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SEDIMENT DELIVERY AND DEPOSITION ESTIMATED USING CESIUM-137 TRACER

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SUMMARY:

Erosion and deposition rates were quantified for a 30 ha corn-cropped watershed by measuring Cesium residuals. An average annual soil loss of 60 MT/ha was determined for western Iowa loess soils. Estimates of net hillside soil displacement were made and an approximate sediment balance was possible.

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Sediment Delivery and Deposition Estimated Using Cesium-137 Tracer

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Abstract

Radioactive isotopes were released into the atmosphere during the nuclear weapon testing that occurred during the decade 1955-1965. One isotope, ^{137}Cs, is adsorbed by the finer soil particles and further movement by chemical processes is limited. Therefore, the measurement of residual ^{137}Cs levels provided a method for estimating soil movement, by physical processes, along a sloping cornfield. Since the tests, the overall average ^{137}Cs concentration on a transect of this cornfield, based on 15 samples, declined to 70 nCi/m^2 or 45 percent of the original 155 nCi/m^2 of ^{137}Cs fallout on the field surface; erosion has removed 55 percent of the ^{137}Cs and a corresponding amount of cultivated soil. The ^{137}Cs computed average annual soil loss for this transect was 60 MT/ha (27 t/a). The portion of eroded soil removed from the field was 57 percent of the average annual soil loss, based on the measured sediment yield of 32 MT/ha/y (14 t/a/y) and 2 MT/ha/y (1 t/a/y) waterway deposition. This compared favorably with the sediment delivery of 55 percent determined photogrammetrically, using the average annual measured sediment yield for the 1965-1981 period. Soil loss determinations using ^{137}Cs and photogrammetric methods were comparable and provided information for a first attempt sediment balance. Hillside net soil displacement rates were estimated to be 25 to 30 MT/ha/y. Long-term USLE computations indicated hillside soil displacement twice these values. Deposition of sediment in waterways draining each of two cornfields was estimated using ^{137}Cs analysis. At watershed 1, our estimate was 42 percent greater than measured by conventional survey; at watershed 2 it was 6 percent greater. These results indicate that the method is viable, but additional cross sections and sampling sites per cross section will improve the accuracy of estimate.

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Introduction

Hillside erosion and subsequent soil movement downslope and to stream channels are natural phenomena, but can be accelerated by man's activities (Task Committee on Preparation of Sedimentation Manual, 1975). Tillage of the fertile but steeply sloping loess hills region adjacent to the Missouri River has resulted in excessive erosion and sediment movement (Spomer et al., 1971). Sediment outflow from the Treynor research watersheds has been measured since 1964; these show great variability by storm, season, and year. Soil losses which are an approximation of total soil displacement on these loess soils have also been estimated, first with the Universal Soil Loss Equation (USLE) and then by measurement along a sidehill transect using photogrammetric mapping procedures (Piest et al., 1976, and Spomer and Mahurin, 1984). Herein, we introduce measurement of residual Cesium-137 (^{137}Cs) levels as an independent check of our previous soil loss measurements on hillsides and in valleys (Ritchie and McHenry, 1973). Using the foregoing independent measurements, we can validate or correct results from other methods. This will increase our knowledge of sediment delivery, landscape change, and accuracy of the USLE when applied to field and watershed size areas.

Atmospheric nuclear weapons testing released radioactive isotopes into the environment in the late 1950's and the early 1960's. Once in the soil, the radioisotope ^{137}Cs is adsorbed by the finer soil particles and further movement by natural chemical processes is limited (Ritchie et al., 1975). Cesium-137 is concentrated in the surface 0-10 cm (0-4 in) of undisturbed soils, but will be distributed throughout the plow layer of cultivated soils (Ritchie and McHenry, 1973). In cultivated areas most of the sediment is derived from sheet-rill erosion of the upper soil layers and, as a result, eroded areas will have smaller concentrations of ^{137}Cs and depositional areas greater concentrations. The half-life of ^{137}Cs is 30 years and correction for radioactive decay may be made to determine accurately the amount of remaining ^{137}Cs in the soil. Adjustment was also made for the original total fallout levels of ^{137}Cs. This was done by sampling undisturbed and uneroded areas near the study site and analyzing for ^{137}Cs.

Investigating sediment origin and delivery to surface waters, Wilkin and Hebel (1982) used ^{137}Cs tracing and concluded that most sediment in surface waters originates on the active flood plain. They stated that sediment delivery should only be a few percent from agricultural watersheds based on their research on a 526 ha (1300 a) watershed in northeast Champaign County, Illinois. It has been shown that sediment delivery varies with watershed size according to Piest et al. (1975) and Beer et al. (1966). Sediment delivery for watersheds 1 and 2 at Treynor, Iowa, averaged 55 percent for the years 1964-1980, confirming the relationship of sediment delivery and watershed size.

Using ^{137}Cs concentrations, soil loss was determined along a hillside transect and sediment deposition was measured in the main waterway of two watersheds. These ^{137}Cs soil loss results were compared with USLE computations, photogrammetric data and measured sediment yield to arrive at a sediment balance.

The Research Site near Treynor, Iowa

The study was conducted on two of the research watersheds in the Missouri Valley deep loess soils near Treynor, Iowa. These Monona, Ida, and Napier silt loam soils are classified as Typic Hapludolls, Typic Udorthents, and Cumulic Hapludolls (Soil Conservation Service, 1975). Excellent crop yields are produced when fertility and soil moisture are adequate. The slopes are steep, averaging 8 and 9 percent based on area weighting. About 65 percent of this region of Iowa is cropped with nearly 90 percent of the cropland planted to corn and soybeans according to United States Department of Agriculture (1970-1980), and Skow and Halley (1983). Corn planted on approximate contour and clean-tilled is a typical practice of the area. This intensive row cropping, coupled with severe spring and summer rainstorms, results in excessive erosion. The loess soil with its high (65-75) percentage of silt is easily eroded (Spomer et al., 1980). Measurement of soil displacement using ^{137}Cs concentrations was possible on these sites where erosion is excessive.

Sidehill Transect Study Method

Since a soil movement study by photogrammetric methods was already underway at the transect site shown in Figure 1 on a subwatershed of Watershed 1, this site was selected for the ^{137}Cs study. A profile of the study transect is shown in Figure 2 with ^{137}Cs sampling sites identified. Nine sites were sampled in 1974 and six additional sites were sampled in 1979 (Table 1). Specifically, sites of fill or scour were sampled in 1979 to provide needed supplementary data. Failure to sample an adequate depth was indicated when ^{137}Cs concentrations did not decrease at the 20 to 25 cm (8-10 in) depth. A few profiles were sampled more deeply in anticipated deposition areas and indicated that most radioactive material is in the top 25 cm (10 in) of the soil profile. Procedures for sampling, handling and analyzing soil samples were described by McHenry and Ritchie (1980).

