Spatial variability of soil redistribution processes in a small agricultural watershed

by John Cornelius Pings

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University

Abstract:
Physical soil redistribution processes were studied in a small (61 ha) watershed in a region of dryland winter wheat agriculture in north-central Montana. Two approaches were used, a model approach using the Universal Soil Loss Equation (USLE) and Wind Erosion Equation (WEE) soil erosion models, and a field sampling approach using 137Cs. The 137Cs was used as a tracer of erosion and deposition from upland sites (hilltops, midslopes and footslopes) to depositional zones (channels and a pond reservoir bottom). Cesium-137, a fallout product of atmospheric nuclear testing, is strongly adsorbed to clay and has been proven to trace sediment movement. A volumetric approach, developed by De Jong and associates of the University of Saskatchewan, was used to estimate erosion rates of eroding sites and deposition rates of the depositional sites. Landscape units, labelled topographic positions and depositional zones, were defined from a 1:2500 scale plane table topographic contour map, and analyzed for areal concentration of 137Cs to attain erosion rate estimates.

A 125 m random sample grid was used to generate USLE and WEE erosion rate estimates. USLE estimates were calculated using the point method of Griffin et al. (1988). WEE estimates were calculated using equations of Skidmore (1988) which were developed to fit the nomographs conventionally used in WEE applications. The model approach yielded an erosion estimate of approximately 9.0 Mg ha-1 yr-1; combining a USLE average estimate of 4.5 Mg ha-1 yr-1 with a WEE average of 4.5 Mg ha-1 yr-1. A site by site comparison of combined model and 137Cs estimates for the 137Cs sample sites yielded a regression output of .07, possibly indicating poor model performance. However, problems in assessing the spatial and temporal variability of soil redistribution indicate a need to further refine the cesium method to reduce variances.

Using the 137Cs method, hilltops, midslopes and footslopes were found to be eroding at 22.9, 28.1, and 0.5 Mg ha-1 yr-1, respectively, for a total net erosion rate of 10.4 Mg ha-1 yr-1. Ponds and channels were found to have deposition rates of 243.9 and 43.0 Mg-1 ha-1 yr, respectively, for a total net deposition rate of 5.0 Mg-1 ha-1 yr. The USLE estimated 90 % of the measured value while the WEE predicted only 44 % of the measured wind erosion. The poor model performance and low precision of the cesium method suggests that the use of the models needs to be considered carefully, especially with regard to watershed scale soil erosion assessments.

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John Cornelius Pings

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency and is ready for submission to the College of Graduate Studies.

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Chairperson, Graduate Committee

Approved for the Major Department

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I dedicate this thesis to my wife, Laura, to my daughter, Lauren Michelle and to my great uncle Robert W. O'loughlin.

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ABSTRACT

Physical soil redistribution processes were studied in a small (61 ha) watershed in a region of dryland winter wheat agriculture in north-central Montana. Two approaches were used, a model approach using the Universal Soil Loss Equation (USLE) and Wind Erosion Equation (WEE) soil erosion models, and a field sampling approach using ^{137}Cs. The ^{137}Cs was used as a tracer of erosion and deposition from upland sites (hilltops, midslopes and footslopes) to depositional zones (channels and a pond reservoir bottom). Cesium-137, a fallout product of atmospheric nuclear testing, is strongly adsorbed to clay and has been proven to trace sediment movement. A volumetric approach, developed by De Jong and associates of the University of Saskatchewan, was used to estimate erosion rates of eroding sites and deposition rates of the depositional sites. Landscape units, labelled topographic positions and depositional zones, were defined from a 1:2500 scale plane table topographic contour map, and analyzed for areal concentration of ^{137}Cs to attain erosion rate estimates.

A 125 m random sample grid was used to generate USLE and WEE erosion rate estimates. USLE estimates were calculated using the point method of Griffin et al. (1988). WEE estimates were calculated using equations of Skidmore (1988) which were developed to fit the nomographs conventionally used in WEE applications. The model approach yielded an erosion estimate of approximately 9.0 Mg ha^{-1} yr^{-1}; combining a USLE average estimate of 4.5 Mg ha^{-1} yr^{-1} with a WEE average of 4.5 Mg ha^{-1} yr^{-1}. A site by site comparison of combined model and ^{137}Cs estimates for the ^{137}Cs sample sites yielded a regression output of .07, possibly indicating poor model performance. However, problems in assessing the spatial and temporal variability of soil redistribution indicate a need to further refine the cesium method to reduce variances.

Using the ^{137}Cs method, hilltops, midslopes and footslopes were found to be eroding at 22.9, 28.1, and 0.5 Mg ha^{-1} yr^{-1}, respectively, for a total net erosion rate of 10.4 Mg ha^{-1} yr^{-1}. Ponds and channels were found to have deposition rates of 243.9 and 43.0 Mg^{-1} ha^{-1} yr, respectively, for a total net deposition rate of 5.0 Mg^{-1} ha^{-1} yr. The USLE estimated 90 % of the measured value while the WEE predicted only 44 % of the measured wind erosion. The poor model performance and low precision of the cesium method suggests that the use of the models needs to be considered carefully, especially with regard to watershed scale soil erosion assessments.

CHAPTER 1

INTRODUCTION

Scope and Purpose

The increasing scale of human impact in agricultural areas and a desire to reduce soil erosion problems have provided the impetus for soil erosion assessments in recent years. The U. S. Department of Agriculture (USDA) Soil Conservation Service (SCS) regularly utilizes models such as the Universal Soil Loss Equation (USLE) and a version of the Wind Erosion Equation (WEE) to guide the implementation of conservation procedures, and recent work has focused on improving the methods of estimating model inputs to produce erosion estimates that are spatially variable. In the State of Montana there is a need for large scale soil erosion studies to assist in the development of soil erosion/crop productivity assessments. Similarly, there is a need to collect soil erosion data independent of these modeling efforts so that the contribution of the modeling efforts, themselves, can be evaluated.

This study addresses both needs by quantifying soil erosion and deposition in a small agricultural catchment. Two approaches have been used. The first approach uses the USLE and WEE to estimate soil losses from water and wind, respectively, in the watershed. The second approach uses the spatial variability of Cesium-137 (^{137}Cs) detected in soil samples to quantify erosion from both water and wind and deposition by water.

The USLE and WEE have emerged as the most widely used soil erosion models in North America. It has been used for many national and state/provincial assessments in the United States and Canada and for watershed- and plot-scale studies in both countries (Trimble, 1974, 1977, 1983; van Vliet and Wall, 1979, 1981; Coleman, 1982; Snell, 1984, 1985; Wilson, 1989). USLE and WEE soil loss estimates are also used by the USDA SCS to determine qualification and maintenance requirements for Conservation Reserve Programs (C.R.P.) in Montana.

The techniques used in this study to estimate erosion and deposition rates from ^{137}Cs areal concentrations were developed by Brown and associates (1981a, 1981b) and later refined by De Jong and associates (1983). The ^{137}Cs isotope acts as a tracer of physical soil redistribution processes by its adhesion to fine soil grains. It is a by-product of atmospheric nuclear testing and is delivered through precipitation and wind-carried sediments. Its use as an indicator of erosional and depositional processes has been widespread (Ritchie et al., 1974; Pennington et al., 1976; McHenry and Ritchie, 1977; McCallan et al., 1980; Wise, 1980; Brown et al., 1981b; De Jong et al., 1983; Arnalds, 1984; Arnalds et al., 1989; Dibb, 1989).

Using these approaches, the objectives of this study were twofold. The first objective was to estimate soil losses with the USLE and WEE for a small agricultural watershed. The second objective was to quantify soil erosion and deposition using ^{137}Cs and to use these results to evaluate USLE and WEE performance in the same watershed. The following kinds of data were generated and analyzed to answer these research questions: 1) analysis of climatic, soil, topographic and vegetative cover factors to produce USLE and WEE soil loss estimates at multiple sites; 2) analysis of ^{137}Cs samples to define total and incremental ^{137}Cs areal concentrations for several sites, and determine relative erosion and deposition; and 3) extrapolation of USLE and WEE estimates and ^{137}Cs areal concentration averages by landscape units to obtain erosion and deposition rates for those units and the entire watershed.

Previous Watershed Scale Soil Erosion Studies

Model Studies and Applications

The USLE was derived from 10,000 plot-years of data at locations throughout the United States. This model estimates erosion through the quantification of factor values for rainfall-erosivity (R), soil erodibility (K), topographic factors defined by slope length (L) and slope steepness (S), cover management (C) and supporting practices (P). The USLE is frequently used by the SCS as a tool to determine conservation practices for the control of fluvial erosion, including contour strip-cropping and terracing (Wischmeier, 1976; Wischmeier and Smith, 1978).

Some recent studies have tried to improve the USLE by developing new methods of estimating factor values, particularly the topographic factors, L and S. Williams and Berndt (1977), for example, proposed a method of generating slope frequency data by using a third-order natural spline function developed by Greenville (1967) for points defined by horizontal distances and elevations of contours that cross grid lines on topographic maps. Slope in the direction of the grid lines was determined by differentiating the spline function at each grid intersection point. Wilson (1986a, 1986b) developed a different approach using topographic map input data and Greenville's (1967) spline function to estimate slope length, shape and steepness for slope profiles that cross the elevation contours perpendicularly. Statistical analysis of slope segments was used to divide computer generated slope profiles into segments and the irregular slope method of Foster and Wischmeier (1974) was used to estimate LS values. Griffin and his associates (1988) developed a method of estimating LS factor values for a series of random points. Their method used the distance downslope from the top of the slope profile as well as cumulative and slope segment gradients to estimate LS values for specific points in a landscape.

A more comprehensive revision of several factors will result in the publication of a computer program and manual for the Revised Universal Soil Loss Equation (RUSLE) in 1990 (Renard, 1989, personal communication). The original USLE and RUSLE will most likely be replaced by a completely new physically-based modeling technology in the mid-1990s (Foster, 1989, personal communication).

The Wind Erosion Equation (WEE) was developed at about the same time as the USLE to assess the susceptibility of field soils to wind erosion and to help with the selection and design of wind erosion control practices (Chepil et al., 1962; Woodruff and Siddoway, 1965). This equation estimates erosion as a function of magnitude and direction of wind as well as soil erodibility (I), soil ridge roughness (K), vegetation orientation and cover (V), and field fetch length (L). The WEE equation was used in early conservation applications. Skidmore and Woodruff (1968) later compiled pertinent climatic data for many stations from existing sources to assist in the application of the WEE throughout the country. The model and climatic data were published for farmers and conservation program workers. In one of the most innovative applications of the WEE to date, Bondy et al. (1980) estimated wind erosion by cropstage period as a function of wind energy distribution. Their method used temporally variable vegetative residue equivalents, soil tillage conditions and soil erodibility to estimate wind erosion for 10 different cropstage periods in a winter wheat/summer fallow system in Kansas and a spring wheat/spring wheat/fallow system in North Dakota. Skidmore (1988) substituted equations to estimate WEE factor values for the tables and nomographs of Woodruff and Siddoway (1965). These equations, first proposed by Williams et al. (1984), eliminate the need to interpolate factor inputs and reduce the time and effort needed to apply the WEE. The SCS Agricultural Research Service developed a version of the WEE, the WEQ, for use by SCS personnel in field applications.

Previous Cesium-137 Studies

Cesium-137 is a widely dispersed radioactive isotope that is a by-product of atmospheric nuclear testing which the United States, Soviet Union and United Kingdom began on a frequent basis in 1954 (Campbell et al., 1982). These tests are still carried out on a much smaller scale by France and China (Anonymous, 1989). The period of most intense atmospheric dispersion occurred between 1962 and 1965 immediately before the United States, Soviet Union and 41 other nations signed a treaty suspending atmospheric testing of nuclear weapons in 1966 (Campbell et al., 1982). Cesium-137 has a regional distribution that is linked to precipitation sources and quantities. The isotope is transported through the stratosphere and troposphere by global circulation patterns and delivered to soils through two methods. One method involves delivery through precipitation, and the second method involves dry deposition of ^{137}Cs with atmospheric particulate matter from the atmosphere. Its local concentration is dependent upon the available amount of the isotope in the atmosphere at the time of precipitation events, its altitude, and prevailing regional and local meteorological conditions (McCallan et al., 1980).

Several assumptions govern the use of this isotope as a tracer of soil redistribution process analysis. It is assumed that: 1) the isotope has been delivered to the watershed uniformly; 2) the ^{137}Cs becomes adsorbed to the clay- and silt-sized soil particles when it reaches earth; 3) these sediments have not undergone any sorting; and 4) the redistribution of ^{137}Cs by winter winds, plant and animal life has been minor (< 5 percent) and/or at least uniform throughout an individual watershed (Brown et al., 1981a, 1981b; De Jong et al., 1982, 1983; Arnalds, 1984).

Cesium-137 can be used to quantify soil erosion and deposition rates because its half-life (30.2 years) and known period of existence (dispersion since 1954) allow estimates of average annual erosion and deposition rates to be made (Brown et al., 1981a). Once these rates are known, additional variables such as intensity of areal concentration, topographic position, and maximum depth of ^{137}Cs activity in the soil profile facilitate the delineation of erosional and depositional zones in watersheds because the ^{137}Cs moves only with sediment that is transported

(De Jong et al., 1982, 1983).

A conceptual model of ^{137}Cs input, activity and transport in a drainage basin is reproduced in Figure 1. Most studies use this type of model to quantify erosion and deposition rates. The bar diagrams of typical ^{137}Cs areal concentrations for various landscape units in Figure 1 illustrate the variable nature of ^{137}Cs activity at different locations in a watershed.

Several studies have examined ^{137}Cs in test plots and watersheds to determine regional concentrations (e.g., Rogowski and Tamura, 1970; Lance et al., 1986; Kachanoski, 1987; Dibb, 1989). Arnalds (1984) measured average ^{137}Cs areal concentrations between 3.6 and 20.2 picocuries per square cm (pCi cm^{-2}) at 12 sites throughout Montana. These concentrations were strongly related to precipitation ($R^2 = 0.92$), indicating that local precipitation totals will provide a good first estimate of expected ^{137}Cs levels (Arnalds, 1984; Arnalds et al., 1989). Given the previously mentioned regional sources and controls and the assumptions noted above, several researchers have constructed ^{137}Cs mass balances to infer soil erosion and deposition rates (De Jong et al., 1983; Arnalds, 1984; Pennock and De Jong, 1987).

Cesium-137 has been applied to erosion and sedimentation studies in a variety of contexts. Several studies have shown that concentrations have increased in areas of sediment accumulation such as valley floors, lakes, reservoirs and salt marshes (e.g., McHenry et al., 1973; Ritchie et al., 1974, 1975; Pennington et al., 1976; Delaune et al., 1978; McCallan et al., 1980; Brown et al., 1981a, 1981b; Campbell et al., 1982; De Jong et al., 1983; Arnalds, 1984; Pennock and De Jong, 1987). Cesium-137 has been used to determine erosion of natural and clearcut

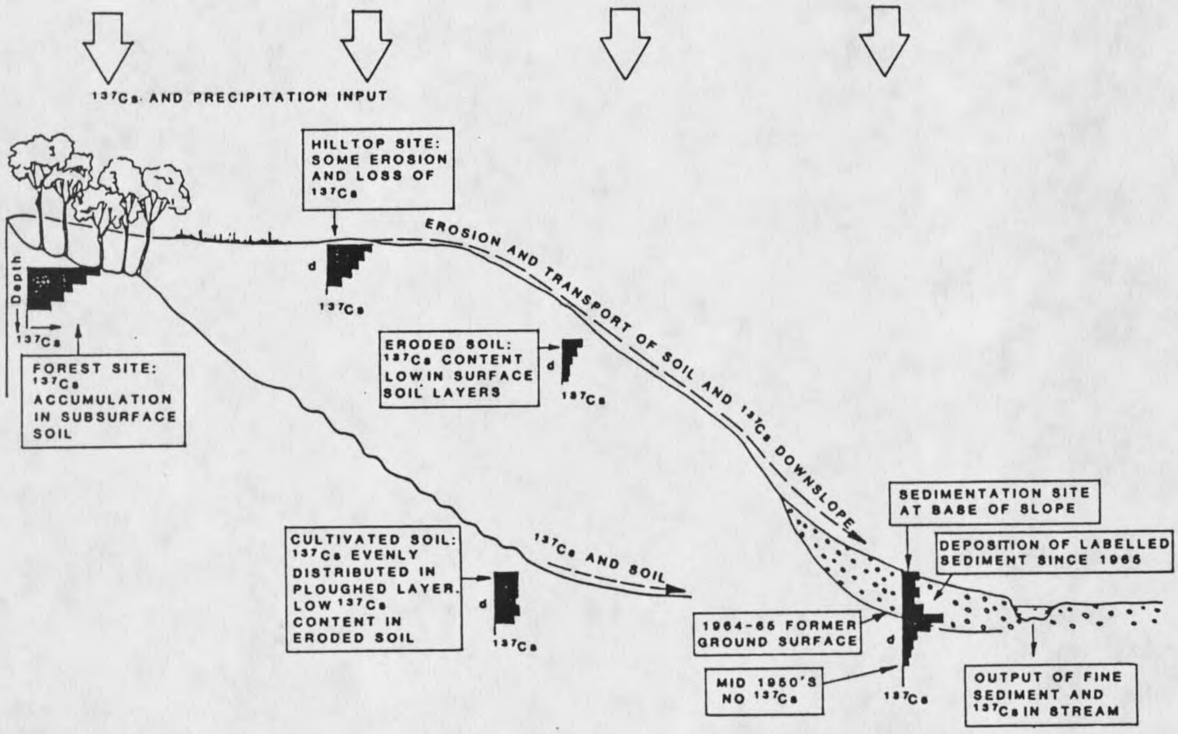

Figure 1. Cesium-137 in a drainage basin (from Campbell et al., 1982).

forests and forest/field systems at a variety of spatial scales (Brown et al., 1981a, 1981b; Campbell et al., 1982; Lowrance et al., 1988). Other studies have used ^{137}Cs to evaluate soil erosion and deposition on agricultural soils (Brown et al., 1981b; Campbell et al., 1982; De Jong et al., 1983; Arnalds, 1984; Pennock and De Jong, 1987).

Recent studies have quantified erosion and deposition rates for entire watersheds by using weighted average areal concentrations for different landscape units (Brown et al., 1981b; De Jong et al., 1983; Arnalds, 1984; Pennock and De Jong, 1987). Several methods have been developed to distinguish landscape units. For example, Brown et al. (1981b) divided their watershed into erosional and depositional zones, with hilltops and midslopes representing erosional zones and footslopes and an alluvial fan representing depositional zones. De Jong et al. (1983), on the other hand, distinguished three landscape units - upper, middle, and lower slopes - determined in the field by pacing. Arnalds (1984) added two further units to this classification, shoulder slopes between hilltops and midslopes, and toeslopes beneath lower slopes (footslopes) but defined his transects by selecting soil samples for ^{137}Cs analysis 50 m apart. Pennock and De Jong (1987) used a similar approach to De Jong et al. (1983) in an attempt to decipher the influence of profile and plan curvature on soil redistribution processes. A digital terrain model was created from an existing digitized topographic survey and used to distinguish convergent and divergent backslopes, convergent and divergent shoulders, convergent and divergent footslopes, and level areas (Pennock and De Jong, 1987). Care must be exercised when using this terminology because the landscape units are defined and labeled using different methods and definitions in different studies. However, the general approach of extrapolating average ^{137}Cs areal concentrations to landscape units is now widely used to estimate average annual erosion and deposition rates.

Most recent studies have undertaken ^{137}Cs detection with laboratory analysis using a lithium-drifted germanium semi-conductor gamma ray detector coupled to a nuclear data multi-channel analyzer (Cutshall and Larsen, 1980; Larsen and Cutshall, 1981; Brown et al., 1981a, 1981b; De Jong et al., 1983; Arnalds, 1984). Cesium-137 concentrations are calculated by multiplying the ^{137}Cs activity in core samples (pCi g^{-1}) by the soil mineral bulk density (g cm^{-3}) and depth of the soil sample (cm).

Results are expressed as radioactivity per unit surface area of soil surface or the "areal concentration" (e.g., Brown et al., 1981b; De Jong et al., 1983; Arnalds, 1984; Pennock and De Jong, 1987).

Campbell et al. (1982) used a different approach to determine ^{137}Cs areal concentrations. Their approach relies on the fact that ^{137}Cs adheres to fine soil fractions, so that the areal concentrations are calculated using only the silt and clay fractions. Silt and clay fractions were estimated using the hydrometer method and their bulk densities were used instead of that of the total sample. This study used an experimental watershed in New South Wales, Australia, which was found to have ^{137}Cs distributed evenly in upper soil layers due to plowing. Areal concentrations were quantified for a variety of topographic positions in upland and lowland areas although no erosion or deposition rates were estimated (Campbell et al., 1982).

