DISSERTATION

CESIUM-137 IN AN ALPINE WATERSHED

Submitted by

John Edward Hubbard

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY JOHN EDWARD HUBBARD

ENTITLED CESIUM-137 IN AN ALPINE WATERSHED

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate Work

F. Ward Whicker

W. R. Schmehl

B. C. Goodell

William D. Striffler
Adviser

Arthur T Wilcox
Head of Department

Examination Satisfactory

Committee on Final Examination

W R Schmehl

F. Ward Whicker

B C Goodell

William D. Striffler
Adviser

Permission to publish this thesis or any part of it must be obtained from the Dean of the Graduate School

ABSTRACT OF THESIS

CESIUM-137 IN AN ALPINE WATERSHED

A study was made of the distribution of the fallout radionuclide Cs-137 on the surface and in the stream channel of an alpine watershed in the Colorado Front Range. Cs-137 activities of the surface (mean = 266 nCi/m^2) were considerably higher than at Fort Collins, Colorado.

The effects of snow-accumulation, soil-vegetation complexes and the hydrologic surface were studied in relation to Cs-137 activity. Snow-accumulation areas contained significantly more Cs-137 than snow-free areas. Alpine Bog contained significantly more Cs-137 than did Alpine Turf and Alpine Meadow soils. Micro-channels and micro-depressions had significantly higher levels of Cs-137 activity than areas characterized as surface runoff.

Concentrations of Cs-137 in stream bottom sediments and stream vegetation decrease exponentially downstream with distance from a permanent snowfield at the headwaters. There is some evidence that Cs-137 in sediments is accumulating in a marshy area where the stream flows across the moraine of a former mountain glacier. Cs-137 activities of the sediments were not highly related to percent silt+clay. Evidence did not support the hypothesis that most Cs-137 would concentrate in the silt+clay as it moved downstream.

Significant quantities of Cs-137 were not found in stream water or the 1967 or 1968 snowpack. Measurable Cs-137 activities were found in litter and inorganic materials in and about the permanent snowfield, and in moss on rocks in the stream channel.

John Edward Hubbard
Department of Recreation and
Watershed Resources
Colorado State University
Fort Collins, Colorado 80521
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CHAPTER I

INTRODUCTION

High levels of radioactivity associated with atmospheric testing of nuclear weapons have been observed in alpine watersheds (Osburn, 1963). Although fallout rates have diminished markedly since the cessation of atmospheric testing, residual radionuclides, notably Sr-90 and Cs-137, remain in the environment.

Recent studies of the concentration of Cs-137 in fish from high mountain lakes indicate that this radionuclide is present in lake and stream biota, possibly being transported in from adjacent land areas (Nelson and Whicker, 1967). Soils studies indicate that cesium is strongly sorbed to the soil system, since it is more strongly bonded to soil particles than the more abundant ions of calcium, sodium, potassium, and magnesium (Sayre, Guy and Chamberlain, 1963). This suggests that the transport of Cs-137 is largely a function of erosion and sedimentation. Erosion in alpine areas may be both fluvial and wind processes.

The studies of Osburn and Nelson and Whicker also show that some radionuclides tend to become concentrated in organic matter, both living and dead. This suggests that the distribution and movement of Cs-137 on a watershed may also be a function of the distribution and movement of organic debris.

Cesium-137 is of interest because, if concentrated, it is a potential hazard to man. It is also important when used as a tracer within the environment because of its radioactive properties and unnatural occurrence. Determination of Cs-137 distribution within a watershed as related to soil, hydrologic, and snow-accumulation factors may permit prediction of the dispersal of radionuclides in other, similar watersheds. Measurements made over time may contribute to understanding of relationships existing between living and nonliving compartments of ecosystems since they allow estimation of intercompartmental transfers of the nuclide.

CS-137 TRANSFERS IN AN ALPINE WATERSHED

A concept of cesium-137 movement in an alpine watershed system is represented in Fig. 1. Although zoological components are omitted, some insight may be gained from discussion of relations among the compartments illustrated.

Cesium-137, distributed largely as worldwide fallout, (Klement, 1965) enters the troposphere from the stratosphere through what is called a folding or region of cyclogenesis in the tropopause. The subsequent distribution of Cs-137 by tropospheric circulation is affected by the geographical location of the fold, the frequency and intensity of its occurrence, and seasonal variations in stratospheric circulation.

Entrance of fallout into an alpine watershed may be with rain, dry dusts and pollens, or by being swept from the air by

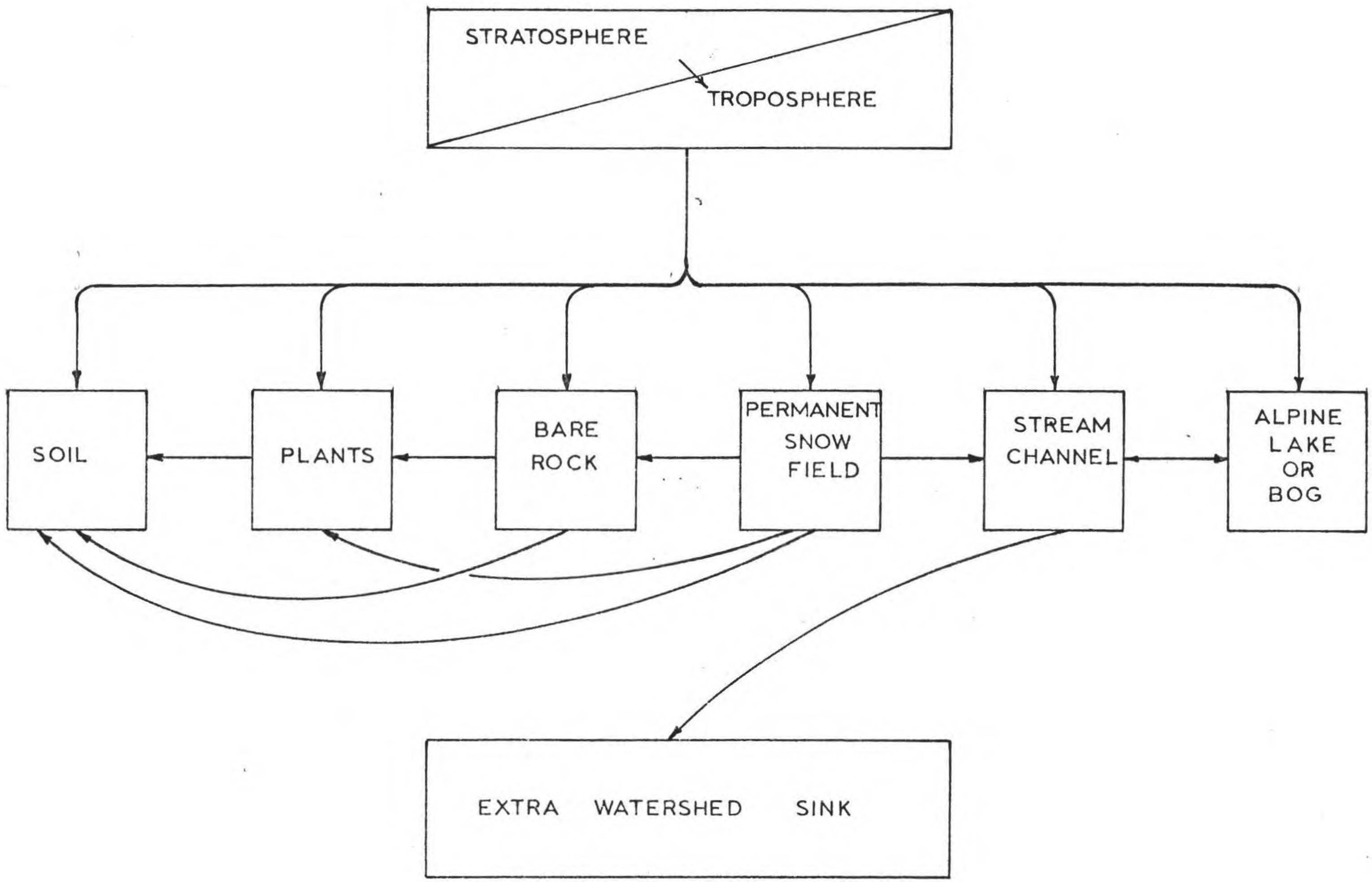

Figure 1. Compartmental illustration of Cs-137 transfers in an alpine watershed

snow, the dominant form of alpine precipitation (Gartska *et al.*, 1958). Upon snowmelt Cs-137 is sorbed to organic and inorganic debris incorporated in the snowpack, or to litter, soils or vegetation beneath or downslope from the snow (Osburn, 1967).

Upon reaching the soil, cesium is strongly retained, unless transported with the soil by erosive processes. If the snow is in contact with surface waters, large amounts of radioactivity may be filtered by aquatic vegetation (Sturges and Sundin, 1968), possibly to be concentrated in aquatic organisms by nutrient cycling processes (Nelson and Whicker, 1967).

Most cesium-137 deposited on bare rock is transported and redeposited on plant foliage or soils, with long term transfer from foliage to soil.

The major path for cesium-137 dispersal from the alpine watershed, except for wind erosion, is by transport in the stream channel. Concentration may be associated with sediment deposition downstream.

OBJECTIVES

The object of this study was to make measurements within and among some of these model compartments, principally to evaluate cesium-137 distribution as it presently exists. Repeated measurements made over a sufficient length of time might permit more understanding of the model, and of the mechanisms of transfer within it.

More specifically, the objectives were:

1. To determine the Cs-137 activity within the surface of an alpine watershed, and its distribution as related to factors describing the watershed.
2. To determine the Cs-137 distribution within a stream channel, and to investigate possible mechanisms related to its hydrologic dispersal.

CHAPTER II

LITERATURE REVIEW

With the advent of the Atomic Age in 1945, cesium-137, with other radioactive fallout nuclides, was introduced into the environment and is now distributed throughout the world. This isotope of the relatively rare element cesium is chemically an alkali metal, the most electropositive of the elements. Its chemical properties are discussed by Finston and Kinsley (1961).

Cesium-137, along with strontium-90 and iodine-131, is considered one of the three fallout radionuclides most important for study. It has a high yield as a fission product, a relatively long half life of 30.5 years, and is chemically similar to the element potassium (Comar and Lengemann, 1967).

Because of its chemical similarity to potassium, the ecological and physiological behavior of cesium-137 is also similar. Because it is formed relatively late after nuclear detonation from gaseous precursors, Cs-137 is more likely to be distributed as stratospheric worldwide fallout (Davis, 1963).

Cs-137 is one of more than 200 nuclides between atomic numbers 28 and 65 produced as fission products in fission and thermonuclear bomb explosions (Klement, 1965). The larger, hotter, high-rising fireball of the latter weapons introduces radionuclides into the stratosphere, reducing the proportion of local "close-in" fallout.

FALLOUT TRANSPORT AND DEPOSITION

Bjornerstedt and Edvarson (1963), Wilson (1967) and Klement (1965) provide comprehensive reviews of fallout production, atmospheric transport, removal from the stratosphere, and deposition.

Local or "close-in" fallout from surface bursts may be deposited shortly after detonation near "ground zero." It is distributed leeward from that point by tropospheric winds, traveling perhaps several hundred miles within a day's time.

Worldwide fallout refers to those radioactive materials injected into the stratosphere by high-yield thermonuclear weapons tests. Fallout was assumed by early investigators to remain for many years in the stratosphere, but has been found to reach the earth's surface in larger concentrations and after a shorter residence time than expected (Stewart et al., 1957).

Although nuclear detonations have occurred near the equator and in polar regions, the greatest proportion of radioactive fallout has reached the earth's surface at mid-latitudes in the Northern Hemisphere (List et al., 1965). This has led to a model involving the folding of the tropopause. This is associated with cyclone formation at jet stream level. Stratospheric air, bearing radioactive debris passes through the fold.

Mahlman (1966) showed that discrete quantities of stratospheric air enter the troposphere in association with cyclogenesis at the jet stream level. This explained short term variations in fallout and its latitudinal distribution.

Mahlman found large increases in fallout activity on the earth's surface in the spring of the year to be due to a breakdown of a strong polar winter stratospheric vortex. Subsequent horizontal transport of stratospheric air and accompanying debris to the fold occurs with the vortex breakdown.

Materials carried to the stratosphere may remain there for several months to several years. Fabian, Libby and Palmer (1968) report a stratospheric residence time of 1.6 years for strontium-90. Mean residence time in the troposphere is on the order of 30 to 40 days.

Deposition from the troposphere may be categorized as rainout, where the radioactive particle is the nucleus of an ice crystal; washout, in which radionuclides are scavenged from the air by falling rain or snow; or as direct aerial deposition (Perkins and Engelmann, 1966).

Wilson (1967) cites several reports indicating the mode of fallout deposition to be washout. Itagaki and Koenuma (1962) used this to explain observations made of concentrations of radioactivity in precipitation. They observed lower concentrations at high altitudes, corresponding to cloud tops, than at low altitudes.

Perkins and Engelmann (1966) found snow to be more efficient than rain in removing radioactive aerosols. But Kruger and Hosler (1963) observed radioactive particles to be removed as a result of the condensation process in convective clouds penetrating the tropopause. The debris formed the droplet nucleus. In arid and semiarid regions direct dry deposition has been shown to account for significant deposition upon vegetation, particularly when dew-moistened (Wilson, Ward and Johnson, 1967).

List _et al_. (1965) have prepared maps of strontium-90 distribution in the United States through 1963. Values representing subsequent deposition have been presented by Gustafson, Brar and Muniak (1965) and by Klement (1965). Those presented by Klement indicate large increments in regions receiving more than 20 inches of precipitation yearly and smaller increments in more arid areas.

One may calculate Cs-137 activity for the Fort Collins, Colorado, region from this table. It involves utilizing the nearest Sr-90 isoline, adding increments appropriate to a region of low rainfall, and multiplying by a Cs-137/Sr-90 ratio of 1.6 (Comar and Lengemann, 1967; Hardy and Chu, 1967).

Results of these calculations give surface activities of Cs-137 of 120 nanocuries/square meter (nCi/m^2) for the area of this study and 94 nCi/m^2 for Fort Collins, Colorado. Determinations of strontium-90 activities in Fort Collins soils yield values in close agreement with Sr-90 values calculated by this method (D. Wilson, personal communication).

There has been a general decrease in fallout deposition since 1964 (Volchok, 1967). Annual values for strontium-90 deposited at Denver, Colorado, are reported by the U. S. Atomic Energy Commission (1967) and are expressed below in nanocuries/square meter:

1959	1960	1961	1962	1963	1964	1965	1966
4.31	0.66	1.30	4.38	10.70	9.18	3.74	1.43

Wilson (1968) reports a similar trend, upon which spring seasonal maxima are superimposed, for Fort Collins.