Estimated Soil Loss by Measuring Cesium Levels

Soil samples collected from 1974 to 1979 along the sidehill transect on Watershed 1 were analyzed for ^{137}Cs and adjusted for a half-life of 30 years. These data are listed in Table 1 and some, but not all, data are plotted on Figure 2. Before any interpretations could be made, it was necessary to establish the original concentration of ^{137}Cs fallout at several undisturbed sites. Cesium-137 levels at these undisturbed sites, which included an abandoned orchard and a grassland area in the immediate area near Treynor, Iowa, and a grassed headland near Syracuse, Nebraska, are shown in Table 1. Cesium-137 concentrations adjusted for decay averaged 155 nanocuries per square meter (nCi/m^2) for these sites and are plotted separately in Figure 2.

TABLE 1.--CESIUM-137 LEVELS AT WATERSHED 1 TRANSECT AND UNDISTURBED SITES, NANOCURIES PER SQUARE METER nCi/m^2

	UNDISTURBED			TRANSECT SITES					
DEPTH CM	ORCHARD SITE	WATERSHED 1 WEIR SITE	SYRACUSE NEBR SITE	SITE 1	SITE 2	SITE 3	SITE 4	SITE 5	SITE 6
0-5	89.53	107.06	98.27	21.51	9.67	16.22	22.88	16.06	19.16
5-10	42.37	37.63	38.76	29.96	18.15	20.05	18.94	20.12	3.27
10-15	10.38	6.55	11.74	5.59	31.95	18.64	26.98	18.27	15.44
15-20	5.99	3.10	5.90	00.00	6.02	2.46	3.99	11.69	00.00
20-25	1.90	1.28	2.63	00.00	7.91	1.52	00.00	4.20	00.00
25-30	----	----	----	00.00	7.56[1/]	----	5.95[1/]	00.00	00.00
30-35	----	----	----	----	----	----	----	00.00	----
TOTAL	150.17	155.62	157.30	57.06	81.26	58.89	78.74	70.34	37.87

DEPTH CM	SITE 7	SITE 8	SITE 9	SITE 10	SITE 11	SITE 12	SITE 13	SITE 14	SITE 15
0-5	13.00	17.12	21.76	15.31	26.23	22.11	21.23	15.04	13.83
5-10	11.67	16.43	24.65	22.51	16.91	13.87	26.43	15.40	13.95
10-15	13.78	9.45	26.68	14.80	27.52	21.39	25.81	14.22	15.79
15-20	14.34	00.00	24.93	6.72	11.85	0.65	26.59	10.66	16.93
20-25	8.43[1/]	00.00	16.29	0.93	1.53	1.13	1.76	2.37	8.19[1/]
25-30	----	0.91	1.94	----	----	----	----	----	----
30-35	----	----	2.28	----	----	----	----	----	----
TOTAL	61.22	43.91	118.53	60.27	84.04	59.15	101.82	57.69	68.69

1/ Depth of ^{137}Cs exceeded cultivation depth because both deposition and erosion occurred.

Average ^{137}Cs level of 15 samples (Table 1) was 70 nCi/m^2, indicating that, overall, there has been erosion along the transect. Forty-five percent of the original 155 nCi/m^2 of the ^{137}Cs fallout remained in the eroded soil or, conversely, 55 percent of the cultivated topsoil had been eroded and moved off this hillside. Nearly all the upper and midslope sites show erosion, with most ^{137}Cs levels one-half or less than the original fallout amount. Sites with ^{137}Cs levels greater than 70 nCi/m^2 may have experienced some soil deposition as well as erosion. For example, site 9 where the slope was 0.07, had a ^{137}Cs value of 118 nCi/m^2. Our photogrammetric study confirmed that deposition from upslope erosion and/or cultivation occurred (Piest et al., 1976).

Soil loss from 1959 to 1978 was computed using:

$$E = \frac{DPK}{Y} \text{ where:}$$

E = soil erosion MT/ha/y

D = average tillage mixing depth in cm = $\frac{d_1y_1 + d_2y_2}{Y}$

P = percent ^{137}Cs removed

K = constant MT/ha - cm (weight of 1 ha of soil 1 cm deep)

Y = years

d_1 = plow mixing depth

d_2 = disk mixing depth

y_1 = years plowed

y_2 = years disked

Management records show that watershed 1 was plowed 13 years at an average depth of 17.8 cm (7 in) and disked 5 years at a depth of 15.2 cm (6 in). The mixing depth for plowing was the total tillage depth while mixing was about half of the tillage depth for disking[1/]. For two years, 1961 and 1962, this area was not tilled, had good cover, and had little or no erosion; therefore, 18 years of cultivation were used to compute soil erosion.

$$D = \frac{(17.8 \times 13) + (7.6 \times 5)}{18} = 15 \text{ cm } (5.9 \text{ in})$$

$$E = \frac{15 \text{ cm} \times 0.55 \times 132 \text{ MT/ha-cm}}{18 \text{ years}} = 60 \text{ MT/ha/y } (27 \text{ t/a/y})$$

1/ Personal communication with Dr. Don Erbach, USDA-ARS, ISU, Ames, IA

The resultant sediment delivery (sediment yield divided by soil movement) was 57 percent using the average annual measured sediment yield and waterway deposition of 34 MT/ha/y (15 t/a/y) and the above soil loss value (Table 2).

Using photogrammetric techniques, Spomer and Mahurin (1984) reported a sediment delivery of 42 percent for this same sidehill transect for the 9-year period, 1969 to 1978 (waterway deposition was not considered). The determination of erosion and sediment yields is not an exact science, but these results by different methods are compatible. A sediment delivery value of 55 percent for these steep watersheds is reasonable based on the above two methods of determination. It appears that a reasonable estimate of soil loss can be made using ^{137}Cs concentrations in the soil.

Waterway Deposition Rates

Deposition of sediment with time was observed in the main waterways to the extent that reduced flow capacity was noted. During the fall of 1980, waterways were re-excavated to increase flow capacity and return flow to the original waterway at several locations. This eliminated water flowing out of the waterways and through the field. Excavated waterway reaches are shown in Figures 3a and b. Before excavation, several sites were sampled for ^{137}Cs analysis along two selected cross sections on each of the main waterways.

Concentrations of ^{137}Cs are shown in Figures 4 through 7. All centerline sites show deposition since excavation and waterway shaping in 1963. Relocation of waterways in 1963 required excavation depths that removed all soil contaminated with ^{137}Cs. The samples at the waterway centerline at cross sections A and B in Figures 4 and 5 both indicated about 45 cm (18 in) of deposition since construction in 1963. The presence of ^{137}Cs in the soil indicates deposition while the small amount of ^{137}Cs between 50 and 65 cm (20 and 25 in) at the centerline of cross section A in Figure 4 may be due to the presence of some unexcavated material or perhaps, and less likely, the result of sampling in an old animal burrow. Fourteen meters (45 ft) to the left of the centerline we estimated that net erosion had been 9 cm (3.5 in) since remaining ^{137}Cs is less than background concentration. Sediment deposition of about 15 cm (0.5 ft) is indicated 21 m (70 ft) to the right of the centerline since the ^{137}Cs level exceeds the decayed fallout concentration and additional ^{137}Cs with depth is likely at this site based on the high concentration of ^{137}Cs in the 25-30 cm (8-10 in) depth.