In contrast, many North American studies have tried to estimate erosion and deposition zones and rates from ^{137}Cs analysis. Brown and associates (1981b) computed erosion estimates ranging from 3 to 27 t ha^{-1} yr^{-1} for erosional zones based upon detected ^{137}Cs ranging from 3.5 to 15.2 pCi cm^{-2} in two Willamette Valley, OR watersheds. Six out of eight footslopes tested were found to be eroding (Brown et al., 1981b). In another study, De Jong et al. (1983) found upper slopes to have lost 200 to 600 t ha^{-1} of soil while lower slopes were found to have gained 250 to 800 t ha^{-1}. However, middle slopes were found to be both depositional and erosional over 20 to 25 years in eight small Saskatchewan, Canada basins with glacial soils (De Jong et al., 1982; 1983).

Arnalds (1984) examined erosion in a small watershed near Power, MT in which he detected ^{137}Cs areal concentrations ranging from 2.4 to 24.6 pCi cm^{-2}. Hilltops and footslopes both were found to be eroding at 16.5 Mg ha^{-1} yr^{-1}, while shoulders and midslopes were eroding at 20.9 and 45.1 Mg ha^{-1} yr^{-1}, respectively. Toeslopes were found to have deposition occurring at a rate of 9.9 Mg ha^{-1} yr^{-1}. The estimates for the shoulders, midslopes and footslopes compared favorably with USDA SCS soil loss estimates produced with the USLE and WEE models.

Lance et al. (1986) collected data on ^{137}Cs activities in the southwestern United States as well as in adjacent cultivated and grassed watersheds in Oklahoma. A major conclusion of this study based upon the results of a soil mass balance was that ^{137}Cs activity might be a more sensitive indicator of soil productivity losses than measurements of total mass of soil removed from a field caused by highly localized erosion and deposition. McIntyre et al. (1987) found a clearcut forest to be eroding at only 0.2 t ha^{-1} yr^{-1} and attributed the erosion to soil compaction by livestock grazing of native grasses. In a related study Lowrance et al. (1988) estimated erosion and deposition rates of 63 and 256 Mg ha^{-1} yr^{-1}, respectively, for a riparian forest/field system watershed on the southern Georgia coastal plain. The unusually high deposition was attributed to sediment that was transported from upstream locations and deposited during flood events. Three different calculation methods produced nearly identical results.

Pennock and De Jong (1987) examined more landform elements than the other studies and found four of seven to be erosive, from most to least erosive: convergent shoulders, divergent backslopes, convergent backslopes and divergent shoulders. The depositional units were, in order from least depositional to most: divergent footslopes, level areas and convergent footslopes. Soil loss predictions for these same areas using the USLE were two to nine times lower than those indicated by the ^{137}Cs method (Pennock and De Jong, 1987).

Description of Study Area

The study watershed covers approximately 61 ha and is located in Choteau County near Carter, Montana at 47° 53′30" N and 110° 52′00" W (Figure 2). It is located on the U.S.G.S. Carter N.E. 7.5 minute quadrangle in the SW and SE 1/4′s of section 30, Township 25 North, Range 7 East. The watershed is located within a mapped unit of the Colorado Shale and is located approximately 40 km north of the southernmost extent of the Laurentide ice sheet.

The watershed consists of hummocky terrain of glacial origin. Local relief is 22 m, with the highest elevations along the western boundary approaching 922 m. The watershed is drained by an unnamed tributary of the Frank Gilbert Coulee, which drains to the Teton River and eventually to the Missouri River. The area is a mixture of gentle slopes in the west and steeper slopes along the eastern boundary. A well defined ephemeral channel system drains into an incised channel and a 0.25 ha pond situated behind an earth dam constructed in 1973.

The annual average precipitation measured in nearby Great Falls is 390 mm yr^{-1}, with a May-June maximum. Average annual rainfall varied from 186 to 475 mm yr^{-1} between 1954 and 1986. Analysis of wind data for Great Falls between 1950 and 1955 indicates a predominant annual wind direction

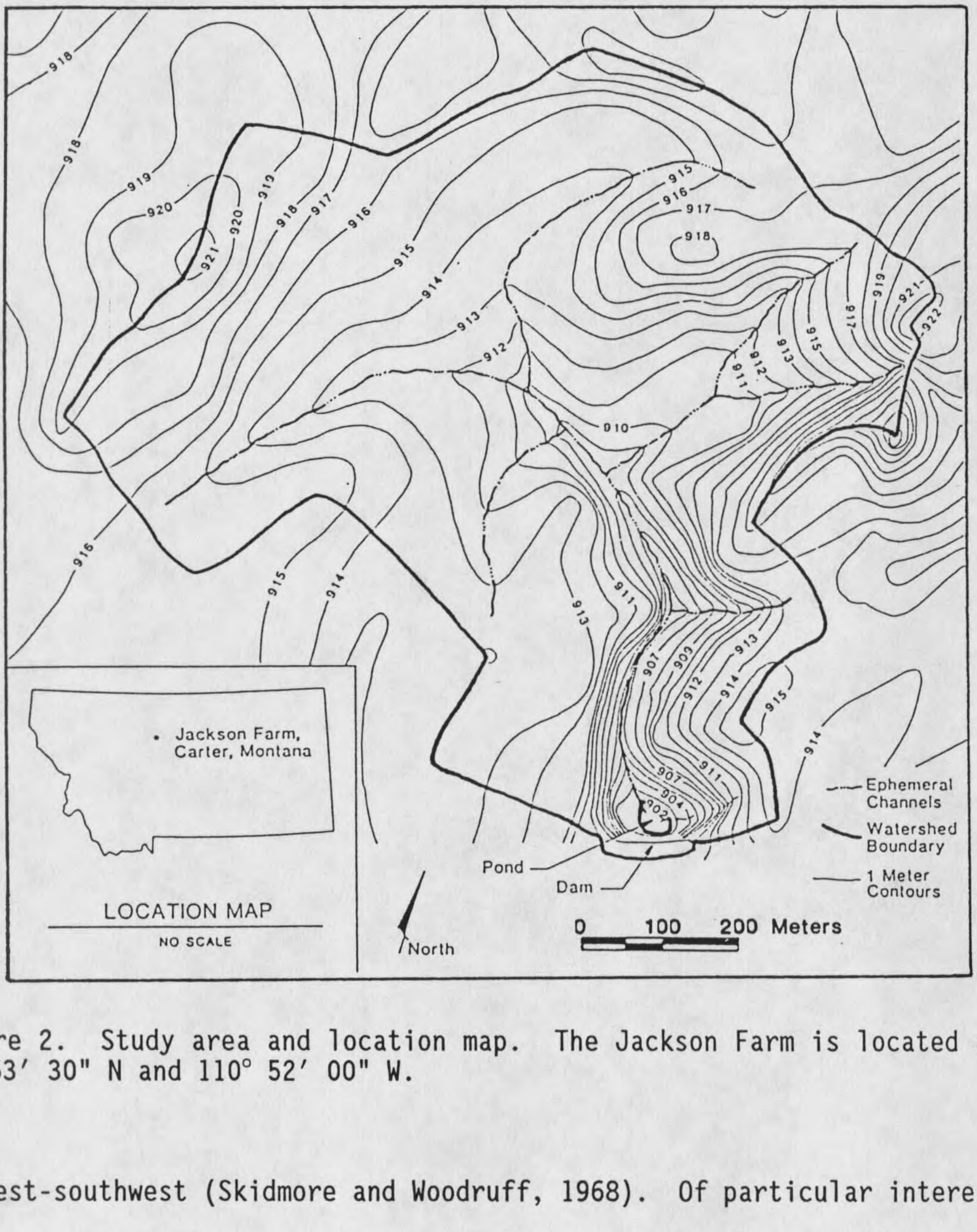

Figure 2. Study area and location map. The Jackson Farm is located at 47° 53′ 30" N and 110° 52′ 00" W.

of west-southwest (Skidmore and Woodruff, 1968). Of particular interest to this study is the percent of cumulative erosive wind energy (EWE) that occurs by a particular month (see Table 1). According to the data, the critical period for erosive wind is between October and April, during which 83 % of the erosive wind occurs.

The soils of the study area are fine, montmorillonitic Aridic Argiborolls (Ethridge series, a silty clay loam) and fine, montmorillonitic frigid, Typic Albaqualfs (Nishon series, a silty clay) (unpublished soil survey maps, Mr. Raymond McPhail, SCS District Conservationist, Choteau County, MT, 1987) (Figure 3). The watershed is part of the Mr. Norman W. Jackson farm which is used mostly for the cultivation of winter wheat. The farm is managed in a winter wheat/summer fallow system. The watershed is almost completely tilled with the exception of the incised channel and pond areas and their margins.

The watershed has undergone considerable change in the last half-century. The middle portion of the study area was formerly a small, seasonal lake. In the 1940's, a channel was incised from the lake to the coulee bottom to drain the lake to allow tillage. The incised channel remains an active component of the fluvial system, channeling overland flow from the upland areas of the watershed. An earth dam was constructed across the mouth of the coulee to create a pond in 1973. The landowner had planned to stock this pond with fish but the pond has always emptied after precipitation events and spring runoff because of a slow leak (Norman Jackson, Carter, MT, personal communication, 1987). This has prevented permanent filling of the reservoir, but it drains slowly enough (a period of months) to be an efficient sediment trap. The ephemeral nature of the pond was beneficial to the present study because it provided access to reservoir bottom sediments.

Table 1. Erosive Wind Energy Occurring by Month at Great Falls, MT.[a]

Month	J	F	M	A	M	J	J	A	S	O	N	D
Monthly Total (%)	15	14	9	9	5	4	2	2	4	9	12	15
Cumulative Total (%)	15	29	38	47	52	56	58	60	64	73	85	100

[a]Erosive wind greater than 8 m sec^{-1}. Source: USDA SCS 1988 National Agronomy Manual.

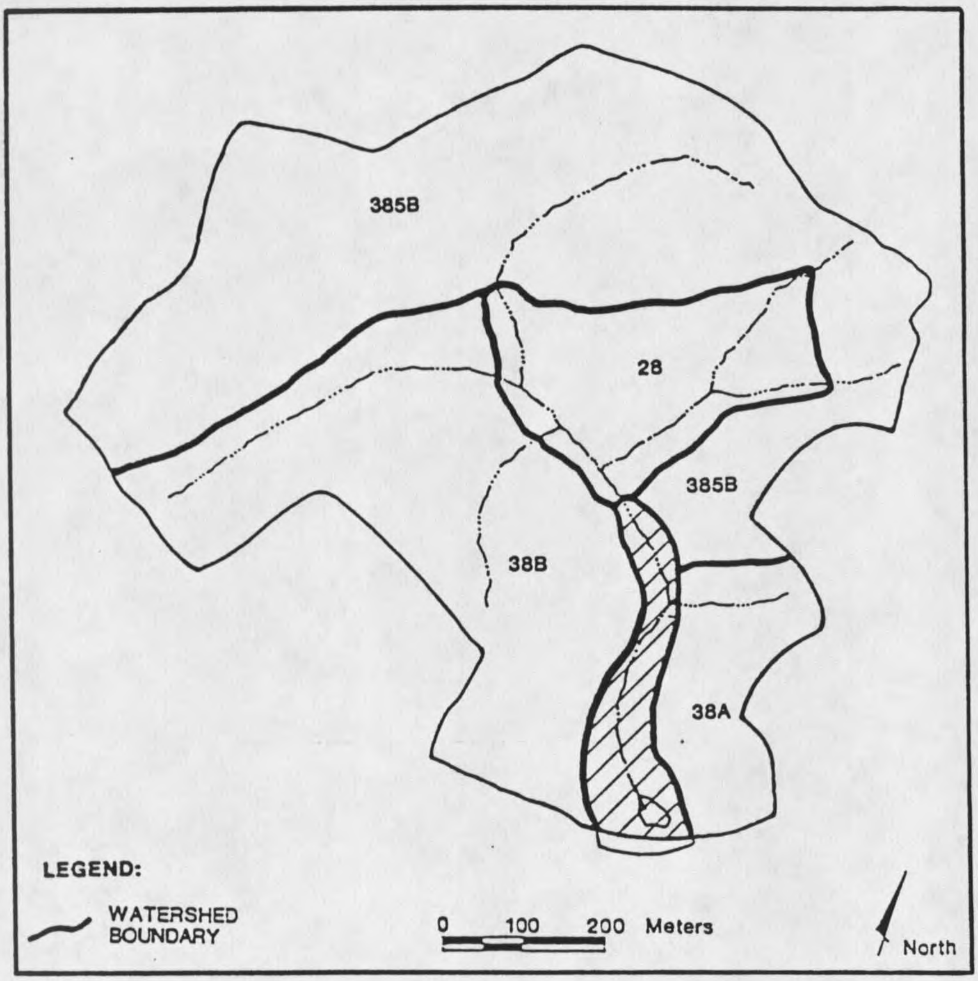

Figure 3. Soil series map showing soil mapping units as defined by the soil survey team, SCS Choteau County Conservation District. Ethridge soils are 38A, 38B and 385B, and Nishon soil is 28. Stippled area was undefined by SCS.

Thesis Organization

This first chapter has described the scope and purpose of the study, previous soil erosion studies which use the USLE and WEE models and ^{137}Cs techniques, and the study watershed.

Chapter 2 describes the methods of data collection, assumptions used and the computations required to use both the soil erosion models and ^{137}Cs method. It describes the method used for the topographic survey and the division of the watershed into landscape units. Data sources and methods used to estimate USLE and WEE factor values are also described. Soil sampling procedures and laboratory analysis for ^{137}Cs detection in the watershed are outlined as are the methods of calculation of the areal concentrations, erosion and deposition rates, and watershed mass balance.

Chapter 3 is a substantive review of all the results from both the model and ^{137}Cs methods. It includes average annual erosion rate estimates from the USLE and WEE, as well as an analysis of the spatial variability of those estimates. The ^{137}Cs results included are 1) the ^{137}Cs activity for each site, 2) the soil erosion and deposition rates for each site, 3) average erosion and deposition rates by topographic position, 4) the average areal concentrations by topographic positions, and 5) a total watershed erosion and deposition mass balance.

Chapter 4 is a discussion of the results and the implications of the performance of these methods of estimating soil erosion and deposition to soil erosion productivity assessments of other similar watersheds in north-central Montana. Possible sources of error are also discussed. The final part of Chapter 4 is the conclusions section.

CHAPTER 2

METHODS AND DATA SOURCES

Topographic Map Generation

The study area was mapped using a plane table, telescopic alidade and the beaman arc procedure described by Compton (1962). The topographic map was drawn at a scale of 1:2500 using a 1 m contour interval. The starting elevation was determined by locating the highest point in the watershed and assigning it the elevation of the point of highest relief on the U.S.G.S. Carter NE 15 minute quadrangle (3023 feet or 921.4 m) (Table Station A in Figure 4). All elevations and linear distance measurements were rounded to the nearest .1 m.

A baseline was established between two central hilltops (Figure 4). The baseline was hand measured twice (632.2 m and 632.6 m) using a 100 m tape, giving an average distance of 632.4 m. Plane table measurements of the base line fell within ± 4 m of this length, indicating errors of less than .7% when measuring linear distances. No check on the accuracy of elevation measurements is possible using the method described by Compton (1962).

Following establishment of the baseline, flags were set at each end to facilitate telescopic sighting from anywhere in the watershed. This was not possible in several instances, so two additional flags were set

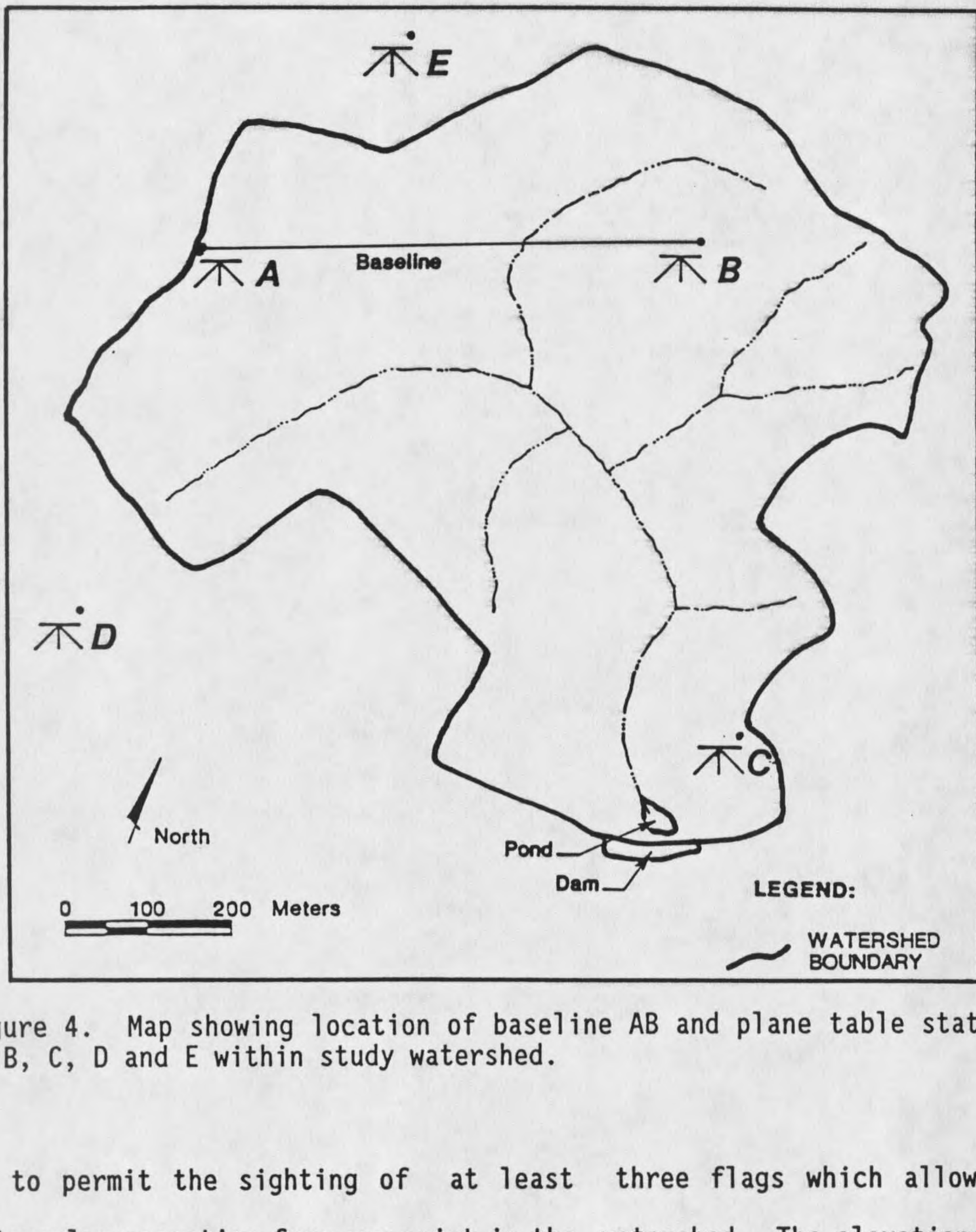

Figure 4. Map showing location of baseline AB and plane table stations A, B, C, D and E within study watershed.

up to permit the sighting of at least three flags which allowed a triangular resection from any point in the watershed. The elevations and locations of the flag sites were established with the alidade relative to the known elevation at one end of the baseline and its length. These flag points became plane table stations A, B, C and D.

One additional table station (E) was added to allow coverage of the extreme northern part of the watershed. It was located on the plane table map using a triangular resection method. Hence, a total of five plane table stations was used and those established at flag stations were located exactly 1 m east of each flag. Four stations could be relocated from anywhere in the watershed by sighting their flags with the telescopic alidade.

The mapping was accomplished by sighting the stadia rod through the telescopic alidade to reveal a stadia intercept, direction and cross hair reading. Trigonometric calculations yielded distance and elevation differences and direction was established by marking the plane table map with a ray drawn along the fiducial edge of the telescopic alidade. Topographic features were identified in the watershed by placing the stadia rod directly on them. Two hundred and eighty points were marked on the plane table map in this manner. The first draft of a contour map was drawn in the field to allow for collection of more points wherever definition of local topography became difficult.

