t = the level of significance referred to as the t - distribution.

To find the probability of "t" being due to chance, the "t" value is referred to the t - distribution under n-2 degrees of freedom, and the corresponding probability of the relationship being due to chance alone is noted.

APPENDIX V

DATA PRESENTATION

TABLE 1

STUDENT'S "t" CRITICAL POINTS

		Probability				
n-2		0.10	0.05	0.025	0.01	0.005
degrees of freedom	4	1.533	2.132	2.776	3.747	4.604

TABLE 2

MEAN GULLY WIDTH AS THE DEPENDENT VARIABLE

Independent Variable	"t" value	Correlation Coefficient	Significance Level At Or Above 0.10
D	1.4301	0.7149	
W/D	0.1811	0.0900	
θ	0.6106	0.3052	
θN	0.7026	0.3512	
θS	0.4818	0.2408	
θT	-0.9424	0.4706	
F	1.7305	0.8652	0.10
L	1.3082	0.6540	
A	3.9754	0.8087	0.01
a	1.9081	0.9539	0.10
v	1.3448	0.6723	
V/L	1.5356	0.7672	0.10
θ/θT	1.2151	0.6075	
E	-1.4242	0.7008	
%G	-1.7940	0.8969	0.10
%S	1.7245	0.8622	0.10
%S-C	1.8513	0.9244	0.10
α	-0.8172	0.4047	

TABLE 3

LOGARITHM MEAN GULLY WIDTH AS THE DEPENDENT VARIABLE

Logarithm Independent Variable	"t" value	Correlation Coefficient	Significance Level At Or Above 0.10
D	1.5108	0.7511	
W/D	-0.1277	0.0682	
θ	0.7409	0.2722	
θN	0.8396	0.3508	
θS	0.6222	0.2978	
θT	-0.9160	0.4501	
F	1.8411	0.9177	0.10
L	1.5653	0.7813	0.10
A	1.7565	0.8779	0.10
a	1.8482	0.9235	0.10
v	1.1813	0.9054	0.10
V/L	1.5704	0.7847	0.10
θ/θT	1.1136	0.5530	
E	1.2282	0.6759	
%G	-1.5130	0.7555	0.10
%S	1.7823	0.8779	0.10
%S-C	1.8853	0.9420	0.10
α	-0.8597	0.4274	

TABLE 4

LINEAR REGRESSION OF THE FORM $Y = a + b X$

Dependent Variable	Independent Variable	Intercept (a)	Slope (b)
W	D	0.1710	0.3930
W	$W/_D$	2.6743	- 0.0329
W	θ	33.4672	1.0173
W	θN	34.2086	1.3471
W	θS	32.7347	0.6845
W	θT	0.2652	- 0.0180
W	F	- 7.9670	4.1718
W	L	-316.7495	82.5718
W	A	- 26.6721	6.6055
W	a	- 6.2416	2.4256
W	v	- 50.5611	11.7884
W	$V/_L$	- 0.3752	0.1422
W	$\theta/_{\theta T}$	- 0.0085	0.8301
W	E	0.3582	- 0.0188
W	%G	74.3101	- 7.9868
W	%S	34.8991	5.3737
W	%S-C	- 8.6111	2.4795
W	α	23.6500	- 0.0152

W = Mean Gully Width

TABLE 5

POWER FUNCTION OF THE FORM $Y = a X^b$

Logarithm Dependent Variable	Logarithm Independent Variable	Intercept (a)	Slope (b)
W	D	0.3431	1.0966
W	$^W/_D$	2.6749	-0.0582
W	θ	28.6550	0.1788
W	θN	28.3139	0.2225
W	θS	28.7276	0.1377
W	θT	0.5126	-0.7112
W	F	0.9858	1.5599
W	L	1.2894	2.5211
W	A	0.0113	3.6540
W	a	0.1488	2.1933
W	v	0.1859	4.7324
W	$^V/_L$	0.0022	3.0717
W	$^θ/_{θT}$	1.1361	0.7880
W	E	0.5612	-0.4768
W	%G	742.2223	1.9952
W	%S	38.8536	0.4721
W	%S-C	0.0072	3.6317
W	α	42.4100	-0.6503

W = Mean Gully Width

TABLE 6

MEAN GULLY DEPTH AS THE DEPENDENT VARIABLE

Independent Variable	"t" value	Correlation Coefficient	Significance Level At or Above 0.10
W	1.4298	0.7149	
W/D	-1.4966	0.7481	
θ	1.6459	0.8229	0.10
θN	1.7052	0.8526	0.10
θS	1.5524	0.7762	0.10
θT	0.0057	0.0007	
F	1.1720	0.5860	
L	0.6537	0.3268	
A	0.6081	0.3039	
a	1.7032	0.8516	0.10
v	0.7271	0.3634	
V/L	1.9181	0.9584	0.10
θ/θT	0.7890	0.3944	
E	-1.3609	0.6711	
%G	-1.0705	0.5346	
%S	0.9707	0.4853	
%S-C	1.2494	0.6246	
α	0.1529	0.0734	

TABLE 7

LOGARITHM MEAN GULLY DEPTH AS THE DEPENDENT VARIABLE

Logarithm Independent Variable	"t" value	Correlation Coefficient	Significance Level At or Above 0.10
W	1.5180	0.7567	
W/D	-1.4123	0.6977	
θ	1.6361	0.8006	0.10
θN	1.6653	0.8227	0.10
θS	1.5403	0.7395	0.10
θT	-0.2051	0.1000	
F	1.4890	0.7425	
L	0.9939	0.4964	
A	0.9462	0.4817	
a	1.8613	0.9301	0.10
v	1.4599	0.7293	
V/L	1.9533	0.9764	0.10
θ/θT	0.8427	0.4167	
E	-1.2695	0.6306	
%G	-0.7855	0.3911	
%S	1.1352	0.5560	
%S-C	1.7102	0.8548	0.10
α	-0.0409	0.0000	

TABLE 8

LINEAR REGRESSION OF THE FORM $Y = a + b X$

Dependent Variable	Independent Variable	Intercept (a)	Slope (b)
D	W	2.5919	1.3006
D	W/D	3.6882	- 0.4945
D	θ	27.1851	4.9884
D	θN	27.4908	5.9477
D	θS	26.9055	4.0163
D	θT	0.1612	0.0002
D	F	3.5407	5.1402
D	L	- 24.0762	75.0666
D	A	0.3486	4.5225
D	a	- 1.8336	3.9392
D	v	- 1.9138	11.5949
D	V/L	- 0.3431	0.3232
D	θ/θT	2.3840	0.9806
D	E	0.3298	- 0.0328
D	%G	49.4078	- 8.6609
D	%S	52.4424	5.5032
D	%S-C	- 1.7413	3.0444
D	α.	13.6200	0.0050