In Figure 5 we estimated 45 cm (18 in) of deposition at the waterway centerline on Watershed 1. The ^{137}Cs levels 23 m (75 ft) to the left indicated no net change while sampling 8 m (25 ft) to the right did not penetrate non-contaminated cesium soil. Since ^{137}Cs levels through the 25 cm (10 in) depth were about the same for these sites, left and right of the centerline, we assumed a similar total cesium level for the site right of center, resulting in no net change. With this limited data, probable cross sections like those in Figure 8 were drawn and deposition areas computed. Finally, the deposition volume for a 152 m (500 ft) reach of the main waterway

TABLE 2.--SEDIMENT BALANCE BY THREE METHODS

Method	Soil Loss (gross erosion) MT/ha/y	Measured Sediment yield MT/ha/y	Estimated waterway deposition MT/ha/y	Sidehill net soil displacement MT/ha/y	Sediment delivery %
^{137}Cs/survey 1962-1979	60	32	2	26	57
Photogrammetric/ survey 1969-1978	40	18	2	20	50
Adjusted photogrammetric/ survey 1965-1981	62	32	2	28	55
Long-term USLE/survey 1965-1981	93	32	2	59	37

on Watershed 1 was estimated using end area calculations resulting in 1400 m^3 (1830 yd^3) or 1820 MT (2005 t) of deposition.

Figures 6 and 7 show the ^{137}Cs levels in the main waterway on Watershed 2. At the centerline on cross section C in Figure 6, we estimated that ^{137}Cs was present to a depth of 60 cm (24 in) because levels were high at the 45 cm (18 in) depth and samples at other centerline sites on both watersheds indicated ^{137}Cs levels would exist about 15 cm (6 in) below the high concentrations. The sample 24 m (80 ft) to the left of the centerline had a ^{137}Cs level about two-thirds of the original background. This sample site was not disturbed by construction; therefore, we estimated about one-third of the plow layer or 6 cm (2.4 in) was removed. Since ^{137}Cs was found over 30 cm (12 in) deep, there was also fill, so we estimated no net change. The sample on the right side had to be disregarded because the area was filled 30 to 46 cm (12 to 18 in) during construction in 1963. Finally, at cross section D in Figure 7, the ^{137}Cs data indicated deposition of 45 cm (18 in) at the centerline. Left of the centerline, the ^{137}Cs level indicated about 15 cm (6 in) of erosion, but ^{137}Cs to the inadequate sampling depth of 30 cm (12 in) suggested fill and so we again estimated no change. Again using only two cross sections, we estimated fill areas and computed deposition in the 183 m (600 ft) reach to be 1870 m^3 (2445 yd^3) or 2430 MT (2677 t).

Conventional cross section surveys spaced at 15 m (50 ft) were made prior to excavation of these waterways; these were compared with design cross sections for 1963 construction. The fill volume was determined by planimeter and end area calculations. Results indicated a net deposition of 990 m^3 (1295 yd^3) or 1290 MT (1421 t) for Watershed 1 waterway and 1760 m^3 (2302 yd^3) or 2290 MT (2524 t) on Watershed 2. The agreement with our estimate using ^{137}Cs is within 6 percent for Watershed 2 while the error increased to 42 percent on Watershed 1. Our estimate of no change at the left sampling site on cross section D in Figure 7 was shown to be in error when compared with plottings of conventional cross sections. Instead of no change, deposition was more than 30 cm (12 in) deep for cross section D in Figure 8, while in other areas deposition was overestimated, but in this case the errors averaged out and a good estimate of deposition resulted. The ^{137}Cs tracing technique was successfully used to provide information on soil loss and movement, sediment deposition and delivery.

Sediment Balance for Watershed 1

The results of three methods for determining soil loss, sidehill erosion, and deposition are given in Table 2 along with measured sediment yield and waterway deposition on Watershed 1. This is an attempt to more completely identify the fate of eroded soil.

The sidehill net soil displacement was determined by subtracting the measured sediment yield and waterway deposition from the USLE, ^{137}Cs, and photogrammetric soil loss determinations. Surface runoff was used to adjust soil loss upward for the short-term photogrammetric data to make direct comparison of the data. The ratio of the long-term 1965-1981 average annual surface runoff to the 1969-1978 average was 1.5, indicating that the long-term average annual soil loss would be 1.5 times greater than measured during the 9-year photogrammetric study.

These results of ^{137}Cs and photogrammetric procedures permit us to estimate that net sidehill soil displacement has been about 45 percent of the soil loss or about 30 MT/ha/y. This admittedly is a rough estimate, but is a first step in determining a sediment balance. The much larger soil loss value with the USLE is expected since our work and others (Piest et al., 1975; Piest and Spomer, 1968; Spomer et al., 1980) have shown that the USLE overestimates soil loss when rainfall intensities are low to moderate and large R[1/] values are possible with minimal erosion. Using the USLE soil loss value resulted in a large sidehill net soil displacement value and a smaller delivery percentage. The significance of Table 2 is that a sediment balance is possible because we have been able to measure soil loss by several methods.

Conclusions

The ^{137}Cs tracing and photogrammetric mapping procedure results were compared with USLE computations, and helped us obtain a more complete picture of a changing landscape — erosion of soil from cropland and its subsequent transport and deposition to downslope and downstream locations. We were able to prepare a sediment balance that reasonably agreed for the Treynor watershed, using ^{137}Cs and photogrammetric procedures. An estimate of sediment delivery, i.e. the portion of total eroded soil that is transported from these 30 ha (75 a) cornfields, seems to be about 55 percent, based on our studies.

Results of ^{137}Cs analysis for sediment deposition showed that the number of sites sampled per cross section was inadequate and additional cross sections would be advisable. Sampling depth should be sufficient [> 60 cm (24 in)] to insure sampling all of the ^{137}Cs in the profile. On Watershed 2 our sediment deposition estimate was quite good, within 6 percent of the value determined by conventional surveying. On Watershed 1 our estimate of deposition with ^{137}Cs data was 42 percent greater than the conventional survey. The method has potential for estimating deposition where no previous data exist.

To better understand and describe the impact of erosion, sediment transport, and sediment deposition on landform change, more studies similar to this effort will be necessary. These data become increasingly important as we seek to improve models to predict soil loss sediment yield and resultant landform change.

