EROSION ASSESSMENT AT THE PETROGLYPH NATIONAL MONUMENT AREA, ALBUQUERQUE, NEW MEXICO

By Allen C. Gellis

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch	2.540	centimeter
foot	0.3048	meter
mile	1.609	kilometer
acre	0.4047	hectare
square mile	2.590	square kilometer
cubic foot per second	0.02832	cubic meter per second
ton per day	0.0105	kilogram per second

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

Areas of the Petroglyph National Monument, specifically those located along the West Mesa escarpment, are being affected by erosion and gullying. A reconnaissance along the 17-mile-long escarpment identified 50 gullies. The gullies were given a qualitative ranking of Class I, least erosion, to Class IV, highest erosion. Of the 50 gullies identified, 21 were assigned Class I, 22 to Class II, 6 to Class III, and 1 to Class IV. Although the gullies may not be a direct threat to petroglyphs, the effects of gullying may have a greater effect on the aesthetics of the monument and the residences located downgradient from a gully.

Most of the gullies were found along the northern part of the escarpment. This area, which is more developed than the southern areas of the escarpment, contains many dirt roads and nonpaved foot and bicycle paths. These features channel surface runoff and increase erosion. Thirty of the 50 gullies were noted as being connected to the runoff from dirt roads.

High-intensity storms during the summer of 1991 may have caused or increased gullying. Analyses of these storms indicate recurrence intervals of rainfall of no more than 2 years. Indirect measurements of peak discharge in La Boca Negra Arroyo after the August 22, 1991, storm indicate that this runoff event may have a frequency of no more than 10 years. Regional frequency reports on rainfall and data collected at the rain gages indicate that gullying and erosion that occurred during the summer of 1991 were not a result of infrequent rainfall or runoff events.

INTRODUCTION

The Petroglyph National Monument is located on the West Mesa, a distinct landform feature west of Albuquerque, New Mexico (fig. 1). The 7,160-acre monument is the first national park area specifically established for petroglyphs (National Park Service, 1991). A striking feature of the monument is a 17-mile-long basalt escarpment. This escarpment contains more than 15,000 petroglyphs and is also an area of numerous gullies.

Much of the area northeast of the escarpment is developed, and additional subdivisions are planned west of the escarpment on the mesa tops. The population of Albuquerque in 1985 was 425,000 (National Park Service, 1988). The population is expected to increase more than 70 percent between 1980 and 2010, with more than half of this growth expected to be on the West Mesa (National Park Service, 1988). As part of this development process, the City of Albuquerque has proposed that the access roads, Paseo del Norte and Unser Boulevard, be extended through the monument. This expected growth along the West Mesa could place a considerable stress on the natural and cultural resources of the monument.

Because of concern about the location and causes of gullying and its effects on the petroglyphs, the U.S. Geological Survey (USGS), in cooperation with the National Park Service, began an investigation of gullying and erosion along the West Mesa escarpment. The purpose of this report is to (1) identify areas of gullying along the West Mesa escarpment, and (2) compile hydrologic data on rainfall and runoff at the monument between October 1989 and November 1991.

Gullying and Definition of Terms

The term "gully" is generally applied to a channel that has ephemeral flow and is incised into unconsolidated material. Gully erosion or gullying, as defined by Emmett (1968), "* * * is the wearing away of the land surface mainly by detachment and transport of mineral grains through the action of geological agents; these may be mechanical or chemical." Commonly the propagation of a gully occurs in an area where no channel had previously existed or is the re-incision of an existing channel.

The causes of gullying are varied and may involve a combination of either natural or human-induced changes imposed on the fluvial system. Natural causes can be a climatic change, intense storms, or oversteepening of alluvial-valley floors. Human-induced causes of gullying can be the removal of vegetation by overgrazing, timbering, or recreational activities; construction of roads with poor drainage design; and increases in runoff from urbanized areas. To provide a basis for further discussion, the following terms are defined (Gary and others, 1974).

(1) Rill - a small channel resulting from the removal of soil by runoff. A rill is generally not a permanent feature and may be destroyed in the next runoff event. If not destroyed, rills often coalesce and form a more permanent channel or gully.

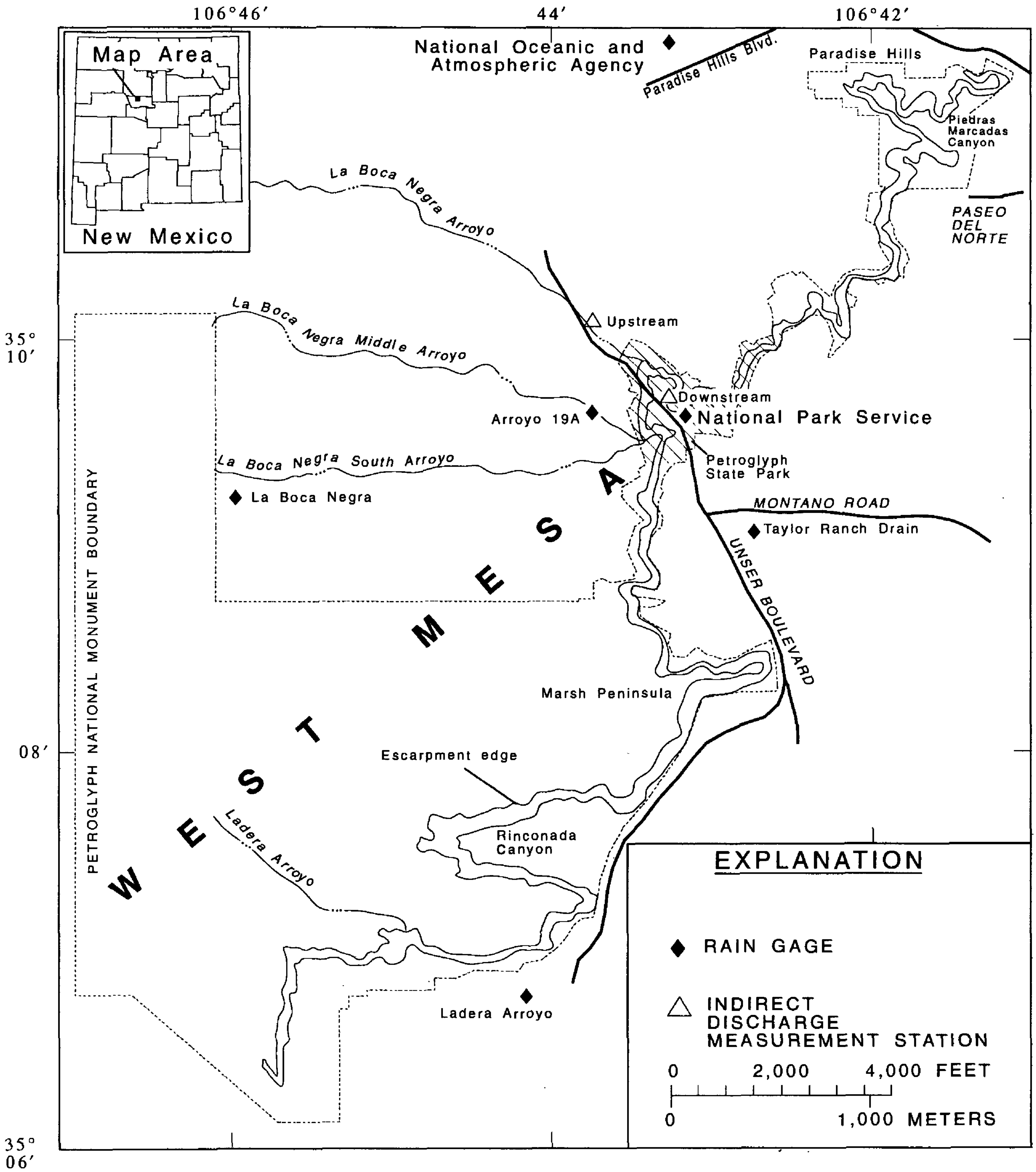

Figure 1.--Location of the Petroglyph National Monument, rain gages, and indirect discharge measurements on the West Mesa, Albuquerque, New Mexico.

(2) Gully - a channel eroded into unconsolidated material by running water that runs only after a rain. A gully can form in the natural environment, such as on a hillslope, or it may form on a constructed feature, such as a road or construction site. Gullying is defined as the active erosion occurring on the hillslope or in the channel.

(3) Headcut - a vertical drop on the bed of the gully. It is similar to a waterfall and moves upstream in the channel through time by erosion and runoff.

(4) Bank failure - the collapse or slumping of the gully sidewalls or banks. Failure can be caused by numerous processes, including undercutting of the banks by flow or overloading by saturated soil. Bank failures are common in recently formed gullies and indicate that the channel is unstable.

(5) Thalweg - the line connecting the lowest point along a streambed or gully bed.

Equilibrium Theory

A channel or hillslope has its characteristic form because of an equilibrium between sediment, slope, and runoff. This relation is generally known as equilibrium or regime theory (Mackin, 1948; Lane, 1955) and for a channel is expressed in the form of the equation:

$$Q_s d_{50} = QS \qquad (1)$$

where Q_s = sediment discharge, in tons per day;
d_{50} = median diameter of bed material, in inches;
Q = mean water discharge, in cubic feet per second; and
S = channel slope, in feet per feet.

Changes in any variable in equation 1 can lead to channel instability. For example, an increase in discharge can lead to an increase in stream power. Stream power is defined as the product of discharge and slope, and increases the ability of the water to erode sediment grains. This erosion leads to channel deepening and then widening. Schumm (1977) presented this concept as generalized equations that relate channel morphology to discharge (Q) and sediment discharge (Q_s):

$$Q^{+} \approx (b^{+}, d^{+}, S^{-}) \qquad (2)$$
$$Q^{-} \approx (b^{-}, d^{-}, S^{+}) \qquad (3)$$
$$Q_s^{+} \approx (b^{+}, d^{-}, S^{+}) \qquad (4)$$
$$Q_s^{-} \approx (b^{-}, d^{+}, S^{-}) \qquad (5)$$

where b = channel width, in feet; and
d = channel depth, in feet.

A (+) indicates an increase in the magnitude of the variable and a (-) indicates a decrease in the magnitude of the variable.

The development of a gully at a particular location in a watershed is a function of upstream or downstream changes that affect the variables in equations 2 through 5. Changes in a watershed may result from human activities, such as road building or housing construction, or natural factors, such as climatic change or oversteepening of a valley by deposition. Patton and Schumm (1975) defined a line relating drainage area to valley slope that separates gullied from ungullied areas (fig. 2). The steepening of the valley floor leads to an increase in valley slope, thus increasing the possibility of erosion.

Another important factor in the development of gullies is exceeding a threshold gradient, defined by Harvey and others (1985, fig. 3) as a value in which a geomorphic change occurs. In figure 3, the diagonal line represents the aggradation of the valley floor through time. The dashed horizontal line is the maximum slope at which the valley is stable. The effect of storms on gullying might be minor until the valley floor approaches line 2. However, a severe storm might occur that crosses the threshold line and causes erosion (point A in fig. 3).

Erosion generally is initiated as a headcut that forms the arroyo or gully and moves upgradient along the valley floor or an existing channel. Headcut advancement can be related to watershed area, rainfall intensity, and soil properties (Thompson, 1964; Seginer, 1966). Once a gully is formed, a long time may pass before a new equilibrium is attained. During this time, the gully or arroyo will go through a series of changes that ultimately lead to a new state of equilibrium (Heede, 1974; Gellis and others, 1991). These changes in gully shape follow the advancement of the headcut, from the lower to the upper reaches.

Changes in gully shape can also be observed through time at one selected location in the gully. Generally, the channel changes through time from a narrow, V-shaped gully that has low width-to-depth ratios to a wide, U-shaped gully that has high width-to-depth ratios. Width is measured from the top of one bank to the top of the other bank. Depth is measured from the intersection of a line drawn across the top of both banks to a line drawn vertically from the thalweg. Seginer (1966) found a positive correlation for gullies in Israel between the distance from the headcut to the cross-sectional area.

