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SEDIMENT IN LAKE TANEYCOMO, MISSOURI, 1913 TO 1987

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ABSTRACT

Lake Taneycomo, Missouri, was formed in 1913 by the completion of Ozark Beach Dam on the White River in southwest Missouri. Sediment accumulation in Lake Taneycomo from 1913 to 1935 and from 1913 to 1987 was determined with data collected by the U.S. Soil Conservation Service and the U.S. Geological Survey. Relations between cross-sectional area and distance upstream from Ozark Beach Dam were determined for the 1913 (original), 1935, and 1987 volumes of water at 700 feet above sea level. Between 1913-35, 42 percent of the original volume of the lake was filled with sediment and between 1913-87, 49 percent of the original volume of the lake was filled with sediment. Cesium-137 isotope was used as a tracer to determine the quantity of sediment deposition in the lake after 1954. Completion of Table Rock Dam upstream from Lake Taneycomo in 1958 eliminated most of the sediment load from 92 percent of the original drainage area of Lake Taneycomo. Cesium-137 data indicate that, after Table Rock Dam was completed, most of the sediment accumulated in the downstream section of Lake Taneycomo.

INTRODUCTION

The area near Lake Taneycomo (fig. 1) is becoming an increasingly popular tourist attraction. Tourist activities and attractions, such as country music theaters, craft stores, and amusement parks, are common, especially near Branson. The population of Branson increased from 2,175 in 1970 to 3,070 in 1987 (city of Branson, written commun., 1988). An estimated 5 million people visited Branson during 1986. About 50 resorts are located on Lake Taneycomo and most cater to trout fishermen. In 1987, a State trout hatchery stocked Lake Taneycomo with 80,000 trout monthly (Shepherd of the Hills Fishery, oral commun., 1988). The owners of the fishing resorts are concerned that continued development in the watershed of the lake will add to sediment accumulation in the lake and, thus, harm the fishing industry.

Study Area

Lake Taneycomo is on the White River, about 50 miles south of Springfield near the Missouri-Arkansas border (fig. 1). Lake Taneycomo was formed in 1913 after Ozark Beach Dam was built by the Ozark Power and Water Company to generate electricity. The dam is relatively small, rising 50 feet from the river channel and creating a 23-mile-long lake that covers less than 3 square miles. About half of the width of the dam is a reinforced concrete spillway that has an elevation of 697.10 feet. After 1924, the dam has operated with flashboards that raised the water-surface elevation to 700 feet. The flashboards usually are washed away during high-flows.

Table Rock Dam was completed on the White River directly upstream from Lake Taneycomo in 1958. The drainage area upstream from Table Rock Dam is 4,280 square miles; the drainage area upstream from Lake Taneycomo is 4,644 square

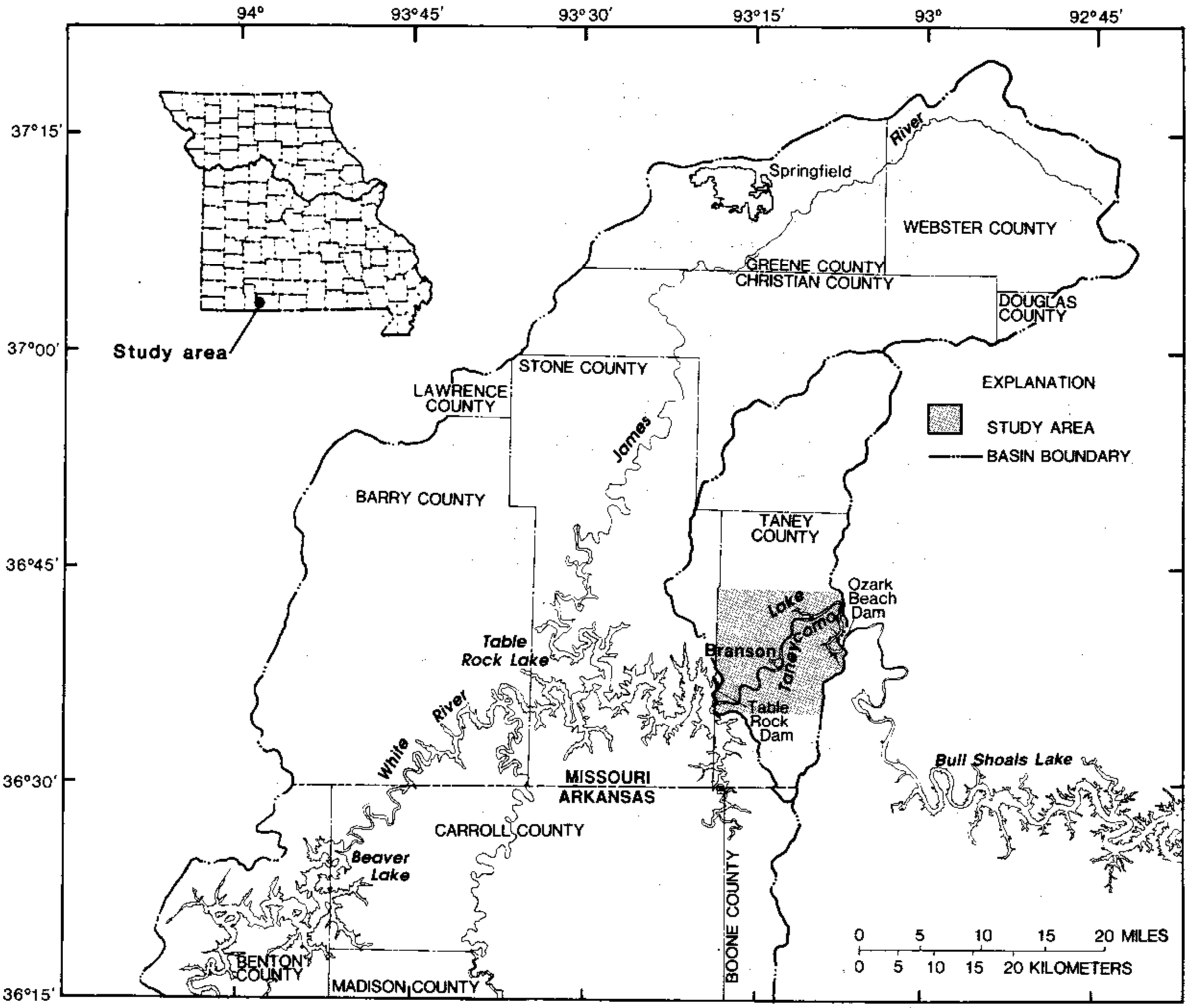

Figure 1.—Location of study area and part of the Lake Taneycomo drainage basin.

miles. Therefore, only 364 square miles, 8 percent of the total drainage area (fig. 1), drains directly into Lake Taneycomo.

Purpose and Scope

This paper presents the results of a study made to determine the quantity of sediment accumulation in Lake Taneycomo from 1913 to 1987. The quantity of sediment that reached Lake Taneycomo has been affected by Table Rock Dam. Therefore, sediment accumulation was determined for both before and after 1958, when the dam was completed. Results from this study will assist by local land-use managers in defining areas in the Lake Taneycomo watershed suitable for development.

SEDIMENTATION SURVEY

Two sedimentation surveys were made on Lake Taneycomo in 1987 by the U.S. Geological Survey (USGS). The first survey was a volumetric survey in which the volume of water retained behind Ozark Beach Dam during 1987 was determined. This survey replicated much of the work done by the U.S. Soil Conservation Service (SCS) in 1935 (Kesler, 1936). The USGS and SCS surveys were used to determine the volume of sediment deposited between 1913-35 and between 1913-87.

In the second survey, cesium-137 isotope data were used to determine sediment accumulation after 1954 at selected points in the lake. After Table Rock Dam was completed in 1958, sediment transport into Lake Taneycomo changed drastically. The presence of the cesium-137 isotope is useful for determining the quantity of sedimentation that has occurred since 1954 when cesium-137 first appeared in the environment as a result of atomic testing.

Volumetric Survey

A volumetric survey involves measuring the volume of a lake and subtracting that volume from a volume measured at an earlier time. The difference is the volume of accumulated sediment. This study includes three lake volumes; the original volume estimated from sediment corings made by the SCS in 1935, the volume determined by the SCS in 1935, and the volume determined by the USGS in 1987. The volume of sediment accumulated in Lake Taneycomo between 1913-35 and between 1913-87 was determined with this information.

Sand and gravel was removed from Lake Taneycomo from 1961 to 1987 by Table Rock Asphalt Construction Company (Robert Simmons, Table Rock Asphalt Construction Company, oral commun., 1987). The locations measured in 1987 that showed signs of disturbance by dredging were not used in volume computations and elevation comparisons.

The method used by the SCS for the 1935 survey is unknown. The method used by the USGS for the 1987 survey is a curve method (relation between cross-sectional area and distance upstream from the dam). This method was chosen because Lake Taneycomo is long and narrow, and it would be extremely difficult to determine contours of the lake bottom without expending tremendous effort and resources. Also, the data collected during the 1935 survey would be most suitable for the curve method.

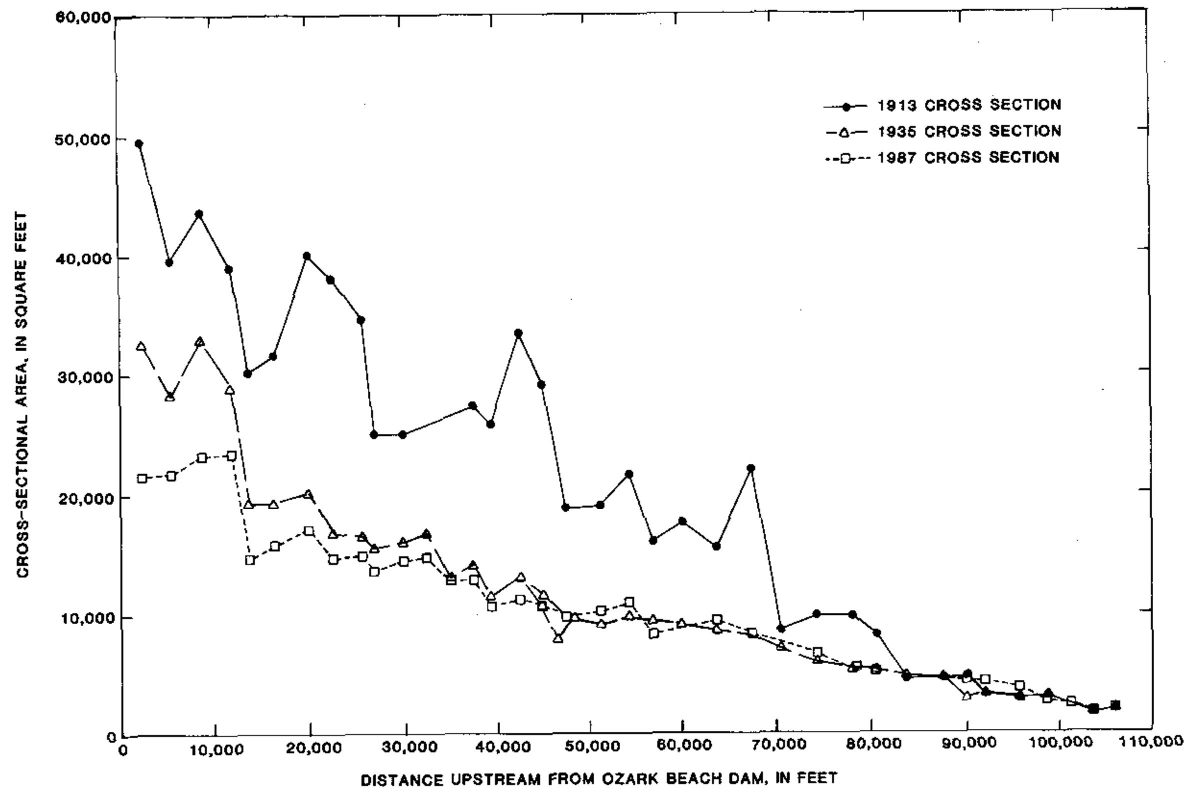

Figure 2.—Relation between cross-sectional area of Lake Taneycomo and distance from Ozark Beach Dam.

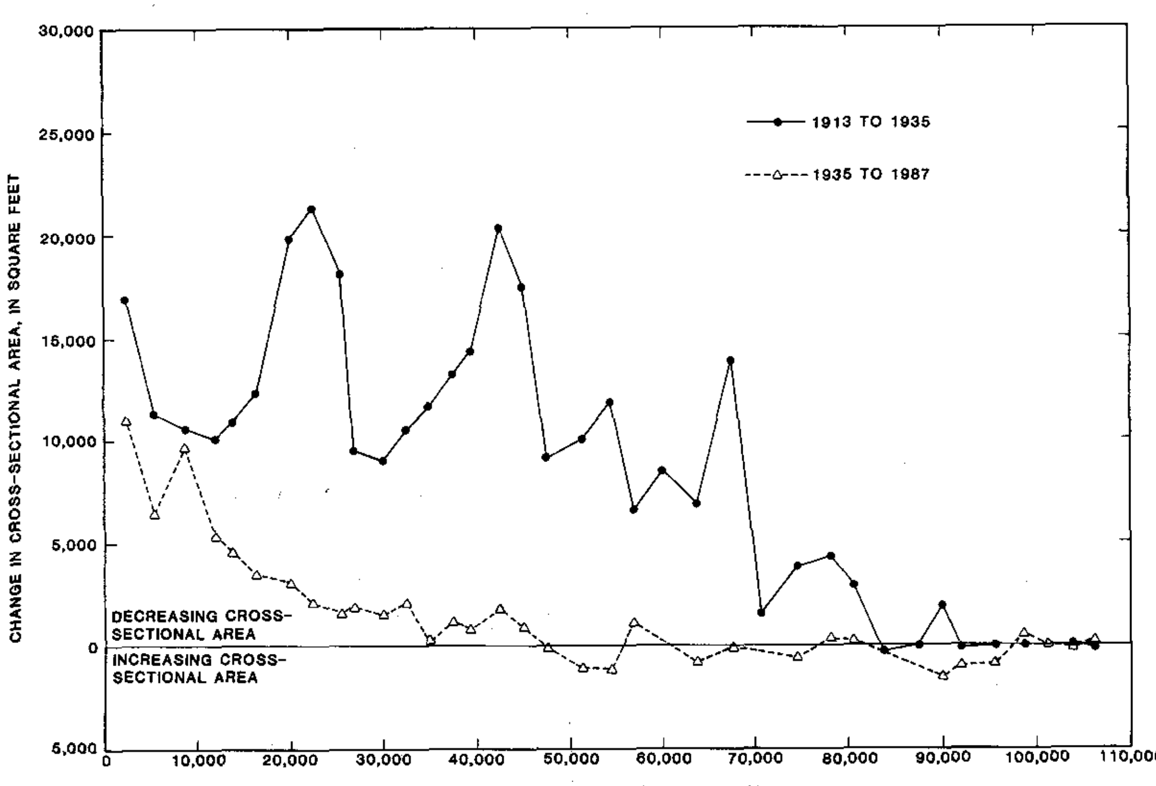

Figure 3.—Changes in cross-sectional area of Lake Taneycomo.

The curve method uses cross sections to determine the volume of a lake (Vanoni, 1975, p. 379). Cross sections of the lake are obtained at various locations. The cross-sectional areas and the distance the cross sections are upstream from the dam are plotted on a graph and a line is fitted to the points. The area under the line is the volume of the lake. It is assumed that the change in cross-sectional area between consecutive cross sections is uniform.

The cross-sectional area of the lake was determined assuming a water-surface elevation of 700 feet. A graph of the relation between cross-sectional area and distance from the dam was plotted (fig. 2). The following lake volumes were determined:

Year	Lake water volume (cubic feet)
[1]1913	2,155,000,000
[1]1935	1,245,000,000
1987	1,089,000,000

[1]Data from SCS files.

The following volumes of accumulated sediment were determined:

Date	Accumulated sediment (cubic feet)	Percentage of original volume
[1]1913 to [1]1935	910,000,000	42
[1]1913 to 1987	1,066,000,000	49

[1]Data from SCS files.

Virtually all of the sediment transported into Lake Taneycomo comes during floodflows (Kesler, 1936). When the impounded water decreases flow velocities sufficiently, sediment deposition begins. In an effort to locate where deposition begins in the lake, differences in cross-sectional area were compared for 1913-35 and for 1935-87 (fig. 3).

Between 1913-35, the flood water began depositing sediment at about 90,000 feet upstream from Ozark Beach Dam. Plots of the elevation of the channel thalweg (the deepest part of the channel cross section) for 1913 and 1935 (fig. 4) indicate that sediment did not accumulate in the channel until 50,000 feet upstream from the dam. Although flood velocities were slowed sufficiently to allow deposition downstream from about 90,000 feet upstream from the dam, velocities in the old river channel apparently were large enough to prevent deposition in the channel until about 50,000 feet upstream from the dam.

Partly in response to Table Rock Dam trapping practically all of the potential sediment yield to Lake Taneycomo, the downstream channel has changed after 1935. Generally, the cross-sectional areas from Table Rock Dam to 50,000 feet upstream from Ozark Beach Dam increased between 1935-87 (fig. 3). The 1987 downstream thalweg elevations generally are less than the 1935 thalweg elevations until 30,000 feet upstream from Ozark Beach Dam (fig. 4). Although sediment deposition in Lake Taneycomo continued downstream from about 50,000 feet upstream from Ozark Beach Dam, flows from Table Rock Dam appear to have eroded the channel that was present in 1935 to within 30,000 feet upstream from Ozark Beach Dam where Lake Taneycomo continues to fill.

Cesium-137 Measurements

Lake Taneycomo was not surveyed when Table Rock Dam was completed in 1958, so the volume of sediment accumulated after 1958 cannot be calculated with volumetric methods. Therefore, cesium-137 measurements were obtained from sediment cores to determine sediment accumulation after 1954. Cesium-137, a radioactive fallout product of atmospheric nuclear testing, first appeared in the environment in 1954 (McHenry and others, 1975). The isotope is tightly adsorbed onto fine soil particles and can be used to trace soil as it is redistributed by erosion and deposited in lakes as sediment. Cesium-137 is not present in undisturbed sediment deposited before 1954.

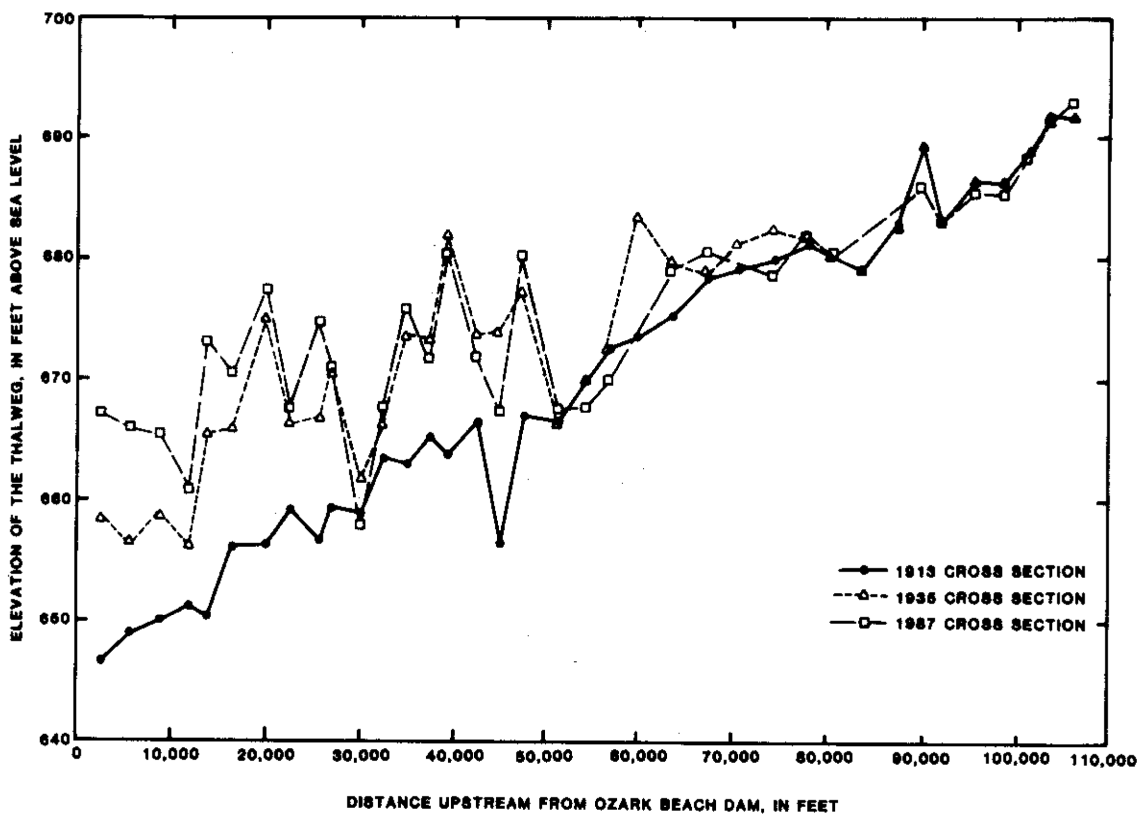

Figure 4.—Elevation of the thalweg in the 1913, 1935, and the 1987 cross sections of the Lake Taneycomo.

Sediment profiles were obtained at 23 locations in Lake Taneycomo in October 1987. Three sediment cores were obtained at each location with a modified 6-inch-diameter piston corer. The corer was forced into the bottom sediment about 75 centimeters and then removed. The sediment cores were extruded, measured, and cut into 5-centimeter layers beginning with the top (the water-sediment interface). Corresponding layers from the three cores were composited and sent to the Water Quality and Watershed Research Laboratory operated by the U.S. Department of Agriculture, Agricultural Research Service, at Durant, Okla. Calculations of sediment deposition were made by using the midpoint of the deepest sediment layer containing detectable cesium-137 activity.

The quantity of sediment deposited after 1954 that was calculated from cesium-137 analysis is shown in table 1 for each sample site. Samples were not obtained further downstream than about 50,000 feet upstream from the dam because the sediment profile lacked enough silt or clay to give the sample enough cohesiveness to be retrieved from the lake bottom.

Although the volumetric survey indicated that the thalweg channel of Lake Taneycomo was scoured from Table Rock Dam to about 30,000 feet upstream from Ozark Beach Dam, the cesium-137 analysis showed at least 7.5 centimeters of sediment accumulation. Samples collected near the thalweg showed the least accumulation when compared to samples collected about the same distance from the dam but near each bank. Samples collected nearest the dam showed the least percentage of difference between the thalweg and the bank.

The cesium-137 analyses indicated that from Ozark Beach Dam to 50,000 feet upstream from the dam, sediment accumulation in Lake Taneycomo from 1954 to 1987 followed the sediment accumulation pattern indicated by the volumetric survey for 1935-87. Although the quantity of sediment transported into Lake Taneycomo has decreased by the completion of Table Rock Dam, the largest quantity of sediment accumulation in a cross section continues to be away from the thalweg, and the quantities of sediment accumulated in the longitudinal axis of the lake continue to increase downstream. Sediment is being deposited in a manner characteristic of an alluvial river whose base level has been elevated.

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Table 1.--Sediment deposition after 1954 as determined from cesium-137 analyses

[>; greater than, ND; not determined]

Location number	Near thalweg	Distance upstream from Ozark Beach Dam (feet)	Sediment deposition after 1954 (centimeters)
CS1	No	44,700	>45.0
CS2	No	ND	47.5
CS3	No	42,500	27.5
CS4	No	39,400	>60.0
CS5	Yes	35,000	45.0
CS6	Yes	32,500	25.0
CS7	Yes	30,000	7.5
CS8	Yes	ND	12.5
CS9	No	26,900	62.5
CS10	No	ND	32.5
CS11	Yes	25,600	>61.0
CS12	No	22,500	47.5
CS13	No	20,000	27.5
CS14	Yes	16,300	42.5
CS15	Yes	13,700	32.5
CS16	No	11,900	52.5
CS17	Yes	8,800	32.5
CS18	No	ND	42.5
CS19	No	ND	>55.0
CS20	No	5,600	>80.0
CS21	No	ND	>60.0
CS22	Yes	2,500	42.5
CS23	No	2,500	7.5

Ephemeral Gully Erosion Model

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ABSTRACT

Erosion of farmlands due to concentrated flow is severe on many unprotected fields across the country. Small channels can form large gullies if not controlled or filled. These small channels are routinely obliterated by tillage of the field and other routine farm operations only to be formed again. Since the 1960s, the Universal Soil Loss Equation (USLE) has been used to estimate rill and interrill (sheet) erosion. A model and computer program called Ephemeral Gully Erosion Estimator (EGEE) was developed by Agricultural Research Service (ARS). This paper describes the development of the Ephemeral Gully Erosion Model (EGEM), a modification of the EGEE computer model, to meet Soil Conservation Service (SCS) needs.

INTRODUCTION

Concentrated flow is severe on many unprotected farm fields across the country. Small channels can grow into large gullies if not controlled or filled. These small channels are routinely obliterated by tillage of the field and other farm operations only to be formed again. Crops are washed out by scour as these small gullies form. The severity of this problem is masked due to the routine fillings. The voiding and filling operations reduce the long-term productivity of the farmland because significant amounts of soil are lost each year. Soil to fill these small channels comes from areas adjacent to the channel, thus reducing topsoil depth. These small channels, obliterated by routine operations, are called ephemeral gullies. The location of ephemeral gullies is usually in the same place year after year, though the size of a gully varies from year to year due to factors such as duration and intensity of rainfall, type of crop grown, type of tillage practice, and time of year. Ephemeral gully erosion rates as high as 26 to 30 tons per acre per year have been measured.

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Since the 1960s, the Universal Soil Loss Equation (USDA-ARS, 1978) has been used widely to estimate rill and interrill (sheet) erosion and to compare the effects of alternative conservation systems and practices. However, there has been a pressing need for a procedure to predict erosion along well refined concentrated water flow courses on cropland (ephemeral gully erosion), a feature not incorporated in the Universal Soil Loss Equation.

It is of major importance to understand the magnitude of ephemeral gully erosion and its relationship to other erosion and sediment transport processes prior to comparing alternative solutions to erosion problems. Without this understanding, selection of the appropriate conservation system is difficult.

Ephemeral gully erosion data were collected by the SCS at selected sites across the United States. Geomorphic, soil, hydrologic, and cropping data were included. This information was collected in order to help develop and validate a mathematical model.

Several procedures for predicting ephemeral gully erosion were developed by researchers for SCS. A model and computer program called Ephemeral Gully Erosion Estimator (EGEE), developed by Dr. John M. Laflen of the ARS and others, was selected by SCS for further development as a computer program for field use. The EGEE program was modified to include user friendly input/output, help screens, revised hydrology computations, and ability to analyze three periods in a typical year.

MODEL DESCRIPTION

The model, developed to estimate ephemeral gully erosion has two major components. The hydrology component uses the SCS curve number, drainage area, watershed flow length, average watershed slope, and 24-hour rainfall with standard temporal distributions to estimate peak discharge and runoff volume. This peak discharge and runoff volume drives the erosion process. The erosion component is a combination of empirical relationships and physical process equations to compute the width and depth of the ephemeral gully based on the hydrology outputs.

The model may be used to estimate ephemeral gully erosion for a single 24-hour storm or the average annual conditions using a standard rainfall distribution. For average annual estimates, the 2-year and 25-year, 24-hour frequency rainfalls are used. The erosion-probability (percent chance) curve is integrated to estimate the average annual tons of erosion. For average annual estimates, the year may be divided into up to three periods representing different soil and crop conditions. For example, the year may be divided into (1) time after tillage, (2) crop maturing phase, and (3) winter crop or fallow condition. The ephemeral gully erosion for each of these seasons is then weighted by the fraction of rainfall erosive energy or the rainfall erosivity index (Fei) for the associated months of the year to estimate annual erosion (USDA-ARS, 1978).