CESIUM-137 DISTRIBUTION IN THE ENVIRONMENT

The distribution of fallout and natural radioactivity in the environment has been thoroughly discussed by Eisenbud (1963). Whicker (1965) reviewed the distribution of fallout radiocesium associated with precipitation, soils, surface waters and vegetation. Much of this is included in the discussion below.

The amount and frequency of precipitation is associated with fallout deposition (Pelletier, Whipple and Wedlock, 1964).

It is also associated with Cs-137 levels in soils (Low and Edvarson, 1960), and Cs-137 concentrations in conifer twigs and needles (Davis, Hanson and Watson, 1963).

Ritche (1962) collected litter, humus, and mineral soil under natural vegetation in the Great Smoky Mountains. He found significant increases in Cs-137 concentrations in the soil with increased elevation and related the increase to increased annual precipitation. Whicker (1965) observed increasing levels of radioactivity in soils, and of Cs-137 in vegetation and mule deer with elevation in the Cache la Poudre drainage, Colorado.

These increased levels of activity with increases in elevation may be explained in terms of increased precipitation and increased proportions of snow in annual precipitation. Meiman (1968) reports an increase in snow, measured as water equivalent, with altitude. Perkins and Engelmann (1966) indicate elevational increases in activity are associated with an increase of radionuclide concentration with altitude in the troposphere.

Osburn (1963,1967) reports instances where snowfields in high mountain watersheds contained radioactivity levels high enough to be considered hazardous for drinking water purposes. He suggests the scavenging of radionuclides by snowflakes as they fall is supplemented by further capture as the snow is windblown into areas of accumulation. Thus radioactive aerosols also may tend to be deposited in cirques and pockets on the lee sides of alpine ridges.

Sturges and Sundin (1968) report high activities in debris filtered from snow in a high mountain bog in Wyoming. This was also observed by Osburn (1963), who suggested that radioactivity within the solid phase snow becomes sorbed to debris past which it flows when melting occurs in the snowpack.

Osburn (1967), in his study of gross activity of fallout in a similar Colorado mountain watershed, described the importance of snow as follows:

"1. approximately two-thirds of the annual precipitation is in the form of snow.
2. falling snow may be carried many miles by wind, thereby encountering a greater amount of fallout-laden atmosphere than would a comparable amount of rain.
3. the amount of atmosphere washed free of fallout, per unit volume of water, is greater via snow than via rain.
4. the time of the largest amount of snowfall is coincident with the spring break of the tropopause which enriches the lower atmosphere with fallout."

Soils and sediments

The cesium ion is an alkali metal cation. Clay minerals and organic matter in soils have high cation exchange capacities and sorption of Cs-137 to earth materials is highly probable.

Sayre, Guy and Chamberlain (1963) discussed physical and chemical sorption mechanisms. In general, sorption is greater as particle size decreases. Sorption on sand or silt particles is a physical process associated with van der Waals forces between the solid and the radionuclide. Physical sorption is reversible and sensitive to the concentration of the radionuclide in the soil or stream water.

Chemical sorption, on the other hand, is due to stronger forces. It varies with the chemical nature of the clay minerals in the clay soil or sediment fraction. It also varies with the amount of organic matter present.

Baker _et al_. (1966) examined sorption equilibria in terms of distribution coefficients and ion competition. This was to determine whether Cs-137 would remain in solution in natural waters following a nuclear blast at Cape Thompson, Alaska.

The distribution coefficient is the ratio of the fraction of radionuclide sorbed to earth material to that remaining in solution times the ratio of the volume of solution to the mass of suspended earth material. The major cations competing for sorption in aqueous systems are those of calcium and magnesium. With increased concentration of these ions, and of other positive competing cations including stable cesium, there is decreased opportunity for sorption of Cs-137.

Results of their experimental study revealed extremely high distribution coefficients for cesium. This indicated that one day after detonation there would be little danger of much Cs-137 remaining in solution.

Greater sorption occurred when smaller quantities of competing cations were present. The percentage of cesium sorbed increased with the passage of time. This was evidence that fixation was occurring. Baker _et al_. attributed this to the presence of 2:1 clay minerals. They suggested that because of specific fixation sorption of Cs-137 is independent of concentration of competing cations.

Schultz, Overstreet and Barshad (1960) reported that carrier-free cesium-137 is fixed as a precipitate on surfaces of micaceous minerals. There is fixation on the edges where broken bonds may account for negatively charged sites. And there is interlayer fixation in clay minerals with high cation exchange capacities. Schultz _et al_. reported that illite, which has a natural C-axis spacing of 10 angstroms, is most efficient among the clay minerals for sorbing clay Cs-137 from waste solutions.

Sawney (1967) reports that biotite from which potassium has been extracted, and which should behave similarly to illite, actually becomes vermiculite in the sorption reaction. It then has an expanded 14-angstrom lattice spacing and a larger cation exchange capacity. Sawney generalizes that "these sorptions by mixtures of biotite and vermiculite, thus, do not support the contention that cesium is sorbed selectively by minerals of 10-angstrom spacing."

Coleman, Craig and Lewis (1963) found that the cesium sorption by montmorillonite is reversible although montmorillonite has a high exchange capacity. Cesium is fixed in interlayer spaces by vermiculite. Cesium fixation is high in weathered, potassium-depleted clays. The depletion of potassium in the intercellular spaces along the planes of the expanded lattice allows Cs^+, K^+, or $(NH_4)^+$ to invade. Upon saturation with these ions the lattice collapses to the unexpanded state and irreversible fixation occurs.

Johnson (1965) found that considerable Cs-137 that entered the digestive tract of cattle was not taken up as had been expected. He also found that fallout cesium in the Colorado portion of the Great Plains was not soluble to the extent that had been reported in New York City and Oregon. Apparently the radiocesium found in the fallout collectors was already fixed to what x-ray analysis indicated were montmorillonite and illite dust particles. The trace quantities of fallout Cs-137 probably result in strong fixation by most mineral surfaces.

D. Wilson (personal communication) among others has found negligible uptake of fallout Cs-137 by plants from soils. Davis

(1961) mentions several experiments that have shown uptake of Cs-137 from nutrient solutions. He suggests that there is reason to expect uptake from soils that are largely organic and peat.

Whicker (1965) found almost all fallout Cs-137 to be concentrated in the top inch of soils sampled in the Cache la Poudre drainage. Many other investigators (Pavlotskaya, Tyuryukanova and Baranov, 1967; Gustafson, Brar and Muniak, 1965) have found it to be concentrated near the surface.

Squire and Middleton (1966) sprayed an aqueous solution of Cs-137 on bare soil and pastures. After six years, 70 to 90 percent was retained in the upper inch. Downward movement was greatest in calcareous soil and least in high clay soils. Delp (1968) applied carrier-free Cs-134 to soils obtained from an area burned by fire. He found penetration to be no more than 4 millimeters.

Alexander (1967) reports that 83 percent of the fallout Cs-137 reaching a forest soil in Maryland has remained in the top inch depth. But approximately half of the fallout has not reached the soil and may be in live trees or their roots. Gorham (1963) found strong concentrations of fallout in living organic matter and in the organic litter layer of soils under pine in Ontario, Canada. Small amounts of fallout radionuclides were in the mineral soil beneath the litter.

Russell (1967) suggests that uptake by plants from soil occurs most easily from organic soils although he refers to experiments using higher Cs-137 concentrations than would be true of fallout. Larson (1963) found fallout Cs-137 deposited close-in to the Nevada test site was almost totally fixed to the clay fraction of the soil.

An instance was reported in which Cs-137 washed in from stemflow in a Tennessee forest was leached through the soil by subsequent stemflow to a depth of 15 inches (Franklin _et al._, 1967). Olson (1965) describes the transfer of Cs-137 inoculated into tulip poplar trees from the trees to the forest soil. He explains the build-up in soil radioactivity in terms of root-soil turnover, which is greater than that which occurs with rain-out or autumn leaf fall.

Erosion by wind and water

Huff and Kreuger (1967) have considered it possible to utilize levels of surface soil contamination by Cs-137 to quantitatively study the erosion process. They would estimate surface erosion by observing stream sediment discharge. This involves the comparison of sediment activity per unit mass with activity per unit area of surface soil.

They proposed utilizing erosion measurements made on a small erosion watershed and measurements of sediment activity downstream. These measurements would be used to develop a predictive model based on the Stanford Watershed Model (Crawford and Linsley, 1966). Measurement of sediment activities in natural streams would provide data for the digital computer model. This in turn would indicate the extent of surface erosion in the watershed.

Rogowski and Tamura (1965) sprayed carrier-free Cs-137 in aqueous solution on plots of alluvial soil in Tennessee. They measured the extent of leaching and the losses of soil and of Cs-137 by runoff. Cs-137 losses were related to the logarithm of soil losses. Vegetated plots retained Cs-137 to a greater extent than did plots of bare soil.

The model proposed by Huff and Kreuger assumes uniform distribution of fallout Cs-137 on the watershed surface. But Osburn (1967) found considerable variation in fallout radioactivity on the surface of an alpine, snow-accumulation watershed. The pattern of radioactivity, measured as gross beta activity, was superimposed on the pattern of accumulated snow and its incorporated debris.

The debris blown in from the soil surface contributed to the radioactivity of the snowfield. But as the snow meltwater percolated through the snowfield the debris served as a sorption surface for the snow radioactivity, filtering the fallout materials from the water. This caused high levels of activity in areas of debris deposition.

Osburn observed dry fallout in the alpine watershed. He reports a case where fallout radioactivity associated with pollen indicated pollens and dusts had travelled from watersheds hundreds of miles away. This, along with soil particles picked up by the wind within the watershed, tends to be deposited where wind deposits snow.

Distribution in aquatic environments

Parsont (1967) reviews the factors affecting the transport and distribution of radionuclides in water. He studied the distribution of radium-226 downstream from a uranium mine. Wruble et al. are cited in a statement that there is a direct relationship between radioactivity in sediment and the stream flow rate. Sedimentation concentrates activity and is associated with low stream velocities.

Removal of radioactive materials from the water may be effected by the sedimentation of silt, clay, organic matter and chemical deposition. The latter occurs when the solubility product is exceeded. As the radioactivity moves downstream it tends to accumulate in catch basins and other areas where stream velocity is reduced. The sediment may build up or be scoured from the stream bottom by flows of high velocity.

Radioactivity may also be transported or detained by biological means. Davis, Hanson and Watson (1963) observed the highest levels of radioactivity in plants they surveyed were in mosses.

The moss filtered the water of a small stream that drained a barren, high-altitude watershed.

Osburn (1963) reported that radioactivity in the snowfields on the watershed was high enough so as to make the melted snow fail the standards for drinking water of the U. S. Public Health Service. But the water in the channels downstream was several orders of magnitude less radioactive. The soils and surface vegetation of the watershed were an effective filter for gross radioactivity.

Sturges and Sundin (1968) collected samples in 1965 from a mountain bog in the Elk Creek watershed in southern Wyoming. They also found that the standing vegetation, and litter and moss on the bog surface significantly screened the fallout radionuclides from the snowmelt water.

The mobility of organisms and the intricate aquatic food web also affect radionuclide distribution in stream environments. Nelson and Whicker (1967) measured the Cs-137 concentration in fish muscle tissue in waters at various elevations in Colorado. They observed increased concentration of activity with altitude. Cs-137 concentrations also were related to such limnological characteristics of the water as productivity and area of contributing watershed.

Gustafson (1967) reports a study at Red Lake, Wisconsin. Samples of bottom sediments indicated uniform levels of Cs-137 in the lake proper, with higher levels observed near the mouth of the influent Black Duck River.

Field studies of specific radionuclide distribution have been made in streams on which nuclear processing plants have been located. Porcella and Friend (1966) have studied several of these streams. They observed Cs-137 and other radionuclides in water, suspended and sedimented particulate matter, and stream biota.

Cs-137 discharged into the Clinch River is removed rapidly and sorbed irreversibly by the illitic clays that are characteristic of the basin. But in Lower Three Runs Creek, where the clays are kaolinitic and of lower concentration, the Cs-137 is not removed as thoroughly nor as abruptly.

CHAPTER III

PROBLEM DESIGN AND METHODS

STUDY AREA

The study was conducted in the Hourglass watershed, a subwatershed of the Little South Fork drainage of the Cache la Poudre River. The area is north of Rocky Mountain National Park in north-central Colorado (Fig. 2).

The glaciated, northeast-facing Hourglass watershed accumulates large amounts of winter snow in a cirque at alpine elevations and in the forest below. It is quite typical of drainage basins on the east slope of the Rocky Mountains. These areas of snow-accumulation are important in terms of the yield, timing and storage of water (Megahan, 1968).

Comanche Peak (elevation 12,700 feet) lies on the southernmost portion of the divide separating the Hourglass and Fall Creek watersheds. Relatively gentle windswept slopes descend from the ridge at alpine elevations. The Hourglass cirque is incised into these slopes, its upper rim at 11,500 feet elevation.

Characteristics of the Hourglass watershed were reported by Cerillo (1967). The area is 3.8 square miles and the

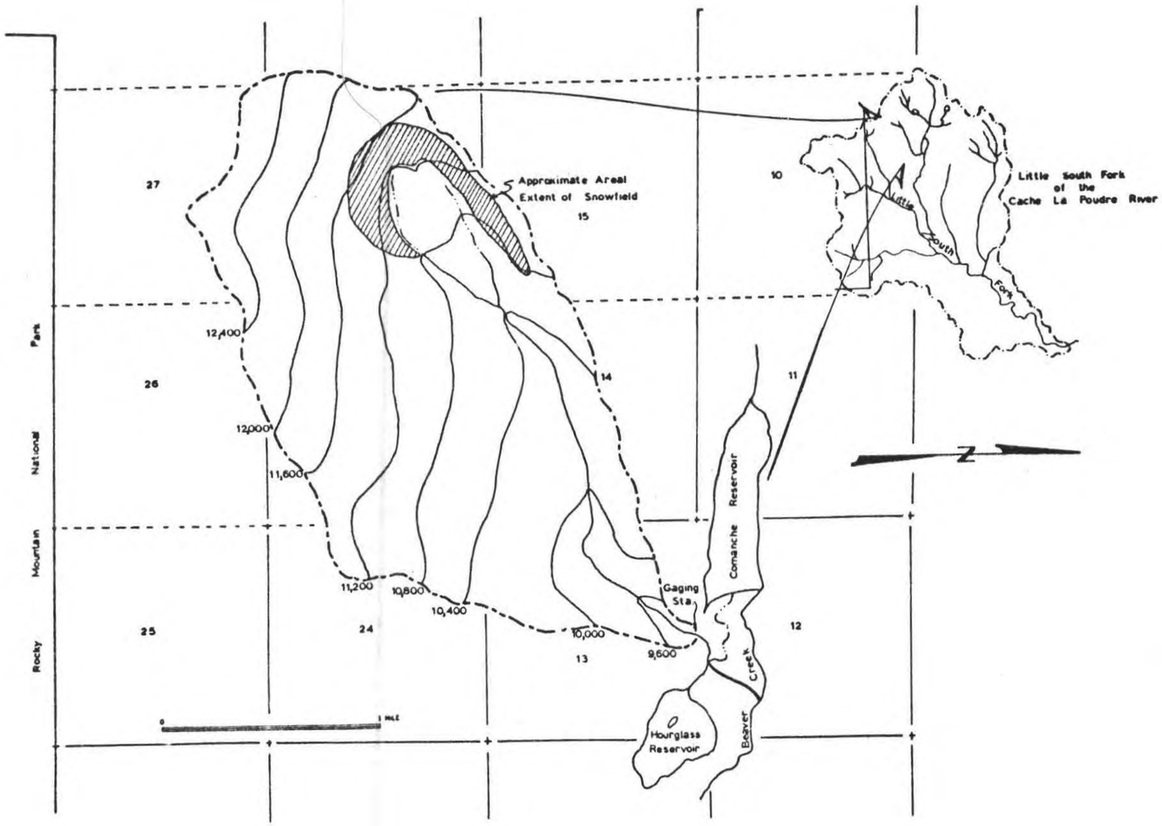

Fig. 2. Location of the Hourglass Creek watershed.

perimeter is 8.6 miles. The circularity ratio for the basin is 0.646 and its relief ratio is 0.18. The drainage density is 0.95 miles per square mile and the average stream gradient is 615 feet per mile.