1/ U.S.L.E. rainfall factor

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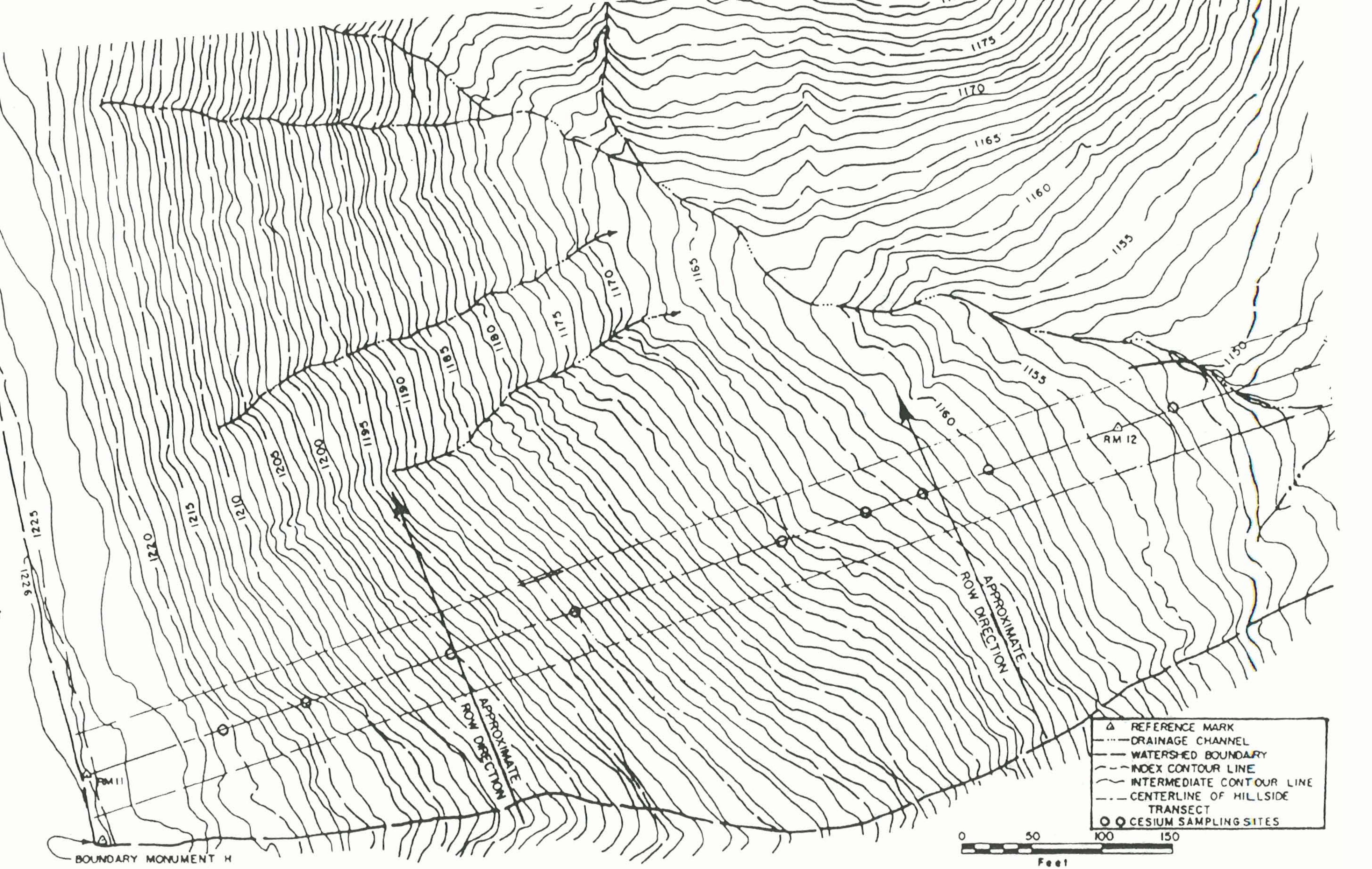

Figure 1.--Topographic map of portion of 75-acre row-cropped watershed near Treynor location of sidehill transect and ^{137}Cs sampling sites.

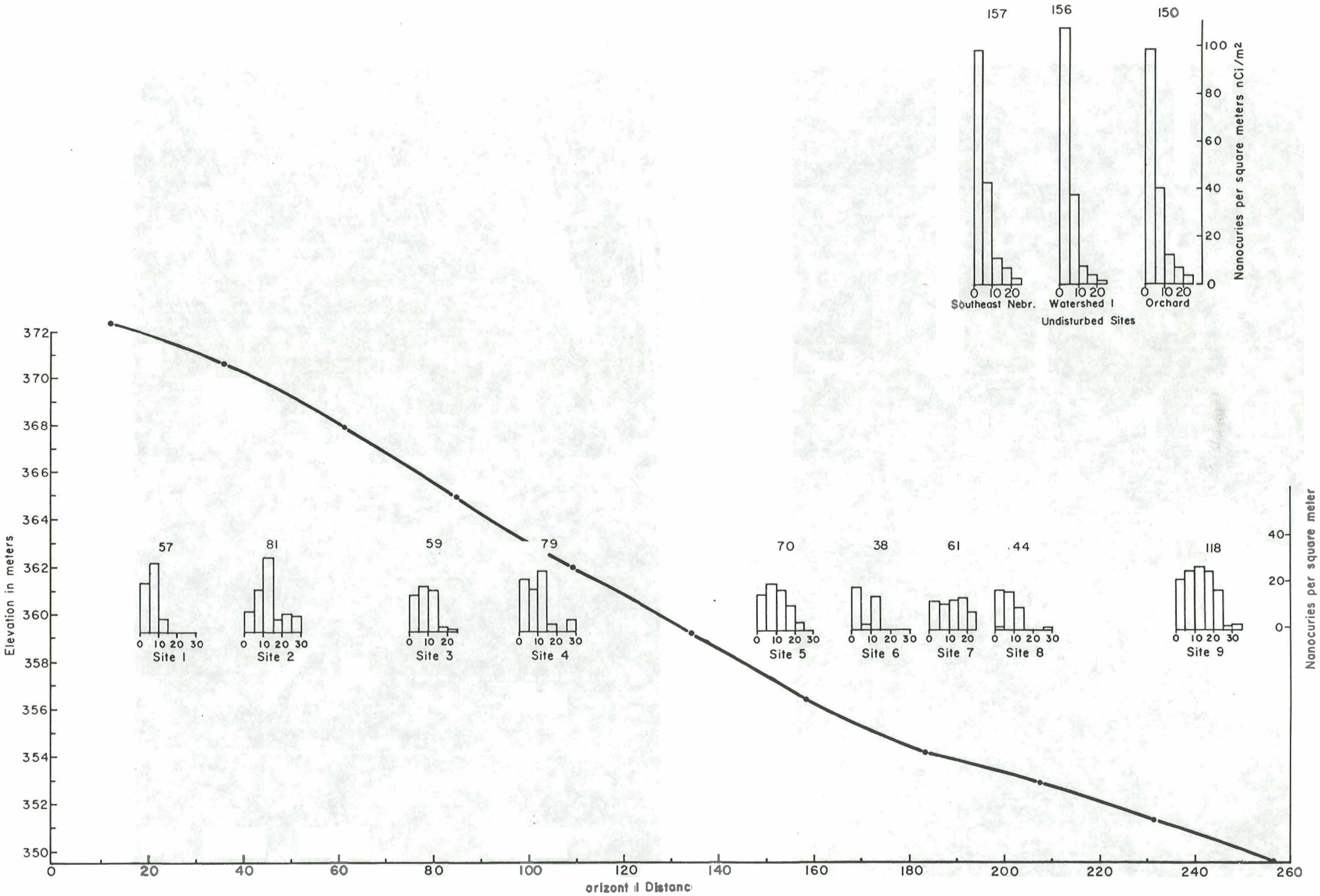

Figure 2 --Profile of sidehill transect showing representative Cesium 137 sample sites, amount and distribution; also three undisturbed sample sites.