HYDROLOGY MODEL

The hydrology model is based on the simplified procedures in Chapter 2 of the Engineering Field Manual (USDA-SCS, 1989). Peak discharge and volume of runoff are estimated based on a single event flood model.

EROSION MODEL

The erosion from concentrated flow is driven by the peak discharge and volume computed from the hydrology component. The erosion methanics are procedures simplified from those in CREAMS (USDA-ARS, 1980). Regression equations are used to estimate equilibrium gully width (w_e) and ultimate gully width (W_u). The erosion process begins with a gully of width W_e. Depending on the duration of runoff, the gully deepens until an erosion resistant layer is reached. Then, also, depending on the duration of runoff, the gully remains at that depth and widens towards the ulimate width, W_u. The detachment rate of the eroding soil is computed from the equation

$$D = KCH\ (1.35\ t - tc) \qquad \text{(Eq. 1)}$$

where: D = detachment rate, grams/sq. meter/sec.;
KCH = channel erodibility factor, grams/sec/Newton;
t = average shear stress of flowing water, Newton/sq. meter; and
tc = critical shear stress of soil, Newton/sq. meter.

This equation is described in CREAMS (USDA-ARS, 1980 and Foster, 1982).

The peak discharge is used to calculate t. The erosion model does not operate in time steps but treats the erosion process in three phases described above. The peak discharge is assumed to act over the duration of runoff volume. The average shear stress is multiplied by 1.35 to represent maximum stress at the channel bottom. KCH and tc are soil parameters estimated from field experiments of concentrated flow over various soil types (Franti, et al., 1985), (Laflen and Beasley, 1960), (Lyle and Smerdon, 1954), (Smerdon and Beasley, 1961), and (Franti, 1985).

The amount of detachment is balanced with the amount of sediment carried by the flowing water. The equation (Foster and Meyer, 1975)

$$\frac{D}{Dc} + \frac{G}{Tc} = 1 \qquad \text{(Eq. 2)}$$

where: D = detachment rate;
Dc = maximum detachment rate or capacity;
G = sediment load; and
Tc = sediment transport capacity.

All units are mass/unit area/unit time.

Tc is calculated from the Yalin equation (Yalin, 1963) and CREAMS (USDA-ARS, 1980).

Since EGEM works on a space and time averaged basis, this equation was modified to

$$\frac{Da}{Dca} + \frac{Ga}{Tca} = 1 \qquad \text{(Eq. 3)}$$

where: Da = mass of soil detached;
Dca = maximum capacity for detachment;
Ga = mass of sediment transported; and
Tca = maximum mass of sediment transportable.

All units are mass/unit area.

The width of the ephemeral gully, w, computed is at its outlet. Based on the work of Dr. Laflen, a factor of .664 W is used to represent the average width assuming the gully width varies from zero to some value. The depth of the gully is assumed constant for its entire length. Tons of erosion are calculated using the volume voided and the bulk density of the soil.

<u>Model Assumptions and Limitations</u>

1. Ephemeral gullies typically erode to the tillage depth. Some soils erode to greater depths. These depths are controlled by the peak discharge and volume of runoff. The user needs to estimate the expected maximum depth of the ephemeral gully.

2. Depth is limited to 18 inches or less. Deeper than that, the ephemeral gully erosion equations do not apply. Bank sloughing and head cutting, which are characteristics of classic gully erosion, are not characteristics of ephemeral gully erosion.

3. Increased erosion potential caused by freezing and thawing is not considered directly. However, the

user may adjust the KCH, critical shear, and runoff curve number to allow for more or less erosion under these conditions.

4. Erosion prediction for a single ephemeral gully is currently operational. Future work will involve capability to simulate erosion in a branching gully network.

5. The ephemeral gully is modeled as a rectangular shape with width narrowing in the upstream direction. A single Manning's "n" and slope are used, thus erosion and deposition may not be analyzed simultaneously.

COMPUTER PROGRAM

The EGEM computer program is written in BASIC to run under MS-DOS. Core requirements are under 256 K. Program features include user-oriented input, help screens, function key use, and user data files.

User-Oriented input

Full screen input display with the ability to move about the screen was implemented. The HOME, END and arrow keys are utilized to move the cursor from one data field to another. The use of insert, delete, and backspace keys make changes within a field easy. The PgUp and PgDn keys let the user move between input screens for season 1, 2, or 3 of the year. Data is checked when the user tries to leave a data field. These data fields are checked against upper and lower limits and for any meaningless key entries.

Help Screens

Help screens serve two functions: (1) to explain how the program operates and (2) to provide information on input parameters. These screens contain basic descriptions of items such as input data, function keys, and cursor control keys. Some tables to assist in input data selection have been used. However, the Help screens are not intended to be a complete substitute for the user manual.

Function Keys: The active function keys are displayed on the bottom line of the input screen.

Runoff Curve Number Module: The use of the F9 function keys allows the user to access a land use/hydrologic soil group/runoff curve number (CN) table. Entry of a drainage area in acres or percent of total drainage area on a land use line for a hydrologic soil group causes the appropriate CN to be weighted by the area and added to the composite CN.

A running total of drainage area is accounted for, and weighted CN is displayed.

Input Requirements: Input data is grouped into four major categories: identification information, watershed data, soil data, and rainfall data. The watershed and rainfall data are used to compute the peak discharge and runoff volume. The soil data one used primarily to compute the size of the ephemeral gully and the tons of soil eroded. Attempts were made to use readily available data at a typical SCS field office. Guidance for selection of input values is given in the user manual and Help screens. A list of key input data descriptions follows.

1. Average annual or single storm. The user may select either.

2. Drainage area at the outlet of the ephemeral gully. The terms drainage area and watershed are interchangeable.

3. Watershed length indicates the length of flow from the farthest drainage divide to the watershed outlet.

4. Concentrated flow length represents the potential length of the ephemeral gully. The lengths of persistent depositional zones are excluded from the concentrated flow lengths.

5. Watershed slope represents the average land slope in the watershed.

6. Concentrated flow slope represents the slope of the concentrated flow course.

7. Curve number represents the SCS curve number associated with the watershed land use, cover condition, and hydrologic soil group.

8. KCH represents the channel erodibility factor for the soil where the ephemeral gully will form.

9. Critical Shear (Te) is the critical shear stress at which soil will begin to erode.

10. Soil depth represents depth to a less erodible layer such as the tillage depth.

11. Bulk density of the soil is used to compute tons of erosion and depends on compaction of the tilled soil.

12. Particle diameter and specific gravity of particles are used in the Yalin sediment transport equation.

13. Manning's "n" represents the roughness factor for the area where the ephemeral gully will form.

14. Width depleted represents the width of land, adjacent to the ephemeral gully, from which soil is used to fill the gully during tillage or other farm operations.

15. Rain distribution type represents one of four standard SCS 24-hour rain distributions (see TR-55) (USDA-SCS, 1986).

16. Twenty-four hour rain represents the total 24-hour rainfall used for a single storm erosion estimate or the 2-year, 24-hour rainfall if average annual estimates are desired.

17. Twenty-five year, 24-hour rain is used for average annual estimates only.

18. Seasonal Fei represents the percent of the total rainfall erosivity index that applies to a particular season or part of the year. The source for this data is Agricultural Handbook 537 (USDA-ARS, 1978).

Output Description

Ephemeral gully erosion is reported as total tons. Voided area represents the surface area of the ephemeral gully. Depleted area represents the area for which soil is depleted due to filling of the ephemeral gully during tillage or other farm operations. For average annual erosion estimates, both seasonal values and annual values are reported.

Validation Studies

The EGEM computer program has been run using actual field data for a single event as shown in Table 1.

Initially, the information was not collected for EGEM model validation, but as an indication of the erosion rate for particular soil types. This data set is the best available at this time. SCS is in the process of refining the data set and is developing plans to include data from critical locations such as Georgia, Mississippi, and Idaho.

As indicated in Table 1, the EGEM computer program simulates the single event erosion rate reasonable well.

Conclusion and Future Efforts: SCS has developed a microcomputer program to provide estimates of the average annual material removed from a single ephemeral gully knowing selected watershed characteristics. The program is user friendly and incorporates the Help screen and function key concepts from the TR-55 computer program (USDA-SCS, 1986).

Limited validation studies indicated that the EGEM computer program provides reasonable estimates of the material removed from a single event.

There is a need to incorporate into the computer program techniques to simulate ephemeral gully erosion in a branching network and to distribute the erosion on the landscape.

ACKNOWLEDGEMENT

The authors would like to express much appreciation to the ARS scientists, John M. Laflen, Dale A. Watson, Chris Kohl, and T.G. Franti, for the basic soil erosion research that went into the development of the EGEM model.

Table 1.--Comparison of Estimated and Measured Erosion Rates

State	Number of Gullies	Average Material Removed Measured	Average Material Removed Estimated	R
		-tons-	-tons-	
Maine	309	9.3	18.1	.33
Michigan	12	7.9	10.7	.85
Wisconsin	14	2.1	2.4	.75
Kansas	21	3.9	1.1	.62
New York	32	53.3	36.8	.83
Louisiana	10	67.0	39.3	.98
Washington	30	12.9	12.4	.65
Delaware	10	5.8	7.6	.48

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CESIUM-137 STUDY OF SEDIMENT FROM CHANNEL PROJECTS

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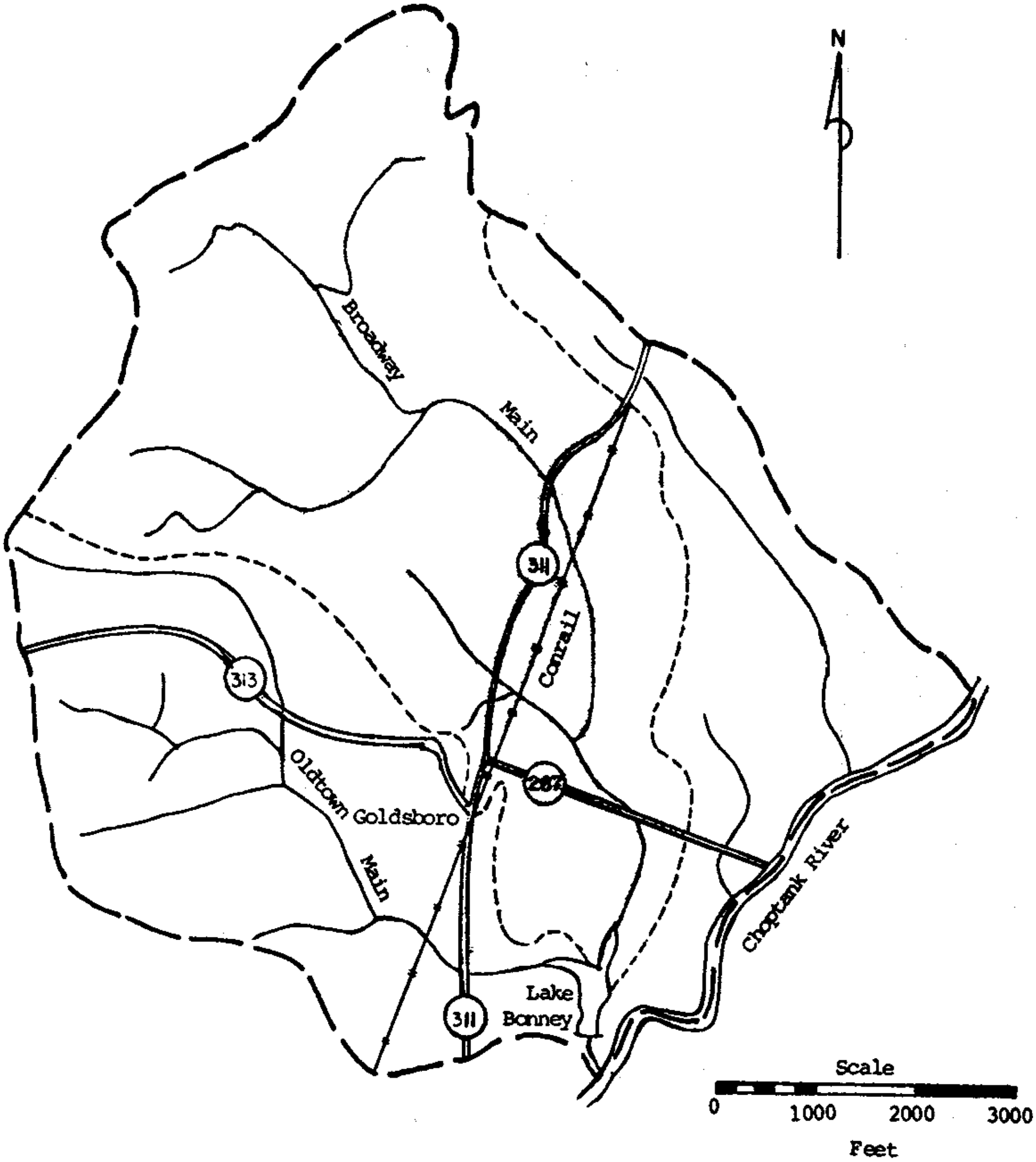
ABSTRACT

A reconnaissance sediment survey was performed on Lake Bonney, Goldsboro Watershed, Caroline County Maryland to determine the amount of sediment delivered to the lake following channel modification construction and to compare a subwatershed constructed with in-channel sediment traps with another subbasin which has no traps. Stratigraphic layers of sediment were dated by measuring cesium-137 fallout and sedimentation rates determined by referencing the fallout data planes. Sediment yield from the subwatershed with sediment traps and other soil conservation practices installed was 4-5 times less than the similar subwatershed with no conservation measures installed.

INTRODUCTION

Goldsboro Watershed (Fig.1) project is a partially installed flood prevention, land treatment, and agriculrural water management/drainage project installed under the Soil Conservation Service's small water protection program. The plan for the project was completed in July 1967 and called for the construction, or modification of 47 miles of channel within the 9214 acre watershed to reduce flooding and drainage problems on cropland. Construction commenced in 1973 and by 1974, the 26 miles of channel modification on the Broadway Branch subwatershed immediately above Lake Bonney had been completed. Further construction on the Oldtown Branch above the lake along with some minor channel modification on small tributaries below the lake was postponed pending the preparation of an environmental assessment and impact statement.

Channels in Broadway Branch were constructed or modified to a trapezoidal cross-section with 1.5 to 1 side slopes. Bottom width varied from 3.0 to 10.0 feet with depth of cut ranging from a minimum of 3.0 to 3.8 feet. Channel grades ranged from 0.05 to 01.2 percent and averaged approximately 0.125 percent. Designed velocities ranged from 0.6 to 3.02 feet/second and averaged approximately 2 feet/second. In- channel sediment traps were constructed at the lower end of each tributary or lateral, and at the lower end of the main stream. The traps were constructed by over-excavating the tributary channels 2 feet for a distance of 300 feet and the main stem 4 feet for a distance of 700 feet. During and immediately after construction, the traps were cleaned out as needed. After construction, the traps remained in place to provide storage for future sediment deposits and for fish and wildlife habitat. Exposed channel banks were temporarily seeded at the end of each day of construction. A 1220 foot section of



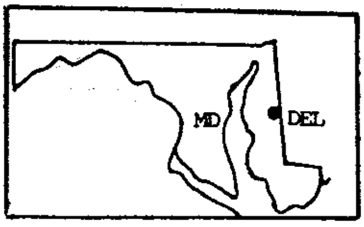


Figure 1

PROJECT MAP
GOLDSBORO WATERSHED
Caroline County, Maryland

stream channel was left undisturbed at the outlet end of the improved channel between the sediment trap and Lake Bonney.

Other practices installed to reduce erosion and sedimentation included 1) reverse grading of spoil away from the channel, 2) installation of surface water inlet structures, and 3) construction of a pilot channel on the lower three miles of the Broadway main to dewater the site and stabilize the channel banks

Although construction was not performed on the Oldtown Branch as part of the Goldsboro project, local drainage authorities had excavated much of the drainage system between 1952 and 1957. Trapazoidal channels with 1 to 1 side slopes were constructed and dredged spoil was piled on the banks and left in place. Sediment traps were not installed, no seeding took place, and other mitigation/conservation measures were not installed. As a result banks sloughed and eroded, and considerable sediment continues to be transported out of the subwatershed into Lake Bonney.

STUDY AND FINDINGS

Because Lake Bonney is a "Y" shaped reservoir with Broadway Branch outletting into one arm and Oldtown Branch outletting into the other, the opportunity existed to measure and compare sediment yield and quality of sediment from a drained watershed with no mitigation or conservation practices, with a drained watershed with sediment traps and other extensive conservation practices and measures installed. Lake Bonney is an old 24 acre man-made mill pond with an estimated trapping efficiency of 90-95 percent. Because Oldtown Branch and Broadway Branch subwatersheds are similar in both drainage area and land use, their sediment yields can be meaningfully compared. No significant change in land use has occured in either watershed (drainage of agricultural land was the purpose of the project: drainage of woodland for conversion to cropland was not a purpose).

	OLDTOWN	BROADWAY
Cropland	1833 ac	2467 ac
Woodland	1380 ac	1305 ac
Misc	231 ac	314 ac
Total	3444 ac	4100 ac

Sediment Samples were taken in both arms of the reservoir by using 3 inch thinwall samplers and 1 inch Porter sample tubes for stratigraphic measurement and qualitative analyses. Samples from the small sampler were used for measuring total sediment thickness, and obtaining samples for textural classification and determining organic matter content. The larger undisturbed samples were sent to the USDA-ARS laboratory in Oxford, Mississippi to determine cesium-137 content by layer. Fallout of radioactive isotopes of cesium released into the environment

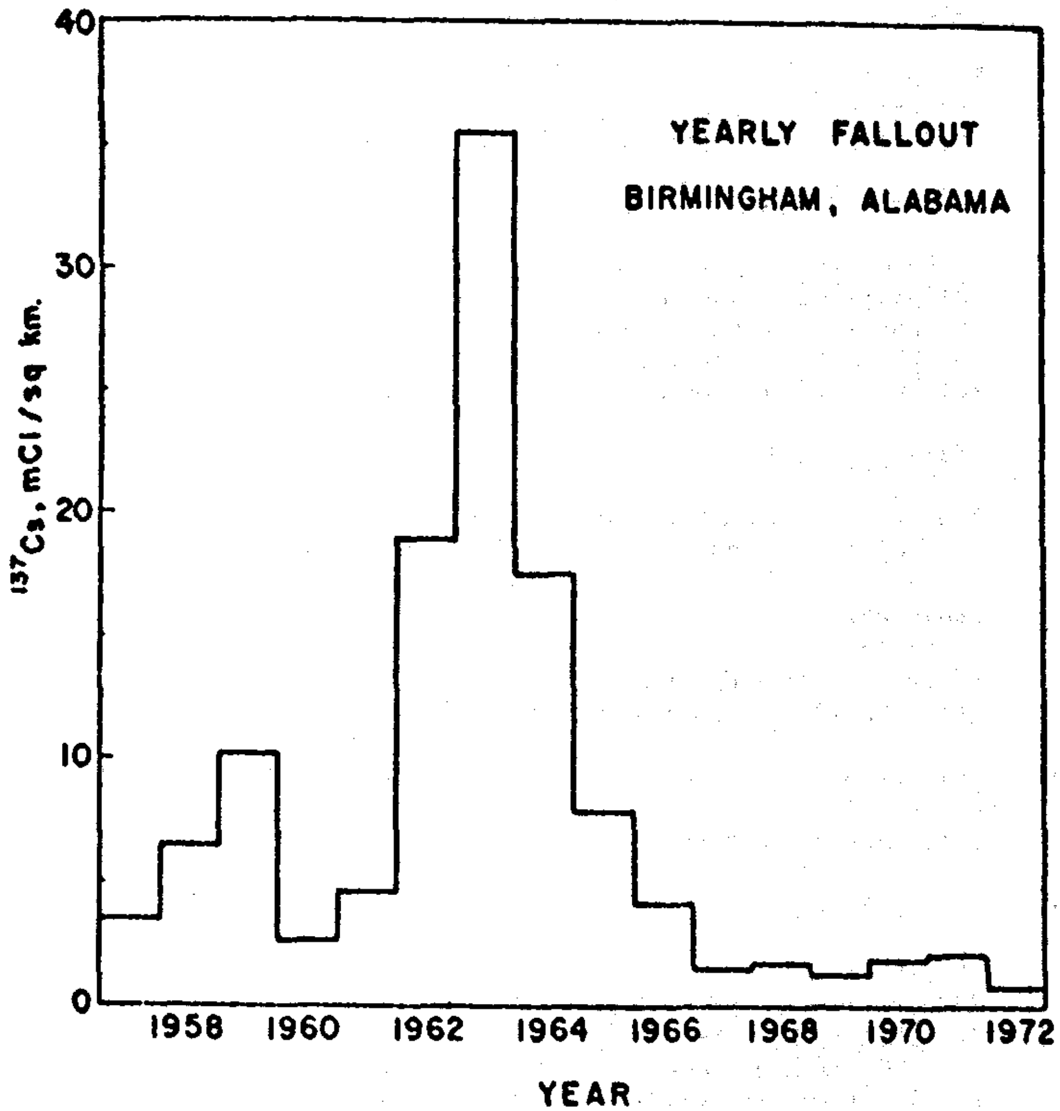


Figure 2. Typical Cs-137 Fallout Pattern

during atmospheric testing of nuclear weapons occurred in definite yearly variations (Fig 2)(Ritchie, 1975, 1972). By measuring relative cesium-137 concentrations, it is possible to determine and evaluate sedimentation rates within Goldsboro Watershed.

Data derived from analysis of the sediment profiles indicate that Lake Bonny has received a much greater volume and mass of sediment from the Oldtown system. In sediment profiles located on the Broadway Branch arm of the lake, all of the cesium-137 was found in the upper 12 inches, and most concentrated in the upper 6 inches. The uppermost 12 inches was therefore probably deposited since 1954, the first year during which a significant amount of cesium-137 fallout was incorporated in sediments. The top 6 inches were probably deposited after 1964, the year of the most extensive atmospheric nuclear testing. Sediment deposition from Broadway Branch averaged 0.7 inches per year from 1954 to 1963, a period which included no extensive channel work, and 0.3 inches per year from 1964-1982, a period during which the Broadway system was excavated and the sediment traps installed. Sediment profiles located on the Oldtown Branch arm of the lake, showed a peak concentration of cesium-137 in the 6-12 inch layer. A significant concentration of cesium-137 was present to a depth of 18 inches--the limit of sampling. It appears that at least 18 inches of sediment have been deposited since 1954. The highest highest average rate of deposition from the Oldtown Branch (1.2+ in/yr) occured from 1954-1964, a period which included channel construction. From 1964-1982, during which there was no channel work, the rate dropped to 0.4 inch/year.

Sediment samples taken near the the Broadway outlet contained a significantly higher percentage of fine grained material and decaying organic matter (aquatic vegetation and some leaves) than did samples taken near the Oldtown outlet. The average unit weight (density) of the sandy sediments in the Oldtown Branch arm is nearly twice as much as the silty-clayey sediments in the Broadway Branch (80-85 lb/cu ft vs 38-43 lb/cu ft), indicating that the sediment yield is nearly three times higher from the Oldtown watershed as compared to the Broadway watershed. When the organic fraction is removed from the sediment samples, the sedimentation differences are four to five times less on the Broadway watershed.

Other studies in the Delmarva Penninsula have shown similar reductions in sediment yield when in-channel traps are constructed and other soil conservation measures are installed. Hunt (1976) in a sediment study of the nearby Marshyhope Creek Watershed, Maryland and Delaware, showed an 81 percent reduction in sediment loading when in-channel sediment traps were installed. A 50 percent reduction in sediment yield from pre-channelization conditions occured in the Nanticoke Watershed project, Sussex County, Delaware (Iivari, 1990) when in-channel sediment traps and other channel modification conservation practices were installed.

Sediment studies and evaluations in the Coastal Plain of North Carolina (Simmons, 1988, Simmons and Watkins, 1982) found ten fold increases in suspended sediment during excavatiuon phases of channel projects; but within a year following excavation, levels had decreased to about 5 times those of pre-excavation levels. Mean sediment concentration and yield remained several times higher than nearby unchannelized rural streams. Long term averages indicate a doubling of sediment yield when channelized and non-channelized watershed are compared.. Watkins and Simmons attributed these increases to eroding spoil piles and stream banks, and alteration of natural pool characteristics of the stream. No in channel traps nor other conservation measures were utilized in the North Carolina channelization projects.

Based on the results of this assessment and the cesium-137 analysis, it appears that the sediment traps and utilization of other channel modification conservation practices on Broadway Branch have performed as anticipated by reducing the total sediment load by 80-85 percent to Lake Bonney when compared to the Oldtown Branch.

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INSTRUMENTATION FOR UPLAND EROSION RESEARCH

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ABSTRACT

An automated system for data acquisition and runoff sample collection is being used in the recently implemented study of erosion control practices for loessial uplands in northern Mississippi. The main components of this system are programmable, analog/digital data loggers. Runoff from standard-size erosion plots and from field-sized watersheds is gaged using appropriately sized flumes equipped with FW-1 recorders with potentiometer output. Potentiometer voltage is converted to discharge via flow depth, and incremental discharge rates and cumulative discharge volumes are stored as separate data files. In usual operation, individual data loggers are used for 4 runoff plots. The runoff-plot data loggers interrogate all sensors every 30 seconds and "rest" until the next interrogation time. During events, rainfall and runoff values are logged every 30 seconds and written to data files every N minutes where N is an integer selected by the operator. Cumulative discharge volumes per runoff plot are used to control collection of discharge-weighted composite samples. Individual pump samplers are activated when the cumulative discharge volume equals or exceeds the program critical value for a plot. All calibration constants and critical program variables are easily accessible in the field using an internal calibrate subroutine. Total run time for each sampling cycle is less than 10 seconds. Data are transferred to the laboratory mainframe computer via a 256 KB digital notebook. The watershed data loggers record sensor output every minute during a rainfall/runoff event and control collection of either time-based incremental samples or discharge-weighted composite samples. Data is stored serially and transferred to the laboratory via data storage packs. Other features are generally comparable with runoff-plot loggers, and rainfall data can be recorded on either logger as desired. Advantages of this system include increased resolution of rainfall/runoff values, an accurate time base for all sites, and minimum labor for data reduction.

INTRODUCTION

As one part of the Interagency Demonstration Erosion Control Project in the Yazoo Basin, northern Mississippi, the USDA National Sedimentation Laboratory has initiated a study of cost-effective practices for control of upland erosion. Subsidiary objectives addressed needs related to implementation of the 1985 Farm Bill and application of the WEPP model. This research includes parallel studies of profitability and of erosion-control capabilities of practical farming systems. Assessment of erosional characteristics was implemented as a hierarchy, ranging from specialty plot and rainfall simulator tests, to standard sized runoff/erosion plot studies, and to field-sized evaluations of runoff and soil loss. Equipment and procedures documented in the literature were generally adequate for implementation except in the area of data logging. Agricultural Handbook No. 224 (Brakensiek et al., 1979) was last revised in 1979 and hence does not cover adaptation of more recently-developed field computer capabilities. This report is intended to partially alleviate this deficiency by documenting the use of commercially-available data loggers in plot and field-sized watershed studies of runoff and erosion.