TABLE 9

POWER FUNCTION OF THE FORM $Y = a X^b$

Logarithm Dependent Variable	Logarithm Independent Variable	Intercept (a)	Slope (b)
D	W	3.6585	0.5213
D	W/D	3.4834	-0.4429
D	θ	31.3040	0.2673
D	θN	32.3817	0.3036
D	θS	30.0400	0.2346
D	θT	0.1645	-0.1097
D	F	7.1105	0.8713
D	L	40.2624	1.1104
D	A	1987.0098	1.3883
D	a	1.8767	1.5200
D	v	75.7356	2.6235
D	V/L	0.0358	2.6089
D	θ/θT	3.1579	0.4102
D	E	0.3141	-0.2948
D	%G	42.6580	-0.7145
D	%S	54.8025	0.2107
D	%S-C	0.5876	2.2713
D	α	14.0500	-0.0213

TABLE 10

MEAN GULLY SIDE - SLOPE ANGLE AS THE DEPENDENT

Independent Variable	"t" value	Correlation Coefficient	Significance Level At or Above 0.10
W	0.6106	0.3052	
D	1.6468	0.8229	0.10
$^{W}/_{D}$	-1.6899	0.8453	0.10
θN	1.8497	0.9974	0.10
θS	1.9910	0.9953	0.10
θT	1.1052	0.5479	
F	0.1994	0.0994	
L	-0.4451	0.2224	
A	-0.4540	0.2269	
a	0.8927	0.4463	
v	-0.3665	0.1830	
$^{V}/_{L}$	1.3705	0.6866	
θ/θT	-0.1335	0.1679	
E	-0.4897	0.2389	
%G	-0.5366	0.2681	
%S	0.4816	0.2406	
%S-C	0.7133	0.3566	
α	1.0925	0.5462	

TABLE 11

LOGARITHM MEAN GULLY SIDE - SLOPE ANGLE AS THE DEPENDENT VARIABLE

Logarithm Independent Variable	"t" value	Correlation Coefficient	Significance Level At or Above 0.10
W	0.7418	0.2716	
D	1.6360	0.7976	0.10
W/D	-1.6970	0.7905	0.10
θN	2.0593	0.8918	0.10
θS	2.0942	0.8725	0.10
θT	0.9633	0.4646	
F	0.6256	0.2716	
L	-0.1789	0.0748	
A	-0.1258	0.0000	
a	1.1624	0.5740	
v	0.4085	0.1992	
V/L	1.3979	0.6949	
$\theta/\theta T$	-2.0745	0.1380	0.10
E	-0.4470	0.0000	
%G	-0.3549	0.1303	
%S	0.6691	0.0780	
%S-C	1.1349	0.5640	
α	1.0052	0.4766	

TABLE 12

LINEAR REGRESSION OF THE FORM Y = a + b X

Dependent Variable	Independent Variable	Intercept (a)	Slope (b)
θ	W	2.1546	0.0916
θ	D	- 2.9028	0.1357
θ	W/D	6.1066	- 0.0921
θ	θN	- 2.9342	1.1426
θ	θS	3.2693	0.8496
θ	θT	- 0.0861	0.0063
θ	F	10.3740	0.1443
θ	L	490.1534	- 8.4319
θ	A	33.2561	- 0.5570
θ	a	- 5.6719	0.3406
θ	v	55.2155	- 0.9642
θ	V/L	- 1.0549	0.0381
θ	θ/θT	7.4794	- 0.0689
θ	E	0.3247	- 0.0019
θ	%G	56.5241	- 0.7169
θ	%S	48.1221	0.4504
θ	%S-C	- 5.6073	0.2867
θ	α	- 8.3700	0.0059

TABLE 13

POWER FUNCTION OF THE FORM $Y = a X^b$

Logarithm Dependent Variable	Logarithm Independent Variable	Intercept (a)	Slope (b)
θ	W	0.3383	0.7670
θ	D	0.0003	2.4078
θ	W/D	857.2352	- 1.6002
θ	θN	0.6604	1.1306
θ	θS	1.0807	0.9602
θ	θT	0.0005	1.5511
θ	F	0.2567	1.1022
θ	L	908.6570	- 0.6022
θ	A	45.9515	- 0.5454
θ	a	0.0002	2.8579
θ	v	0.1997	2.2102
θ	V/L	0.0000	5.6193
θ	θ/θT	16.0879	- 0.3522
θ	E	0.7743	- 0.3125
θ	%G	832.5302	- 0.9715
θ	%S	16.1622	0.3806
θ	%S-C	0.0000	4.5511
θ	α	0.0400	1.5738

TABLE 14

GULLY FALL AS THE DEPENDENT VARIABLE

Independent Variable	"t" value	Correlation Coefficient	Significance Level At or Above 0.10
W	1.7342	0.8671	0.10
D	1.1719	0.5860	
W/D	-0.1143	0.0565	
θ	0.1994	0.0994	
θN	0.3032	0.1509	
θS	0.0600	0.0300	
θT	-1.0769	0.5349	
L	1.8282	0.9141	0.10
A	1.8486	0.9242	
a	1.7955	0.8975	
v	1.8513	0.9256	0.10
V/L	1.5208	0.7619	
θ/θT	1.6362	0.8179	0.10
E	-1.6666	0.8078	0.10
%G	-1.1893	0.5946	0.10
%S	1.0620	0.5309	
%S-C	1.3219	0.6607	
α	-0.9181	0.4606	0.10

TABLE 15

LOGARITHM GULLY FALL AS THE DEPENDENT VARIABLE

Logarithm Independent Variable	"t" value	Correlation Coefficient	Significance Level At or Above 0.10
W	1.8452	0.9180	0.10
D	1.4902	0.7424	
W/D	-0.2612	0.1187	
θ	0.6262	0.2789	
θN	0.7379	0.3586	
θS	0.4957	0.1749	
θT	-1.0083	0.5026	
L	1.7514	0.8752	0.10
A	1.7034	0.8513	0.10
a	1.8180	0.9085	0.10
v	1.9133	0.9564	0.10
V/L	1.6247	0.8119	0.10
θ/θT	1.2612	0.6296	
E	-1.5673	0.7788	0.10
%G	-1.0598	0.5286	
%S	1.3141	0.6404	
%S-C	1.7002	0.8497	
α	-0.9381	0.4658	

TABLE 16

LINEAR REGRESSION OF THE FORM $Y = a + b X$

Dependent Variable	Independent Variable	Intercept (a)	Slope (b)
F	W	3.0207	0.1736
F	D	1.3613	0.0668
F	W/D	2.5540	- 0.0043
F	θ	38.2176	0.0689
F	θN	40.0343	0.1202
F	θS	36.3943	0.0177
F	θT	0.2290	- 0.0042
F	L	-225.4926	23.9325
F	A	- 13.7994	1.5673
F	a	0.1260	0.4733
F	v	- 36.7121	3.3656
F	V/L	- 0.0253	0.0292
F	θ/θT	1.0517	0.2317
F	E	0.3222	- 0.0045
F	%G	45.9559	- 1.0981
F	%S	54.8194	0.6863
F	%S-C	- 0.2247	0.3671
F	α	20.2300	- 0.0034