Data points were eliminated if the elevations could not be reproduced using the mathematical formulae described in Compton (1962). Four data points (1.4% of those mapped in the field) were eliminated because there was a difference between the elevations calculated in the field and those generated during subsequent rechecking of computations.

Differences between the elevation computed for table station B from table station A and from later, shorter sightings of data points A27 and A28 from table station B were discovered when the computations were rechecked. The elevation at table station B was determined from Table 2, which shows the relative confidence values associated with the individual telescopic alidade sightings. Hence, an elevation of 918.7 m was chosen for table station B due to the high confidence values associated with shorter sightings. The elevations determined after the sighting of station B were adjusted to reflect this change in elevation (since table stations C, D and E relied on this elevation to determine their elevations) and all data points were rechecked. All elevation contours were redrawn and a final revision of the topographic contour map was drawn.

Model Estimates

Universal Soil Loss Equation

The modified version of the USLE developed by Griffin et al. (1988) to estimate sheet and rill erosion at different points in a landscape was used in this study. This equation, which combines the method of Foster and Wischmeier (1974) for measuring the L and S factors for irregular slopes with the original model (Wischmeier and Smith, 1978), can be written as follows:

$$D = (m + 1)\ R\ K\ (x/l_u)^m\ S\ C\ P \qquad (1)$$

where D is soil loss in tonnes per hectare per year (t ha^{-1} yr^{-1}), m is the slope length exponent, R is the rainfall-erosivity factor in megajoules per millimeter per hectare per hour per year (MJ mm ha^{-1} hr^{-1} yr^{-1}), K is the soil erodibility factor in tonnes per hectare per hour per hectare per megajoules per millimeter (t ha hr ha^{-1} MJ^{-1} mm^{-1}); x is the distance of the sample point from the top of the slope profile in meters (m), l_u

Table 2. Confidence of table station B elevation determined by different sightings.

Known	Route	Unknown	Distance	Elevation	Confidence
A[a] (921.4 m)	⟶	B	632 m	918.1 m	Moderate
A	⟵	B	630 m	918.7 m	Moderate
A	⟶ A27 ⟵	B	700 m	918.7 m	High
A	⟶ A28 ⟵	B	700 m	918.7 m	High
A	⟶ X ⟵	B	1,080 m	918.3 m	Low

[a]Elevation of highest hilltop from U.S.G.S. 15 minute Carter N.E. quadrangle. Table station A is located on the highest point of the same hill. See Figure 3 for location.

is the length of the USLE unit plot (22.13 m), S is the slope gradient factor, C is the cropping management factor and P is the supporting practices factor. A grid with perpendicular lines drawn 125 m apart was placed randomly over the study watershed to determine the locations at which soil losses were to be estimated. This grid was then shifted 62.5 m in both southerly and easterly directions to generate additional sample points. The sample grid points generated and their labels are shown in Figure 5.

Although this approach produced 81 locations marked by grid line intersection points, soil losses from sheet and rill erosion were estimated at only 60 of these locations. Twenty-one points (locations) were eliminated as follows: 1) nine points located on or near hilltops were eliminated because slope lengths and related USLE erosion estimates

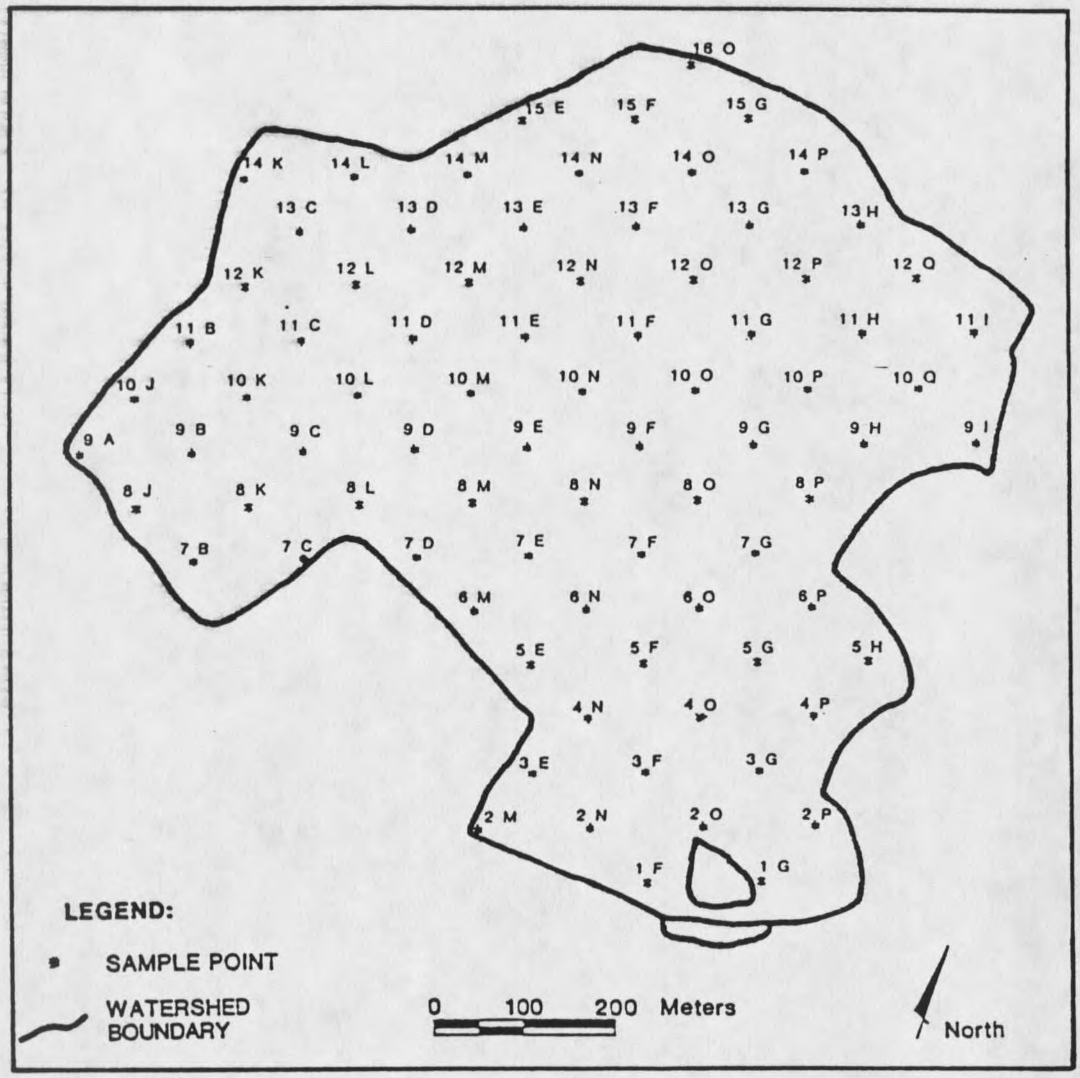

Figure 5. Map showing location of randomly selected 125 m grid points and labels used for USLE and WEE calculations.

are zero in these circumstances (Wischmeier and Smith, 1978); 2) six points located immediately adjacent to and/or in channels were eliminated because the USLE does not apply to channel erosion (Wischmeier and Smith, 1978); and 3) six points located on concave slope segments with slope gradients less than one half of the cumulative average slope gradient from the drainage divide to this location were eliminated based on the assumption that these areas represent depositional zones (to which the USLE does not apply) (Wilson, 1986b; Griffin et al., 1988). Determination of soil losses at the remaining 60 sites involved estimation of USLE factor values at these locations.

The rainfall-erosivity and soil erodibility values used by the USDA Soil Conservation Service in this watershed (R = 476.6 MJ mm ha^{-1} hr^{-1} yr^{-1} and K = .049 tonnes ha hr ha^{-1} MJ^{-1} mm^{-1} for both the Ethridge and Nishon series) were used as well (McPhail, personal communication, 1987). This R value includes the R_s adjustment for snowmelt.

Slope length (L) and slope gradient (S) factor values were determined from the topographic map constructed for this project. The slope length (x) was measured by extending a line from each sample point (grid intersection) up the slope to the drainage divide, perpendicular to the contours. The remaining inputs required to estimate L (l and m) were taken from Wischmeier and Smith (1978). The slope gradient factor was estimated at each point using the method for irregular slopes first proposed by Foster and Wischmeier (1974).

The crop management (C) factors were computed using the procedure of Wischmeier and Smith (1978, 28-34). Table 3 summarizes the methodology and intermediate results of computing an annual average C factor value for the winter wheat/summer fallow system employed on the Jackson farm. Cropstage C values were estimated for each time period of the two year winter wheat/summer fallow cycle by using a weighted average of C according to the amount of plant cover and EI (rainfall-erosivity) in each period. EI in the period was taken from Table 7 and the soil loss ratios were taken from Table 5 of Wischmeier and Smith (1978). Time

Table 3. Computation of Average Annual C Factor for Tilled Soils.[a]

Date[b]	Activity[c]	Cumulative % of EI[d]	EI in Period[e]	Soil Loss Ratio[f]	Cropstage C Value	Crop Year Totals
Year 1						
10/1	Pl	98	.06	.17	.0102	
4/15	1	4	.16	.14	.0224	
5/15	2	20	.43	.12	.0516	
6/15	3	63	.16	.07	.0112	
8/15	Harvest	79	.25	.04	.0100	
						.1054
Year 2						
4/15	Cultivation 1	4	.02	.23	.0046	
5/1	Cultivation 2	6	.92	.39	.3588	
10/1	--	98	--	--	--	.3634
Rotation Totals			2.00		.4688	
		Average C Value Year^{-1}			.2344	

[a]Annual C value calculated for residue = 2500 kg ha^{-1}.
[b]Date by which cropstage growth or tillage operation is completed.
[c]Cropstage abbreviations, Pl = plant crop; 1 = 10 % crop canopy cover; 2 = 50 % crop canopy cover; 3 = 75 % crop canopy cover.
[d]Cumulative EI for Great Falls, MT from Wischmeier and Smith, 1978, Table 7.
[e]EI for period ending at date in first column, from Wischmeier and Smith, 1978, Table 7.
[f]Soil loss ratio for period ending at dates shown in first column, from Wischmeier and Smith, 1978, Table 5, 5-D.

periods were distinguished by activity and cropstage with the assistance of the Soil Conservation Service and the landowner. The cropstage C values were obtained by multiplying the EI by the soil loss ratio. Cropstage (C) values were then added together and divided by two years to obtain the average annual C value for the winter wheat/fallow system of 0.2344 reported in Table 3. A value of 0.053 was interpolated from Table 10 of Wischmeier and Smith (1978) for the untilled, grassed parts of the watershed. The supporting practices (P) factor was ignored since no conservation practices for water erosion are used in the study watershed. All USLE factor estimates were converted to metric using the method of Foster et al. (1981) and combined using the point method of Griffin et al. (1988).

Wind Erosion Equation

The modified version of the WEE proposed by Skidmore (1988) to estimate wind erosion at different points in a landscape was used in this study. This version of the WEE substitutes a series of equations (calculated in stages) for the original nomographs and can be written:

$$E1 = I' \qquad (2)$$

where E1 is the first stage erosion estimate in tonnes per hectare per year ($t\ ha^{-1}\ yr^{-1}$) , and I′ is the soil erodibility factor value in tonnes per hectare per year ($t\ ha^{-1}\ yr^{-1}$).

$$E2 = I'K \qquad (3)$$

where E2 is the second stage erosion estimate in tonnes per hectare per year ($t\ ha^{-1}\ yr^{-1}$), and K is the soil ridge roughness factor.

$$E3 = I'KC \qquad (4)$$

where E3 is the third stage erosion estimate in tonnes per hectare per year ($t\ ha^{-1}\ yr^{-1}$) and C is the climatic factor.

$$E4 = (WF^{0.348} + E3^{0.348} - E2^{0.348})^{2.87} \tag{5}$$

where E4 is the fourth stage erosion estimate in tonnes per hectare per year ($t\ ha^{-1}\ yr^{-1}$), and WF is a field length weighting parameter defined by equation 5a.

$$WF = E2(1.0 - 0.122(L/Lo)^{-0.383} \exp(-3.33\ L/Lo)) \tag{5a}$$

where L is the strip field length in meters (m) and Lo is a field length parameter defined by equation 5b.

$$Lo = 1.56 \times 10^{6}(E2)^{-1.26} \exp(-0.00156\ E2) \tag{5b}$$

$$E5 = P_1\ E4^{(P2)} \tag{6}$$

where E5 is the final erosion estimate in tonnes per hectare per year ($t\ ha^{-1}\ yr^{-1}$) and P_1 and P_2 are vegetative parameters defined by equations 6a and 6b.

$$P_1 = \exp(-\ 0.759V - 4.74 \times 10^{-2}V^2 + 2.95 \times 10^{-4}V^3) \tag{6a}$$

$$P_2 = 1 + 8.93 \times 10^{-2}V + 8.51 \times 10^{-3}V^2 - 1.5 \times 10^{-5}V^3 \tag{6b}$$

where V is the vegetative factor input in tonnes per hectare ($t\ ha^{-1}\ yr^{-1}$) defined by equation 7a.

The vegetative residue was estimated using the equations of Armbrust and Lyles (1985) reported in Skidmore (1988) which compute the residue as a function of small grain equivalents. The equations used for winter wheat are:

$$V = 0.2533\ (SG_e)^{1.363} \qquad (7a)$$

where V is the vegetative factor input for equations 6a and 6b in kilograms per hectare (kg ha^{-1}), and SG_e is the small grain equivalent calculated using equations 7b, 7c and 7d for standing stubble, flattened stubble, and growing crop in flattened stubble, respectively.

$$SG_e = 4.3\ (R_{ws})^{.97} \qquad (7b)$$

where SG_e is the small grain equivalent, and R_{ws} is the above-ground dry weight of the standing stubble residue in kilograms per hectare (kg ha^{-1}).

$$SG_e = 7.3\ (R_{wf})^{.8} \qquad (7c)$$

where SG_e is the small grain equivalent, and R_{wf} is the above-ground dry weight of the flattened stubble residue in kilograms per hectare (kg ha^{-1}).

$$SG_e = (8.9)^{.172}(7.3)^{.828}(R_{wg})^{(.9)(.172)+(.8)(.828)} \qquad (7d)$$

where SG_e is the small grain equivalent, and R_{wg} is the above-ground dry weight of the crop growing in flattened residue in kilograms (kg ha^{-1}). The I, L, Lo and V factor values were then determined for the same sample points generated for the USLE application (see Figure 5) and used in equations 1 through 7d to estimate WEE soil losses.

Soil erodibility (I) was estimated by determining the non-erodible fraction of the surface soil. The non-erodible fraction (i.e., particles greater than 0.84 mm in diameter) was determined for 50 surficial soil samples by standard dry sieving using a 0.84 mm circular flat screen sieve. Initial I values were calculated for these samples using Table 1 of Woodruff and Siddoway (1965) (see Table 18, Appendix C) and grouped by soil mapping unit. Average values were computed for each group and a series of difference of means tests was used to determine if differences between means were statistically significant (Table 4). Statistically significant differences were found between the means for the Ethridge (#38A) map unit and the Nishon series (#28) and other Ethridge map units (#38B and #385B) at the 5 % and 10 % levels of significance. The four means were used to estimate I values because the soil units were not sampled proportionally and because the wind erosion model was used here to assess spatial variability of wind-generated soil losses. One point (2F) that fell within the incised channel was excluded from the WEE analysis because wind does not erode this area.

After the initial computation of I, the points located on windward slopes shorter than 152 m were adjusted using Figure 1 of Woodruff and Siddoway (1965). This diagram computes knoll erodibility (I_s) as a function of slope gradient for two different landscape positions. Knoll erodibility (I_s) was expressed as a percentage (> 100 %) for qualifying points and I′ (the factor combining I and I_s) was estimated by computing the product of I and I_s for these points (Chepil et al., 1962; Woodruff and Siddoway, 1965). Following periods of cultivation, I′ was reduced by 50 % until seeding following the advice of Bondy and associates (1980).

K factor values were obtained from the equations of Williams et al. (1984) in Skidmore (1988). K values were estimated for each

Table 4. Soil Erodibility by Soil Mapping Unit.[a]

Soils[b]	Number of Samples	Average I Value[c]	28	38A	385B	38B
Nishon(28)	3	280.9	-			
Ethridge(38A)	7	180.2	.05	-		
Ethridge(385B)	27	253.3	#	.05	-	
Ethridge(38B)	13	234.2	#	.10	#	-

[a]Difference of means test results indicating level of significance of difference of means in proportions. The # symbol indicates no significant difference.
[b]Soil numbers are soil mapping units used by the soil survey team, SCS, Fort Benton (see also Figure 3).
[c]See Appendix C for table showing map identification codes, soil mapping unit, percentages of soil aggregates > 0.84 mm and soil erodibility (I) index values for each of the 50 surficial soil samples.

cropstage period or tillage operation. A ridge height of 42 mm and a ridge spacing of 356 mm was used to estimate K for periods of cultivation (.90); while a ridge height of 102 mm and a ridge spacing of 356 mm was used for periods immediately following seeding (.49); and a ridge height of 25 mm and a ridge spacing of 610 mm was used for the periods following cultivation with a toolbar and duckfoot implements (.66) (see Table 5).

At this stage, each point's location within a soil mapping unit was recorded (see Figure 3 and Table 18, Appendix C). Using the appropriate average I′ (E1, equation #2), E2 (equation #3) was computed for each period of the winter wheat/summer fallow system as the product of I′ and K. Next, the annual C value, 0.90, was multiplied by E2 to compute E3 (equation #4). This C value is used by the SCS to represent the vicinity

Table 5. Estimates of K Factor, Vegetation Weight and Erosive Wind Energy for Cropstage Periods and Tillage Operations, Jackson Farm, Carter, MT.

Period	Activity[a]	Loss of Residue %	Vegetation Weight kg ha^{-1}	Small Grain Equivalent kg ha^{-1}	K	EWE in Period[b]
8/15-10/1	Harvest	-	3035	10270	.49	.05
10/1-4/1	Winter	.20[c]	2430	8270	.66	.74
4/1-5/1	Cultivation(2)	.30[d]	1190	2110	.90	.09
5/1-10/1	Summer Fallow	.20[c]	950	1765	.90	.17
10/1-11/1	Seeding	.30[d]	760	1705	.49	.09
11/1-4/1	Winter	.20[c]	180	520	.49	.65
4/1-5/1	3 - 4 weeks growth	-	390	980	.49	.09
5/1-8/15	Mature growth	-	1100	2310	.49	.12

[a]Activity or cropstage growth completed during period in Column 1.
[b]Proportion of erosive wind energy.
[c]Loss of dead residue for summer and winter due to biomass decomposition.
[d]Estimates of residue loss due to tillage operations from National Agronomy Manual, Montana Supplement, Table 1, (USDA-SCS, 1988); 60 kg ha^{-1} assumed to remain after deep furrow drill seedings (Nadwornick, personal communication, 1990).

of Carter, MT and was interpolated from a statewide contour map of C values (McPhail, personal communication, 1987).

The next stage of the computation incorporated the field length factors, L and Lo. The field length of the study area was a function of the unsheltered distance (i.e., distance in which wind barrier erosion control measures were not used) of the field strips. On the Jackson farm this was simply the width of the field strips from the western edge to the location of the sample point along the wind erosion direction due to the fact that no barrier and/or other wind control practices were employed. Data characterizing wind direction and intensities at Great Falls, MT from the Montana Supplement of the 1988 National Agronomy Manual (SCS, 1988) and WEE handbook (Skidmore and Woodruff, 1968) were used to determine the predominant wind erosion direction.

The minimum windspeed necessary for wind erosion is approximately 29 km hr^{-1} (8 m sec^{-1}) (Bondy et al., 1980). The evaluation of wind direction and intensity only considered winds above this threshold and revealed two predominant wind erosion directions of SW and WSW. The WSW direction applied to the periods of January to March and October to December. The SW direction applied to the period of April to September. The unsheltered distance for each point was obtained by measuring lines drawn parallel to this predominant wind direction (WSW) from the western edge of the field strip to the sample point. This value was used for January to March and also for October to December. The unsheltered distance along the SW direction was estimated by dividing the L along WSW by the cosine of 22.5° (the angle of the difference between the two directions). This L value was applied between April and September. These L values were then used to compute the field length weighting factors WF and Lo (equations #5a and 5b). E4 was then calculated for each period of the cycle (equation #5).

The final factor of the WEE, the vegetative cover factor (V), was needed to complete the computation of erosion estimates. The V factor was a function of cropstage period, tillage operation and stubble residue above-ground weight (Table 5). The V factor for each period was converted to a small grain equivalent using equations 7b, 7c or 7d. Equation 7a was then used to determine the factor value input, V, which was used in equations #6a and #6b to estimate soil losses at each sample point.

