HILLSLOPE EROSION AT THE MAXEY FLATS RADIOACTIVE WASTE DISPOSAL SITE, NORTHEASTERN KENTUCKY

By William P. Carey, Mark A. Lyverse, and Cliff R. Hupp

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CONVERSION FACTORS

Multiply	By	To obtain
Cubic feet per second (ft^3/s)	0.02832	cubic meters per second (m^3/s)
Curie	3.7×10^{10}	becquerel
foot	0.3048	meter
inch	2.540	centimeter
mile	1.609	kilometer
picocurie	3.7×10^{-2}	becquerel
pound	0.4536	kilogram
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	2.59	square kilometer (km^2)

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

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ABSTRACT

Maxey Flats, a disposal site for low level radioactive waste, is on a plateau that rises 300 to 400 feet above the surrounding valleys in northeastern Kentucky. Hillslope gradients average 30 to 40 percent on three sides of the plateau. The shortest distance from a hillslope to a burial trench is 140 feet on the west side of the site. Rates of hillslope retreat were determined through a combination of direct erosion measurements during the 2-year study and through dendrogeomorphic techniques. Because the dendrogeomorphic rates are average rates during the last 90 years, they were used to estimate the amount of time required for the hillslopes to retreat into the trenches. Rates of hillslope retreat determined from dendrogeomorphic evidence range from 3.8 to 9.1 inches per century, so that time to exposure of the trenches ranges from 35,000 to 65,000 years. The minimum estimate of 35,000 years is for the most actively eroding southern slope.

Throughout tens of thousands of years, the rate of hillslope retreat is determined more by the occurrence of infrequent extreme events such as slope failure than by the continuous processes of slope wash observed in this study. Shallow slope failures were observed on the east and south slopes of the site. Large slope failures form mappable units on the geologic quadrangle containing the study area. These slope failures cause as much erosion in one event as hundreds or even thousands of years of slope wash. Periods of tens of thousands of years are also sufficiently long for significant changes in climate and tectonic activity to occur. Rates of erosion observed during this 2-year study are highly unlikely to be indicative of rates averaged over periods of tens of thousands of years during which many extreme events can occur. Thus, the long-term geomorphic stability of the Maxey Flats disposal site will be highly dependent upon the magnitude and frequency of extreme erosive events and upon trends in climate change and tectonic activity.

INTRODUCTION

Maxey Flats, a disposal site for low level radioactive waste, is on a plateau that rises 300 to 400 feet above the surrounding valleys in northeastern Kentucky. Burial of nuclear waste at the site began in 1963 and continued until 1977. Estimates of the volume of buried waste range from 167,000 to 178,000 cubic yards of material that contains more than 2.4 million curies of by-product material, plus 431 kilograms (950 pounds) of "special" nuclear material, and 533,000 pounds of source material (Zehner, 1983). Briefly defined: by-product material is material made radioactive by exposure to radiation; special nuclear material consists of plutonium, uranium-233, and enriched uranium-235; and source material consists of uranium and thorium

(Zehner, 1983). By convention, the unit for quantity of special nuclear material is the gram, whereas that for source material is the pound (Zehner, 1983). Most waste is in solid form and is buried in rectangular trenches about 25 feet deep. The trenches are separated by about 5 to 10 feet of shale and thin sandstone beds. When filled, they were covered with approximately 3 to 10 feet of compacted clay and crushed shale (Zehner, 1983). Measures designed to prevent infiltrating rainfall from reaching the trenches have substantially altered surface drainage above the trenches. Impervious plastic material has been placed over the trench-cap material, and runoff from this impervious cover is directed off site and down existing drainage channels.

Long-term geomorphic trends in hillslope retreat and channel enlargement are important with regard to the stability of the site because of the long half-lives of some of the buried material (24,360 years for plutonium-239) and the proximity of the trenches to the hillsides. Rates of these processes are of substantial interest given the relatively high average annual rainfall (45.4 inches) and the steepness (30 to 40 percent) of slopes on three sides of the burial site. The main variables affecting rates of geomorphic processes on slopes are climate (with associated vegetation), rock type, slope steepness, and anthropogenic influences (Saunders and Young, 1983, p. 474). The purpose of this study was to estimate the current rate of hillslope retreat and channel enlargement in the vicinity of the Maxey Flats disposal site by using dendrogeomorphic analysis and direct measurement, and to make some inferences regarding long-term migration of the hillslopes toward the burial trenches.

Purpose and Scope

This report presents the results of a 2-year study of slope erosion processes at the Maxey Flats disposal site, and comments on the long-term integrity of the burial trenches with respect to slope retreat. Thus, the report is of much broader scope in terms of earth-surface processes than the period of data collection would suggest. As such, the discussion and emphasis is placed on infrequent, large-magnitude events that are known to occur over the time scale of interest, but have not been specifically documented at the site. Similarly, the potential for changes in intensity of erosive processes due to influences of tectonic activity and climate change must be considered, but a discussion of the structural evolution and Quaternary climate of eastern Kentucky is not presented here.

DESCRIPTION OF STUDY AREA

The physical and climatological description of the Maxey Flats area has been presented in several references. A brief description, taken mostly from Zehner (1983), is presented here for completeness. A more detailed description, particularly of the geology, is available in the text and references of Zehner (1979, 1983).

Geographic Setting and Climate

Maxey Flats is in the Knobs physiographic region of east-central Kentucky, approximately 9 miles northwest of the city of Morehead (fig. 1). The Knobs region of Kentucky is the remnant of an eroded plateau, characterized by the presence of many knoblike erosional remnants of Silurian, Devonian, and Mississippian rocks (McFarlan, 1943). Local differences in relief between the knob and valley bottoms at the study site are considerable and range from 300 to 400 feet. Valleys border part of the site, with an unnamed valley to the east, Rock Lick Creek to the south, and Drip Springs Hollow to the west (fig. 2). Stream channels on the hillslope between the burial site and the valley bottoms are relatively steep, and gradients average 30 to 40 percent. Some channels contain boulders larger than 5 feet in diameter. Slopes of the streams vary with local sequences of sandstone and shale, which crop out in the channels.

Mean annual precipitation at a U.S. Weather Bureau station at Farmers (fig. 1), 8 miles southwest of the Maxey Flats site, was 45.4 inches for 1941 through 1984 (National Oceanic and Atmospheric Administration, 1984). Most rain in the summer and fall consists of relatively short but intense periods of precipitation associated with convective storms. Rainfall in the spring and winter generally is longer in duration and less intense, and is associated with frontal storms.

Runoff of precipitation from the disposal site has been altered since the Fall of 1981 when approximately 25 acres were covered with impermeable polyvinylchloride (PVC) that inhibits vertical infiltration of water into the burial trenches. This cover has increased runoff to the three main channels that drain the site. These channels, called main drain (on the east side of the site), south drain, and west drain are shown in figure 2.

Soil Characteristics

Within the study area, soils generally can be divided into two groupings: ridgetop and sideslope. Ridgetop soils consist of a silty loam of the Tilsit and Johnsburg series. They are as much as 2.0 feet in thickness and have average slopes of 2 to 6 percent. The Tilsit soils are moderately well drained at the ridgetop location. Typically, they formed in weathered siltstone or sandstone. Erodibility of these soils is classified moderate when cultivated or disturbed. The Johnsburg soils are more poorly drained than the Tilsit soils and originate from the weathering of sandstone, siltstone, and shale. These soils have a tendency to become saturated during wet seasons; their clay content ranges from 10 to 35 percent.

Sideslope soils belong to the Brownsville-Berks or Muse-Trappist series. The Brownsville-Berks series consist of deep, well drained soils formed from colluvium and residuum of weathered, fractured siltstone and very fine grained sandstone. The Muse-Trappist series are moderately deep to deep, well drained, occur on uplands and footslopes, and have formed from residuum or colluvium of acid fissile shales. Clay content of these sideslope soils ranges from 7 to 60 percent, and hillslope gradients range from 20 to 55 percent.

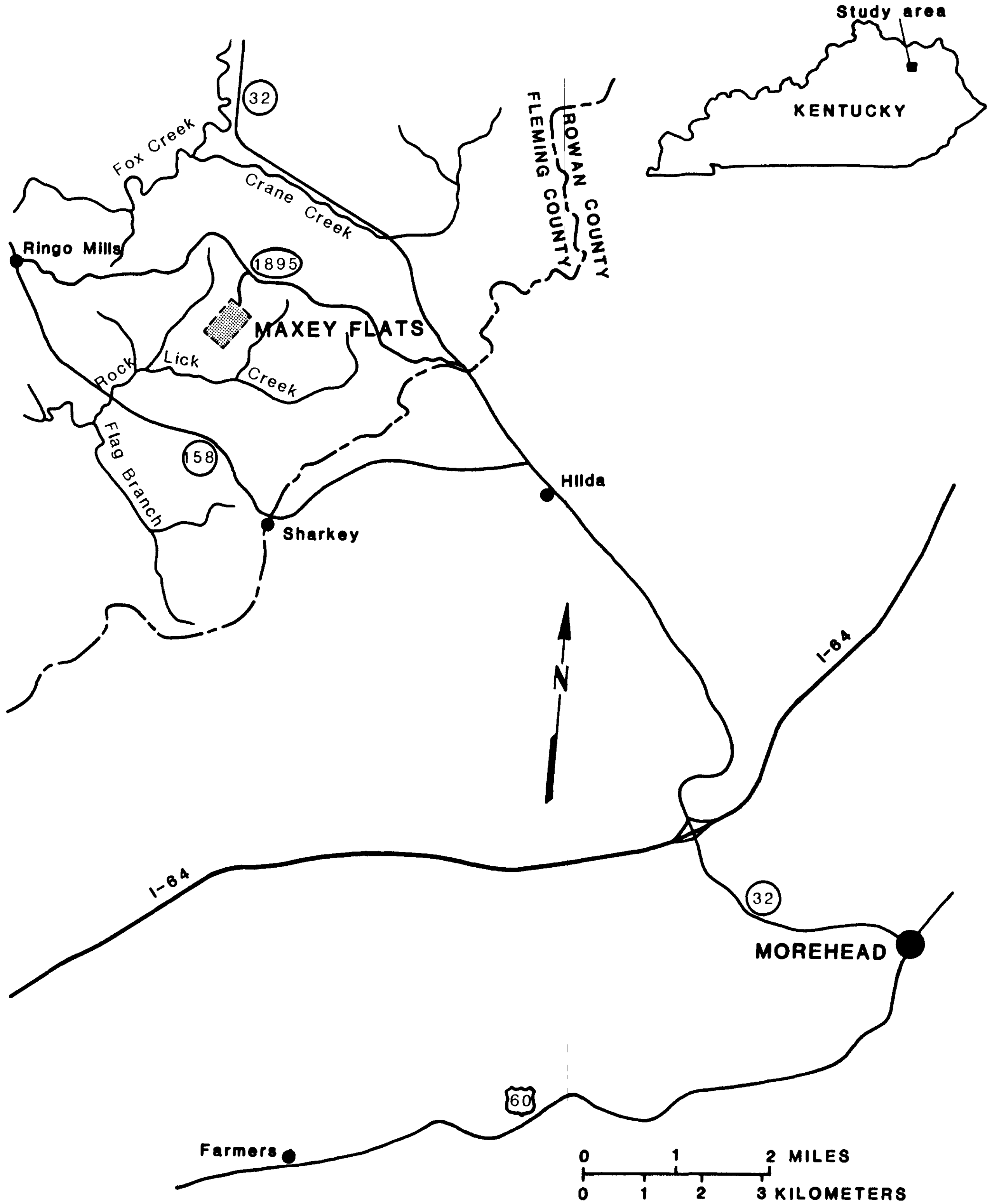
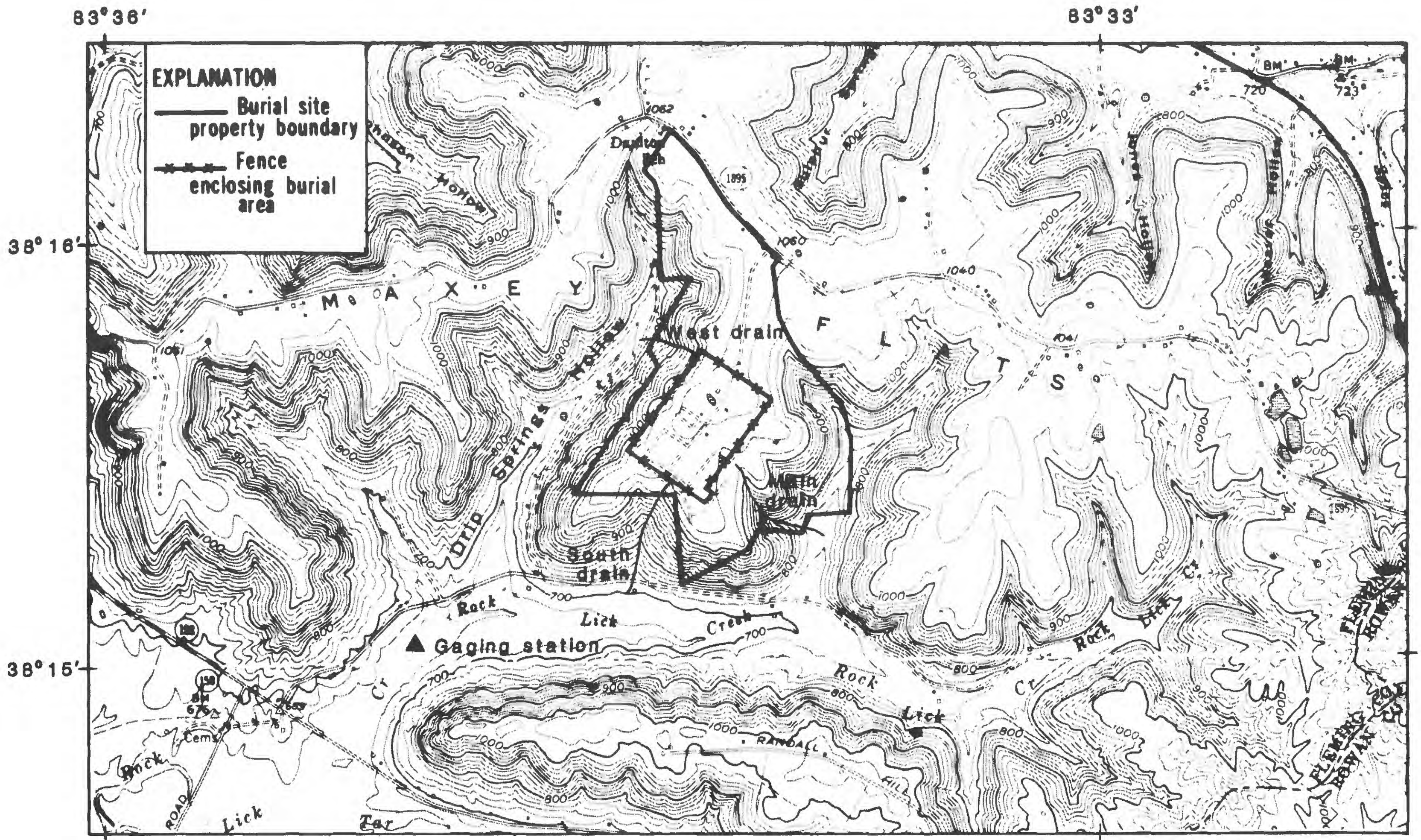