STUDY AREA

The intensive study area is located in the loessial uplands of Tate County, northern Mississippi immediately east of the Mississippi Alluvial Plain. The loess stratigraphy at this location is comparable with that described by Buntley et al. (1977) for West Tennessee. Soils range from Grenada to Loring to Memphis, depending upon soil depth to the fragipan horizon, and no materials coarser than fine sand are present in the upper soil horizons. The plot/watershed layout in the intensive study area is shown in Fig. 1.

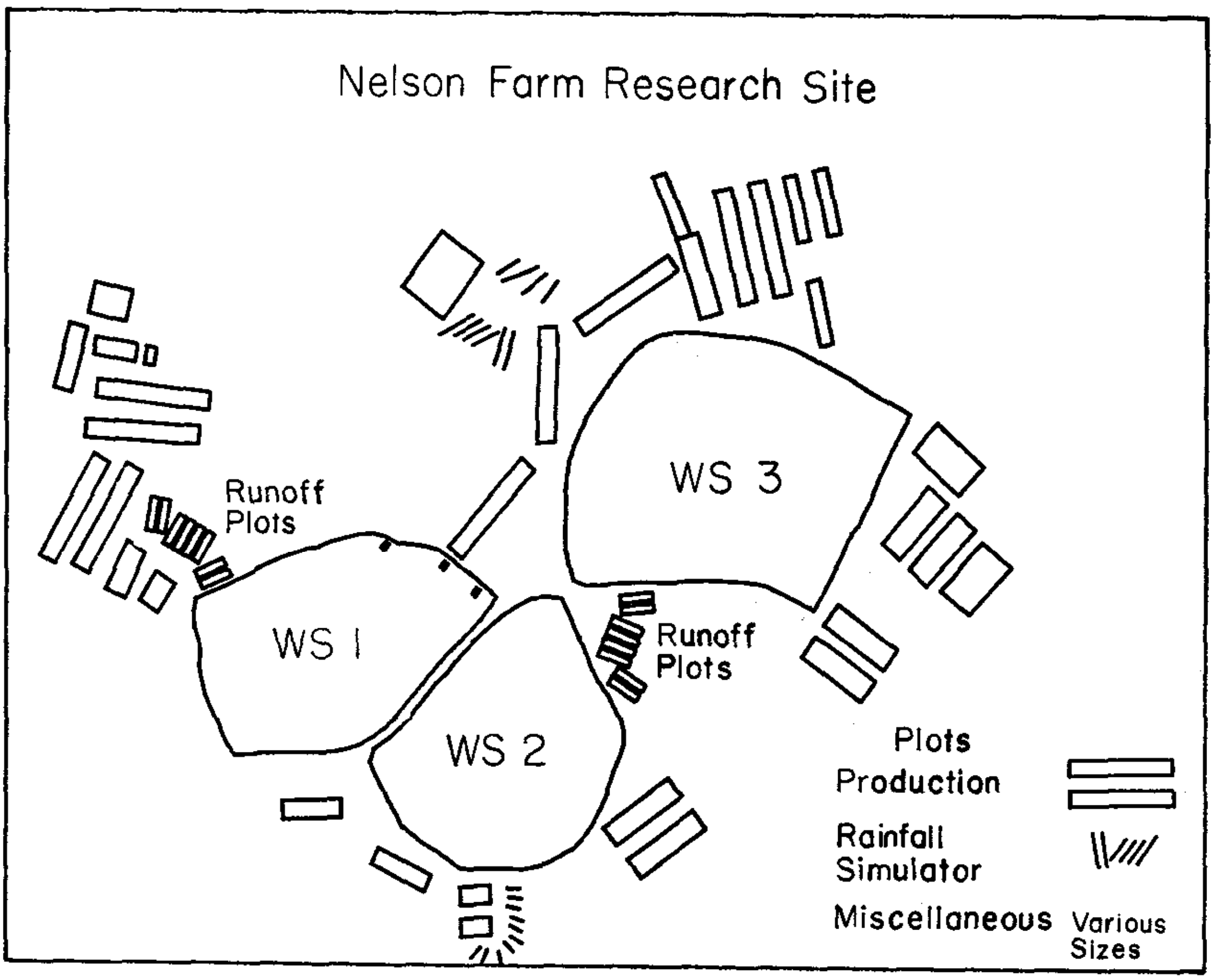

Fig. 1 Study area, Tate County, Mississippi. (ws = watershed)

INSTRUMENTATION

Instrumentation selection was based on the following general criteria:

1. All instrumentation must be DC powered,

2. Site modification must be minimal,

3. Service and data reduction requirements must be minimal, and

4. The sampling equipment must be capable of collecting either discharge-weighted composite samples or time-based discrete samples.

The collection of discharge-weighted samples for the runoff plots was necessary to reduce the sample analysis load to levels realistic to available resources. Based on these criteria and previous experience with comparable products, the following components were selected[1]:

1. ISCO pump samplers were installed at all gaging sites,

2. FW-1 stage recorders with potentiometric output were used with all flumes,

3. Omnidata analog/digital data loggers were used for all data collection. Loggers with time-of-event, event-triggering, or program-driven output control capabilities were used at each watershed to control sample collection. Loggers with multiple-station, program-driven output controls were used at all runoff plot sites to control collection of discharge-weighted samples. Each logger serviced four runoff plots. This multiplexing was made possible by the close proximity of these plots (Fig. 1).

Watershed Instrumentation

Instrumentation used to gage watershed runoff and to collect time-based discrete or program-controlled composite runoff samples for suspended sediment analysis required little modification. Omnidata Easy Loggers (Version 3.0) are used at each site to activate the ISCO samplers. All sensors are scanned each minute, the potentiometer output is converted to discharge, and the resultant discharge data are logged every N minutes where N is any positive integer. Sampling times are similarly established every N minutes or every specified increment of runoff. All data are stored on plug-in EPROM data storage packs. Each unit is powered by a 12 volt battery and the complete gaging/sampling system housed in a small (4 ft. by 8 ft.) shelter house. An example of the data record for a storm on 5/21/90 at Watershed 1 is presented in Fig. 2.

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[1]Use of trade names in this report is for information only and does not constitute endorsement by the U. S. Department of Agriculture.

Runoff Plot Instrumentation

One analog/digital 516C Series Polycorder with 32KB RAM services every four runoff plots and accompanying rain gages. In routine operation, each 516C unit interrogates all sensors every thirty seconds, converts all sensor values to desired units, logs all data by plot number and time, and controls pump sampling times independently for each of the four plots. During post-storm plot servicing, the data is downloaded from the 516C units to a 256 KB Series 600 digital unit for transportation to the NSL mainframe computer. Again, small (4 ft. by 8 ft.) shelters are used to house all gaging/sampling equipment.

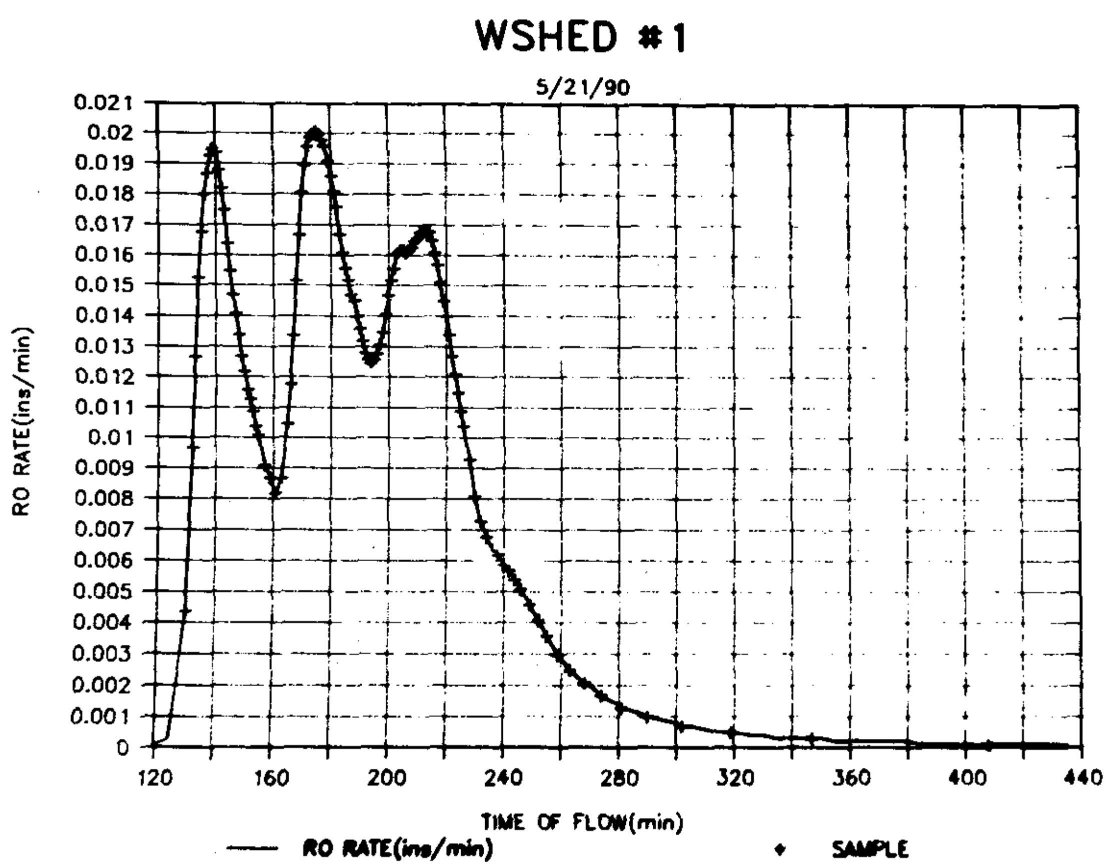

Fig. 2 Runoff and sampling times for a storm on 5/21/90, Watershed 1.

Software

Obviously, the software for this application is specialized to the study needs but can easily be modified to meet the needs of comparable studies and applications. *For ease of servicing and maintenance in the field, the following* program options have been incorporated into the Series 516C Polycorder.

1. Set Clock

   The only use for this option is to validate or reset the date and time of the internal clocks.

2. Calibrate

   This option is used to specify the report interval at which data are written from the working registers to the data storage register. It is also used to set the flow limit for each plot (that is, the volumetric discharge limit for actuating individual ISCO samplers) and for calibration of individual FW-1 potentiometers at 0.0 flow depth.

3. Stop Logging

   This option stops the autologging program and recalls the main menu.

4. Xmit Data

   This option is used for downloading data from the Series 516C units to the Series 600 unit.

5. Erase Data

   This option is used to erase all data from storage in the Series 516C after successful downloading to the Series 600.

6. Diagnostic Data

   This option is primarily used for inspection or troubleshooting in the field. It allows the user to inspect the time and date, battery voltages, available memory, current sensor readings, current calibrations, accumulated runoff and rainfall, and the total number of pump cycles for each plot.

7. Poly Op System

   This option is used to activate standard polycorder modes of operation. It is used primarily in program debugging and/or modification.

8. Quit

   This option is the sole means of turning the units off.

9. Start Logging

This option initiates autologging, the program for unattended data collection. Once initiated, data recording will continue until the Stop Logging option is selected.

The schematic for the autologging program is shown in Fig. 3. STM1 scans all sensors every 30 seconds. If no events are sensed and no events were sensed on the previous scan, the unit is put to rest until the next scan time. If no events are presently sensed but were sensed on the previous scan, storm summary totals are written to data storage prior to resting. If sensors indicate either rainfall or runoff magnitudes greater than minimal values of interest, all sensors are rescanned by RNFF. Discharge rates are calculated by FLDPTH using appropriate equations to convert FW-1 potentiometer output to flow depth and flow depth to discharge rate. For ease of calculations, the (nonlinear) rating of discharge on depth was separated into three linear segments by break points at 0.071 and 0.279 feet of depth. The minimum r^2 for any of these linear segments was 0.9998.

Subsequently, runoff plot discharge volumes are calculated, summed for each storm, and summed since last activation of each ISCO sampler. Incremental rainfall and runoff values are recorded as specified by the report interval. Available memory is monitored and the report interval lengthened as available capacity is reduced. Finally, the calculated discharge volumes are compared with plot flow limits (in PMPSMPL), and individual ISCO samplers are activated when the calculated volume equals or exceeds the plot flow limit. When this is completed, the unit is put to rest until the next scan time. Each autolog cycle takes about 7 seconds and the total Series 516C Polycorder program is 7300 KB.

Five program options have been incorporated into the Series 600 Polycorder menu.

1. Poly mode

   This option is used to activate standard polycorder modes of operation. It is used primarily in program debugging and/or modification.

2. Data-soak

   This option soaks data from the Series 516C to the Series 600 polycorder.

3. Xmit to PC

   This operation transmits data from the Series 600 unit to the NSL mainframe computer, using Crosstalk.

4. Erase Data

   This option is used to erase all data from storage in the Series 600 unit after successful downloading to the mainframe computer.

5. Quit

   This option turns the unit off.

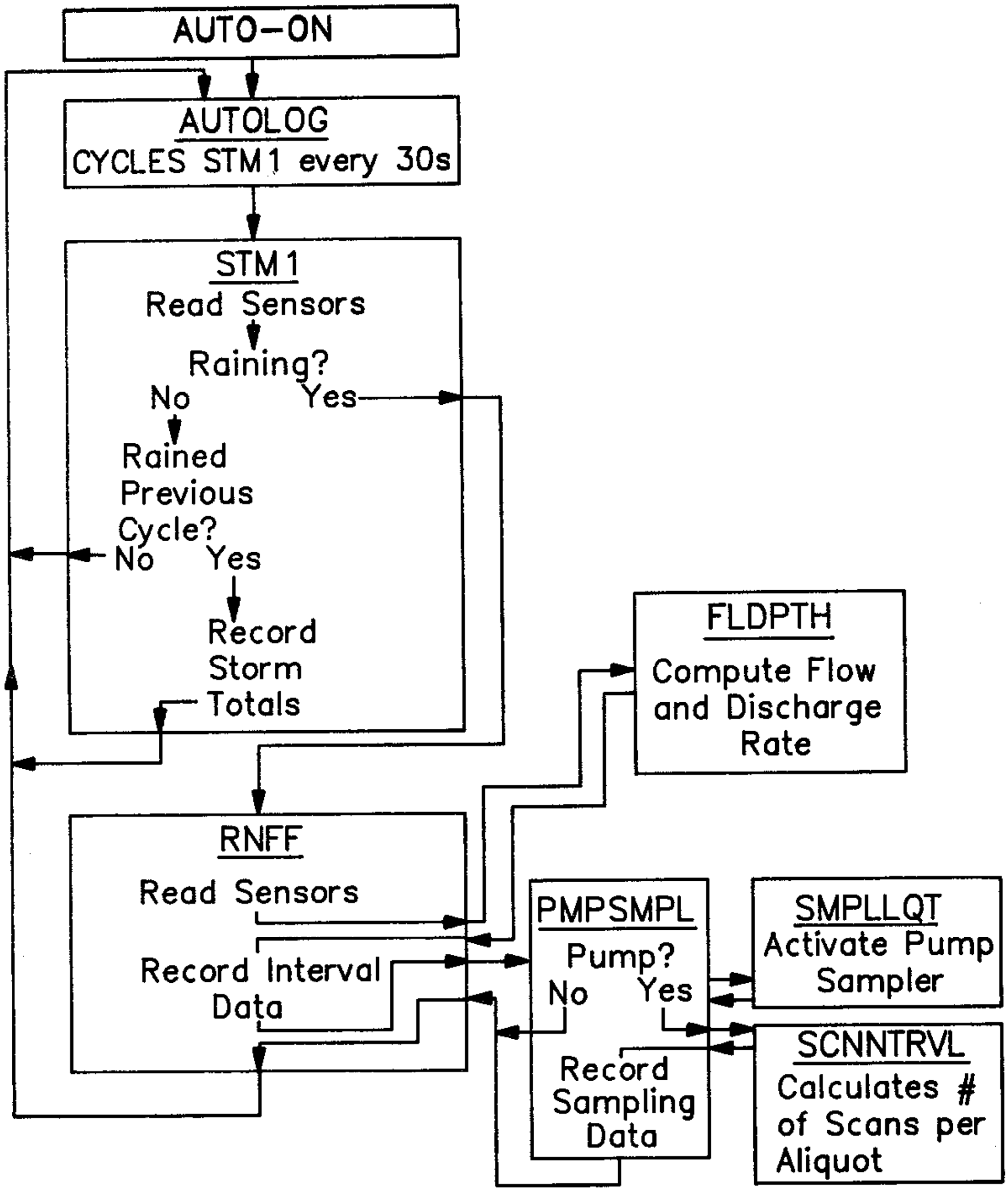

Fig. 3 Schematic of autlogging program.

Equipment Modifications and General Considerations

Whenever possible, commercially available equipment was used. Several modifications, however, were necessary. The Series 516C Polycorders were modified by Omnidata International, Inc. for operation with a standard 12- volt battery. This was necessary to maximize unattended operation in the field. Omnidata also fabricated and supplied an accumulator to interface tipping bucket rain gages with the 516C units. This interface continuously records the number of tips and, when interrogated, relays the total tips per scan interval to the 516C. Modifications designed in-house include a minimum friction coupling for mounting potentiometers on FW-1 shafts (by Oscar W. Sansom) and a modified slotted sampler/turbulence box (by C. E. Murphree, Jr.) for collecting outflow from the H flume. The intake port for the ISCO pump sampler is mounted on this box. Other miscellaneous considerations that have proven beneficial for routine operation include burying all cable, sheathing it with PVC tubing around access sites (to minimize stripping by field mice), and protecting all sites against stray ground-transmitted electrical signals by installation of a ground plane.

SUMMARY

We have described the equipment and software programs employed in our recently initiated study of control of upland erosion. Advantages of this system include (a) increased resolution of rainfall/runoff values, (b) an accurate time base for all sampling sites, and (c) minimized labor requirements for data reduction and hence reduced probability of human error. System costs were reduced by about $2,000 per plot by the use of this data-logging/pump-controller equipment.

We believe this type of gaging system has appreciable potential for adaptation to a wide variety of studies. Complete documentation is available upon request to the authors.

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GOODWIN CREEK BANK INSTABILITY AND SEDIMENT YIELD

By Earl H. Grissinger, Soil Scientist, Andrew J. Bowie, Hydraulic Engineer, and Joseph B. Murphey, Geologist, USDA National Sedimentation Laboratory, Oxford, Mississippi.

ABSTRACT

Goodwin Creek Experimental Watershed was instrumented in the early 1980's to study stream channel instability problems and remedial practices. The two downstream-most gaging sites in this watershed bracket a 1.96 mile length of channel with no major tributaries, making this an ideal reach for bank instability studies. Selected channel cross sections have been surveyed quarterly to document the magnitude of channel changes. This paper documents relations between the measured channel bank changes and sediment yield differences between these gaging sites. Results are based on fine sediments only since gage data are not complete for coarser fractions at all gaging sites. For the five year period from 11/82 to 10/87, bank erosion estimated by surveying totaled 50,200 tons. Differences in load between these gaging sites from 11/82 to 10/87 differed by only about 1% from the bank erosion survey data. Comparable annual rates, however, are not significantly related. This lack of significance is thought to reflect basic differences between short-term rates of sediment production by mass bank failure and rates of entrainment of sediments produced by such failures but temporarily stored in the channel proximal to failure sites. A watershed sediment budget based on gaged sediment loads and on load estimates calculated from land use data, indicates that about three-fourths of the total fines load of the watershed originated from channel and gully erosion. This suggests that better than 85% of the total sediment yield for Goodwin Creek originates as channel and gully erosion.

Introduction

Goodwin Creek Experimental Watershed was instrumented in the early 1980's as part of a cooperative effort between the Vicksburg District Corps of Engineers and the USDA National Sedimentation Laboratory to study stream channel instability problems and remedial practices. Instrumentation has been described in several reports (see for example Bowie and Sansom, 1986). Gaging results have been reported as Goodwin Creek Watershed Database Reports to the Vicksburg District, Corps of Engineers. Results of the concurrent channel stability evaluations have been documented in a series of reports, most recently by Grissinger and Murphey (1989a, b). This report documents relations between these two watershed properties, i.e., between watershed sediment yield and stream channel bank failure rates and magnitudes.

Study Site and Procedures

Goodwin Creek Experimental Watershed is located in the loessial uplands of northern Mississippi (Figure 1). Soils are silt loams, generally comparable with those described in western Tennessee by Buntley et. al. (1977). Land use ranges from cultivated row crops to pasture, timber, and idle lands subjected to minor management disturbances. Between 11/82 and 10/87, cultivated acreage decreased from 1144 to 695 acres, i.e., from about 25% to 15% of the contributing watershed

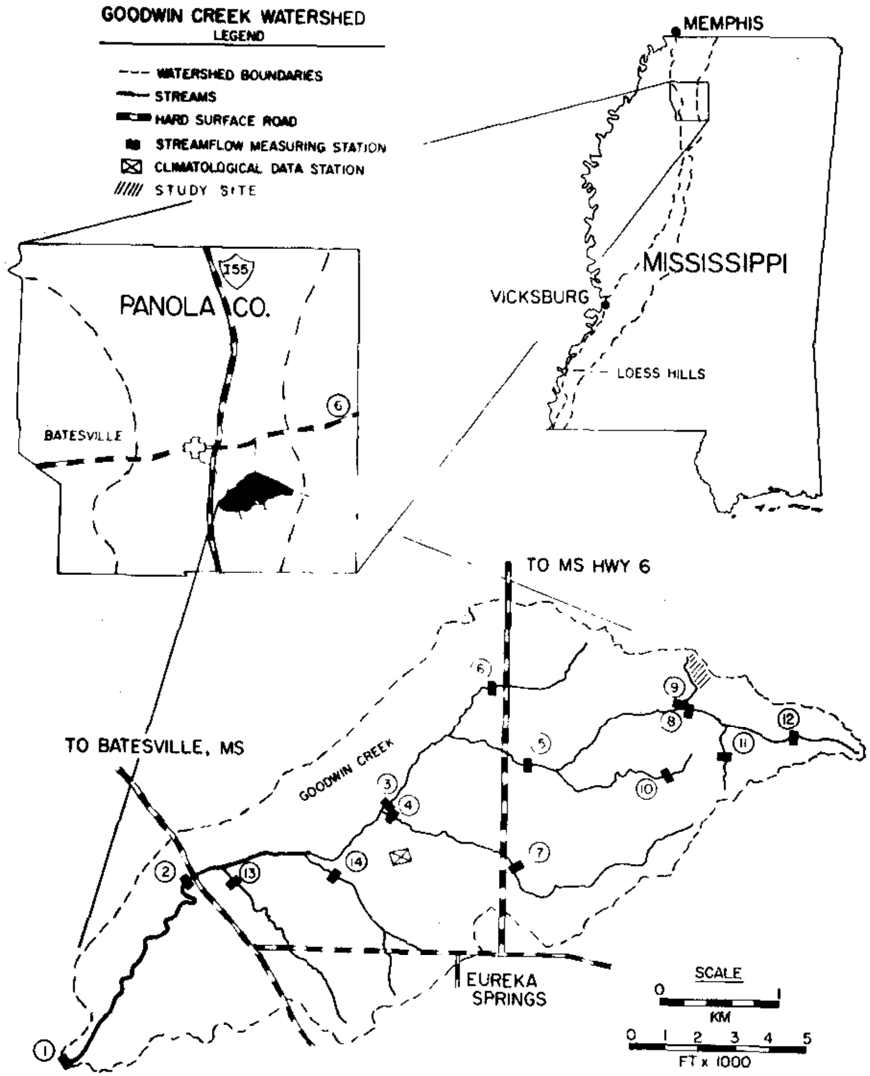

Figure 1. Goodwin Creek Experimental Watershed, Panola County, Mississippi.

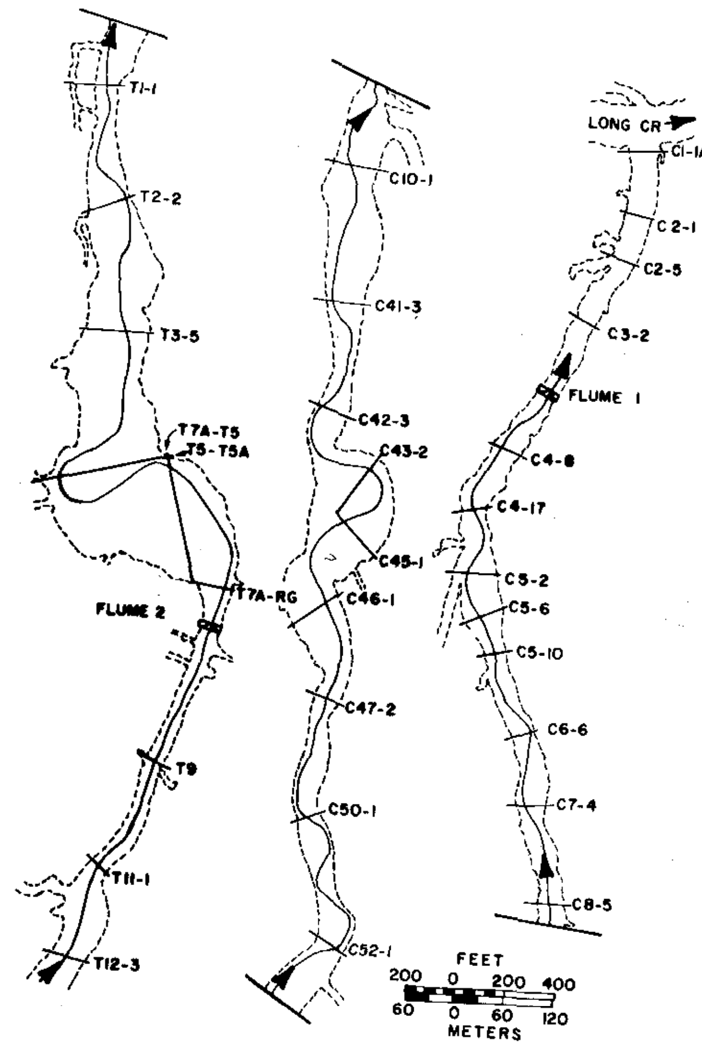

Figure 2. Plan map of bank stability study reach of Goodwin Creek.

area. Almost all of the cultivated cropland is in the alluvial floodplains. Most of the abandoned cropland was left unattended and has been reclassified as idle. Stream flow is flashy following storm events with base flow restricted to the trunk channel starting just upstream of Gaging Station 2 (Figure 1). Survey ranges for the intensive bank stability evaluation are shown in Figure 2.

Repetitive cross-section surveys in the 1.96 mile length of channel between Gaging Stations 1 and 2 (Figure 2) were used to compute bank failure rates. To facilitate direct comparison of these survey results with comparable estimates based on sediment load differences, the fines (<0.062 mm) loads at Gaging Station 2 were weighted using the ratio of runoff at Gaging Station 1 per runoff at Gaging Station 2. Only the fines were used in this comparison since gage data are not complete for coarser fractions at all gaging sites. This weighting was judged appropriate due to the relative similarity of land use within these two areas. The annual yield for fines calculated from documented land use was 1.30 tons per acre for the watershed upstream of Gaging Station 1, and 1.27 tons per acre for that upstream of Gaging Station 2. Yield values for individual land uses were estimated from gaged unit source areas within Goodwin Creek Experimental Watershed. Measured sediment yields for the gaged cultivated areas were adjusted to compensable for the excessive relief in these areas relative to most cultivated lands in the watershed. This adjustment was based on differences of the USLE Length-Slope topographic factors between the gaged areas and the average for the cultivated acreage. Individual annual values were 0.12 tons per acre for forest lands, 0.4 tons per acre for pasture, 1.4 tons per acre for idle lands, and 4.7 tons per acre for cultivated crop lands. Lastly, the watershed sediment budget was estimated by comparing the gaged fine sediment loads with the yields of fines estimated from land use acreage for the individual gaged watersheds.