TABLE 17

POWER FUNCTION OF THE FORM $Y = a X^b$

Logarithm Dependent Variable	Logarithm Independent Variable	Intercept (a)	Slope (b)
F	W	1.3204	0.5407
F	D	0.4100	0.6359
F	W/D	2.9181	- 0.0700
F	θ	30.7539	0.0888
F	θN	30.5633	0.1149
F	θS	30.6549	0.0645
F	θT	0.5161	- 0.4606
F	L	1.1487	1.6679
F	A	22.9668	2.0919
F	a	0.2210	1.2657
F	v	0.2535	2.9341
F	V/L	0.0021	1.8534
F	θ/θT	1.0827	0.5257
F	E	0.5640	- 0.3092
F	%G	215.0800	- 0.8235
F	%S	37.3078	0.2083
F	%S-C	0.0214	1.9345
F	α	0.4219	- 0.4171

APPENDIX VI

REGRESSION PLOTS

FIGURE I

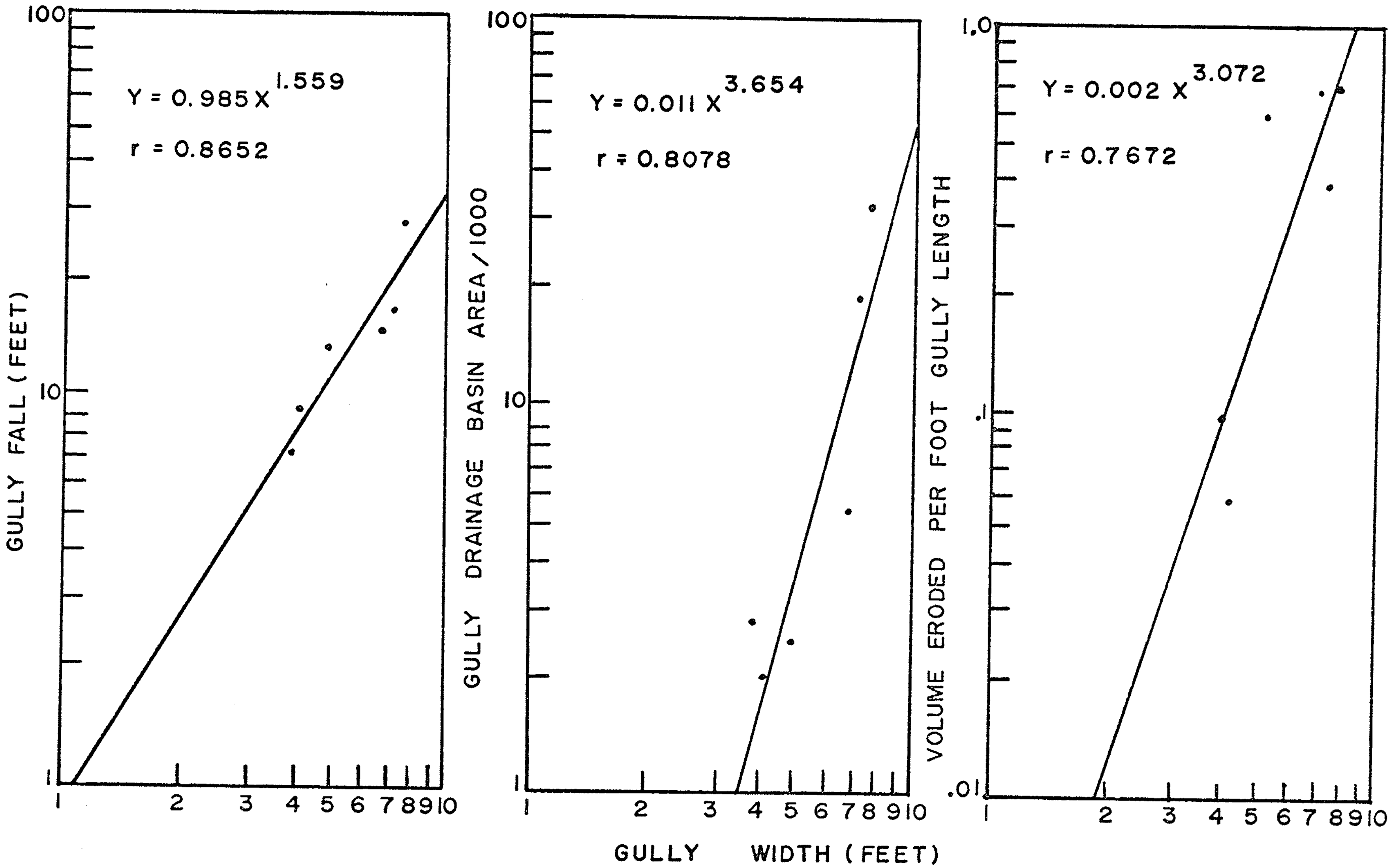
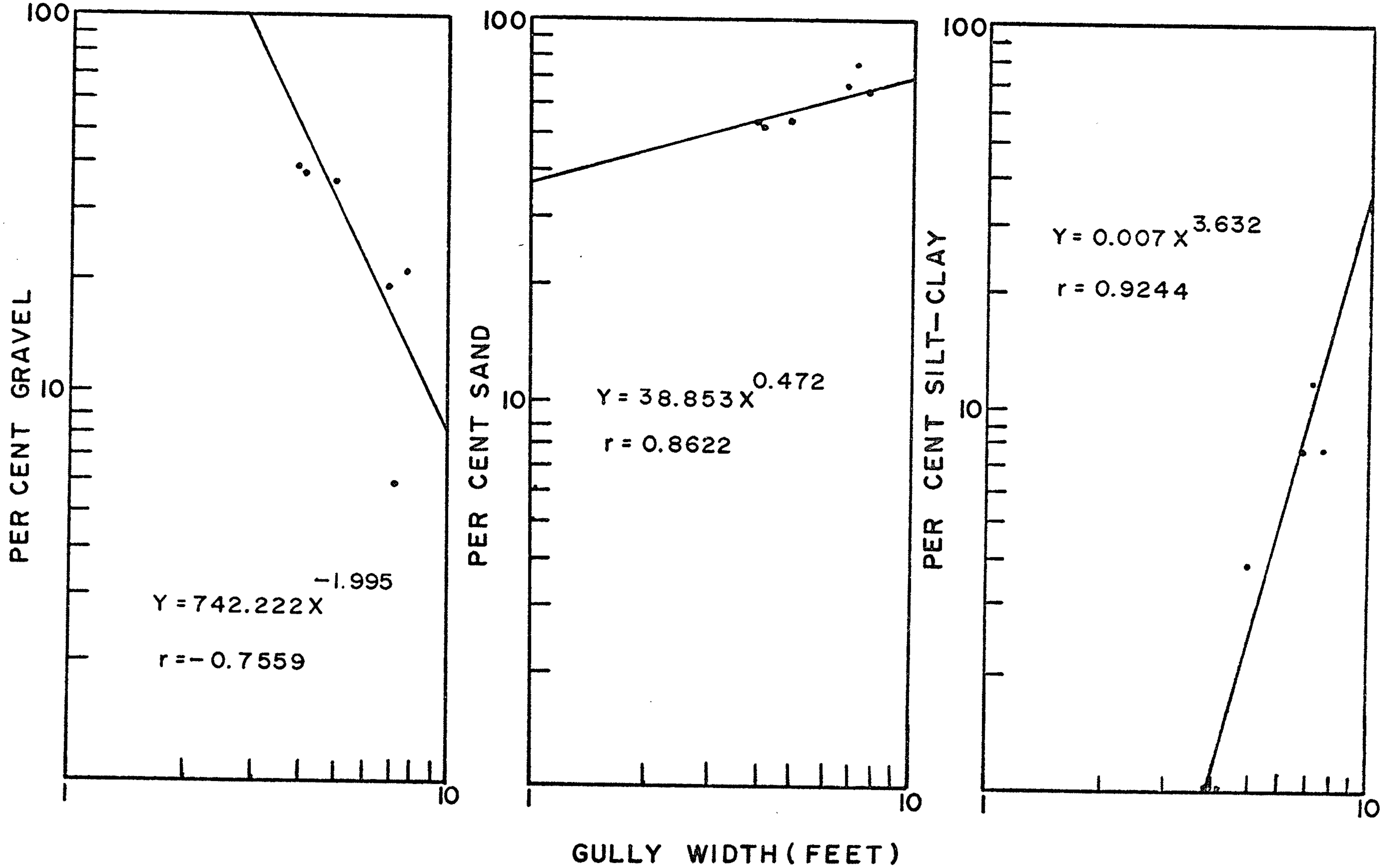