Figure 1.--Location of the Maxey Flats site.



Modified from H. H. Zehner 1983

Base from U.S. Geological Survey Plummers Landing 1:24000, 1951, revisions as of 1979 and Farmers 1:24000, 1970.

1 ½ 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 .5 0 1 KILOMETER

CONTOUR INTERVAL 20 FEET

National Geodetic Vertical Datum of 1929

Figure 2.--Topography of the Maxey Flats site and major drainage channels.

Geology

The rock strata and geologic systems underlying the Maxey Flats site consist of interbedded sandstones and shales of Mississippian, Devonian, and Silurian age. A diagrammatic geologic section of the Maxey Flats site, to the level of valley alluvium, is shown in figure 3. Sandstone beds become more numerous, and shale interbeds become thinner, progressing downward from the lower part of the Nancy Member to the lower part of the Farmers Member, both in the Borden Formation. The shales tend to fragment quickly upon exposure to the surface, apparently due to wetting and drying, and to some extent, stress relief. This fissility is most apparent in the Nancy Member, the Henley Bed of the Farmers Member, and the underlying Bedford Shale. All radioactive waste is buried in shale of the Nancy Member (Zehner, 1979). The base of most trenches consists of a 1.5-foot-thick sandstone bed (not shown in fig. 3) at a depth of about 25 feet below ground level (Zehner, 1983).

Colluvium covers much of the hillslope area, but bedrock is exposed in places, particularly on the upper part of the hillsides where the erosion-resistant Farmers Member forms steep scarps. These scarps form as the more easily erodible shale retreats and undermines the more resistant sandstones. The valley bottoms are covered with alluvial deposits that grade laterally into the colluvium on the hillslopes.

Relation of Hillsides to Burial Trenches

The relation of hillsides to burial trenches is important when considering rates of hillslope retreat and long-lived radioactive wastes. Upper hillslope contours and the orientation of burial trenches are shown on the location map in figure 4. The average distance from the relatively flat perimeter edges of most burial trenches to the sloping hillsides varies. Ends of trenches are closest to the crest of hillslopes near the southwestern edge of the western trench area. Along this southwestern edge, the horizontal distance between the 1,000-foot contour and the nearest burial trench, as measured on the Farmers 1:24,000 topographic quadrangle, is about 140 feet. Other horizontal distances between the 1,000-foot contour and the trench boundaries are 260 feet on the south side, 400 feet on the east side, and 260 feet on the northwest side of the site.

METHODS OF INVESTIGATION

Observations of hillslope processes were made from measurements of direct ground-surface lowering, sediment transport from small areas, and dendrogeomorphic techniques. Observations of possible channel enlargement were made using monumented cross-section measurements. Final results for slope retreat are reported in inches per century (in/ct) and represent hillslope retreat perpendicular to the ground surface. The accuracy of methods used in this study is not sufficient to justify resolving ground-surface lowering into its vertical and horizontal components (Saunders and Young, 1983, p. 474).

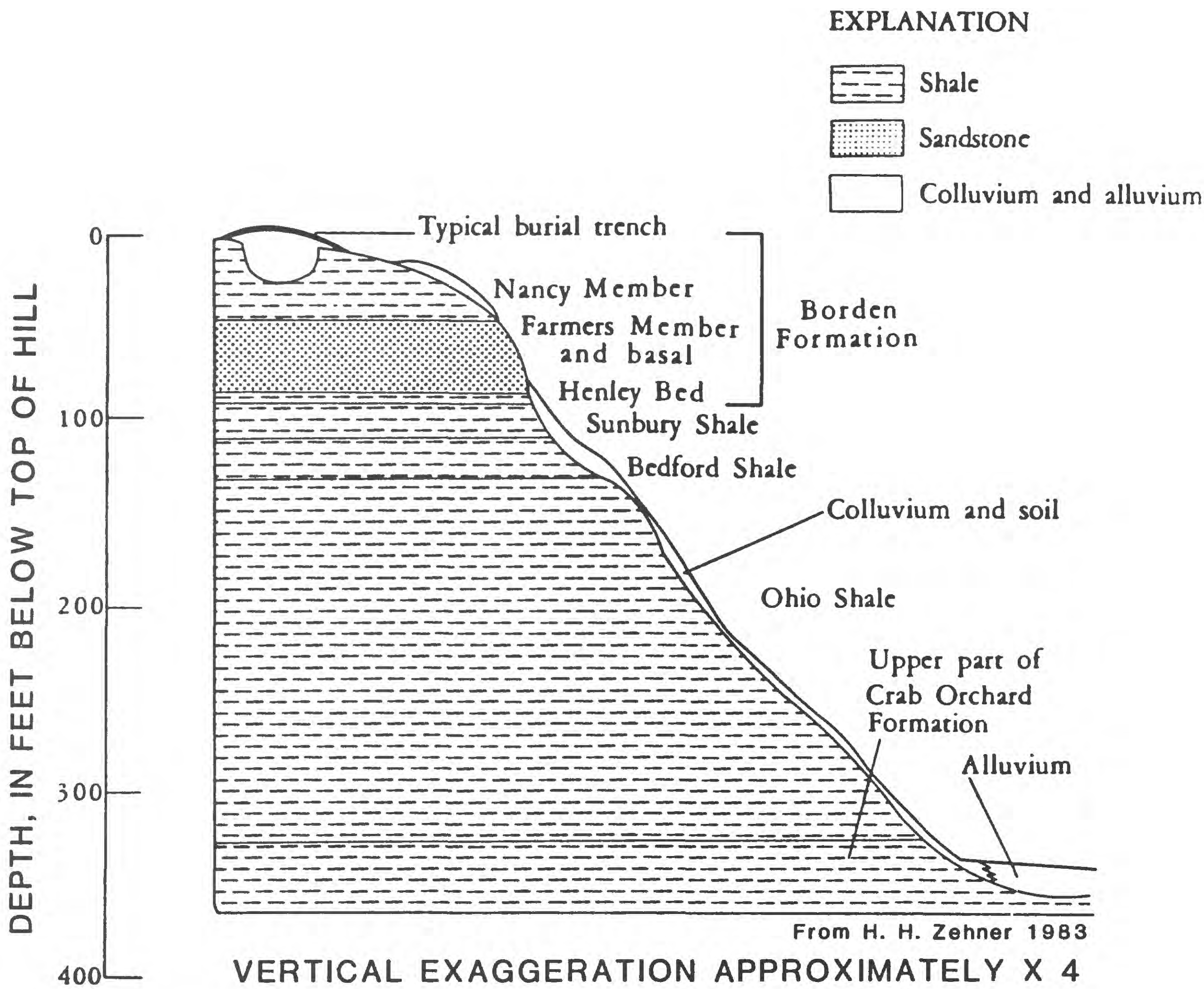


Figure 3.--Diagrammatic geologic section of the Maxey Flats site.