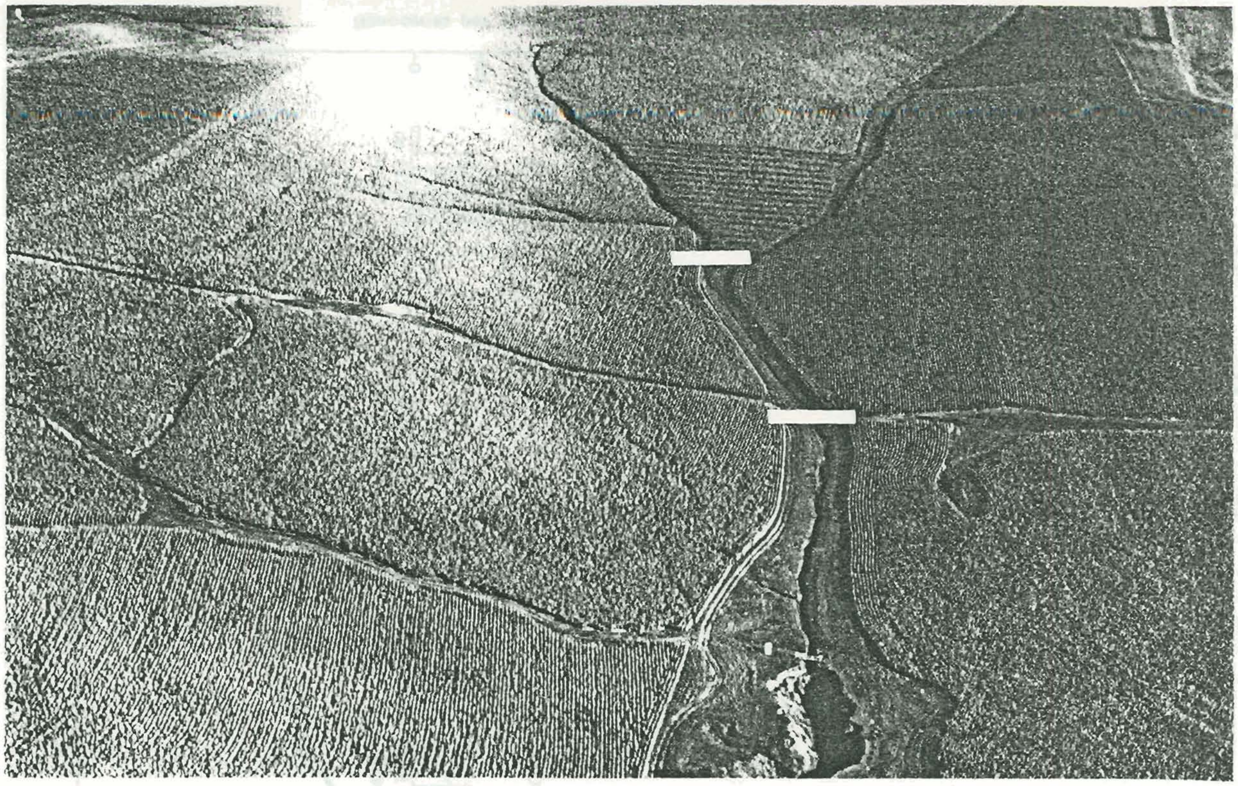

Figure 3a.--1971 photograph of main waterway (between white lines) on watershed 1 near Treynor, Iowa showing the reach which was excavated in the fall of 1980.

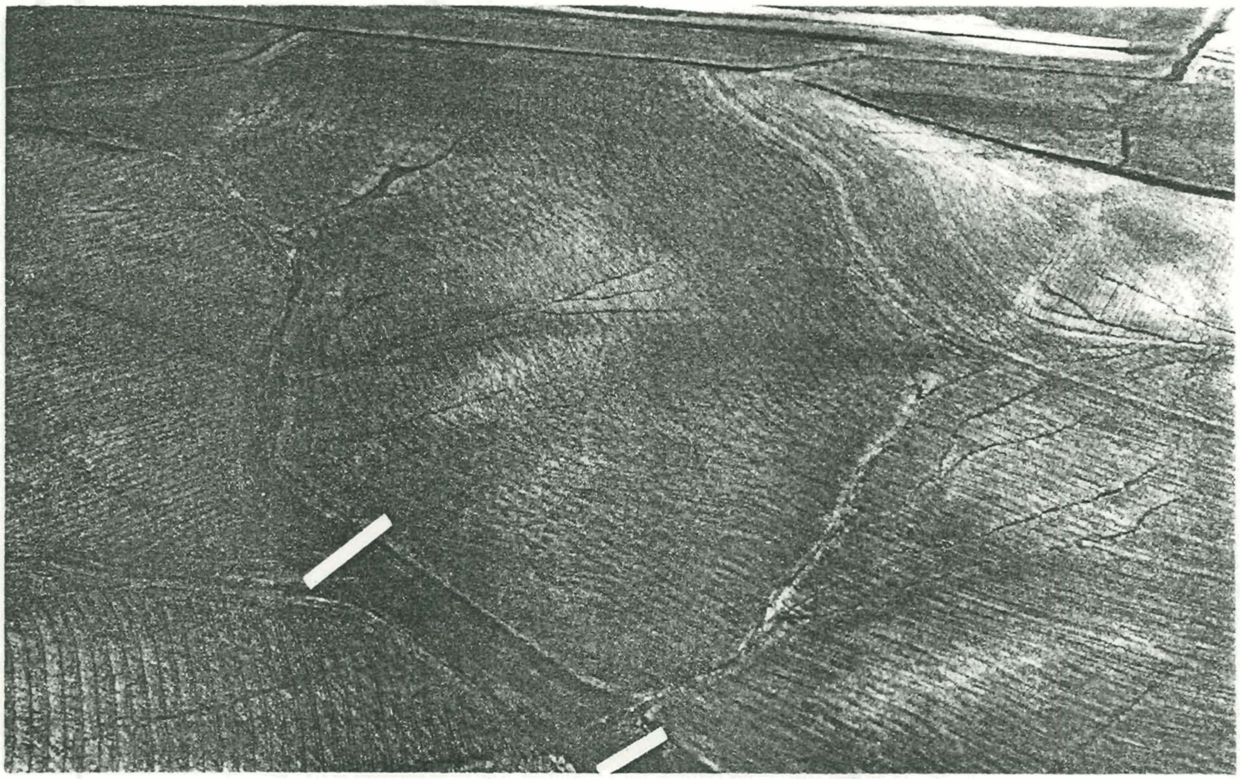

Figure 3b.--1972 photograph of main waterway (between white lines) on watershed 2 near Treynor, Iowa showing the reach which was excavated in the fall of 1980.