Y = 0.985 X^1.559
r = 0.8652
GULLY FALL (FEET)
Y = 0.011 X^3.654
r = 0.8078
GULLY DRAINAGE BASIN AREA/1000
Y = 0.002 X^3.072
r = 0.7672
VOLUME ERODED PER FOOT GULLY LENGTH
GULLY WIDTH (FEET)

FIGURE 2



100
10
1
10
PER CENT GRAVEL
Y = 742.222 X^-1.995
r = -0.7559
PER CENT SAND
Y = 38.853 X^0.472
r = 0.8622
PER CENT SILT-CLAY
Y = 0.007 X^3.632
r = 0.9244
GULLY WIDTH (FEET)

FIGURE 3

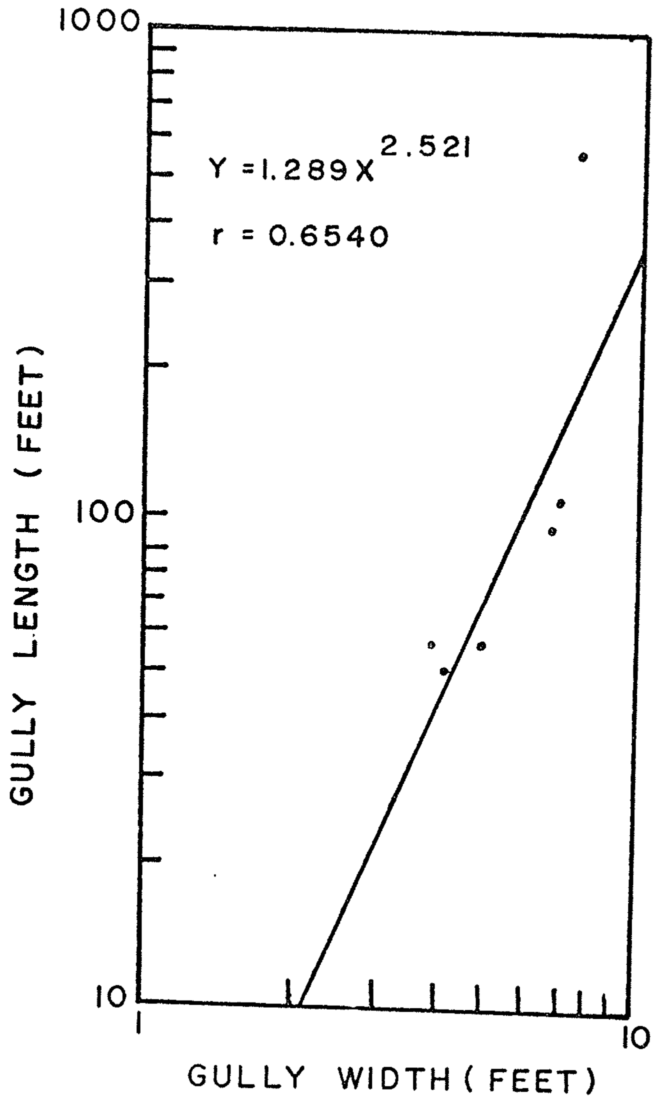
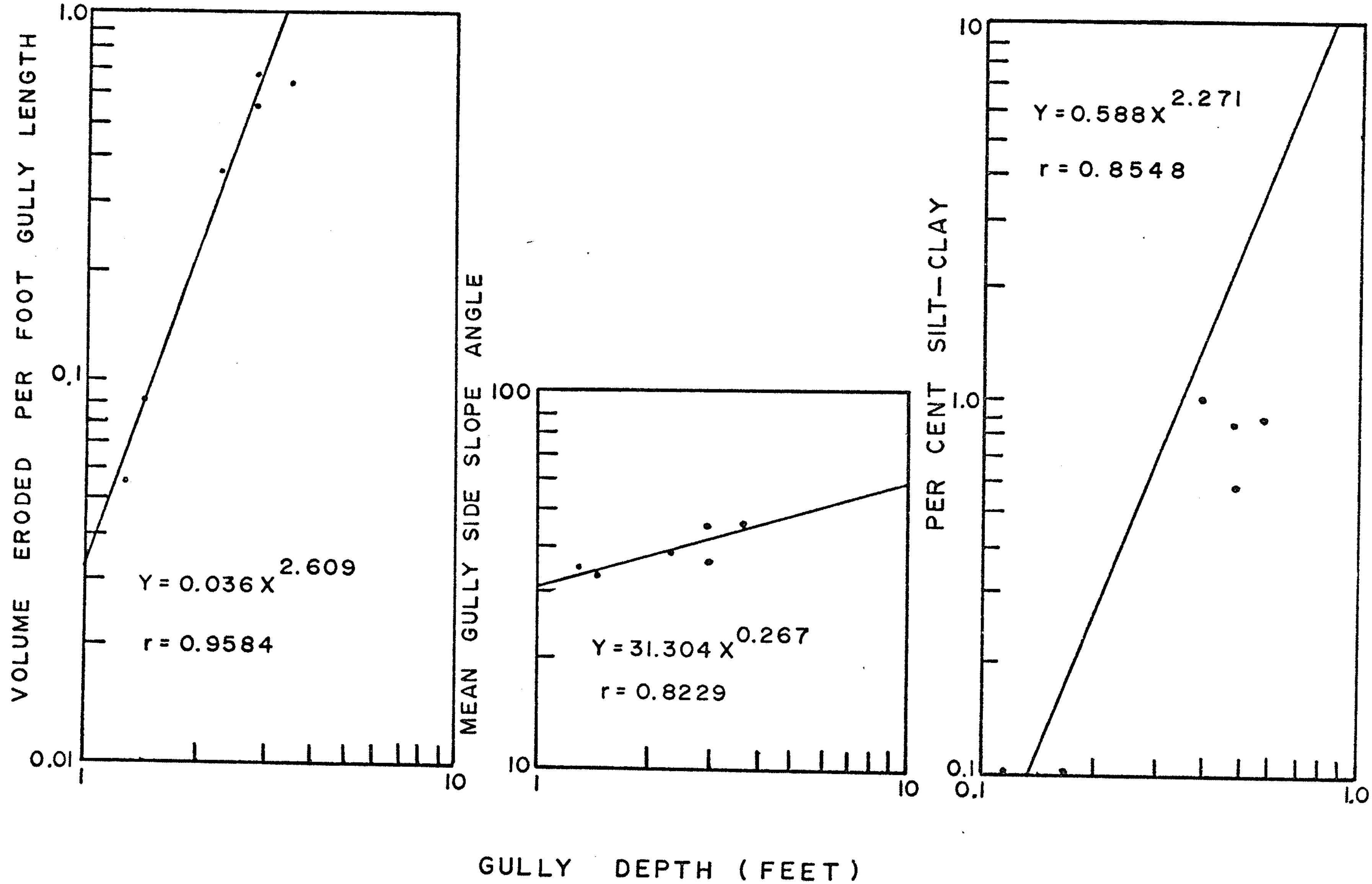