Results and Discussion

Values for annual runoff, fines loads at Gaging Stations 1 and 2, and estimated bank erosion between Gaging Stations 1 and 2 are presented in Table 1. From 11/82 to 10/87, the surveyed bank erosion totaled 50,200 tons and that estimated from differences in the fines load was 50,900 tons. These two estimates of total bank erosion differ by less than 1.5%. Comparable annual values, however, are not significantly correlated. We believe this seeming contradiction results from the two-stage process of cyclic bank failures typical for this area.

For channels at constant depth, bank failures occur when the combination of bank oversteepening and reduced bank-material shear strength becomes critical (Little et al., 1982). For a given bank material, the critical variables affecting failure are bank oversteepening due to toe erosion by fluvial shear, and minimum (worst case) shear strength development resulting from bank material saturation and the development of tension cracks. Thus, although runoff magnitude is a control of toe erosion and bank oversteepening it is not the singular control of failure frequency (see also Grissinger and Little, 1986). Annual bank erosion survey valves and annual runoff (Table 1) are not significantly correlated.

Runoff magnitude is the singular dominant control of entrainment and transport of the slough material. Values of annual fines load at Gaging Station 1 and of annual fines load attributed to bank erosion (Table 1) are both significantly correlated to annual runoff at 99% probability. For both correlations, better than 90% of the variation of the fines load is explained by runoff variation.

The correlation of monthly values for the fines load at gaging Station 1 and the fines load attributed to bank erosion has comparable significance (Figure 3).

Table 1.

Measurement Period	Runoff	Loads of Fines				Surveyed Bank Erosion*
		Gaging Station 1*	Gaging Station 2 Measured	Gaging Station 2 Weighted	Attributed To Bank Erosion*	
	inches	tons	tons	tons	tons	tons
11/82-10/83	39.1	56,100	35,400	37,500	18,600	14,500
10/83-10/84	23.6	41,200	25,100	26,500	14,700	16,400
10/84-9/85	18.4	23,800	15,100	16,000	7,800	4,100
9/85-9/86	5.6	6,400	4,000	4,200	2,200	5,800
9/86-10/87	16.1	13,300	5,500	5,700	7,600	9,400
Total	102.8	140,800	85,100	89,900	50,900	50,200

*Values rounded to nearest 100 tons.

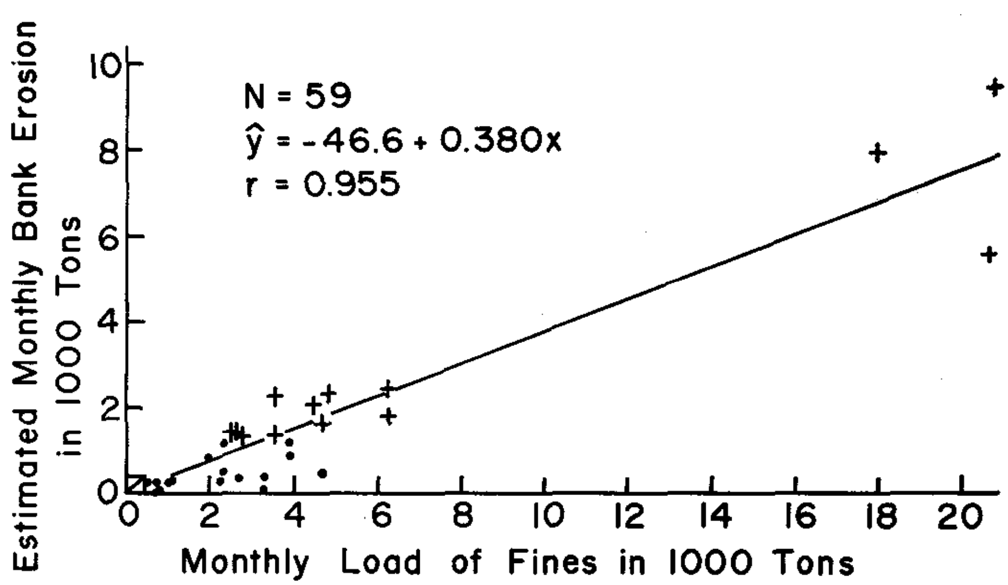

Figure 3. Monthly fines loads at Gaging Station 1 versus monthly fines loads attributable to slough from prior bank erosion between Gaging Stations 1 and 2

About 80% of the fines load attributed to bank erosion was produced during only 13 of the 59 months of this study. Values for these 13 months are identified by a + symbol in Figure 3. Daily values for fines load attributed to bank erosion and for runoff are presented in Figure 4 for significant events during these 13 months. These daily data were partitioned on the relative amount of runoff (Table 1). The curve for 12/82 to 5/83 represents bank slough entrainment per runoff magnitude during times of excessive runoff. The curve for 5/84 to 2/87 represents the comparable relation during times of relatively reduced runoff. Both regressions are significant at 99% probability. The significantly larger regression slope term for the times of reduced runoff is believed to reflect the greater supply of bank slough material available for entrainment. This relatively large supply of slough resulted from the reduced frequency of entrainment and transport from the watershed. In this scenario, bank failure produces slough which resides in a sink proximal to the bank toe until entrained by a subsequent runoff event. Thus, the residence time and magnitude of the slough vary with bank failure rate and with runoff recurrence interval. Since slough resides proximal to the bank toe, slough entrainment is not inherently coupled with toe removal and bank oversteepening, and short-term bank failure rates are not coupled with short-term sediment loads resulting from bank erosion.

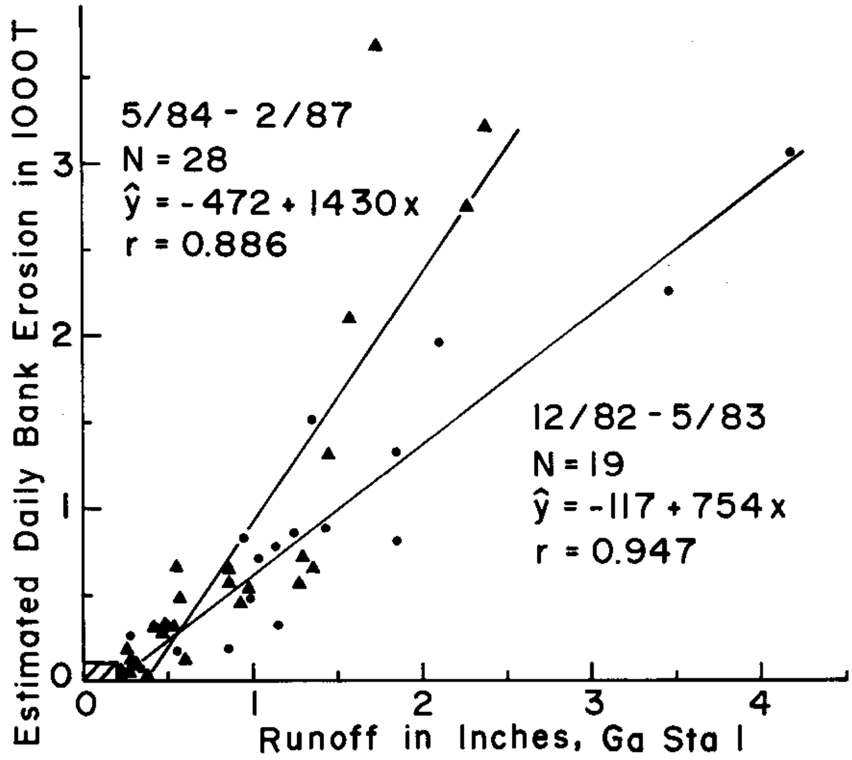

Figure 4. Daily runoff at Gaging Station 1 versus daily fines loads attributable to slough from prior bank erosion for 12/82 to 5/83 (·) and for 5/84 to 2/87 ( ).

The agreement between the total measured bank erosion and the total fines load attributed to bank erosion (Table 1), indicates that the gaged data could be used to estimate channel and gully erosion for the entire Goodwin Creek Experimental Watershed. The budget, based on estimated fines loading from documented land use and gaged fines loads per subwatershed, estimates that 110,400 ton of fine sediments originated from channel and gully bank erosion during the 59 month period of study (Table 2). This represents about 75% of the total watershed fines load. Assuming that all of the coarse load documented by Kuhnle et al. (1989) also originated from gully and channel erosion, the sediment yield from Goodwin Creek Experimental Watershed due to gully and channel erosion was about 85% of the total. Obviously, these percentages reflect the yield values for individual land uses employed in calculating the fine sediment budget. However, even if the sediment yield from cultivated cropland was doubled (to 9.4 tons per acre) the percentage of sediment yield due to gully and channel erosion would be reduced by only about 10%, to about 75% of the total sediment yield.

The budget (Table 2) indicates two primary sources of channel and gully erosion, one in the trunk channel downstream of Gaging Station 2, and the second in headwater areas. Although the occurrence of this type of valley trenching in headwater areas has been described (for example see Happ et al., 1940), it has not been quantified sufficiently for comparison with present results. Data for channel erosion in other trunk streams in northern Mississippi are sufficient for limited comparisons. Bowie and Mutchler (1986) reported annual channel erosion rates of about 3,900 tons per channel mile for a 6-year period from 1971 to 1976 for gaging sites at the lower end of Pigeon Roost Creek (Gaging Stations 32, 34, and 35). The 5-year annual average for the Goodwin Creek channel between Gaging Sites 1 and 2 is about 5,200 tons per mile, 33% greater than from the lower end of Pigeon Roost Creek. At this time it is not known to what degree this difference originated from rainfall differences, from land use or topographic differences, or from material erodibility differences. Due to the larger sediment yield from upland sources in the Pigeon Roost Creek Watershed, the percentage of total sediment yield attributable to bank erosion was 32% in contrast to the estimated 85% for Goodwin Creek. Annual channel erosion for an 18-year period from 1958 to 1976 for Hotophia Creek, however, averaged about 11,300 tons per mile, about 2.2 times greater than that for Goodwin and 2.9 times that for Pigeon Roost Creek (Little and Murphey, 1981). This relatively high rate for Hotophia was associated with progressive entrenchment of the system. In contrast, the trunk channels for Pigeon Roost and Goodwin Creeks had previously entrenched and their erosion rates reflected channel widening at relatively constant channel depth.

Table 2.

Gages	Gaged* tons	Estimated From Land Use*+ tons	Gaged from Upstream Subareas* tons	Differences Attributed to Channel & Gully Erosion* tons
Peripheral				
14	7400	2200		5200
13	7400	1100		6300
12	1500	400		1100
11	1000	100		900
10	0	0		0
9	2200	200		2000
7	20500	1800		18700
6	5500	2200		3300
Nested				
8	9400	700	2500	6300
5	25200	2700	11600	10900
4	25200	2000	20500	2600
3	36100	5400	30700	-0-
2	85100	5900	76100	3100
1	140800	5700	85100	50000
Total		30400		110400

*Values rounded to nearest 100 tons.

+Excludes estimated erosion included with upstream gaged acres.

Summary

The significance of stream bank and gully erosion as a source of sediment has been documented for Goodwin Creek Experimental Watershed. About 75% of the fines load and 85% of the total load are estimated to have originated from channel and gully erosion. The significance of slough sinks proximal to bank failure sites is briefly discussed in relation to yields of fine sediments.

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IMPACT OF ALLUVIAL SEDIMENTATION ON HYDROLOGY

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INTRODUCTION

The Southeast Watershed Research Laboratory (SEWRL) of the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS) has conducted extensive research on sediment transport and deposition in low-gradient watersheds of the Coastal Plain region of the southeastern United States. The SEWRL has contributed substantially to the understanding of sediment transport and deposition in floodplain riparian zones characteristic of Coastal Plain watersheds, and of the role of the resulting alluvial aquifers on the hydrologic performance of watersheds in this region. This paper examines the results of SEWRL research on rates of transport of sediment in streamflow from Coastal Plain watersheds, on rates of deposition and aggradation of sediments in riparian areas, and examines implications of continued alluvial aggradation on future watershed hydrologic response characteristics.

STUDY AREA DESCRIPTION

Watershed-scale sediment transport and deposition studies have been conducted on subunits of the Little River Watershed (LRW) near Tifton, GA., an instrumented 334 km^2 experimental watershed operated by the SEWRL since 1968. The study area is divided into subwatersheds ranging from 2.6 to 115 km^2, and is considered representative of southern Coastal Plain soils, geology, land use, management and cultural practices.

Geology and Topography

Little River Watershed is located within the Tifton Upland of the Southern Coastal Plain physiographic region of the southeastern United States. The Coastal Plain extends from New England, south along the Atlantic Coast, and then west into Texas (Fenneman, 1970). Topographically, LRW is in an area of floodplains, river terraces, and gently sloping uplands. Valley bottoms are nearly level, and valley side slopes are generally less than 5 percent, although some range from 5 to 15 percent. Floodplains range in width from 60m to 0.8 km (Jensen, 1959). Surface elevations within the watershed range from 80 to 146 m above MSL. Low-lying, poorly-drained, seasonal wet areas generally coincide with riparian forests in this region and are a characteristic feature of the Coastal Plain landscape.

Soils and Vegetation

Soils of the watershed are predominantly sandy and light-colored with high infiltration rates (Rawls et al., 1976). Upland soils are classified as fine-loamy or loamy, siliceous, thermic Plinthic Paleudults (Calhoun, 1983). Internal drainage of upland soils is good to very good. Soils adjacent to drainage networks are loamy, siliceous, thermic Arenic Plinthic Paleaquults with some Fluvaquents and Psammaquents (Calhoun, 1983). Soils on stream terraces and bottoms of creeks and rivers are derived from alluvium washed from upland soils

(Jensen, 1959). Drainage of alluvial soils is poor to very poor with standing water during portions of the year (Calhoun, 1983).

Native upland vegetation (long-leaf pine/perennial wiregrass) has been almost totally replaced by row crops, pastures, and pine plantations (Lowrance et al., 1984). A transitional area of hardwood-pine generally occurs between the dry uplands and the wet bottomlands. Swamp hardwood communities occur along stream edges--the canopy is closed and undergrowth is thick. This vegetative community is characteristic on the alluvial soil series.

Land Use

Land use on the LRW is mixed, but predominantly agricultural cropland, forest, and pasture. Cropland includes peanuts, corn, soybeans, tobacco, cotton, and vegetable crops. Pastures are generally planted in bahia or bermuda grasses. Slash and long-leaf pine are the dominant species grown in pine plantations.

Climate and General Hydrology

The region is humid subtropical, with precipitation occurring almost exclusively as rainfall. Recorded annual rainfall extremes at Tifton, GA are 59.1 and 179.2 cm, with a mean of 120.1 cm (1925-1988). During the late spring and summer months, convective thunderstorms often produce localized, short duration rainfall events with high intensities which may briefly exceed the generally high infiltration capacities of Coastal Plain soils. Frontal storms with moderate rainfall amounts and intensities are typical of the winter and early spring months. The fall months generally have low rainfall.

Annual water yields for LRW averaged 36.5 cm for the period 1968-1981, with extremes of 3.8 and 58.4 cm/yr (Sheridan and Mills, 1985). Recent studies (Hubbard and Sheridan, 1983; and Shirmohammadi et al., 1984) have shown that 60 to 80% of the total annual streamflow from Coastal Plain watersheds is delayed subsurface flow from adjacent upland areas. Storm runoff results primarily from rainfall occurring on saturated, low-lying areas, and may result from relatively low rainfall amounts in the winter and spring when phreatic groundwater is recharged and wet areas are extensive (Shirmohammadi et al., 1984). During prolonged periods of low rainfall, streamflow ceases on the smaller streams and rivers, typically in the late summer and fall months.

EROSION ON UPLAND AREAS

Erosion on upland areas has not always been perceived to be a significant problem in the Coastal Plain. There was little sediment deposition in culverts and hydraulic structures, and early water quality surveys showed low concentrations of sediment in streamflow. However, observations by SEWRL scientists indicated that erosion rates on cropped upland areas could be quite high, particularly when intense storm events occurred after field tillage or cultural operations. Sheridan et al. (1982) reported average annual erosion rates for cropped upland areas on Watershed K of 17.9 Mg/ha. These erosion rates were estimated for 1974, 1975, and 1976 using the Universal Soil Loss Equation (USLE), cropping practice and cultural information determined from field-by-field surveys, and observed rainfall data.

Lowrance et al. (1986) reported long-term (100-yr) average upland (cropped plus non-cropped) erosion rates of 15 Mg/ha/yr for Watershed K. Long-term cropped upland erosion rates averaged 21.8 Mg/ha/yr (25.3 Mg/ha/yr prior to institution of conservation practices - circa the 1930's, and 18.2 Mg/ha/yr following). These estimates were developed using the USLE and 100 years of historical land use information and rainfall data. While the impact of soil conservation programs established in the 1930's was evident, with an approximate 35% reduction in erosion rates on upland cropped areas, the post-implementation rates were about twice the "soil loss tolerance level (T)".

TRANSPORT OF SEDIMENT IN STREAMFLOW

Despite the high rates of erosion on cropped uplands, suspended sediment concentrations in streamflow from Coastal Plain watersheds are quite low. Suspended sediment (SS) concentrations in runoff from the LRW for 1974 thru 1981 averaged 15 mg/L (Sheridan and Hubbard, 1987). The SS concentrations reported for LRW compare favorably with published SS data for other Coastal Plain streams in Georgia. Perlman (1985) reported SS concentrations of 13 mg/L (1794 samples) in streamflow from 33 sites in seven Coastal Plain river basins. The low average SS concentrations in streamflow from other Coastal Plain locations indicate that the low SS concentrations observed in runoff on LRW are typical of the region.

Hubbard et al. (1990) also reported low SS concentrations in streamflow for subwatersheds of the LRW for the period 1984-1986. Observed SS concentrations ranged from 1 to 137 mg/L, with a mean value of about 15 mg/L.

DEPOSITION OF SEDIMENT IN FLOODPLAINS

Sheridan et al. (1982) concluded that most of the sediment eroded from cropped Coastal Plain fields was being deposited in heavily-vegetated floodplain areas, and at edge-of-field slope breaks near stream networks. This deposition occurs due to decreased transport velocities that result from decreased gradients near floodplains, to the decreased flow velocities that occur when flows exceed channel capacities at low flow rates and spread over the broad floodplains, to the high flow retardance of the heavily-vegetated floodplains, and to the coarse nature of the soil material being transported.

Cross-sectional characteristics of floodplains in the region are conducive to sediment deposition - even during intense storm events. As streamflow rates increase, flows rapidly exceed the rather minimal channel capacities and spread across the broad, heavily-vegetated flood plain. Effective flow velocities may not increase substantially with increasing flow rate, because flow depths are relatively shallow across the floodplain and hydraulic resistance to flow is high on floodplains and adjacent terraces (Sheridan et al., 1982). The floodplain-riparian areas, which have dense vegetative canopies and may be covered with water for extended periods, have little potential for detachment of sediment by rainfall, even for intense storm events.

Floodplains on Coastal Plain watersheds can therefore be considered to function essentially as settling basins or depositional areas. Lowrance et al. (1986), in a study to quantify the rate of sediment deposition in riparian areas concluded that the average long-term depositional rate on Watershed K was in the range of 35-52 Mg/ha/yr. These estimates were made by direct measurement on transects at selected points within and adjacent to riparian areas of Watershed

K; and indirectly, using the USLE, 100-years of rainfall data, historical land-use and cropping information, and previously-developed sediment delivery information. Lowrance et al. (1986) concluded that these rather significant rates of sediment deposition could potentially have significant effects on the dynamics of nutrient cycling within the riparian zones.

ROLE OF ALLUVIUMS ON WATERSHED HYDROLOGY

Deposition of eroded materials in floodplains and riparian zones along streams and rivers has produced rather extensive alluvial stream-channel aquifer systems. The floodplain/riparian areas represent a significant areal expanse (20-25%) on these watersheds and the alluvial aquifers represent a large potential available storage for incident rainfall, as well as for storm runoff and delayed subsurface flows from adjacent upland areas. Shirmohammadi et al. (1986) found that the overall hydrologic response (total runoff volume, peak flow rate, as well as timing of runoff events) was dependent upon the total available storage and the antecedent condition of the aquifer system. This study, based on 13 years of alluvial groundwater observations on three LRW study areas, explained the role of the stream-channel alluvial aquifer system in determining the overall hydrologic response characteristics of Coastal Plain watersheds. The antecedent conditions (i.e., the available storage) of the alluvial aquifers were found to vary in a characteristic seasonal pattern. This phenomena accounts for the extreme seasonal dichotomic behavior of these drainage systems, i.e. quick flow response with relatively high runoff even for small storm events during the wet season (typically winter thru early spring); and low-to-no runoff response during the dry season (typically summer thru fall), even for large storm events (up to $\approx$ 10 cm).

Storage in alluvial aquifers is satisfied during the winter and early spring by prolonged subsurface flow from adjacent upland areas, keeping available storage to a minimum even for periods of below normal rainfall. However, as ET demand increases in late spring, subsurface flows from upland areas are curtailed, and streamflow is diminished due to reduced inflows and increased ET within the riparian zone. This process increases available storage within the alluvial aquifer for incident rainfall, and for storm runoff from adjacent uplands. Available storage within the aquifer generally reaches a maximum in the late summer and fall.

HYDROLOGIC IMPLICATIONS OF CONTINUED DEPOSITION

Despite research and education efforts regarding the need for conservation, application of conservation practices on cropped land has apparently declined gradually since their initial implementation (Lowrance et al., 1984). Recent estimates indicate that watershed-weighted erosion rates are approximately 2T, or twice the soil-loss tolerance value on cropped uplands of Watershed K. Continued deposition of eroded materials within floodplains could have a gradual, but perhaps, eventually a significant impact on the hydrologic response characteristics of these watersheds, and possibly on the role of riparian zones in maintaining the quality of flows derived from these areas. Some very simple calculations based on SEWRL research will permit projections regarding the rates of deposition in alluvial aquifer systems for several conservation scenarios and allow us to explore the impact of continued aggradation on the watershed hydrologic responses to storm events.

Recent land-use data on Watershed K shows the upland portion of the watershed in crops to be stable at about 500 ha, and upland noncropped area at about 800 ha (Lowrance et al., 1984). Assuming that land use remains relatively constant, and that erosion rates on cropped and noncropped uplands remain at present levels, we can make some projections on the relative rate of increase in total volume of alluvial materials in the riparian zone and also on the rate of areal expansion of this depositional area.

Assume that the 500 ha of cropped uplands is eroded at the current 2T soil loss rate and that the 800 ha of non-cropped uplands are eroded at the present rate of under 1/2 T reported by Lowrance et al. (1984), and that this eroded material is then deposited in 375 ha of riparian/floodplain area. The annual upland erosion is:

$$\text{Cropped Area X 2T + Non-Cropped Area X 1/2 T,}$$

or, $$\text{500 ha X 18.0 Mg/ha + 800 ha X 4.0 Mg/ha = 12,200 Mg/ha.}$$

Distributed over 375 ha of riparian/floodplain area (the approximate areal extent of the alluvial aquifer), the depositional rate is 32.5 Mg/ha/yr. Assuming a bulk density of 1.27 Mg/cm^3 (Herrick, 1981), this rate of deposition is equal to .26 cm/yr of increased alluvial material. Based on the 1.8 m effective alluvial aquifer depth reported by Shirmohammadi et al. (1986) for Watershed K, this increased depth represents .14% annual increase in alluvial aquifer depth. Projected increases in alluvial depth for 10, 25, 50, and 100 years would therefore be 1.4, 3.6, 7.1, and 14.2 percent.

Similar calculations can be made for differing assumed rates of cropped upland erosion. For this exercise, upland erosion rates on cropped land equal to T and 3T were chosen for comparison. Soil loss rates equal to T would represent a 50% reduction from present levels of erosion on cropped land. The T rate would perhaps represent large-scale institution of conservation management practices such as conservation, or minimum tillage. The T rate is used for this exercise as a "best-case" projection.

The 3T soil-loss rate would represent a considerable further decline in the use of sound conservation management practices, and, as such, is presented as a "worst-case" scenario. Results of the change in alluvial depth/volume computed for the T, 2T, and 3T projections for Watershed K are shown in Table 1.

Assuming floodplain side slopes of about 2% (the maximum slope for the dominant soil series on this position of the landscape), projections in the rate of lateral expansion of alluvial depositional materials can also be made for the three cases. For 10-year projections at the T soil loss rate, the change in depositional material would be 1.62 cm (.162 cm/yr X 10 yr). For a 2% slope, this amounts to approximately 0.81 m lateral expansion. Multiplying by the total channel length for Watershed K (26.87 km) X 2 (for both sides of the channel), and dividing by the total riparian area, one obtains a total areal expansion of 1.2% over 10 years. Similar calculations made for the other erosion projections and lengths of accumulation are shown in Table 2. The projected increases in total volume of deposited alluvial materials and the area expansion of the alluvial aquifer for the selected time intervals and the three conservation scenarios are illustrated in Figs. 1 and 2.

IMPACT OF PROJECTED DEPOSITION

Since total volume and available storage within the stream channel alluvial aquifer have been shown to be related to the runoff volume and the peak flow rate for storm events on Coastal Plain watersheds, increases in total volume of deposited materials within the alluvial aquifer systems should result in some gradual alterations in watershed hydrologic response characteristics. Assuming that the newly-deposited materials have about the same water-holding characteristics as the previously-deposited materials, a 15% increase in the deposited alluvial material, for example, should result in about a 15% increase in total available storage within the aquifer. This increase in total storage could, depending upon alluvial antecedent conditions, mean significant reductions in storm runoff volumes and in peak flow rates --- ranging from 100% reduction (for small events with total runoff volumes less than or equal to the increased aquifer storage) to ≈ 15% for large events under maximum available storage conditions. However, when aquifer storage is satisfied prior to the occurrence of a storm event, there would be little effect on storm runoff volume or peak flow rate. Since storm peak flow rates are highly correlated with storm runoff volumes, any reductions in storm runoff volume would have a similar effect on storm peak flow rate.

The degree of reduction in storm runoff volume and peak flow rate compared to current storm response characteristics would depend upon the antecedent condition (i.e., the available storage) of the alluvial aquifer, the amount and intensity of rainfall, the volume of surface runoff and subsurface flow/seepage to the alluvium, and the cumulative change in alluvial storage in time due to continuing deposition of eroded materials. For making estimates of changing watershed hydrologic response characteristics in time due to continued alluvial deposition, a model capable of accounting for changing total storage/available storage within the alluvial aquifer system, and for relevant inputs (rainfall, surface runoff, and subsurface seepage) and outputs (ET, streamflow, and subsurface losses) to the aquifer would be required.

Changes in hydrologic response characteristics would probably be most pronounced during the low to no-flow summer and fall months. Fewer storms would result in appreciable storm runoff, and no-flow periods would gradually be extended. For the wet winter-early spring season, the effects of increased alluvial capacity would probably not be significant. Despite projected areal expansion of alluvial depositional material and the predominance of saturated, overland flow from this zone during the wet season, total runoff volume and peak flow rates would not likely be greatly affected since alluvial aquifers are typically bordered by high runoff-producing seepage faces during this portion of the year.

Gradual areal expansion of alluvial depositional materials, while perhaps not resulting in significant increases in storm runoff, would result in increases in total area of poorly-drained soil material with conditions suited to the gradual expansion of riparian-type vegetative growth.