Standing stubble weight was estimated by multiplying the average yield for the Jackson Farm, 25 bushels acre^{-1} (Jackson, personal communication, 1987; McPhail, SCS, personal communication, 1990), by 110 pounds bushel^{-1} to obtain an above-ground weight estimate of residue of 3025 kg ha^{-1} (USDA-SCS, 1988). The small grain equivalent of the six points that fell in the grassed area was estimated to be 5600 kg ha^{-1} (John Siddoway, SCS-Fort Benton, MT, personal communication, 1990). Sixty kilograms per hectare of dead residue was assumed to remain after seeding and four weeks crop growth, weighing approximately 120 kg ha^{-1}, was assumed before dormancy in winter, for a total of approximately 180 kg ha^{-1} (Nadwornick, SCS State Agronomist, Bozeman, MT, personal communication, 1990).

A soil loss estimate for each period of the crop/fallow cycle was calculated by using E5 (equation #6). The annual erosion rate estimates for each period were then multiplied by a weighted average of erosive wind energy (see Table 1 for monthly totals) in the same period to estimate period wind erosion rates. The period totals were then added to estimate annual wind erosion rates for the crop and fallow years of the cycle. Table 6 shows these computations for sample point 1D.

Table 6. Sample WEE Computation for Sample Point 2M.[a]

Period	K	Residue	SG_e	V	EWE[b]	E5	Period Erosion
		kg ha^{-1}		Mg ha^{-1}			t ha^{-1} yr^{-1}
Fallow year							
8/15-10/1	.49	3035	10270	74.40	.05	0.0	0.0
10/1-4/1	.66	2430	8270	55.39	.74	0.0	0.0
4/1-5/1[c]	.90	1190	2110	8.60	.09	0.1	0.0
5/1-10/1[c]	.90	950	1765	6.74	.17	0.1	0.0
Crop Year							
10/1-11/1	.49	759	1705	6.43	.09	0.1	0.0
11/1-4/1	.49	180	520	1.27	.65	5.4	3.5
4/1-5/1	.49	390	985	3.04	.09	2.0	0.2
5/1-8/15	.49	1100	2310	9.78	.12	0.0	0.0
Total Cycle					2.0		3.7
Average					1.0		1.8

[a]WEE computed using I′ of 234.2 t ha^{-1}, C of .90, L of 85 m.
[b]Proportion of cumulative erosive wind energy (EWE) in period in Column 1.
[c]Periods in which soil erodibility (I′) is reduced by 50 % following plowing (Bondy et al., 1980).

Cesium-137 Erosion Estimates

Cesium-137 Sample Site Selection

Slopes were paced in the field to determine the location of ^{137}Cs transects. The highest point on the transect was chosen as a hilltop sample site and the lowest point was chosen as a channel sample site. Following the method of Brown et al. (1981b) slopes were segmented by pacing uphill, following the path of greatest slope, dividing slope lengths into thirds with footslope and midslope sample sites chosen at distances one third and two thirds up the slope, respectively. Figure 6 illustrates how this selection was made for each transect, with the other half selected by using the same method on the opposite slope starting at the same channel site. A total of six transects with seven sample sites (two hilltops, two midslopes, two footslopes and one channel) were delineated in the field. Due to the high cost of laboratory analysis, only a portion of the samples were analyzed for ^{137}Cs activity. The samples collected during the first sample collection were analyzed first. Unfortunately, enough funds were not available to analyze the samples collected during the second collection period, one year later. Therefore, the ^{137}Cs results are biased towards the steeper sloping, eastern portion of the study area, where the first samples were collected (see Figure 7).

Figure 7 also indicates the sites that were sampled in the incised channel leading from the drained lake to the pond (n = 3), in the pond bottom (n = 4), and along a fence line 250 meters from the study watershed (n = 4). The samples taken along the fenceline represent (uneroded) control sites because the fence acted as a barrier to wind erosion and a tillage berm prevented overland flow from crossing this fenceline. Overall, a total of 53 sites was used and soil samples representing 261 increments were collected, although only 83 increments from 25 sites were analyzed for ^{137}Cs activity.

Following the method used by Brown et al. (1981b), a strategy to define areas of landscape units, termed topographic positions, was used. These areas were computed using slope profiles which were divided into segments by assigning boundaries to points halfway between each ^{137}Cs

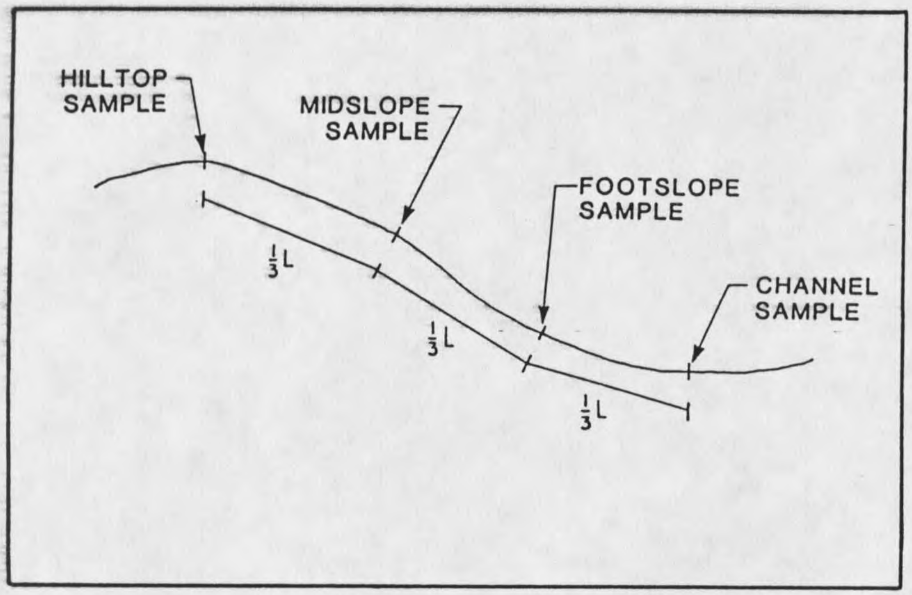

Figure 6. Diagram showing topographic positions.

sample location. The profiles were drawn 2 cm (50 m) apart on a copy of the topographic map and areas for each topographic position were defined by connecting each boundary point to its counterpart on adjacent slope profiles. These areas were calculated by adding up 2.5 m^2 squares within the boundary lines using metric grid paper. The areas corresponding to each of the topographic positions are shown in Figure 8.

<u>Cesium-137 Sample Collection</u>

The ^{137}Cs samples were gathered from 1 m^3 hand excavated soil pits. Care was taken to preserve the soil pedon in a natural, uncompacted state. After the soil pit was dug, the ^{137}Cs samples were removed in a lateral method to minimize the effects of compaction during sampling. A 5.1-cm diameter PVC tube with a cap affixed to one end to prevent loss was used to collect the samples. Holes were drilled into the cap to allow air to

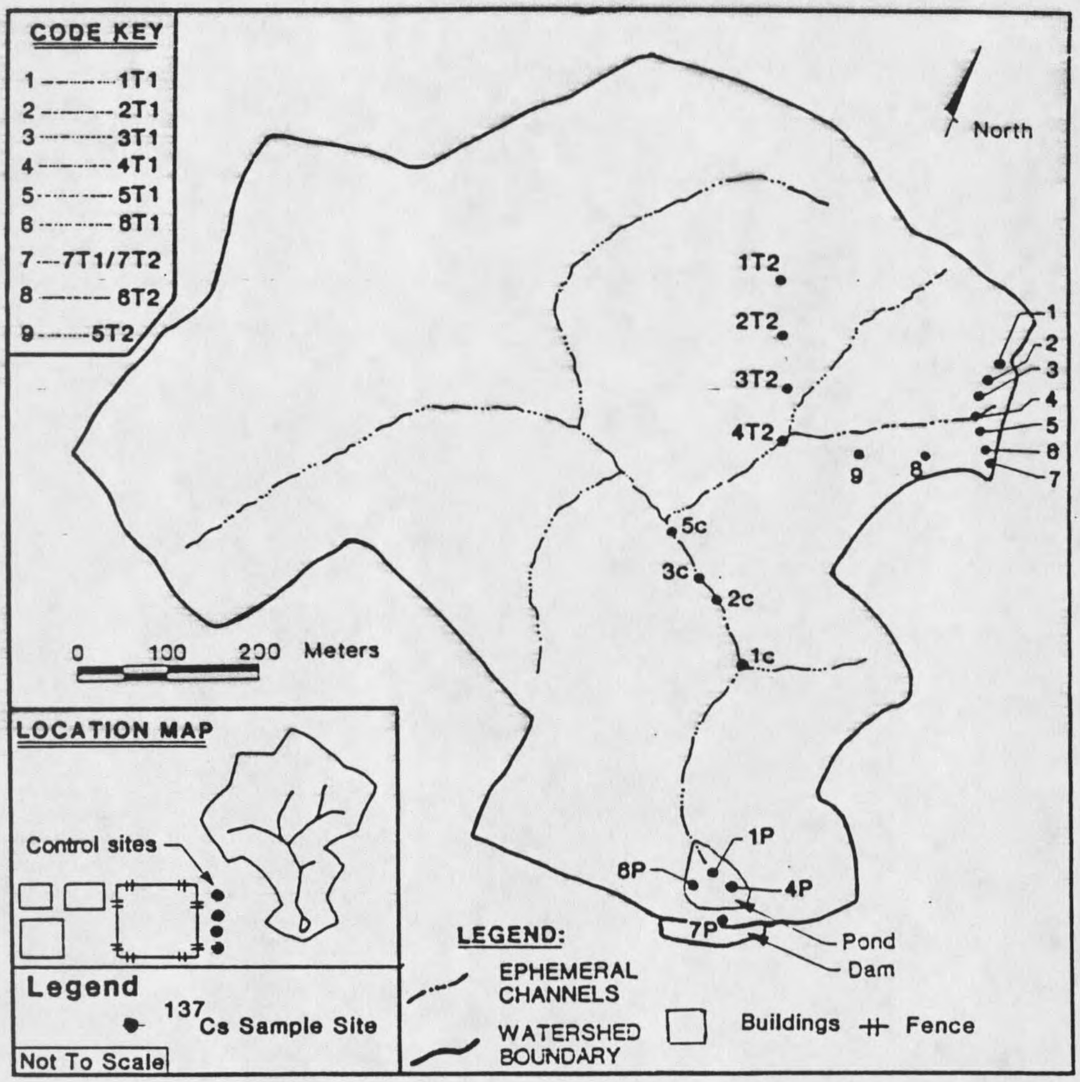

Figure 7. Study area map showing locations of ^{137}Cs samples within study watershed and locations of control samples on the Jackson Farm.

escape so it would not displace potential sample volume.

The tube was driven horizontally into the wall of the soil pit with a mallet. The tube was 7.6 cm long and was completely filled with each sample to obtain standard sample volumes. The tube was removed from the pit wall with a large knife. Care was taken to preserve the integrity of the sample by preventing the entry of topsoil and organic matter into the tube during extraction. The samples were then placed in plastic lined

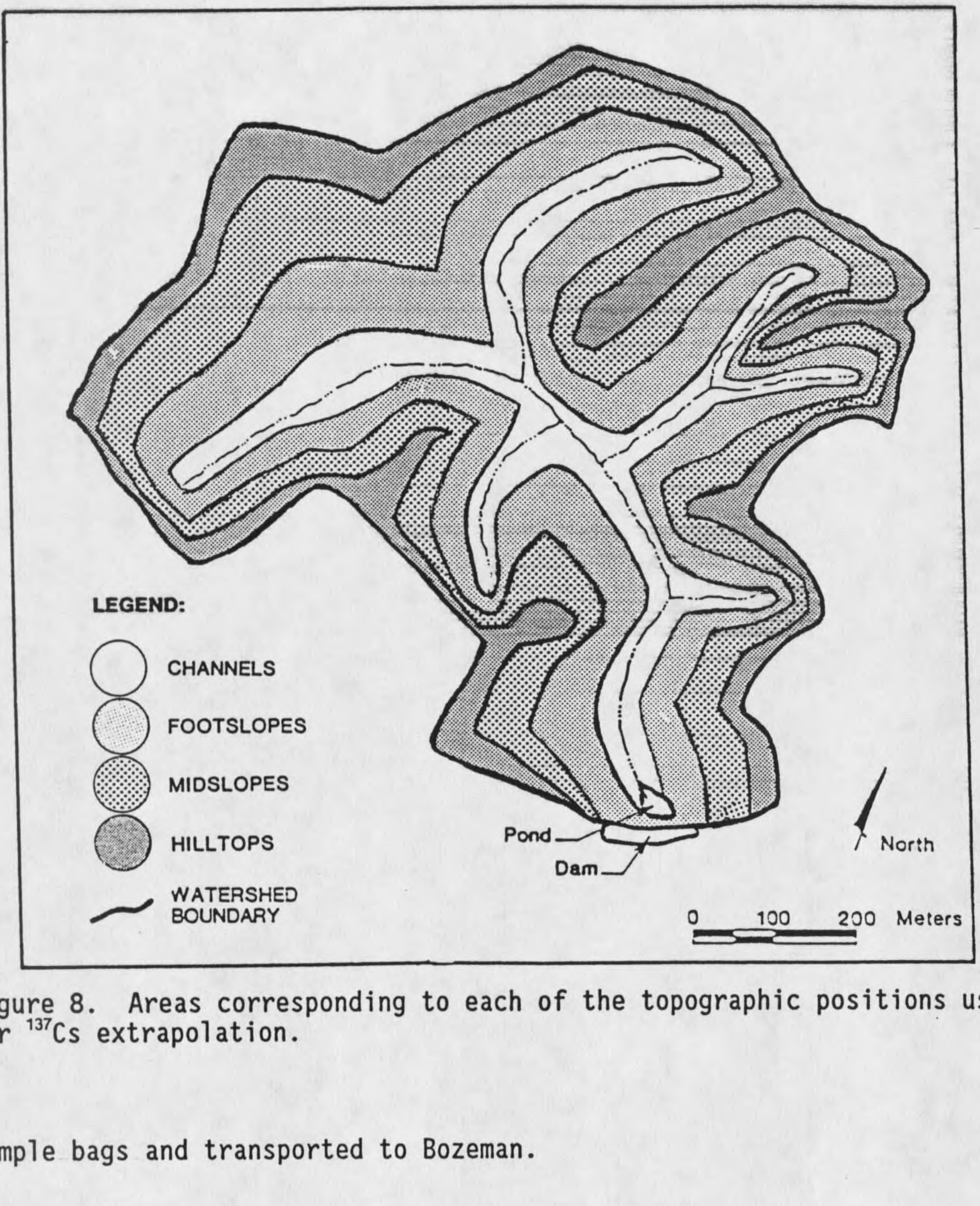

Figure 8. Areas corresponding to each of the topographic positions used for ^{137}Cs extrapolation.

sample bags and transported to Bozeman.

Cesium-137 Sample Increments

The samples were taken in increments whose depths corresponded to the width of the sampling device, 5.1 cm, or multiples of it, depending on tillage practices at different sampling sites. Plowed sites were assumed to have uniform ^{137}Cs activity in their plow layer, or Ap horizons

(Brown et al., 1981b; Campbell et al., 1982). The plow layer was set as 15 cm (Jackson, personal communication, 1987; McPhail, personal communication, 1987). This sample was collected as three successive 5.1 cm deep increments and then bulked. From that point it was treated as a homogeneous sample. Below these increments, samples were gathered as single increments of 5.1 cm to a total depth of about 30 cm for the plowed sites. The non-tilled sites (i.e., in the incised channel, pond bottom and the control sites) were sampled from the top of the soil pit in 5.1 cm increments. A minimum of five samples were collected for each non-tilled site.

Cesium-137 Sample Preparation

In the lab, the ^{137}Cs samples were dried at 105° C for a minimum of 72 hours, and then mechanically ground and sieved through a 2 mm screen. Each sample was weighed and a riffle splitter was used to remove a representative 100 g sample. This uniform 100 g sample size was required to standardize the counting times (Dr. Ingevar Larsen, Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN, personal communication, 1988). The samples were then transferred to dry soil sample bags, closed and wrapped for shipment.

Cesium-137 Laboratory Analysis

The samples were analyzed for ^{137}Cs concentrations by Dr. Ingevar Larsen at Oak Ridge National Laboratory with a Canberra lithium drifted germanium (Ge(Li)) gamma ray detector coupled to a Nuclear Data No. 6700 4096 channel data analyzer system (Cutshall and Larsen, 1980; Larsen and Cutshall, 1981). The procedure required a counting time of 60 to 100 minutes per sample. Eighty-three sample increments were analyzed for ^{137}Cs activity, expressed in picocuries per gram of soil (pCi g^{-1}). A curie is a measure of radioactivity such that one curie is 3.7 x 10^{10} disintegrations per second per gram of radium and one picocurie is 10^{-12} curies (Cutshall and Larsen, 1980; Arnalds, 1984). The ^{137}Cs mass concentrations are reported in units of pCi g^{-1}. The ^{137}Cs data were transformed from pCi g^{-1} to pCi cm^{-3} by multiplying mass concentrations by average bulk densities (obtained from a weighted average bulk density by depth of the horizon in which the ^{137}Cs sample was collected). This ^{137}Cs activity was converted to areal concentration by multiplying the activity (pCi cm^{-3}) by the depth of the sample layer (cm).

Bulk Density Sample Collection

Bulk density measurements were required for the ^{137}Cs areal concentration calculations. Bulk density samples were taken at the same time as the ^{137}Cs samples using soil sampling tins of known volume. Every soil horizon was sampled in each soil pit. The generally dry soil samples were dried and weighed to determine dry bulk density. It was not possible to determine water content or moist bulk density due to the lack of control of evaporation in the storage area at the field site and the long time between sampling collection (two 4-week periods, one year apart).

Method of Areal Cesium-137 Analysis

Areal analysis relies on the fact that ^{137}Cs loss has been found to be proportional to soil loss and to vary at depth (Rogowski and Tamura, 1970; McHenry et al., 1973; McHenry and Ritchie, 1977). The method used for areal analysis of ^{137}Cs in this study was taken from De Jong and associates (1983). This method computes soil loss using the following equations:

$$^{137}Cs \text{ loss} = [0.95\ X - Y]\ [0.95\ X]^{-1} \qquad (8)$$

where ^{137}Cs loss is the amount of ^{137}Cs lost (percent), X is average ^{137}Cs present at control site (pCi cm^{-2}), Y is average ^{137}Cs present at eroded sites (pCi cm^{-2}); and

$$\text{soil loss} = {}^{137}Cs \text{ loss} \times d \times BD \qquad (9)$$

where soil loss is the amount of soil (g cm^{-2}), d is the thickness (cm) of the layer in which ^{137}Cs is present, and BD is the average bulk density (g cm^{-3}) of the layer in which ^{137}Cs is present (De Jong et al., 1983).

A value of 95 % of the ^{137}Cs areal concentrations was used to make the calculations because previous studies had found that removal of ^{137}Cs by crops, animals and snow drifting is approximately 5% (De Jong et al., 1982; Arnalds, 1984). The concentrations of ^{137}Cs were expressed in pCi cm^{-2} and were generated by multiplying the laboratory concentration data (pCi g^{-1}) by the bulk density (g cm^{-3}) and the increment depth (cm) (De Jong et al., 1983).

In tilled sites, gains of ^{137}Cs by deposition were calculated using ^{137}Cs distribution at depth. The depth to which ^{137}Cs was present in these areas was estimated by subtracting 15 cm (plow layer depth) from the maximum depth in which ^{137}Cs was present. The thickness of soil deposited by soil redistribution was found by:

$$D_1 = D_2 - 15 \text{ cm} \qquad (10)$$

where D_1 is the thickness (cm) of soil deposited, D_2 is the maximum depth (cm) to which ^{137}Cs is present, and 15 cm is the depth of cultivation. Soil gain was estimated as

$$\text{soil gain} = D_1 \times BD \quad (11)$$

where BD is soil bulk density (g cm^{-3}), and soil gain is expressed in g cm^{-2} (De Jong et al., 1983). For untilled sites, gains of ^{137}Cs were estimated by multiplying the maximum depth of ^{137}Cs activity detected by the site's average bulk density. Soil gains were only computed if the site's total areal concentration was greater than that of the average of the control sites (11.10 pCi cm^{-2}).