1000
100
10
1
10
GULLY LENGTH (FEET)
GULLY WIDTH (FEET)
Y = 1.289 X 2.521
r = 0.6540

FIGURE 4



VOLUME ERODED PER FOOT GULLY LENGTH
1.0
0.1
0.01
1
10
Y = 0.036 X^2.609
r = 0.9584
MEAN GULLY SIDE SLOPE ANGLE
100
10
1
10
Y = 31.304 X^0.267
r = 0.8229
PER CENT SILT—CLAY
10
1.0
0.1
0.1
1.0
Y = 0.588 X^2.271
r = 0.8548
GULLY DEPTH (FEET)

FIGURE 5

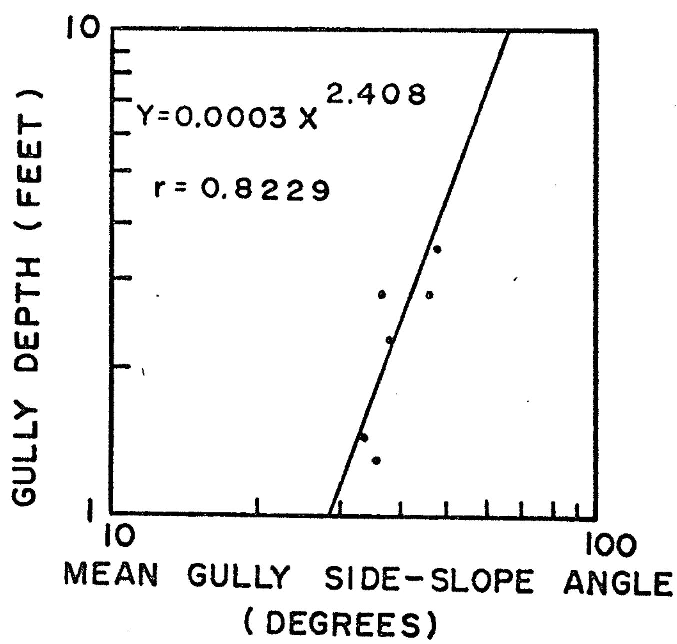
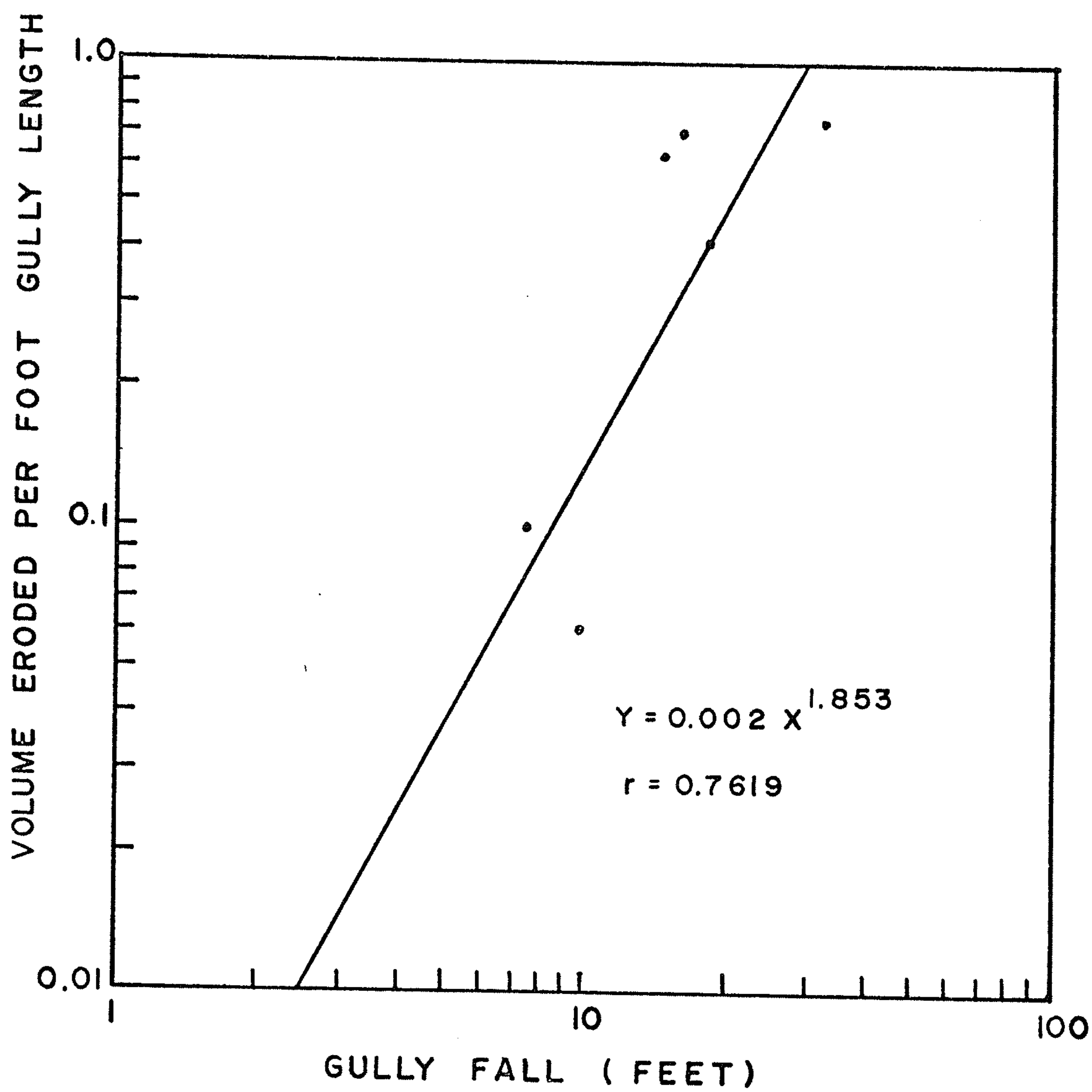