CONCLUSIONS

Continued high rates of erosion from uplands and deposition of eroded materials in low-lying, riparian floodplain areas in the Coastal Plain will result in gradual volumetric and areal expansion of stream-channel alluvial aquifer systems. The resulting increase in alluvial storage should result in gradually damped hydrologic response characteristics for storm events occurring on these watersheds, particularly when available storage within the aquifer is not satisfied - typically, the late spring, summer and fall.

Erosion and sedimentation on Coastal Plain watersheds continue to be significant despite the considerable efforts to establish conservation programs on these lands. The need for, nor the effectiveness of, conservation programs and management practices on cropped uplands in the Coastal Plain cannot be measured simply by monitoring sediment levels in streamflow. Since essentially all (≈ 99%) of the sediment moving from cropped uplands is deposited in the low-gradient riparian/floodplain zones, high levels of erosion on the uplands will not be evidenced by high sediment concentrations in streamflow. Continued high rates of erosion on the uplands will impact riparian zones and stream-channel alluvial aquifer systems, gradually altering the hydrologic response characteristics of these watersheds, and perhaps, the dynamics of the current environmental role of these seasonal wetland areas.

TABLE 1. Percent Change in Alluvial Aquifer Depth for Projected Upland Cropped Erosion Rates (Watershed K)*/

Years	Percent Change		
	T	2T	3T
10	0.9	1.4	2.0
25	2.2	3.6	4.9
50	4.5	7.1	9.8
100	9.0	14.2	19.5

*/ Assumes current upland non-cropped erosion rate of ≈ 1/2 T

TABLE 2. Estimated Areal Expansion of Alluvial Deposition for Selected Rates of Upland Cropped Erosion (Watershed K)*/

Years	Percent Change		
	T	2T	3T
10	1.2	1.8	2.5
25	2.9	4.6	6.3
50	5.8	9.2	12.6
100	11.6	18.3	25.2

*/ Assumes current upland non-cropped erosion rate of ≈ 1/2 T

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SEDIMENT-NUTRIENT TRANSPORT DURING SEVERE STORMS

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ABSTRACT

Prediction of sediment-nutrient transport in surface runoff is important from land use, management, and environmental standpoints. Because sediment and associated nutrient transport are greatest from severe storms, accurate prediction during these events is critical. The study here comprises 17 grassland, cropland, and drastically disturbed watersheds in the Reddish Prairie and Rolling Red Plain land resource areas of Oklahoma and Texas, involving the ten most severe storm events during periods of 3 to 10 years. Sediment transport was predicted using the Modified Universal Soil Loss Equation, which is designed for individual storms. Corresponding losses of N and P were predicted by a desorption equation or an enrichment ratio (nutrient content of sediment/source soil) approach. Overall, maximum discharge observed per severe storm event for sediment, soluble P, particulate P, and particulate N, averaged 51,000 , 0.2, 6, and 19 kg/ha, respectively. The severe storms provided rigorous tests of the predictive approaches and, for the most part, realistic sediment and nutrient predictions were obtained. However, the constancy of prediction equation factors and/or exponents is less uniform for severe storms than under more normal events and land conditions.

INTRODUCTION

Sediment and associated nutrient transport in the Southern Plains can be large, due to the erratic timing and intensity of severe storms that occasionally occur. Accurate prediction of sediment-nutrient transport during these severe storms is necessary for devising management practices that are compatible from both an agronomic and environmental standpoint. The study here considers prediction of sediment-nutrient transport during severe storms from grassland, cropland, and drastically disturbed land watersheds in the Reddish Prairie and Rolling Red Plain major land resource areas of Oklahoma and Texas (Soil Conservation Service,1981), over the past decade. To provide rigorous tests of the transport equations, the ten most severe storms for each watershed were selected. Such storms typically provided 4 to 5+ cm rainfall, and can be expected to occur in the general area about once per year. Sediment prediction was on the basis of the Modified Universal Soil Loss Equation (Williams, 1975), and nutrient predictions involved desorption/enrichment ratio techniques (Sharpley et al., 1985, Smith et al., 1986).

TRANSPORT EQUATIONS

Sediment

In MUSLE, the rainfall energy term of USLE is basically replaced by a runoff energy term (Williams, 1975). This allows application to individual storms, eliminates the need for sediment delivery ratios, and provides greater accuracy, because runoff generally accounts for more sediment yield variation than does rainfall. The MUSLE may be stated as:

$$Y=11.8\ (Qq_p)^{0.56}\ KCPSL \qquad [1]$$

where Y= sediment yield in metric tons, Q= runoff volume in m^3, q_p= peak runoff rate in m^3/sec, K= soil erodibility factor, C= crop management factor, P= environmental practice factor, and SL= slope length gradient factor.

The factors K, C, P, and SL were obtained from Agricultural Handbook 537 (Wischmeier and Smith, 1978). For the grasslands, P was unity and K, C, and SL ranged from 0.24 to 0.34, 0.005 to 0.007, and 0.32 to 1.06 respectively. For the croplands, P was unity and K, C, and SL ranged from 0.24 to 0.40, 0.03 to 0.80, and 0.27 to 1.14, respectively. For the drastically disturbed lands, P, K, C, and SL ranged from 15 to 75, 0.20 to 0.26, 0.042 to 0.20, and 0.32 to 0.67, respectively.

Nutrients

Predictions of nutrient transport were made for Nitrogen (N) and Phosphorus (P), the two plant nutrients most frequently associated with soil fertility losses and degraded water quality. Soluble P (SP) in runoff was described by a soil P desorption equation that incorporates the depth of surface soil-runoff interaction, storm size, and the runoff water-suspended soil ratio. The equation (Sharpley et al., 1981). may be written as:

$$P_r = K\ P_a\ E\ B\ t^{\alpha}\ W^{\beta}/V \qquad [2]$$

Where P_r= storm average SP concentration of runoff (mg L^{-1}), K, α, and β are constants for a given soil. P_a = soil available P content (mg kg^{-1}), E = effective depth of interaction between surface soil and runoff in SP transport (mm), B = bulk density (Mg m^{-3}), t = storm duration (min), W = water: soil ratio (cm^3 g^{-1}), and V = total runoff (mm) during the event.

In the case of soluble N, no desorption equation was employed, because the primary constituent, nitrate, is not generally sorbed by surface soil material.

Sediment associated nutrients, particulate N (PN) and particulate P, (PP) in runoff were calculated using an enrichment ratio (ER) approach (Sharpley et al., 1985), where:

$$PN = \text{Soil TN} \cdot \text{Sediment concentration} \cdot NER \quad [3]$$
$$PP = \text{Soil TP} \cdot \text{Sediment concentration} \cdot PER \quad [4]$$

with soil units as mg kg^{-1}, sediment units as g L^{-1}, and enrichment ratios according to the referenced publication.

MATERIALS AND METHODS

The 17 study watersheds provide good representation of the Reddish Prairie and Rolling Red Plain major land resource areas. General information about the watersheds is given in the left part of Table 1, with more detailed information available in Allen and Naney (1990), Berg et al., (1988) and Sharpley et al. (1987). Overall, the watersheds comprised a range of sizes (0.4 to 5.7 ha), slopes (0.2 to 8.6%), vegetation (wheat, sorghum, peanuts, and native grass), and tillage (conventional, reduced, and no-till).

Watershed runoff was measured using pre-calibrated flumes or weirs equipped with FW-1 stage recorders. Sediment discharge was determined from suspended sediment samples taken automatically for the duration of each hydrograph. After comparison with the runoff hydrograph, samples for the subject watershed were composited in proportion to total flow to provide a single representative sample of liquid and sediment. Sediment concentration was determined gravimetrically after removal of liquid. Soluble P, particulate P, and particulate N were determined as described previously (Smith et al., 1983).

Statistical methods were conducted using standard procedures given in Snedecor (1956). In the case of the linear regression analysis, a slope greater than unity indicates sediment or nutrient discharge is overpredicted, whereas a slope less than unity indicates the same is underpredicted.

RESULTS AND DISCUSSIONS

Sediment

A comparison of the MUSLE predicted and measured amounts of sediment yield on a severe storm event basis for the individual watersheds is given in Table 1. Mean measured sediment yield per severe storm event ranged from 33 kg ha^{-1} for a native grass watershed (WW1) to 50,768 kg ha^{-1} for a rural roadside, bar-ditch, watershed (5215). MUSLE predicted values ranged from 0.49 to 2.05 times measured values, and about one-half were within 10 percent of measured. However, most predicted values were not statistically different to measured values, even at the 10 percent level, and regression slopes tended to be less than unity. Consequently, while the MUSLE predicted values were often fairly close to measured values, statistical significance was relatively poor.
Combinining the data according to major land use, improved the

statistics considerably (Table 2), yielding one percent significance levels, and regression slopes much closer to unity for predicted compared to measured values. Evidently, much of the earlier problem involving the individual watersheds originated from having just a few degrees of freedom (8 per correlation), and a limited regression curve segment.

While the predicted results for the severe storm events were improved by combining the data, they were still not as good as those reported for all runoff events (Smith et al., 1986). This means that, for severe storm events in the Southern Plains, some adjustment may be required in the Qq_p runoff energy exponential term and/or the K, C, P, and SL terms. Nevertheless, the general results observed here indicate that, even under the most rigorous and wide-ranging land use conditions, realistic sediment yield predictions could be obtained. The ultimate goal is to refine MUSLE applicability for severe storm usage with computed Qq_p terms, thereby extending applicability to ungaged field situations.

Nutrients

Mean per severe storm event comparisons of nutrient transport for SP, PP, and PN are given in Table 3A. Measured nutrient yields ranged as follows: 2 to 238 g SP ha^{-1}, 16 to 6116 g PP ha^{-1}, and 0.10 to 18.8 kg PN ha^{-1}. Highest SP losses were on the cropped lands, whereas highest PP and PN losses were on the disturbed lands. Except for the disturbed lands, the predictions were generally significant at the 1 percent level or less.

Because the disturbed lands are severely eroded, the main zone of interaction with rainfall/runoff and source of runoff sediment contains primarily subsoil material. When properties reflecting the subsoil materials were used in Eq [2] (i.e.P_a, α, β , and K), more accurate SP predictions were obtained (Table 3B). Improved PP and PN predictions were also obtained when subsoil N and P contents were used in Eq [3] and [4], respectively (Table 3B). Consequently, realistic soluble and particulate nutrient predictions (generally significant at the 1 percent level or less), were possible for all the field situations.

PERSPECTIVE

The results obtained here for predicting both sediment and nutrients in runoff encompass rigorous cases. They cover not only the severest storms, but also an extremely wide range of land conditions, from relatively pristine native grasslands to severely gullied situations. In all cases, realistic sediment and nutrient predictions could be obtained. However, as might be expected, the constancy of predictive equation factors and exponents under severe conditions is less uniform than under more frequently occurring events and land conditions.

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Table 1.
Comparison of MUSLE predicted and measured sediment yields of the 10 most severe runoff events for the watersheds.

Major Land Use	Watershed	Size (ha)	Average Slope (%)	Study period	Mean Sediment Yield/Event Meas	MUSLE	MUSLE/Meas	r2	Regression slope
					-----------kg/ha---------				
Grasslands:									
native	FR 3	1.6	3.2	77-88	33	37	1.12	0.02	0.09
native	WW 1	4.8	7.0	77-88	38	25	0.66	0.01	0.06
native	WW 2	5.6	8.2	77-88	566	542	0.96	0.27	0.43
Croplands:									
wheat/sorghum	FR 5	1.6	3.5	77-88	2120	2583	1.22	0.61**	0.89
clean-till wheat	FR 6	1.6	2.9	77-88	5210	5926	1.14	0.30+	0.69
no-till wheat	FR 7	1.6	2.9	77-88	267	548	2.05	0.05	-1.05
sweep-till wheat	FR 8	1.6	2.7	77-88	3076	3751	1.22	0.56*	0.47
clean-till peanuts	FC 2	2.0	1.7	82-88	9904	5253	0.53	0.23	0.23
sweep-till wheat	5275	0.6	0.2	80-85	833	408	0.49	0.05	0.19
lo-till wheat	5276	0.5	0.2	80-85	689	357	0.52	0.003	-0.04
sweep-till wheat	WW 3	2.7	8.6	77-88	9489	7105	0.63	0.90**	0.50
no-till wheat	WW 4	2.9	7.4	77-88	501	653	1.30	0.21	0.54
Disturbed lands:									
severe gullys	5201	3.8	5.0	80-88	15365	15378	1.00	0.08	0.23
severe gullys	5202	5.7	5.3	80-84	25670	25635	1.00	0.20	0.58
treated gullys	5202	5.7	5.3	84-88	2472	2623	1.06	0.05	-0.12
rural roadside	5215	0.4	4.2	80-85	50768	50759	1.00	0.56*	0.94
rural roadside	5227	3.2	3.3	80-82	19437	18702	0.96	0.29+	0.21

+, *, and ** represent significance at 10, 5, and 1% levels, respectively.

Table 2.
Comparison of MUSLE predicted and measured sediment yields after combining results according to land use.

Major land Use	No Watersheds	Mean Sediment Yield/Event Meas	MUSLE	MUSLE/Meas	r2	Regression Slope
		----------kg/ha---------				
Grasslands	3	212	201	0.95	0.56**	0.67
Croplands	9	3565	2603	0.73	0.56**	0.42
Disturbed lands	5	22742	22619	0.99	0.74**	0.84
All lands	17	8787	8219	0.94	0.81**	0.85

** represents significance at 1.0% level.

Table 3. Comparison of predicted and measured nutrient yields of the 10 most severe runoff events for the watershed.

Watershed	Soluble P (mean g/ha/event)					Particulate P (mean g/ha/event)					Particulate N (mean kg/ha/event)				
	Meas.	Pred.	Pred/Meas	r2	Slope	Meas.	Pred.	Pred/Meas	r2	Slope	Meas.	Pred.	Pred/Meas	r2	Slope
						A. (Using constants based on surface soil properties)									
Grasslands															
FR 3	35	33	0.94	0.87**	1.21	40	41	1.03	0.92***	0.87	0.69	0.64	0.93	0.77**	0.90
WW 1	8	9	1.12	0.86**	1.07	16	17	1.06	0.90***	0.91	0.10	0.09	0.90	0.92***	1.04
WW 2	8	7	0.88	0.77**	0.97	203	209	1.03	0.95***	1.04	0.47	0.49	1.04	0.97***	1.00
Croplands															
FR 5	88	86	0.98	0.96***	0.97	1559	1607	1.03	0.90***	1.12	5.87	5.80	0.99	0.93***	1.17
FR 6	99	109	1.10	0.75*	0.88	244	240	0.98	0.87**	0.97	1.54	1.61	1.05	0.91***	0.91
FR 7	238	227	0.95	0.94***	1.01	288	268	0.93	0.91***	0.87	2.04	1.78	0.87	0.93***	1.09
FR 8	61	64	1.05	0.87**	1.09	1466	1514	1.03	0.94***	1.11	5.46	5.72	1.05	0.92***	1.05
FC 2	86	72	0.84	0.91***	1.03	2528	2705	1.07	0.96***	0.97	9.06	9.93	1.10	0.94***	0.96
5275	46	49	1.06	0.89***	1.10	600	590	0.98	0.88***	0.89	2.77	2.92	1.05	0.86**	0.92
5276	36	35	0.97	0.92***	0.77	382	330	0.86	0.90***	0.80	1.97	2.04	1.04	0.92***	1.65
WW 3	132	130	0.98	0.97***	1.28	3052	2976	0.98	0.96***	0.92	11.94	12.83	1.07	0.97***	0.94
WW 4	119	121	1.02	0.95***	.86	286	375	1.31	0.86**	1.41	1.26	1.34	1.06	0.70*	1.02
Disturbed lands															
5201	2	21	10.50	0.01	-6.36	1457	2202	1.51	0.03	0.80	2.88	20.69	7.18	0.30	7.61
5202A	8	51	6.37	0.46	-7.96	2829	4131	1.46	0.03	0.55	9.49	41.65	4.39	0.09	1.92
5202B	5	14	2.80	0.17	-2.13	427	817	1.91	0.34	1.50	0.82	7.11	8.67	0.34	7.52
5215	3	54	18.00	0.13	7.73	6116	10276	1.68	0.32**	-1.05	18.75	112.08	5.98	0.89***	-2.75
5227	5	72	14.40	0.08	-1.99	3900	8900	2.28	0.25	0.49	5.97	38.24	6.41	0.26	3.88
						B. (Using constants corrected for subsoil properties)									
5201	2	3	1.50	0.85**	1.00	1457	1472	1.01	0.87**	1.15	2.88	2.92	1.01	0.92***	1.01
5202A	8	6	0.75	0.99***	0.78	2829	2388	0.84	0.94***	0.86	9.49	9.48	0.99	0.90***	0.72
5202B	5	5	1.00	0.85**	1.11	427	584	1.37	0.95***	1.07	0.82	0.76	0.93	0.93***	0.99
5215	3	2	0.67	0.87**	0.84	6116	6059	0.99	0.88***	0.83	18.75	19.91	1.06	0.96***	1.17
5227	5	4	0.80	0.90***	0.76	3900	3663	0.94	0.89***	0.67	5.97	5.60	0.94	0.89***	0.82

*, **, and *** represent significance at 5, 1.0, and 0.1% levels, respectively.

SEDIMENT TRAPPING EFFECTIVENESS OF GRASS STRIPS

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ABSTRACT

The sediment trapping effectiveness of grass buffer strips was determined by sampling sediment-laden runoff above and below a bordered area of established ryegrass and fescue. Runoff rates between 11 and 55 l/min. per m of strip were studied for strip lengths of 1.5, 3.0, and 6.1 m (in downslope direction). Sediment and runoff were generated by applying simulated rainstorms (73 mm/hr) 1 month apart to an area of tilled soil upslope of the grass.

Results showed that the trapping effectiveness of the 1.5-m long grassed areas ranged from 0.80 to 0.40 while those of the 3.0- and 6.1-m long strips ranged from 0.95 to 0.72. Sediment size data established that at least 89 percent of all sediment larger than 250 µm in diameter entering the grassed area was trapped in or just above the grass. In addition, results showed that the trapping effectiveness of strips decreased with increasing runoff rate due mainly to reduced trapping of sediment less than 125 µm in size.

INTRODUCTION

Vegetative buffer strips (VBS) are relatively narrow bands of close growing vegetation, usually grass, planted on sloping cropland. The VBS are designed to break up long reaches of erodible land and to filter sediment and nutrients from runoff originating upslope of the strip. Secondary benefits of the strips include cover for wildlife, windbreaks for wind-sensitive crops, and occasional roadways. Though VBS are similar to traditional vegetative filter strips established around the lower edge of fields (Dillaha et al. 1989), they are planted within fields, to trap sediment and nutrients on the field. Currently, VBS are being used in some cases to bring highly erodible land into compliance with the soil conservation provisions of the 1985 Farm Bill (Leidner, 1988), and many more miles of strips are being planned.

Most research related to VBS such as Dickey and Vanderholm (1981), and Young et al. (1978) has focused on the effectiveness of vegetated filter strips wider than 20 m (direction parallel to flow) at removing suspended solids and nutrients from runoff enriched by animal wastes. Because VBS are used in cropland fields, minimizing their width and therefore the amount of productive land they displace, is very important. Thus, VBS of limited width (<10m) need to be evaluated to determine optimal strip widths for given runoff rates, slope steepnesses, and sediment loading conditions.

Studies by Dillaha et al. (1989) and Magette et al. (1989) examined the overall nutrient and sediment filtering effectiveness of vegetative filter strips 4.6 and 9.1 m wide for a storm or series of storms. They reported that strips were generally more effective at filtering sediment than nutrients.

This study was designed to evaluate the overall sediment-trapping ability of grass buffer strips 1.5, 3.0, and 6.1 m wide by evaluating a 0.9-m section of experimental strips. In addition, the size distribution of the trapped sediment was determined.

SETUP AND PROCEDURE

A series of 10 experimental field plots were constructed on a Grenada silt loam soil (thermic Glossic Fragiudalf) in northern Panola county, Mississippi. Each plot included a tilled area 0.9 m by 9.1 m upslope of a grassed area 0.9 m wide by either 1.5, 3.0, or 6.1 m long (Fig. 1). The vegetation in the grassed area

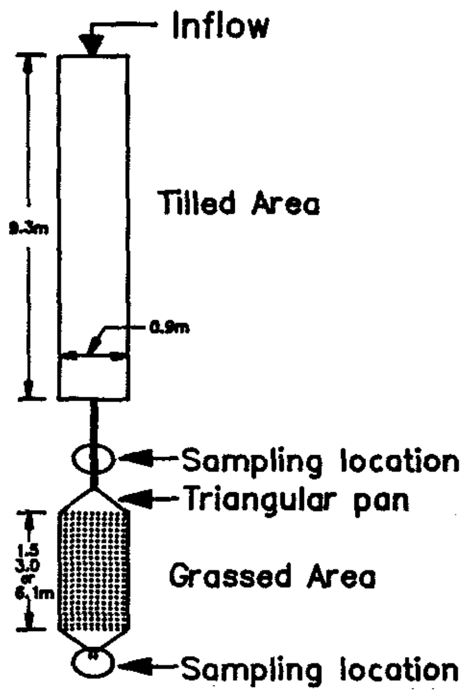

Fig. 1 Diagram of experimental field plots.

was primarily 2-year old, established ryegrass and fescue mixture which provided nearly 100 percent cover. However, at ground level there were bare spots between the clumps of stalks, but most of these areas were covered by decaying plant material. Also, there were several cattle track holes scattered throughout the plots.

Each grassed area was oriented such that its length corresponded to what is normally considered the width of a grass strip. With this in mind, the area's crosslope was negligible and the average longitudinal slope was between 5.0 and 5.5 percent. Because the tilled area had to be directly upslope and in-line with the grassed area, its average slope could not be rigidly controlled; therefore, it varied from 5.3 to 8.2 percent as shown in Table 1.

Each plot's tilled area was cultivated to an average depth of 0.1 m using a tractor-mounted roto-tiller. After 3 passes with the tiller the soil was raked into an uniform 9.1-m long row of parabolic cross section. Metal borders were installed along the plot's outside boundaries on both the tilled and grassed areas.

A 150-mm wide rectangular aluminum channel was used to convey runoff from the tilled area to the grassed area. A method of sampling the runoff before it entered the grassed area was considered necessary because of the relatively high

Table 1. Plot and Rainfall/Inflow Data.

Test Date Run1	Run2	Plot	Grassed Area Length m	Tilled Area Slope %
5/17		1	3.0	7.0
5/21		2	1.5	6.6
5/24		3	6.1	7.6
5/26		4	3.0	7.4
5/30	7/18	5	3.0	6.9
6/01	7/20	6	6.1	8.2
6/07	7/21	7	6.1	7.6
6/09	7/25	8	1.5	7.9
6/13	7/26	9	1.5	5.3
7/28		10	3.0	5.3

Rainfall/inflow sequence:
30 min of rainfall only
12 min of rainfall + 19 kg/min inflow
12 min of rainfall + 38 kg/min inflow
12 min of rainfall + 57 kg/min inflow

variability in sediment yield and sizes that often occurs even between replicate plots. Therefore, a sampler consisting of a set of five, 203-mm long fins equally spaced across the channel was positioned about halfway between the tilled and grassed areas. The space between the first and second fins was blocked at the downstream end and a hole was cut to divert a representative section of flow through the bottom of the channel for sampling. Calibration of the sampler established that an average of 17.2 percent of the sediment and 16.7 percent of the runoff water was diverted through the hole for sampling. This sampling method was relatively consistent as long as the channel's cross slope was negligible, its longitudinal slope was steep enough to prevent significant deposition, and it was kept relatively free from debris. A 75-mm deep flat-bottomed triangular pan (Fig. 1) was used between the downstream end of the rectangular channel and the upper edge of the grassed area to allow the flow to spread out to a generally uniform depth over the width of the grassed area before entering the grass. A similar triangular pan was placed at the downslope end of the grassed area to collect the runoff leaving the grass. The edge of each pan was placed at the mean ground level to minimize ponding and sealed to the soil with a water-proofing spray.

Simulated rainfall was applied at a nominal intensity of 73 mm/hr to both the tilled and grassed areas for a total of 66 minutes. After 30 minutes of rainfall alone, clear water was added at the upper end of the tilled area at a rate of approximately 15 kg/min. This rate of inflow is approximately equivalent to the maximum rate of runoff expected from a section of cropland 13 m long and the width of the plot (0.9 m). Two additional 15 kg/min step increases in inflow were made at 12-minute intervals.

Seven pairs of timed runoff samples from above and below the grassed area were collected during the 30-minute rainfall-only period. Four pairs (above and below) were collected for each level of inflow. Five pairs of samples, two from the rainfall only and one from each inflow period were analyzed to determine the size distribution of the sediment. The sediment sizes were determined using a combination sieve (≥ 0.063 mm) and pipette (< 0.063 mm) method outlined by Meyer and Scott (1983). The remaining runoff samples were weighed and then dried and weighed again to determine runoff and sediment delivery rates.

Plots 1 through 9 were tested between May 17 and June 13, 1989 during which time the ryegrass was about 1 m tall and near maturity while the fescue was half grown and somewhat spotty. Approximately 1 month later, plots 5 though 9 were prepared and tested again using the same equipment and procedures as the first test except that the grass was cut to a uniform height of 100 mm. Between the first and second set of tests, plots 1 through 4 had been damaged by floodwater. Consequently, plot 10 was prepared to add another plot with a 3.0 m grassed area, thereby making 2 replications of each grassed strip length for run 2 (Table 1). In addition, by the second run the ryegrass had died leaving only the fescue and dead stalks during the second set of tests.

After the first set of tests, the grassed area was trimmed by hand and the clippings were dried and weighed. The number of stalks in representative samples of the clippings from each plot were determined and used to estimate the overall plant densities. Also, sediment deposited in the pan above the grass was weighed and sampled for dry mass basis moisture content determination.

RESULTS AND DISCUSSION

Sediment and Runoff Measurements

The rates of sediment leaving the tilled area and entering the grassed area of each plot were computed by multiplying the sampler calibration for sediment by the sampling rates. The differences between these rates and the rates of sediment leaving the grassed area were then multiplied by the corresponding time increments and summed to yield the total amount of sediment trapped for each plot. These totals are shown on Table 2, column 3, except for plot 9 run 1 which

Table 2. Sediment trapped, grass density, and runoff rate data.

Plot	Strip Width m	Total Sediment Trapped kg	Sediment Trapped[a] Above kg	Stalk Density no./m^2	Runoff Rate Below Grass: Zero (kg/min)	Low[b] (kg/min)	Med (kg/min)	High (kg/min)
Run 1								
2	1.5	19.0	6.4	72	8.9	18.4	35.9	54.0
8	1.5	41.7	11.7	137	8.9	22.6	37.2	57.6
9	1.5[c]	NA	NA	102	NA	NA	NA	NA
1	3.0	17.1	8.9	46	8.4	18.8	31.5	43.5
4	3.0	21.1	4.0	88	9.1	20.5	34.5	49.7
5	3.0	16.7	7.0	87	8.5	26.6	33.4	55.3
3	6.1	25.6	7.5	169	2.0	19.9	36.3	46.1
6	6.1	43.0	9.1	104	8.9	19.6	37.7	54.6
7	6.1	25.6	4.2	87	17.1	32.8	49.5	62.2
Run 2								
8	1.5	39.9	14.1	-	8.0	18.0	32.0	48.6
9	1.5	28.1	14.0	-	6.3	18.8	31.7	50.6
5	3.0	49.0	12.4	-	5.8	19.3	33.5	44.2
10	3.0	33.5	9.8	-	9.3	20.8	33.7	48.0
6	6.1	23.5	7.4	-	10.3	25.5	38.9	33.8[d]
7	6.1	35.9	11.3	-	13.7	25.4	31.3	42.9

[a] Estimated mass of sediment deposited above grass only.
[b] Inflow rate setting (19, 38, and 57 kg/min).
[c] Plot 9 testing was interrupted by a natural rainstorm.
[d] High inflow rate was low due to low pump pressure.

was interrupted by natural rainfall during testing. The totals range from 16.7 kg of sediment for plot 5, run 1 to 49.0 kg for run 2 on the same plot. The relatively high variability was caused mostly by the variability in the sediment entering the grassed area. For example, the 1.5-m long grassed area of plot 8 trapped more sediment (81.6 kg) over the 2 runs than either of the longer grassed areas. Sediment data and visual observation of this plot during the run revealed that, generally, both the rate and sizes of sediment entering the grassed area were greater, thus making more sediment available and more readily trapped than sediment from other plots. Variability in the sediment generated among plots on the same soil in close proximity is not uncommon in erosion experiments, therefore, characterizing the sediment on each plot is necessary.