The basement structure of the watershed consists of highly jointed precambrian granites, gneisses and schists. These outcrop in the cirque and at the ridges. Highly fractured rock, rock glaciers and talus slopes characterize the area below the ridges. Alpine Meadow and Alpine Turf soils have developed on the more gentle slopes.

Glacial drift from advances in Wisconsin time overlies the narrow stream valley. The steep valley gradient decreases in two places. One is in an area associated with indications of an advance by a mountain glacier called Pinedale III (Cerillo, 1967). The second is downstream in the glacial outwash in the basin of Beaver Creek to which Hourglass Creek is tributary.

Climate

The climate is considerably colder and the precipitation more abundant than on the plains to the east. Most of the precipitation falls as snow between October and April. The Department of Recreation and Watershed Resources maintains a weather station at nearby Pingree Park. Mean monthly data for precipitation averaged over 1964-1966 and for temperature in 1966 are presented below:

Precipitation (inches) - annual total is 21.00

J	F	M	A	M	J	J	A	S	O	N	D
1.43	1.08	1.58	3.29	1.94	2.24	2.36	2.40	1.96	0.58	0.58	1.56

Temperature (degrees Fahrenheit) - annual mean is 34.2

J	F	M	A	M	J	J	A	S	O	N	D
12.8	9.7	27.0	28.9	41.4	49.3	56.9	51.3	46.5	36.2	31.0	20.0

The alpine lands receive as much snow, and probably more, than the areas at lower elevations (Nishamura, 1964). Wind redistributes snow into alpine cirques and the forest below. Cold air drainage and upslope afternoon mountain breezes affect temperature patterns on the watershed. Small intense thunderstorms commonly occur on summer afternoons, and strong winds are especially intense and common above the cirque in the winter.

Hydrology and soils

The discharge of Hourglass Creek is a function of snowmelt. Flows at the Lower gaging station vary from a base flow of 5 cubic feet per second to a snowmelt peak ten times that discharge. In June 1965 a snowmelt peak of 65 cubic feet per second was observed.

Although the stream gradient is more than 600 feet per mile a stream velocity of only 1.5 feet per second was measured along its length in early July 1967. This uniformly low velocity is caused by frictional effects of numerous downed trees and large boulders in the stream channel.

Very little overland flow is observed over either forest or alpine soils. That occurring is associated with melting of late-lying snow and intense summer storms. In these cases the water flows relatively short distances and then infiltrates into coarse soil, often in small micro-channels and micro-depressions, respectively. The permanent snowfield continuously feeds the stream and subsurface flows resulting in springs are active throughout the year.

Studies of the water quality of streams throughout the Little South Fork basin of the Cache la Poudre River have been made by Kunkle and Meiman (1967). Hourglass Creek is among the lowest in sediment, turbidity, dissolved solids, temperature and bacterial indicators.

The soil-vegetation complex in the alpine portion of the watershed are categorized principally on the basis of drainage. Alpine Turf, soil unit 918 (Nishamura, 1964) and called Ptarmigan by Retzer (1962), is well-drained, slightly acid, very dark brown and friable in the A horizon, and strong brown in the B horizon.

Alpine Meadow, soil unit 917 (called Vasquez by Retzer) is poorly drained, moist and of pH5. It is dark gray to very dark brown in the B horizon. Short-growing sedges, hairgrass and bluegrass, and short patches of willow are characteristic of Alpine Turf vegetation. Coarse sedges, tufted hairgrass, shoulder-high willows and many herbaceous plants are present in the Alpine

Meadow. In general Alpine Turf is more characteristic of the areas above the cirque. Alpine Meadow soils are more common on alluvial-colluvial soils below the Alpine Turf.

Alpine Bog (called Nystrom by Retzer) consists of moist, dark gray and highly organic soils. These saturated soils would include the sedge mats by Osburn (1963) in his vegetational analysis. They often occur in this watershed in basins below late-lying snow, and often have a hummocky character associated with frost action.

These soils and patches of bare rock and soil are characteristic of the alpine-subalpine ecotone (Marr, 1961). Spruce-fir "krumholz" thickets, meadow, mounds of boulders and isolated trees are present in the area.

A spruce-fir forest dominates the subalpine portion of the watershed. Picea englemanii and Abies lasiocarpus are dominant. Soils in the forest are gray podzolics to coarse lithosols with rocks occupying much of the landscape.

COLLECTION AND PREPARATION OF SAMPLES

Two transects were made in the North Fork portion of the watershed to determine the Cs-137 activity of the surface (Fig. 3). These transects were in the alpine and in the alpine-subalpine ecotone.

Sediment Sampling Sites
(proceeding downstream)

Snowfield
North Flume
Meadow
Knife
Upper Flume
Pinedale III
Intermediate
Lower Station
Beaver Falls

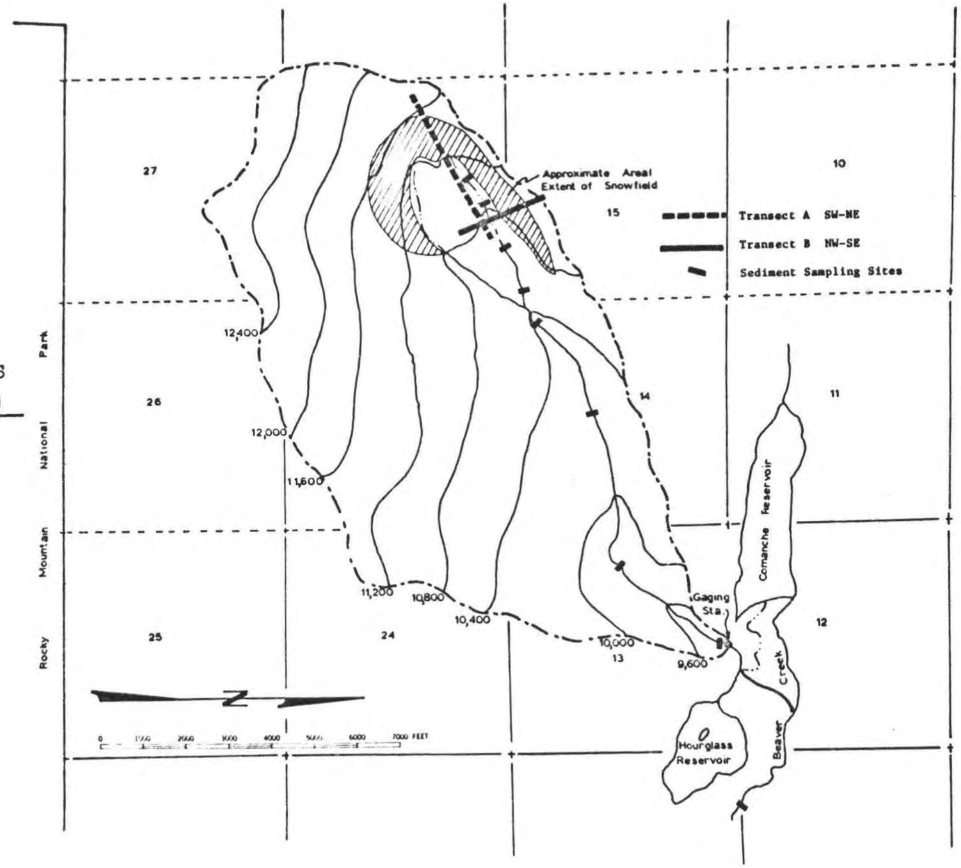

Fig. 3. Location of transects and sampling sites within the Hourglass Creek watershed.

Fig. 4. Hourglass cirque with Comanche Peak in the background.

The C-transect across the watershed was approximately 1600 feet long. It was divided into eight equal segments. Within each segment four samples of the watershed surface were taken at randomly chosen distances. The samples, one-half square feet in area and approximately one inch deep, were placed in two-quart plastic containers. The A-transect down the watershed from near the divide to the subalpine zone was also made. This transect was 3200 feet long. It was divided into eight equal segments and treated similarly.

Each sampling point was characterized as to whether accumulated snow was still present July 7, 1967. The soil-vegetation complex was described as Alpine Bog, Alpine Turf, Alpine Meadow, bare soil, bare rock or litter on rock. The bare soil classification included unconsolidated material Retzer (1962) included as rimland.

In addition to differential accumulation according to vegetation types, Osburn (1967) observed that radioactive debris often was carried into small depressions in the landscape when snowmelt occurred. Accordingly, each sampling site in this study was characterized as either a surface runoff area, micro-channel, or micro-depression.

Surface runoff described an area where meltwater or rain-water flows relatively uniformly across the land surface. It may flow to a channel or infiltrate the soil surface. A micro-channel is a small furrow-like depression in which water concentrates and flows turbulently. These are often active only with snowmelt and intense storms. Micro-depressions are closed depressions in which water accumulates and infiltrates the soil.

In order to determine if Cs-137 was present in natural streamflow water samples were taken from Hourglass Creek. Samples of 300 liters were taken at the North Flume and Lower Hourglass gaging stations during the peak snowmelt period in June 1967. The water was poured through Dowex #50 cation exchange resin (Fig. 5). The resin was then analyzed for Cs-137 by gamma spectrometry.

Similarly, snow samples were obtained from zones of snow deposition in the watershed in 1967 and 1968. The snow samples were melted and analyzed as were the stream samples.

Since Cs-137 transport from the watershed was most likely in conjunction with sediment transport, bottom sediments were sampled at points representing natural sediment accumulation areas. Eight sediment sampling sites were located along Hourglass Creek (Fig. 3). One was located at Beaver Falls on Beaver Creek, to which Hourglass Creek is tributary. Another site was at the City of Greeley water treatment plant reservoir at Bellevue, Colorado. Bellevue is located at the mouth of Cache la Poudre canyon, sixty miles downstream from the study area.

Initial sediment samples were taken at four sites in early August 1967. The North Flume site is 700 feet below the permanent snowfield. The Upper Flume site is near the junction

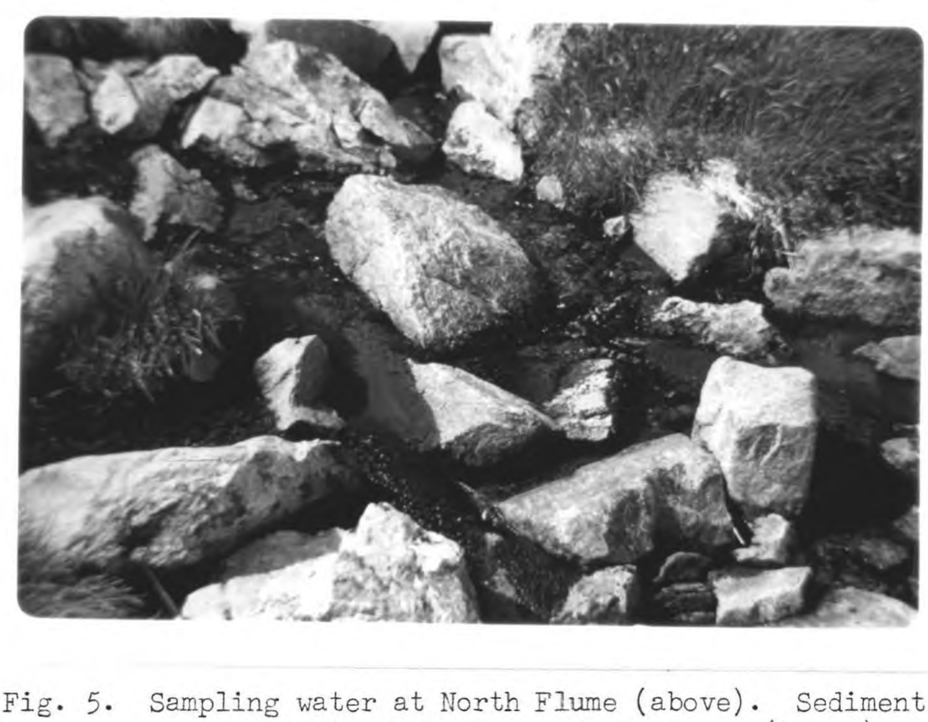

Fig. 5. Sampling water at North Flume (above). Sediment in the stream bottom near North Flume (below).

of the North and South creek forks. Samples were also taken at the Intermediate site near the major bend in the creek, and at the Lower Hourglass gaging station. At each site eighteen samples from pools, behind logs and in other areas of deposition were taken. Each sample was placed in a container and oven dried at 105°C.

Additional sampling sites were then established. The station called Snowfield was established at the headwaters. Deposits of sediment found there are associated with channels in the permanent snowfield. Two intermediate sites, Meadow and Knife, are between the North and Upper Flumes.

Pinedale III was established in the area where the stream braids through the moraine of the glacier of the same name. Five samples of bottom sediments were taken at these sites and the Beaver Falls and Bellevue sites. Thirteen additional samples were taken at Pinedale III in June 1968.

Samples of vegetation from the creek channel and its banks were taken with the sediment samples. They were classified as moss, sedge or broad-leaved plants. These were dried and analyzed for Cs-137 concentration per unit mass.

RADIOASSAY

Analysis for Cs-137 content was done by gamma-ray spectrometry. The samples in two-quart polyethylene containers were centered on a paper towel on a white wooden stand. The radiation from the samples was counted for 15 minutes by means of an 8 x 4 inch NaI(Tl) scintillation crystal beneath the stand.

The scintillations were detected by matched photomultiplier tubes connected to an RIDL 34-12 multi-channel gamma pulse height analyzer. The detector was housed in a steel-walled low background chamber.