A gully in the early stages of development is characterized as a state of erosion with high sediment production and bank failures. The lower and middle reaches of a gully, which are further away from the headcut and have had more time to develop, may be in a more advanced stage than the upper reaches. A gully in advanced stages of development is aggrading and has stable banks. A more developed or mature gully has the appearance of being fully aggraded, shallow, and typically well vegetated.

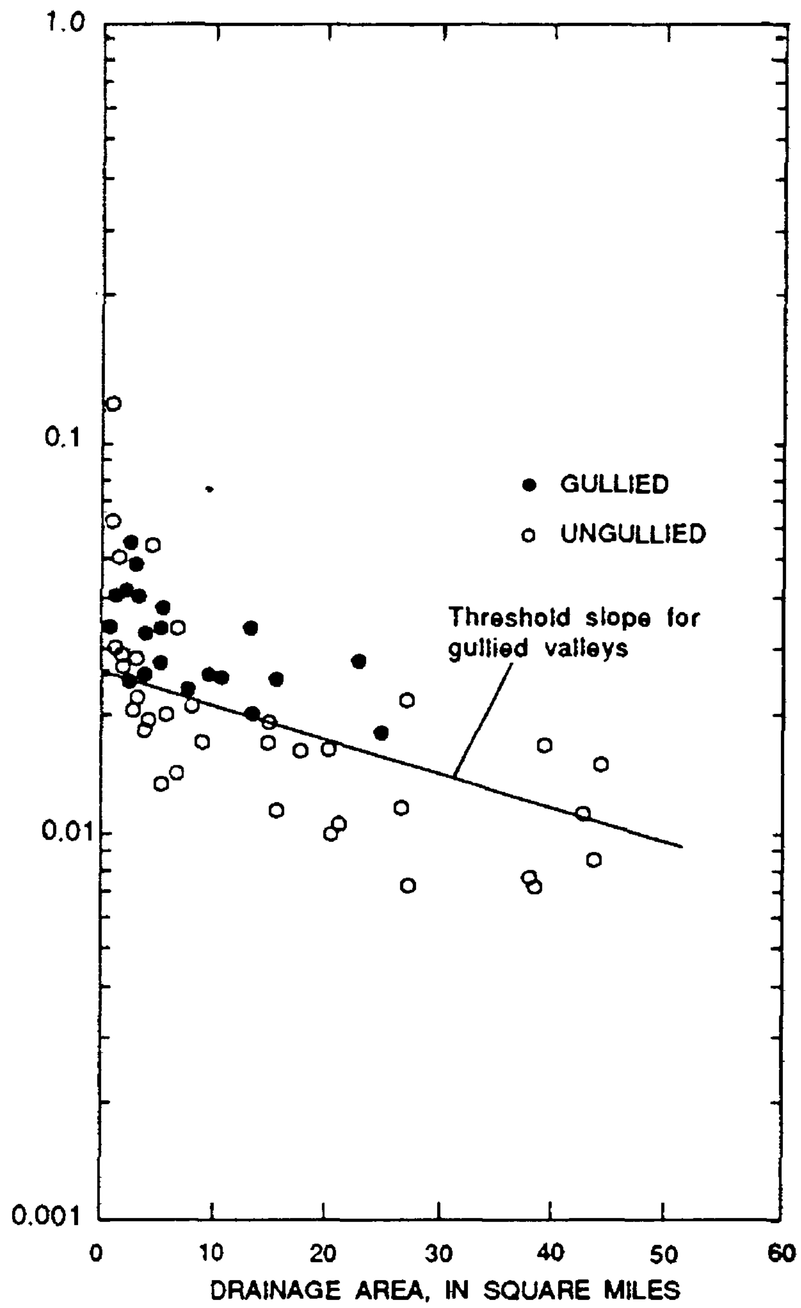

Figure 2.--Relation between valley slope and drainage area, Piceance Creek Basin, Colorado (modified from Patton and Schumm,1975).

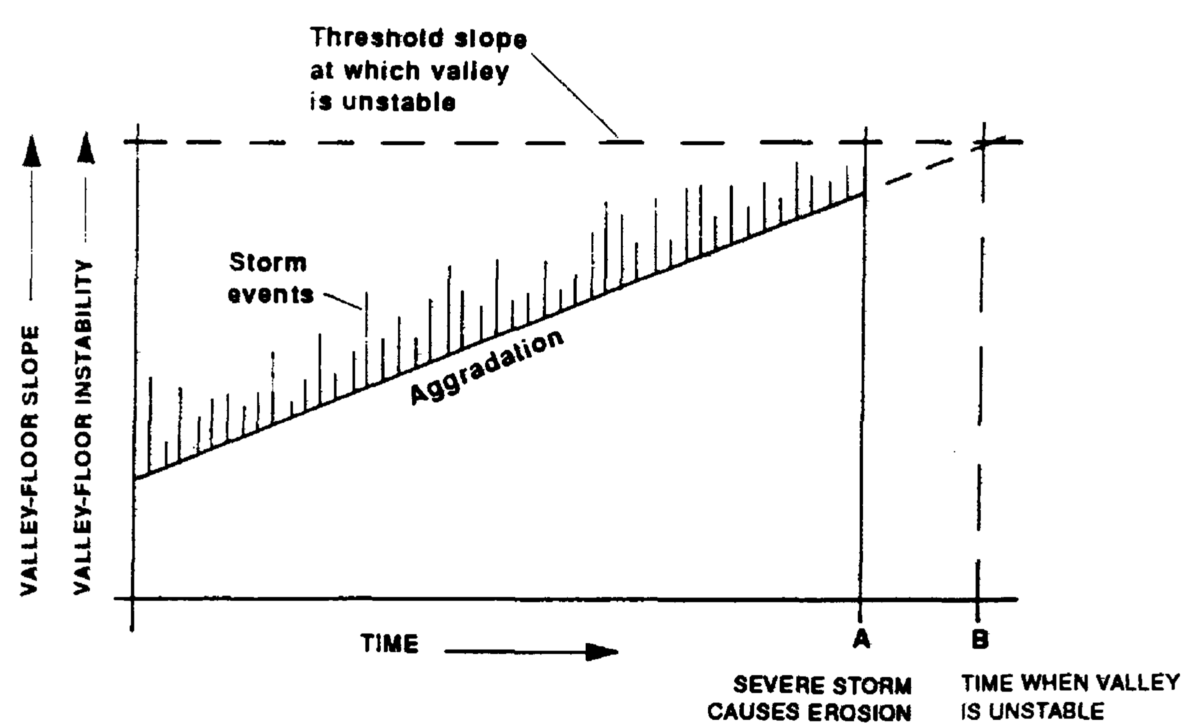

Figure 3.--Hypothetical relation between valley-floor slope and valley-floor instability with time (modified from Harvey and others, 1985).

Methods of Investigation

A reconnaissance was conducted by walking and driving the 17-mile-long escarpment in the Petroglyph National Monument during October and November 1991. Important geomorphic characteristics of the gullies along the escarpment, such as location, aspect, land use/land cover, erosion, depth, width, etc., were observed and recorded on a form (fig. 4). A qualitative assessment of the degree to which gullies were eroding was based on these geomorphic characteristics. On the basis of these assessments, a relative ranking was applied to the magnitude of erosion in each gully.

Three of the gullies were surveyed to define the cross-sectional and longitudinal geometry. Cross sections at each gully were surveyed to enable documentation of gully growth through resurveys. To facilitate future surveys, elevation reference marks, made of steel bars, were established at selected cross sections. A total station survey instrument was used in the surveying.

EROSION ASSESSMENT

A total of 107 observation sites were selected along the West Mesa escarpment (fig. 5; table 1; tables are in the back of the report). A site was selected if erosion was occurring on the site. At random intervals a site was identified even if no erosion was occurring. Of the 107 observation sites, 50 were identified as having a gully (fig. 6). Because some gullies possibly were overlooked during the reconnaissance, 50 gullies might not be the total number of gullies in the area. All of the gullies were incised into unconsolidated loamy sand. For this report, gullies were classified for magnitude of erosion as follows:

Class I - erosion is slight; rills or a small gully is developing on some part of the hillslope. Class I may represent a minor episode of erosion or a gully that is stabilized.

Class II - erosion moderate; a gully is developing on some part of the hillslope. Bank failures are occurring in some reaches of the gully but tributaries are not eroding. Class II may represent an advance stage of a gully development.

Class III - erosion intense; all of hillslope is in a stage of active gullying. Bank failures and headcuts are common in most reaches. The gully might be widening in the middle and lower reaches. Tributaries could be eroding. Class III represents a recent stage of gully development.

Class IV - erosion severe; deep incision of the gully is occurring on most of the hillslope. Large bank failures and gully widening are occurring. Width-to-depth ratios are low. Headcuts are found in the middle and upper reaches of the gully. Large boulders are found in the bed of the gully. Tributaries are actively eroding. Although Class IV and Class III may be the initial stages of gullying, Class IV is differentiated by the magnitude of erosion.

Of the 50 gullies identified along the escarpment in the Petroglyph National Monument, 21 were identified as Class I, 22 as Class II, 6 as Class III, and 1 as Class IV (fig. 6). Fourteen of the gullies were eroding dirt roads, 7 were eroding foot or bike trails, 11 were associated with a permanent channel or drainage, and 18 were located on hillslopes that were not affected by the aforementioned features.

Location ____

Aspect ____

LAND USE (Road, Trail, Unaffected Hillslope, other ________)

Bank Erosion - Major (10); Minor (0) ______________________________

Headcuts Found _______ Boulders Exposed ______________________

Connected To Mesa Roads (Y ? N) ______________________________

Approximate Maximum Depth ______________________________

Maximum Width ______________________________________

Erosion on Hillslope (crest, middle, toe) ________________________

Tributaries gullying (Y ? N) ______________________________

OTHER ____

Figure 4.--Form used in the evaluation of gullies.