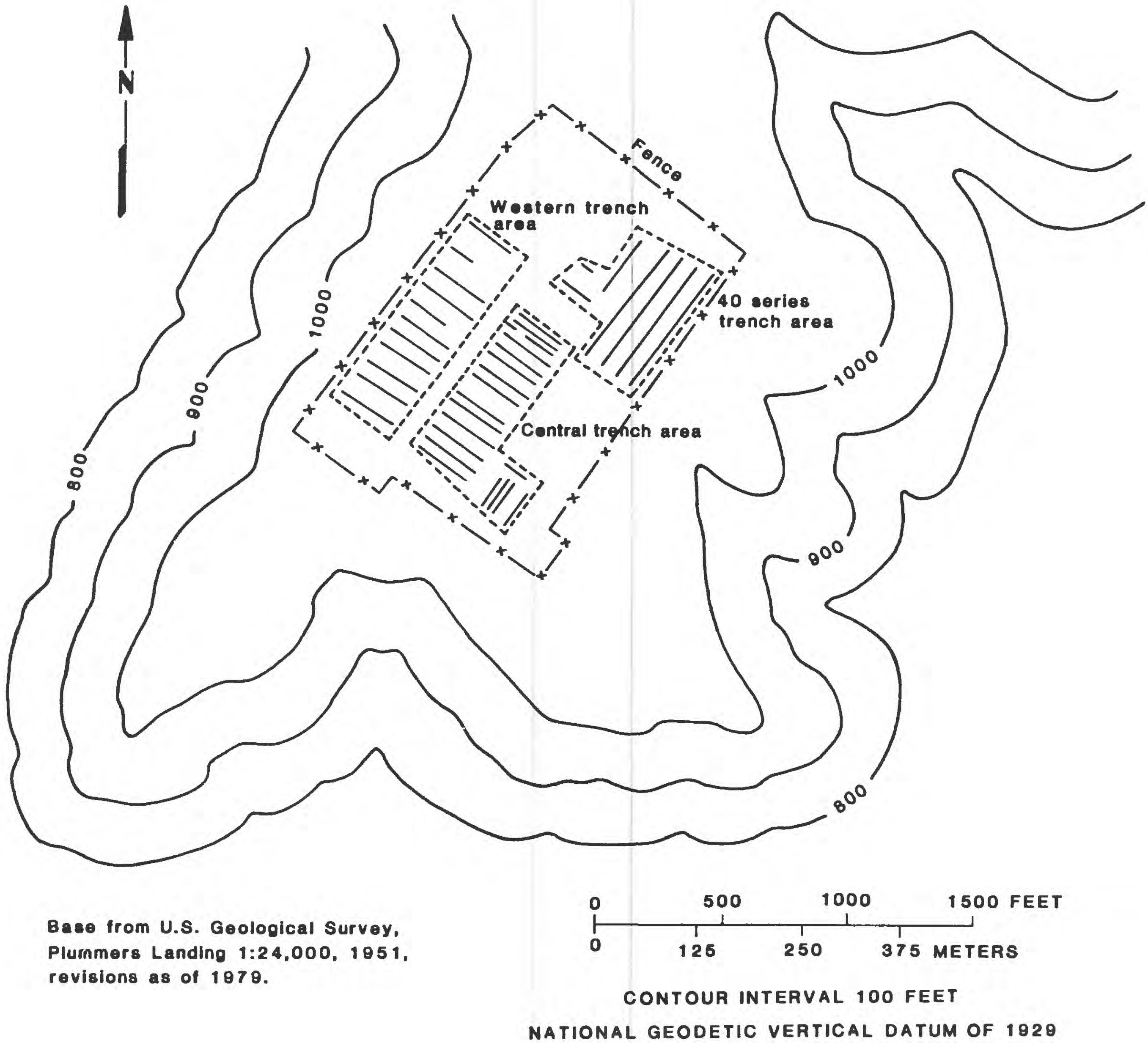


Figure 4.--Burial area and orientation of trenches.

Instrumentation

Erosion Frames

Erosion frames (Goudie, 1981) were used to directly measure ground-surface lowering. When measurements are taken the erosion frame is positioned over four permanently installed threaded-steel stakes that are driven into the ground at a measuring location (fig. 5). A depth-gauging rod is then passed through 24 holes drilled into the bars of the frame to measure changes in elevation of the soil surface with respect to the frame. The most significant advantages of erosion frames are: no disturbance of the soil occurs at the measuring location, the measurement is taken over an area instead of at a single point, and a number of observations (24) are made within the sampled area.

Three erosion-frame measurement sites were established on the eastern hillslope areas, and one site was established on the gently sloping grass covered area within the fenced-in area of the site (fig. 6). Criteria for selecting measurement sites on the hillslopes were: (1) areas of bare mineral soils (shale) were preferred so that measured changes did not result in overestimation of ground-surface lowering due to the removal of vegetation and organic litter by running water; (2) a slope angle typical for the hillslope was required; and (3) locations of measuring sites were restricted to state-owned land. Criteria for selecting a measurement site for the gently sloping grass-covered area differed from the other three sites in that an estimate of erosion from grass-covered trench caps was needed.

Sediment Plots

Soil transported from small, enclosed hillslope areas (fig. 6) was measured. The areas of the enclosed plots ranged from 35 to 150 square feet, width ranged from 5 to 14 feet along contour and downslope length ranged from 9 to 20 feet. Each plot was bordered with 10-inch wide strips of sheet metal buried vertically so that approximately 4 inches of metal were exposed. The border isolated the plot from external runoff and sediment supply and allowed conversion of sediment yield to ground lowering. Runoff and sediment from each of six plots were collected in a PVC trough that was embedded in concrete and spanned the downslope edge of the plot (fig. 7). Each trough was equipped with a 12-inch-wide concrete lip on the upslope side that conducted runoff into the trough while a removable plywood roof prevented direct entry of rain (Leopold and Emmett, 1967). Connected to the PVC trough, was a flexible rubber hose through which the water and sediment flowed into a collection bottle.

Two plots differ from those described above. These two plots (plots 7 and 8 in fig. 6) were on the trench-cap cover material and were equipped with small Parshall flumes instead of concrete and PVC troughs. The original intentions were to develop a stage-discharge relation for these two plots and to collect discrete samples during individual storms. However, water levels in the Parshall flume were never sufficient for discrete sampling, so composite samples were collected.

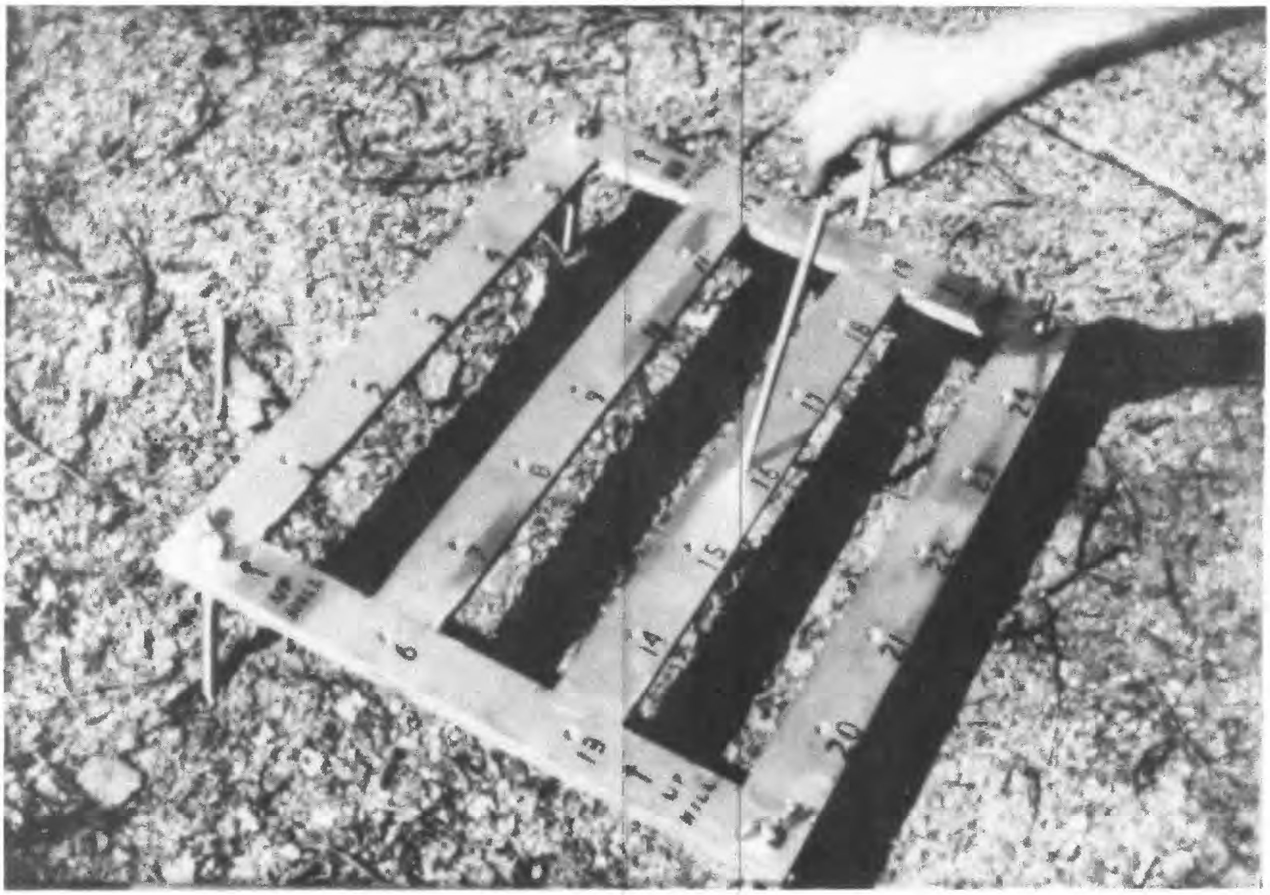
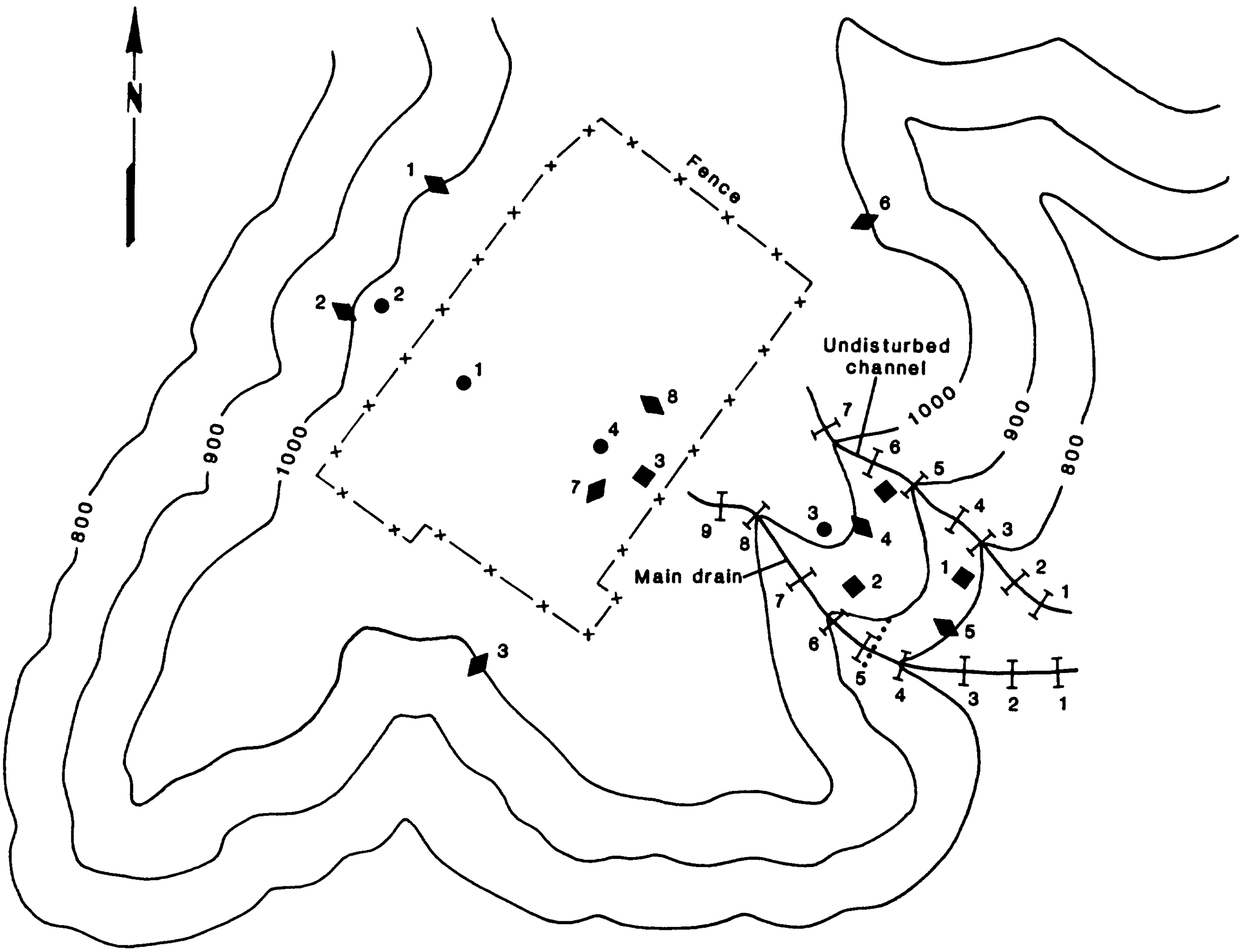


Figure 5.--Erosion frame and depth-gauging rod.