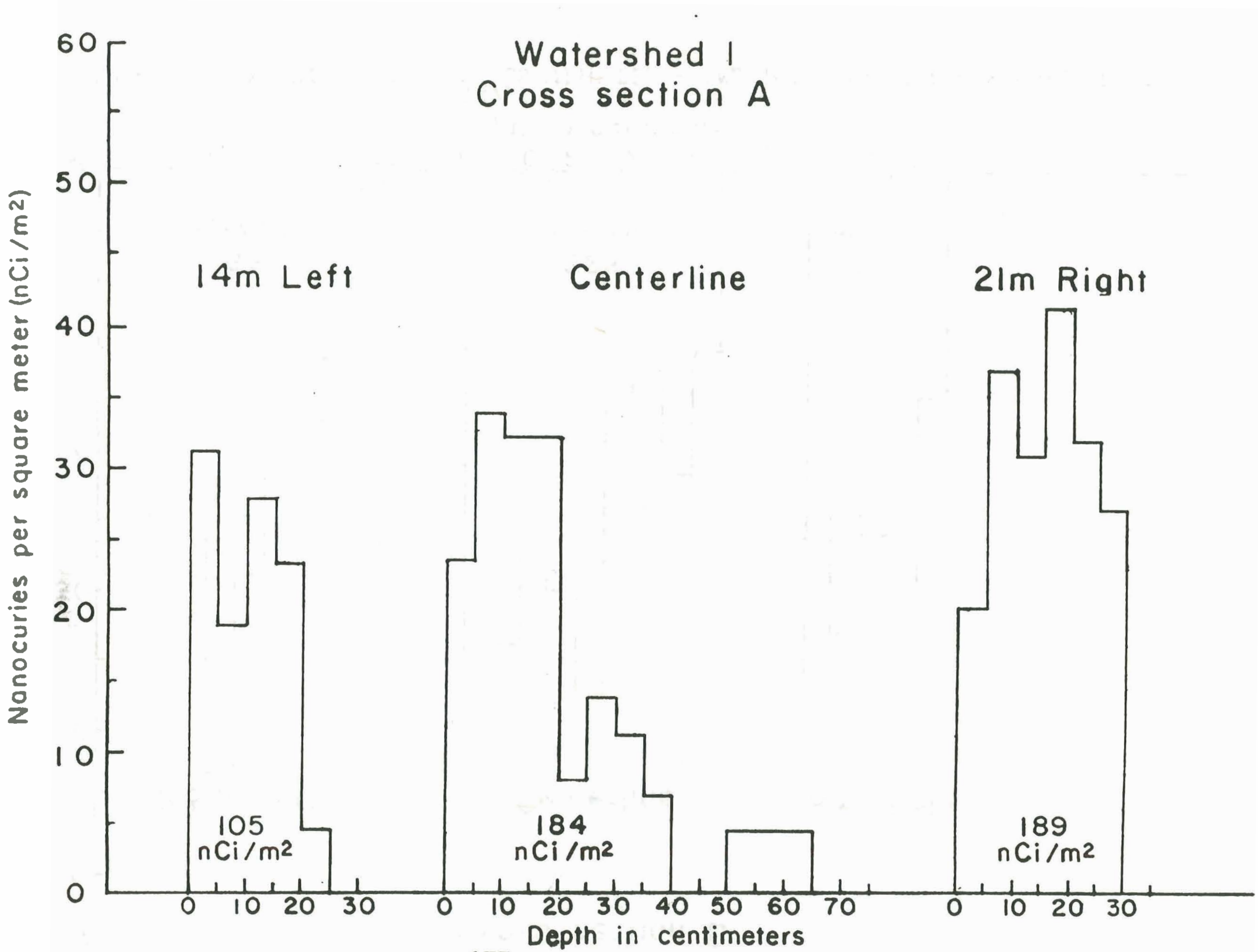

FIGURE 4.--CONCENTRATION OF ^{137}Cs WITH DEPTH AND TOTAL IN WATERWAY SOIL PROFILE

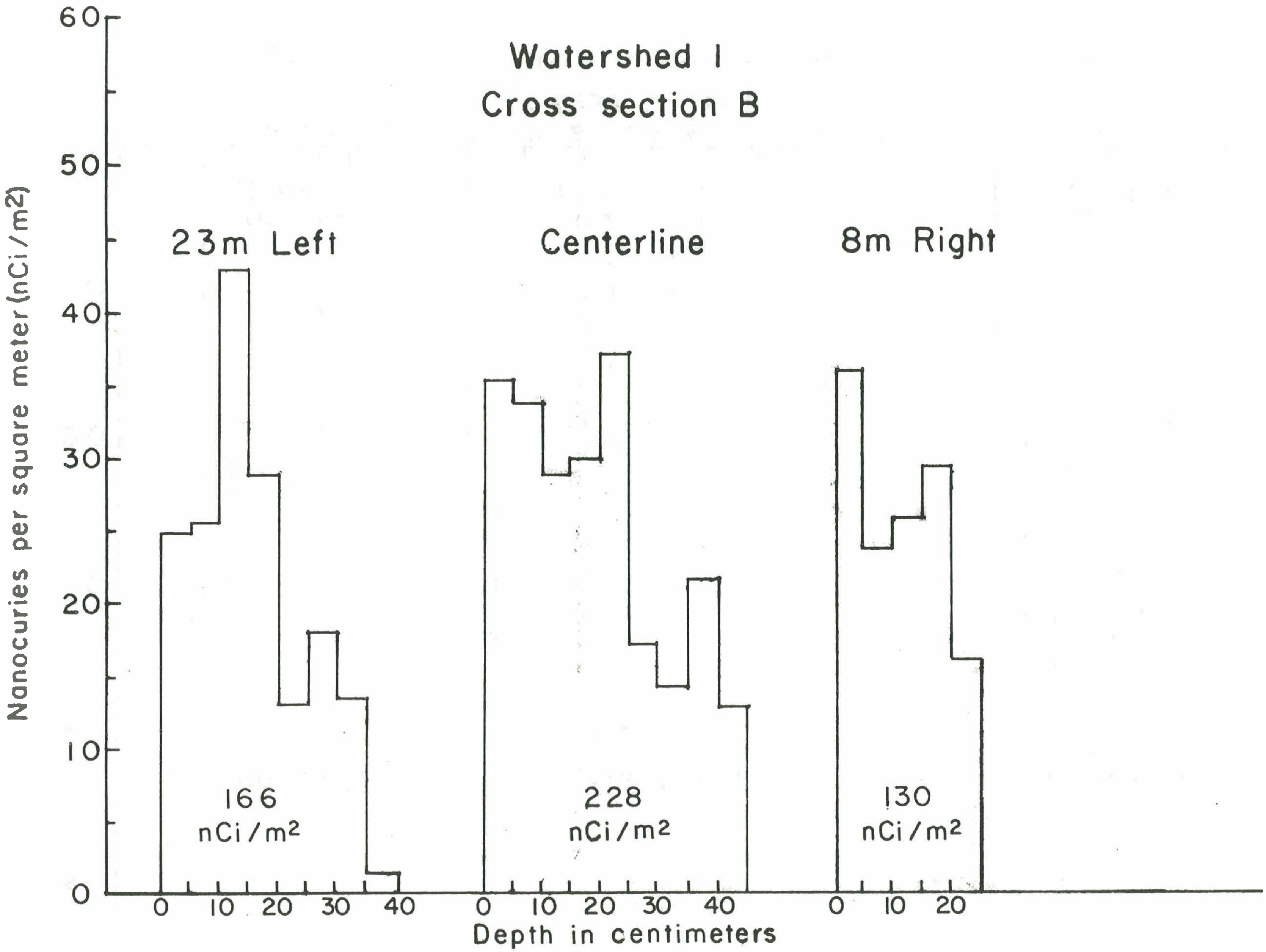