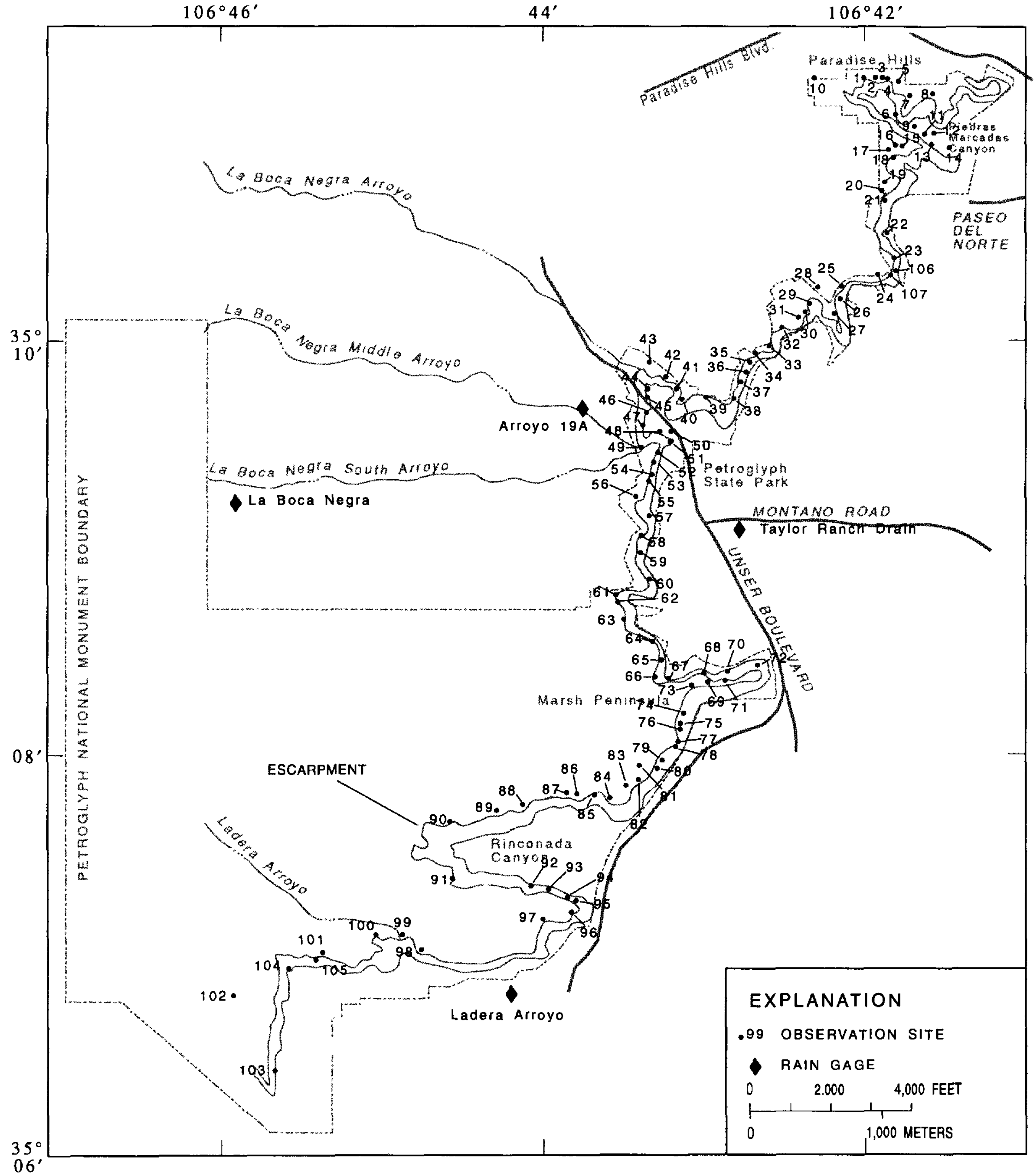

Figure 5.--Location of observation sites selected for study of the Petroglyph National Monument. [For characteristics of each site see table 1.]

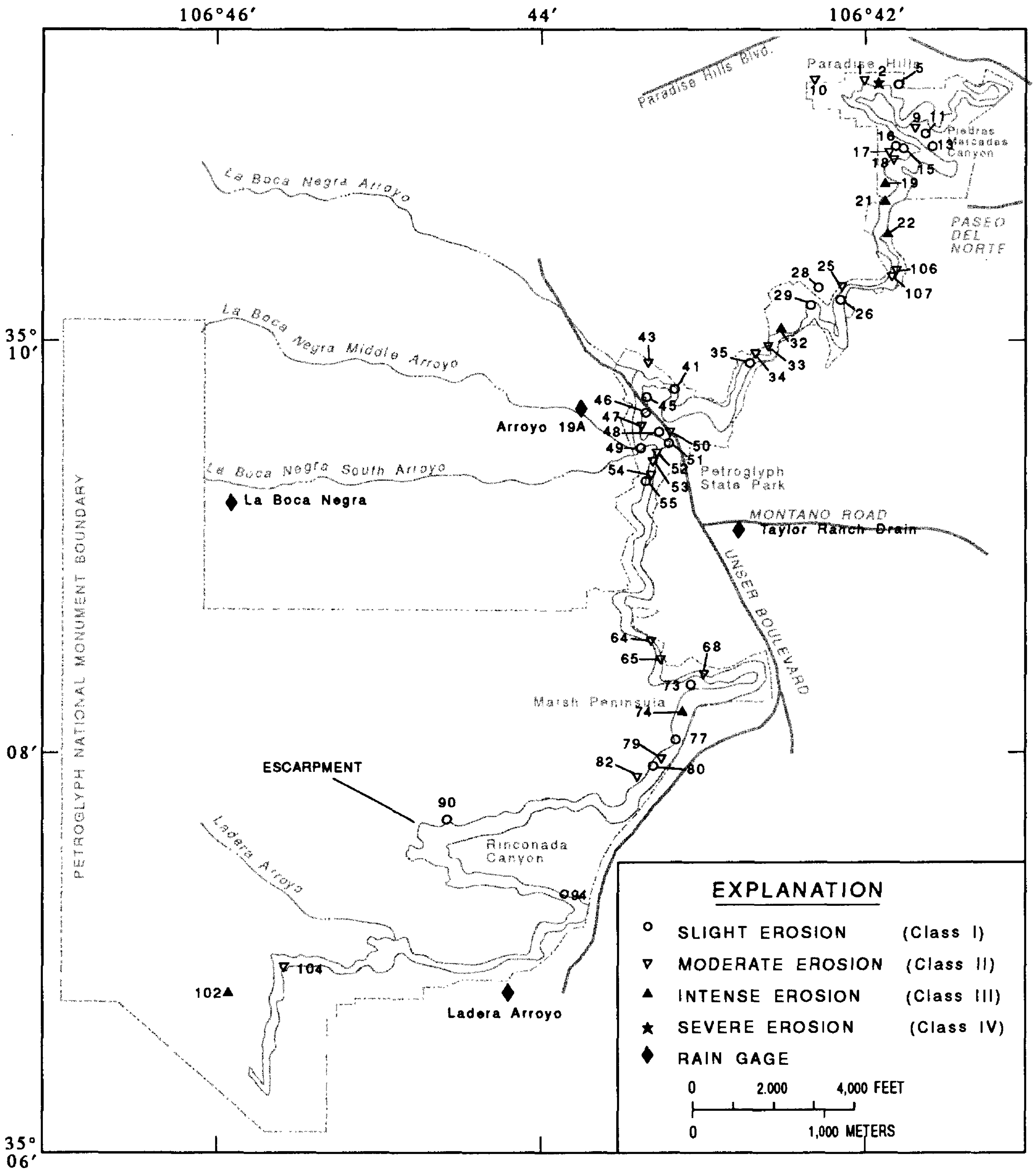

Figure 6.--Location of selected gullies and magnitude of erosion.

In the West Mesa escarpment there may be a relation between gully density and vegetative cover. The northern areas of the escarpment have less dense vegetative cover than the southern areas and a higher occurrence of gullies (figs. 7 and 8). Of the 50 gullies identified, 37 gullies, or about 75 percent, are located in the northern area of the escarpment between escarpment mile 0 and mile 9 (fig. 7). Housing communities are adjacent to and downgradient from the northern areas of the escarpment. Local residents use the foot and bike trails to reach the top of the mesa. Many of the gullies described in table 1 are located on these trails. Foot and bike traffic on the vegetation in northern parts of the escarpment might be decreasing the vegetative cover and promoting gullying. The number of gullies per square mile decreases slightly around escarpment mile 9; however, the density of gullies decreases even more around escarpment mile 12 (fig. 7). Mile 12 is south of the Marsh Peninsula (fig. 1) where there are fewer housing subdivisions.

The northern areas of the escarpment also have a denser network of dirt roads near the edge of the mesa than the southern areas. Rills and gullies in these dirt roads indicate that the roads channel surface flow (fig. 9). During a storm, runoff down these dirt roads can overtop low points in the road and spill over the edge of the mesa, which often is close to the roads. Thirty of the 50 gullies were identified as being connected by surface drainage to these mesa roads. Therefore, observations suggest that the dirt roads channel surface runoff, causing erosion in the road bed and delivery of surface runoff over the mesa that can incise into the unconsolidated material found at the escarpment.

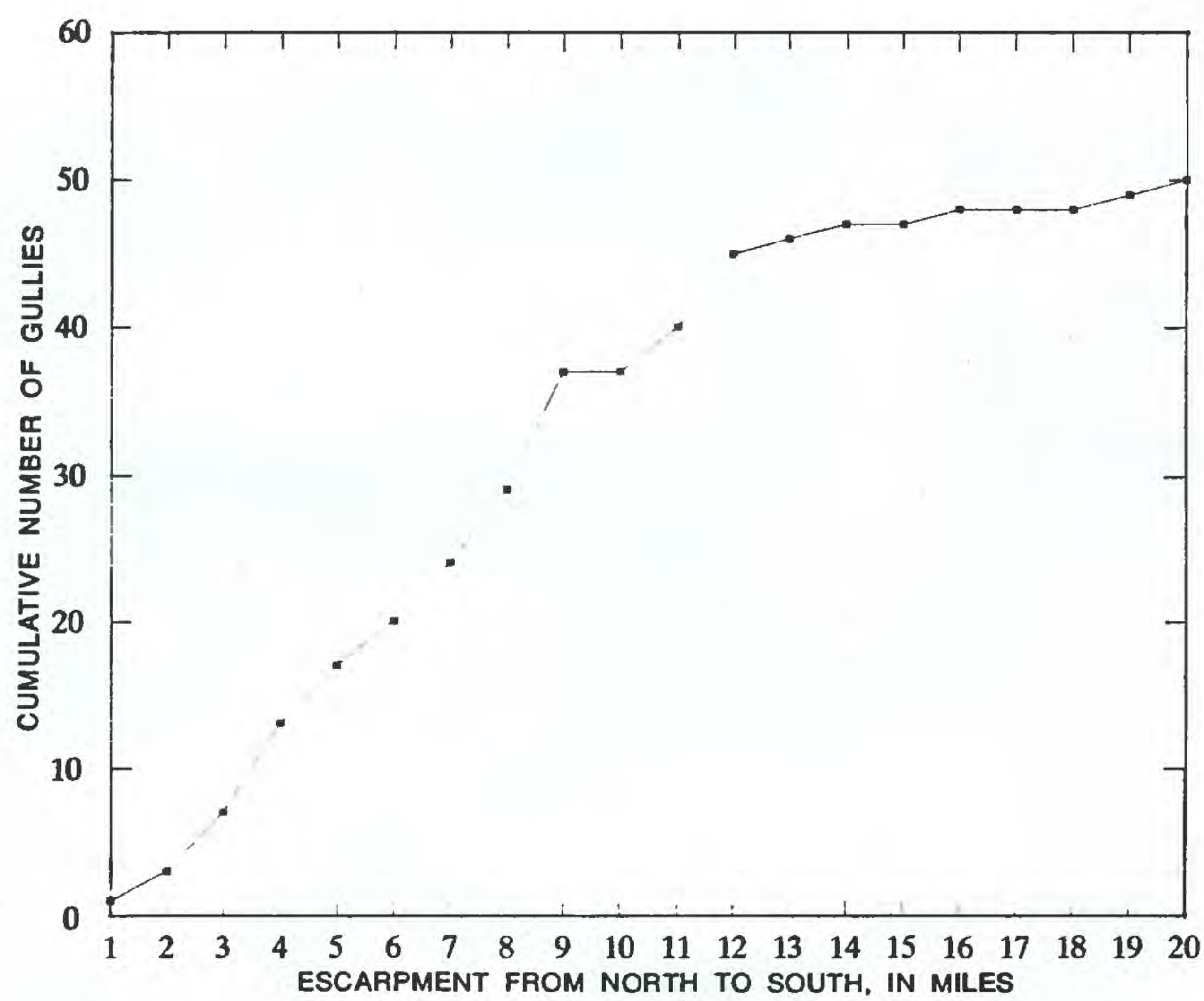

Figure 7.--Cumulative plot of number of gullies per escarpment mile.

A

B

Figure 8.--Contrasts in vegetation density from the northern to the southern areas of the escarpment. (A) Low vegetation density in the La Boca Negra Arroyo Canyon (site 43). (B) High vegetation density in the Rinconada Canyon area (site 81). (See figure 5 for location and table 1 for detailed characteristics.)

Figure 9.--Gullying near a dirt road at the Petroglyph National Monument, site 102.

Soils along the escarpment where gullies are located are classified as Bluepoint loamy fine sand, Bluepoint-Kokan association, and Kokan-Rock association (Hacker, 1977). Soils on top of the mesa are classified under several names. Bluepoint soils are generally the lower unit below the basalt outcroppings and are formed in alluvial and eolian deposits. Kokan soils are on the near-vertical basalt rock outcrop and are formed in alluvial gravel and sands of mixed sources from the Santa Fe Formation. On both soils, permeability is rapid, runoff is slow, and the water erosion hazard is moderate or severe (Hacker, 1977).