Base from U.S. Geological Survey, Plummers Landing, 1:24,000, 1951, revisions as of 1979.

0 500 1000 1500 FEET

0 125 250 375 METERS

CONTOUR INTERVAL 100 FEET

NATIONAL GEODETIC VERTICAL DATUM OF 1929

EXPLANATION

7 INSTRUMENTATION--Numbers accompanying symbols refer to data in tables

Monumented cross section

...... Erosion pin line

● Tipping bucket rain gage

■ Erosion frame

◆ Sediment trough

Figure 6.--Location of instrumentation used to measure hillslope erosion.

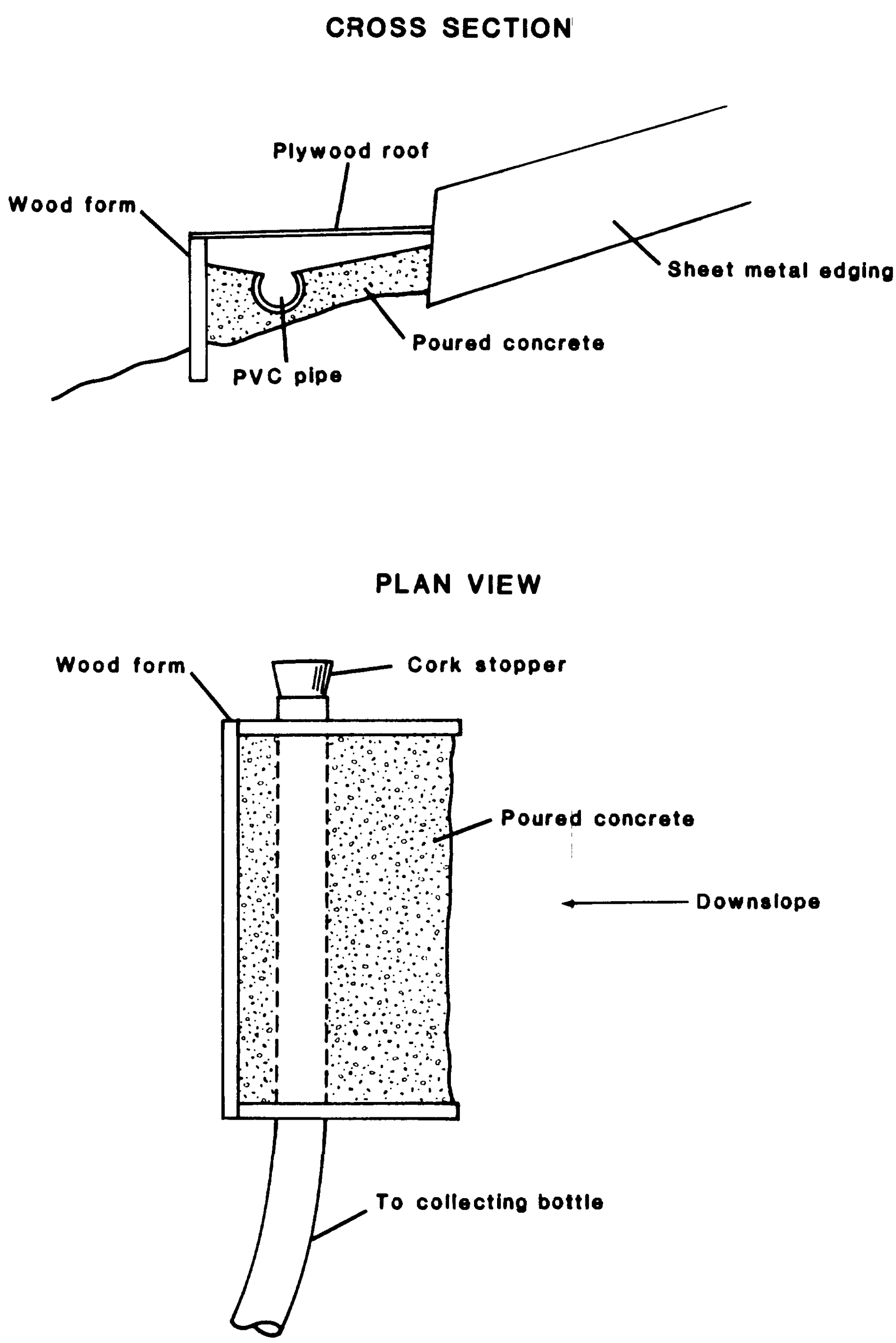


Figure 7.--Diagram of sediment-collection trough.

Each time a plot was serviced, the volume of water and sediment in a sample bottle was noted and the sediment was allowed to settle. Most of the remaining clear water was decanted, and the remaining sample was analyzed for concentration and particle size. Two soil samples were obtained from inside the perimeter of each plot for bulk-density analysis. Samples from within the plot area were considered to be more representative than samples from areas outside the plot, which are subject to considerable disturbance. The area disturbed by extracting the samples was minor compared to the plot area. The average of the two bulk-density samples for each plot was used to convert the weight of sediment to ground-surface lowering.

Erosion Pins

Erosion pins, as described by Emmett (1965), were used to measure surface erosion on a steep hillslope bordering the main drainage channel from the Maxey Flats burial site. The pins consist of a 12-inch nail put through a washer and driven flush with the ground surface. As erosion undermines the washer it slips down the shaft of the pin. The pins were arranged in a line as a transect on a steep shale slope near cross section number 5 on the main drain (fig. 6). The erosion line consisted of 35 pins spaced approximately 6 feet apart. Hillslope gradients generally ranged from 40 to 70 percent. Seven pins were aligned across the main drain as a cross-section. The remaining 28 pins traversed an upslope line from the creek bottom to the sandstone outcrop of the Farmers Member. The distance from the nail head to the washer was measured twice a year beginning in April 1985.

Monumented Cross Sections

A set of measurements was designed specifically to provide information on channel aggradation and degradation for two streams draining the Maxey Flats site. These measurements consisted of cross-sectional surveys at a total of 16 observation sections on the main drain and a nearby, undisturbed channel (fig. 6). Longitudinal profiles of the two streams are shown in figure 8.

One channel (main drain) received increased runoff due to the impermeable PVC covering over the burial trenches; the other channel remained relatively unaffected by site activities. The monumented cross sections do not indicate scour and fill, but, only provide estimates of net aggradation or degradation. Locations for measurements were selected at approximate 150 to 200 feet spacings along the stream channels. Because more rapid lateral movement could be expected in the stream curves, the sections were located upstream or downstream from curves to make comparisons compatible.

Locations of cross-sectional measurements were monumented at each end point by using 3 to 4 foot lengths of 1/2-inch-diameter steel bars driven to within several inches above ground surface. A 5/8-inch-diameter "fork" was placed over each bar and a set screw was tightened to hold it in place. These forks held a section of aluminum channel that was used as a datum to measure down to the creek channel. A carpenter level was used at each measuring point to insure the aluminum channel was unchanged from previous measurements and that all measurements had the same datum. Periodically, the steel bars were surveyed by level to check for changes in elevation.

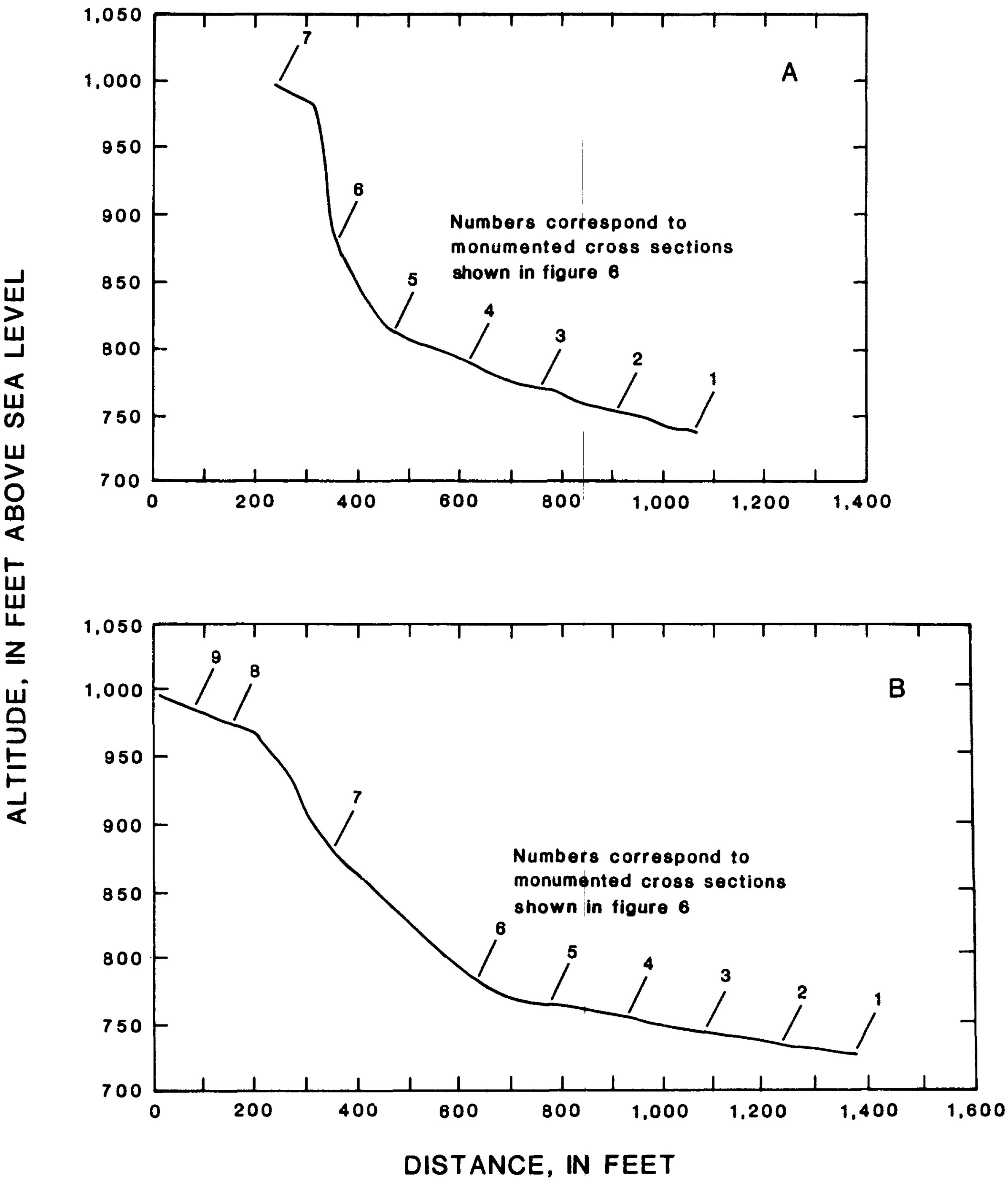


Figure 8.--Longitudinal profiles and location of monumented cross sections for (A) channel receiving flow from undisturbed area of the site, and (B) channel receiving flow from impervious trench cap covers.

Rain gages

Four tipping-bucket rain gages were installed to measure areal variations in rainfall received at the site (fig. 6). Two were installed in unforested areas of the site, and two were installed on the tree-shielded hillslopes near instrumented locations.

The two rain gages in open areas of the site were installed at different times. Gage 1 was installed near the center of the site in April of 1985, and gage 4 was installed at sediment plot 7 in September 1986. These two gages were used to provide information on variability of rainfall received in open areas, as well as providing backup in case of failure. Rain gages 2 and 3 were installed in January 1986 on the forested hillslopes at sediment plots 2 and 4, respectively. These gages measured rainfall amounts that actually reached ground surface through the forest canopy.