Erosion and Deposition Rate and Mass Balance Estimation Method

Annual erosion and deposition rates were determined by dividing total soil loss/gain by the time that ^{137}Cs has been deposited in the watershed (since 1954) except for the pond sites. Deposition at those sites was computed using the time period since dam construction (i.e., 1973 to 1987, or 14 years). Averages based upon the areal concentrations and areas of landscape units (topographic positions) were used to determine the erosion or deposition rate associated with each topographic position. These values were then multiplied by the area of each topographic position to obtain mass erosion and deposition rates in Mg yr^{-1}. Hilltop, midslope, footslope and incised channel erosion rates were combined to estimate a net mass erosion rate and tilled channel and pond deposition rates were combined to obtain a net deposition rate.

CHAPTER 3

RESULTS

USLE Erosion Estimates

USLE soil loss estimates were computed at 81 points on a randomly located 125 m grid using constant R, K and P values and spatially variable C, L and S values in this study. Most of the variability in the erosion estimates was due to variations in the topographic factors, L and S, because one C was used with the exception of six points which fell within the grassed margin of the pond area. The final 60-sample set was determined using the method of Griffin et al. (1988) and Wilson (1986b) to eliminate sample grid points near hilltops and in depositional environments. The USLE factor values were combined using the point method of Griffin et al. (1988).

The topographic factor and soil loss estimates are summarized in Table 7. The slope gradients and slope lengths varied considerably from point to point and account for most of the spread in soil loss estimates. Watershed soil losses averaged 4.5 t ha^{-1} yr^{-1}. All 81 point estimates are reproduced in Figure 9 as a frequency histogram (including the 21 points where erosion equals 0.0 t ha^{-1} yr^{-1}. This diagram indicates how the distribution of point estimates is positively skewed with large numbers of estimates concentrated in the 0 - 6 t ha^{-1} yr^{-1} range and smaller

Table 7. USLE Soil Loss Estimates.[a]

	Minimum	Maximum	Average	Standard Deviation
Slope Length (m)	19.0	373.0	92.2	71.3
Slope Gradient (%)	0.3	16.0	4.2	3.0
Soil Loss (t ha^{-1} yr^{-1})	0.0	14.9	4.5	3.6

[a]USLE estimates using sample generated from a random 125 m grid (n = 81).

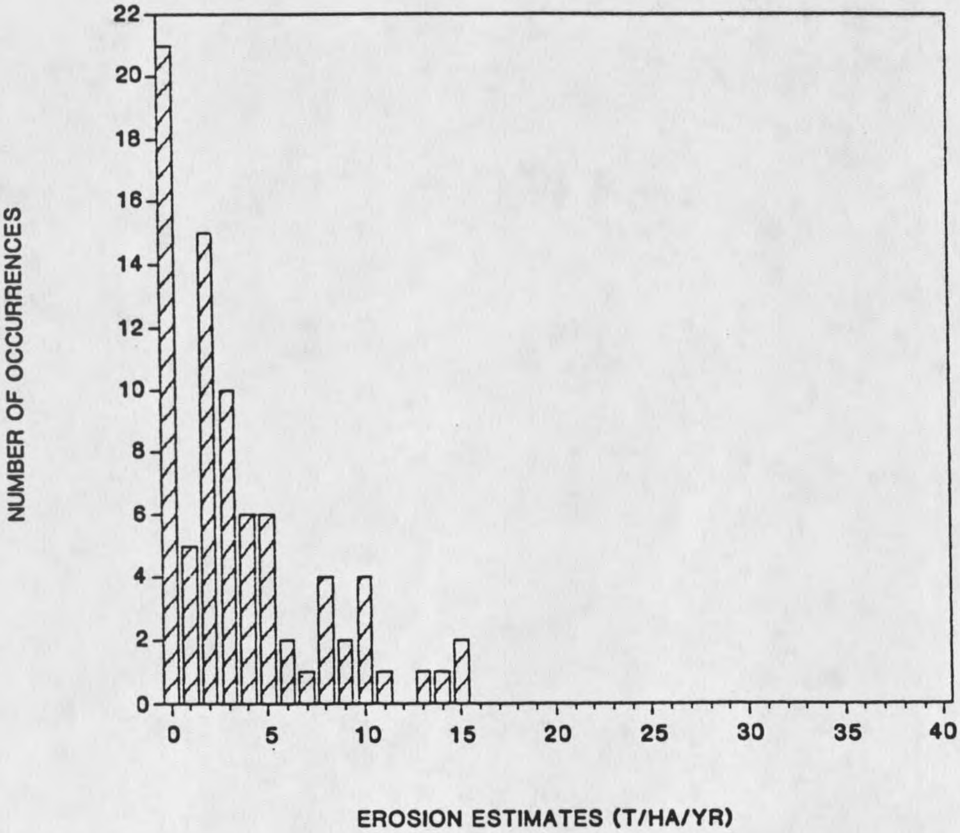

Figure 9. Distribution of USLE soil loss rates for Carter watershed (n = 81).

numbers spread throughout the 7 - 18 t ha^{-1} yr^{-1} range. A nonparametric statistical analysis was conducted to determine the level of confidence of the watershed USLE soil loss average. Using a sample size of 60, the watershed soil loss average of 4.5 t ha^{-1} yr^{-1} and standard deviation of 3.6 t ha^{-1} yr^{-1}, and a desired precision of $\pm$ 1.0 t ha^{-1} yr^{-1}, Z equaled 2.13, corresponding to an area under a normal curve of 0.4834. Soil formation rates commonly assumed for soils developed in glacial tills exceed 1.0 t ha^{-1} yr^{-1} (Dr. Gerald Nielsen, Department of Plant and Soil Science, Montana State University, Bozeman, MT, personal communication, 1990). This analysis indicates that the sample mean fell within $\pm$ 1.0 t ha^{-1} yr^{-1} of the true mean with a confidence level of 96.7 % (level of significance of 0.033).

The spatial variability of USLE soil loss estimates is depicted by Figure 10. The squares, triangles and circles denote points that represent hilltops, ephemeral channels and concave slopes, respectively. These points were excluded from the original 81 point sample set and erosion was estimated to be 0.0 t ha^{-1} yr^{-1} for them. Examination of this diagram shows an area of high erosion due to water in the eastern half of the watershed. This fluvially erosive area corresponds to steeper sloping areas of the eastern half of the watershed (compare Figures 2 and 10).

WEE Erosion Estimates

Eighty points were sampled for the WEE calculations. The WEE calculations were based upon spatially variable I′ and L, temporally variable I′, K and V, and constant C factor values. The I′ and L factor

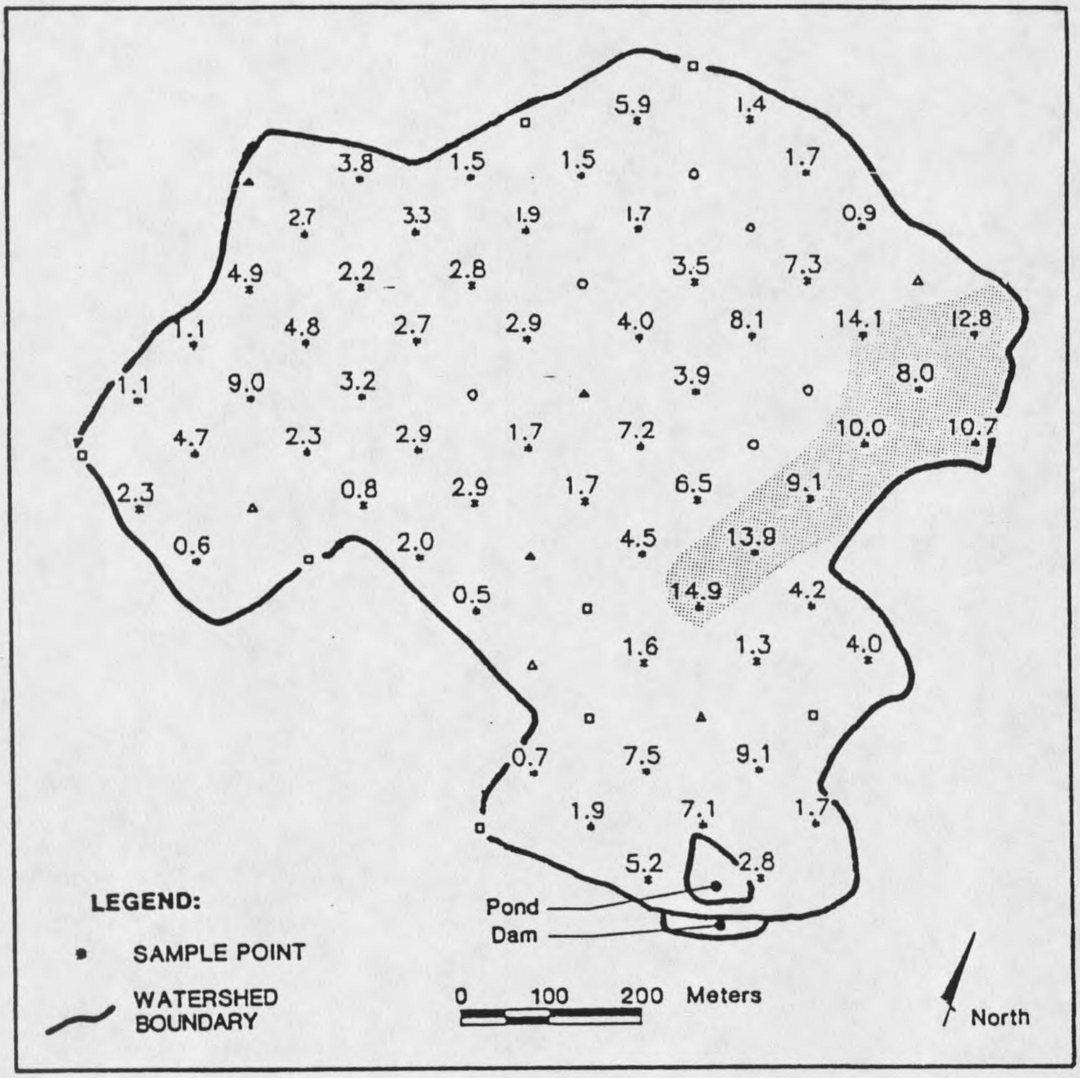

Figure 10. Spatial variability of USLE soil loss rates (t ha^{-1} yr^{-1}) for Carter watershed. Squares, triangles and circles represent points where the USLE estimated erosion as 0.0 t ha^{-1} yr^{-1}. Shaded area represents area of high water erosion.

values were obtained using topographic and soils maps. L was adjusted to reflect a seasonal shift in the wind erosion direction. Similar to Bondy et al. (1980), K and V factors were estimated using the 1988 National Agronomy Manual and the equations reported in Skidmore (1988). The C value was held constant over time but erosive wind energy (EWE) values, which varied by period, were incorporated. Wind erosion was estimated for each cropstage and tillage period of the two year crop/summer fallow system for all 80 points. A two year weighted average was computed based upon period estimates of soil loss, obtained by multiplying the period soil loss estimate by the cumulative erosive wind energy in the period.

Table 8 summarizes the watershed minima, maxima, averages and standard deviations for I′ and L factors and watershed WEE soil loss estimates. The watershed WEE average was 4.5 t ha^{-1} yr^{-1}. Figure 11 shows all 80 soil loss estimates as a frequency histogram. This diagram reveals a positively skewed distribution, influenced by the large number of estimates that were 0.0 t ha^{-1} yr^{-1}. A nonparametric statistical test was used to determine the level of confidence of the WEE watershed average. Using a sample size of 80, the watershed average (4.5 t ha^{-1} yr^{-1}), and standard deviation (4.6 t ha^{-1} yr^{-1}) and a desired precision of $\pm$ 1.0 t ha^{-1} yr^{-1}, Z equaled 0.65, corresponding to an area under a normal curve of 0.2422. Therefore, with a sample size determined by the intersections of a 125 m grid, the watershed WEE average estimates erosion for the watershed within $\pm$ 1.0 t ha^{-1} yr^{-1} of the true mean with a confidence level of 48.4 % (level of significance of 0.516). This low level of confidence occurred because of the high standard deviation that is due to the influence of the outlying point's (2P) extremely high estimate (See Figure 11). This point had a high wind erosion estimate due to its high soil erodibility caused by a high I_s adjustment of 671 %.

Table 8. WEE Soil Loss Estimates.[a]

	Minimum	Maximum	Average	Standard Deviation
I′ Factor Values (t ha^{-1} yr^{-1})	180.2	670.3	256.0	56.0
Field Length L (m)	0	155	41	43
Soil Loss (t ha^{-1} yr^{-1})	0	34.8	4.5	4.6

[a]WEE soil loss rate estimates using a sample set generated from a random 125 m grid (n = 80).

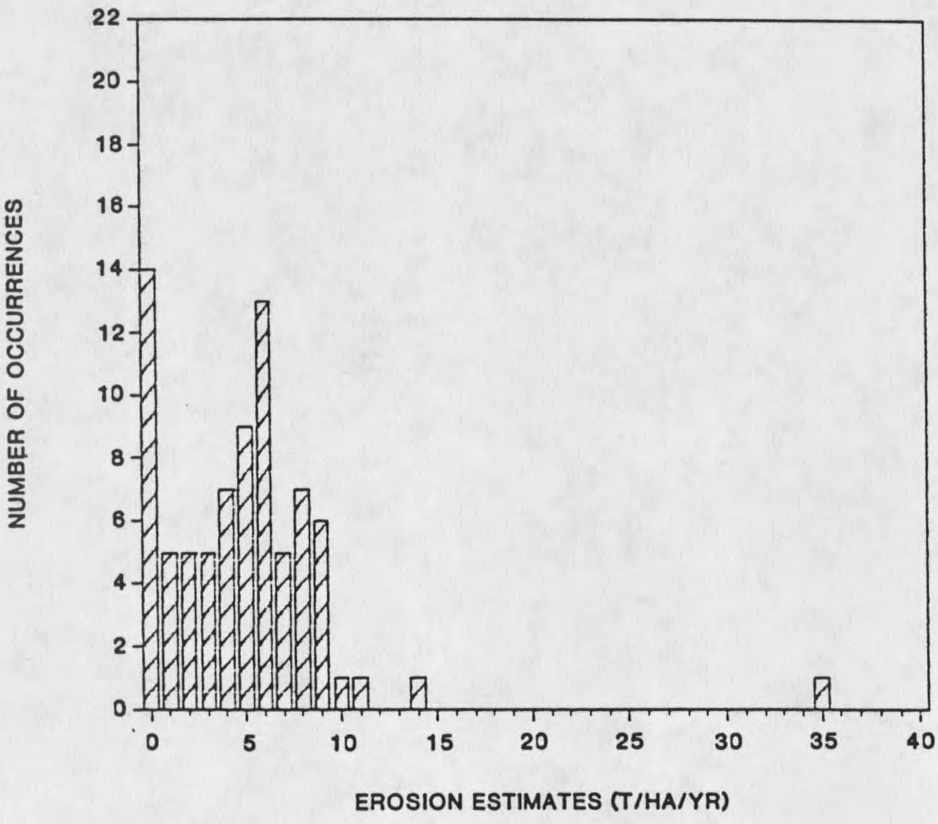

Figure 11. Distribution of soil loss rates for Carter watershed using WEE point method and 125 m grid (n = 80).

The spatial variability of the WEE results is depicted in Figure 12. The highest estimated soil losses were located on or near hilltops (compare Figures 2 and 12). There was also a group of high estimates in the central portion, near the old lakebed. Another trend is located in the grassed area near the pond, where the high small grain equivalent assigned to crested wheatgrass resulted in estimates of 0.0 t ha^{-1} yr^{-1}.

USLE and WEE Erosion Rate Estimates Combined

Though not customarily done, USLE and WEE results were combined to determine if any spatial patterns existed in the estimated soil losses. This was done to permit a rough comparison to the ^{137}Cs results, which include erosion from both water and wind, even though the models do not estimate gully erosion. This allowed for the identification of highly erosive areas and their spatial relationship to the location of the ^{137}Cs sample sites. Combining the USLE and WEE watershed averages, a predicted erosion rate of 9.0 t ha^{-1} yr^{-1}, based on a range from 0 to 36.5 t ha^{-1} yr^{-1}, was computed. The 81 point estimates were combined and depicted as a frequency histogram (Figure 13).

The spatial variability of the USLE/WEE combined results is shown in Figure 14. The diagram shows the combined result from the two models for each grid point, with the squares, triangles and circles representing the points were water erosion equaled zero for the USLE. The point that was excluded from the WEE analysis was assumed to have erosion equal to 0.0 t ha^{-1} yr^{-1} due to its location in the bottom of the 4-feet deep incised channel (excluding it from both the USLE and WEE). These data indicate very high soil loss rates along the eastern margin because of

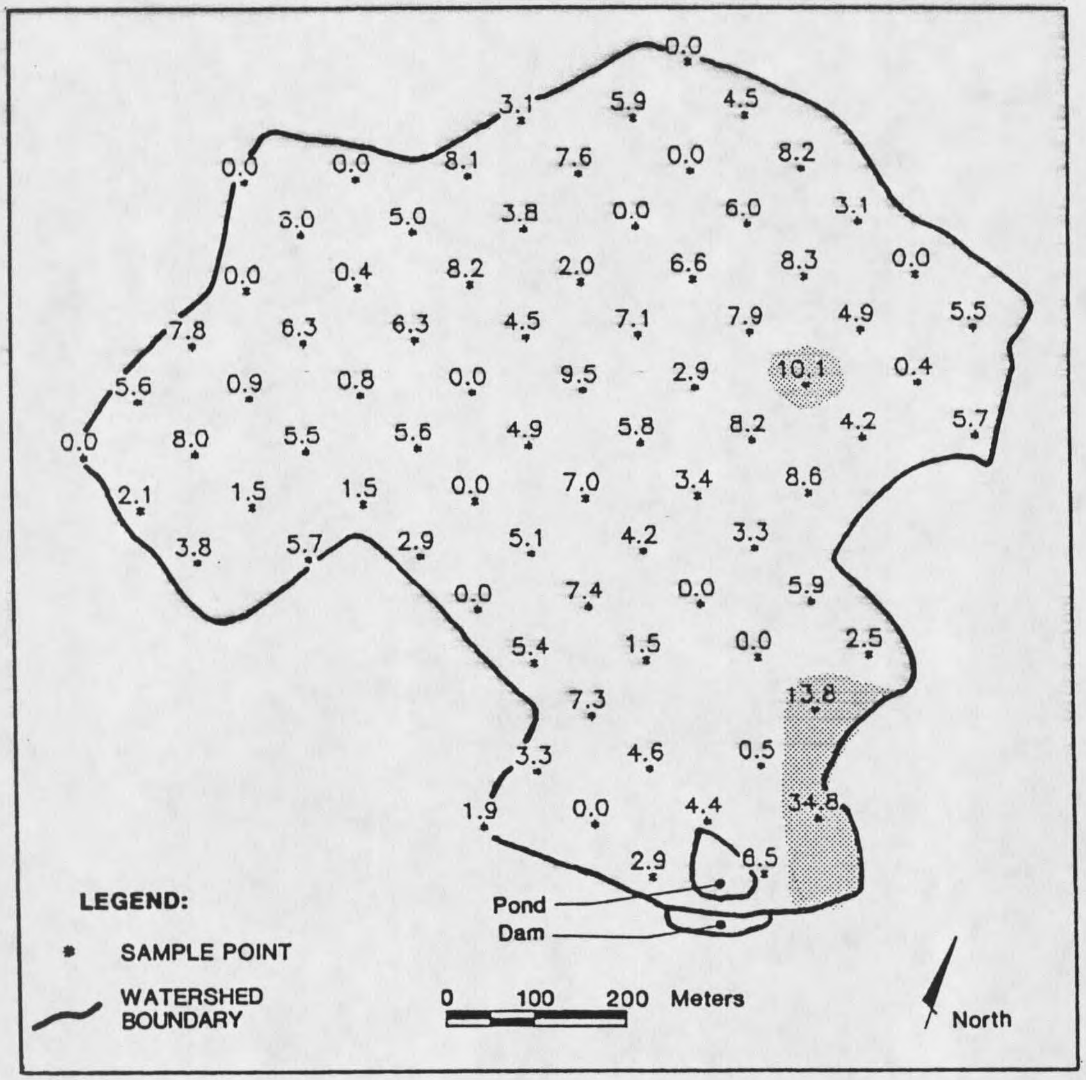

Figure 12. Spatial variability of soil loss rates (t ha^{-1} yr^{-1}) for Carter watershed using WEE point method and 125 m random grid. Shaded areas represent areas of high wind erosion. Excluded point (40) not shown.

both high fluvial erosion rates and high rates for wind erosion on the hilltops. This result shows how the ^{137}Cs transect sample sites were located in high soil loss areas.