Most of the petroglyphs are on basaltic outcroppings and loose boulders. More gullies are generally found in areas of loamy sands, which are easily erodible, than in areas containing a higher density of basaltic boulders. It is possible that a gully may develop into the soil below a petroglyph boulder and cause it to roll. However, the channeled flow from dirt roads could be a greater hazard to the petroglyphs. Increases in surface runoff over petroglyphs might increase erosion on the boulder surface and could lead to a deterioration of the petroglyph. Determining a relation between boulder erosion and surface runoff was not part of this study.

Survey of Three Selected Sites

Three sites were surveyed for channel geometry, and steel bar elevation-reference marks were established in selected cross sections. At all three sites, gullies were eroding into a loamy-sandy soil.

Site 1

The gully at site 1 (fig. 6) in Piedras Marcadas Canyon is approximately 300 feet long (fig. 10). Nineteen cross sections were surveyed and two cross sections, 12 and 19, had elevation-reference marks emplaced for the purpose of resurveys (fig. 11). The lower reaches of the gully, from cross sections 1 to 5, have a relatively flat slope and a poorly defined channel. From cross section 6 to 16 the gully is incised into a loamy-sandy soil, and an active headcut is located upgradient from cross section 13. Cross section 14 is at the mouth of a tributary gully on the left bank and cross section 15 is at a tributary on the right bank. Upgradient from cross section 15 to just downgradient from cross section 19, the gully loses its form. Gullying is absent in this portion of the drainage because soils are lacking and bedrock and boulder outcroppings line the hillslope. On top of the mesa, at cross section 19, the gully is again incised into a loamy-sandy soil. A longitudinal profile of the gully (fig. 12A) shows an increase in gully gradient in an upstream direction. Width-to-depth ratios along the profile indicate a general widening in a downstream direction (fig. 12B). Reaches that are further downstream and away from the headcut might be closer to obtaining a new equilibrium condition than reaches immediately downstream from the headcut. Gully 1 was assigned an erosion classification of Class II (fig. 6; table 1).

Figure 10.--Gully viewed upstream at site 1. [See figure 5 for location and table 1 for detailed characteristics.]

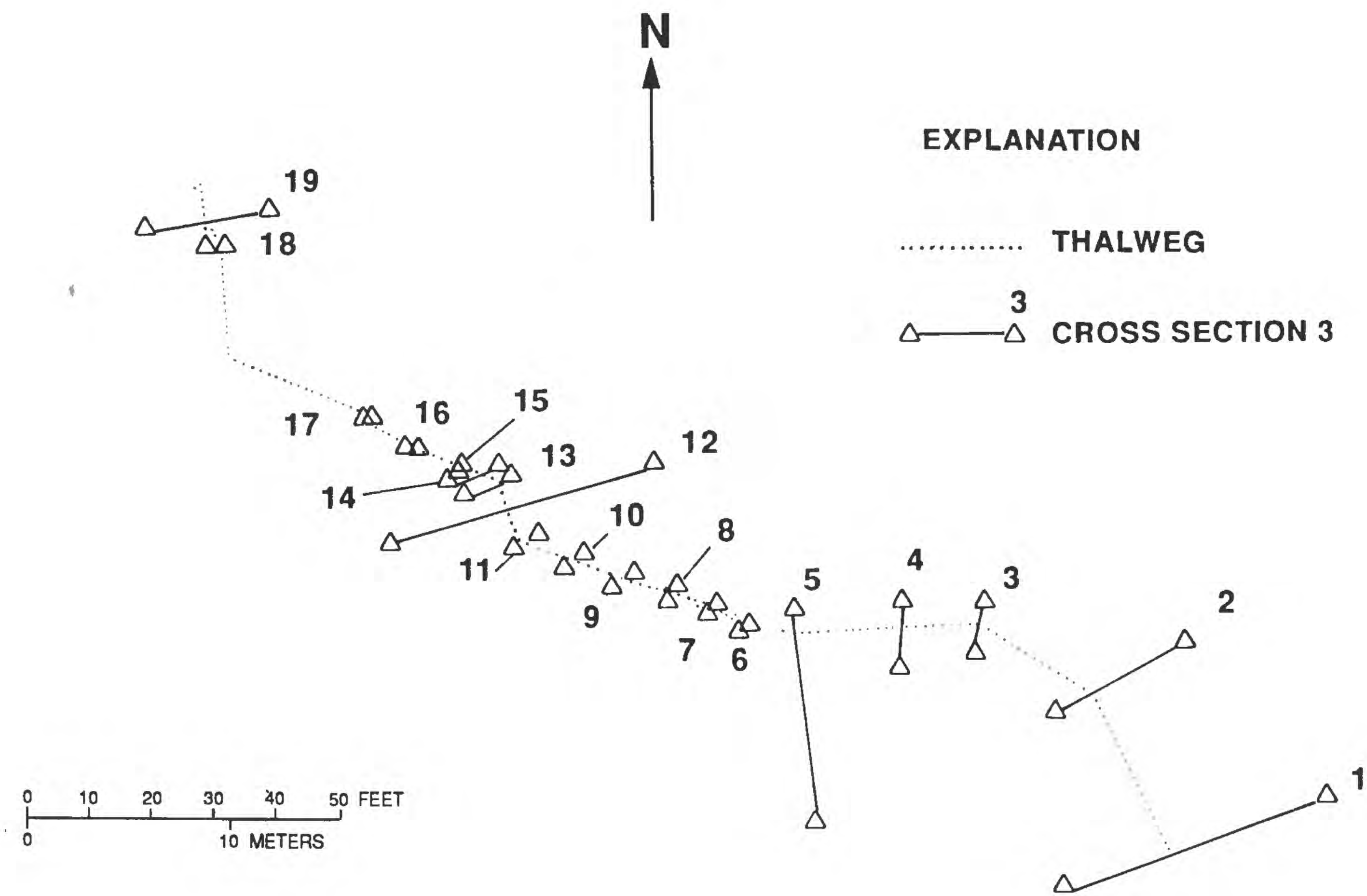

Figure 11.--Main gully channel and surveyed cross sections for site 1. [See figure 5 for location and table 1 for detailed characteristics.]

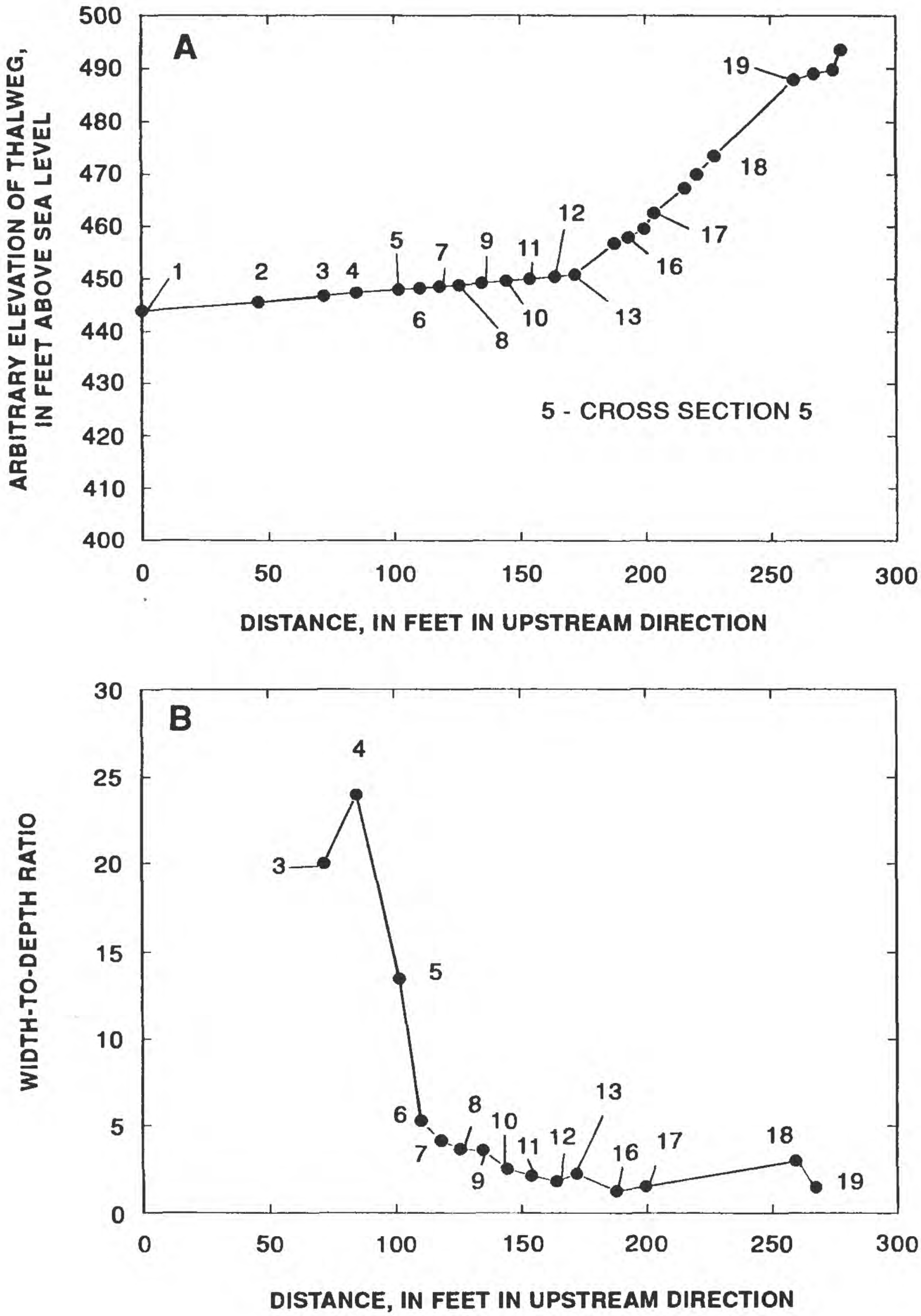

Figure 12.--Longitudinal profile, in distance upstream from the gully mouth (A), and width-to-depth ratios (B) of a gully at site 1.

Site 2

The gully at site 2 (fig. 6) is immediately east of site 1. This gully had the most incision of any gully observed in the study area and was assigned an erosion classification of Class IV. A gully at site 2 viewed downstream is shown in figure 13. The gully is approximately 300 feet long. Ten cross sections were surveyed in the main gully and a tributary that enters the gully from the left bank (fig. 14). At three of these cross sections, 3, 8, and 9, elevation-reference marks were established. The longitudinal profile of the gully indicates a gradual decrease in gradient downstream from the headcut below cross section 10 (fig. 15A). In a similar fashion to gully 1, width-to-depth ratios increase downstream from the headcut (fig. 15B).

Although a gully was observed at site 2 before the summer of 1991, monument officials observed that the gully eroded appreciably during the summer of 1991 (Larry Beal, National Park Service, oral commun., 1992). Runoff from the Paradise Hills area is routed into the monument by means of a 1,500-foot Paradise Hills trench. Heavy runoff during the summer probably flowed down the trench, spread onto the dirt roads, and further eroded gully 2.

Site 32

The gully at site 32 (fig. 16A) is approximately one-half mile north of the monument (fig. 6). Several houses are immediately below the gully. As figure 16B indicates, the gully is depositing sediment into the backyard of one of the nearby residences. Nine cross sections were surveyed in this gully (fig. 17). At three of these cross sections, 3, 8, and 9, elevation-reference marks were established for future surveys (fig. 17). An active headcut is located in the gully downgradient from cross section 7. The longitudinal profile of the gully indicates a lowering of slope below the headcut (fig. 18A). Immediately below the headcut, the channel is relatively deep. Width-to-depth ratios generally increase above the headcut and at a distance downstream from the headcut (fig. 18B). These changes in width-to-depth ratios in this gully are slightly different than those observed in the other surveyed gullies. Eventually, as the headcut moves further upstream, the depth will increase, which will cause the width-to-depth ratio to decrease.