FIGURE 5.--CONCENTRATION OF ^{137}Cs WITH DEPTH AND TOTAL IN WATERWAY SOIL PROFILE.

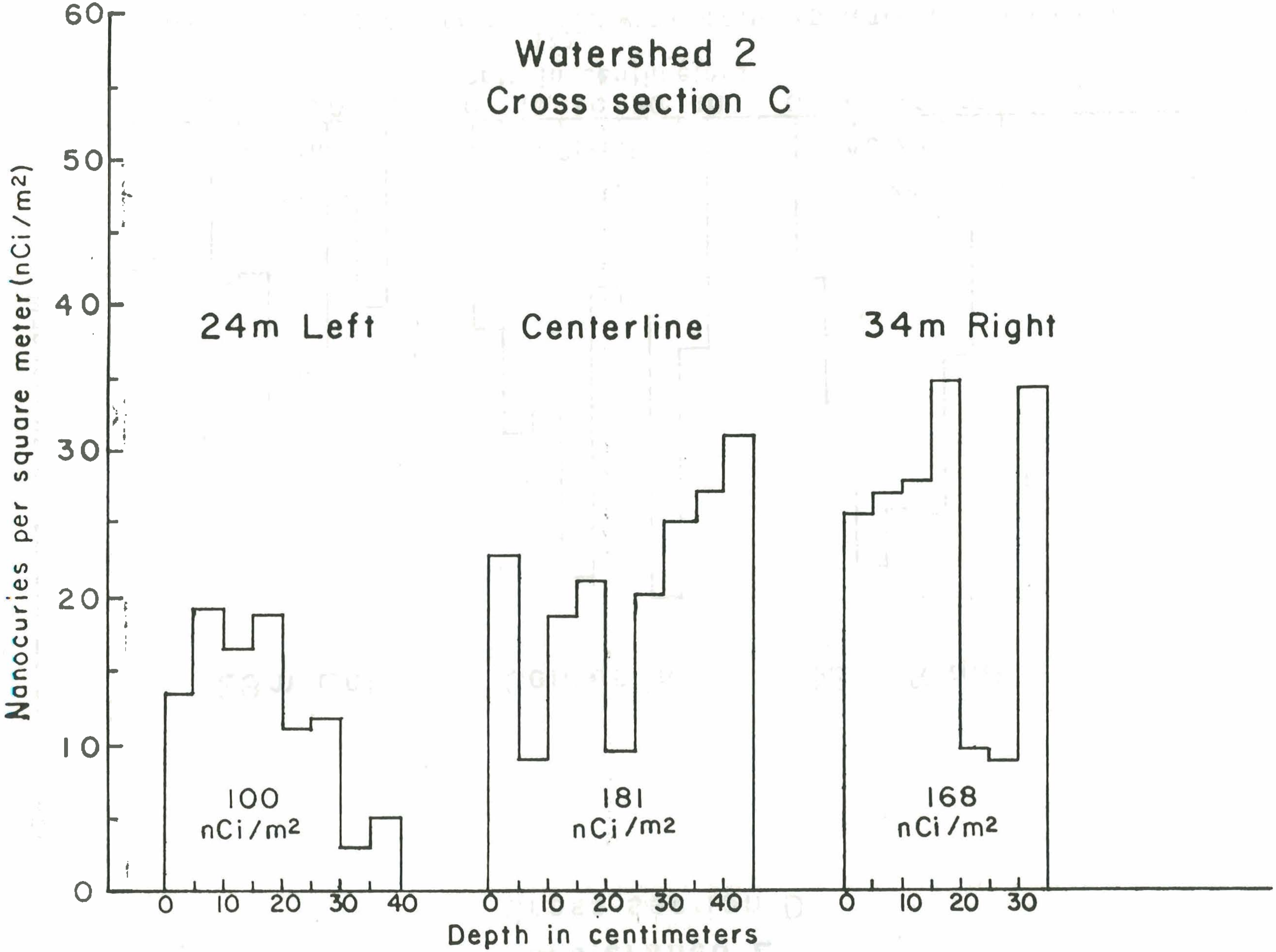

FIGURE 6.--CONCENTRATION OF ^{137}Cs WITH DEPTH AND TOTAL IN WATERWAY SOIL PROFILE.