The spectra representing gamma pulses were stored in 200 channels. The amplifier gain was such that the channels represented 10 Kev increments of absorbed gamma energy, spanning the range of 0 to 2 Mev. These spectra (Fig. 6) were presented for visual inspection on an oscilloscope tube and also punched on Hollerith cards for subsequent Cs-137 activity calculations.

Only the gamma peaks of Cs-137 and K-40 were considered in the determination of Cs-137 activities. Only the bare rock and Bellevue sediment samples contained interfering RaDEF gamma peaks. Some fallout peaks of shorter half-lived radionuclides Zr-95 + Nb-95 were present initially in vegetation and some other samples. These were allowed to decay before counting took place.

The determination of sample Cs-137 activities requires an accounting of contributions made to the photopeak by sources other than Cs-137. These include background pulses and Compton and secondary pulses made by other radionuclides. In this study K-40 was the only other radionuclide present in significant quantity.

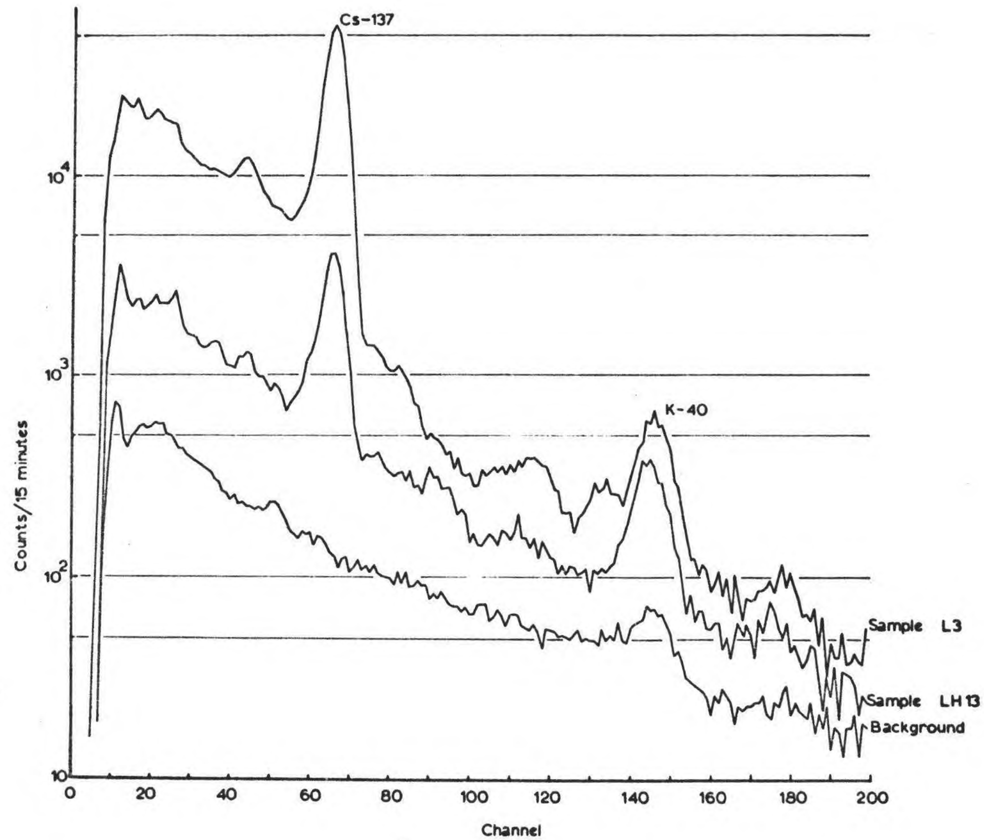

Fig. 6. Gamma-ray spectra (one channel equals 10 Kev) showing Cs-137 and K-40 photopeaks. L3 is from the permanent snowfield. LH13 is from the Lower Hourglass gaging station.

This accounting is called "spectrum stripping." It involves counting standards of known activity in the same geometry. The counts less background are summed over the channels in the photopeaks of the radionuclides of concern. The ratio of counts for a given radionuclide falling into the photopeaks of other nuclides to the counts falling into its own photopeak is calculated. Corrections for the effects of other radionuclides are made using the ratios thus determined.

For example, channels 62-70 correspond to the Cs-137 photopeak and channels 141-151 correspond to the peak of K-40. The net count rate in the Cs-137 photopeak is equal to the total count rate less background less the product of the determined ratio and the count rate in the K-40 channels.

Background counting rates were determined from a 600 or 1000 minute count taken shortly before or following a period of counting.

Cs-137 and K-40 standards were prepared by spiking water, hay and fuming nitric acid. Known activities were uniformly dispersed in these materials. Their densities spanned the range of densities of the samples, but density seemed to make little difference in the Cs-137 gamma ray detection. Therefore, the water standard (Fig. 7) was used for calculations of sample activities. Fig. 7 shows the linear relationship between detector sensitivity, picocuries per counts per minute, and sample thickness. This relationship was applied to all samples.

2210 pCi Cs-137

in

⊙ - water

⊡ - nitric acid

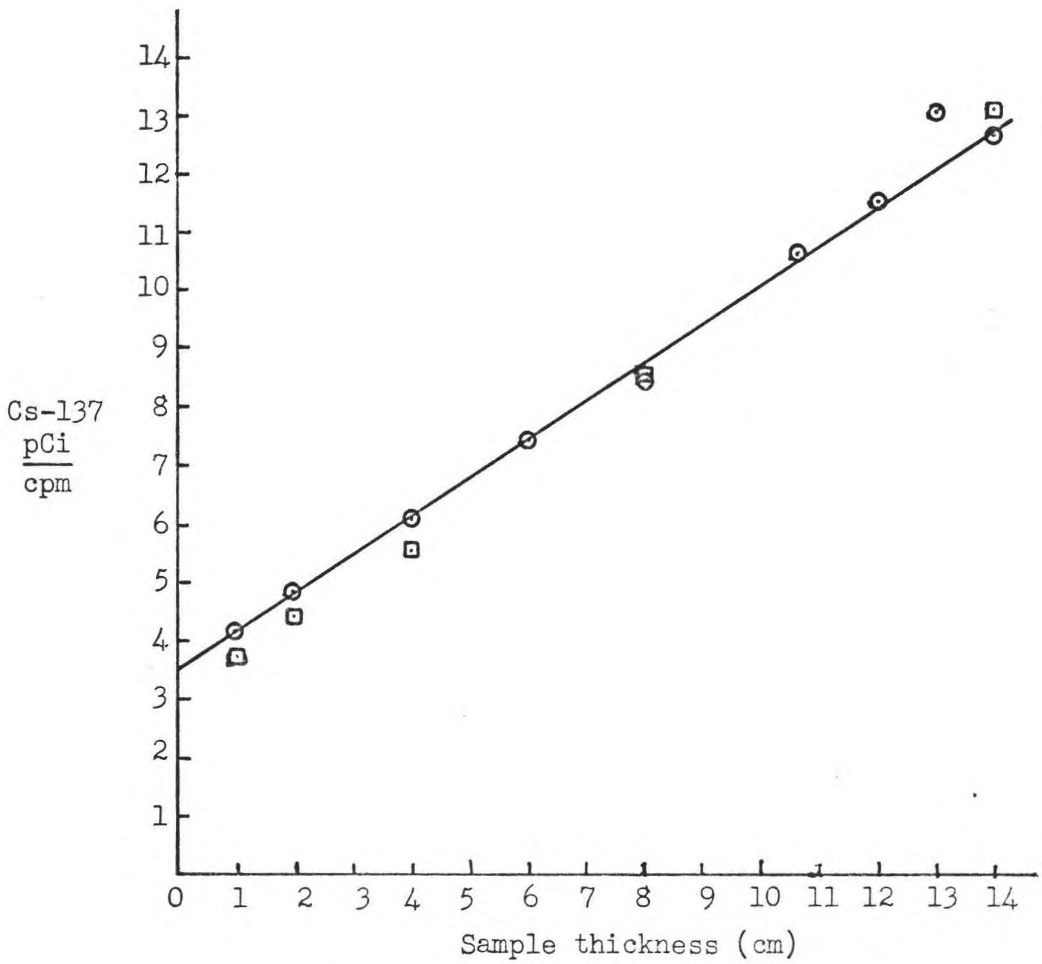

Fig. 7. Relationship of Cs-137 activity per counts detected to sample thickness.

A computer program was used to determine the true Cs-137 activities of surface, vegetation and sediment samples. The program that performs these calculations was adapted from a program written by Anthony Gallegos, Department of Radiology and Radiation Biology, Colorado State University, Fort Collins, Colorado.

OTHER MEASUREMENTS

Each of the sediment samples was divided into four portions according to particle size. This was accomplished by gently breaking the aggregates and dry-sieving for ten minutes. The sieving process resulted in separation into gravel (particles of diameter greater than 2.0 mm), coarse sand (0.25 to 2.0 mm), fine sand (0.053 to 0.25 mm), and silt+clay (diameter less than 0.053 mm).

The smaller particles have a much greater specific surface (surface area to volume ratio). This greater relative surface area favors sorption. In addition, some clay minerals, particularly vermiculite, have the property of fixing cesium and potassium ions permanently in their intercellular spacing. Silt+clay and fine sand were used as independent variables in an attempt to account for Cs-137 activities of the sediment samples.

The dry-sieving method described was checked by hydrometric analysis. They agreed when the aggregates in dry-sieving were well broken.

The divided samples from each site were then mixed together according to size fraction. Organic material was separated from these mixed samples by floatation in water. The coarse inorganic materials were washed free of organic and fine inorganic matter. These mixed samples were dried and analyzed for Cs-137 content in a manner similar to that used with the original samples.

To compare the relative activities of silt and clay in the silt+clay size fraction, sediment samples from the North Flume were dispersed and separated by hydrometric techniques. They were dried and subsequently counted for Cs-137 content.

Parsont (1967) reported the organic content of sediments is a significant factor contributing to their content of radium-226. His study was downstream from a uranium mine that acted as a point source of radium contribution to the stream.

Since Parsont found organic content significant and since high specific activities of Cs-137 were noted in organic materials in this study, percent organic determinations were run on samples taken from the Pinedale III site. The clay content of these samples was low. Therefore, the determinations of organic content were made by ignition techniques. The organic content was estimated by subtracting the percentage of ash from 100 percent.

It was expected that Cs-137 sorbed originally to organic and coarse inorganic materials would shift to fine inorganic material over time and with distance downstream. The specific activities of the former were compared to those of the latter material at each sampling site proceeding downstream to see if any trend was evident.

Some of the watershed surface samples were also broken into the size fractions described for the sediments above. These were also analyzed by gamma spectrometry for specific Cs-137 activity.

STATISTICAL ANALYSIS

Variations of watershed surface activities as related to the sample classification were tested by analysis of variance techniques. Each sample was classified with regard to snow accumulation, the soil-vegetation complex and hydrologic characteristics as indicated previously. Analyses of variance for the surface samples were prepared for each classification system including and excluding samples of bare rock surfaces.

The sampling design resulted in unequal replication. Therefore, the significance of factors and combinations of factors was appraised by Scheffe's S-test as presented by Ostle (1963). A computer program (Frayer, 1968) was utilized to perform the S-contrasts.

A standard stepwise multiple regression computer program was used to account for the activity of Cs-137 in the stream bottom sediments. The independent variables were distance, percent silt+clay and percent fine sand.

This program computes a sequence of multiple linear regression equations. At each step the variable is entered which is not already in the equation but which makes the greatest reduction in the error sums of squares. This is the variable which would have the highest partial correlation with the dependent variable after the variation associated with variables already added has been accounted for.

Another multiple regression program (Van Dyne, 1965), which computes both simple and partial correlation coefficients for all variables, was used. The partial regression coefficient for each variable is taken holding all other independent variables constant. The partial correlation matrix can be used to infer relations among variables.

CHAPTER IV

RESULTS

WATERSHED SURFACE

The mean Cs-137 activity of the surface of the alpine watershed was 265.65 nanocuries per square meter (nCi/m^2). There was considerable variation among the samples. The 95-percent confidence interval about the mean was 62.1 nCi/m^2. The mean activity is approximately 2.5 times the value calculated for Cs-137 in soils at Fort Collins, Colorado.

Each sampling point was classified in terms of its characteristics with regard to snow-accumulation, soils and vegetation, and the hydrologic nature of its surface. The distribution of these characteristics among the samples is summarized in Table 1.

Twelve of the samples were bare rock surfaces. Cs-137 activity of these rock surfaces was extremely low. Analyses of variance of the associated factors were made with the rock samples excluded to make best use of the classification system. These are presented in Table 2. Analyses of variance with the rock samples included are presented in Appendix Table B.

The analyses of variance in Table 2 revealed significant differences among the factors involved in each case. High

Table 1. Distribution of watershed surface samples with regard to factor classification.

Type of Factor	Classification	Number	Percent
Snow-accumulation	Yes	47	73
	No	17	27
	Total	64	100
Hydrologic	Surface runoff	46	72
	Micro-depression	9	14
	Micro-channel	9	14
		64	100
Soil-vegetation	Alpine Meadow	17	27
	Alpine Turf	8	12
	Alpine Bog	8	12
	Bare soil	16	25
	Bare rock	12	19
	Litter	3	5
		64	100

Table 2. Variation of Cs-137 activity of the watershed surface with descriptive factors.

A. Snow-accumulation factors

Classification	Mean
Yes	381.0 nanocuries/square meter
No	205.0 " "

Analysis of variance

Source	DF	Mean square	F	
Factors	1	354,821	15.6	**
Error	50	22,721		

B. Hydrologic factors

Classification	Mean
Surface runoff	282.1 nanocuries/square meter
Micro-depressions	402.5 " "
Micro-channels	415.6 " "

Analysis of variance

Source	DF	Mean square	F	
Factors	2	91,928	3.45	*
Error	49	26,680		

C. Soil-vegetation factors

Classification	Mean
Alpine Meadow	320.2 nanocuries/square meter
Alpine Turf	195.9 " "
Alpine Bog	493.9 " "
Bare soil	279.4 " "
Litter	462.6 " "

Analysis of variance

Source	DF	Mean square	F	
Factors	4	112,898	5.10	**
Error	47	22,118		

* Statistically significant at the 5 percent level.
** Statistically significant at the 1 percent level.

levels of Cs-137 activity were associated with snow-accumulation. The variation among soil-vegetation factors was highly significant, and significant variation was found among the hydrologic factors.

Scheffe's S-contrasts involving linear combinations of the means showed significantly higher concentrations of Cs-137 in the micro-channels and micro-depressions than in runoff areas. However, contrasts of the individual means did not reveal differences of significance between areas of differing hydrologic character.

In the soil-vegetation classification system, several Scheffe contrasts involving Alpine Bog were significant. Alpine Bog has higher Cs-137 activity than either Alpine Turf or bare soil and also higher than the combination of Alpine Meadow and Alpine Turf.