Summary of Three Surveyed Sites

Gully changes recorded at the three surveyed gullies in Petroglyph National Monument were defined in an earlier section of this report. Width-to-depth ratios increase at a distance downstream from headcutting. This indicates that downstream reaches are widening and filling. This trend of widening may continue upstream through the gully system until it reaches a new equilibrium. Older, mature gullies that were observed at sites 34, 53, and 76 (fig. 6; table 1) have reached a new stage of equilibrium as evidenced by the absence of a shallow channel with rounded, well-vegetated banks.

Figure 13.--Gully viewed downstream at site 2. [See figure 5 for location and table 1 for detailed characteristics.]

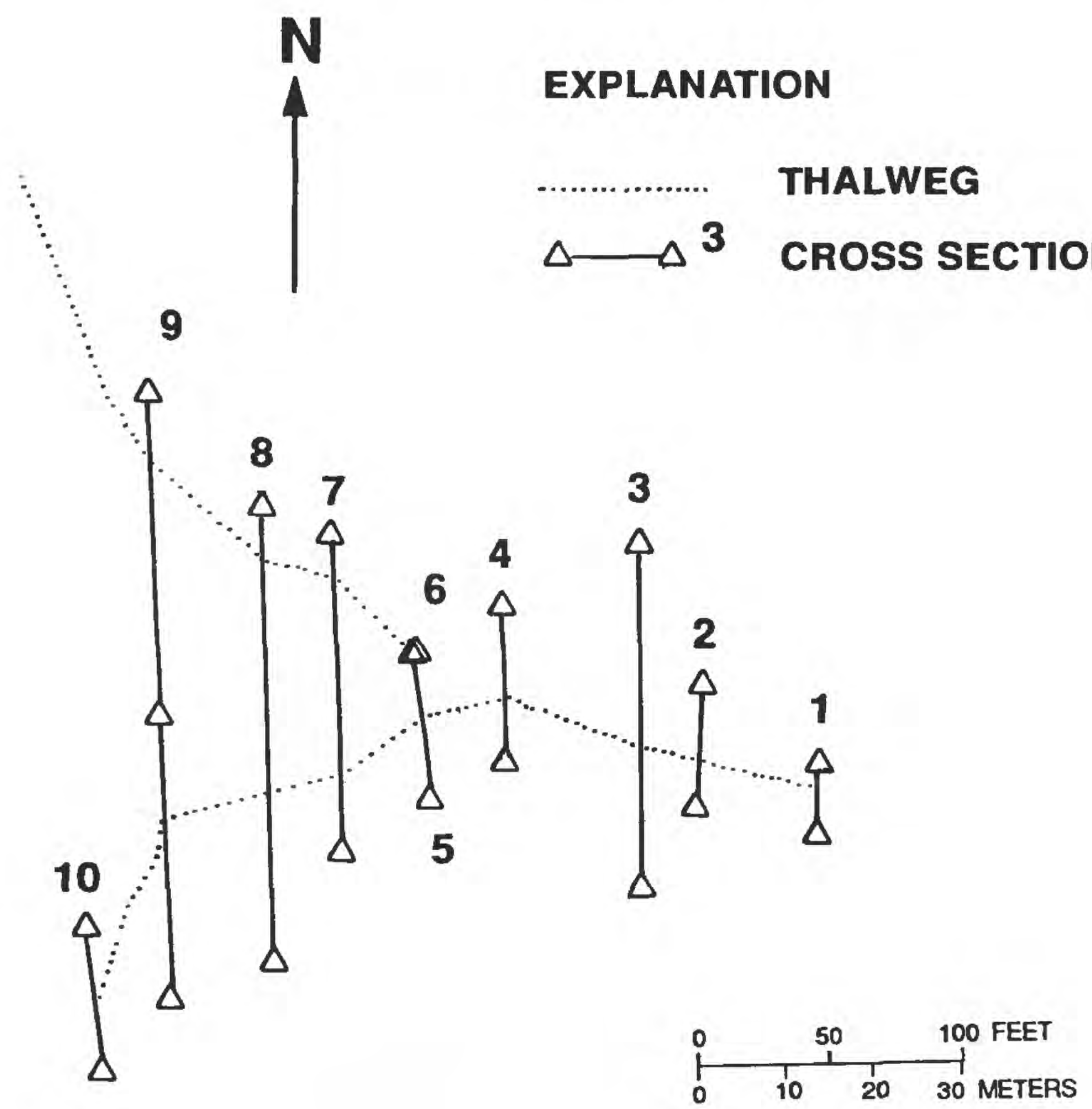

Figure 14.--Main gully channel and surveyed cross sections for site 2. [See figure 5 for location and table 1 for detailed characteristics.]

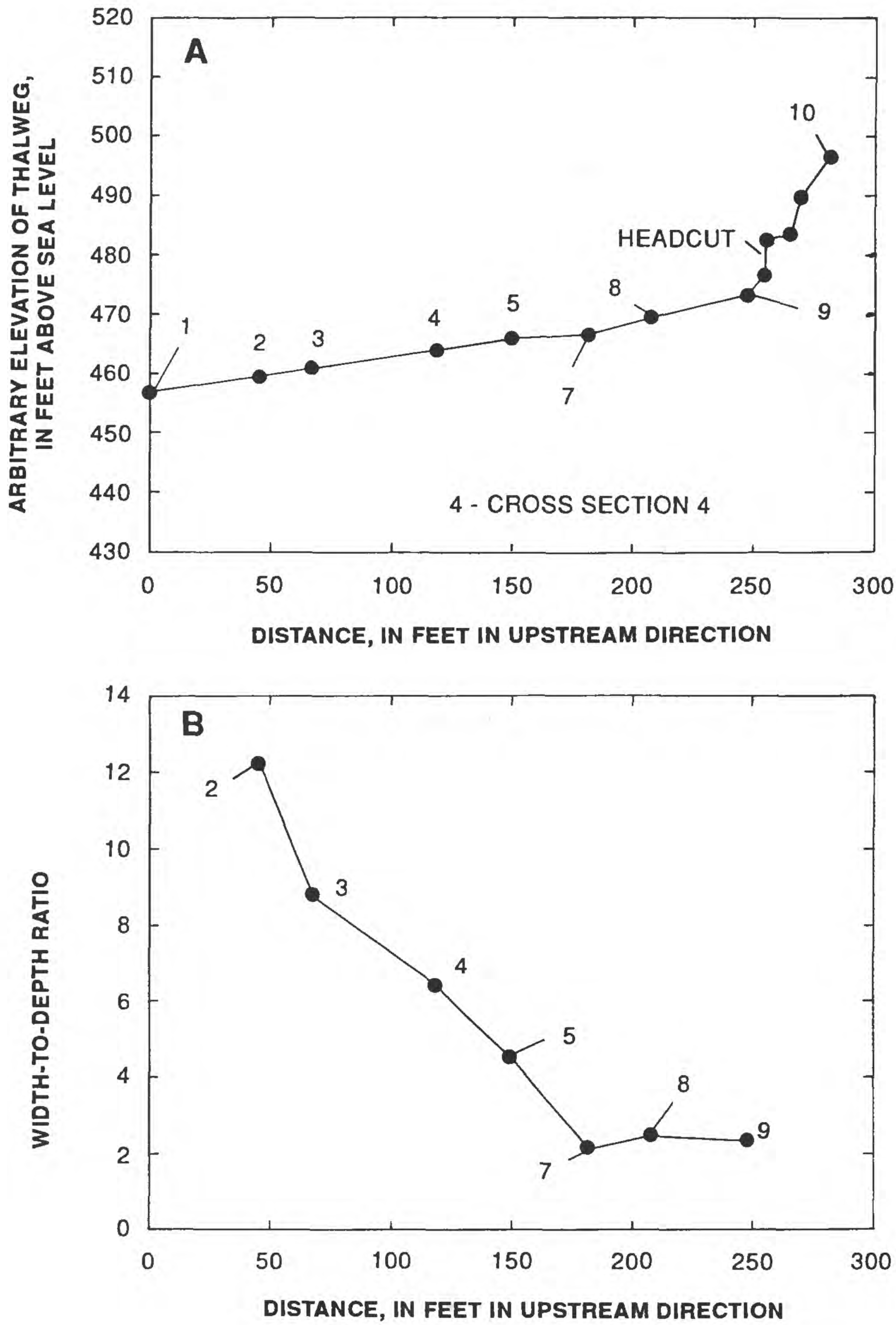

Figure 15.--Longitudinal profile, in distance upstream from the gully mouth (A), and width-to-depth ratios (B) of a gully at site 2.

(A)

(B)

Figure 16.--(A) Gully viewed upstream at site 32. (B) Deposition from gully at site 32. [See figure 5 for location and table 1 for detailed characteristics.]

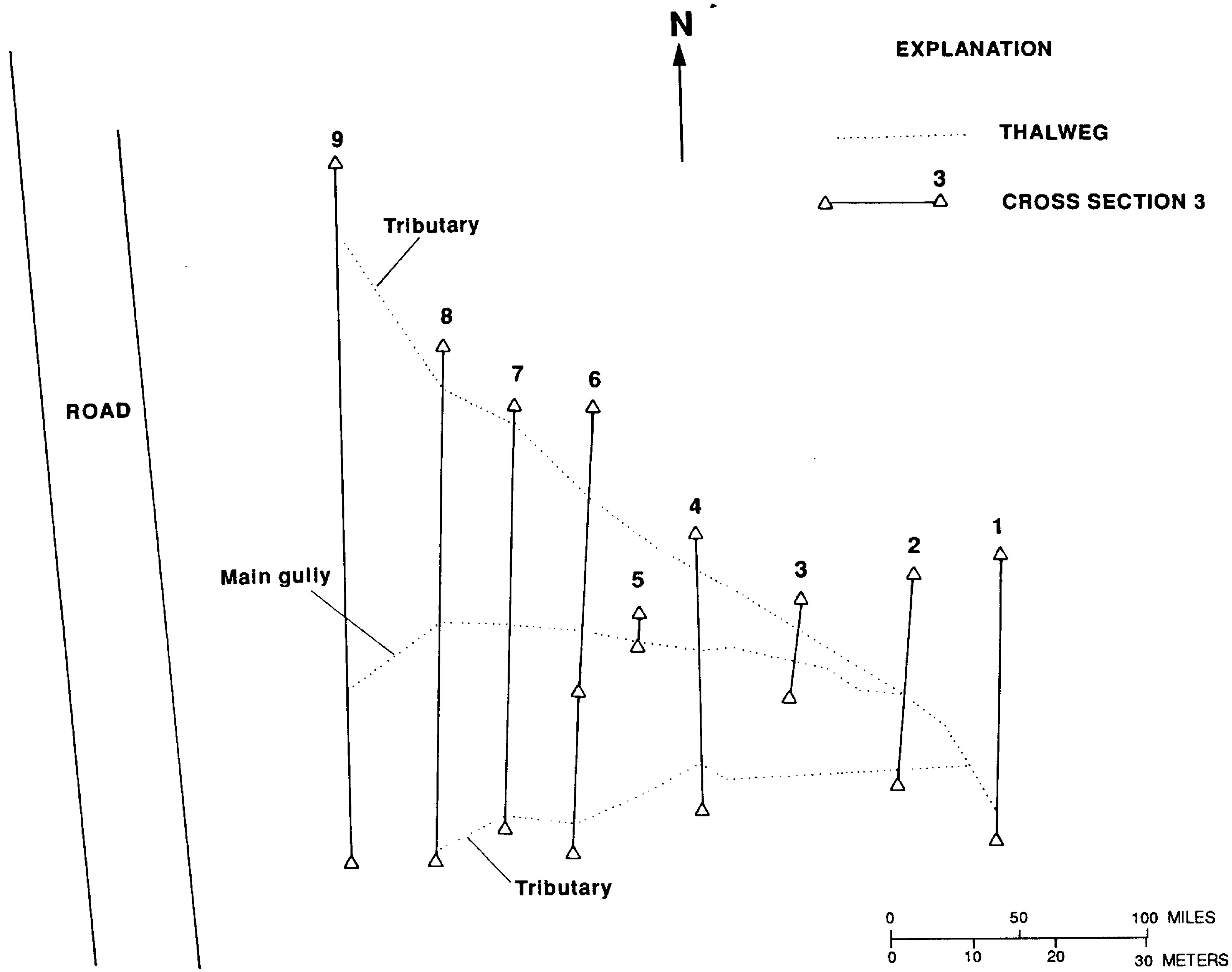

Figure 17.--Main gully channel and surveyed cross sections for site 32. [See figure 5 for location and table 1 for detailed characteristics.]