10
Y=0.0003 X 2.408
r = 0.8229
GULLY DEPTH (FEET)
1
10
100
MEAN GULLY SIDE-SLOPE ANGLE
(DEGREES)

FIGURE 6



1.0
0.1
0.01
VOLUME ERODED PER FOOT GULLY LENGTH
Y = 0.002 X1.853
r = 0.7619
1
10
100
GULLY FALL (FEET)

FIGURE 7

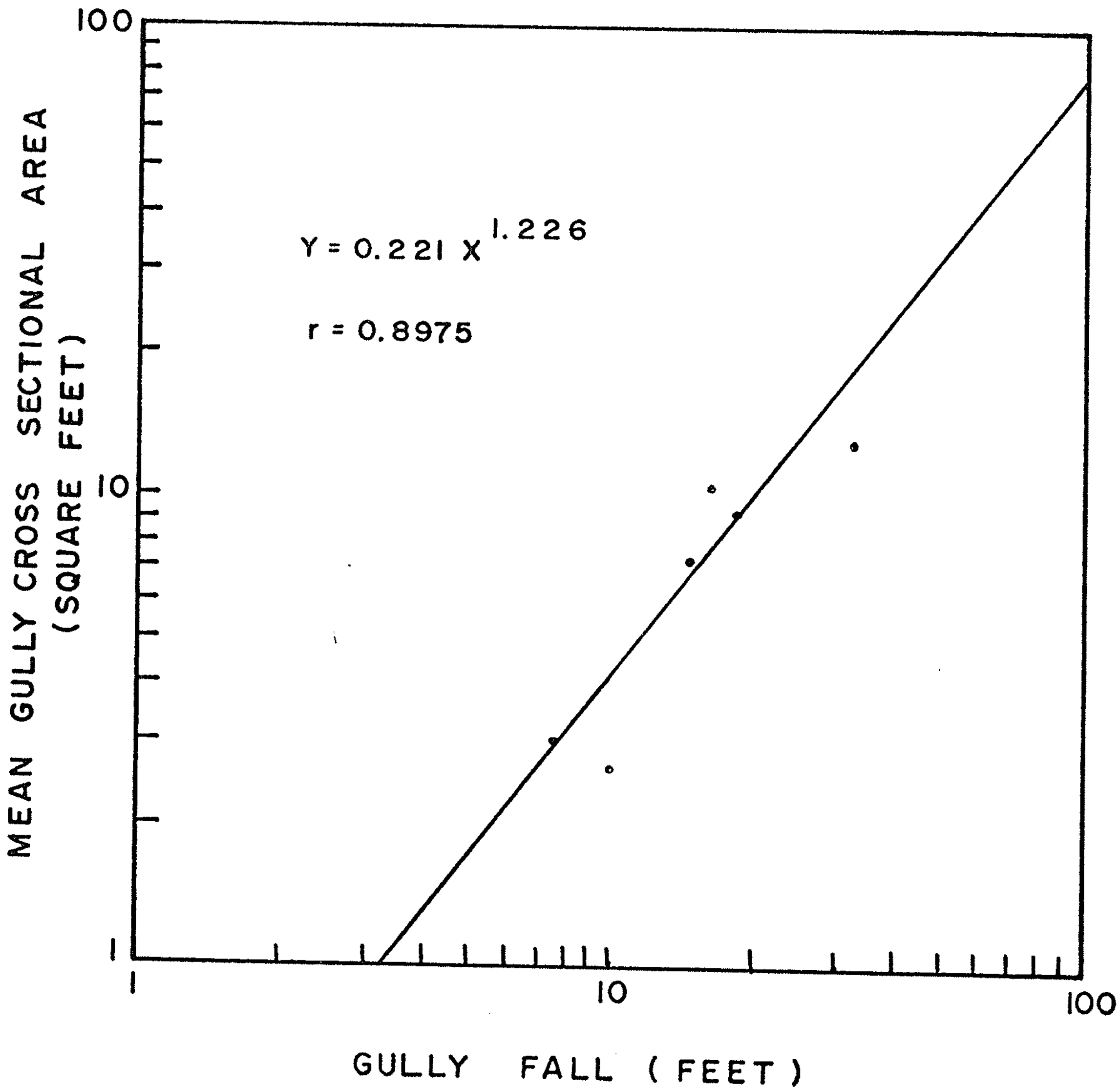

Y = 0.221 X^1.226
r = 0.8975
MEAN GULLY CROSS SECTIONAL AREA (SQUARE FEET)