Specific activity of surface components

Some surface samples from areas of snow-accumulation were studied in terms of the specific activities of their components. Organic material was separated and inorganic material broken down according to particle size. A summary of their specific activities is shown below:

organic (spruce needle litter)	-	1,000 pCi/g
organic (Alpine Bog)	-	85 pCi/g

silt+clay	-	50 pCi/g
fine sand	-	21 pCi/g
coarse sand	-	5 pCi/g

The sample with the highest activity was a sample of organic litter located in a small depression on bare rock. The sample consisted largely of dead spruce (Picea englemanii) needles that lay on the rock beneath the snow.

STREAM-RELATED CESIUM-137 ACTIVITY

Water samples of 300 liters were taken from Hourglass Creek at the North Flume and Lower Hourglass gaging stations. The water was poured through ion exchange resin, which revealed no indication of the presence of Cs-137 when it was analyzed. Small peaks of shorter half-lived radionuclides Ru-106 and Zr-95 were noted.

Bottom sediments

Samples of bottom sediments taken from the four initial sites indicated a decreasing trend of sediment activity per unit mass as one travels downstream. After the addition of other sampling sites and sample analysis the results of the sediment activity to distance relationship are shown in Table 3 and Fig. 7.

There is an apparent exponential decrease in sediment Cs-137 activity downstream, dropping sharply from the permanent

Table 3. Cs-137 activities of bottom sediments downstream from the permanent snowfield by sampling location.

Sampling Site	Cs-137 Activity (pCi/g) Mean	Std. Error	Conf. Int. (95%)	Distance (thousands of feet)
Snowfield	124.0	7.4	20.5	0.0
North Flume	50.4	6.9	14.5	0.7
Meadow	28.4	4.2	11.8	1.8
Knife	25.3	4.3	12.0	2.8
Upper Flume	22.6	2.0	4.3	3.9
Pinedale III*	28.7	6.0	16.5	6.0
Intermediate	12.2	1.1	2.3	10.5
Lower Station	8.4	1.3	2.7	13.8
Beaver Falls	3.6	0.6	1.7	18.5
Bellevue	3.4	0.4	1.1	320.0

* If samples taken at Pinedale III in 1968 are added to the previous samples results are as follows:

	Mean	Std. Error	Conf. Int. (95%)
Pinedale III	26.1	3.8	7.9

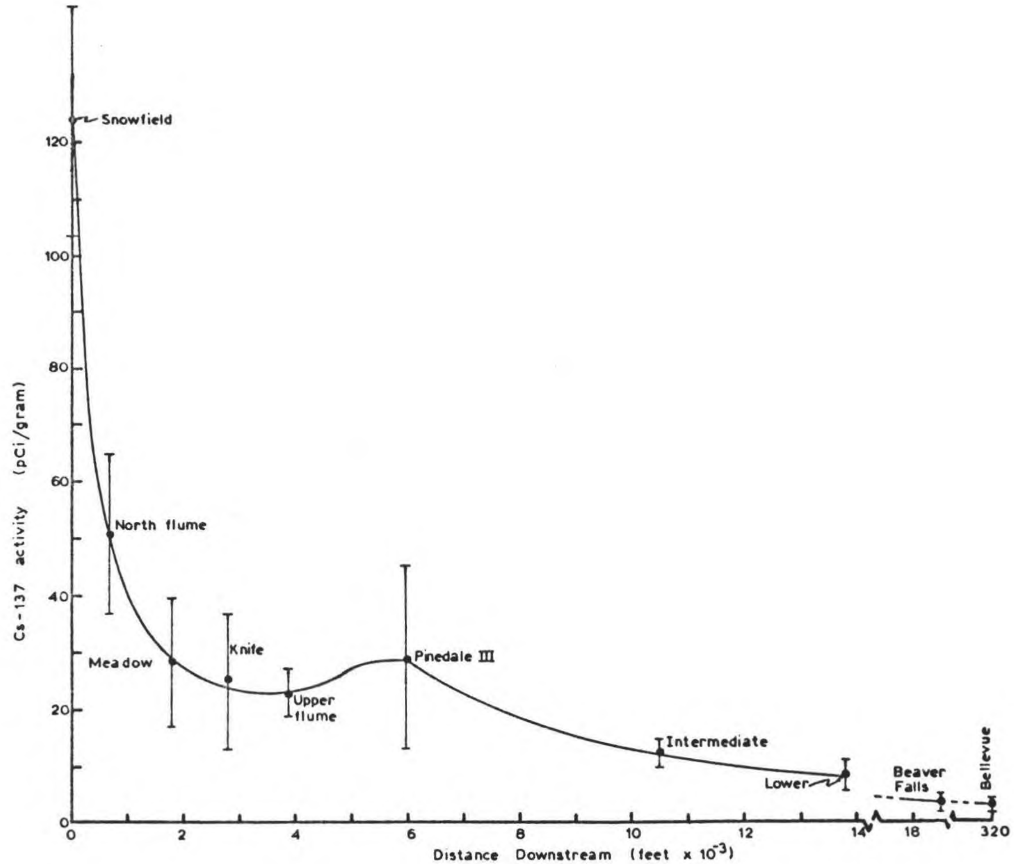

Fig. 8. Relation of Cs-137 activity in bottom sediments to distance downstream.

snowfield. Accumulation of Cs-137 is indicated in the swampy area denoted as Pinedale III. The trend of decreasing activity is continued with the succeeding downstream stations.

Values are presented for two other stations below Hourglass Creek. Beaver Falls is on Beaver Creek (Fig. 3). Bellevue is sixty miles downstream from the study area at the City of Greeley water treatment plant reservoir. The Cs-137 activity determinations were complicated by gamma emissions from radionuclides of the radium decay series, and the values presented are less reliable.

It was hypothesized that Cs-137 activity in the channel bottom sediments was a function of distance from the snowfield and a function of the percentage of fine material in the individual samples. The following multiple regression was run:

$$Y = Z + Be^{-X_1} + CX_2 + DX_3$$

where Y is Cs-137 activity in pCi/g.

X_1 is distance downstream in thousands of feet.

X_2 is percent silt+clay determined by sieving.

X_3 is percent fine sand.

Only the first independent variable (X_1) accounted for significant variation in Y. The best least-squares fit equation is:

$$Y = 13.85 + 93.35e^{-X_1}.$$

The correlation coefficient is 0.84 and the coefficient of determination is 0.71. The effect of the exponential decrease downstream therefore accounts for 71 percent of the Cs-137 activity (Appendix Fig. A).

Simple regressions run on X_2 and X_3 did yield F values that were significant. They were very small compared to that of X_1 and did not significantly enter the stepwise multiple regression (Appendix Figs. B and C).

The organic and inorganic components of the sediments also had the same trend of decreasing Cs-137 activity with distance. Their specific Cs-137 activities with relation to sampling location are presented in Table 4. The ratios of specific activities of fines to organic matter are presented also.

It was hypothesized that Cs-137 associated with organic and coarse inorganic material would be exchanged with time and distance downstream and become sorbed to silt and clay. However, as indicated in Table 4 there is no general trend in these activity ratios with distance. Several ratios among these fractions were calculated with no trends evident.

The relationship between sediment activity and organic content was studied with samples obtained at Pinedale III. The correlation coefficient obtained between the percentage of organic material and Cs-137 activity is 0.71 with 12 d.f. (Appendix Fig. D). This is significant at the one percent level.

Table 4. Cs-137 activities of components of bottom sediments downstream from the pernament snowfield by sampling location.

Sampling site	Cs-137 Activity (pCi/g)				Distance (thousands of feet)	Silt+ Clay to Organic ratio
	Organic	Silt+clay	Fine sand	Coarse sand		
Snowfield	267.6	190.5	39.6	25.5	0.0	0.71
North Flume	91.4	101.5	45.2	17.4	0.7	1.11
Meadow	69.4	68.3	14.1	6.2	1.8	0.98
Knife	56.4	50.3	16.3	4.5	2.8	0.89
Upper Flume	49.6	62.8	19.8	6.8	3.9	1.27
Pinedale III	67.5	55.7	24.2	8.9	6.0	0.83
Intermediate	28.3	27.9	10.7	3.8	10.5	0.99
Lower Station	10.4	25.4	12.6	3.2	13.8	2.43
Beaver Falls	6.6	4.7	3.0	0.7	18.5	0.71
Bellevue	5.8	4.3	2.7	1.4	320.0	0.74

Stream vegetation

Results of the measurements of Cs-137 concentrations in stream vegetation are presented in Table 5. These also show Cs-137 activity decreasing with distance. The mosses exhibit an activity relationship with distance very similar to that of the sediment means.

The mosses occur in combination with inorganic material filtered from the stream. An attempt was made to determine whether the high activity of the moss is due to the associated inorganic material or if it is in the moss itself. Water containing a dispersing agent was added to a sample from the North Flume. The sample was agitated by a sieve shaker and the inorganic portion separated from the moss.

The inorganic material had an activity of 104.4 pCi/g. The washed moss had a Cs-137 activity of 153.3 pCi/g.

Cs-137 IN SNOW

Snow samples were collected in the watershed in April 1967 to determine if fallout radiocesium was detectable in the year's snowpack. The 46 liters of meltwater produced were passed through ion-exchange resin which revealed no Cs-137 peak when analyzed. Litter associated with the snow exhibited small peaks. These were identified as the gamma peaks of cerium-144 and ruthenium-106.

Table 5. Cs-137 concentrations in stream vegetation samples, August 1967.

A. Mosses

Sampling Site	Distance Downstream	Cs-137 Activity
North Flume	700 feet	175 pCi/gram
Meadow	1,800 feet	70 pCi/gram
Knife	2,800 feet	56 pCi/gram
Upper Flume	3,900 feet	41 pCi/gram
Pinedale III	6,000 feet	46 pCi/gram
Intermediate	10,500 feet	12 pCi/gram
Lower Station	13,800 feet	22 pCi/gram

B. Sedges

Sampling Site	Distance Downstream	Cs-137 Activity
North Flume	700 feet	47 pCi/gram
Meadow	1,800 feet	9 pCi/gram

C. Broad-leaved Plants

Sampling Site	Distance Downstream	Cs-137 Activity
Upper Flume	3,900 feet	16 pCi/gram
Pinedale III	6,000 feet	18 pCi/gram
Intermediate	10,500 feet	6 pCi/gram
Lower Station	13,800 feet	11 pCi/gram

Snow samples taken in the watershed and on Chalk Mountain in winter 1968 produced 100 liters of meltwater. They also showed no evidence of Cs-137 in the winter snowpack.

CHAPTER V

DISCUSSION

INPUT TO THE WATERSHED

Osburn (1967) described the vectors transporting fallout radioactivity into an alpine watershed. He listed these in order of importance as snow, rain and dry fallout. The reasons given by Osburn for the importance of snow have been cited previously. But measurements of this likely Cs-137 input in the snowpack of 1967 and 1968 revealed little evidence of the nuclide.

Reasons for this failure to detect Cs-137 include (1) the sampling design provided samples that were too small; (2) sampling technique permitted Cs-137 to be sorbed before it reached the ion-exchange resin; and (3) there are now extremely low levels of Cs-137 in the winter snows.

Data provided by Wilson (1968) suggest that air concentrations of Cs-137 at Fort Collins decreased by a factor of approximately 25 from 1963, during Osburn's study, to 1967. The size of snow samples used should have been adequate for detection of Cs-137 even with a decrease of this magnitude. Osburn reported gross beta activities of snowmelt on the order of thousands of picocuries per liter. Sturges and Sundin reported gross beta activity of 20 pCi/liter in 1965 for snowmelt in a mountain bog in Wyoming.

This suggests that the decrease in fallout Cs-137 in snow since 1963 may be much greater than 25 times. Indeed, Osburn reported that some of the input in his study was local fallout from the Nevada test site 600 miles to the west. Except for leaks from underground tests, this latter input ceased in 1962. Neither Osburn nor Sturges and Sundin reported Cs-137 activities in their studies.

The snow samples were collected and stored in polypropylene containers. The snow was melted as rapidly as possible by use of a steam generator and the meltwater filtered through cation-exchange resin, touching only plastic materials. These materials, with the exception of the large 20-gallon containers, were examined for gamma emission and revealed no Cs-137.

Trace quantities of Cs-137 may have been sorbed to the large container or debris in the meltwater. More fallout activity (although little Cs-137) was present in the debris than in the ion exchange resin.

Evidence leads to the conclusion that the winter snow contained very low levels of Cs-137 compared to that which entered during and shortly after periods of atmospheric testing. Future sampling should provide for larger samples. Timing should be such as to take advantage of spring seasonal maxima and precipitation in the lee of high-altitude pressure troughs.

No efforts were made to measure Cs-137 associated with rain or dry fallout. However, both of these factors were associated with large inputs in 1962 and 1963 into the watershed studied by Osburn. It seems reasonable that the areas in which accumulation of snow occurred were also depositional areas for dry fallout and windblown particles contaminated by fallout in rain.

WATERSHED SURFACE

Measurements made of the alpine portion of the North Fork sub-watershed indicate that snow accumulates on 73 percent of the area. A larger portion of the South Fork sub-watershed is swept free of snow. If this had also been sampled the value of the mean surface activity might have been less. However, the mean activity of the snow-free areas sampled was twice the value calculated for Fort Collins.

The significantly higher Cs-137 activities of areas of snow accumulation may be explained by (1) the concentration of the snow perse; (2) higher deposition of tropospheric Cs-137 where turbulence deposits snow; and (3) deposition of windblown debris from the watershed surface with its associated Cs-137 activity.

Observations made in summer 1967 of the Hourglass snowfield indicate that the third factor may be of major importance in buildup of present surface activity near the snowfield.

Organic matter, including the obvious remains of sedges and hairgrass, were observed to be present in a fresh August snow. The specific Cs-137 activity of this litter was more than 100 pCi/g. Inorganic debris was present in smaller quantities.

This debris, both organic and inorganic, sinks through the snow and ice and may then be carried in meltwater channels within the snowfield to the surface or face of the snowfield (Fig. 9) at the head of the creek. The inorganic portion of the debris is mostly coarse and fine sand and may be covered with an organic film which includes the pigment of red algae identified by Osburn as Chladymonas nivalis. There is a question as to whether the sand is derived from wind erosion or hydraulic scouring beneath the snowfield.

Much of the debris precipitates onto vegetation and soil below the snow when melting occurs. It may remain there or be carried into micro-depressions or micro-channels on the surface. Small piles of matted debris are subject to movement by wind or by surface runoff associated with meltwater or intense rainstorms.

Fig. 9. Debris and channel at the face of the permanent snowfield.