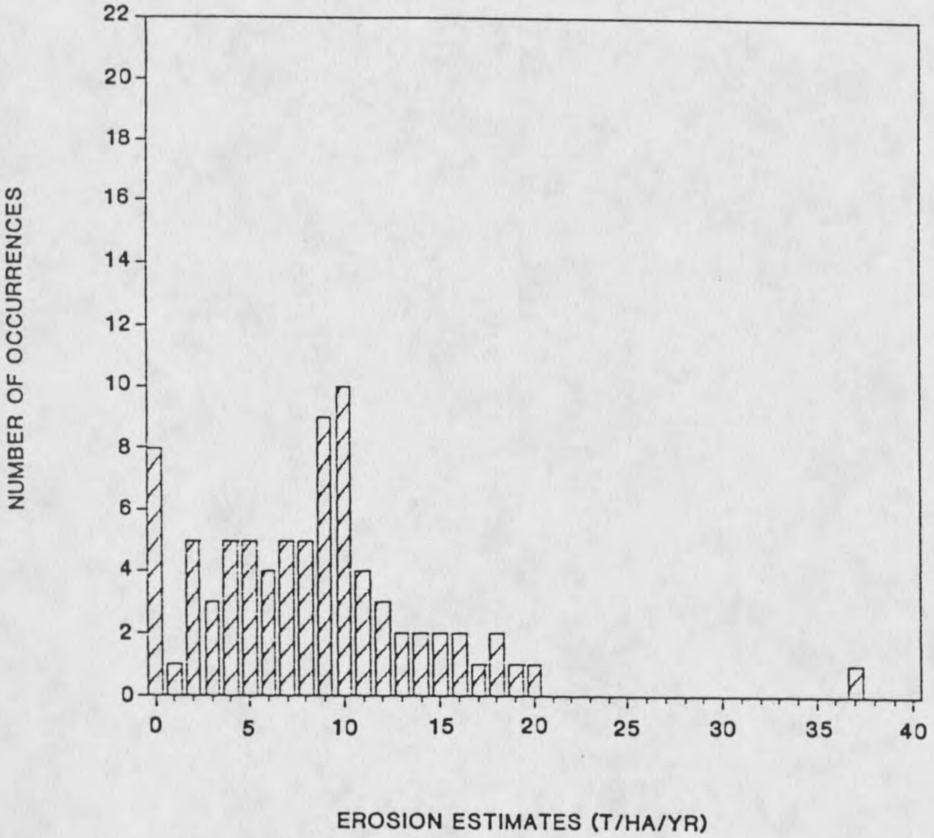

Figure 13. Distribution of total soil loss rates for Carter watershed using USLE/WEE point methods and 125 m grid (n = 81).

Cesium-137 Results

The results of the laboratory analysis for ^{137}Cs activity are depicted in Figure 15. The ^{137}Cs areal activity at each sample site varied with depth and is reproduced in Figure 15 as bar graphs representing each increment's ^{137}Cs activity. The ^{137}Cs activities (pCi cm^{-3}) shown were calculated by multiplying the mass concentrations of ^{137}Cs activity (pCi g^{-1} by the increment's bulk density (g cm^{-3}). Note that 3 of 4 pond sites and sites 3C and 5C did not reach a depth of zero detection, causing estimates of deposition rates to be underestimated. The total sample

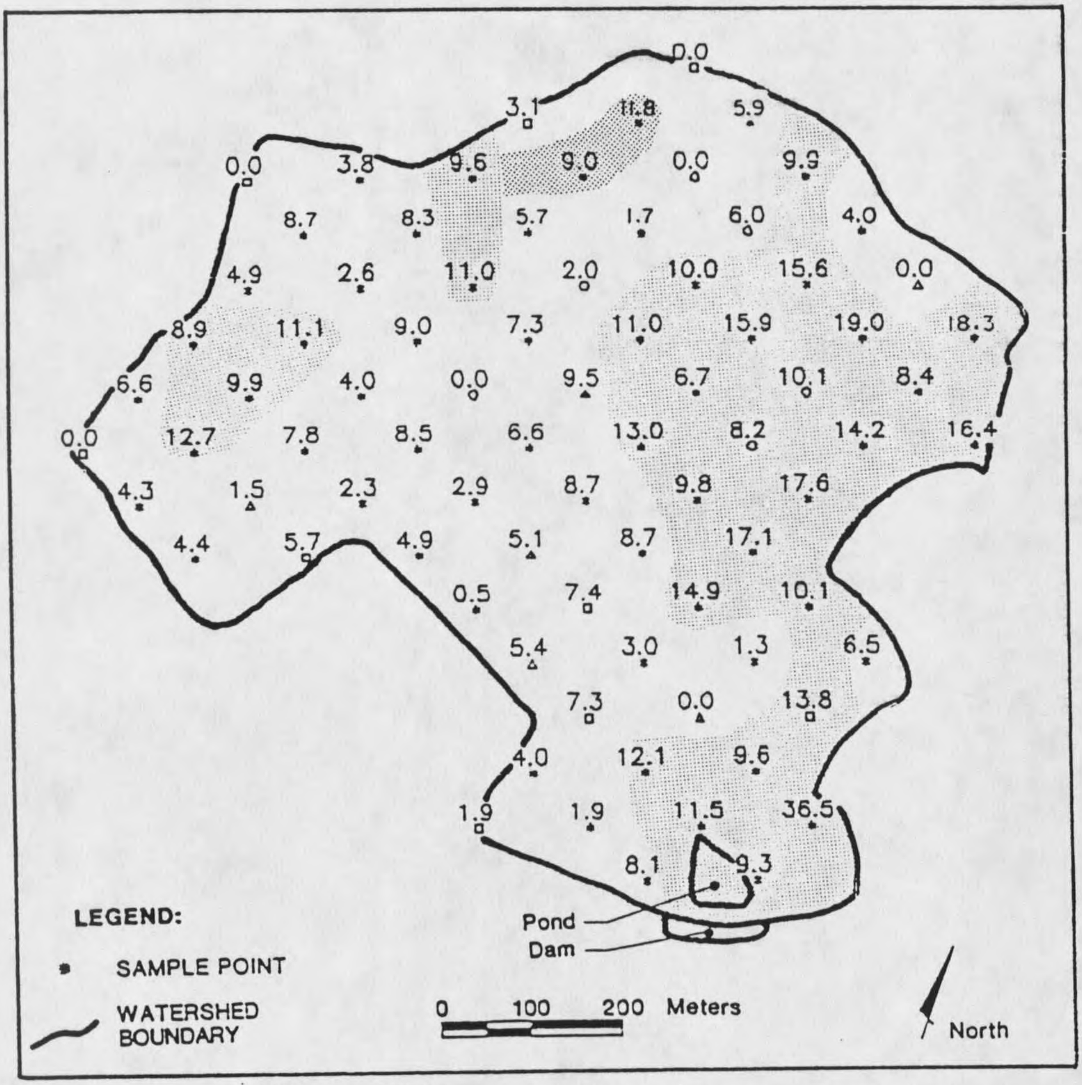

Figure 14. Spatial variability of soil loss rates for Carter watershed using USLE and WEE point methods. Squares, triangles and circles represent points where the USLE estimated erosion as 0.0 t ha^{-1} yr^{-1}. Shaded areas represent areas of high net erosion.

depth was inadequate for these samples. Site 3C's total areal concentration (pCi cm^{-2}) was lower than the control sites average, so, even though its depth profile is similar in shape to that of a depositional site, it was treated as an eroding site. The changes in activity for the control, pond and 5C sites are important to notice as they reflect much greater ^{137}Cs activity than the transects and three of

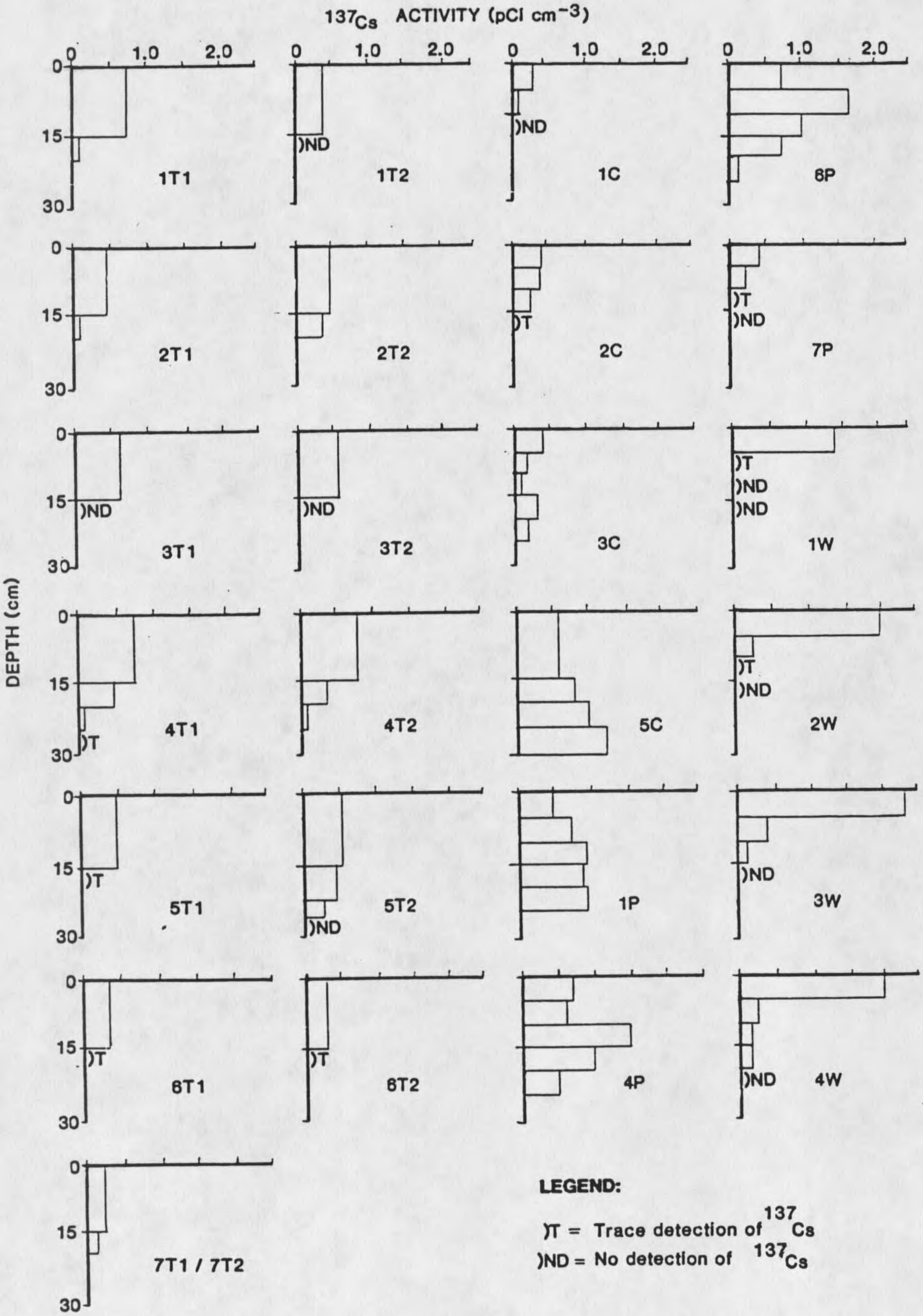

Figure 15. Site areal ^{137}Cs activities (pCi cm^{-3}) for Carter watershed.

the four incised channel sites (site 5C is a depositional site and therefore an exception). The diagram of site 7P stands out in comparison to the other pond sites. Its profile is typical of an eroding site, which is unusual because it was located on the margin of the pond. In general, however, the diagrams for different landscape positions are similar to those in the general model reproduced in Figure 1.

The ^{137}Cs sample sites were grouped and averaged, with the results shown in Figure 16. This graphical illustration shows the relationship of the topographic positions to the control samples by dividing the graph into two sections. Those topographic positions with averages to the left of the average areal concentration of the control sites, 11.10 pCi cm^{-2}, represent erosional sites, while those topographic positions with averages to the right of the line represent depositional sites. The average areal concentration is marked on the bar by a tick mark in the middle portion of the bar, with the whole bar representing the range of values. It is important to point out that several bars overlap, indicating the wide range of distributions and great spatial variability of the ^{137}Cs in sediments.

The equation based on a strong correlation of ^{137}Cs and annual precipitation of Arnalds (1984) and Arnalds et al. (1989) was used to predicted the amount of ^{137}Cs deposition at Carter. This predicts an areal concentration, 7.9 pCi cm^{-2}, 71 % of the amount found in the control average of this study, 11.1 pCi cm^{-2}.

Table 9 shows the results of the erosion and deposition rate calculations for each site. These rates characterized the soil erosion or deposition relative to the control sites. The fourth column of the

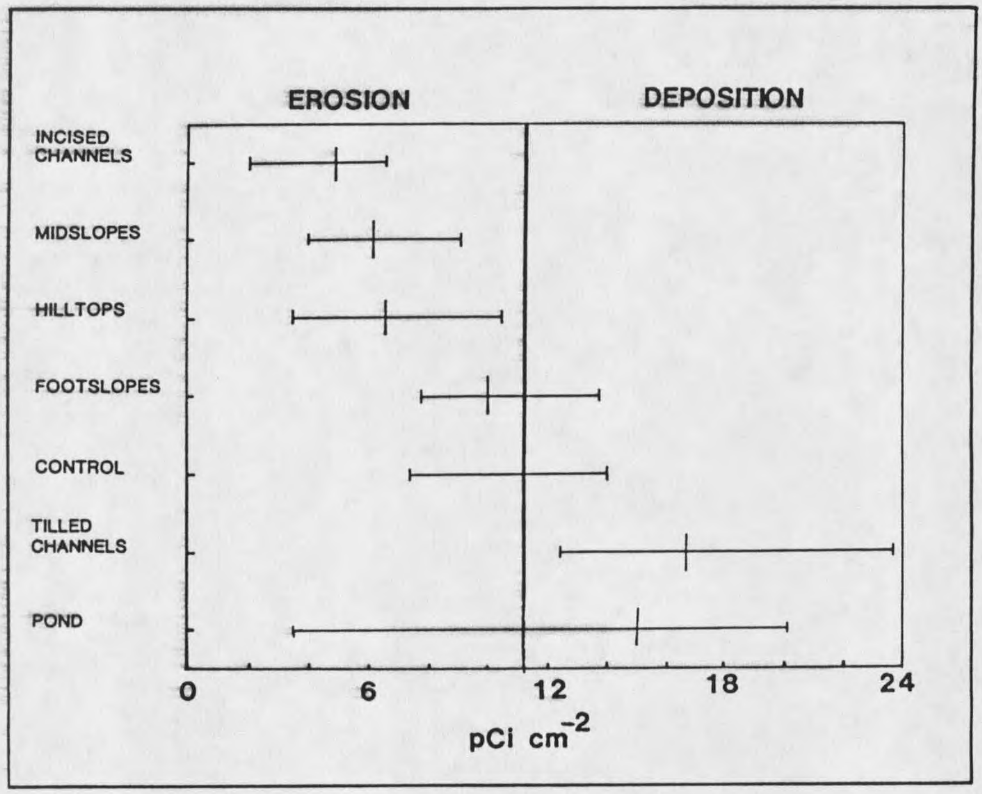

Figure 16. Range and average ^{137}Cs areal concentrations by topographic position.

table lists the ^{137}Cs depletion (a percent) for each site. This estimate was made only if a site's total areal concentration was less than the control site average. The average ^{137}Cs activities used for the control site's plow (0 to 15 cm) and 16 to 20 cm layers were 11.03 and 0.07 pCi cm^{-2}, respectively, or a total of 11.10 pCi cm^{-2}. Some of the 16 to 20 cm increments collected from transect sites had slightly greater ^{137}Cs than the 0.07 pCi cm^{-2} of the control site average. This would cause the comparison to result in a negative ^{137}Cs depletion value, although these results were disregarded following the advice of De Jong et al. (1983). Total soil loss or gain is shown in the fifth and sixth columns.

Table 9. Cesium-137 Erosion and Deposition Rate Estimates.

Site #	Topographic Position	Bulk Density g cm^{-3}	Cesium Depletion[b]	Total Soil Loss (or)	Total Soil Gain g cm^{-2}	Site Rate[a] Mg ha^{-1} yr^{-1}	Site Error (±)
1T1	Hilltop	1.27	0.08	1.61	--	4.9	0.6
7T1/7T2	"	1.23	0.76	13.44	--	40.7	3.2
1T2	"	1.25	0.42	7.67	--	23.3	4.1
2T1	Midslope	1.32	0.40	7.78	--	23.6	3.6
6T1	"	1.27	0.61	10.92	--	33.1	6.6
2T2	"	1.19	0.36	5.77	--	17.5	2.1
6T2	"	1.32	0.65	12.56	--	38.1	7.4
3T1	Footslope	1.32	0.17	3.29	--	10.0	1.1
5T1	"	1.37	0.32	6.11	--	18.5	2.5
3T2	"	1.30	0.22	3.98	--	12.1	1.8
5T2	"	1.30	--	--	12.70	-38.5	3.4
4T1	Tilled Channel	1.39	--	--	13.73	-41.6	3.3
4T2	"	1.35	--	--	12.50	-37.9	4.2
5C	"	1.23	--	--	16.35	-49.6	3.7
1C	Untilled Channel	1.40	0.81	17.00	--	51.5	9.0
2C	"	1.40	0.54	11.27	--	34.2	5.3
3C	"	1.40	0.42	8.74	--	26.5	6.2
1P	Pond Bottom	1.30	--	--	32.50	-232.1	32.2
4P	"	1.44	--	--	36.00	-257.5	24.5
6P	"	1.33	--	--	33.25	-237.5	21.2
7P	Pond Margin	1.40	0.82	5.76	--	41.1	5.9

[a]Positive site rates indicate erosion and negative rates indicate deposition.
[b]Cesium-137 loss as proportion as computed using equation # 8.

The site erosion rates are shown in the next column. The last column shows the counting error. For erosional sites the error was initially expressed as a proportion of the ^{137}Cs depletion and then put into the soil loss equations (#8 and #9) shown in Chapter 2. For depositional sites, the error was calculated as a soil gain in equation 11 and then expressed as a proportion of the site's soil gain.

The results in Table 9 show several interesting insights about the spatial variability of ^{137}Cs activity and erosion/deposition rates. The transect site with the greatest erosion was site 7T1 (40.7 t ha^{-1} yr^{-1}), located on a hilltop in the steeper eastern portion of the watershed. However, two other hilltop sites have suffered much lower erosion rates -- 4.9 t ha^{-1} yr^{-1} for 1T1 and 23.3 t ha^{-1} yr^{-1} for 1T2 -- indicating that as a group the hilltops vary greatly in rate of erosion.

The midslopes have erosion rates that are less variable. The two midslopes that were on the north ends of the transects, 2T1 and 2T2, had lower erosion rates (23.6 and 17.5 t ha^{-1} yr^{-1}), than those on the southern ends, 6T1 and 6T2, (33.1 and 38.1 t ha^{-1} yr^{-1}). It is also interesting to note that the midslope with the highest erosion rate was located on the same transect directly uphill from a footslope site (5T2) that experienced ^{137}Cs enrichment.

This site showed a net gain of ^{137}Cs activity, indicating deposition, while the other footslopes (3T1, 5T1 and 3T2) had ^{137}Cs losses, reflecting erosional cases. A possible explanation for this different result could be the fact that 5T2's ^{137}Cs activity reflects sediment transport. Its position on a short, steep slope could relate to sediment transport from site 6T2, and possibly from 7T2, which was also on the same transect and had the highest hilltop erosion rate. The fact that the other footslopes were located on slopes that were not as steep could indicate that either the sediment has already been transported through those sites or that it has not yet reached them (see Figures 2 and 7).

The tilled channel sites, 4T1, 4T2 and 5C, all have deposition rates that are closely grouped, ranging from 37.9 to 49.6 t ha^{-1} yr^{-1}. The standard deviation for this group, 4.9 t ha^{-1} yr^{-1}, was the lowest in the entire watershed. The other ephemeral channel site, 5C, has a large amount of ^{137}Cs activity in the deepest sample increment (see Figure 15). This indicated that this site would likely have more ^{137}Cs at depths below those sampled. Therefore, its deposition rate is almost certainly underestimated. This is very significant since 5C's deposition rate was already the highest in the watershed.