Dendrogeomorpic Methods

Dendrogeomorphology is the study of geomorphic processes through the use of dendrochronologic (tree-ring) analysis. Tree-ring analysis involves the coring or cross sectioning of specific trees affected by some geomorphic process. Thus, for this investigation, specimen trees were selected primarily on a geomorphic basis, rather than on a biological basis, as is commonly done in standard dendrochronologic analysis. For basic age determination, an increment core is taken from near the base of the tree; ring counts then are made from the biological center (first year of growth) to the outside ring (last year of growth).

Initial tree roots form, upon germination, just below the ground surface; in time, these first rootlets form the major root trunks that radiate out from the initial germination point. The basal flare or root collar (trunk inflection point) and initial root zone form a distinctive marker of the original ground surface. Root exposure is the principal form of botanical evidence of erosion, in this case, hillslope retreat. Measurements from exposed roots to ground surface are used to determine the amount of erosion, which then is divided by the age of the tree to determine the rate of degradation in the vicinity of the specimen tree (LaMarche, 1968).

Depths of erosion, mean slope angle, and tree age were determined at specimen trees on four hillslope units (fig. 9). The field routine consisted of selecting specimen canopy trees, coring the trees with an increment borer, determining the mean degree of slope in the vicinity of each specimen tree with a hand level, and measuring the amount of erosion along lateral roots (fig. 10). Detailed notes were taken on the aspect, slope profile, ground surface material, degree of root exposure, and presence or absence of mass wasting for each slope unit. Specimen tree selection within geomorpically selected sampling areas was largely arbitrary; however, diseased trees or those of otherwise poor growing condition were excluded to avoid sampling trees with hollow centers. Sampled trees were usually growing on side slopes, as opposed to nose (convex) or cove (concave) slopes, (Hack and Goodlett, 1960) in order to obtain values from specimens exposed to intermediate amounts

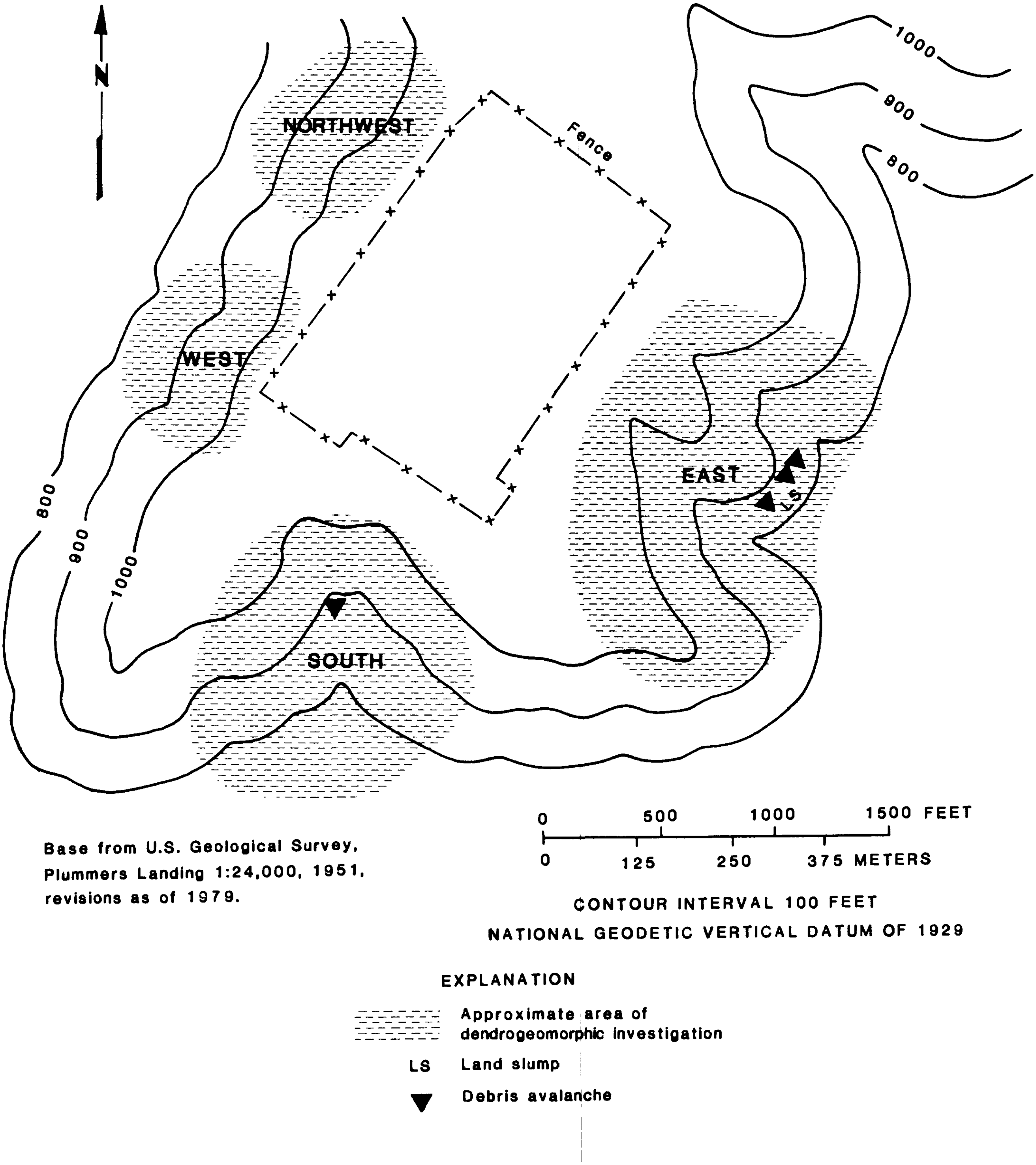


Figure 9.--Areas of dendrogeomorphic investigation, land slumps, and debris avalanches.

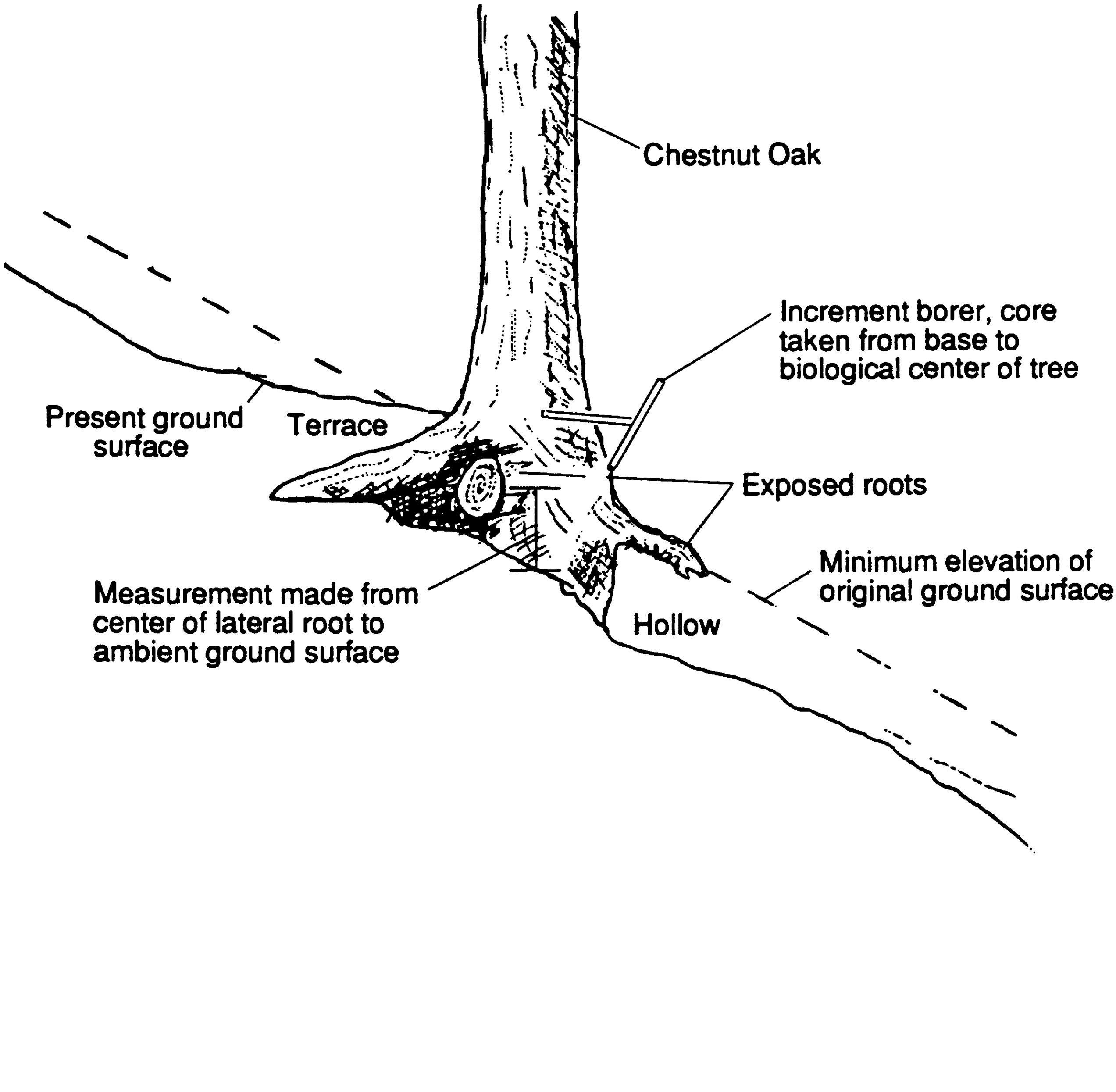


Figure 10.--Aspects of dendrogeomorphic investigation.

of slope wash. Where possible, trees with major roots radiating along slope contours were selected to avoid areas of aggradation and erosion upslope and downslope of the tree trunk.

Slope wash tends to result in the accumulation of colluvium as terraces on the upslope sides of tree trunks, and simultaneously creates hollows on the downslope sides (fig. 10). Measurements of slope erosion were obtained from lateral roots along contour (fig. 10) to avoid these terraces and hollows. The slope erosion measurements are considered to be conservative because all measurements were made between the middle of a lateral root and the ambient ground surface (fig. 10). Slope-angle measurements were also taken a distance away from these terraces and hollows.

Mass wasting in the form of small debris avalanches is evident on the south and east slope units (fig. 9). Trees in the vicinity of slope failures were sampled to determine date of failure, and estimates of hillslope erosion were made by measuring the average depth within the erosional portion of these failures. Methods of this analysis are explained in Hupp (1983) and Hupp and others (1987).

CLIMATIC CONDITIONS DURING STUDY

Mean annual precipitation at a U.S. Weather Bureau station in Farmers (8 miles south of the Maxey Flats site) was 45.4 inches for 1941 through 1984 (National Oceanic and Atmospheric Administration, 1984). Precipitation received at rain gage 1 on the burial site was 44.0 inches during 1985 and 37.1 inches during 1986. Precipitation during the first 4 months of 1987 (after which data collection ceased) totaled 9.9 inches, which is considerably less than the long-term mean for the same period (15.1 inches) as measured at the Farmers gage. Thus rainfall at the Maxey Flats site during the study was below the 1951 to 1980 average.

Variability of Precipitation

Monthly rainfall at the site during the study is listed in table 1. Monthly precipitation at rain gage 1 ranged from 0.73 inches (September 1985) to 7.46 inches (November 1986). Comparison of monthly precipitation at gages 1 and 4, both in unforested areas, shows little variability between gages. For all months, except February 1987, rainfall received at these two gages was within 10 percent of each other.