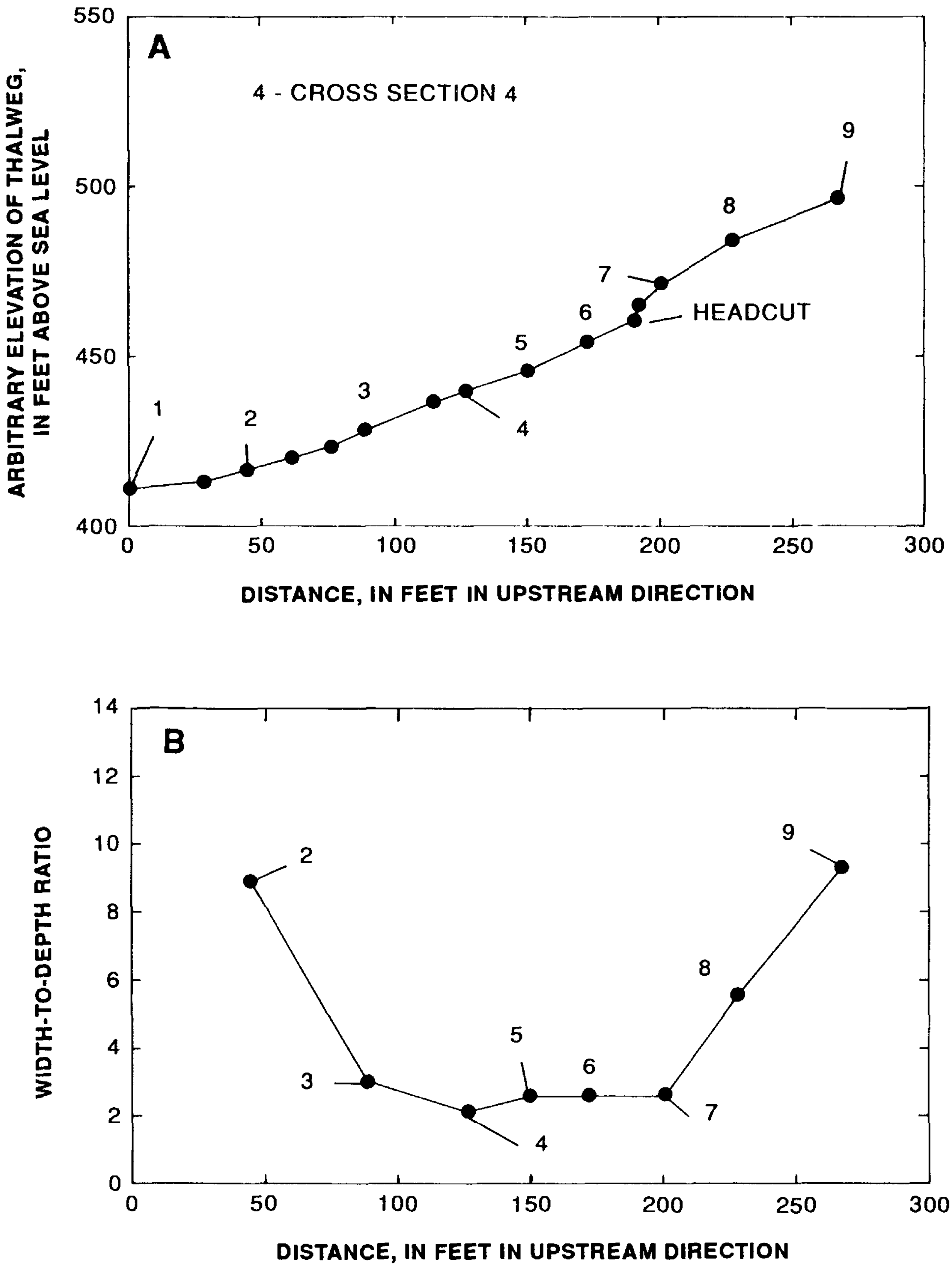

Figure 18.--Longitudinal profile, in distance upstream from the gully mouth (A), and width-to-depth ratios (B) of a gully at site 32.

HYDROLOGIC DATA

Hydrologic data on rainfall were obtained from four USGS rain gages in the monument area: Arroyo 19A, La Boca Negra Arroyo, Ladera Arroyo, and Taylor Ranch Drain (fig. 1). All of these gages are float-in-pipe rain gages that record rainfall at 5-minute intervals (Fischer and others, 1984). Spring, summer, and fall monthly rainfall totals for Arroyo 19A and Ladera Arroyo for water years 1990-91 are shown in figure 19. The rain gages are not operated during the winter months.

Precipitation

Several storms of high intensity occurred during the summer of 1991. The gully at site 2 was observed to have eroded substantially during this period. In an effort to determine the significance of these summer storms, frequency and recurrence intervals were determined from a U.S. Weather Bureau rainfall frequency report (Hershfield, 1961). A summary of and recurrence intervals for these summer storms are listed in table 2. According to the Weather Bureau report, the storms recorded at the Arroyo 19A and Ladera Arroyo rain gages during the summer of 1991 had recurrence intervals of 2 years or less. However, storms that might have produced gullying could have been highly localized and could have missed the rain gages.

Indirect Discharge Measurements

The August 22, 1991, storm (table 3) produced intense runoff at La Boca Negra Arroyo. The National Oceanic and Atmospheric Administration observer rain gages in the Petroglyph National Monument area (one is shown in figure 1; the other is outside the study area) recorded a total rainfall of 1.16 inches and 0.80 inch for August 22, and the National Park Service rain gage reported a total rainfall of 1.50 inches (Larry Beal, National Park Service, written commun., 1992). The only substantial rainfall recorded at the USGS rain gages was at Arroyo 19A, which recorded a total rainfall of 0.63 inch (table 2). Portions of the entrance road to the monument were eroded by the high flow. High-water marks were surveyed at two sites at La Boca Negra Arroyo, upstream and downstream from the escarpment, to determine the peak discharge (fig. 1). The indirect discharge measurements were made in accordance with Benson and Dalrymple (1984). The slope-area method was used for the indirect discharge measurements. Results of the indirect discharge measurements indicate that the peak discharges upstream and downstream from the escarpment were 480 and 510 cubic feet per second, respectively (table 3).

Recurrence intervals for the discharges (table 3) were estimated using a report by Waltemeyer (1986). Waltemeyer used data for 219 streamflow-gaging stations in New Mexico, which represented various basin and climatic characteristics, to develop recurrence interval equations for flood discharge. Sixteen sites were used to develop equations for the central mountain-valley region. Based on the the flood-flow frequency from Waltemeyer (1986) (table 3), the runoff on August 22, 1991, was probably between a 2-year and 5-year event.

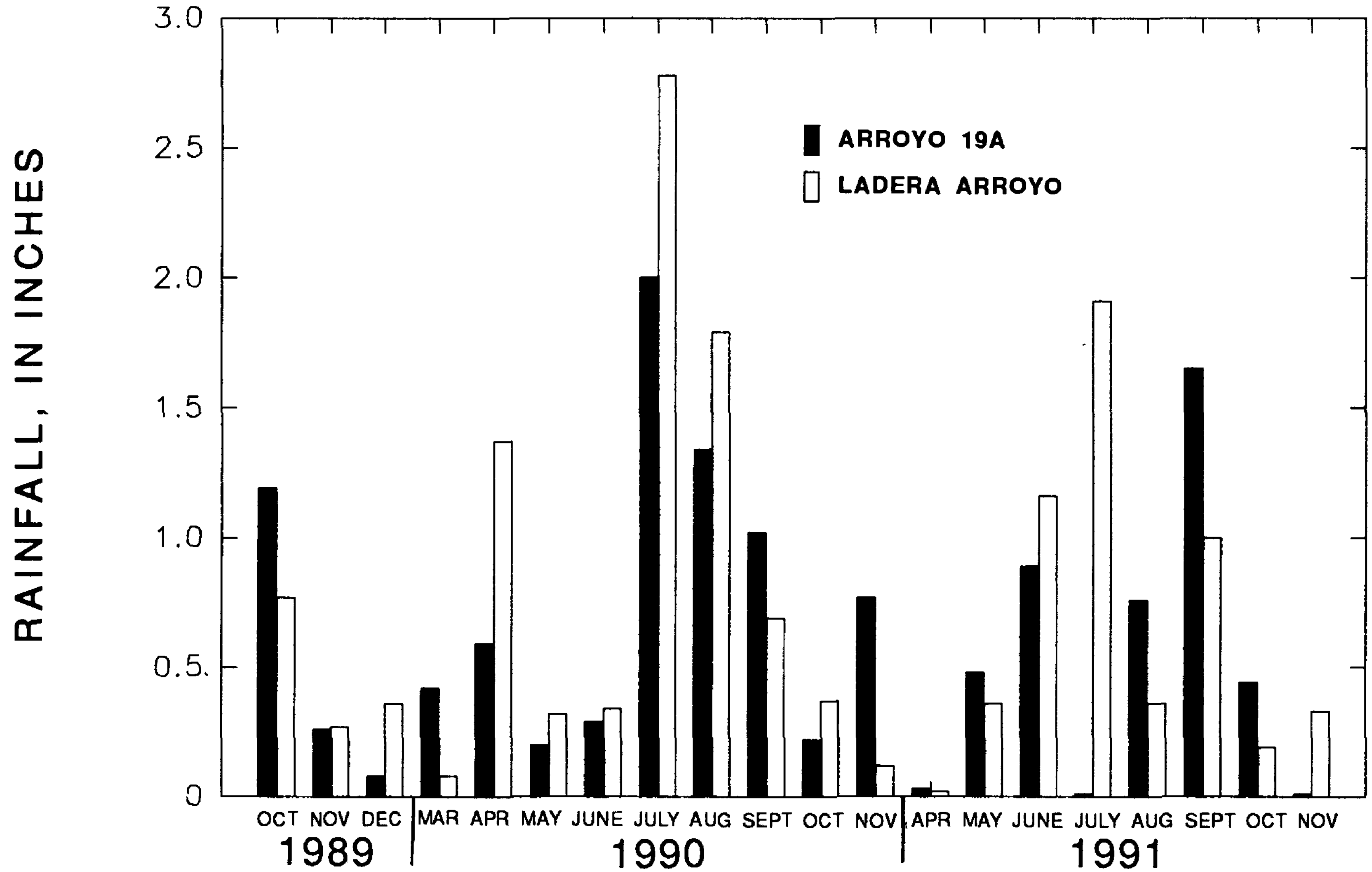

Figure 19.--Monthly rainfall totals, October 1989 to November 1991, for Arroyo 19A and Ladera Arroyo. [Rainfall measurements are not reported during the winter months. See figure 5 for location and table 1 for detailed characteristics.]

SUMMARY AND CONCLUSION

A reconnaissance along the West Mesa's escarpment in the Petroglyph National Monument identified 50 gullies. These 50 gullies were ranked according to four erosion classes: Class I is defined as slight erosion, Class II as moderate erosion, Class III as intense erosion, and Class IV as severe erosion. The 50 gullies that were identified were classified as follows: 21 were Class I, 22 were Class II, 6 were Class III, and 1 was Class IV. Fourteen of the gullies are located on dirt roads, 7 are on foot or bike trails, 11 are associated with a permanent channel, and 18 are located on hillslopes not affected by the aforementioned features.