The site with the highest erosion in the watershed (51.5 t ha^{-1} yr^{-1}) was 1C, located in the incised channel. The other incised channel sites, 2C and 3C, have erosion rates of 34.2 and 26.5 t ha^{-1} yr^{-1}, respectively. Site 3C's result is misleading because it did not reach "zero" activity. However, it was treated as an erosional site because its total concentration was much less than the control. The possibility that recently deposited sediments have buried the naturally deposited ^{137}Cs is remote because the sample was collected from between large boulders that were placed in the incised channel bottom to prevent channel scour. Despite this protective measure this channel was actively eroding at an average erosion rate of 37.4 t ha^{-1} yr^{-1}.

The results for the pond sites indicated the same problem with sample depth. Referring to Figure 15, sites 1P, 4P and 6P all indicate that the sample depth did not reach an increment with "zero" ^{137}Cs activity, which suggests that pond ^{137}Cs deposition was almost certainly underestimated. Pond site 7P, located on the pond margin, exhibited ^{137}Cs activity that was characteristic of an erosional site. This site was located on the margin of the pond near the dam, which was built in 1973 with excavated soils from other areas. Its ^{137}Cs activity and erosion rate probably indicate a site that was modified during dam construction (i.e. it is not a natural soil pedon). This site was eliminated from the calculation of the average areal concentration for the pond sites.

Using the erosion and deposition rates, it was possible to determine averages of erosion or deposition rates for each topographic position (Table 10). The topographic position with the highest erosion rate was the incised channel and the lowest was the footslopes. Mass rates of deposition were 243.0 and 61.0 Mg yr^{-1} for the tilled channels and pond, respectively. The highest mass rate of erosion was attributed to the midslopes at 609.8 Mg yr^{-1}, which also had the largest area of the topographic positions, 21.7 ha. This group of samples also had a high level of confidence and, considering the problems pertaining to sample depth for the channel and pond sites, is likely the most accurate of all the topographic positions. This is reinforced by its low standard deviation (8.0 t ha^{-1} yr^{-1}).

The mass rate estimates indicated actively eroding midslopes and hilltops, both erosional and depositional footslopes, significant storage of ^{137}Cs laden sediments in the ephemeral channel system and substantial deposition in the small pond. The watershed net mass erosion rate is approximately 631 Mg yr^{-1}, which is the sum of the mass rates in Table 10.

Table 10. Average Cesium-137 Erosion and Deposition Mass Rates by Topographic Position.

Topographic Position	Sample Size	Area	Erosion/ Deposition Rate[a]	Standard Deviation	Confidence Level[b]	Total Erosion/ Deposition
		ha	$t\ ha^{-1}\ yr^{-1}$		%	$Mg\ year^{-1}$
Hilltops	3	13.5	23.0	14.6	44.4	310.5
Midslopes	4	21.7	28.1	8.0	78.9	609.8
Footslopes	4	19.6	0.5	22.7	34.0	9.8
Tilled Channels	4	5.65	-43.0	4.9	95.5	-243.0
Incised Channels	4	0.15	37.4	10.5	65.8	5.6
Pond	4	0.25	-243.9	9.3	72.9	-61.0

[a]Erosion and deposition rates, negative rates indicate deposition.
[b]Confidence values from nonparametric statistical analysis.

CHAPTER 4

DISCUSSION

USLE and WEE Soil Loss Estimates

The USLE and WEE are the most widely used models for evaluating erosion hazard in Montana. The Soil Conservation Service applies the USLE and a version of the WEE, the WEQ, to determine qualification for and maintenance in the Conservation Reserve Program (CRP) program. SCS estimates for this watershed are 0.7 and 10.10 t ha^{-1} yr^{-1} for the USLE and WEQ, respectively. The underlying objective of SCS application's of these models is to determine average conditions. This study sought to estimate average conditions as well as the spatial variability of soil losses by using spatially variable factor values (Tables 11 and 12).

The study incorporated spatially variable topographic factor values into the USLE while the SCS's application incorporated only one value for the entire watershed. Both studies used the same R, K and P factors and the C factors were similar (0.234, this study, and 0.242, SCS) with the exception of six points in the grass area for which a different value was used (0.053). The topographic factors of the two studies are very different. The SCS's estimates reflect a slope length greater than ten times the longest slope length measured in this study and a slope gradient slightly larger than the smallest gradient measured in this

Table 11. Comparison of USLE Factor Estimates Used by Author and USDA-SCS.

Factor	By Author	By USDA-SCS
Rainfall -erosivity, R	476.6	476.6
Soil erodibility, K	0.049	0.049
Slope length, L	19.0 m to 92.2 m	1,600 m
Slope gradient, S	0.30 % to 4.17 %	0.4 %
LS	0.01 to 0.56	0.12
Cover management, C	0.2344 or 0.053	0.242
Supporting practices, P	1.0	1.0
Soil loss, A	4.47 t ha^{-1} yr^{-1}	0.67 t ha^{-1} yr^{-1}

study. Neither of these values is close to watershed averages computed from a series of 81 points and are therefore not representative of the study watershed. The accuracy of the topographic factors' estimation for the USLE greatly affects the model's ability to predict spatially variable erosion rates in the watershed (Wischmeier, 1976; Wischmeier and Smith, 1978; Wilson, 1986b). This study also distinguishes net erosion and deposition areas. The average results produced from these two USLE applications are very different and the point results produced in this study were highly variable.

Table 12. Comparison of WEE Factor Estimates Used by Author and WEQ Factor Estimates Used by USDA-SCS.

Factor	By Author	By USDA-SCS[a]
Soil erodibility, I′	180.2 to 670.3 t ha^{-1} yr^{-1}	107.6 t ha^{-1} yr^{-1}
Soil ridge roughness, K	0.49, 0.66 and 0.90	1.00
Climate, C	0.90	0.90
Field length, L	0 to 155 m	142 m
Vegetation Residue, V	130 to 3025 kg ha^{-1}	1200 kg ha^{-1}
Soil loss, E	4.7 t ha^{-1} yr^{-1}	10.10 t ha^{-1} yr^{-1}

[a]WEQ estimates made by SCS field personnel, Fort Benton, MT, for Jackson Farm for use in Conservation Reserve Program (CRP) contracts.

The WEE application in this study differs from the SCS WEQ application because it computes wind erosion by periods where the SCS method utilizes single factor estimates that are neither temporally nor spatially variable (See Table 12). The mean of the I′ values used in this study is more than twice as large as the SCS value. This study also adjusted I′ for periods following cultivation, and also incorporates the I_s, knoll erodibility, factor at five points. Eighty-one L factors were varied at each point according to strip fetch length. Many of the L estimates were less than the SCS L estimate of 142 m, accounting for many low wind erosion estimates and a low average erosion estimate (4.7 t ha^{-1} yr^{-1}) in comparison to the SCS (WEQ) estimate (10.1 t ha^{-1} yr^{-1}). The C factors used are the same but this study determines period soil losses as a function of the distribution of erosive wind energy (EWE) over the two year crop/fallow cycle. The SCS estimate of K was held constant at its maximum possible value, whereas, this study calculated period K values as a function of tillage operations. The V factor in this study also varied by period, as opposed to the single, low estimate preferred by SCS. However, the SCS application suggested that the watershed is eroding at 10.1 t ha^{-1} yr^{-1} while this study found an average of only 4.5 t ha^{-1} yr^{-1}. Figure 12 shows that these results also were highly variable, confirmed by the standard deviation of the WEE average (4.6 t ha^{-1} yr^{-1}). This is similar to the variability of this study's USLE estimate (3.6 t ha^{-1} yr^{-1}), confirming the fact that modeled wind and water erosion rates in the watershed are highly variable.

It is possible to make several general observations based on these results. The SCS appears to apply these models at too coarse a scale (at least in landscapes with hummocky relief). They also have used non-representative L and S factors in the USLE; where the L is too long and the S is near the gentle end of the measured distribution. This study delineated erosional and depositional zones, while the SCS made no attempt to do this and consequently characterizes the entire watershed as erosive. This is obviously not true for the ephemeral channel and pond where deposition was indicated by the ^{137}Cs method. This suggests that the SCS's estimates are not additive because they were not produced with a particular point in mind and because of the failure to define net erosion and deposition areas.

The model results show a great deal of variability (see Figures 10, 12 and 14). The model results are combined in Figure 14 to depict each point's net erosion. This step was based on the fact that the depositional zones were identified by arbitrary rules for the USLE (water), but this was not done (nor could it be done) for the WEE (wind). This alludes to the question at issue, "How accurately do the USLE and WEE estimate soil loss and spatial variability ?".

Validation of USLE and WEE Soil Loss Estimates

A possibility exists that the models or the ^{137}Cs method, or both are simply wrong, at least for estimating soil redistribution processes in the northern Great Plains and Montana. In the past, an assessment of the validity of model results was difficult because there were no data available to answer this (above) question. However in the last several years, ^{137}Cs has offered an opportunity here and elsewhere to attain field data to address the question and assess spatial variability in soil loss (De Jong et al., 1983; Arnalds, 1984; Pennock and De Jong, 1987). However, the application of this method in this study revealed two major limitations which warrant further explanation.

The inability of the stratified sampling scheme used in this and other studies to capture the spatial variability of ^{137}Cs activity is one limitation. Although a larger number of data points might improve the confidence levels of the erosion estimates different landscape units, the inclusion of samples collected from the gently sloping, western portion of the watershed may make matters worse. The transect samples used were concentrated in the steeper, eastern portion of the watershed and extrapolating their average ^{137}Cs activities to the eroding portion of the whole watershed might have indicated more net erosion than has really occurred. Even if both areas of the watershed were sampled proportionally, the stratified sample scheme employed would still be a major limitation because it might not capture all aspects of the spatial variability of ^{137}Cs activity and soil erosion/deposition. An alternative approach could be to incorporate divergence and convergence of overland flow into the landscape units such as that used by Pennock and De Jong (1987).

Temporal variability is a second limitation and may be just as difficult to account for in soil samples analyzed for ^{137}Cs activity. The frequency and magnitude of wind and water erosion events play an important role in the dynamics of soil loss. Most wind erosion occurs between October and March in this region. Water erosion has frequent, small magnitude events moving sediments to footslopes and the ephemeral channel system, and, infrequent, large magnitude events moving sediments from these sites through the incised channel to the pond. It is important to know the stage of soil redistribution represented by the ^{137}Cs activity. This activity depends on the recent history of fluvial erosion events (i.e. whether or not a large magnitude event has occurred in the short-term past). Therefore, careful designation of sample locations and landscape units is critical to the accurate quantification of ^{137}Cs and soil gains/losses. This study used sample locations based on equal areas of slope delineated by field pacing and soil samples collected over a four week period in mid-summer. This sample delineation method failed to adequately characterize the temporally variable dimensions of ^{137}Cs and soil redistribution on the Jackson Farm.

Despite these problems some data were collected that can be used to quantify and interpret soil erosion/deposition rates at sites from which soil samples were collected. A site by site comparison of soil erosion/deposition rates estimated by the models and ^{137}Cs approaches was performed to evaluate the model results. The individual sites' predicted and measured rates were analyzed with linear regression. Predicted rates were computed by adding together USLE and WEE estimates for each of the eroding ^{137}Cs sample points (Table 13). The ^{137}Cs depositional sites were not used because the models do not apply to them. A linear regression of rate estimates for the 10 remaining sites yielded an R^2 of 0.07. If the three sites for which the USLE did not apply (i.e., based on the hilltops, channels, and/or concave slope exclusion rules) are removed from the sample set the result improves only marginally (R^2 = 0.14, n = 7). A scatterplot is shown in Figure 17. These results indicate the models may not work for estimating total erosion in the Carter watershed.

Soil Erosion/Deposition Rates Inferred from Cesium-137 Gains/Losses

Based on the comparison of measured versus predicted rates, the USLE and WEE do not appear to work very well in the study watershed. However, it appears that the ^{137}Cs method is not very good either, particularly with respect to understanding spatial variability and estimating a sediment budget unless many more data points are collected and analyzed (levels of confidence range from 34.0 to 95.5 % by landscape unit).

Table 13. Site by Site Comparison of Model and ^{137}Cs Erosion/Deposition Rate Estimates.

Site	Models USLE	Models WEE	Models Total	^{137}Cs
		t ha^{-1} yr^{-1}		
1T1	0.0	10.2	10.2[a]	4.9
2T1	10.4	9.9	20.3	23.6
3T1	15.0	9.2	24.2	10.0
4T1	0.0	8.5	8.5	-41.6[b]
5T1	45.6	9.0	44.6	18.5
6T1	9.3	9.7	19.0	33.1
7T1	0.0	10.1	10.1[a]	40.7
1T2	0.0	10.4	10.4[a]	23.2
2T2	13.2	12.7	25.9	17.5
3T2	1.9	12.7	14.6	12.1
4T2	0.0	12.7	12.7	-37.9[b]
5T2	11.5	5.1	16.6	-38.5[b]
6T2	5.1	4.5	9.6	38.1

aSite predicted value attained from WEE estimate only (shown as empty symbols in Figure 17).
[b]Depositional site excluded from regression analysis.

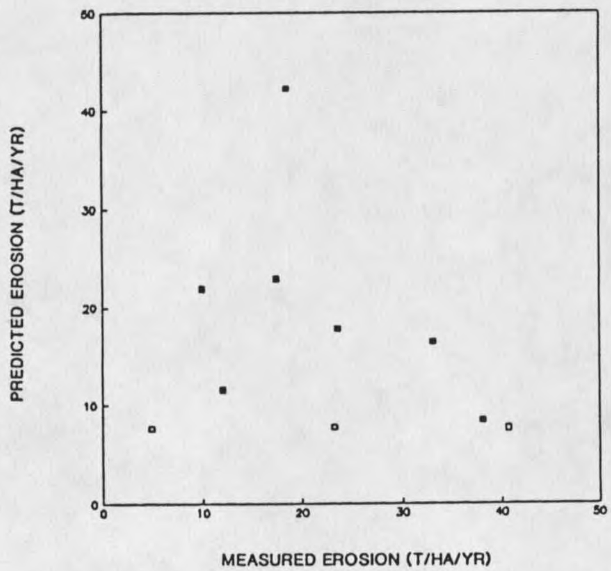

Figure 17. Scatterplot diagram of measured and predicted values generated for site by site comparison of ^{137}Cs sample sites (R^2 = 0.07, n = 10). Empty symbols are sites with WEE estimate only, with these sites removed, R^2 = 0.14 (n = 7).

However, it is possible to compute a first estimate of the watershed sediment budget (Table 14) with the data that were collected. Several problems, including the low (less than 60 %) levels of confidence for two of the landscape units, the inability to separate wind and water processes, overlapping erosion and deposition areas, the inadequate pond sample depth and the fact that the ^{137}Cs activities are time-dependent (particularly the tilled channels) indicate the need to interpret such results cautiously.

The ^{137}Cs activities indicated a net mass erosion rate for the eroding portions of the watershed (about 54 ha) of 936 Mg yr^{-1}. The mass deposition rate attributable to fluvial deposition (304 Mg yr^{-1}) could be interpreted to represent fluvial erosion. Subtracting this mass water erosion rate from the total erosion rate yielded a mass erosion estimate for wind (a net value not counting deposition) of 632 Mg yr^{-1}. The mass wind erosion rate was used to compute the net wind erosion rate of 10.4 t ha^{-1} yr^{-1} and the mass water erosion rate was used to compute a net water erosion rate of 5.0 t ha^{-1} yr^{-1} for a total of 15.4 t ha^{-1} yr^{-1}.

The USLE and WEE estimates of soil loss (4.5 t ha^{-1} yr^{-1} for both), predicted a net soil loss of 9 t ha^{-1} yr^{-1} in the study watershed (exclusive of several USLE points representing deposition and one WEE point where wind erosion does not apply). This result suggests that the models predicted only 58 % of the total erosion estimated with the ^{137}Cs method. A comparison of the net fluvial erosion rate (5.0 t ha^{-1} yr^{-1}) and the USLE watershed average showed that the USLE predicted 90 % of the measured water erosion even though this USLE average was known to be low because it did not include channel erosion. The WEE estimate (4.5 t ha^{-1}

Table 14. Summary of Watershed Average ^{137}Cs Erosion and Deposition Mass Estimates.

	Topographic Position	Area ha	Mass Estimates[a] Mg yr^{-1}
Erosion (fluvial and aeolian)			
	Hilltops	13.5	311
	Midslopes	21.7	610
	Footslopes	19.6	10
	Incised Channel	0.15	6
	Measured Erosion Mass Estimate		936
Deposition (fluvial and aeolian)			
	Tilled Channels	5.65	-243
	Pond	0.25	-61
	Measured Deposition Mass Estimate		-304

[a]Mass estimates were calculated by multiplying the topographic positions' average erosion/deposition rate by its' area. Negative values reflect deposition.

yr^{-1}) was much less than the watershed net wind erosion rate (10.4 t ha^{-1} yr^{-1}) and accounted for only 44 % of the measured wind erosion. The SCS's WEQ estimate (10.1 t ha^{-1} yr^{-1}) is similar to the net wind erosion rate, but difficult to explain because they did not use representative soil erodibility or field length factor estimates. Therefore, if the ^{137}Cs results were truly indicative of the soil redistribution processes in the study watershed, then the USLE has performed much better than the WEE in predicting spatially variable erosion rates. However, we probably cannot totally reject the WEE results unless more ^{137}Cs data are gathered in the hope of reducing the variances.

Conclusions

Both the USLE and WEE model and ^{137}Cs methods indicated a substantial erosion hazard and a great deal of spatial variability. Neither approach is perfect as applied here but sufficient to show the extent and variability of the hazard. Clearly, the results indicate that there has been significant fluvial and aeolian erosion of hilltops, midslopes, some footslopes and an incised channel over 33 years, and significant fluvial deposition on one footslope, in the pond and in the ephemeral channel system over 14 years.

Despite problems associated with capturing temporal and spatial variability, the ^{137}Cs data suggests that the USLE point method used was much more effective than the point WEE method used. Measured aeolian and fluvial erosion rates were 10.4 and 5.0 t ha^{-1} yr^{-1}, respectively; while the modeled erosion rates were 4.5 t ha^{-1} yr^{-1} for both wind and water.

These results have important consequences for crop productivity now and in the future (despite low precision). At present, 50 years of erosion and deposition has occurred, just one of many factors influencing and explaining current crop productivity. For the future, there is still a need to compute spatially variable soil erosion rates in order to better understand soil erosion/crop productivity relationships at watershed scales.