As expected, precipitation at rain gages in forested areas was considerably less than that in open areas. For February 1986 to June 1987, precipitation at rain gages 2 and 3, which are in forested areas, averaged between 24 and 51 percent of that received at rain gage 1. Most of this variation can be explained as canopy interception that redirects water down the tree trunk.

Table 1.--Monthly total rainfall received at the site during the study

[-, time prior to gage installation]

Date	Rain gage (rainfall in inches)			
	1	2	3	4
04/85	1.99	-	-	-
05/85	5.04	-	-	-
06/85	5.87	-	-	-
07/85	4.09	-	-	-
08/85	4.89	-	-	-
09/85	.73	-	-	-
10/85	6.13	-	-	-
11/85	6.48	-	-	-
12/85	1.18	-	-	-
01/86	1.00	-	-	-
02/86	1.94	0.92	0.72	-
03/86	2.32	.89	.80	-
04/86	1.41	.49	.47	-
05/86	4.55	1.76	1.72	-
06/86	2.34	1.04	.63	-
07/86	4.42	2.09	1.73	-
08/86	2.71	.87	1.28	-
09/86	3.49	1.43	1.57	-
10/86	2.88	1.26	1.22	2.86
11/86	7.46	3.33	3.66	7.47
12/86	2.56	1.16	.95	2.80
01/87	1.36	.06	.57	1.49
02/87	3.14	.75	1.06	2.53
03/87	2.30	.67	.95	2.26
04/87	3.15	1.29	1.62	3.16

DATA ANALYSIS AND INTERPRETATION

Erosion-Frame Data

Two types of observations are made at each erosion frame. The first is a check on the altitude of the anchor pins, and the second is the measurement of distance between the frame and the ground surface. In the case of the anchor pins, the measurement is used to determine if the pins have moved. Given that the anchor pins have not moved, the erosion-frame data are used to determine if there is a significant difference between measurements of ground-surface elevation.

Statistical tests for significant differences between measurements are used to aid in the interpretation of the data. The results of all statistical tests are presented in terms of the probability value associated with an observed test statistic. If the probability value, or p-value, is less than or equal to a selected level of significance, the null hypothesis (H_o) is rejected. Stating a p-value instead of a significance level (α) provides much more information about how far away the p-value is from a selected significance level (Iman and Conover, 1983, p. 217).

Because there are only four anchor pins at each location the check measurements consist of only four observations per data set. This low number of observations essentially eliminates the possibility of testing for conformance to various test assumptions, so the nonparametric sign test is used (Ryan and others, 1985, p. 277). The sign test does not make any assumptions about the shape of the population distribution (Ryan and others, 1985, p. 277). Paired observations at each anchor pin are subtracted and the median of the differences is tested under H_o: μ=0, H_1: $\mu \neq 0$. It should be noted that because the sign test makes no assumptions about the population distribution, it is not a very powerful test.

Results of the sign test listed in table 2 indicate that there is little evidence to show that the pins actually moved. Therefore it is assumed that the anchor pins have remained stationary, and observed differences in the frame data are due to ground-surface lowering.

Changes in the measured distance from the erosion frame to the ground surface provide a direct measure of ground-surface lowering. Because the value of any observed change in this distance is important the analysis is designed to test the significance of the changes. Paired observations at each hole are subtracted such that subsequent observations are always subtracted from an earlier observation. This convention results in negative values when ground surface lowering occurs. The mean of these remainders is then computed and is tested under H_o: μ=0, H_1: $\mu \neq 0$. Net positive values, indicating that the ground surface rose, did occur for some 6-month intervals, and are attributed to sediment transported from upslope areas and deposited in the vicinity of the frame. All frames recorded net negative values when beginning and ending measurements for the period of record were compared. These beginning and ending measurements span the greatest length of time so they will be used to determine rates of ground-surface lowering. The number and arrangement of erosion frames was not considered sufficient to analyze shorter term fluctuations that were observed between the beginning and ending measurements.

Table 2.--P-values for testing H_o: μ=0, H_1: $\mu \neq 0$ for pairs of anchor-pin measurements

[Anchor pins were not measured in 1987]

Frame number	Dates of measurements	
	4/85-10/85	4/85-4/86
1	0.250	0.625
2	.125	.625
3	.250	.125
4	.625	.625

The measurement of distance between the erosion frame and the ground surface consists of 24 observations per data set (n=24). The correct parametric test for comparing paired observations when n<30 is the paired-sample t-test which requires that the differences are random, independent, and normally distributed (Iman and Conover, 1983, p. 247). Nonparametric alternatives to the paired t-test include the sign test, which makes no distributional assumptions, and the Wilcoxon Signed Rank test, which requires that the differences are independent and symmetrically distributed (Ryan and others, 1985, chap. 12).

The requirement of random sampling provides a representative sample of the population because every member of the population has an equal probability of being sampled. This is very important when the sample size is very small compared to the population. For the erosion frames, however, the sample density is very high within the area beneath the frame, and each measurement is assumed to be representative even though sampling is not random. The differences between paired observations representing the first and last measurement in the period of record were tested for normal distribution using the Lilliefors Test for Normality (Iman and Conover, 1983, p. 153). Data for each of the four erosion frames turned out to be approximately normal so the assumptions of normality for the t-test and symmetry for the Wilcoxon test appear to be satisfied. The requirement of independence maximizes the information content of each sample by minimizing the chance that an observation repeats part of the information contained in previous observations (Matalas and Langbein, 1962). Actual tests for spatial independence were not performed because the measuring holes are so close together that dependence is virtually certain. Again it is assumed that the sample density compensates for any lack of independence. Because requirements for all tests appear to be satisfied or accounted for, the paired t-test, and only one nonparametric test, the Wilcoxon test, were applied to the data.

P-values for both tests are listed in table 3. The period of record for frame number two is only 1 year long because a tree fell on, and displaced some of the anchor pins. The results of the statistical tests consistently reinforce each other so there is no ambiguity in interpretation. Mean lowering values are significantly different from 0 for frames 1 and 2 regardless of the selected significance level, but for frames 3 and 4 a significance level of 0.001 might lead to an acceptance of H_o. However, because a level as low as 0.001 is much too stringent for this application, the conclusion is that all frames recorded significant ground-surface lowering. Observed rates of ground-surface lowering indicate mean ground-surface lowering of about 7 to 32 inches per century. Frames 1 and 2 are on steeper slopes and correspondingly higher rates of erosion were measured at these frames.

Table 3.--P-values for testing H_o: $\mu=0$, H_1: $\mu\neq0$ for erosion frame data, and rates of ground-surface lowering

Frame number	Period	Lowering, in inches Mean	Lowering, in inches Median	P-values t-test	P-values w-test	Mean lowering, in inches per century
1	4/85-4/87	-0.64	-0.59	0.0001	0.0001	32
2	4/85-4/86	-.29	-.29	.0001	.0001	29
3	4/85-4/87	-.13	-.14	.0014	.0040	7
4	4/85-4/87	-.28	-.35	.0010	.0010	14

Erosion-Pin Data

The erosion pins were measured every 6 months from April 1985 through April 1987. Analysis of erosion-pin data is very similar to the analysis of erosion-frame data. Subsequent observations are always subtracted from previous observations so that ground loss is indicated by a negative number and ground gain is indicated by a positive number. Erosion-pin data may be examined individually or collectively. When groupings of pins are analyzed, the same statistical tests used for analysis of erosion-frame data can be applied. The relative merits of analyzing individual pin data or groupings of data can be determined by plotting the difference in beginning and ending data versus pin number.

Pins 8 through 35 (table 4) were aligned from the creek bottom upslope to the sandstone outcrop of the Farmers Member. A plot of the difference between beginning and ending measurements for each pin (fig. 11A) shows no visible trend with distance upslope. The absence of a trend with distance upslope makes the analysis of individual pin data a questionable exercise, so the data were examined as a group. The mean of differences between the beginning and ending measurements is -0.10 inch, the median is -0.08 inch, and the standard deviation is 0.17. P-values for the t-test and w-test are 0.0053 and 0.007 respectively, and the conclusion is that the observed values are significantly different from zero. Dividing the mean by the period of record (2 years) and multiplying by 100 yields an erosion rate of 5 inches per century, which is about 3 to 6 times less than the rates observed at the three erosion frame sites on the hillslope. It is interesting to note that all of the April 1987 measurements are less than the October 1986 measurements (table 4) indicating that widespread aggradation took place on the slope. The mean of differences between the April 1985 and October 1986 measurements yields an erosion rate of 20 inches per century which is in very good agreement with the three erosion frames located on the hillslope. This 4-fold decrease in erosion rate indicated by successive measurements serves to highlight the sensitivity of short-term observations.

Pins 1 through 7 were aligned across the main drain as a cross section. The difference between beginning and ending measurements for these seven pins is shown in figure 11B. In this case, there are two distinct groups of points, and it is worthwhile to consider their relative differences. Again, these differences are so obviously different from zero that no statistical tests were applied. Pins 1, 2, and 7 are on the channel banks, and pins 3 through 6 are on the channel bed. The relative differences between these two groups of pins (fig. 11B) indicate higher erosion rates on channel banks than in the channel bed. The erosion rates indicated by the differences illustrated in figure 11B are the highest rates measured in the study. The average rate of erosion at the four pins in the channel is 42 inches per century, and the average rate of erosion at the three pins on the banks is 124 inches per century. These rates are very site specific, and without comparative data, the contribution due to increased runoff being diverted to the main drain cannot be estimated.

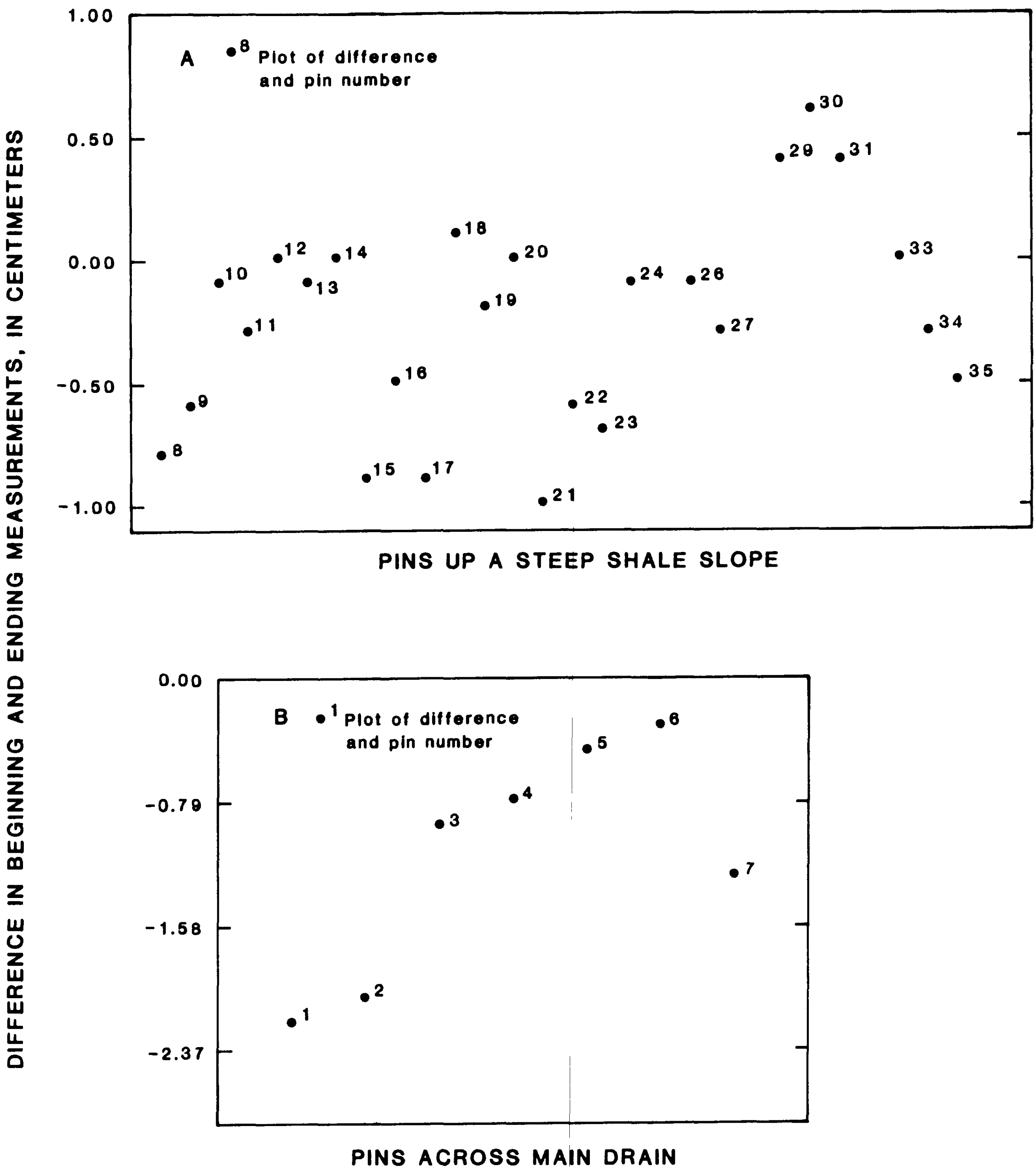


Figure 11.--Difference in beginning and ending erosion-pin measurements, (A) for pins up a steep shale slope, (B) for pins across main drain.