GULLY FALL (FEET)
100
10
1
1
10
100

FIGURE 8

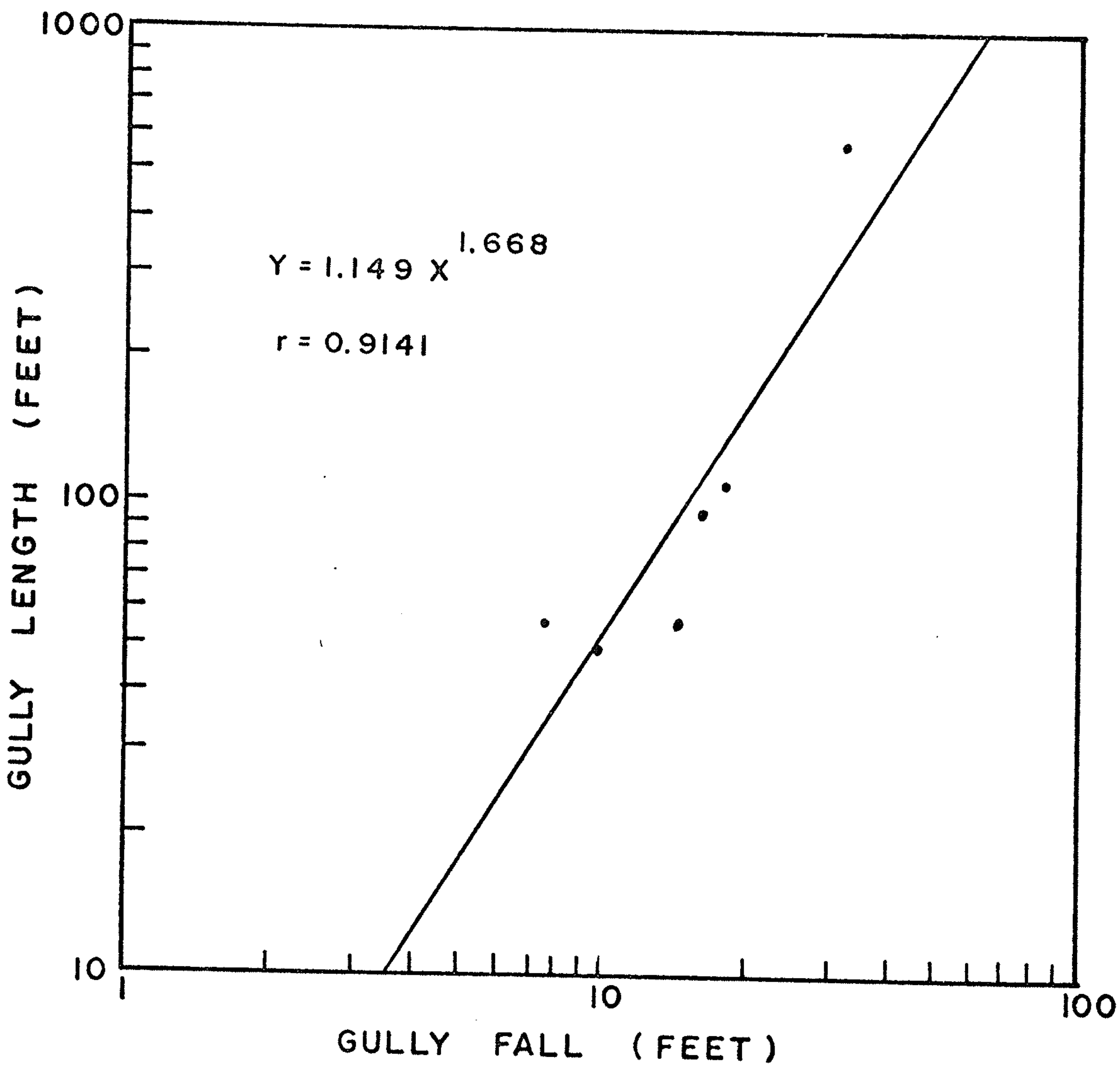

1000
100
10
1
10
100
GULLY LENGTH (FEET)
GULLY FALL (FEET)
Y = 1.149 X^1.668
r = 0.9141

FIGURE 9

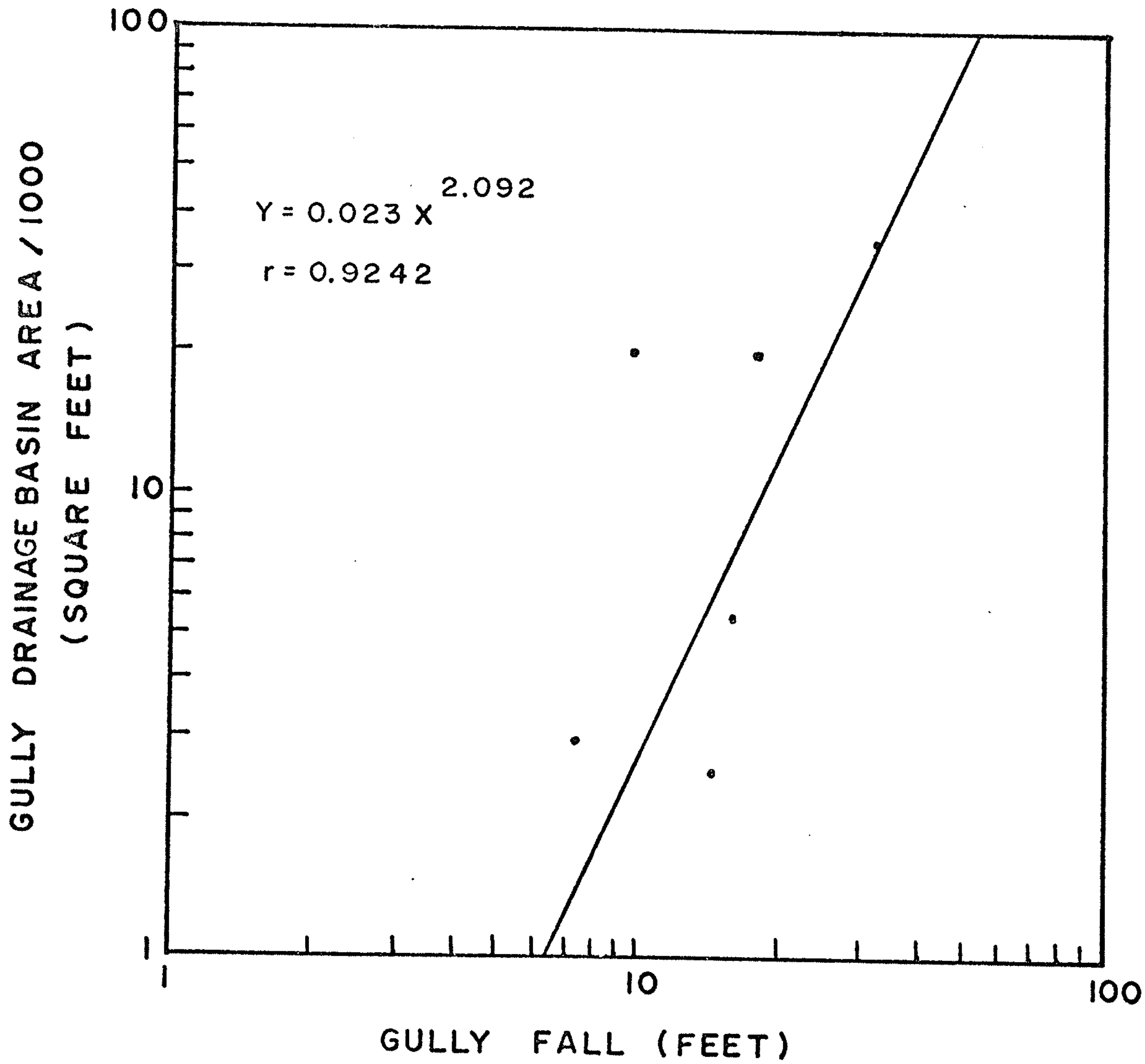

100
10
1
1
10
100
Y = 0.023 X 2.092
r = 0.9242
GULLY DRAINAGE BASIN AREA / 1000
(SQUARE FEET)
GULLY FALL (FEET)