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APPENDICES

APPENDIX A

EROSION MODEL RESULTS

Table 15. USLE Factor and Soil Loss Point Estimates.[a]

Point #	Slope Gradient %	Slope Length m	USLE C Value[b]	USLE S Value[c]	Exclusion Rule[d]	Erosion Estimate[e] $t\ ha^{-1}\ yr^{-1}$
1F	10.7	105	0.053	1.295	0	5.20
1G	6.7	120	0.053	0.661	0	2.84
2M	0.2	0	0.234	0.074	1	N/A
2N	1.7	118	0.234	0.161	0	1.88
2O	16.0	55	0.053	2.455	0	7.14
2P	8.0	26	0.053	0.844	0	1.69
3E	0.8	33	0.234	0.105	0	0.74
3F	6.7	43	0.234	0.661	0	7.50
3G	7.3	50	0.234	0.743	0	9.09
4N	0.0	10	0.234	0.065	1	N/A
4O	0.0	0	0.053	0.065	1	N/A
4P	0.0	18	0.234	0.065	1	N/A
5E	0.9	33	0.234	0.111	2	N/A
5F	1.8	60	0.234	0.168	0	1.60
5G	7.3	19	0.053	0.743	0	1.27
5H	4.3	50	0.234	0.380	0	4.01
6M	0.3	25	0.234	0.079	0	0.53
6N	2.4	13	0.234	0.211	1	N/A
6O	7.3	135	0.234	0.743	0	14.94
6P	4.4	53	0.234	0.391	0	4.21
7B	0.3	45	0.234	0.079	0	0.59
7C	0.2	2	0.234	0.074	1	N/A
7D	2.1	80	0.234	0.189	0	1.96
7E	0.0	0	0.234	0.065	2	N/A
7F	5.7	24	0.234	0.535	0	4.54
7G	8.0	90	0.234	0.844	0	13.87
8J	2.5	80	0.234	0.219	0	2.27
8K	1.4	108	0.234	0.141	2	N/A
8L	1.1	20	0.234	0.123	0	0.84
8M	2.8	123	0.234	0.243	0	2.87
8N	1.7	83	0.234	0.161	0	1.69
8O	6.3	38	0.234	0.609	0	6.50
8P	6.7	63	0.234	0.661	0	9.08
9A	0.7	13	0.234	0.100	1	N/A
9B	3.6	123	0.234	0.313	0	4.72
9C	1.8	213	0.234	0.168	0	2.34
9D	3.1	55	0.234	0.268	0	2.93
9E	1.3	153	0.234	0.135	0	1.70
9F	4.7	168	0.234	0.422	0	7.22
9G	0.8	190	0.234	0.105	3	N/A
9H	7.3	60	0.234	0.743	0	9.96
9I	10.0	28	0.234	1.169	0	10.71

Table 15. USLE Factor and Soil Loss Point Estimates (Continued).[a]

Point #	Slope Gradient %	Slope Length m	USLE C Value[b]	USLE S Value[c]	Exclusion Rule[d]	Erosion Estimate[e] t ha^{-1} yr^{-1}
10J	1.4	30	0.234	0.141	0	1.09
10K	5.2	120	0.234	0.477	0	9.04
10L	2.7	200	0.234	0.235	0	3.21
10M	0.4	380	0.234	0.084	3	N/A
10N	0.0	0	0.234	0.065	2	N/A
10O	3.1	112	0.234	0.268	0	3.90
10P	0.8	80	0.234	0.105	3	N/A
10Q	5.3	90	0.234	0.488	0	8.02
11B	1.5	30	0.234	0.148	0	1.14
11C	3.6	125	0.234	0.313	0	4.75
11D	1.9	285	0.234	0.175	0	2.65
11E	1.9	373	0.234	0.175	0	2.88
11F	4.0	60	0.234	0.351	0	3.97
11G	5.5	83	0.234	0.511	0	8.07
11H	6.5	165	0.234	0.635	0	14.12
11I	10.0	40	0.234	1.169	0	12.80
12K	5.0	38	0.234	0.454	0	4.85
12L	1.9	163	0.234	0.175	0	2.25
12M	2.0	288	0.234	0.182	0	2.77
12N	1.1	153	0.234	0.123	3	N/A
12O	3.6	58	0.234	0.313	0	3.49
12P	8.0	25	0.234	0.844	0	7.31
12Q	0.0	0	0.234	0.065	2	N/A
13C	3.1	44	0.234	0.268	0	2.68
13D	3.0	80	0.234	0.260	0	3.30
13E	1.4	198	0.234	0.141	0	1.92
13F	1.4	138	0.234	0.141	0	1.73
13G	1.2	125	0.234	0.129	3	N/A
13H	1.2	23	0.234	0.129	0	0.92
14K	1.6	5	0.234	0.154	1	N/A
14L	3.1	104	0.234	0.268	0	3.79
14M	2.0	38	0.234	0.182	0	1.51
14N	1.3	95	0.234	0.135	0	1.48
14O	1.4	125	0.234	0.141	3	N/A
14P	1.8	68	0.234	0.168	0	1.66

Table 15. USLE Factor and Soil Loss Point Estimates (Continued).[a]

Point	Slope Gradient	Slope Length	USLE C Value[b]	USLE S Value[c]	Exclusion Rule[d]	Erosion Estimate[e]
#	%	m				t ha^{-1} yr^{-1}
15E	1.3	15	0.234	0.135	1	N/A
15F	5.0	45	0.234	0.454	0	5.28
15G	1.3	75	0.234	0.135	0	1.37
16O	0.0	8	0.234	0.065	1	N/A

[a]USLE soil loss estimates calculated using R = 476.6, K = .049, L as calculated using equation # 1, page 21 and P = 1.0.
[b]USLE C factor from Table 2.
[c]USLE S factor using formula of Foster and Wischmeier (1984).
[d]Exclusion code; 0 = apply USLE, 1 = exclude due to hillcrest rule, 2 = channel rule, and 3 = concave slope rule.
[e]N/A = USLE does not apply, erosion = 0.0 t ha^{-1} yr^{-1}.

Table 16. WEE Factor and Soil Loss Point Estimates.[a]

Site	Soil Group[b]	I[c]	Is	I′[c]	Fetch Length	Soil Loss Estimates Fallow	Crop	Total Cycle
#			(%)		m		$Mg\ ha^{-1}\ yr^{-1}$	
1F	38B	234.2	100	234.2	38	0.0	5.8	2.9
1G	38B	234.2	100	234.2	113	0.0	13.0	6.5
2M	38B	234.2	100	234.2	28	0.0	3.7	1.9
2N	38B	234.2	100	234.2	5	0.0	0.0	0.0
2O	38B	234.2	100	234.2	58	0.0	8.7	4.4
2P	38A	180.2	372	670.3	80	1.2	68.4	34.8
3E	38B	234.2	100	234.2	43	0.0	6.6	3.3
3F	38B	234.2	100	234.2	63	0.0	9.2	4.6
3G	38A	180.2	100	180.2	28	0.0	1.0	0.5
4N	38B	234.2	100	234.2	148	0.0	14.6	7.3
4O	d	-	-	-	5	-	-	-
4P	38A	180.2	215	387.4	80	0.2	27.4	13.8
5E	38B	234.2	100	234.2	80	0.0	10.8	5.4
5F	38B	234.2	100	234.2	25	0.0	2.9	1.5
5G	38A	180.2	100	180.2	18	0.0	0.0	0.0
5H	38A	180.2	100	180.2	63	0.0	5.0	2.5
6M	38B	234.2	100	234.2	13	0.0	0.0	0.0
6N	38B	234.2	102	238.9	140	0.0	14.8	7.4
6O	38B	234.2	100	234.2	8	0.0	0.0	0.0
6P	385B	253.3	100	253.3	70	0.0	11.7	5.9
7B	38B	234.2	100	234.2	50	0.0	7.6	3.8
7C	38B	234.2	100	234.2	88	0.0	11.4	5.7
7D	38B	234.2	100	234.2	38	0.0	5.8	2.9
7E	38B	234.2	100	234.2	73	0.0	10.2	5.1
7F	38B	234.2	100	234.2	55	0.0	8.3	4.2
7G	385B	253.3	100	253.3	35	0.0	6.5	3.3
8J	38B	234.2	100	234.2	30	0.0	4.1	2.1
8K	38B	234.2	100	234.2	25	0.0	2.9	1.5
8L	38B	234.2	100	234.2	25	0.0	2.9	1.5
8M	38B	234.2	100	234.2	8	0.0	0.0	0.0
8N	38B	234.2	100	234.2	133	0.0	14.0	7.0
8O	28	280.9	100	280.9	28	0.0	6.7	3.4
8P	385B	253.3	100	253.3	155	0.1	17.0	8.6
9A	385B	253.3	160	405.3	5	0.0	0.0	0.0
9B	385B	253.3	100	253.3	130	0.1	15.9	8.0
9C	38B	234.2	100	234.2	83	0.0	11.0	5.5
9D	38B	234.2	100	234.2	85	0.0	11.2	5.6
9E	38B	234.2	100	234.2	68	0.0	9.7	4.9
9F	28	280.9	100	280.9	50	0.0	11.6	5.8
9G	28	280.9	100	280.9	90	0.1	16.2	8.2

Table 16. WEE Factor and Soil Loss Point Estimates.[a]

Site	Soil Group[b]	I^c	Is	I'^c	Fetch Length	Soil Loss Estimates Fallow	Crop	Total Cycle
#			(%)		m		$Mg\ ha^{-1}\ yr^{-1}$	
9H	385B	253.3	100	253.3	45	0.0	8.4	4.2
9I	385B	253.3	100	253.3	68	0.0	11.4	5.7
10J	385B	253.3	100	253.3	65	0.0	11.1	5.6
10K	385B	253.3	100	253.3	18	0.0	1.7	0.9
10L	38B	234.2	100	234.2	20	0.0	1.5	0.8
10M	38B	234.2	100	234.2	1	0.0	0.0	0.0
10N	28	280.9	100	280.9	128	0.1	18.8	9.5
10O	28	280.9	100	280.9	23	0.0	5.7	2.9
10P	28	280.9	100	280.9	150	0.1	20.0	10.0
10Q	385B	253.3	100	253.3	15	0.0	0.7	0.4
11B	385B	253.3	100	253.3	123	0.1	15.5	7.8
11C	385B	253.3	100	253.3	78	0.0	12.6	6.3
11D	385B	253.3	100	253.3	80	0.0	12.6	6.3
11E	38B	234.2	100	234.2	60	0.0	8.9	4.5
11F	28	280.9	113	317.4	45	0.0	14.1	7.1
11G	28	280.9	100	280.9	83	0.1	15.6	7.9
11H	28	280.9	100	280.9	40	0.0	9.8	4.9
11I	385B	253.3	100	253.3	63	0.0	10.9	5.5
12K	385B	253.3	100	253.3	10	0.0	0.0	0.0
12L	385B	253.3	100	253.3	15	0.0	0.7	0.4
12M	385B	253.3	100	253.3	140	0.1	16.3	8.2
12N	385B	253.3	100	253.3	25	0.0	4.0	2.0
12O	385B	253.3	100	253.3	86	0.0	13.1	6.6
12P	385B	253.3	100	253.3	143	0.1	16.5	8.3
12Q	385B	253.3	100	253.3	8	0.0	0.0	0.0
13C	385B	253.3	100	253.3	73	0.0	11.9	6.0
13D	385B	253.3	100	253.3	73	0.0	11.9	6.0
13E	385B	253.3	100	253.3	55	0.0	9.9	5.0
13F	385B	253.3	100	253.3	40	0.0	7.5	3.8
13G	385B	253.3	100	253.3	8	0.0	0.0	0.0
13H	385B	253.3	100	253.3	33	0.0	6.1	3.1
14K	385B	253.3	100	253.3	5	0.0	0.0	0.0
14L	385B	253.3	100	253.3	8	0.0	0.0	0.0
14M	385B	253.3	100	253.3	133	0.1	16.0	8.0
14N	385B	253.3	100	253.3	115	0.0	15.1	7.6
14O	385B	253.3	100	253.3	10	0.0	0.0	0.0
14P	385B	253.3	100	253.3	138	0.1	16.3	8.2

Table 16. WEE Factor and Soil Loss Point Estimates (Continued).[a]

Site	Soil Group[b]	I[c]	Is	I′[c]	Fetch Length	Soil Loss Estimates Fallow	Crop	Total Cycle
#			(%)		m		Mg ha^{-1} yr^{-1}	
15E	385B	253.3	100	253.3	48	0.0	8.9	4.5
15F	385B	253.3	100	253.3	33	0.0	6.1	3.1
15G	385B	253.3	100	253.3	70	0.0	11.7	5.9
16O	385B	253.3	100	253.3	5	0.0	0.0	0.0

[a]WEE soil loss estimates calculated using K = 0.49, 0.66 and 0.9, C = 0.90, and V varying by periods (see Table 5).
[b]Soil mapping unit numbers; 28, Nishon series, 38A, 38B and 385B, Ethridge series (see Figure 3).
[c]Soil erodibility (I and I′) in t ha^{-1} yr^{-1}.
[d]Point excluded due to its location in the incised channel.

APPENDIX B

CESIUM-137 LABORATORY DATA AND AREAL CONCENTRATIONS

Table 17. Cesium-137 Laboratory Data and Areal Concentrations.

Site[a] #	Depth of Increment	Bulk Density	Mass Concen-tration	Counting Error (±)	Increment Areal Activity	Error (±)	Total Site Activity
	cm	g cm^{-3}	pCi g^{-1}			pCi cm^{-2}	
1T1	0 - 15	1.27	0.53	0.05	10.10	0.95	
	16 - 20	1.28	0.05	0.01	0.32	0.06	
							10.42
2T1	0 - 15	1.30	0.34	0.04	6.63	0.78	
	16 - 20	1.34	0.05	0.01	0.34	0.07	
							6.97
3T1	0 - 15	1.30	0.47	0.04	9.17	0.78	
	16 - 20	1.34	0.00	0.00	0.00	0.00	
							9.17
4T1	0 - 15	1.35	0.51	0.04	10.33	0.81	
	16 - 20	1.44	0.33	0.03	2.38	0.22	
	21 - 25	1.44	0.07	0.03	0.50	0.22	
	26 - 30	1.44	0.02	0.03	0.14	0.22	
							13.35
5T1	0 - 15	1.29	0.39	0.04	7.55	0.77	
	16 - 20	1.41	0.03	0.01	0.21	0.07	
							7.76
6T1	0 - 15	1.19	0.24	0.04	4.28	0.71	
	16 - 20	1.36	0.02	0.01	0.14	0.07	
							4.42
7T1	0 - 15	1.18	0.15	0.01	2.66	0.18	
	16 - 20	1.27	0.05	0.01	0.32	0.06	
							2.98
1T2	0 - 15	1.22	0.35	0.05	6.41	0.92	
	16 - 20	1.27	0.00	0.00	0.00	0.00	
							6.41
2T2	0 - 15	1.07	0.44	0.05	7.06	0.80	
	16 - 20	1.39	0.25	0.01	1.74	0.07	
	21 - 25	1.39	0.00	0.00	0.00	0.00	
							8.80

Table 17. Cesium-137 Laboratory Data and Areal Concentrations (Continued).

Site[a] #	Depth of Increment	Bulk Density	Mass Concen-tration	Counting Error (±)	Increment Areal Activity	Error (±)	Total Site Activity
	cm	g cm^{-3}	pCi g^{-1}			pCi cm^{-2}	
3T2	0 - 15	1.19	0.48	0.06	8.57	1.07	
	16 - 20	1.41	0.00	0.00	0.00	0.00	
							8.57
4T2	0 - 15	1.25	0.54	0.06	10.13	1.13	
	16 - 20	1.46	0.26	0.06	1.90	0.44	
	21 - 25	1.46	0.06	0.02	0.44	0.15	
							12.47
5T2	0 - 15	1.27	0.45	0.04	8.57	0.76	
	16 - 20	1.33	0.38	0.05	2.53	0.33	
	21 - 25	1.33	0.19	0.01	1.26	0.07	
	26 - 30	1.33	0.00	0.00	0.00	0.00	
							12.36
6T2	0 - 15	1.29	0.20	0.03	3.87	0.58	
	16 - 20	1.35	0.03	0.02	0.20	0.14	
							4.07
7T2	0 - 15	1.18	0.15	0.01	2.66	0.18	
	16 - 20	1.27	0.05	0.01	0.32	0.06	
							2.98
1C	0 - 5	1.40	0.24	0.03	1.68	0.21	
	6 - 10	1.40	0.06	0.01	0.42	0.07	
	11 - 15	1.40	0.00	0.00	0.00	0.00	
							2.10
2C	0 - 5	1.40	0.27	0.03	1.89	0.21	
	6 - 10	1.40	0.28	0.03	1.96	0.21	
	11 - 15	1.40	0.18	0.04	1.26	0.28	
	16 - 20	1.40	0.02	0.04	0.14	0.28	
							5.25
3C	0 - 5	1.40	0.30	0.05	2.10	0.35	
	6 - 10	1.40	0.12	0.01	0.84	0.07	
	11 - 15	1.40	0.08	0.03	0.56	0.21	
	16 - 20	1.40	0.26	0.04	1.82	0.28	
	21 - 25	1.40	0.16	0.16	1.12	0.07	
							6.44

Table 17. Cesium-137 Laboratory Data and Areal Concentrations (Continued).

Site[a] #	Depth of Increment	Bulk Density	Mass Concen-tration	Counting Error (±)	Increment Areal Activity	Error (±)	Total Site Activity
	cm	g cm^{-3}	pCi g^{-1}		pCi cm^{-2}		
5C	0 - 15	1.09	0.54	0.04	8.83	0.65	
	16 - 20	1.36	0.59	0.03	4.01	0.20	
	21 - 25	1.36	0.65	0.05	4.42	0.34	
	26 - 30	1.36	0.93	0.06	6.32	0.41	
							23.58
1P	0 - 5	1.30	0.36	0.05	2.34	0.33	
	6 - 10	1.30	0.55	0.02	3.58	0.13	
	11 - 15	1.30	0.71	0.01	4.62	0.07	
	16 - 20	1.30	0.69	0.08	4.49	0.52	
	21 - 25	1.30	0.71	0.04	4.62	0.26	
							19.65
4P	0 - 5	1.44	0.42	0.04	3.02	0.29	
	6 - 10	1.44	0.38	0.01	2.74	0.07	
	11 - 15	1.44	1.01	0.09	7.27	0.65	
	16 - 20	1.44	0.59	0.06	4.25	0.43	
	21 - 25	1.44	0.32	0.02	2.30	0.14	
							19.58
6P	0 - 5	1.33	0.56	0.05	3.72	0.33	
	6 - 10	1.33	1.16	0.02	7.71	0.13	
	11 - 15	1.33	0.70	0.05	4.66	0.33	
	16 - 20	1.33	0.51	0.06	3.39	0.40	
	21 - 25	1.33	0.06	0.01	0.40	0.07	
							19.88
7P	0 - 5	1.40	0.28	0.04	1.96	0.28	
	6 - 10	1.40	0.12	0.03	0.84	0.21	
	11 - 15	1.40	0.04	0.01	0.28	0.07	
	16 - 20	1.40	0.00	0.00	0.00	0.00	
							3.08
1W	0 - 5	1.24	1.14	0.11	7.07	0.68	
	6 - 10	1.24	0.03	0.03	0.19	0.19	
	11 - 15	1.24	0.00	0.00	0.00	0.00	
	16 - 20	1.24	0.00	0.00	0.00	0.00	
							7.26

Table 17. Cesium-137 Laboratory Data and Areal Concentrations (Continued).

Site[a] #	Depth of Increment	Bulk Density	Mass Concen-tration	Counting Error (±)	Increment Areal Activity	Error (±)	Total Site Activity
	cm	g cm^{-3}	pCi g^{-1}		pCi cm^{-2}		
2W	0 - 5	1.26	1.59	0.10	10.02	0.63	
	6 - 10	1.26	0.16	0.04	1.01	0.25	
	11 - 15	1.26	0.02	0.04	0.13	0.25	
	16 - 20	1.26	0.00	0.00	0.00	0.00	
							11.16
3W	0 - 5	1.13	2.07	0.12	11.70	0.68	
	6 - 10	1.13	0.29	0.06	1.64	0.34	
	11 - 15	1.13	0.06	0.04	0.34	0.23	
	16 - 20	1.13	0.00	0.00	0.00	0.00	
							13.68
4W	0 - 5	1.13	1.68	0.09	9.49	0.51	
	6 - 10	1.13	0.40	0.05	2.26	0.28	
	11 - 15	1.13	0.05	0.02	0.28	0.11	
	16 - 20	1.13	0.05	0.03	0.28	0.17	
	21 - 25	1.13	0.00	0.00	0.00	0.00	
							12.31

[a]Sample site code; T1 = transect 1,T2 = transect 2, C = channel, P = pond, W = control.

APPENDIX C

SIEVING RESULTS

Table 18. Sieving Results.

Soil Mapping Unit	Site	Non-erodible Particles > 0.84 mm %	WEE I Factor t ha^{-1} yr^{-1}
Nishon Series (28)			
	4T2	36.5	314
	5T2	43.5	253
	4C	40.5	275
Ethridge Series (385B)			
	1T1	53.0	157
	2T1	45.0	242
	3T1	53.1	155
	4T1	48.2	212
	5T1	37.4	307
	7T1	52.6	161
	1T2	36.5	314
	6T2	49.0	206
	1TA	41.5	267
	2TA	28.5	392
	3TA	52.2	166
	4TA	49.5	195
	5TA	51.2	177
	6TA	32.3	354
	7TA	40.0	282
	1TB	40.2	280
	2TB	44.8	244
	3TB	50.8	182
	4TB	48.8	204
	5TB	35.5	321
	6TB	44.8	244
	2TC	39.5	379
	2TD	40.0	282
	3TD	33.2	345
	2TE	35.5	320
	3TE	41.5	267

Table 18. Sieving Results (Continued).

Soil Mapping Unit	Site	Non-erodible Particles > 0.84 mm %	WEE I Factor t ha^{-1} yr^{-1}
Ethridge Series (38A)			
	19T3	51.0	179
	25T4	62.0	96
	26T4	52.8	170
	27T4	52.2	188
	28T4	54.8	139
	29T4	44.8	244
	30T4	44.8	244
Ethridge Series (38B)			
	22T3	45.6	238
	23T3	49.9	193
	24T3	52.2	166
	3TC	39.0	291
	4TC	49.5	202
	5TC	50.8	182
	6TC	35.8	318
	7TC	51.7	170
	4TD	40.4	278
	4TE	48.0	215
	5TE	40.6	276
	6TE	46.7	229
	7TE	39.5	287