Soils and vegetation

The vegetation and ground cover types and densities agree with values reported by Livingston (1966). He surveyed an area in the South Fork sub-watershed in Alpine Turf near Comanche Peak. Alpine Turf occurred mostly on the slopes above the cirque. Alpine Meadow occurred above and within the cirque but most commonly on the side of the cirque. Alpine Bog occurred below late-lying snow, in depressions, and near the stream.

Data revealed that Alpine Bog had significantly higher Cs-137 activity than bare soil and Alpine Meadow and Alpine Turf. All of the Alpine Bog samples were taken at areas covered with snow in early July. One could observe when these areas emerged that the debris from the snow is trapped by the fast-growing sedges and other plants in these areas. Osburn (1963) spoke of this filtering effect in describing the Carex scopulorum "sedge mats" downhill from snowbanks.

The Alpine Bog, Alpine Meadow and Alpine Turf classifications in this study appear to be more general but comparable to the respective Carex scopulorum, Deschampsia caespitosa and Kobresia myosuroides plant communities described by Osburn (1967).

The high activities of the litter on bare rock have been noted. Each of these samples was also in an area of major snow-accumulation. They contained dead spruce needles through which several seasons of snowmelt had apparently filtered. The litter was trapped by adjacent shrubs or rock. These litter samples had the highest specific activities of any samples in the study. Living needles on snow-covered spruce shrubs had little trace of Cs-137.

The bare soil was generally more than 50 percent gravel. The organic content of the bare soil was almost zero. The Cs-137 activity was mostly in the fine sand and silt+clay fractions and is explained by the higher specific surface of fine particles.

The specific surface of a particle is the ratio of its surface area to its volume or mass. If one considers the particle as a sphere, the specific surface is proportional to the reciprocal of the particle radius. For example, a particle of clay of radius 0.001 mm has a specific surface 1,000 times as great as a particle of gravel with a radius of 1.0 mm. Therefore, the finer material has 1,000 times more surface area available for sorption on the basis of equal mass or volume.

Surface hydrology

The significantly higher activity in micro-depressions and micro-channels than in surface runoff areas indicates that Cs-137 distribution on the watershed is associated with hydrologic concentration processes. The micro-channels filter and retain Cs-137 as their streams pass and infiltrate the coarse soil and voids in shattered rock. Micro-depressions are a sink for radioactive debris. The micro-hotspots observed by Osburn were in depressions. These may have exceptionally high activities when large portions of their drainage is bare rock on which run-off easily transports radioactive debris.

In many similar alpine situations in the Rocky Mountains large depressions are filled by bogs and cirque lakes. The concentration of highly active debris in these areas is a large scale duplication of the processes observed in the micro-depressions. The Cs-137 activities in a depression would be a function of the accumulation of activity in the drainage and the processes acting to transport the radionuclide into the depression. Some cirque lakes are directly below large snowfields and debris is washed easily over bare rock outcrops into the lakes. Nelson and Whicker (1967) observed high Cs-137 levels in fish obtained from lakes such as these.

One deterrent to the hydrologic method of classification is the changing character of the alpine surface. The climate is optimum for various forms of frost action. Large variations in temperature result in cycles of freezing and thawing on a daily basis. Frost heaving lifts the soil surface. When it occurs on steep slopes frost action results in mass wasting. The action of burrowing animals also disturbs the surface.

It was quite difficult to find the original sampling sites because of changes in vegetation and the surface when the area was revisited in October 1967. However, the classification of the hydrologic surface of sample C-439 was the only one that changed. It was classified as a micro-channel originally, but frost heaving at the site had made it an area of surface runoff.

STREAM-RELATED CESIUM-137 ACTIVITY

Results of the measurement of Cs-137 in the stream water were negative. This is understandable in terms of the high distribution coefficient obtained for cesium in fresh water by Baker _et al_. (1966). There was very little suspended sediment evident in the filters or exchange resin through which the water was passed. The decreasing rate of fallout input and the filtering effect of snowfield debris and the watershed surface have previously been discussed.

Cs-137 in sediments

Since there is no measurable Cs-137 in the water, the mode of transport from the watershed is with suspended and bed-load sediment. Stream sediment includes both organic and inorganic materials and was measured as bottom sediment in areas of deposition.

The mean sediment activity decreases exponentially from the headwaters downstream (Fig. 8). An area of Cs-137 accumulation is shown on the figure with a second decrease downstream from that point. The relationship between distance and the sediment Cs-137 means is also observed in vegetation and components of the sediment. Cs-137 in moss, silt+clay, organic sediment, and gross sediment means are plotted against distance in Fig. 10.

Parsont (1967), who studied radium-226 concentrations downstream from a uranium mine, also reported an exponential decrease of specific activity of that nuclide in sediment.

Parsont suggested that the strong negative correlation between the specific activity of sediment Ra-226 and distance downstream from the mine is due to increased stream velocity. Evidently increased velocity downstream would result in more scouring of radioactive bottom materials reducing the Ra-226 concentrations of the sediment. However, with the exception of an extreme flood in June 1965, Parsont observed a lack of movement of sediment Ra-226 downstream even during periods of high flow.

Velocities of Hourglass Creek were measured using concentrated injections of Rhodamine WT dye. The stream velocity was surprisingly low (1.5 ft/sec) and relatively constant over several segments of the stream.

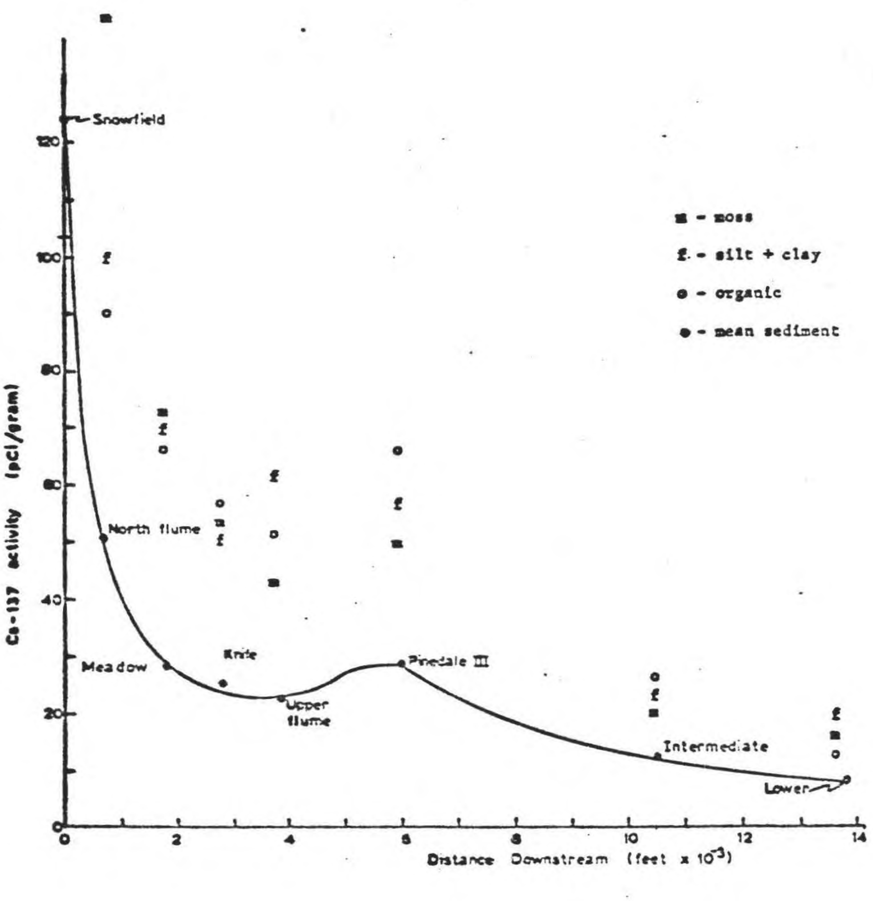

Fig. 10. Relationship of the specific Cs-137 activity of moss, silt+clay, organic fraction and sediment means to distance downstream in Hourglass Creek.

This suggests that the exponential decrease in Cs-137 activities in the sediment may be explained in terms of dilution of highly active sediments from a point source. The point source is the area represented by the permanent snowfield at the stream headwaters.

Dilution of the highly active sediment may be considered in two ways. One view considers that these highly active sediments enter the stream directly as debris from the snowfield. As they pass downstream these sediments mix with less active sediments that are entering from areas of lower source activity. This may be by surface runoff, wind erosion and transport by other streams.

A second view suggests that movement of Cs-137 sediment from the source downstream is occurring very slowly. Dilution is by sediment that moved previously by similar means through the watershed before the large-scale occurrence of fallout Cs-137.

It suggests that small quantities of highly active material move as suspended sediment mostly with the annual high flows associated with the snowmelt period. Kunkle and Meiman (1967) found suspended sediment to be correlated with rate of flow. But they also observed extremely low concentrations of suspended sediment in Hourglass Creek.

The second view is more important within the Hourglass basin than in the large Little South Fork drainage which includes

Hourglass Creek. There is little evidence of sediment transport by surface runoff as Hourglass Creek passes through the forest. Most water from the forest to the stream is subsurface in nature.

The only major channel entering the system is the South Fork of Hourglass Creek. This also has a permanent snowfield at its headwaters. The entrance of an intermittent stream near Pinedale III may account for variation of activity with sampling sites at that location. Gorham (1963) noted that coniferous forests tend to retain their radioactivity in litter and living organic systems.

The sharp rate of decrease tends also to favor the view that Cs-137 transport is occurring with sediment and very slowly. It would require large quantities of sediment from sources other than the main channel to account for the rate of decreasing activity with distance.

The stream originates on igneous and metamorphic rock. It was expected therefore that if clay were present it would contain vermiculite and illitic type clay minerals. These can irreversibly fix cesium such that the Cs-137 sorbed would be greater than would be expected in equilibria based on the larger specific surface of clay-sized minerals alone. Porcella and Friend (1966) found removal of Cs-137 from stream waters near nuclear processing plants was accomplished rapidly and irreversibly by these clay minerals.

However, data from this study suggest that specific irreversible fixation is not important when dealing with trace concentrations of fallout Cs-137. The high distribution coefficients and the lack of competing cations in the aqueous system lead the author to believe that once Cs-137 is sorbed to organic or inorganic material of any size it tends to stay there.

The original location of the sorbing surface with respect to opportunity for Cs-137 sorption appears to be the most important requisite for high Cs-137 activities in earth materials. The higher specific activity of finer inorganic particles can be explained in terms of increased specific surface available for sorption. The high specific activity of organic materials is related to their high cation exchange capacities.

The percentage of silt+clay was highest at the North Flume site in the cirque. This value is higher than those observed in sediments at Pinedale III and Bellevue where deposition of fine materials was expected. The high fraction of fines 700 feet below the permanent snowfield may be a measure of wind erosion in the alpine. Healy and Fuquay (1958) indicate that silt and fine sand are most susceptible in terms of particles size to wind pickup. The dynamic processes which favor snow-accumulation in the cirque would also favor the deposition of windblown earth materials.

Figs. 8 and 10 indicate that Cs-137 activity is accumulating in the region represented by Pinedale III. Meadows and swampy areas are present in this area, and the stream is braided and often appears to flow beneath the surface. There is high variability among sampling sites in this region.

Percent organic content of samples taken at Pinedale III gave a significant correlation coefficient with specific Cs-137 activity. Percent silt+clay and percent fine sand were also significantly correlated to Cs-137 activity when simple correlations were run, but only the exponential relation with distance was significant in the multiple regression performed.

The observation that Cs-137 is not specifically fixed, although highly sorbed, to organic and inorganic matter suggests its availability to benthic organisms in streams and lakes. This availability for uptake and concentration in aquatic food chains may lead to high concentrations in consumers (Nelson and Whicker, 1967).

Streams originating in permanent snowfields do not contribute the majority of flow within the Poudre River basin. Highly active sediment from streams like Hourglass Creek may become diluted in low elevation reservoirs such as Bellevue. However, the occurrence of extreme flows in similar basins, particularly where a high percentage of water is of glacial origin, may redistribute long lived radionuclides like Cs-137 into areas of accumulation at low elevation.

CHAPTER VI

SUMMARY AND CONCLUSIONS

A study of cesium-137 in Hourglass Creek watershed was conducted in 1967 and 1968. Inputs of fallout Cs-137 to the alpine watershed were measured in the winter snowpack. Distribution of Cs-137 on the watershed surface was measured. Surface activities were related to snow-accumulation, soil-vegetation, and hydrologic surface characteristics.

Levels of Cs-137 presently entering the watershed are low compared to inputs received during and shortly after periods of major atmospheric testing of nuclear weapons. High levels of Cs-137 are present in a snowfield considered permanent with respect to the period of worldwide fallout.

Cs-137 concentrations on the watershed surface are high compared to other regions. High concentrations occur in areas of snow-accumulation and in Alpine Bog soils. Levels are high in areas of hydrologic concentration such as micro-channels and micro-depressions.

Redistribution of Cs-137 in the watershed is associated with wind transport and deposition. Cs-137 in aqueous systems is strongly sorbed to earth materials, especially to fine inorganic and in organic materials.

Distribution subsequent to snowmelt is by hydrologic processes. Much debris with high Cs-137 activity is trapped by the vegetated surface or carried into depressions. Debris with high specific activity enters the stream channel directly at the permanent snowfield. Other debris enters with runoff and wind transport.

Cesium-137 is leaving the watershed sorbed to sediments. Concentration of Cs-137 in the stream water is extremely low because of the high distribution coefficient for cesium and the lack of competing cations.

The specific activity of sediment Cs-137 decreases exponentially with distance downstream. This is because of dilution with sediment from less radioactive sources and because the rate of sediment discharge in the channel is low. Sediment Cs-137 is accumulating in a depositional area associated with the moraine of an advance of a former mountain glacier.

The relationship of sediment activity with distance is similar to that of moss obtained from the stream channel. There is a simple correlation between silt+clay, fine sand, and organic percentages and sediment Cs-137 activity. But these are not significant when considered after the effect of exponential decrease of Cs-137 activity with distance.

SUGGESTIONS FOR FUTURE RESEARCH

A model for cesium-137 transport and distribution in an alpine watershed was presented in the introductory chapter. A series of measurements taken over time of inputs, outputs, and compartmental contents in this watershed would provide rate constants representing transfers in the system. Utilizing measurements of compartmental contents and the rate constants, one could make predictions concerning Cs-137 distribution in other watersheds or in time of greater fallout radioactivity. This would be of use for purposes of public health and ecological study.

The high levels of fallout Cs-137 in the permanent snowfield debris suggest that large quantities of Cs-137 are stored in glaciers and similar snowfields. This is available for release if melting occurs. Studies are now underway which involve harvesting high mountain snowfields to increase the yield of water and alter the time of its delivery.

The snowfield studied in this project is presently scheduled for snowmelt acceleration treatment (Megahan, 1968). Treatment involves spraying a long chain alcohol-blackening mixture on the snowfield from a helicopter. The blackening increases absorption of solar energy and alcohol reduces evaporation. The time of treatment is presently dependent upon calibration of streamflow.