FIGURE 10

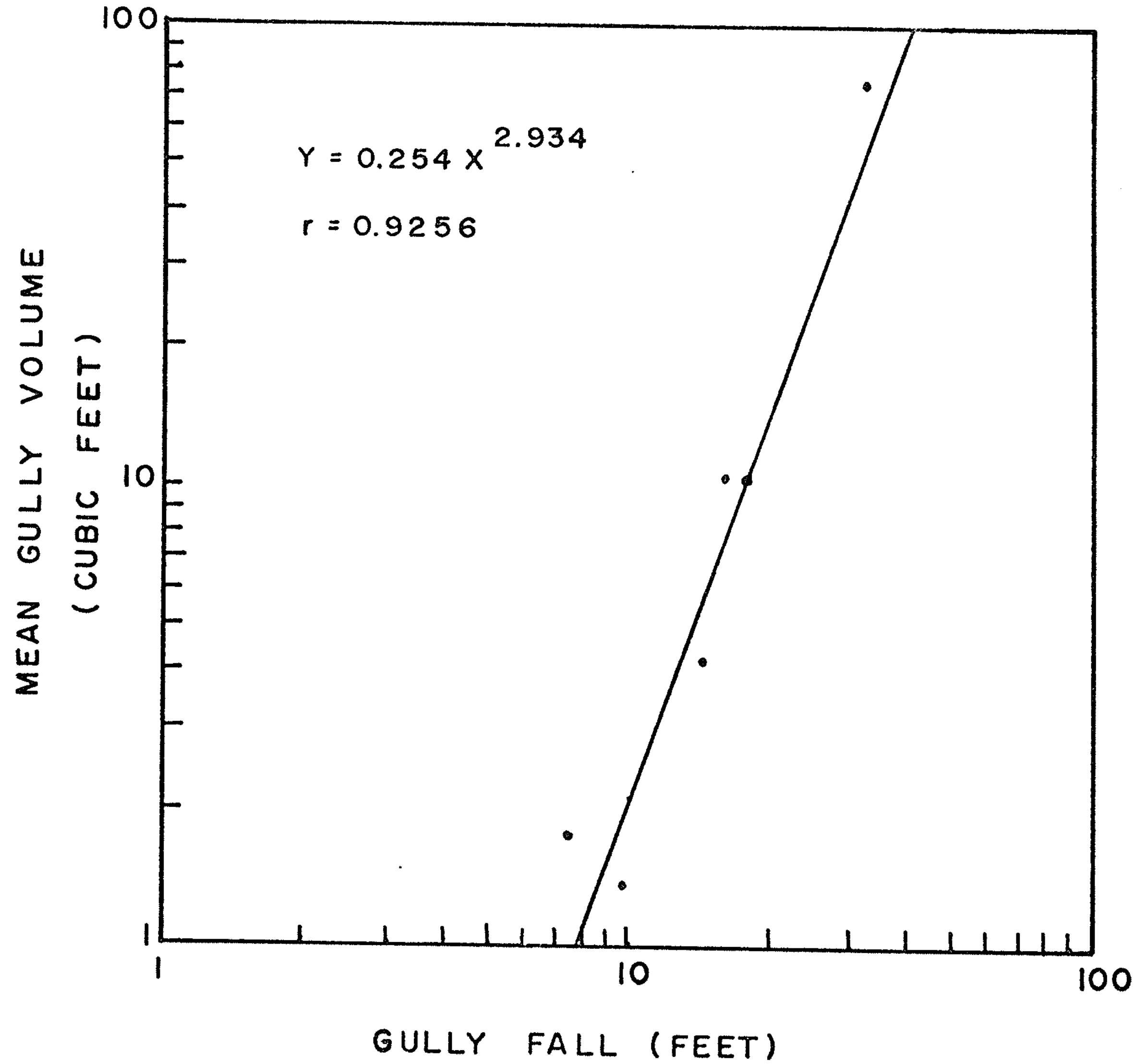
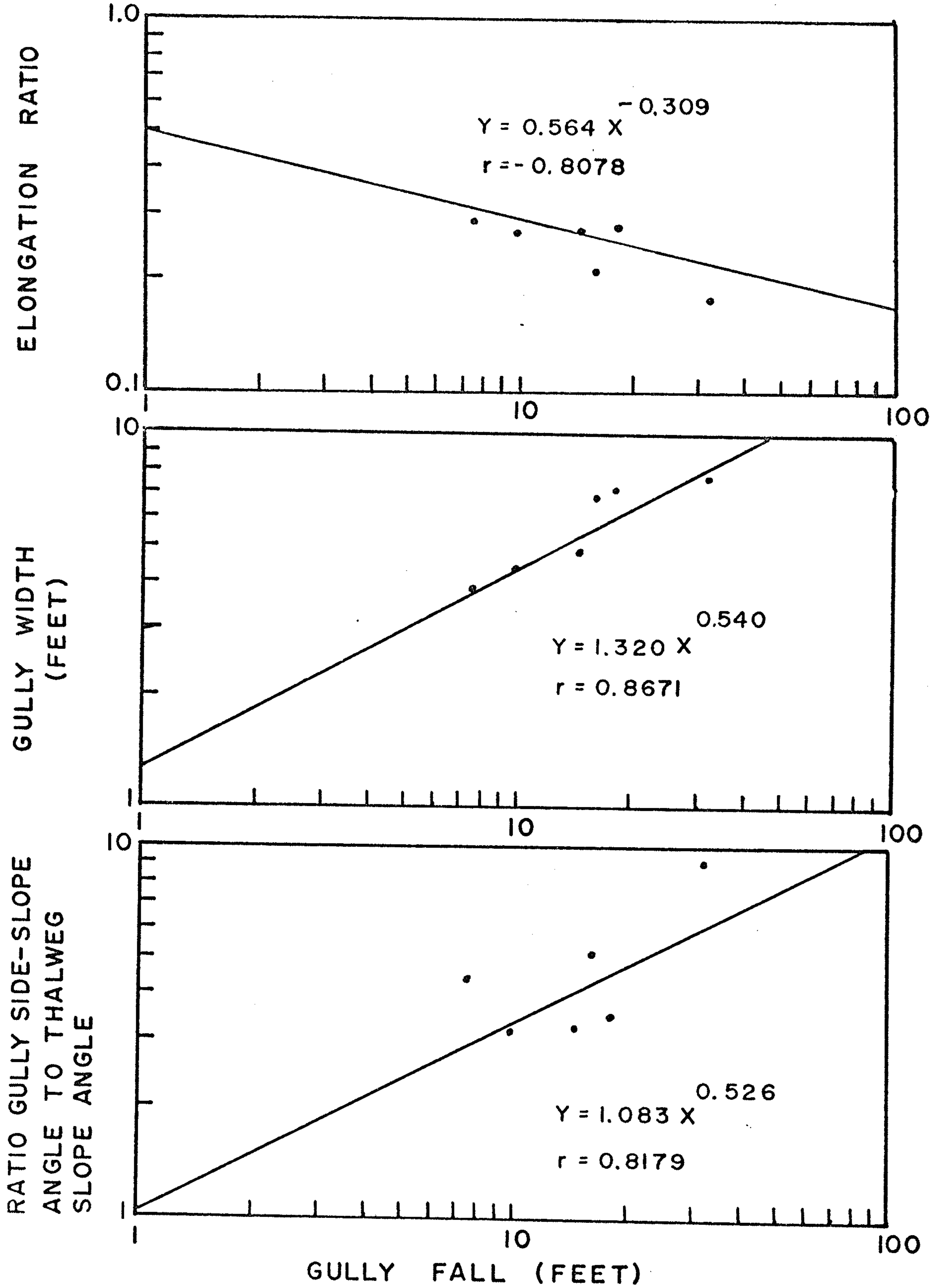

100
10
1
1
10
100
Y = 0.254 X 2.934
r = 0.9256
MEAN GULLY VOLUME
(CUBIC FEET)
GULLY FALL (FEET)

FIGURE II


1.0
0.1
ELONGATION RATIO
Y = 0.564 X -0.309
r = - 0.8078
1
10
100
GULLY WIDTH (FEET)
Y = 1.320 X 0.540
r = 0.8671
RATIO GULLY SIDE-SLOPE ANGLE TO THALWEG SLOPE ANGLE
Y = 1.083 X 0.526
r = 0.8179
GULLY FALL (FEET)