The mass of sediment deposited directly above the grassed area is shown in column 4 of Table 2. This quantity was determined after each run by weighing the wet sediment deposited in the pan, determining the dry mass basis moisture content of 3 samples taken from the sediment, and then computing the average dry mass of sediment from the sample moisture contents. These quantities ranged from a low of 4.0 kg for plot 4 to 14.1 kg for plot 8 run 2 with a standard deviation of 3.3. These values are relatively consistent as expected since the length of the grassed area should not influence the amount of deposition above the grass. Analysis of variance showed that there was no significant difference between the average mass of sediment deposited above the grass for each length of grassed area using the least significant difference test at the 0.05 level (Steel and Torrie, 1980). Comparisons between the amounts in columns 3 and 4, indicate that between 20 and 50 percent of the total sediment trapped was a result of deposition above the grass. Visual observation suggested that most of this deposition occurred during the rainfall-only period of the test; therefore, the relative effect of this deposition decreased for the higher runoff rates.

After run 1, the grassed area was trimmed to a nominal height of 100 mm. Stalk density was estimated by collecting, drying, and weighing the trimmings and then using the average weight of at least 3 representative 100 stalk samples to determine the total number of stalks in the given area. The estimated densities (column 5) ranged from 46 to 169 stalks per m^2 with the 3.0-m long areas generally being the least dense. The effect of stalk density was difficult to isolate since these grasses, like most, tend to have more growth near ground level and ground cover was considerable. However, stalk densities did provide a measure of the quality of the stand of grass.

Columns 6 through 9 of Table 2 contain the rates of runoff water leaving the grassed area. These rates are the averages of 3 repeated runoff samples collected over a 4-minute period after runoff had reached steady state. The higher runoff rates for plot 7 run 1 were due to the relatively high antecedent moisture content of the soil, and the low rate for the plot 6 high inflow treatment resulted from pump problems. Within each of the 4 inflow settings (0, 19, 38, and 57 kg/min) the mean runoff rate for a given length of grassed area was not significantly different (at the 5 percent level) from the means of either of the other 2 lengths using the least significant differences test (Steel and Torrie, 1980). Therefore, treatment difference within each inflow setting should not be attributed to differences in runoff rates.

Overall Trapping Effectiveness

The sediment trapping effectiveness of each plot was determined by dividing the difference in the rates of sediment entering and leaving the grassed area by the rate of sediment entering the area. The average trapping effectiveness for each length of grassed area is plotted on Fig. 2 with respect to their corresponding runoff rates. The effectiveness of each grassed area decreased with increasing runoff rate, becoming more noticeable as the length of grassed area decreased. This decrease was attributed to a combination of factors including increased velocity of flow resulting in greater sediment transport capacity through the grass, increased depth of flow causing decreased surface area of grass per unit of flow, and sediment accumulation above and in the upslope end of the grass as flow rates increased. The accumulation of sediment inundated part of the grass and decreased the effective length.

The sediment accumulation also helped decrease the effectiveness of the grass from run 1 to run 2 for all combinations of grassed lengths and runoff rates, except for runoff rates less than 30 kg/min on the 3.0-m long grassed area. This exception was attributed to both an increase in the average mass of sediment deposited above the grass (Table 2) from run 1 to run 2 and the observation that deposition above the grass was greater for runoff rates less than 30 kg/min.

The average effectiveness of the 1.5-m long grassed areas ranged from 0.8 to 0.6 for the first run (Fig. 2) and from 0.80 to 0.40 for the second. This range was generally lower than that of the 3.0 and 6.1-m long areas which ranged from 0.95 to 0.72. The trapping effectiveness of the 3.0- and 6.1-m long grassed areas seemed to be in a relatively narrow band (0.94 to 0.72) bordered almost entirely by the ranges in the effectiveness of the 6.1-m long strips for runs 1 and 2. This suggests that no significant difference in the trapping effectiveness of these two lengths of strips existed for the conditions studied; however, for situations where deposited sediment inundates a significant portion of the grass, differences would occur.

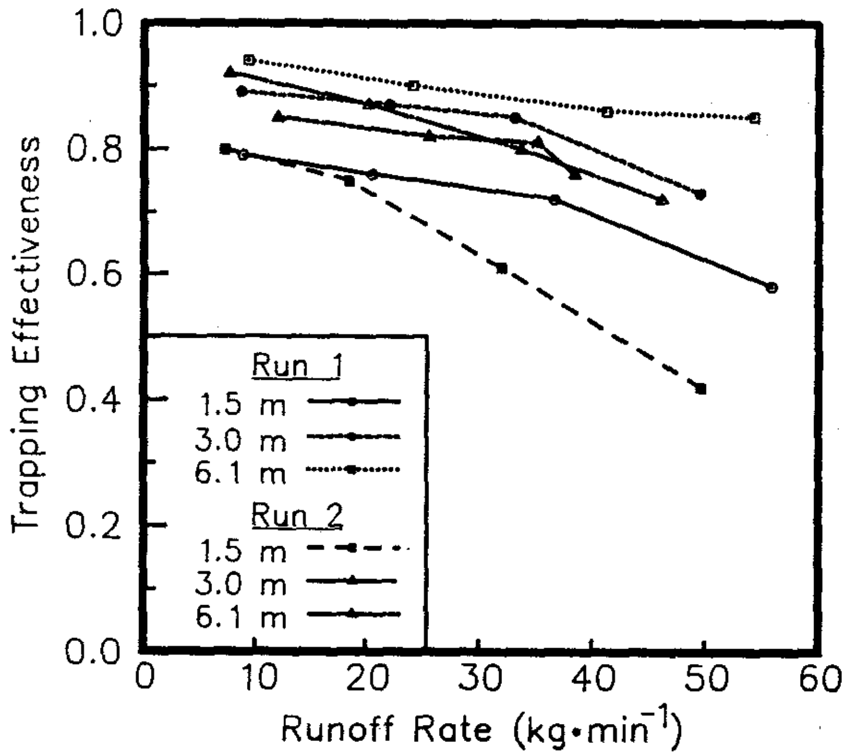

Fig. 2 Sediment trapping efficiencies of 0.91-m wide grassed areas for varying runoff rates.

Trapping Effectiveness by Size of Sediment

The size distributions of sediment entering and leaving the grassed area were determined using the combination sieve (≥ 63 μm) and pipette (<63 μm) method outlined by Meyer and Scott (1983). This method was sometimes inconsistent for low concentrations of sediment in the runoff such as often occurred below the grassed areas. The inconsistencies occurred when the net mass of sediment computed for a given size category, always less than 63 µm, was negative. In these cases, the negative value was set equal to zero and the mass of sediment in the other categories between 0 and 63 µm were changed proportionately.

Sediment size distributions were then used to separate the corresponding average total sediment delivery rates into sizes yielding the rate at which sediment of a given size enters and leaves the grassed area. For each sediment size the differences between the rates of sediment entering and leaving the grass divided by the sediment entering was considered the fraction of sediment trapped. The average percentages of sediment trapped by sizes are shown in Table 3 for each combination of grass length and runoff rate.

As shown in columns 2 through 5 of Table 3, at least 89 percent of all, and 98 percent of most, sediment greater than 250 µm was trapped by the grass. For sediment less than 250 µm, the percent trapped ranged from 100 to 6 percent with the lowest percentages occurring for the 1.5-m long strips. For run 2 on the

Table 3. Percent by size of incoming sediment trapped by grass.

Runoff Rate kg/min	>2000[a]	2000 1000	1000 500	500 250	250 125	125 63	63 31	31 16	16 8	8 4	<4
						%					
					1.5 m Strips Run 1						
8.9	100	99	99	98	97	98	100	75	49	35	35
20.5	100	100	100	100	100	98	95	22	7	11	9
36.6	100	100	100	98	98	91	84	19	29	45	39
55.8	100	99	99	98	96	79	14	53	53	61	57
					3.0 m Strips Run 1						
8.7	89	94	90	89	92	95	97	95	94	88	51
22.0	100	100	100	99	98	98	97	93	71	61	45
33.1	100	100	100	99	99	96	98	86	66	49	45
49.5	99	99	99	99	98	96	93	74	45	17	27
					6.1 m Strips Run 1						
9.3	100	99	100	100	99	99	100	98	99	99	57
24.1	100	100	100	100	100	100	85	99	97	91	66
41.2	100	100	100	99	99	99	100	99	85	59	44
54.3	100	100	100	100	100	99	100	94	80	62	51
					1.5 m Strips Run 2						
7.2	100	99	99	99	99	98	100	92	64	26	-15
18.4	100	99	99	99	99	95	92	75	46	24	23
31.9	100	100	99	98	92	73	60	39	27	31	24
49.6	100	98	98	96	82	43	26	15	14	18	6
					3.0 m Strips Run 2						
7.6	100	100	100	100	100	99	100	100	94	83	64
20.1	100	100	100	100	99	99	100	95	79	61	45
33.6	100	100	100	99	99	98	96	84	62	59	41
46.1	100	99	99	99	97	91	97	66	49	26	40
					6.1 m Strips Run 2						
12	100	100	99	99	99	99	100	100	100	97	39
25.5	100	100	100	99	99	99	100	99	82	42	24
35.1	100	100	99	99	99	99	99	95	74	47	32
38.4	100	97	98	98	97	95	100	87	63	33	26

[a] Size ranges of sediment in microns. Sediment sizes less than 63 microns were determined based on their fall velocity; therefore, they are effective sizes.

1.5-m strips, the negative percentage computed for sediment less than 4 µm (column 12) indicates that more sediment of this size was leaving than was entering the grass. This negative value occurred on only 1 of the 2 replicates (plot 9 run 2) suggesting that it may have been an anomaly. However, sediment deposited in or on the grass during run 1 could have enriched the run 2 runoff with sediment of this size.

For increasing runoff rates on each length of strip the percentage of sediment less than 31µm (columns 9, 10, 11 and 12) trapped generally decreased indicating that most of the loss in overall trapping effectiveness occurs in relatively fine sediment. This decreased effectiveness with increasing runoff rate was more evident for the second run on each strip particularly the 1.5-m long strip starting with sediment as large as 250 µm.

SUMMARY

Sediment-laden runoff generated by applying simulated rainfall (73 mm/hr) and inflow to an area of tilled soil was channeled to a grassed area. The runoff was sampled before entering and after leaving the grassed area to determine sediment delivery rates and size distributions. The mass of sediment deposited within and directly above the grass area was also determined.

Results showed that the overall sediment trapping effectiveness of the 1.5-m long grassed areas varied from 0.80 to 0.40 while those of the 3.0- and 6.1-m long areas ranged from 0.95 to 0.72. The decrease in effectiveness resulted from increased runoff rates and the accumulation of deposited sediment. Sediment size data showed that this drop in trapping effectiveness occurred primarily because of decreased trapping of sediment less than 125 µm in size.

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PARTICLE SIZES OF SEDIMENT FROM CROPLAND SOILS

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ABSTRACT

Size characteristics of sediment that eroded from 22 intensively cropped soils were analyzed before and after dispersion to determine the extent of aggregation and primary particle composition. The undispersed sediment was often much coarser than the primary soil particles, but the size distributions of primary particles in the soil and the sediment were usually very similar. For soils with medium to high clay contents, about half of the sediment was sand sized and was dominantly in the form of aggregates. These coarse aggregates contained much of the eroded clay, so control practices that trap coarse sediment have a major potential to reduce losses of nutrients and pollutants associated with clay particles. For most soils, the sediment data indicated little evidence of clay enrichment from interrill erosion. However, some enrichment occurred if the sediment had an opportunity for deposition during transport. A relationship was determined that approximates the aggregated portion of sand-sized sediment using the clay and sand contents of the soil.

INTRODUCTION

Sediment resulting from cropland erosion is generally coarser than the primary particle sizes of which it consists, because part of the sediment is in the form of aggregates. These aggregates are clusters of finer particles in which the forces holding the particles together are stronger than the dispersive forces exerted on them by rainfall and runoff. Aggregates consist dominantly of clay and silt-sized material, but they behave more like coarser sediment when eroded during storm events. Therefore, the sizes of the aggregates and the amount of aggregation greatly affect the transport and deposition potential of sediment from cropland sources.

The primary particle composition of sediment aggregates is also important, because the clay-sized material is the most chemically active portion. This component contains most of the soil's plant-available nutrients and carries most of the potential pollutants that are associated with the sediment. Therefore, if sediment control practices are used to trap aggregates near their source, loss of adsorbed cropland nutrients and agricultural chemicals can be reduced.

This paper presents information on sediment size distributions, amount of aggregation, and primary-particle content of coarse sediment for cropland soils from several major land resource areas.

PROCEDURE

The soils studied were all in a bare, tilled, initially dry, ridged condition when subjected to erosion events (Meyer and Harmon, 1984). Soils are listed in Table 1, beginning with those of high clay, then high silt, and finally high sand contents. A series of intense simulated rainstorms was applied, and runoff was sampled to obtain erosion rate and sediment size data.

Table 1. Soils that were the source of eroded sediment for this research.

Soil type	Taxonomic Class	Location	Year	O.M.* %	Fe** %
Oktibbeha clay	Vertic Hapludalfs	N.E. MS	1983	1.8	3.2
Leeper clay	Vertic Haplaquepts	N.E. MS	1979	2.0	1.7
Alligator clay	Vertic Haplaquepts	Delta MS	1980	3.1	1.1
Sharkey sic***	Vertic Haplaquepts	Delta MS	1979	2.2	1.5
Brooksville sic	Aquic Chromuderts	N.E. MS	1979	2.3	2.1
Decatur sicl	Rhodic Paleudults	N.W. AL	1983	.9	2.1
Atwood sicl	Typic Paleudalfs	N.E. MS	1981	.9	2.0
Tama sicl	Typic Argiudolls	C. IA	1980	3.6	.8
Monona sicl	Typic Hapludolls	S.W. IA	1980	3.7	.9
Memphis sil	Typic Hapludalfs	N.W. MS	1978	1.1	.8
Lexington sil	Typic Paleudalfs	N.C. MS	1978	1.2	.6
Loring sil	Typic Fragiudalfs	N.W. MS	1979	.8	.8
Grenada sil	Glossic Fragiudalfs	N.C. MS	1978	1.1	.5
Vicksburg sil	Typic Udifluvents	N.W. MS	1978	1.2	.6
Morganfield sil	Typic Udifluvents	W.C. MS	1978	.7	.4
Ora sil	Typic Fragiudults	N.E. MS	1979	1.2	.7
Arkabutla sil	Aeric Fluvaquents	N.C. MS	1978	1.4	.5
Dubbs loam	Typic Hapludalfs	Delta MS	1980	1.5	.6
Clarion loam	Typic Hapludolls	C. IA	1980	3.0	.7
Caledonia loam	Typic Paleudalfs	E.C. MS	1982	1.1	.7
Ochlockonee sl	Typic Udifluvents	N.C. MS	1979	.7	.4
Ariel sl	Fluventic Dystrochrepts	N.C. MS	1987	.3	.4
Brooksville clay	Aquic Chromuderts	E.C. MS	1983	2.4	3.7
Loring sil	Typic Fragiudalfs	N.C. MS	1982	2.3	1.4

* Organic matter content = Organic carbon (%) x 1.7
** Dithionite-Citrate Extractable Iron
*** sic - silty clay; sicl - silty clay loam; sil - silt loam; sl - sandy loam

Size distribution was determined by wet sieving and pipette analysis (Meyer and Scott, 1983) in the condition that the sediment eroded, so the resulting sediment size distributions combine sediment that erodes as primary particles with the rest that erodes as aggregates. Next, the sieved and pipetted material was combined into three sediment-size groups: (a) >250 µm, (b) 63-250 µm, and (c) <63 µm. Each of these size groups was dispersed with sodium hexametaphosphate to obtain the primary particle content of this coarse, medium, and fine sediment.

Sediment sizes were determined for eleven size groups, but adjacent groups were summed for reporting as six groups. The smallest size group was for sediment finer than 4 µm which is designated as clay-sized material in this report. Similarly, material coarser than 63 µm is designated as sand-sized material. The remainder of the material (4 - 63 µm) is designated as silt sized.

The results presented are averages of three or more sediment-size samples each from two or more replicated plots. Samples were collected during storms with a rain intensity of about 70 mm/h after steady-state conditions were reached. The samples for all soils were taken at the same times, so the composition of the eroded material should be a function of soil characteristics only.

Most of the results and discussion are for sediment eroded from the short sideslopes to the furrows of 0.9-m sections of crop rows. For such conditions, the row sideslopes were sources of interrill erosion with little or no deposition or rilling. Some additional data are presented for 9-m sections of rows with different gradients that were subjected to rainstorms similar to those applied to the interrill areas. These latter conditions allowed for partial deposition, total transport, or rilling, depending on the conditions.

RESULTS AND DISCUSSION

The surface horizons of soils studied (data from 12 soils are given in Table 2) ranged in clay content from greater than 50% to less than 5%, in silt content from about 80% to less than 20%, and in sand content from about 70% to less than 5%. Also given in Table 2 are (a) the size distributions of the sediment as eroded from the crop row sideslopes for each soil and (b) the primary particle size distributions of this sediment after it was dispersed. These data show that the size distributions of the eroded sediment were much coarser than the primary

Table 2. Size distribution of dispersed surface soil, eroded sediment, and dispersed sediment from interrill areas during intense rainstorms

Particle size group	Oktibbeha			Alligator			Brooksville 79			Decatur		
	Disp. soil	Erod. sed.	Disp. sed.	Disp. soil	Erod. sed.	Disp. sed.	Disp. soil	Erod. sed.	Disp. sed.	Disp. soil	Erod. sed.	Disp. sed.
µm	---------------			------%	by mass	------						---------------
>1000	0.2	12.2	0.3	0.2	4.3	0.2	0.8	16.0	0.8	0.3	1.4	0.3
250-1000	1.1	26.3	0.8	1.7	27.4	1.3	1.5	39.0	1.2	2.9	24.7	2.0
63-250	12.4	15.2	8.5	18.7	28.5	21.9	1.0	4.5	1.9	11.8	21.6	13.3
16-63	18.1	11.8	17.0	16.9	11.9	18.3	32.6	8.8	26.7	30.0	23.3	32.0
4-16	8.7	14.6	9.4	11.9	9.6	11.0	20.1	10.8	21.0	21.0	18.4	21.1
<4	59.5	19.9	64.0	50.6	18.3	47.3	44.0	20.9	48.4	34.0	10.6	31.3

Particle size group	Tama			Memphis			Grenada			Ora		
	Disp. soil	Erod. sed.	Disp. sed.	Disp. soil	Erod. sed.	Disp. sed.	Disp. soil	Erod. sed.	Disp. sed.	Disp. soil	Erod. sed.	Disp. sed.
	---------------			------%	by mass	------						---------------
>1000	0.2	1.7	0.3	0.0	0.7	0.0	0.1	0.6	0.1	0.2	0.3	0.1
250-1000	0.9	25.6	0.8	0.3	19.4	0.2	2.6	8.2	1.8	6.4	9.9	5.9
63-250	1.3	17.5	2.0	0.7	9.9	0.5	3.9	7.6	3.5	13.8	16.6	14.1
16-63	39.6	26.1	38.8	52.9	48.9	55.8	62.1	62.9	64.1	44.1	43.2	47.4
4-16	23.1	13.9	23.1	19.5	14.3	18.8	16.6	16.0	16.8	22.6	16.8	19.7
<4	34.9	15.2	35.0	26.6	6.8	24.7	14.7	4.7	13.7	12.9	13.2	12.8

Particle size group	Dubbs 80			Clarion			Caledonia			Ariel		
	Disp. soil	Erod. sed.	Disp. sed.	Disp. soil	Erod. sed.	Disp. sed.	Disp. soil	Erod. sed.	Disp. sed.	Disp. soil	Erod. sed.	Disp. sed.
	---------------			------%	by mass	------						---------------
>1000	0.1	1.7	0.1	1.5	1.8	1.3	0.3	0.3	0.1	0.2	0.5	0.3
250-1000	1.4	5.1	0.8	18.3	24.4	16.1	22.1	21.7	17.7	34.6	46.1	31.2
63-250	22.8	32.3	22.6	25.1	36.2	25.6	22.3	25.8	27.2	38.7	33.3	41.6
16-63	49.3	41.4	49.9	19.4	15.2	19.8	27.0	29.2	29.9	18.2	15.3	19.1
4-16	10.4	9.7	10.3	10.2	8.3	12.6	16.7	14.1	14.3	3.6	2.6	3.2
<4	16.0	9.8	16.3	25.5	14.1	24.6	11.6	8.9	10.8	4.7	2.2	4.6

particle sizes of the surface the horizons for many of the soils, because the sediment contained a large portion of relatively stable aggregates. However, some of the soils, particularly those with low clay contents, produced sediment that was only slightly coarser than the soil's primary-particle size distribution. These soils generally eroded dominantly as primary particles with relatively few aggregates.

The primary-particle size distribution of the sediment after dispersion is given in the third column for each soil. These distributions are similar to those of the dispersed soils, indicating that the sediment which eroded from these interrill sources was representative of the surface soil mass from which it was eroded and that little selectivity occurred.

Primary particle size distributions for sediment (a) coarser than 250 µm, (b) between 63 and 250 µm, and (c) finer than 63 µm are given in Table 3. These three size distributions, weighted by the relative amounts in each sediment size group, give the size distribution of the dispersed sediment shown in the third column for each soil in Table 2.

Primary particles finer than 4 µm (Table 3) are of particular interest because of the influence this particle size class has on aggregation and chemical

Table 3. Size distribution of primary particles in three sediment size groups (percentage by mass).

	Oktibbeha			Alligator			Brooksville 79			Decatur		
Sed size	>250 µm	63-250	<63 µm	>250 µm	63-250	<63 µm	>250 µm	63-250	<63 µm	>250 µm	63-250	<63 µm
% sed	38.5	15.2	46.3	31.7	28.5	39.8	55.0	4.5	40.5	26.1	21.6	52.3
Prim. part.												
>1000 µm	0.9	-	-	0.8	-	-	1.5	-	-	1.1	-	-
250-1000	1.9	-	-	4.9	-	-	1.9	-	-	7.9	-	-
63-250	6.6	37.9	-	8.0	60.4	-	1.9	14.1	-	5.6	55.2	-
16-63	17.0	8.1	20.4	12.3	7.7	31.2	27.8	24.5	26.6	26.4	14.0	42.1
4-16	9.1	5.7	10.7	13.4	4.6	14.6	21.7	19.2	20.0	22.8	10.9	24.3
<4 µm	64.5	48.3	68.9	60.6	27.3	54.2	45.2	42.2	53.4	36.2	19.9	33.6

	Tama			Memphis			Grenada			Ora		
Sed size	>250 µm	63-250	<63 µm	>250 µm	63-250	<63 µm	>250 µm	63-250	<63 µm	>250 µm	63-250	<63 µm
% sed	27.3	17.5	55.2	20.1	9.9	70.0	8.8	7.6	83.6	10.2	16.6	73.2
Prim. part.												
>1000 µm	1.0	-	-	0.2	-	-	1.2	-	-	0.6	-	-
250-1000	2.8	-	-	0.9	-	-	21.2	-	-	53.4	-	-
63-250	1.9	7.4	-	0.6	4.4	-	4.7	39.7	-	9.8	75.0	-
16-63	30.2	31.8	45.8	45.2	48.4	59.5	35.7	29.8	70.2	18.8	13.0	60.7
4-16	23.5	22.3	23.6	20.8	17.3	18.5	16.8	10.8	17.4	7.9	5.3	24.6
<4 µm	40.6	38.5	30.6	32.3	29.9	22.0	20.4	19.7	12.4	9.5	6.7	14.7

	Dubbs 80			Clarion			Caledonia			Ariel		
Sed size	>250 µm	63-250	<63 µm	>250 µm	63-250	<63 µm	>250 µm	63-250	<63 µm	>250 µm	63-250	<63 µm
% sed	6.8	32.3	60.9	26.2	36.2	37.6	22.0	25.8	52.2	46.6	33.3	20.1
Prim. part.												
>1000 µm	1.6	-	-	4.9	-	-	0.3	-	-	0.5	-	-
250-1000	16.4	-	-	60.4	-	-	75.0	-	-	68.0	-	-
63-250	11.2	68.8	-	8.2	64.3	-	14.8	88.0	-	28.0	90.1	-
16-63	33.0	19.8	66.6	6.9	10.3	38.6	3.7	4.9	56.7	1.9	7.9	71.2
4-16	12.8	2.7	14.0	5.6	6.8	23.7	2.5	2.5	25.9	.5	.1	13.0
<4 µm	25.0	8.7	19.4	14.0	18.6	37.7	3.7	4.6	17.4	1.1	1.9	15.8

transport. For the two larger sediment size groups, all of this very fine material was part of the aggregates or it would have been in the third size group. In general, the percentage of material finer than 4 µm in the coarsest sediment size group was not much less than in the finest sediment size group, and it often was a little greater. Thus, sediment control practices which trap sediment larger than 250 µm can greatly reduce the loss of clay-sized material.

The lower percentage of clay-sized primary material in the sediment size group between 63 and 250 µm may be attributed primarily to the content of fine sand, because most sand erodes as primary particles and not as a part of aggregates.

Thus, for both larger sediment size groups, the sand in the sediment reduced the aggregated percentage and resulted in lower clay percentages. If all primary material coarser than 63 µm is disregarded and the remainder is apportioned to total 100%, the portion finer than 4 µm is almost always least for the sediment size group finer than 63 µm. This indicates that little selectivity occurs during interrill erosion and therefore shows no appreciable evidence of clay enrichment for these conditions.

To further illustrate the potential for controlling the loss of clay by trapping the coarser sediment from aggregated cropland soils, the clay portion of the total sediment in each of the three sediment size groups is given in Table 4. The first data column shows the percentage of the total sediment that is clay sized for each soil, and the next two columns show the percentage of total

Table 4. Portions of clay-sized particles (<4 µm) for the total sediment that are eroded in sand-sized aggregates (>63 µm).