A higher density of gullies was observed in the northern areas of the monument than in the southern areas; 75 percent of the gullies identified are between escarpment miles 0 and 9 of the 17-mile escarpment. This preponderance of gullies in the northern areas of the escarpment may be related to the higher population in the area and lower density of vegetative cover. The northern areas also have more dirt roads on top of the mesa and more foot and bike trails than the southern areas. Disturbances by people and bicycles may be reducing the vegetative cover, enhancing erosion. The mesa top dirt roads appear to be channeling surface runoff, resulting in gullying and rilling in the road bed. The channeled surface flow can overtop the road at low points and flow over the mesa edge, leading to incision in the loamy-sandy soils. Thirty of the 50 gullies were identified as being connected by surface drainage to these mesa top dirt roads.

Surveys of three gully networks indicate that in most reaches the channel is actively deepening and widening. Width-to-depth ratios generally increase away from headcutting, indicating that downstream reaches are approaching an equilibrium condition. Channel deepening in upstream reaches and widening in downstream reaches will probably continue and may go through a second phase of erosion until the gully has reached an equilibrium condition.

The most severe gully recorded, at site 2, was further eroded during the summer of 1991. An excavated trench located in Paradise Hills routes flow into the monument and might be a major factor in the formation of this gully during intense summer rains. To convey some of the runoff from Paradise Hills into existing surface depressions and prevent further erosion along the escarpment, a small trench was dug west of Piedras Marcadas Canyon. Because gullying did occur in Piedras Marcadas Canyon only during intense storms, the effectiveness of this diversion is not known.

The erosion caused by the gullies may not be a direct concern to the safety of the petroglyphs. Most of the petroglyphs are found on basaltic outcroppings and loose boulders, whereas most of the gullies are in areas of loamy-sandy soils. It is possible that a gully could undercut into the soil below a petroglyph boulder and cause it to roll, but the likelihood of this is not known. It may be of interest to the National Park Service to correlate petroglyph sites to the gully sites.

The channel of flow from dirt roads may be a greater hazard to the petroglyphs. Increases in surface runoff over petroglyphs could increase erosion on the boulder surface and deteriorate the petroglyphs.

Analyses of storms during the summer of 1991 indicate a recurrence interval of no more than 2 years at the USGS rain gages. Indirect measurements of peak discharge of 510 and 480 cubic feet per second, associated with the August 22, 1991, storm, indicate that these may have a frequency of no more than 5 years. Therefore, gullying that occurred during the summer of 1991 was not the result of an unusually high rainfall or runoff event. However, the storms that produce gullying may be highly localized and may have missed the gages.

The channeling of surface runoff by dirt roads located on top of the mesa appears to be a major factor in gullying. Storms do not have to be unusually intense to cause erosion. Resurveying the three selected observation gullies, as well as other gullies in the monument, after substantial storms at selected intervals could help determine rates of channel changes. With long-term records of streamflow and rainfall, more accurate flood-frequency predictions can be made, and any effects of upgradient developments on runoff can be documented.

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Table 1.--Characteristics of observation sites selected for the study of the Petroglyph National Monument, New Mexico

[Erosion site: see figure 5 for location. Erosion class: IV-severe erosion, III-intense erosion, II-moderate erosion, I-slight erosion. Aspect: N = north, S = south, E = east, W = west. Bank erosion: major (10) to minor (0)]

Erosion			Connected						
Site	Class	Land use	to road drainage	Aspect	Bank erosion	Depth (feet)	Width (feet)	Site on hillslope	Description
1	II	Hillslope	No	S	5	0	0	Crest, toe	Actually two gullies located here. The gully to the west has less incision. The gully to the east was surveyed.
2	IV	Road	Yes	SSE	9	0	0	Crest, middle, toe	This is a large gully. Tributary on left bank is also incised. Bank failures are large near crest. This gully was surveyed.
3		Hillslope	No	S	0	0	0		Area of no gullies, but small rill system exists.
4		Road	Yes	S	0	0	0		Road connected to escarpment but no gullies are present, possibly due to the road draining into bedrock.
5	I	Channel	No	SW	2	0	0	Toe	Tributary to Piedras Marcadas Arroyo. Some degree of incision to the base of the mesa. Incision is impeded by boulders.
6		Hillslope	No	N	0	0	0		Area of no erosion.
7		Hillslope	No	E	0	0	0		Area of no erosion.
8		Road	Yes	S	0	0	0		Located in concavity (cove) in the mesa; no erosion in the area. There are remnants of an old road. The area is an extensive alluvial fan. No outcropping or boulders observed below escarpment.
9	II	Road	Yes	NE	3	0	0	Crest, middle	Three gullies in area. The two gullies to the west are part of a road going over mesa. The road is rilled and eroded.
10	II	Road	Yes	E	5	0	0		Gullying and headcutting along mesa road.
11	I	Road	Yes	N	1	0	0	Crest	Small amount of rilling in road; no gullies present.
12		Hillslope	No	N	0	0	0		No erosion. Area is similar to site 2 but has not developed gullies. Area contains silty-sandy deposits.
13	I	Hillslope	No	S	2	0	0	Crest	Small gully in concave area of escarpment.
14		Road	Yes	E	0	0	0		No erosion; evidence of an old road.
15	I	Channel	No	S	1	0	0	Toe	Small channel connected to mesa drainage; no erosion.
16	I	Channel	No	S	1	0	0	Crest	Small channel, minor bank erosion. This gully is a tributary to site 18.
17	II	Hillslope	No	E	3	3	2	Crest	Small active gully. Piping hole present on right bank tributary. This gully is a tributary to site 18.

Table 1.--Characteristics of observation sites selected for the study of the Petroglyph National Monument, New Mexico--Continued

Erosion Site	Erosion Class	Land use	Connected to road drainage	Aspect	Bank erosion	Depth (feet)	Width (feet)	Site on hillslope	Description
18	II	Channel	Yes	ENE	5	0	0	Crest, middle	Main channel is actively eroding its banks and channel bed. The bed is below the base of the left bank tributary. Area is intensively gullied. The gullies are not deep but are active. Headcut found near crest.
19	III	Hillslope	Yes	E	6	0	0	Crest, middle, toe	Large gully on south side of concavity. Large degree of bank erosion. Gully is connected to mesa road runoff.
20		Hillslope	No	E	0	0	0		Small rilling; no erosion.
21	III	Road	Yes	E	6	3	0		Active erosion in road. Road heads east over escarpment just north of housing development. The road gully is 2-3 feet deep, actively undercutting banks. Tributary on the left bank is gullied from road runoff. The gully is perched above the natural channel or depression in concavity.
22	III	Road	Yes	E	7	5	5	Crest	Major erosion on road heading east over mesa. Bank slumping is common and boulders are exposed and appear to be transported. Extension cracks on surface. This site is just west of Shenandoah subdivision. Location is along an E-W fence line.
23		Road	Yes	E	0	0	0		No erosion, but numerous roads present on mesa. Housing development abuts escarpment.
24		Hillslope	No	SSE	0	0	0		Just north of development; no erosion.
25	II	Road	Yes	E	3	4	0	Crest, middle	Erosion and gullying on road going over escarpment. Some bank slumping.
26	I	Trail	Yes	E	2	0	0	Crest, middle	Minor erosion; either a foot path or mountain bike trail.
27		Channel	No	S	0	0	0		Small drainage; no erosion.
28	I	Road	Yes	S	2	0	0	Middle	In an area of enclosed drainage; small amount of erosion on north side of basin.
29	I	Road	Yes	E	2	0	0	Middle	Minor road gullying.
30		Hillslope	No	SE	0	0	0		Just west of housing development. No erosion in area, although several roads are present.
31		Hillslope	No	SE	0	0	0		Small concavity in mesa; no erosion.
32	III	Trail	Yes	E	6	0	0	Crest, middle	Gullying on trail. Deposits are fanning into residential backyards. Gully was surveyed.
33	II	Trail	Yes	S	4	0	0	Crest, middle	Minor gullying along trail that goes over mesa. Some rilling on left bank. Located in mesa concavity.

Table 1.--Characteristics of observation sites selected for the study of the Petroglyph National Monument, New Mexico--Continued

Site	Erosion Class	Land use	Connected to road drainage	Aspect	Bank erosion	Depth (feet)	Width (feet)	Site on hillslope	Description
34	II	Channel	Yes	SE	5	0	0	Crest, middle, toe	Mature gully system. Middle reaches have exposed boulders. Crest is incised up to the mesa road.
35	I	Channel		SE	1	0	0	Middle	Small channel; minor erosion.
36		Hillslope		ESE	0	0	0		Located in mesa concavity; no erosion.
37		Other	No	E	0	0	0		No erosion in area. Area has several small concavities in mesa.
38		Hillslope	No	S	0	0	0		Site is at promontory in escarpment. No gullies are present. Extreme end of promontory is fenced off. Petroglyph National Monument visitor center is in view.
39		Hillslope	No	S	0	0	0		No gullies present, although this site is at a major concavity in the mesa. Not many trails are in this area going over the escarpment. Some silty-sand deposits are present. This site is immediately above the visitor bathroom.
40		Hillslope	No	SW	0	0	0		Area is in the concavity of La Boca Negra Arroyo. No erosion on escarpment. Some erosion on right bank tributary to La Boca Negra Arroyo. Lots of rill erosion below paved road (Unser Blvd) near visitor picnic area. Note patterned striations of basalt on escarpment; most striations are in interfluve area, possibly as remnants of erosion that has occurred around it.
41	I	Hillslope	No	W	1	0	0	Toe	Site at small notch in a major concavity in the escarpment. Permanent channel feature; erosion occurring only at toe of hillslope. No erosion at crest. The gully at the toe fans out into La Boca Negra Arroyo.
42		Hillslope	No	S	0	0	0		Area of no erosion. Some indentations in mesa present, but no gullying.
43	II	Channel	Yes	SE	5	0	0	Middle, toe	La Boca Negra Arroyo - Many areas along right bank have gullies, most of which are connected to the asphalt road, so erosion seems to be due to road runoff; erosion characteristics are rills and gullies. The main arroyo channel does not appear to be incised and appears to be transporting much sediment. Some tributaries appear gullied. Minor volume of water was seen discharging over the escarpment.
44		Hillslope	No	E	0	0	0		Site is on the west side of La Boca Negra escarpment. No erosion in area. A fine, silty (aeolian?) material is on hillslope. Trails and switchbacks are present at this site but no gullies.
45	I	Road	Yes	E	2	2	4	Crest	Site just NE of site 44. Small gully forming from road runoff. This is a side road of the main mesa dirt road network that heads over the escarpment.