Table 4.--Erosion-pin data, in centimeters

[-, missing data]

Pin number	Measurement Dates 4/85	10/85	4/86	10/86	4/87	Differences 4/85-10/86	4/85-4/87
8	0.1	0.1	0.9	1.1	.9	-1.0	-.8
9	.1	.1	.7	.9	.7	-.8	-.6
10	.1	.1	.8	1.2	.2	-1.1	-.1
11	.1	.1	-	.7	.4	-.6	-.3
12	.1	.3	.6	.8	.1	-.7	.0
13	.1	.1	.5	.5	.2	-.4	-.1
14	.1	.2	.5	-	.1	-	.0
15	.1	.4	.9	1.3	1.0	-1.2	-.9
16	.1	.4	.6	1.0	.6	-.9	-.5
17	.1	.1	.1	1.3	1.0	-1.2	-.9
18	.1	-	.1	-	.0	-	.1
19	.1	.1	.3	.6	.3	-.5	-.2
20	.1	.1	.1	-	.1	-	.0
21	.1	.2	.8	1.4	1.1	-1.3	-1.0
22	.1	-	.5	.8	.7	-.7	-.6
23	.1	-	.6	1.0	.8	-.9	-.7
24	.1	-	.4	-	.2	-	-.1
25	.1	-	-	-	-	-	-
26	.1	.5	.3	.6	.2	-.5	-.1
27	.1	.5	.6	.9	.4	-.8	-.3
28	.1	.5	-	-	-	-	-
29	8.2	8.2	8.2	8.5	7.8	-.3	.4
30	2.3	2.3	2.3	2.1	1.7	.2	.6
31	2.5	2.7	2.7	2.7	2.1	-.2	.4
32	.1	-	-	-	-	-	-
33	.1	.3	-	1.0	.1	-.9	.0
34	.1	.4	.6	1.0	.4	-.9	-.3
35	.1	.5	.9	1.2	.6	-1.1	-.5

Dendrogeomorphic Data

Although the present study was not specifically designed to investigate differences in erosion with slope aspect, vegetative and geomorphic differences with respect to slope aspect are quite common and provide some valuable insight into slope processes at Maxey Flats. Hack and Goodlett (1960) noted consistent geomorphic and vegetative variation relative to aspect, which they attributed to moisture and drainage-network development rather than lithologic differences. Given the uniform, horizontal stratigraphy of the Maxey Flats area, the role of lithology in slope development should be nearly constant. Variation in moisture between relatively wet north-facing and relatively dry south-facing slopes has long been noted and reported in ecological literature. At Maxey Flats, there is a north-facing component to the west slope units, and a south-facing component to the east slope units. Tree-species distribution indicates that the west and northwest slope units (fig. 9) decidedly are more moist than the south and east slope units. Vegetation on south-facing hillslopes also tends to be relatively sparse in all vegetation layers, which again agrees with the general findings of Hack and Goodlett (1960). The relative density of vegetation indicates that precipitation and slope wash have more eroding and transporting power on south-facing slopes. South-facing slopes also show a greater diurnal temperature range than north-facing slopes (Wolfe and others, 1949). These larger temperature fluctuations tend to promote rock weathering on the south facing slopes. The tendency of greater rock weathering and erosion on slopes with southern exposure may account for the steepness and erosion rates of these slopes relative to the north-facing slopes.

Measured erosion rates indicate that the south and east slope units are retreating much more rapidly than the north and west slope units (table 5). These values of hillslope retreat compare well with other published slope-retreat estimates (LaMarche, 1968, Saunders and Young, 1983). These slope-retreat estimates are based on processes that have occurred during the last 90 years. Although dendrogeomorphic analyses allow for the integration of longer periods of time than other methods used in this study, they cannot account for changes in climatic processes occurring over tens of thousands of years.

Mass Wasting

The long-term erosional effects of mass wasting are difficult to evaluate, however mass wasting is observed on both the east and south slope units of the study area, and large slope failures have been mapped in the vicinity of Maxey Flats (McDowell, 1975). Evidence of three failures was observed on the east slope unit, and dendrogeomorphic data indicated that all three had occurred within the last 36 years. These failures ranged in length from 18.5 to 25 yards measured from toe to head scarp. The average degradation within the erosional portion of these failures was 1.6 to 2.5 feet. Other parts of the slope showed evidence of earlier debris avalanching but these were too old to be dated botanically and were considerably smoothed by slope wash. A series of rotational slump failures were observed on the south slope unit encompassing an area of about 360 square yards. As on the east slope unit, other parts of the slope had evidence of earlier mass wasting.

Table 5.--Summary of dendrogeomorphic data

[Rate, slope degradation; W, west; NW, northwest; E, east, and S, south; SD, standard deviation]

Slope aspect	Number of samples	Row labels	Diameter, in inches	Slope, in degrees	Erosion, in inches	Age, in years	Rate, in inches per century
W	14	Mean	12.2	24.4	2.9	84.9	3.8
		SD	2.2	5.3	1.1	17.5	2.4
NW	17	Mean	10.3	23.4	3.3	74.4	4.8
		SD	3.4	5.3	1.9	19.9	3.7
E	23	Mean	12.0	34.4	7.9	93.3	9.1
		SD	4.3	3.8	2.6	28.8	3.6
S	15	Mean	14.3	37.6	6.8	107.7	8.8
		SD	4.0	4.6	2.9	63.2	6.7

The effect of mass wasting was not calculated in the rates of hillslope degradation (table 5) because the magnitude and frequency of mass wasting is unknown. Mass wasting undoubtedly quickens the overall rate of slope degradation by direct erosion, and by steepening and exposing fresh material to slope wash. For example, the average degradation of 1.6 to 2.5 feet measured in the east-slope failures is equivalent to 211 to 330 years of erosion by slope wash using the east-slope rate from table 5. The available data cannot be used to quantify the magnitude and frequency of mass wasting and thereby estimate its long-term contribution to slope degradation.

Sediment-Plot Data

Data from sediment plots indicate net erosion from surface flow for a section of slope under the assumption of uniform delivery of eroded material. These data do not provide a direct measure of ground-surface lowering, so a conversion to values of ground-surface lowering is necessary. The measurement of net erosion over a section of slope and the assumption of uniform delivery of eroded material indicate that the sediment-plot data represent average values over the contributing area of the plot. Although the areas enclosed by the plots appear small, they are, in fact, relatively large when compared to the areas associated with erosion pins and frames.

Direct-measurement devices such as erosion pins and frames measure fluctuations in ground-surface altitude without regard to the mechanisms that produce those fluctuations. Sediment plots measure surface-flow erosion only, and do not account for other mechanisms of erosion such as solution and wind. In addition to these differences, values of the bulk density or unit weight of the surface material must be obtained in order to convert the weight of eroded material to units of ground-surface lowering. Representative values of bulk density depend upon the number of samples collected, the variance of bulk density across the plot, and ability to obtain undisturbed samples. The number of samples required to define variance across a plot would constitute a major disturbance to the plot, so only two samples at opposite sides of each plot were obtained. Measured values of bulk density are given in table 6.

Table 6.--Bulk-density values for sediment plots, in grams per cubic centimeter

Plot number	Sample 1	Sample 2	Difference	Mean	$\frac{\text{Difference}}{\text{Mean}}$ X 100
1	1.03	1.27	0.24	1.15	21
2	.99	.86	.13	.93	14
3	1.26	1.28	.02	1.27	2
4	1.13	.70	.43	.92	47
5	1.14	1.18	.04	1.16	3
6	1.23	1.32	.09	1.28	7
7	1.58	1.28	.30	1.43	21
8	1.56	1.61	.05	1.59	3

Because only two samples were collected at each plot, the measure of variance shown in table 6 is simply the difference of the two samples divided by their mean. The samples for plots 3, 5, 6, and 8 show good agreement. Plot 2 is acceptable but plots 1, 7, and particularly 4 have quite different values. It is not possible to tell if these differences represent true variability in bulk density or if they are the result of differential compaction caused by some outside influence like the sampling device. The mean values listed in table 6 were used to compute ground-surface lowering for their respective plots.

Values of ground-surface lowering computed from the plot data are listed in table 7. Rates determined from the plot data are considerably less than rates determined from the erosion-frame data, erosion-pin data, and the dendrogeomorphic data.

Table 7.--Ground-surface lowering computed from sediment-plot data

Plot number	Ground-surface lowering, in inches per century
1	0.0022
2	.0019
3	.0017
4	.0036
5	.0018
6	.0750
7	.0120
8	.0083

Rates indicated by the sediment plots are as much as four orders of magnitude less than the frame and pin rates and as much as three orders of magnitude less than the dendrogeomorphic rates. These plot rates also are very low relative to published rates for sediment traps (Saunders and Young, 1983, table III). The reasons for these large discrepancies are not clear. An attempt was made to determine the possible contribution of solution using dissolved solids and discharge data from the Rock Lick Creek near Sharkey, Ky. gaging station (fig. 2). This estimate was very crude and indicates that solution might be responsible for on the order of 0.28 inches per century, which agrees well with published rates (Saunders and Young, 1983, table IV). This analysis indicates that solution is roughly 10 times more important than erosion and transport by surface wash, which is highly unlikely in a sandstone and shale environment. Even with the solution component added to the plot data, the resulting sum is still much less than the rates indicated by the frame, pin, and dendrogeomorphic data.

There are several other factors, in addition to solution that could be cited for the observed discrepancies. Most of the sampled material may have been derived from an area close to the trough, thus invalidating the assumption of uniform delivery. Some eroded material may not have been accounted for due to experimental error, some of the finer material may have been transported downward through soil macropores (Pilgrim and Huff, 1983), and bulk density estimates may be high due to compaction during sampling. The significance of these various factors in explaining the observed discrepancies cannot be evaluated. Therefore, the dendrogeomorphic, erosion-frame, and erosion-pin data are considered as better estimates of slope erosion.

Monumented Cross-Section Data

Data from the monumented cross sections were analyzed by calculating the cross-sectional area below a selected top width. The same top width altitude is used for all measurements at a section, and this altitude corresponds to the minimum top-of-bank or minimum-endpoint value for each set of measurements. Incremental differences in cross-sectional areas over time were computed by subtracting each consecutive measurement from the previous measurement so that negative values indicate degradation and positive values indicate aggradation. Net changes in cross-sectional area were computed by subtracting the ending measurement from the beginning measurement.