Soil	Primary particles <4 µm in sediment of:				Percent of total particles <4 µm in sed >63 µm
	All sizes	>250 µm	63-250 µm	>63 µm	
	--------------------%	of total	sediment	----------------	
Oktibbeha	64.0	24.8	7.4	32.2	50
Leeper	55.9	25.1	3.1	28.2	50
Alligator	47.3	19.2	7.8	27.0	57
Sharkey 79	53.8	22.9	6.5	29.4	55
Brooksville 79	48.4	24.9	1.9	26.8	55
Decatur	31.3	9.4	4.3	13.7	44
Atwood 81	29.1	11.7	3.1	14.8	51
Tama	35.0	11.1	6.7	17.8	51
Monona	27.9	5.7	4.7	10.4	37
Memphis	24.7	6.5	3.0	9.5	38
Lexington 78	22.7	5.5	2.9	8.4	37
Loring 79	17.5	.6	.8	1.4	8
Grenada 78	13.7	1.8	1.5	3.3	24
Vicksburg 78	8.5	.6	1.1	1.7	20
Morganfield	10.7	.9	1.0	1.9	18
Ora	12.8	1.0	1.1	2.1	16
Arkabutla	17.4	2.6	2.4	5.0	29
Dubbs 80	16.3	1.7	2.8	4.5	28
Clarion	24.6	3.7	6.7	10.4	42
Caledonia	10.8	.8	1.2	2.0	19
Ochlockonee	5.3	.3	.3	.6	11
Ariel 87	4.6	.5	.6	1.1	24

sediment finer than 4 µm in the two sand-sized sediment groups. For the well-aggregated finer textured and Iowa soils, much of the clay was in sediment coarser than 250 µm and additional clay was in sediment between 63 and 250 µm. Comparison of the fourth column with the first column shows that sediment from several of the soils has over half of the clay-sized material tied up in sand-sized aggregates and that many of the other soils with major contents of clay-sized material have much of it in this larger sediment. Since sediment of this size can be trapped in dense grass strips (Line, 1991), sedimentation basins, and channels of limited gradient, these data show the potential of such control practices in reducing the loss of clay-sized soil material and any attached nutrients or pollutants.

The extent of aggregation present in sediment eroded from different soils is important in various ways, so the data were analyzed to determine the aggregate content for the two sand-sized sediment groups. (Aggregation could not be determined for sediment finer than 63 µm because of difficulties in separating such fine material.) The determination was made by comparing the amount of sediment coarser than 250 µm or 63 µm before and after dispersing (Table 5). For several well-aggregated soils with low sand contents, greater than 90% of the sediment coarser than 63 µm was in the form of aggregates. For more than half of the soils, over 50% of this sand-sized sediment was aggregates. The remaining soils were high-sand soils. Even the high-silt soils with minor amounts of sand-sized sediment had a majority of their coarse sediment in the form of aggregates.

Table 5. Aggregated portion of sediment from different soils.

Soil	Sediment >250 µm		Sediment 63-250 µm			Aggregates in sed
	Primary sand	Aggregates	Primary sand	Aggregates	Aggregates >63 µm	>63 µm
	-------------------%	of total	sediment	---------------		%
Oktibbeha	1.6	36.9	5.8	9.4	46.3	86
Leeper	3.8	42.6	4.0	5.5	48.1	86
Alligator	2.6	29.1	17.8	10.7	39.8	66
Sharkey 79	.9	39.9	.9	11.0	50.9	97
Brooksville 79	2.4	52.6	.6	3.9	56.5	95
Decatur	3.0	23.1	11.9	9.7	32.8	69
Atwood 81	10.5	28.0	3.7	7.0	35.0	71
Tama	1.2	26.1	2.0	15.5	41.6	93
Monona	1.1	13.3	1.6	12.6	25.9	91
Memphis	.3	19.8	.7	9.2	29.0	97
Lexington 78	3.3	15.2	5.6	8.5	23.7	73
Loring 79	.8	2.7	1.0	3.5	6.2	78
Grenada	1.9	6.9	3.0	4.6	11.5	68
Vicksburg 78	1.5	2.0	3.4	3.5	5.5	53
Morganfield	.2	3.0	4.3	3.0	6.0	57
Ora	6.3	3.9	12.5	4.1	8.0	30
Arkabutla	5.0	7.5	16.8	5.9	13.4	37
Dubbs 80	1.5	5.3	22.2	10.1	15.4	39
Clarion	18.5	7.7	24.4	11.8	19.5	31
Caledonia	19.7	2.3	22.8	3.0	5.3	11
Ochlockonee	32.0	.9	27.7	1.0	1.9	3
Ariel	43.9	2.7	31.9	1.4	4.1	5

Using data on percentage of aggregation in sediment coarser than 63 µm and the realization that content of primary sand has a major effect on this percentage, a search for a relationship to predict percent aggregation from soil properties was explored. As shown in Figure 1, the percent of aggregation for sediment from these soils is well correlated with the clay content of the soil divided by the sum of the soil's clay and sand contents. A direct 1:1 relationship (where both parameters are expressed as a proportion) approximates these data. A line of slight curvature, especially at the smaller values, would improve the fit, but would not be necessary for the larger values that are usually of more interest.

The discussion and results given heretofore were for sediment from interrill sources such as row sideslopes. For such conditions, deposition of eroded sediment is unlikely, so nearly all that is detached is measured. However, data are available for other studies on longer sections of rows having different furrow gradients where deposition may occur at the smaller steepnesses or rilling may occur at the steeper gradients. For these conditions, simulated rainstorms were applied to the rows and furrows, and the sediment lost was evaluated at the ends of 9-m long furrows. For the slight gradients, all sediment originated from the row sideslopes and part deposited along the furrows. For the steeper gradients, sediment originated both from interrill erosion of the row sideslopes and from rilling of the furrows.

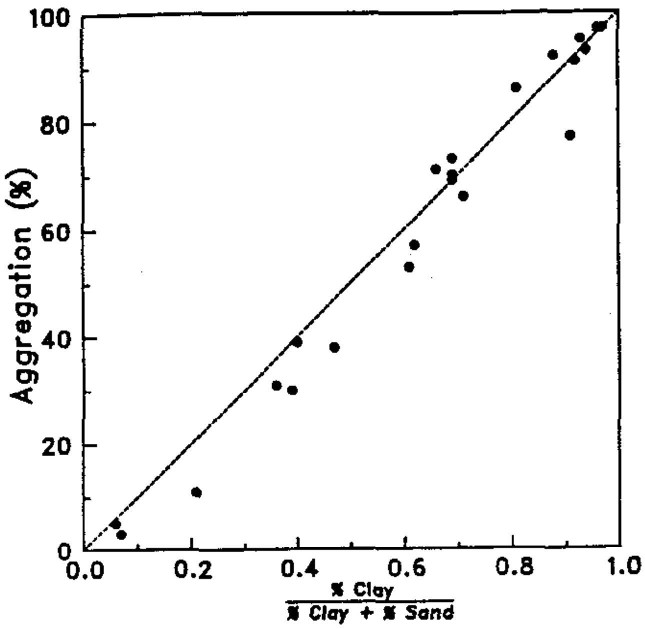

Figure 1. Percentage of aggregation for sediment coarser than 63 µm as a function of clay and sand contents of soil.

Results in Table 6 show that some deposition of row-sideslope sediment along furrows at 0.5% grade caused a small increase in the loss of clay-sized sediment from the ends of the furrows. For both soils studied, loss of the finest size

Table 6. Effect of on-field deposition due to controlled row gradients on losses of clay-sized (<4 µm) sediment from 9-m furrows

Sed Size group µm	Dispersed soil	Dispersed Sediment from: Row sideslopes	6.5% Furrow	5.0% Furrow	3.5% Furrow	2.0% Furrow	0.5% Furrow
	--------------------------	% by mass					
	Loring 82						
>1000	0.1	0.1	0.1	0	0	0.1	0.1
250-1000	1.1	0.4	0.6	0.5	0.5	0.4	0.4
63-250	1.4	1.3	1.0	1.0	1.1	0.9	0.8
16-63	52.1	51.4	47.8	49.3	51.5	46.6	40.0
4-16	24.8	23.4	25.3	24.4	24.5	27.1	30.0
<4	20.5	23.4	25.2	24.8	22.4	24.9	28.7
	Brooksville 83						
>1000	1.6	2.2			1.8		0.6
250-1000	3.6	2.1			2.4		.8
63-250	2.6	1.8			1.3		.9
16-63	19.9	18.9			18.5		11.0
4-16	16.1	17.9			18.0		19.1
<4	56.2	57.1			58.0		67.6

was 10 to 20% greater at 0.5% gradient than at steeper gradients or from the row sideslopes. The consequent reduction in loss occurred for the primary sand and coarse silt. Thus, some clay enrichment may be expected for conditions where sediment from interrill areas is transported through conditions where selective deposition can occur, but enrichment for the conditions studied was not great. For other conditions, little clay enrichment was indicated.

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LS FACTORS FOR THE PACIFIC NORTHWEST

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ABSTRACT

Accurate erosion prediction on non-irrigated cropland of the Pacific Northwest has been severely hampered by lack of length and steepness relationships suitable for the steep slopes of the region. Relationships derived from data from the humid regions of the US over-predicted the effect of slope steepness for the steep slopes commonly cultivated in the Pacific Northwest.

In this 10-year field study, measurements of rill erosion were collected from selected fields along an 80-km transect across eastern Washington and northern Idaho. Data from more than 2100 slope segments were used to develop new slope length and steepness relationships. These new relationships will significantly improve erosion prediction in this region.

INTRODUCTION

The Pacific Northwest dryland is distinguished by its unique combination of climate, topography and capability to sustain high winter wheat yields. Unfortunately, another characteristic is the extremely high erosion levels occurring during the winter months under many of the cropping systems. Most erosion occurs as rills, frequently caused by low-intensity rainfall or snowmelt running over thawing soil (Zuzel et al., 1982). Soil loss rates of 200 to 450 t ha^{-1} have been recorded in a single winter season (USDA, 1978).

Early trials with the Universal Soil Loss Equation (USLE)(Wischmeier and Smith, 1965) indicated the steepness relationship overpredicted soil loss at higher slope steepness. To address this perceived overprediction, this project was initiated to determine the effect of slope length and steepness on rill erosion by measuring rill erosion on selected fields along an 80-km transect across the Palouse region of eastern Washington and northern Idaho. Later the project was expanded to include the five major wheat producing counties of northcentral Oregon, and a major part of the winter wheat area in southeastern Idaho (Figure 1).

THEORY

The methodology for analyzing the data was developed by starting with the basic form of the USLE:

$$A = R\ K\ L\ S\ C\ P \tag{1}$$

where A = soil loss per unit area
R = rainfall and runoff erosivity factor
K = soil erodibility factor
L = slope length factor
S = slope steepness factor
C = cover and management factor
P = supporting conservation practice factor

Based on previous research results (Zingg, 1940; Musgrave, 1947; Smith and Whitt, 1947; and Wischmeier and Smith, 1965), an equation for the slope length and steepness relationship LS can be written as:

$$LS = (\lambda/22.13)^m \, [(\sin \theta)/\sin (5.143°)]^n \qquad (2)$$

where LS = slope length and steepness factor relative to a 22.13 m slope length of uniform 9 percent (5.143°) slope
λ = horizontal slope length, m
θ = slope steepness, degrees
m,n = regression coefficients

The use of 22.13 and sin 5.143° in the denominator of the terms in equation (2) normalizes the relationship to that of a 22.13 m long plot on a 5.143° slope (USLE unit plot condition).

Equation (1) can be rearranged and equation (2) substituted for LS,

$$A/KCP = R(\lambda/22.13)^m \, [\sin (\theta)/\sin (5.143°)]^n \qquad (3)$$

and

$$\ln(A/KCP) = \ln(R) + m \ln(\lambda/22.13) + n \ln(\sin \theta/\sin 5.143°) \qquad (4)$$

In equation (4), R, m and n can be estimated by linear regression techniques if the independent variables are known. A, λ and θ are measured; K is based on soils information; C and P are assigned based on field observations at the time of erosion measurement. Evaluation of R values followed determination of values for m and n and is not a part of this report.

DATA COLLECTION

The designers of the experiment considered an 80-km transect across the Palouse and Nez Perce Prairie of eastern Washington and northern Idaho (Austin, 1965) that was nearly perpendicular to lines of equal elevation and precipitation. The transect extended from just east of the channeled scablands near Endicott, Washington to Troy, Idaho (Figure 1). Mean annual precipitation ranges from 350 mm at the west end to 650 mm at the east end of the transect.

Suitable sites for measurement were located at the end of each winter erosion season. Rills in the measurement strips were typical of the field rill pattern and, where possible, included a range of slope aspects. The strips were selected by isolating a small rill system, from 2- to 12-m wide, and tracing it to the top of the slope or where some tillage feature intercepted runoff and prevented it from reaching the selected strip. The strips were not uniform in width; the nonuniformity was accounted for in the analysis.

At least three measurement cross sections were located on each strip, the lowest cross section was near the toe of the slope, but upstream of any deposition or any major collection of rills into large concentrated flow channels. The top cross section was located to allow measurement of rills near the top of the slope. Intermediate cross sections were determined by slope length and changes in slope steepness. Notes on each strip included crop rotation, residue cover, canopy cover, surface roughness, direction of seeding, and snow drift influence. Also, each strip was marked on a 7.5 or 15 min. USGS map, a soil survey map, and the azimuth was measured and recorded.

Rill cross section data were collected with a rill meter (McCool et al., 1981). At each measurement cross section, the segment length (distance between cross sections), segment steepness, and cross section width were measured, and bulk density samples were collected.

The project was started in the spring of 1973 and continued through 1983. No data were collected in 1977 because there was virtually no erosion because of drought. Several hundred data points were obtained on slopes ranging from 1.5 to 56% steepness. The mean slope was 28.4%, and 95% of the data points were collected from slopes between approximately 9 and 48% steepness.

DATA REDUCTION AND ANALYSIS

The data were reduced to erosion rates by various manual, photographic and digitizer techniques and were developed into sets of segment values. These data included site number, latitude, longitude, azimuth, location on strip, bulk density, slope steepness, segment average width, and segment average soil loss in mass per unit area. Separate data sets of K, C, and P values were also developed. An analysis using an extension of the nonuniform slope method of Foster and Wischmeier (1974) was used to reduce the data into a form suitable for analysis with a standard statistical package.

Values of m and n were determined for the eastern Washington and northern Idaho, the northcentral Oregon, and the southeastern Idaho data sets individually. The following three conditions were considered:
(1) no adjustment for R, K, C or P, that is;

$$A = a[\lambda/22.13]^m \, [\sin(\theta)/\sin(5.143°)]^n \tag{5}$$

where a = regression coefficient that includes effects of RKCP
2) adjust for K, C and P but not R, that is:

$$A/KCP = b[\lambda/22.13]^m \, [\sin(\theta)/\sin(5.143°)]^n \tag{6}$$

where b = regression coefficient that includes effects of R
3) normalize each parameter by its value at the farthest downslope segment:

$$\left[\frac{A_i}{(KCP)_i} \Big/ \frac{A_b}{(KCP)_b}\right] = c\left[\frac{\lambda_i}{\lambda_b}\right]^m \left[\frac{\sin(\theta_i)}{\sin(\theta_b)}\right]^n \tag{7}$$

where A_i = erosion rate in i^{th} segment
A_b = erosion rate in farthest downslope segment
$(KCP)_i$ = values for i^{th} segment
$(KCP)_b$ = values for farthest downslope segment
λ_i = length of i^{th} segment
λ_b = length of farthest downslope segment
θ_i = slope of i^{th} segment
θ_b = slope of farthest downslope segment
c = regression coefficient

RESULTS AND DISCUSSION

The results of the analysis to determine values for m and n without adjusting for K, C and P are presented in Table 1. The results obtained after adjusting soil loss for K, C and P are presented in Table 2. The m and n data in Tables 1 and 2 show somewhat different values depending upon adjustments for K, C and P. Year to year differences in the n value for the Palouse data are rather large in both tables. Considering the composite data set results, there is very little difference between results obtained using equation (5) and equation (6) for the Palouse and southeastern Idaho data sets. However, for the Oregon data, the n value obtained using equation (6) was different from that obtained using equation (5). A previous analysis of the first six years of the Palouse data using equation (5) yielded a composite n value of 0.7 (McCool and George, 1983). Addition of the last four years of the data set decreased the n value to 0.61. The coefficient of determination for the results obtained without adjustment for K, C and P are generally higher, although coefficients of determination are rather low in both Tables 1 and 2.

Results of the analysis normalizing each parameter to its value at the farthest downslope segment are presented in Table 3. Only the m and n values for the composite data sets are given. The results show that the normalization procedure results in a much larger coefficient of determination than use of equations (5) and (6). This is because the normalization procedure removes most of the influences of R, K, C and P as sources of variation and error. The m values in Table 3 are similar to the composite results in Tables 1 and 2. The n values in Table 3 obtained from the northcentral Oregon and southeastern Idaho data are smaller than the composite results in Tables 1 and 2. The reason for the very small n value for southeastern Idaho in Table 3 is not known.

RECOMMENDATIONS

The purpose of the analysis was to determine reasonable values for the slope length exponent, m, and the slope steepness exponent, n, for use on non-irrigated cropland of the Pacific Northwest. From the results of this analysis, values of m = 0.5 and n = 0.6 appear to be reasonable. The LS relationship for use in erosion prediction then becomes:

$$LS = (\lambda/22.13)^{0.5} \, [\sin(\theta)/0.0896]^{0.6} \qquad (18)$$

The graph illustrated in Figure 2 will allow rapid and easy determination of LS values for the Pacific Northwest.

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TABLE 1. Slope length (m) and steepness (n) exponents obtained using equation (5).

Year	Number of segments	m	n	Coefficient of Determination
PALOUSE				
1973	199	0.39	0.55	0.64
1974	466	0.48	0.53	0.54
1975	183	0.43	0.52	0.56
1976	219	0.52	0.76	0.44
1978	223	0.44	0.59	0.55
1979	166	0.65	0.78	0.66
1980	167	0.42	0.54	0.43
1981	212	0.51	0.79	0.78
1982	159	0.57	0.79	0.64
1983	185	0.62	0.36	0.62
Ten-year Composite	2179	0.48	0.61	0.52
NC OREGON				
1976, 1978-81 Composite	245	0.58	0.34	0.41
SE IDAHO				
1976, 1978-1980 Composite	186	0.47	0.44	0.42

TABLE 2. Slope length (m) and steepness (n) exponents obtained using equation (6)

Year	Number of segments	m	n	Coefficient of Determination
PALOUSE				
1973	199	0.44	0.60	0.71
1974	466	0.47	0.64	0.46
1975	183	0.45	0.67	0.48
1976	219	0.48	0.87	0.32
1978	223	0.51	0.58	0.44
1979	166	0.67	0.62	0.64
1980	167	0.47	0.38	0.40
1981	212	0.58	0.38	0.69
1982	159	0.55	0.77	0.51
1983	185	0.65	0.20	0.56
Ten-year Composite	2179	0.50	0.59	0.45
NC OREGON				
1976, 1978-1981 Composite	245	0.54	0.43	0.51
SE IDAHO				
1976, 1978-1980 Composite	186	0.48	0.45	0.40

TABLE 3. Slope length (m) and steepness (n) exponents for composite data sets obtained using equation (7).

Zone or Area	Number of Segments[1]	m	n	Coefficient of Determination
PALOUSE	1616	0.45	0.63	0.76
NC OREGON	173	0.59	0.31	0.78
SE IDAHO	147	0.53	0.15	0.68

[1] Number of segments remaining after normalizing with the bottom segment of each strip. (Each strip loses one segment for fitting purposes.

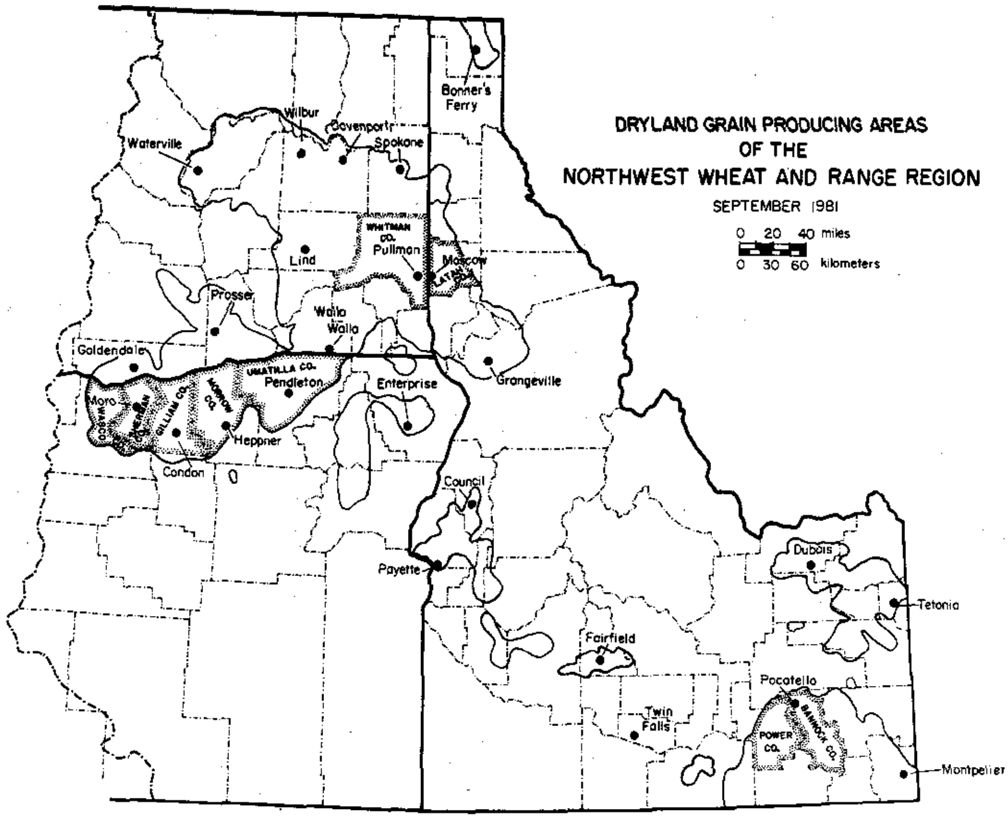

Figure 1. Study Area

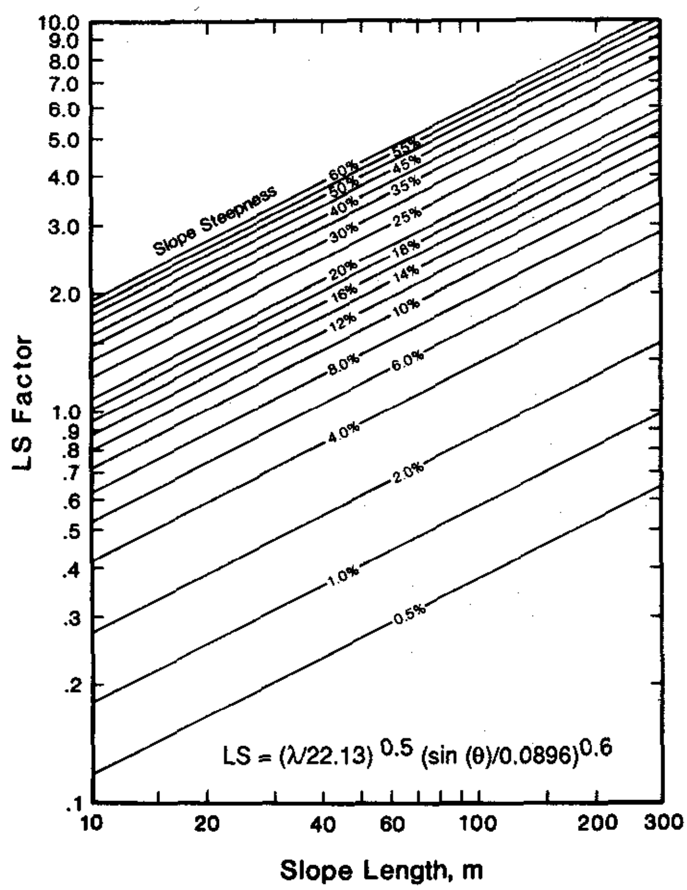

Figure 2. LS factors for non-irrigated cropland of the Pacific Northwest wheat and range region.

EVALUATION OF VEGETATIVE FILTER STRIPS

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ABSTRACT

Descriptive information was obtained for 230 filter strip sites which included locations from 29 states. The sites encompassed a wide range of slopes, slope profiles, soils, crops, management practices, climatic conditions, and filter strip lengths and vegetation types. To appraise projected water quality improvements due to the establishment of filter strips, a series of CREAMS computer model simulations of before and after installation conditions were conducted. Filter strips reduced sediment loss by 10 to 80% depending on the soil type, slope and slope profile. Similar reductions were noted for sediment associated nutrients (P). However no reductions in soluble nutrients or pesticides were noted.

INTRODUCTION

Filter strips are established areas of vegetation for removing sediment, organic matter, and other pollutants from runoff and waste water (SCS, 1984a). As runoff enters a filter strip, runoff flow velocity and transport capacity are reduced. Sediment and other pollutants are thus removed by filtration, deposition, infiltration, absorption, adsorption, decomposition, and volatilization (SCS, 1984a). Filter strips have been used to retain sediment and associated materials from agricultural fields (Aull, 1980), roadsides (Ohlander, 1976), irrigation return flows (Brockway, 1977), and strip mines (Barfield and Albrecht, 1982).

Flanagan et al (1986) compared CREAMS (Chemical, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980) performance with published filter strip data. These results indicated that the model adequately simulated the depositional processes occurring within a grass filter strip. Simulations with CREAMS to compare filter strip effectiveness on uniform, concave, or convex slope configurations indicated that soil loss was greater and filter strip effectiveness in reducing soil loss was less on convex slopes, while concave slopes had less soil loss and greater filter strip effectiveness (Williams and Nicks, 1988a). Further CREAMS simulations indicated that filter strips are more effective, trapping more sediment in less length, with sandy soils, while longer filter strips are required for clayey soils to obtain similar reductions in sediment transport (Williams and Nicks, unpublished data). When nutrients or pesticides are associated with the sediment portion of the runoff, some reduction takes place within the filter. However soluble nutrients and pesticides are generally unaffected.

Currently there are 2,776 contracts nationwide under the SCS's Conservation Reserve Program (CRP) covering 28,704 acres of land associated with filter strips. Water quality improvement is the major objective of setting aside acreage for this land use. To appraise projected water quality improvements due to the establishment of filter strips, a series of CREAMS computer model simulations were conducted. This paper presents some preliminary results.

METHODS

Random samples of filter strip sites by state were selected from contract periods 6 and 7 of the CRP filter strip program. Two hundred and thirty filter strip sites proportioned among 29 states were selected. Information on field size, crop rotations, management practices, slope, slope profile, soils, and filter strip size and vegetation type was obtained from the SCS field offices. Crop rotations and management practices were described with typical planting and harvest dates, as well as fertilizer and pesticide application rates and dates. All sites were assumed to have good productivity in order to estimate residue production, and residue management was included in parameter development. Rainfall, monthly mean air temperature, and solar radiation records were obtained for each site from the nearest weather station.

For all sites field size ranged between 1 and 80 ha, slope length ranged between 90 and 500 m, and the average slope was generally less than 5%; although a few sites did approached 20%. The crop rotations presented in Table 1 are fairly typical for all sites. Most tillage patterns were conventional; either a fall or spring plowing followed by disking, or in some cases a fall or spring chisel plowing followed by disking, and seedbed preparation. In other areas low or minimum tillage methods, or no-till methods were used. Soils ranged from sandy to clay soils, with erodibility (K-factor) ranging between 0.1 and 0.5. The most common filter strip length used was 30.1 m (99 ft). Grasses were typically used as the filtering media, or in some cases a mixture of grasses and legumes. A few sites had trees with grass ground cover. Although most sites were reported with good cover, a few sites had poor cover due to seeding failure or recent establishment of the strip. Since a poor cover condition is inadequate for sediment deposition (Williams and Nicks, 1988a), these sites were modeled with fair cover conditions.