It would be useful to study the redistribution of Cs-137 associated with the melt and the greater streamflow resulting from this treatment. Transport to lower elevation lakes of Cs-137 now stored in the snowfield and stream channel would introduce it into the food chain in these waters.

Concentration of radiocesium in the food web in high mountain lakes is presently being studied (Nelson and Whicker, 1967). High levels of activity observed in plants and sediments near the headwaters of Hourglass Creek suggest studies in aquatic stream ecology. Studies could be made at several sites along the stream and related to the decreased Cs-137 concentration downstream.

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Table A. Activity of cesium-137 in watershed surface samples.

Sample Ident.	Location (feet)	Elev. (feet)	Classification			Activity (nCi/m^2)
			Snow	Hydrologic	Soil-Vegetation	
C-115	60	10,940	Yes	Surface runoff	Alpine Meadow	273.1
C-132	128	10,930	No	Surface runoff	Alpine Turf	150.5
C-133	132	10,930	No	Micro-depression	Alpine Turf	122.9
C-137	148	10,920	No	Surface runoff	Alpine Turf	193.5
C-228	312	10,910	No	Surface runoff	Alpine Meadow	463.1
C-233	332	10,910	No	Surface runoff	Alpine Meadow	129.9
C-238	352	10,905	No	Surface runoff	Alpine Meadow	105.5
C-241	364	10,905	No	Micro-depression	Bare Soil	388.6
C-300	400	10,900	No	Surface runoff	Bare Soil	257.4
C-302	408	10,890	No	Surface runoff	Alpine Meadow	226.2
C-306	424	10,880	Yes	Micro-channel	Bare Soil	294.6
C-318	472	10,870	Yes	Surface runoff	Alpine Meadow	363.7
C-401	604	10,860	Yes	Surface runoff	Alpine Meadow	514.4
C-414	656	10,840	Yes	Surface runoff	Bare Soil	327.6
C-439	756	10,815	Yes	Micro-channel	Bare Soil	459.4
C-449	796	10,800	Yes	Surface runoff	Bare Soil	486.9
C-510	840	10,790	Yes	Surface runoff	Bare Soil	245.7
C-521	884	10,780	Yes	Surface runoff	Alpine Meadow	536.9
C-526	904	10,775	Yes	Micro-depression	Alpine Meadow	398.5
C-543	972	10,770	Yes	Micro-channel	Alpine Meadow	507.4
C-612	1048	10,760	Yes	Micro-depression	Alpine Bog	850.1

Table A. (Continued)

Sample Ident.	Location (feet)	Elev. (feet)	Classification			Activity (nCi/m²)
			Snow	Hydrologic	Soil-Vegetation	
C-628	1112	10,770	Yes	Surface runoff	Alpine Bog	430.2
C-639	1156	10,780	Yes	Surface runoff	Surface Litter	540.7
C-641	1164	10,780	Yes	Surface runoff	Surface Litter	255.0
C-725	1300	10,770	Yes	Surface runoff	Alpine Bog	437.9
C-729	1346	10,775	Yes	Surface runoff	Alpine Bog	299.7
C-739	1356	10,785	Yes	Surface runoff	Bare Rock	26.0
C-741	1364	10,790	Yes	Surface runoff	Alpine Bog	497.0
C-809	1436	10,810	Yes	Surface runoff	Bare Rock	14.9
C-813	1452	10,810	Yes	Micro-depression	Surface Litter	592.2
C-844	1576	10,820	Yes	Surface runoff	Alpine Meadow	343.5
C-845	1580	10,820	Yes	Surface runoff	Alpine Meadow	391.8
A-107	28	11,700	No	Surface runoff	Alpine Turf	249.7
A-123	92	11,660	No	Micro-depression	Alpine Turf	280.2
A-136	144	11,640	No	Surface runoff	Alpine Turf	195.3
A-159	236	11,630	No	Surface runoff	Bare Soil	166.4
A-233	532	11,560	No	Surface runoff	Alpine Meadow	123.5
A-246	584	11,550	No	Surface runoff	Bare Soil	107.0
A-279	716	11,530	No	Surface runoff	Alpine Turf	162.9
A-284	736	11,520	No	Micro-channel	Bare Soil	161.9
A-308	832	11,480	Yes	Surface runoff	Alpine Meadow	109.4
A-330	920	11,540	Yes	Surface runoff	Bare Soil	160.2

Table A. (Continued)

Sample Ident.	Location (feet)	Elev. (feet)	Classification			Activity (nCi/m^2)
			Snow	Hydrologic	Soil-Vegetation	
A-357	1028	11,400	Yes	Surface runoff	Bare Soil	119.3
A-365	1060	11,360	Yes	Surface runoff	Bare Soil	222.4
A-409	1236	11,300	Yes	Surface runoff	Bare Rock	13.2
A-418	1272	11,280	Yes	Micro-depression	Bare Soil	248.9
A-432	1328	11,240	Yes	Surface runoff	Bare Rock	9.9
A-496	1584	11,140	Yes	Micro-channel	Bare Soil	615.8
A-501	1604	11,120	Yes	Micro-depression	Bare Soil	208.9
A-536	1744	11,080	Yes	Surface runoff	Bare Rock	20.4
A-537	1748	11,075	Yes	Surface runoff	Bare Rock	15.7
A-578	1912	11,040	Yes	Micro-channel	Alpine Bog	674.3
A-600	2000	11,030	Yes	Surface runoff	Bare Rock	13.9
A-616	2064	10,980	Yes	Surface runoff	Bare Rock	19.5
A-691	2364	10,900	Yes	Surface runoff	Bare Rock	12.3
A-699	2396	10,880	Yes	Surface runoff	Bare Rock	5.6
A-736	2544	10,860	Yes	Surface runoff	Bare Rock	13.3
A-749	2596	10,850	Yes	Surface runoff	Alpine Meadow	416.1
A-773	2692	10,840	Yes	Surface runoff	Alpine Meadow	155.1
A-786	2744	10,830	Yes	Micro-channel	Alpine Meadow	381.6
A-861	3044	10,780	Yes	Microdepression	Alpine Bog	532.0
A-886	3144	10,760	Yes	Surface runoff	Alpine Turf	212.6
A-889	3156	10,760	Yes	Micro-channel	Bare Rock	17.9
A-892	3168	10,750	Yes	Micro-channel	Alpine Bog	229.7

* Locations on C-transect proceeding southeast.
Locations on A-transect proceeding northeast.

Table B. Analyses of variance of surface activities if bare rock samples are included.

I. Snow Accumulation

Classification	Mean
Yes	287.6
No	204.9

Source	D.F.	M.S.	F	
Treatments	1	85,366	2.27	Not significant
Error	62	37,622		

II. Soil-Vegetation Factors

Classification	Mean
Alpine Meadow	320.2
Alpine Turf	195.9
Alpine Bog	493.9
Bare Soil	279.4
Bare Rock	15.3
Litter	462.6

Source	D.F.	M.S.	F	
Treatments	5	275,620	15.37	Highly significant
Error	58	17,929		

III. Hydrologic Factors

Classification	Mean
Surface Runoff	218.3
Micro-depressions	402.5
Micro-channels	371.4

Source	D.F.	M.S.	F	
Treatments	2	186,210	5.55	Highly significant
Error	61	33,533		

Table C. S-contrasts involving linear combinations of arithmetic means of surface activities.

I. Soil-Vegetation Factors (4 and 47 degrees of freedom)

Contrast	F	
Alpine Meadow vs. Alpine Turf	0.95	NS
Alpine Meadow vs. Alpine Bog	1.85	NS
Alpine Meadow vs. Bare Soil	1.55	NS
Alpine Meadow vs. Litter	0.58	NS
Alpine Turf vs. Alpine Bog	4.01	*
Alpine Turf vs. Bare Soil	0.42	NS
Alpine Turf vs. Litter	1.75	NS
Alpine Bog vs. Bare Soil	2.77	*
Alpine Bog vs. Litter	0.02	NS
Bare Soil vs. Litter	0.96	*
Alpine Bog vs. Alp. Mead. & Alp. Turf	3.67	*
Alpine Bog, Meadow & Turf vs. Bare Soil	0.38	NS

II. Hydrologic Factors (2 and 49 degrees of freedom)

Contrast	F	
Surface Runoff vs. Micro-depressions	1.94	NS
Surface Runoff vs. Micro-channels	2.17	NS
Micro-channels vs. Micro-depressions	0.01	NS
Micro-channels & depressions vs. SRO	3.44	*

NS Not statistically significant.
* Significant at the 5 percent level.

Table D. Specific activity of Cs-137 and particle size distribution in stream bottom sediments.

Sample Ident.	Particle Size Distribution (expressed in percent) Gravel	Coarse Sand	Fine Sand	Silt-clay	Specific Activity (pCi/g)
SL01	1	53	35	11	135.0
SL02	2	36	53	9	105.5
SL03	7	45	39	9	146.5
SL04	2	61	33	4	117.5
SL05	1	43	46	10	115.5
NF01	10	19	45	27	56.9
NF02	16	16	47	22	82.4
NF03	2	39	44	14	43.5
NF04	18	29	36	17	53.8
NF05	10	38	37	15	53.5
NF06	25	24	30	21	98.2
NF07	28	44	22	55	17.1
NF08	3	36	43	18	103.6
NF09	7	41	38	14	41.0
NF10	1	22	63	14	11.1
NF11	1	12	67	20	78.6
NF12	21	29	34	16	42.0
NF13	15	32	38	15	71.5
NF14	16	41	30	13	17.6
NF15	25	20	35	20	8.9
NF16	18	37	32	13	21.6
NF17	6	30	49	15	37.0
NF18	1	16	68	15	68.8
M01	7	48	36	8	43.6
M02	4	61	30	6	22.5
M03	12	48	32	8	26.3
M04	12	49	35	4	19.2
M05	2	62	28	8	30.4
K01	18	40	32	10	21.0
K02	11	45	36	8	16.9

Table D. (Continued)

Sample Ident.	Particle Size Distribution (expressed in percent) Gravel	Coarse Sand	Fine Sand	Silt-clay	Specific Activity (pCi/g)
K03	1	33	56	11	36.0
K04	4	36	53	7	35.5
K05	19	45	25	11	17.0
U01	7	56	31	6	21.3
U02	8	64	25	3	15.3
U03	11	36	44	9	32.3
U04	5	65	25	5	15.9
U05	7	66	23	4	15.1
U06	9	55	27	9	30.4
U07	4	66	23	7	30.1
U08	7	56	30	6	24.4
U09	7	52	32	9	34.5
U10	6	67	23	4	21.4
U11	17	41	32	10	8.1
U12	16	44	32	9	10.8
U13	1	23	64	12	39.1
U14	11	61	24	4	19.3
U15	10	67	19	4	20.4
U16	10	57	28	5	23.9
U17	9	54	27	10	29.2
U18	7	68	22	4	15.1
P01	1	29	54	16	46.0
P02	1	67	26	6	18.8
P03	1	29	59	11	40.1
P04	3	61	29	7	17.7
P05	4	63	27	6	20.9
I01	31	41	20	8	5.7
I02	4	57	32	7	7.2
I03	0	29	57	14	15.1
I04	0	24	62	14	13.9
I05	0	49	42	9	9.0

Table D. (Continued)

Sample Ident.	Particle Size Distribution (expressed in percent) Gravel	Coarse Sand	Fine Sand	Silt-clay	Specific Activity (pCi/g)
I06	6	22	55	17	19.1
I07	3	52	37	8	9.9
I08	2	65	29	5	6.0
I09	4	19	55	23	20.2
I10	4	28	56	18	11.2
I11	7	23	56	15	14.1
I12	11	45	38	7	11.9
I13	18	46	29	7	10.6
I14	16	33	41	11	14.9
I15	11	14	58	18	21.8
I16	16	24	51	8	8.7
I17	7	41	45	7	10.0
I18	18	32	43	7	10.4
LH01	2	83	13	2	3.9
LH02	3	80	14	3	4.4
LH03	18	55	24	4	5.8
LH04	7	48	40	5	9.0
LH05	13	54	24	8	14.3
LH06	9	60	24	6	9.6
LH07	2	44	41	14	15.2
LH08	23	62	12	2	4.5
LH09	16	47	30	8	8.2
LH10	8	60	26	6	8.8
LH11	12	24	50	14	15.0
LH12	9	49	31	11	16.7
LH13	8	46	31	15	18.6
LH14	6	68	24	2	6.3
LH15	57	37	5	1	1.6
LH16	50	49	1	1	1.6
LH17	22	71	7	1	2.4
LH18	29	62	7	2	4.7

Table D. (Continued)

Sample Ident.	Particle Size Distribution (expressed in percent) Gravel	Coarse Sand	Fine Sand	Silt-clay	Specific Activity (pCi/g)
BF01	2	74	19	5	1.4
BF02	1	26	55	18	4.0
BF03	1	14	61	25	4.9
BF04	2	16	50	31	4.3
BF05	2	39	42	16	3.5
B01	8	41	44	7	3.4
B02	3	18	72	8	4.0
B03	1	11	69	19	4.4
B04	1	19	74	7	2.7
B05	4	20	69	7	2.3

* Symbols for sampling sites are as follows:

SL - - - Snowfield

NF - - - North Flume

M - - - Meadow

K - - - Knife

U - - - Upper Flume

P - - - Pinedale III

I - - - Intermediate

LH - - - Lower Hourglass Gaging Station

BF - - - Beaver Falls

B - - - Bellevue

Table E. Specific activity of Cs-137 and percent organic content of bottom sediments from Pinedale III.