Table 1.--Characteristics of observation sites selected for the study of the Petroglyph National Monument, New Mexico--Continued

Erosion Site	Erosion Class	Land use	Connected to road drainage	Aspect	Bank erosion	Depth (feet)	Width (feet)	Site on hillslope	Description
46	I	Road	Yes	E	2	0	0		Just NE of site 45. Same type of gully as site 45, but smaller.
47	II	Channel	Yes	E	5	4	4	Crest, middle	This is the main channel in the concavity of this area. Erosion is in the upper and middle portions of the hillslope, depositing sediment at the toe. It is not connected to La Boca Negra Arroyo. The gully is incised in a fine, silty-sandy soil. Incision is likely to continue in this gully in the future. Some bank slumping is present. Some of the headward growth of the gully is cut off by boulders in the channel.
48	I	Hillslope	No	N	2	0	0		Landslide scar. Exposed soil near the crest of the mesa. A berm of boulders is present at the toe of the slide. Some rilling in the exposed soil.
49	I	Channel	Yes	NE	1	0	0	Middle, toe	Site is La Boca Negra South Arroyo draining NE to La Boca Negra Arroyo.It is connected to La Boca Negra Arroyo via pipes. The channel has eroded a distinct notch into the escarpment. Bedrock headcuts at notch. Lots of scarp retreat seen as fallen boulders. One small tributary on NE side is rilled: maximum 2-foot depth and 2-foot width.
50	II	Trail	Yes	NE	3	3	4	Crest, middle	Gully located at apex of concavity. Gully is similar to site 47 but smaller. Some boulders are exposed. Gully is incised in a fine, silty-sandy soil.
51	I	Hillslope	Yes	SE	2	1	1	Crest, middle	This area has 2 to 3 small, shallow gullies.
52	II	Road	Yes	SE	4	4	6	Toe	Gully is on usable dirt road connected to mesa. No gullies on top of mesa. Road has affected the hillslope; some boulders appear dislodged. Some rilling on road bed. At the bottom of the road is the gully at site 53.
53	II	Hillslope	No	E	5	6	20	Crest, middle, toe	Mature gully system. Vegetation is well established in banks. This is gully that bisects road at site 52. Banks are rounded and the channel is filled in with dead vegetation. Possibly an old trail or road. This gully is located immediately over a gas line. Rilling at crest. Located at small concavity in mesa.
54	II	Hillslope	Yes	E	5	4	5	Crest, middle	Medium-sized gully connected to runoff from the mesa road. Some bank slumping.
55	I	Hillslope	Yes	E	2	0	0	Middle	Smaller gully south of site 54. Minor erosion.

Table 1.--Characteristics of observation sites selected for the study of the Petroglyph National Monument, New Mexico--Continued

Erosion Site	Erosion Class	Land use	Connected to road drainage	Aspect	Bank erosion	Depth (feet)	Width (feet)	Site on hillslope	Description
56		Hillslope	Yes	SE	0	0	0		No erosion in area. Area is a distinct notch in the mesa. No gullies are present because the area is mostly boulders and bedrock. Also no deposits of the silty-sandy soil were observed. Well-maintained channel enters notch and is gullied near mesa road intersection. Headcut located just off east side of road. An area 200 feet to the south contains the silty-sand deposit and is not gullied but it is also not connected to the mesa roads.
57		Trail	Yes	E	0	0	0		No erosion on trail. Trail located near end of subdivision. The road leading to the end of the promontory has no gullies.
58		Hillslope	No	SE	0	0	0		No erosion in area, although many undulations are along the mesa front. Just above the Santa Fe Village housing development. Area is mostly bedrock with some deposits of the silty-sandy soil present. A trail located 200 feet to the south has no erosion.
59		Trail	No	E	0	0	0		Trail on hillslope but no erosion.
60		Hillslope	No	ESE	0	0	0		No erosion.
61		Hillslope	Yes	ESE	0	0	0		Located in apex of concavity. No erosion, although this is a well-maintained drainage. Boulders present; no silty-sandy deposits.
62		Hillslope	Yes	E	0	0	0		No erosion. Located at minor indentation in mesa. Mesa road goes near the edge of the escarpment, but no gullies.
63		Hillslope	Yes	E	0	0	0		Area of trails but no gullies. Trails are in the silty-sandy material.
64	II	Trail	Yes	NE	3	2	5	Crest, middle, toe	No gullies between sites 63 and 64. This is an older gully; much vegetation in channel. Some bank failures near toe. Some boulders exposed. Gully is in a silty-sandy material.
65	II	Trail	Yes	E	3	4	10	Middle	Located at concavity in mesa. Older gully system. Banks are rounded and there is vegetation in the gully. Gully is formed in the middle of hillslope; some erosion at crest.
66		Channel	Yes	E	0	0	0		Located at notch in canyon. No erosion.
67		Hillslope	No	NNE	0	0	0		No erosion.
68	II	Hillslope	No	N	3	4	18	Middle	This also appears to be an older gully system. Not much gullying at crest. Gully is in a silty-sandy material. Located at concavity in the mesa. Some gullying on the left bank tributary.

Table 1.--Characteristics of observation sites selected for the study of the Petroglyph National Monument, New Mexico--Continued

Erosion Site	Erosion Class	Land use	Connected to road drainage	Aspect	Bank erosion	Depth (feet)	Width (feet)	Site on hillslope	Description
69		Hillslope	No	S	0	0	0		No erosion.
70		Hillslope	No	N	0	0	0		No erosion.
71		Hillslope	No	S	0	0	0		No erosion.
72		Hillslope	No	E	0	0	0		At tip of promontory; no erosion.
73	I	Road	Yes	SE	2	0	0	Toe	No gullies in area. Some erosion on right bank of the road. This is the area where the road goes over the mesa. Some gullying at the bottom of the road. Pockets of silty-sandy material on hillslope but no gullies. Some of the boulders are sliding downhill, probably as result of the road.
74	III	Hillslope	No	E	7	6	15	Crest, middle, toe	This is a boulder-lined gully that bisects the road at site 73. The road is at the base where there is major gullying. Numerous boulders in the gully seem to have been transported.
75		Hillslope	No	E	0	0	0		Small concavity in mesa; no erosion.
76		Hillslope	No	E	0	0	0		This appears to be an old mature gully system. It has a concave form but no distinct channel or banks.
77	I	Hillslope	No	E	1	1	3	Crest, middle	Small gully; not much erosion. Large deposits of silty-sandy material are in the area.
78		Trail	No	E	0	0	0		Large deposit of silty-sandy material but no gullies. This is also a trail.
79	II	Hillslope	No	E	3	4	10	Middle, toe	Two gully systems are here, labeled A and B. Description is for B, which has more erosion. Most of the erosion at B is at the toe of the hill. Large bank failures at toe. Some of the incision is working up to the middle reaches. Plenty of silty-sandy material at crest. Gully A is less incised.
80	I	Hillslope	Yes	SE	1	0	0	Crest	Area of no erosion. At 80A some of the road runoff is draining over mesa where a small gully is located at the crest.
81		Hillslope	No	SE	0	0	0		Area of no erosion.
82	II	Hillslope	No	SE	5	10	35	Crest, middle	Gully located under power lines. Possibly the area was originally a constructed trench. Large amounts of erosion. Large boulders are falling in gully.
83		Hillslope	No	S	0	0	0		Under the southern power line; no gullies.

Table 1.--Characteristics of observation sites selected for the study of the Petroglyph National Monument, New Mexico--Continued

Erosion		Land use	Connected to road drainage	Aspect	Bank erosion	Depth (feet)	Width (feet)	Site on hillslope	Description
Site	Class								
84		Hillslope	No	SSW	0	0	0		Area of no gullies.
85		Channel	No	S	0	0	0		Natural channel; no erosion. Located at notch in mesa. This area of the mesa is mostly boulders; not much silty-sandy material.
86		Hillslope	No	SSW	0	0	0		Area of no erosion; boulders present.
87		Hillslope	No	S	0	0	0		Area of no erosion.
88		Hillslope	No	SSE	0	0	0		Area of no erosion.
89		Hillslope	No	S	0	0	0		Area of no erosion.
90	I	Channel	No	SSE	1	0	0	Middle	This is a natural channel located at a notch in the mesa. Only minor erosion. Headcuts in the channel are bedrock stair-steps. Some soil present, but mainly boulders. Cows grazing in the area.
91		Channel	Yes	E	0	0	0		Main Rinconada Canyon Arroyo. Channel has a sandy bed and good form. Large stair-step topography from the top to the bottom of the mesa. No gullies in channel. Mainly boulders and bedrock.
92		Hillslope	No	N	0	0	0		Area of no erosion. Mesa roads are located near the edge of the escarpment. The entire Rinconada Canyon area seems to have a higher vegetation density than that found to the north.
93		Hillslope	No	N	0	0	0		Area of no erosion.
94	I	Channel	No	N	1	1	10	Toe	Small channel at notch in mesa. Some evidence of minor gullying at toe. Well vegetated. Plenty of silty-sandy deposits are in the area. This may be an older gully system.
95		Hillslope	No	E	0	0	0		Area of no erosion.
96		Hillslope	No	ESE	0	0	0		Area of no erosion.
97		Hillslope	No	SE	0	0	0		Area of no erosion.
98		Hillslope	No	S	0	0			Area of no erosion; located immediately above a USGS streamflow-gaging station.
99		Channel	No	S	0	2	3		Channel located at notch in mesa; no gullying.
100		Channel	No	E	0	0	0		Another natural channel with no erosion.
101		Hillslope	No	SE	0	0	0		Area of no erosion. Some distinct notches in mesa.

Table 1.--Characteristics of observation sites selected for the study of the Petroglyph National Monument, New Mexico--Concluded

Erosion Site	Erosion Class	Land use	Connected to road drainage	Aspect	Bank erosion	Depth (feet)	Width (feet)	Site on hillslope	Description
102	III	Road	Yes	SE	7	8	6		Massive erosion due to runoff in the dirt roads in the area. Connected to main arroyo system.
103		Hillslope	No	E	0	0	0		Area of no erosion.
104	II	Trail	No	E	4	4	8	Toe	Gully connected to main arroyo. Incised in silty-sandy soil. Gunnery range in area.
105		Hillslope	No	S	0	0	0		Area of no erosion.
106	II	Channel	Yes	E	3	2	1	Middle	Erosion as a result of drainage trench on mesa. Trench is gravel and cobble lined.
107	II	Hillslope	No	SE	4	5	6	Middle	Large headcut or gully on hillslope next to street. It is unclear how this gully is forming. There seems to be little connection to any surface runoff. The hill might have been excavated for fill.

Table 2.--Rainfall data collected during 1991 storms in the vicinity of Petroglyph National Monument for total rainfalls of 0.45 inch or greater

[Recurrence of rainfall intensity is shown in parentheses; see figure 1 for location of rain gages. Values are in inches]

Rain gage	Start date	Time	End date	Time	30-minute maximum rainfall intensity	1-hour maximum rainfall intensity	2-hour maximum rainfall intensity	Total rainfall for storm
Arroyo 19A	6/29/91	1500	6/29/91	2400	0.23	0.25	0.25	0.45
Arroyo 19A	8/22/91	1530	8/22/91	2000	0.44 (1 year)	0.45	0.53	0.63
Arroyo 19A	9/6/91	0005	9/6/91	0630	0.17	0.26	0.47	0.68
Arroyo 19A	9/9/91	1330	9/10/91	0940	0.20	0.21	0.23	0.56
La Boca Negra	6/29/91	1530	6/29/91	2345	0.14	0.24	0.26	0.46
La Boca Negra	8/6/91	1900	8/6/91	2400	0.24	0.32	0.42	0.45
La Boca Negra	9/6/91	0005	9/6/91	0700	0.25	0.35	0.51	0.83
La Boca Negra	9/9/91	1300	9/10/91	1030	0.11	0.16	0.16	0.66
Ladera Arroyo	6/29/91	1500	6/30/91	0200	0.17	0.21	0.21	0.47
Ladera Arroyo	7/23/91	0005	7/23/91	0630	0.07	0.13	0.25	0.57
Taylor Ranch Drain	7/19/91	1700	7/19/91	1900	0.59 (2 years)	0.70 (2 years)	0.71 (1 year)	0.71
Taylor Ranch Drain	7/21/91	2100	7/22/91	2000	0.30	0.39	0.51	0.63
Taylor Ranch Drain	9/6/91	0005	9/6/91	0700	0.29	0.40	0.61	0.78

Table 3.--Estimated recurrence intervals of peak discharge, La Boca Negra Arroyo, upstream and downstream from escarpment, August 23, 1991

[ft^3/s, cubic feet per second]

Recurrence interval (years)	Discharge upstream from escarpment (ft^3/s)	Discharge downstream from escarpment (ft^3/s)	Standard error of estimate	
			Maximum (percent)	Minimum (percent)
Peak discharge	480	510		
2	410	430	+108	-52
5	950	1,000	+79	-44
10	1,450	1,530	+69	-41
25	2,320	2,430	+65	-39
50	3,210	3,280	+65	-39
100	4,020	4,210	+66	-40