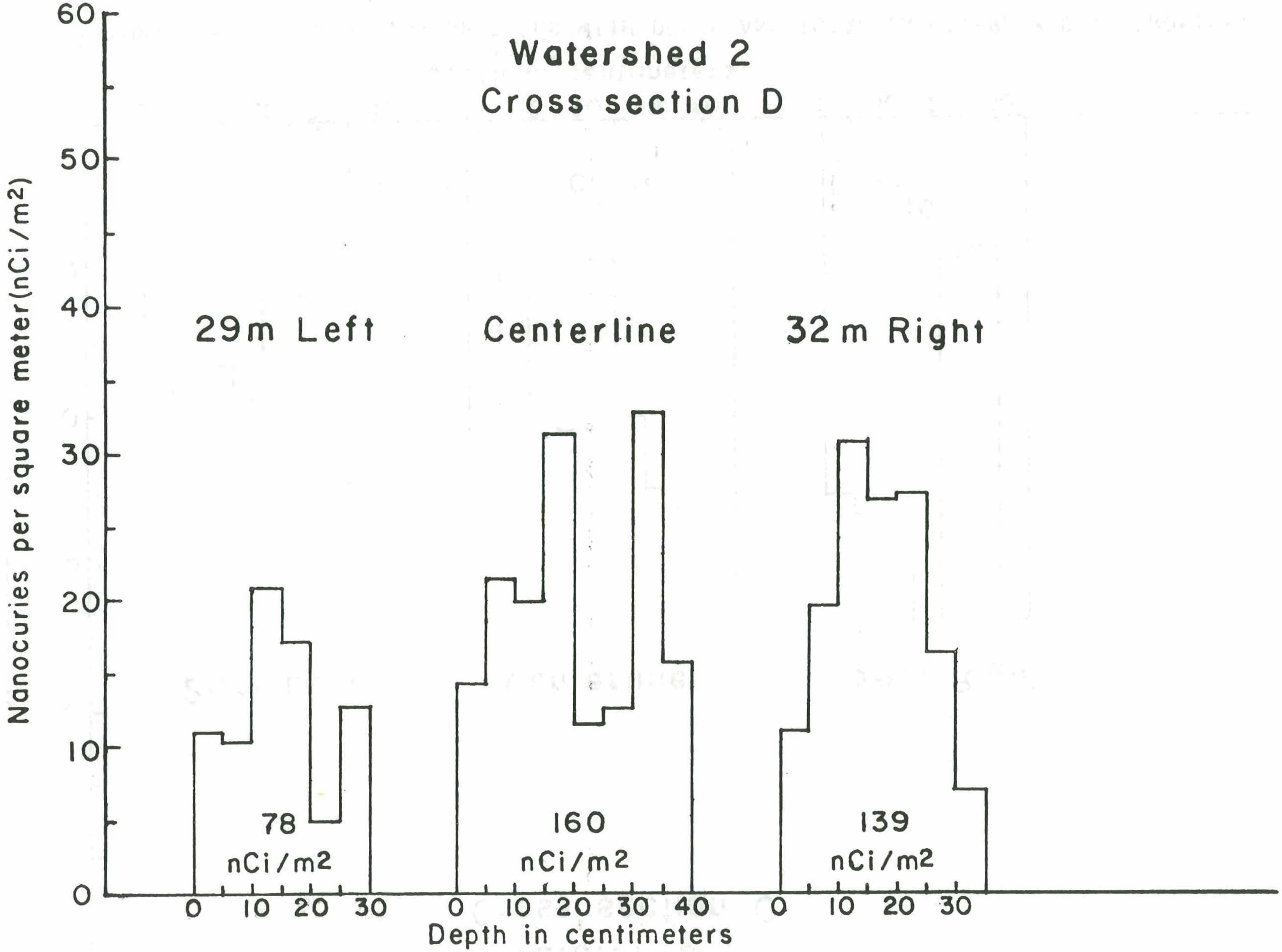

FIGURE 7.--CONCENTRATION OF ^{137}Cs WITH DEPTH AND TOTAL IN WATERWAY SOIL PROFILE.

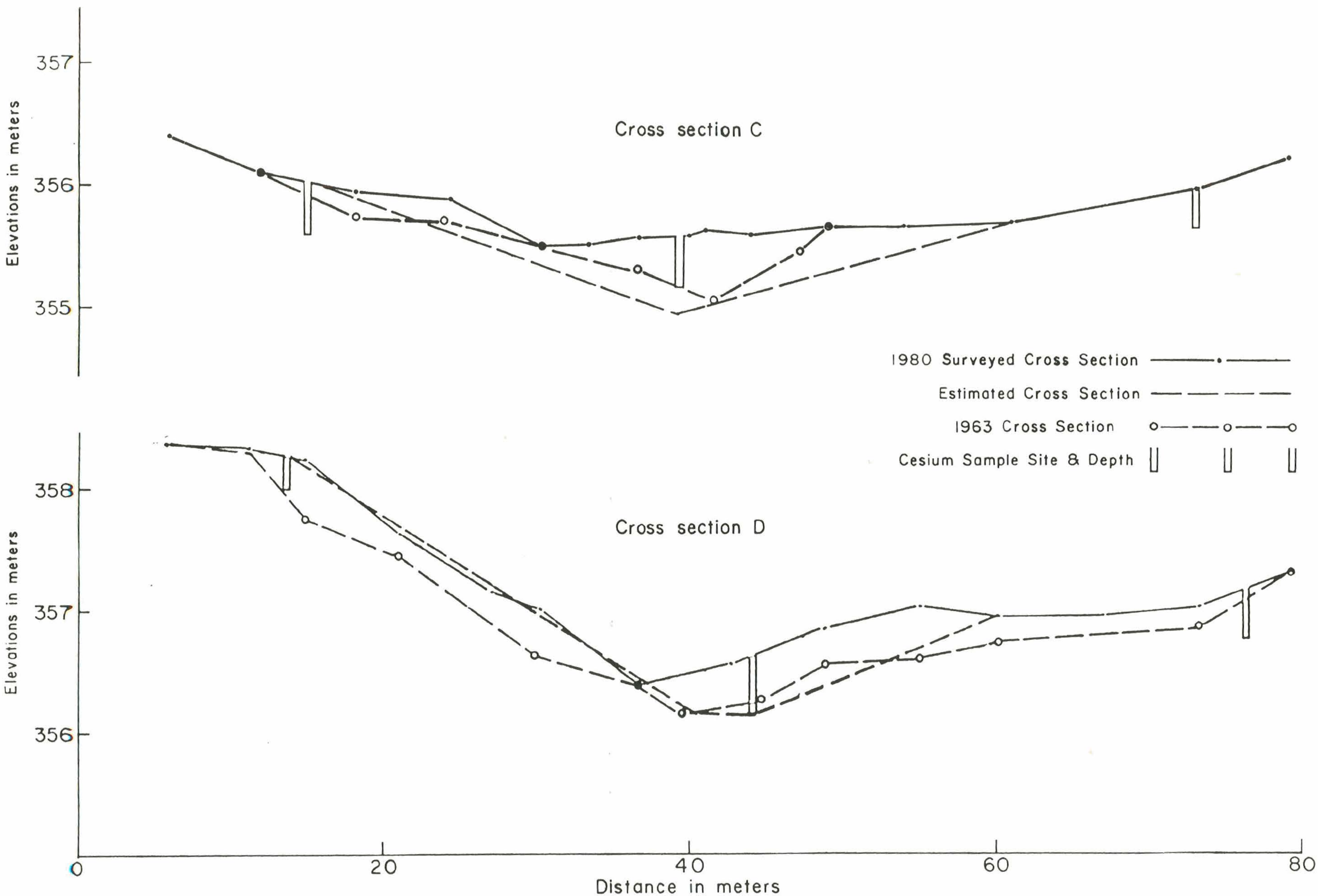

Figure 8.--Cross section before excavation in 1980 and estimated 1963 cross sections based on Cs^{137} data for Watershed 2.