Sample Ident.	Percent Organic Content	Specific Activity (pCi/g)
6	13.7	17.4
7	16.9	9.2
8	4.8	14.4
9	3.2	7.6
10	5.5	15.8
11	9.5	13.5
12	5.0	8.4
13	19.7	54.2
14	17.0	50.3
15	17.8	46.7
16	16.8	36.4
17	13.0	36.9
18	15.4	15.0

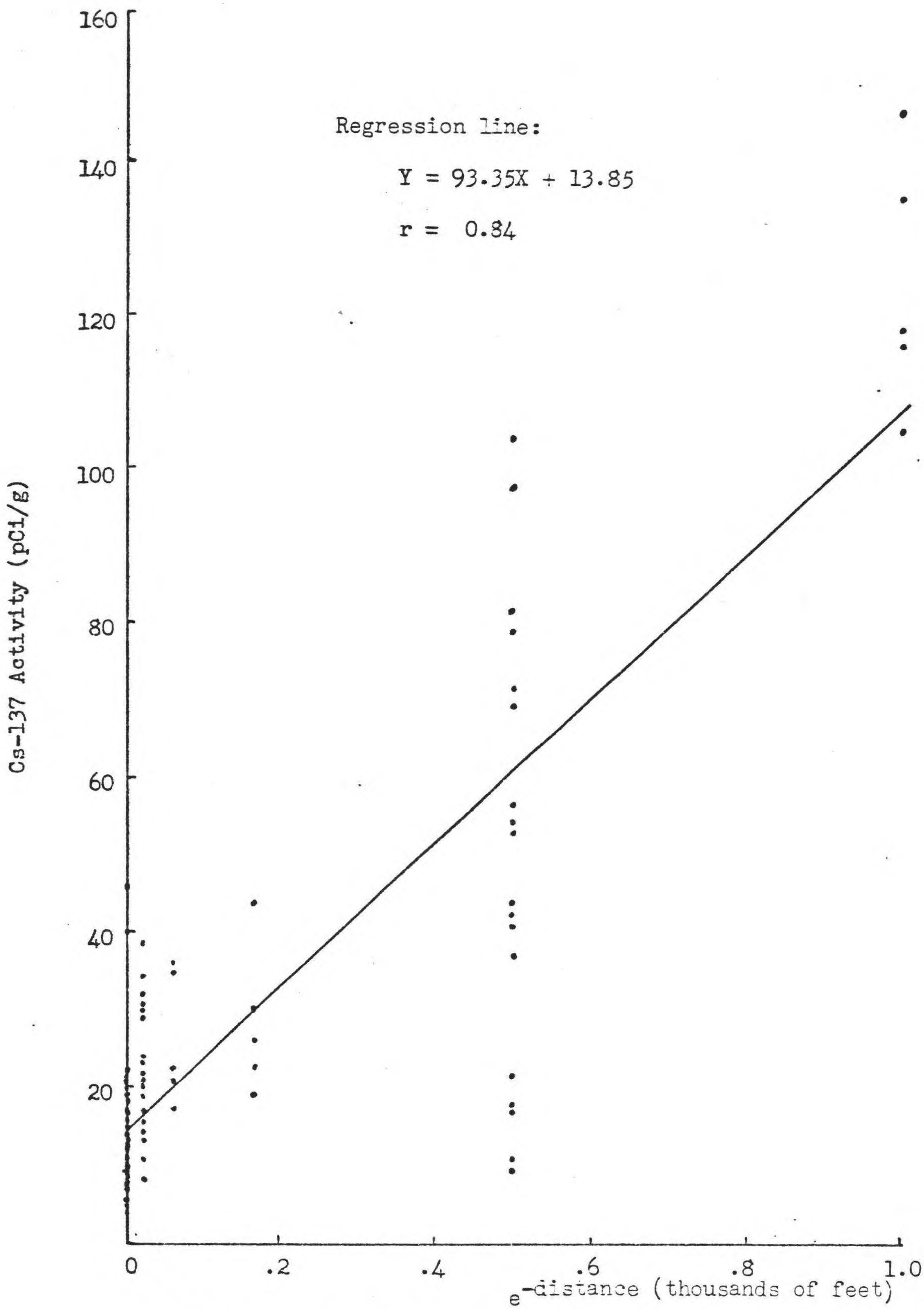

Fig. A. Specific Cs-137 activity of Hourglass Creek sediment vs. the negative exponential function of distance downstream.

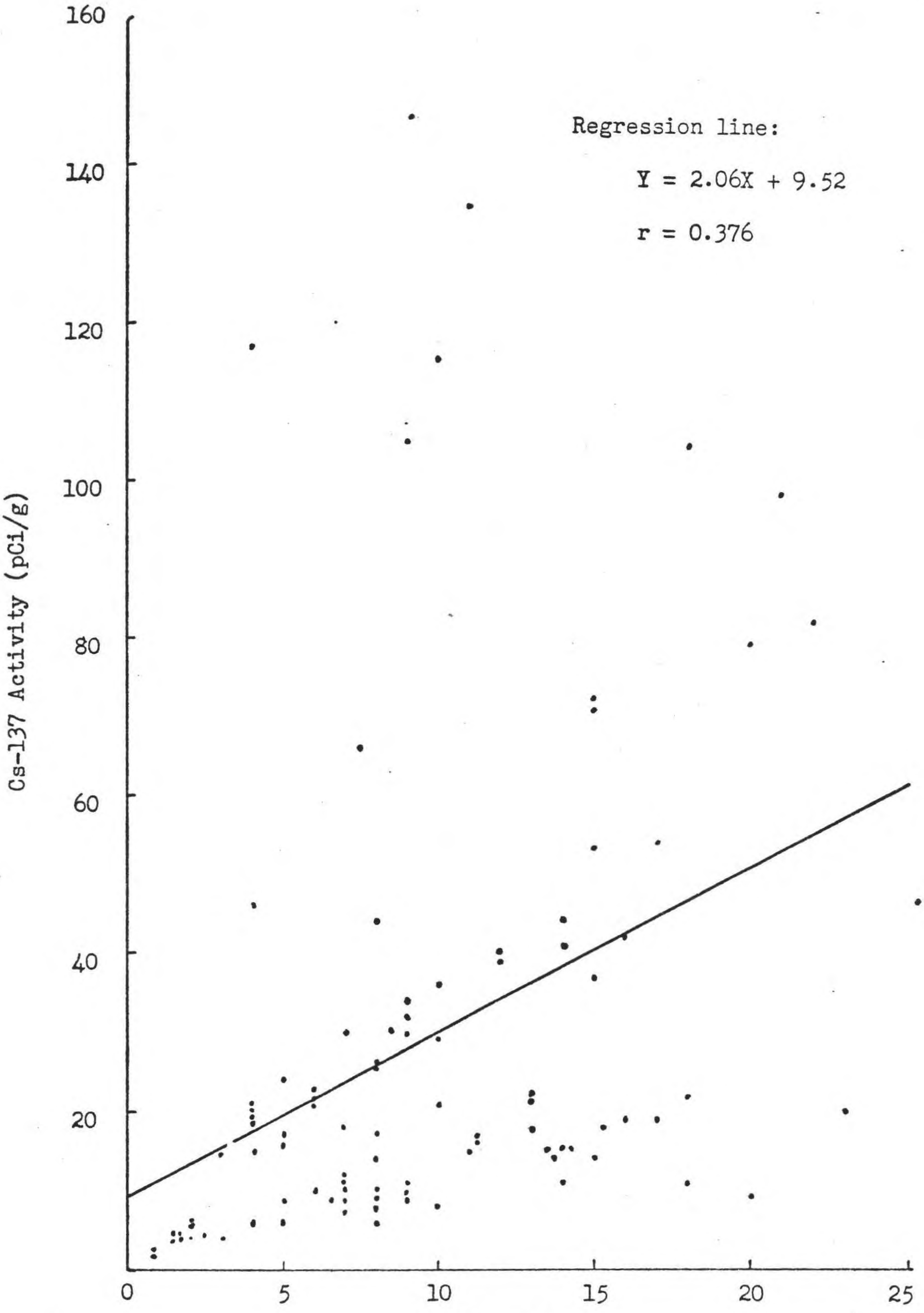

Fig. B. Specific Cs-137 activity of Hourglass Creek sediment vs. percent silt+clay.

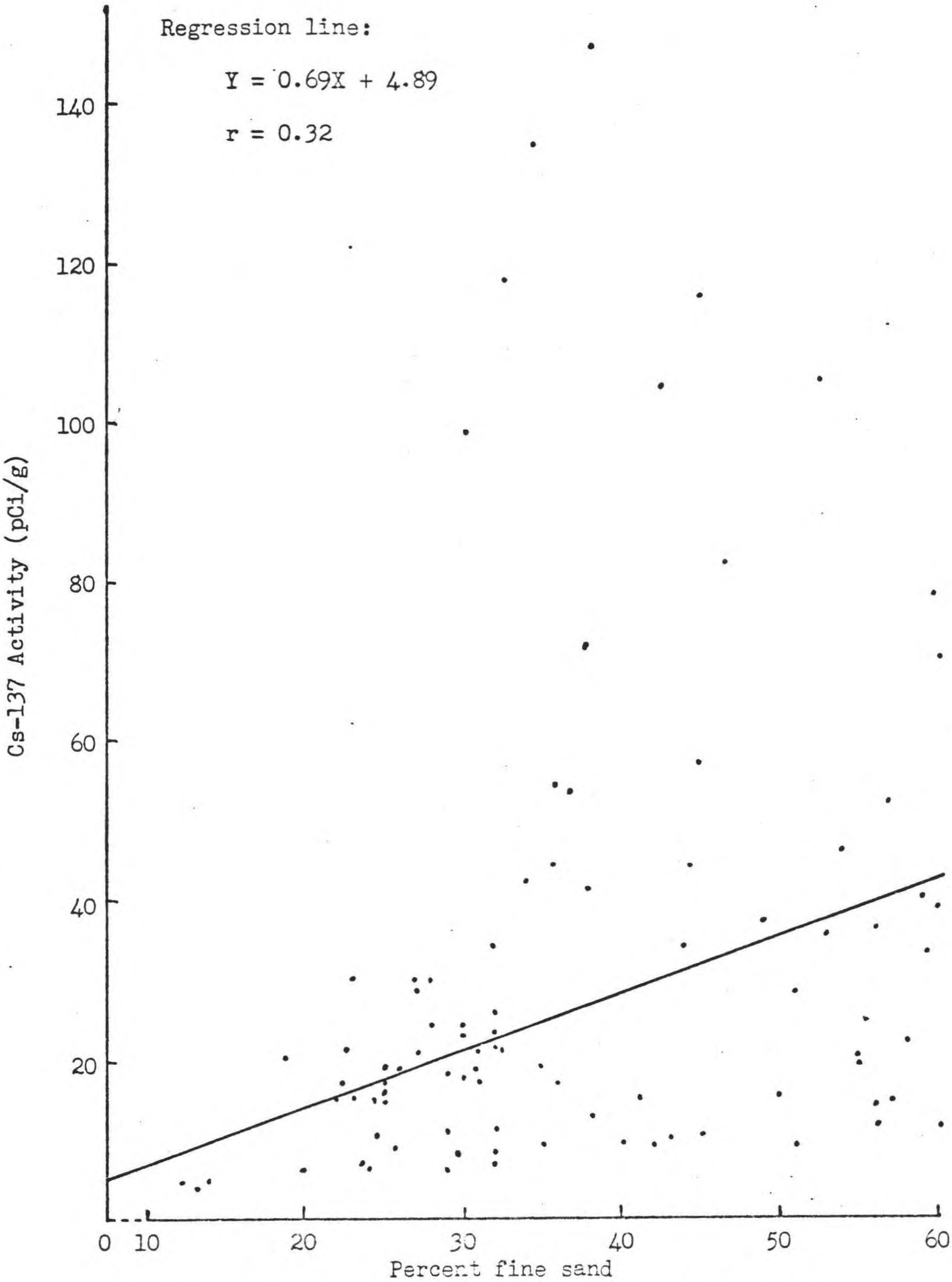

Fig. C. Specific Cs-137 activity of Hourglass Creek sediment vs. percent fine sand.

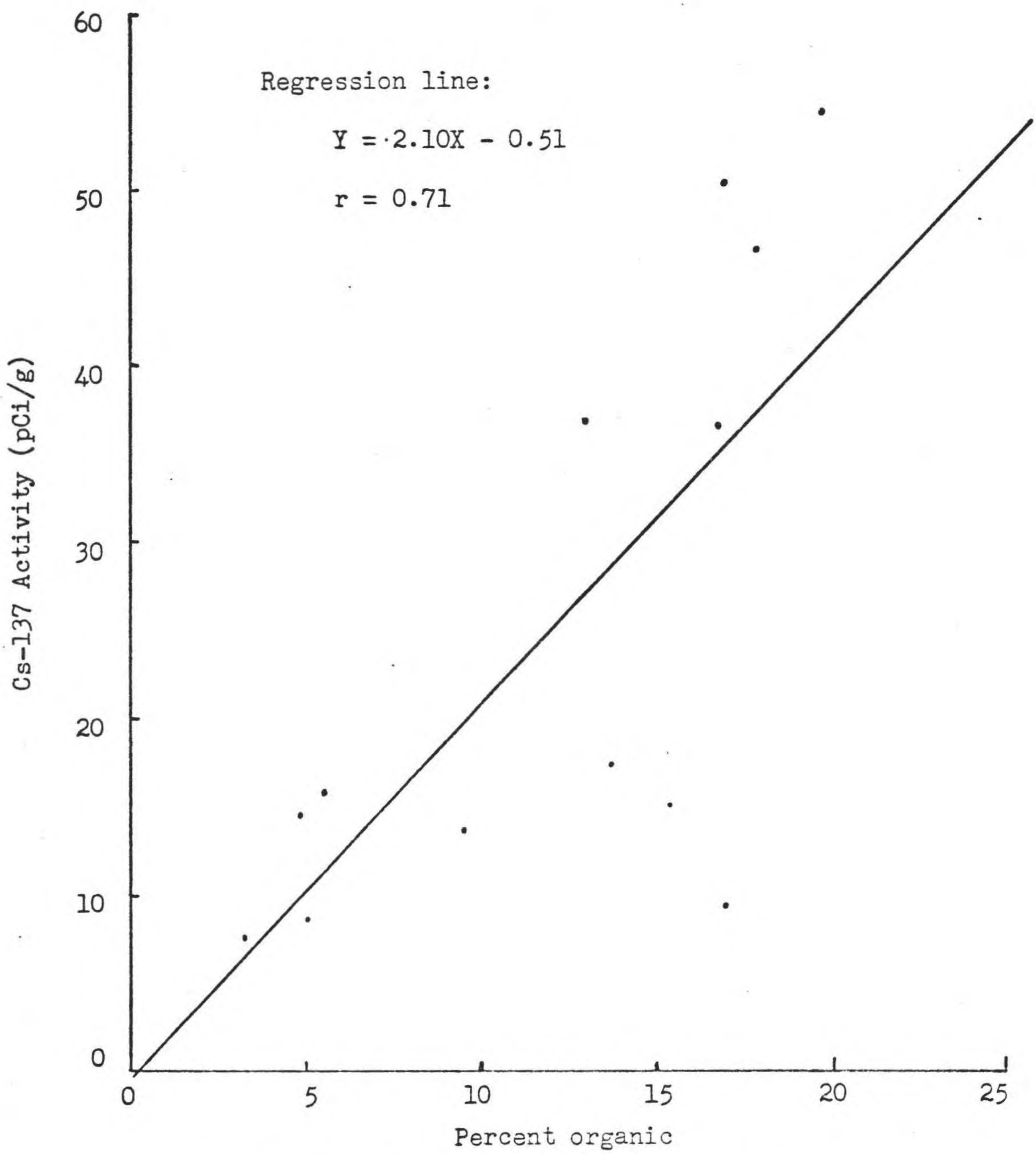

Fig. D. Specific Cs-137 activity of Pinedale III sediment vs. percent organic.