The results of the cross-section measurement analysis are listed in tables 8 and 9. Incremental results are summarized in table 8 by simply indicating + for aggradation, - for degradation, and 0 for no change. This qualitative summary facilitates the identification of patterns in the incremental data. These patterns reflect channel behavior during the 1.5- to 2-year study period and may not be indicative of long-term channel behavior.

Table 8.--Summary of incremental and net area changes in monumented cross sections

[M, main drain sections; U, sections in the unaffected channel; +, aggradation; -, degradation; 0, no change]

Section	10/85	04/86	10/86	04/87	Net
1M	-	+	-	+	-
2M	-	+	-	+	-
3M	+	+	+	+	+
4M	-	+	-	-	-
5M	-	0	-	-	-
6M	-	+	-	+	-
7M	-	-	-	-	-
8M	+	-	-	-	-
9M	-	+	-	-	-
1U		0	+	+	+
2U		-	+	-	-
3U		+	+	-	+
4U		-	+	-	0
5U		-	-	0	-
6U		-	-	+	-
7U		+	+	+	+

Table 9.--Measured incremental and net area changes, in square feet, in monumented cross sections

[M, main drain sections; U, sections on the unaffected channel]

Section	Beginning area 04/85	10/85	04/86	10/86	04/87	Net change
1M	20.1	-0.8	+0.1	-0.1	+0.2	-0.6
2M	21.1	-2.2	+2.2	-1.4	+.5	-.9
3M	22.0	+.2	+2.1	+1.0	+.4	+3.7
4M	19.9	-.9	+1.3	-.9	-1.0	-1.5
5M	20.7	-4.7	.0	-2.7	-1.1	-8.5
6M	23.1	-1.7	+1.6	-2.0	+1.4	-.7
7M	20.9	-1.0	-5.1	-.4	-.7	-7.2
8M	23.5	+.8	-.2	-.9	-.2	-.5
9M	25.4	-2.1	+.7	-.1	-.3	-1.8

Section	Beginning area 10/85	04/86	10/86	04/87	Net change
1U	8.0	0.0	+0.2	+0.1	+0.3
2U	7.2	-.6	+.4	-.4	-.6
3U	5.1	+.9	+1.4	-.8	+1.5
4U	17.2	-.5	+.6	-.1	.0
5U	7.9	-.2	-.7	.0	-.9
6U	14.2	-.6	-.2	+.4	-.4
7U	2.5	+.1	+.2	+.1	+.4

The most interesting pattern in table 8 is the changing number of aggrading and degrading sections with season on main drain. In October 1985, only two sections showed incremental gains and in October 1986, only one section displayed an incremental gain. These numbers are contrasted with April 1986 when six sections showed incremental gains and April 1987 when four sections showed incremental gains. This pattern indicates that during the study runoff from summer convective storms was a major cause of channel erosion in main drain. Runoff from winter frontal storms eroded material from the upper reaches (sections 7,8,9, see fig. 8), but failed to transport that material through the lower reaches. The pattern of the upper, steeper reaches (sections 7,8,9) showing net degradation is persistent throughout the period with only two observations of incremental aggradation. Due to the short period of data collection, and the relatively dry conditions during the study, the long-term implications of these patterns cannot be addressed.

A distinct pattern is not evident in the data from the unaffected channel. The data for October 1986 show that the unaffected channel behaved opposite of main drain with the lower four sections of the unaffected channel showing net aggradation. The numerical data in table 9 quantify the incremental changes listed in table 8. The actual values of cross-sectional area change instead of percentage changes are listed in table 9 because of the variability in initial areas. Summation of the net change column in table 9 yields -18.0 square feet for the main drain and +0.3 square feet for the unaffected channel. Assuming the measured sections are representative of overall channel behavior, it can be concluded that the main drain degraded during the study period and that the unaffected channel showed little or no change.

The long-term channel erosion picture at Maxey Flats is complicated by the local geology. Increased runoff being diverted into the main drain presently is accelerating channel erosion as expected. The highest rates of measured erosion on main drain occur in sections 5 and 7 (table 9). Section 7 is in a steep reach in the highly erodible shale (compare figs. 3 and 8), and its relatively high rate of erosion is an expected result. The reason for the high rate at section 5 is not clear but may be related to alternating storage and flushing mechanisms. Visual evidence at the study site indicates that the shale beds beneath the Farmers Member sandstone erode and undermine the sandstone until blocks of sandstone break off and come to rest on the slopes or in the channels. An acceleration of this process would, in the long term, cause more sandstone blocks to accumulate in the channel and on the side slopes bordering the channel. This accumulation of erosion resistant sandstone should serve to armor the channel and side slope and reduce the rate of erosion. This hypothetical scenario could easily be complicated by other processes such as slope failures which would tend to carry the sandstone blocks down slope and expose fresh shale to erosion.

LONG-TERM RISK

Any attempt to interpret the data collected in this study must be made in terms of the relative periods of observation and interest. The period of observation for instrumentation installed at the site was 2 years or less, and the dendrogeomorphic data span a period of about 90 years. The period of interest, as indicated by the half-life of plutonium-239, is on the order of tens of thousands of years. Any speculations or predictions made under these circumstances, in which the period of interest ranges from three to four orders of magnitude longer than the period of observation, can only be considered as very tentative. The period of interest, in this case, provides ample time for the occurrence of catastrophic events, tectonic activity, and even climatic change. The long-term geomorphic stability of the site is very dependent on the frequency and severity of events such as forest fires, extreme precipitation, earthquakes, and massive slope failures.

The vastly different time scales between the period of observation and the period of interest illustrate the classic problems of time and causality discussed by Schumm and Lichty (1965) over two decades ago. During short periods of time, segments of hillslopes may remain at the same angle of inclination and act as slopes of transportation (steady state), or they may retreat parallel, maintaining their form (dynamic equilibrium) (Schumm and Lichty, 1965, p. 115). Observations made during these short periods of time reflect the existing steady state or dynamic equilibrium conditions and cannot be used to predict the evolution of the landform over much longer time periods. The evolution of landforms is characterized by periods of dynamic equilibrium in which the processes of erosion have equilibrated to the prevailing geologic, climatic, and vegetational conditions. The continuity of this dynamic equilibrium is occasionally interrupted by the occurrence of extreme events. These extreme events accelerate the processes of hillslope and channel erosion, and some are capable of altering the prevailing geologic or vegetational conditions. During a subsequent period of dynamic equilibrium the processes of erosion may equilibrate to a different set of prevailing conditions. The time series of these periods of dynamic equilibrium and extreme events, coupled with possible changes in climatic conditions, are the major factors that ultimately determine the evolution of landforms during time periods spanning tens of thousands of years.

Quantitative assessment of the long-term risk using rates observed during this study is very tenuous. A very crude assessment can be made by using the rates determined from dendrogeomorphic analysis to compute the time necessary for the slopes to erode to the burial trenches. Results of this analysis are presented in table 11. These rates pertain to periods of dynamic equilibrium, and do not account for anthropogenic influences, mass wasting, extreme events or climatic change. It is likely that the long-term erosion rate will be higher than the rates listed in table 10, but how much higher cannot be quantified.

Table 10.--Rate of hillslope retreat, distance to burial trenches, and time to exposure for each slope unit

Slope unit	Slope retreat, in inches per century	Distance to trenches, in inches	Years to exposure
West	3.8	1,680	44,000
Northwest	4.8	3,120	65,000
East	9.1	4,800	53,000
South	8.8	3,120	35,000

The results of the current study provide evidence that the increased runoff from the impervious trench-cap covers has accelerated channel erosion. The uncertain progress of this channel erosion also complicates long-term risk assessment; relative to the importance of extreme events, however, channel erosion and slope erosion are probably of equal significance. Saunders and Young (1983, p. 487) state that where there are many visible landslides or scars, the effects of these processes outweigh the mass transport accomplished by continuous processes. Hack and Goodlett (1960) have observed that extreme events of low frequency may perform the work of thousands of years of creep and slope wash during a single event through mass wasting. For example, in 1969, an 8-hour deluge of up to 28 inches of rain caused the equivalent of several thousand years of "normal" erosion in Nelson County, Va. (Williams and Guy, 1973). Thus, the long-term geomorphic integrity of the Maxey Flats disposal site is probably more at risk from infrequent events or combinations of events than it is from normal hillslope retreat due to the continuous processes of slope wash and channel erosion.

SUMMARY AND CONCLUSIONS

A comparison of observed rates of ground-surface lowering for the dendrogeomorphic, sediment plot, erosion frame, and erosion-pin data is given in table 11, and arranged by slope aspect. Monumented cross-section data are not included because they are specific to drainage channels. Most of the information is from the east slope, which, both from field inspection and dendrogeomorphic analysis appears to be the most active and rapidly eroding. For the purposes of this discussion, attention is focused on rate differences among the various methods and devices used, and on rate differences of at least one order of magnitude.

Table 11.--Observed rates, in inches per century, of ground-surface lowering from dendrogeomorphic, sediment-plot, erosion-frame, and erosion-pin data

		Sediment plots		Erosion frames		
Slope aspect	Tree rate	Plot number	Rate	Frame number	Rate	Erosion pin rate
West	3.8	2	0.0019	-	-	-
South	8.8	3	.0017	-	-	-
East	-	4	.0036	2	29	-
East	9.1	-	-	4	14	5
East	-	5	.0018	1	32	-
Northwest	4.8	1	.0022	-	-	-
Northeast	-	6	.0750	-	-	-
Top	-	7	.0120	3	7	-
Top	-	8	.0083	-	-	-

Erosion rates indicated by dendrogeomorphic analysis range from 3.8 to 9.1 inches per century, and rates indicated by the erosion frames and pins are either comparable to or less than an order of magnitude higher. This discrepancy is not of great concern considering the short period of data collection at the frame and pin sites. Saunders and Young (1983, p. 474) state that an order of magnitude difference between short period direct measurement and longer period indirect methods is quite common based on their extensive literature review.

Rates indicated by the sediment plots, however, are as much as four orders of magnitude less than the frame and pin rates and as much as three orders of magnitude less than the dendrogeomorphic rates. These plot rates also are very low relative to published rates for sediment traps (Saunders and Young, 1983, table III). The reasons for these large discrepancies are not clear. An attempt was made to determine the possible contribution of solution, however, even with the solution component added to the plot data, the resulting sum is still much less than the rates indicated by the frame, pin, and dendrogeomorphic data. There are several other factors that could contribute to the observed discrepancies, including an invalid assumption of uniform delivery, experimental error, loss through subsurface flow, and errors in bulk density estimates. The significance of these various factors in explaining the observed discrepancies cannot be evaluated. Therefore, the dendrogeomorphic, erosion-frame, and erosion-pin data are considered as better estimates of slope erosion.

The long-term channel erosion picture at Maxey Flats is complicated by the local geology. Increased runoff being diverted into the main drain is presently accelerating channel erosion as expected. Visual evidence at the study site indicates that the shale beds beneath the Farmers Member sandstone erode and undermine the sandstone until blocks of sandstone breakoff and come to rest on the slopes or in the channels. An acceleration of this process would, in the long term, cause more sandstone blocks to accumulate in the channel and on the side slopes bordering the channel. This accumulation of erosion resistant sandstone should serve to armor the channel and side slope and reduce the rate of erosion. This hypothetical scenario could easily be complicated by other processes such as slope failures which would tend to carry the sandstone blocks down slope and expose fresh shale to erosion.

Quantitative assessment of the long-term risk using rates observed during this study is very tenuous. A very crude assessment using rates determined from dendrogeomorphic analysis indicates 35,000 to 65,000 years for the slopes to erode to the burial trenches. These rates pertain to periods of dynamic equilibrium, and do not account for anthropogenic influences, mass wasting, extreme events or climatic change. Thus, the long-term geomorphic integrity of the Maxey Flats disposal site is probably more at risk from infrequent events or combinations of events than it is from normal hillslope retreat due to the continuous processes of slope wash and channel erosion.

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