CREAMS hydrology, erosion, and chemical (nutrient and pesticide) parameter files were created using the above information. The first series of simulations were made without the filter strip. Once the initial conditions were completed, the field was then simulated with the filter strip. We assumed that the filter strip vegetation was fully developed and erect, and that flow depth did not exceed the height of the vegetation. Filter strip length was considered as the flow length of the strip, and vegetation density was described as fair, good, or excellent corresponding to Manning's n of .032, .046, and .072, respectively, for overland flow. Each site was simulated as closely as possible to the actual field conditions. Thirty year simulations were made where possible; shorter time frames were used when rainfall records were incomplete.

RESULTS AND DISCUSSION

Simulated soil loss was reduced by 10 to 80% after the installation of the filter strip depending on the average slope, slope profile, and soil texture. However reductions between 30 and 70% were typical (Table 2). In a few cases simulated soil loss increased when the filter strip was installed and the vegetation in the strip provided insufficient cover for the slope conditions above the strip (see for example GA site 2, Table 2). This allowed material not only to move through the strip unchecked, it also enabled erosion to take place within the filter strip itself. Generally as the average slope increased, filter strip effectiveness in reducing soil loss decreased.

Slope profile also had an affect on filter strip effectiveness. Convex and convex-concave slopes generally displayed greater soil loss and less reduction in soil loss due to the presence of the filter strip. Earlier CREAMS simulations suggested that filter strips are more effective on uniform and concave slopes, and less effective on convex slopes and uniform slopes greater than 2.4% (Williams and Nicks, 1988a).

Interactions among soil texture, average slope, slope profile, the filter strip length to field length ratio, and runoff volume also affects, and complicates, the results. Filter strip effectiveness was increased on sandy soils since they were more easily deposited. This trend seems apparent when comparing the Georgia site 1 to the other location in Table 2. Soil loss is not effectively reduced by a filter strip during rainfall events with low runoff volume; the material most easily moved during low-flow events is the clay fraction of the soil which is difficult to trap within the strip.

When nitrogen and phosphorus were associated with the sediment in the runoff, filter strips reduced their loss in proportion to the soil loss (Table 2). However, when the nutrients were associated with the runoff water no reduction in concentration occurred (results not shown). Similar results were obtained in the pesticide simulations.

Strongly adsorbed pesticides were deposited with the sediment in the filter strip, slightly reducing pesticide loss. However, the majority of the pesticides in the study were soluble and associated with the runoff water and little, if any, reduction took place (results not shown). These results are supported by an earlier simulation study where 12 herbicides with various water solubilities were compared (Williams and Nicks, 1988b). Regardless of solubility, the majority of the herbicide loss was associated with the runoff water and herbicide loss was not reduced by the filter strip. Reduction is likely to take place only when the pesticide is strongly adsorbed to the soil.

The question of filter strip trapping of nutrients and pesticides is further complicated by particle size sorting within the strip. This preferential transport enriches the runoff with clay and silt which are more reactive and have a higher capacity for nutrient (P) and pesticide adsorption. Under these circumstances there may be a significant transport of nutrients and pesticides through the filter strip, in spite of a gross decrease in sediment transport.

CONCLUSIONS

Simulations presented here indicate that filter strips can reduce soil loss by 10 to 80%, with similar reductions of nutrients associated with sediment. The results are highly variable and the effectiveness of the filter strip is dependent upon soil, slope, slope profile, and vegetative cover within the strip. For maximum effectiveness, a filter strip should have the densest grass stand possible and the filter strip maintained in a good condition. It is also essential to have uniform flow throughout the filter strip; once the runoff becomes concentrated or channelized the effectiveness of the filter strip is greatly reduced. The simulations presented here assumed a uniform flow throughout the filter strip and that the flow depth did not exceed the height of the filtering media.

Even though filter strips reduce sediment and sediment associated materials, the effects on soluble materials is unclear. In most cases, unless the nutrient or pesticide is bound to the sediment particle, the material can pass through the strip unchecked. The question of nutrient and pesticide movement is further complicated by the enrichment of the runoff water as it passes through the filter strip. This results in the smaller more reactive particles, which are associated with nutrient and pesticide transport, passing through the strip. In most of the simulations, soluble nutrients and the majority of the pesticides were unaffected by the presence of a filter strip. Although filter strips did not control soluble materials, the simulated reduction in sediment and sediment associated materials improved the runoff water quality and they appear to be a simple and cost effective way to protect soil and water resources.

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Table 1. Descriptive information on selected filter strips sites.

		Field description						Soil description					Filter strip		
				Slope					Texture						
State	Site	Size	Ln[1]	Avg	profile[2]	Crop[3]	Tillage[4]	Name	Clay	Silt	Sand	K	Ln	Type[5]	Cover[6]
		(ha)	(m)	(%)					(%)				(m)		
OH	1	4	81	2.6	convex	c-s	low	Fulton	21	59	20	0.43	20	mix	good
	4	13	181	0.6	uniform	c-s-sg	conv	Latty	37	55	8	0.28	30	mix	good
IA	7	16	540	2.2	uniform	c	conv	Kenyon	22	48	30	0.28	20	mix	excel
	18	12	120	3.8	uniform	c-s	conv	Colo	23	74	3	0.28	30	grass	fair
IL	5	1	70	7.3	concave	c	low	Wellston	20	62	18	0.37	30	mix	fair
	27	28	330	.04	uniform	c-s	low	Wakeland	13	72	15	0.37	30	grass	good
KS	3	3	110	.03	uniform	w	conv	Ivan	21	64	15	0.32	30	grass	good
	11	7	120	5.3	vex/cav	s-w-w	conv	Mason	19	72	15	0.37	30	grass	good
GA	1	2	91	2.5	uniform	s	conv	Leefield	7	8	85	0.10	30	trees	good
	2	1	76	1.1	convex	s	conv	Stilson	5	14	81	0.10	30	trees	good

[1] Ln, length.

[2] vex/cav refers to a convex-concave slope profile.

[3] c, s, and w refer to corn, soybean, and wheat, respectively.

[4] conv refers to conventional tillage.

[5] Mix refers to a mixture of grasses and legumes.

[6] Fair, good and excellent cover represent Manning's n of .032, .046, and .072, respectively.

Table 2. Thirty year simulations of soil, nitrogen and phosphorus losses for fields with (w) and without (w/o) filter strips.

		Soil loss			Nitrogen loss			Phosphorus loss		
State	Site	w/o	w	RD[1]	w/o	w	RD	w/o	w	RD
		(Mg/ha)	(Mg/ha)	(%)	(g/ha)	(g/ha)	(%)	(g/ha)	(g/ha)	(%)
OH	1	36	10	71	211	59	72	137	40	72
	4	23	7	71	127	34	73	83	22	73
IA	7	59	15	75	284	83	71	184	54	71
	18	188	73	61	730	336	54	475	218	54
IL	5	48	28	42	175	112	36	114	73	36
	27	21	7	67	107	34	68	70	22	68
KS	3	3	2	33	20	11	45	13	7	46
	11	225	61	76	771	245	68	501	159	68
GA	1	89	14	84	384	72	81	250	51	80
	2	1	3	----	4	18	----	3	11	----

[1]RD refers to percent reduction.

RAINFALL SIMULATORS FOR WATER QUALITY RESEARCH

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ABSTRACT

Although less known, simulated rainfall has been used successfully to study water quality in addition to erosion and sediment transport. Rainfall simulators enable controlled experiments which increase our understanding of the basic processes of foliar-applied pesticide washoff, nutrient-sediment equilibria, nutrient leaching from plants and residues in cropland and forests, and nutrient and chemical transport by water and sediment to streams. This report cites examples that demonstrate the applicability of simulators to these areas of water quality research.

INTRODUCTION

A considerable need exists for assessing the impacts of land use practices on water quality. Much of the research directed at meeting this need is conducted on experimental watersheds, but using water quality analyses of streamflow alone often fails to provide sufficient information to formulate water quality protection measures. Natural environmental factors such as rainfall chemistry, intensity, and duration cannot be controlled. However, rainfall simulators can provide such control and are commonly used to determine basic information on erosion and hydrologic processes. In fact, the frequently-used USLE was developed at about the same time as the larger and better designed simulators (Meyer and Moldenhauer, 1985) which were used to provide data to refine the USLE. Simulators of many sizes have been employed for laboratory and small and large plot experiments and can largely be grouped into two broad categories: those involving nozzles and pressure and those using tips or needles to form drops. Meyer (1988) states that, for soil conservation research, the most important natural rainfall characteristics that need to be closely simulated are raindrop size distribution, raindrop impact velocity, and appropriate intensities. Simulation of these factors plus rainfall chemistry and temperature make simulators useful tools for other aspects of water quality research, as shown by examples cited in this report.

PLANT NUTRIENT STUDIES

Streamflow nutrient concentrations and yields typically vary among events or seasons. Simulator studies help identify the sources of variation by evaluating effects of environmental factors on nutrient flux from the plant canopy through plant residue to soil and runoff in cropland and forests. For example, using a rainfall simulator Sharpley (1981) found that, over a growing season, the P concentration in leachate from cotton, soybeans, and sorghum increased with plant age and soil water stress during 30-min events. In a series of studies (Schreiber, 1985; Schreiber and McDowell, 1985) simulators were used to determine that leachates of wheat and corn residues contained greater N, P, and C concentrations during the lower intensity simulated events and with greater residue amounts. In a forest, the needles, twigs, bole, and lichen in the canopy altered throughfall chemistry of simulated rain which had the ionic composition of summer rain (Reiners and Olson, 1984). A series of simulator studies demonstrated that rainfall intensity, duration, and temperature all influence N, P, and C leaching rates from loblolly pine (*Pinus taeda*) forest floor materials (Duffy *et al.*, 1985; Duffy *et al.*, 1989; Duffy and Schreiber, 1990; Schreiber *et al.*, 1990). Control of these variables at different levels allowed development of simple models relating changes in nutrient levels to changes in environmental factors.

At the soil surface nutrient transport is partitioned, some to overland and some to subsurface flow, with the amounts largely dependent on infiltration rates. Therefore, since simulators are especially useful in determining factors that control infiltration, they also help determine the route of nutrients to streams, as overland or subsurface flow. However, simulators are useful in evaluating other processes which occur at the soil surface and control nutrient flux and equilibria, factors which ultimately influence water quality. For example, in a simulator study raindrop impact was shown to markedly increase the transfer of chemicals from soil solution to surface runoff, with results suggesting that a ground cover would reduce transfer (Ahuja, 1990). Based on simulator experiments simple kinetic models were found to adequately describe P release from soil to runoff (Sharpley *et al.*, 1981a). In another study, soil was found to adsorb P from runoff (Sharpley *et al.*, 1981b). In a simulator study simple chemical extraction models were found to adequately explain the effects of storm pattern on NO_3-N in runoff (Flanagan and Foster, 1989). Movement of K and Cl was traced during prolonged irrigation (Talsma *et al.*, 1980). While water moved below 1.5 m in depth, K penetrated to 0.6 m and Cl to 1.0 m, indicating that immediate stream and groundwater contamination did not occur. In higher intensity simulated rain, surface runoff produced NO_3-N and some PO_4-P beyond root zones (Hubbard *et al.*, 1989a). Results from a simulator study suggest that soil features which slowed drainage also increased chemical loss in runoff (Ahuja and Lehman, 1983). Results cited here suggest that nutrient release and retention from vegetation and soils within rainfall events can be quantified through simulator experiments.

Nutrient sorption by suspended sediment is an important component of nutrient transport. Simulators are especially useful in providing information about source and size-distribution of soil aggregates (Line and Meyer, 1988; Meyer, 1986) and particulate carbon (Lowrance and Williams, 1988). Aggregate and particle size partially determine the capacity of sediment to transport sorbed organic and inorganic compounds and also influence the release of nutrients such as P to aquatic organisms (Dorich *et al.*, 1984).

Another advantage of simulator research is in evaluating proposed best management practices for water quality enhancement. For example, conservation tillage can greatly decrease total nutrient losses relative to other tillage practices (Mostaghimi *et al.*, 1988). Simulator research also showed that other practices, such as tracking (Abo-Abda *et al.*, 1986) and ridge tilling (Hamlett *et al.*, 1986), may reduce fertilizer loss and protect water quality. Simulator experiments have shown that grass filter strips were initially effective in trapping nutrients during shallow flow, but lost effectiveness when inundated by sediment (Dillaha *et al.*, 1989).

PESTICIDE STUDIES

Rainfall simulators are usually not designed with pesticide research in mind (Simmons, 1980). Many pesticide researchers consider a watering can sufficient for their needs, while others have modified commercial irrigation equipment for their studies. An exception was a simulator designed specifically for laboratory pesticide studies, which employed fixed nozzles, a series of fixed V-channels, movable shutters, and a moving trolley assembly containing the pesticide-treated soil/plant matrix (Simmons, 1984). Also Brockman *et al.* (1975) constructed a simulator for soil column pesticide leaching studies that was capable of accurately applying rainfall at intensities of <1 to 28 cm/h. These simulators allowed for the uniform delivery of water to many soil columns and trays of rooted plants over a wide range of natural rainfall intensities.

Some pesticide studies using rainfall simulation have dealt with the effects of simulated rainfall on pesticide bioactivity and transport. Pesticide bioactivity studies almost always involved herbicides with a weed/crop bioassay as a measure of bioactivity. These studies are considered water quality research in the sense that the herbicides are mobilized by simulated rainfall. For example, Anderson (1988) studied the preemergence herbicidal activity of diclofop using an oat root bioassay and simulated rainfall at various times after diclofop surface application and showed weed control required at least 25 mm of rainfall within 2-4 days of herbicide application. The rainfall simulator was a simple sprinkler can. Using a calibrated, automated greenhouse sprinkler, Bovey and Diaz-Colon (1969) found that 12.5 mm of simulated rainfall applied in 1 h generally reduced the phytotoxicity of several water-soluble formulations of herbicides compared with several oil-soluble herbicide formulations. In a field study using a specially-constructed rainfall simulator, Coultas and Harvey (1978) reported that excessive rainfall (38 mm), following preemergence buthidazole and metribuzin application, caused significant injury to shallower-planted corn compared with deeper-planted corn. They stated that the "rainfall simulator can add additional dimensions to field research, if an effective parameter can be found to measure crop injury and provisions are made in experimental design to accommodate natural rainfall." In a somewhat different herbicide bioactivity study (Pipe, 1987), simulated acid rainfall was reported to enhance trifluralin activity on a soil algal species.

The pesticide transport studies employing a rainfall simulator have basically involved applying simulated rainfall at a predetermined intensity/duration and time(s) after pesticide application and measuring the pesticide concentrations in runoff water (and transported sediment), percolating water, or foliage-washoff water. Baker et al. (1978) determined the effects of tillage systems on runoff losses of fonofos, alachlor, and cyanazine from small field plots subjected to 21.6 cm simulated rainfall. Sediment was the major carrier of fonofos and water was the major carrier of the herbicides. The higher herbicide concentrations in runoff from the conservation tillage plots were offset by the lower runoff volume and lower sediment loss. The surface runoff and percolation of cyanazine and sulfometuron-methyl from packed boxes (tilted to give 2% slope) of three soils placed under a rainfall simulator were reported by Hubbard et al. (1989b). For both compounds, percolation was the primary loss pathway from sand and loamy sand, whereas surface runoff was the primary loss pathway from sandy clay loam. Using a very similar tilted bed/rainfall simulator apparatus, Wauchope (1987) reported greater atrazine losses in runoff for dispersible granules and wettable powders (9-12%) than for emulsions and dispersible liquids (4-8%).

Rainfall simulators have proved to be very useful in determining the most important factors that affect pesticide movement from plant canopy to soil during rainstorms. Willis *et al.*, (1982) determined that total storm losses of toxaphene in runoff were independent of rainfall intensity and that equations could be derived relating toxaphene concentrations in runoff with runoff amount. The importance of rainfall amount, not rainfall intensity, on pesticide washoff from plants was also discovered for methyl parathion and EPN (McDowell *et al.*, 1984), permethrin (Willis *et al.*, 1986), and fenvalerate (McDowell *et al.*, 1987). This information greatly simplifies modeling pesticide movement from plant canopy to soil during natural rainstorms. In a similar simulator study, McDowell *et al.* (1985) compared the washoff losses of e.c. formulations of 3 insecticides from cotton. The resistance of methyl parathion residues to washoff increased with time after pesticide application, whereas the washoff of toxaphene and fenvalerate residues was relatively constant regardless of rainfall timing. This information could aid in determining insecticide respraying timing following natural rainfall or overhead irrigation.

SPECIAL WATER QUALITY STUDIES

Sediment from roadways, a special problem since road ditches can quickly deliver sediment and reduce stream water quality, has been evaluated with simulators (Ward, 1985). Simulators are a component of the Water Erosion Prediction Project evaluating sediment yields from forest roads (Foltz and Burroughs, 1990). Simulators are also a potentially valuable tool to gather baseline data to evaluate restoration of surface-mine spoils (Lusby and Toy, 1976), to evaluate release of heavy metals by dredge spoils to surface waters (Lee *et al.*, 1984) and to evaluate effectiveness of erosion control where construction exposes difficult-to-vegetate soils (Lee and Skogerbee, 1985). Within municipal areas simulators have been used to determine fertilizer losses in runoff from lawns (Kelling and Patterson, 1975) and washoff from street surfaces (Mustard *et al.*, 1987), losses that can move rapidly into surface waters.

In a biological study, coliform release in runoff was determined during simulated rain on cattle fecal material (Thelin and Gifford, 1983). Results indicated the potential for bacterial pollution and showed that released bacterial amounts declined with fecal material's age, information that could influence land management decisions.

SUMMARY

Rainfall simulators can be productively used in diverse ways to discover factors that contribute to water quality changes and variability but cannot be adequately evaluated in studies with natural rainfall. Potential effects on water quality of given combinations of rainfall characteristics and land use practices can be evaluated without long waits for natural occurrences. The capacity to closely replicate experiments provides a better understanding of the processes involved and aids modeling of relationships that may influence water quality. Examples cited show that rainfall intensity and temperature influence nutrient leaching and, potentially, water quality and that pesticides differ in response to rainfall. Experiments with natural rainfall may have attributed those differences to land use or practice. While simulator studies significantly contribute to the development of water quality protection measures, there are limitations. Extrapolation of simulator results to watersheds must be done with extreme caution. Also, in some of the cited examples, natural rainfall was not simulated well. If results are to be generally useful, as Meyer (1988) cautions, simulators must closely simulate natural rainfall.

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EFFECTS OF PARAMETER SELECTION ON SEDIMENT MODELING

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ABSTRACT

In the numerical modeling of river systems, a large number of parameters require value assignments to carry out computational tasks. The values of these parameters often lack rigorous verification and thus require value assignments based on heuristic knowledge of the systems. In this paper, the influence of parameter selection on numerical modeling of alluvial rivers is examined. The numerical experiments presented in this paper were conducted utilizing the U.S. Bureau of Reclamation's Generalized Stream Tube model for Alluvial River Simulation (GSTARS). The reported results are also applicable to a large group of sediment routing models using Exner-type sediment continuity equations.

INTRODUCTION

In the numerical modeling of river systems, a large number of parameters require value assignments to properly carry out the computational tasks. The values of these parameters often lack rigorous verification, and thus require value assignments based on heuristic knowledge of the systems. Due to a lack of regularity of real phenomenon and operating conditions in physical experiments, these parameters may assume a varying range of acceptable values. The uncertainties in approximating these values in engineering applications mandate the adoption of tolerances and safety factors in order to minimize risk of design failure. These tolerances or safety factors are often obtained by introducing parameter variability into the system and observing the change in the system's performance. This process is referred to as sensitivity analysis.

The general definition of sensitivity is the rate of change in an output factor with respect to a rate of change of an input factor. The input factors used in sensitivity analyses are grouped into two categories. The first category is input parameter values. The sensitivity analysis may aim toward seeking the variation of output according to variation in this category. The second category is theoretical formulations and equations. The selection of various formulations and equations for the solution of the problem may also be the target of sensitivity analysis.

If the sensitivity analyses indicate a low level of variation with respect to a certain input parameter or algorithm, then the simulation model user may choose tolerance or safety factors to reflect this observation. However, if the system outputs are very sensitive to variation in a parameter, the modeler may wish to reduce variability either by additional research (to obtain higher confidence in the value), or by introducing the appropriate tolerance or safety factor to compensate for the parameter uncertainty. Sensitivity information is therefore very important in the mathematical simulation of alluvial rivers since it can reduce the burden of additional costs associated with applying arbitrary tolerance or safety factors to all of the modeling variables. This information can also reduce modeling data requirements.

The alluvial river simulation model used for this paper is the U.S. Bureau of Reclamation's Generalized Stream Tube model for Alluvial River Simulation (GSTARS) (Molinas and Yang, 1986). GSTARS is a semi-two-dimensional water and sediment routing model which uses streamtubes in its computations. This model, unlike conventional sediment routing models, is capable of simulating a channel widening/narrowing process through the use of the minimum total stream power theory (Yang and Song, 1986).

The GSTARS model is composed of three major components: i) Water Routing; ii) Sediment Routing; and iii) Minimization Component. The water routing component of GSTARS is capable of computing continuous water surface profiles through sub-critical, super-critical, and a combination of both flow conditions involving hydraulic jumps.

In GSTARS, unsteady water inflow hydrographs into the study reach are approximated by bursts of constant discharges. For each burst of constant discharge, first the gradually varied water surface profiles are computed along the study reach. Secondly the stream tube locations across the channel are determined. Streamtubes used in GSTARS are hypothetical tubes bounded by streamlines. By definition, streamtubes carry a constant discharge along their length. For ideal fluids the total energy along streamtubes remains constant. However, for real fluids energy losses due to friction and local disturbances must be considered. GSTARS computes these energy losses by satisfying the gradually varied flow energy equation. For abrupt change of flow conditions from sub- to super-critical flows, the conservation of momentum equation is substituted for the energy equation to avoid the estimation of energy losses through hydraulic jumps. The sediment routing component of GSTARS utilizes the Exner-type sediment continuity equation. This component is coupled with a sediment armoring algorithm to predict long term river sedimentation behaviour.

The minimization component of GSTARS determines whether the channel adjustments at a given time step should proceed in the lateral or vertical directions. The mode of channel adjustment chosen by the model's stream power minimization algorithm is the mode which would result in the least amount of total stream power for the study reach.

MATHEMATICAL FORMULATION

In alluvial river simulation models, the objective function value can be described as a function of independent parameters

$$Y_o = F\left(x_1, x_2, ..., x_i, ..., x_n\right) \quad (1)$$

in which Y_o is the objective function value corresponding to a given base simulation parameter and x_i is the independent parameter. In GSTARS, the variations of water surface elevation and channel bed elevation are the objective function values. Roughness coefficients, time steps, sediment size distribution, etc. are the independent parameters.

The objective function value corresponding to a perturbed parameter (x_i) can be written as:

$$Y_i = F\left(x_1, x_2, ..., x_i + \Delta x_i, ..., x_n\right) \quad (2)$$

in which Y_i = objective function value; Δx_i = the perturbance of the parameter x_i. In this equation, the parameters other than x_i remain unchanged. Using the two equations given above, the coefficient of sensitivity can be formulated as:

$$\alpha_i = \frac{Y_i - Y_o}{Y_o} * 100\,(\%) \quad (3)$$

and

$$\beta_i = Y_i - Y_o \quad (4)$$

in which α = rate of change of the objective function value corresponding to variation (Δx_i) of the base simulation parameter; β = change of the objective function value.

Base Simulation

Parameters for the base simulation are mainly determined by data observed in the field in a certain event. In case of a lack of observed data, the base simulation may be determined based on physical model studies or heuristic knowledge of the project modelers.

Selection of Parameters

Parameters for sensitivity analysis may be selected depending upon the objectives of simulations, useful data, etc. The parameters used in sensitivity analyses of the sediment routing models can be grouped under two main categories: physical and operational parameters. These parameters are given in Table 1.

Limitation of Parameter Variability

For the physical parameters, parameter variability can be limited to the variations experienced in the natural or experimental channel. For the operational parameters, the limitation of the parameter variability can be chosen through analysis, based on the objectives of the model application. Factors which influence the determination of time step, for example, include simulation objective, accuracy required, computational speed of the computer, etc. The relative sensitivity of parameters can be found by varying each one by an equal percentage and comparing corresponding percentage changes in output.

Table 1 - Parameters used in sediment routing models.

Description of Data		Relative Importance of Data		
		High	Medium	Low
Physical parameters	Roughness coefficients	x		
	Sediment inflow	x		
	Water inflow	x		
	Variation of bed elevation		x	
	Sediment size distribution		x	
	Water temperature			x
	Cross-section geometry	x		
	Active layer thickness	x		
	Coefficients of losses			x
Operational parameters	Sediment transport equation	x		
	Time step duration	x		
	Number of stream tubes		x	
	Number of time iterations			x
	Stream power minimization			x
	Roughness equation	x		

APPLICATION

To study the sensitivity of GSTARS to various modeling parameters, a series of microcomputer runs were performed. For these runs a stable uniform reach of Rangpur Canal in Pakistan was chosen. Using the existing cross section and hydrologic data, various modeling parameters were altered. The computational results were analyzed with respect to the amount of variation in the base parameters chosen for sensitivity analysis. Tables 2 through 5 provide a partial list of the computer runs performed in the course of the sensitivity analysis. In these computer runs the effects of selecting the following parameters were studied:

- Roughness coefficient;
- Sediment transport equation;
- Duration of simulation time step;
- Number of stream tubes.

In addition to the computer runs given in Tables 2 through 5, a number of test runs to study the effects of selecting the active layer thickness and the boundary conditions were performed. In Tables 2 through 5, the test conditions used for comparison are referred to as "base conditions". Differences in computed results using the altered modeling parameters from their respective base values are presented as non-dimensional percentage variations whenever possible. In several test cases the computed scour/deposition values to be used as base conditions were very small. For these cases, since expressing other simulated scour/deposition values as percentage variations from the near-zero base values overamplified the importance of the parameter under investigation, deviations were presented as dimensional quantities.

Table 2 - Sensitivity analysis runs for roughness coefficient selection.

RUN NO.	DESCRIPTION
1 - 9	Effects of selecting Manning's n Roughness Coefficient on water and sediment routing results. [Using Yang's Sediment Transport Equation]
10 - 18	Effects of selecting Manning's n Roughness Coefficient on water and sediment routing results. [Using Ackers and White's Sediment Transport Equation]
19 - 27	Effects of selecting Manning's n Roughness Coefficient on water and sediment routing results. [Using Engelund and Hansen's Sediment Transport Equation]
* n = 0.02 used as a base condition for each Sediment Transport Equation; 3 stream tubes	

Table 3 - Sensitivity analysis runs for selecting duration of computational time steps

RUN NO.	DESCRIPTION
28	Duration of time step (days) = 0.125
29	Duration of time step (days) = 0.250
30	Duration of time step (days) = 0.500
31	Duration of time step (days) = 2.000
32	Duration of time step (days) = 4.000
33	Duration of time step (days) = 5.000
34	Duration of time step (days) = 6.000
35	Duration of time step (days) = 10.00
36	Duration of time step (days) = 20.00
* 1 day is used as a base condition with Yang's equation and Manning's coefficient of 0.02; 3 stream tubes	

Table 4 - Sensitivity analysis runs for longer time (1.5- and 8-year) simulations

RUN NO.	DESCRIPTION
37	Number of time steps = 480 and duration of each time step is 1 day.
38	Number of time steps = 480 and duration of each time step is 6 days.
*Using's Yang's equation and Manning's n coefficient of 0.02; 3 stream tubes	

Table 5 - Sensitivity analysis runs for number of stream tubes selection

RUN NO.	DESCRIPTION
39	Water and Sediment Routing using 1 stream tube
40	Water and Sediment Routing using 2 stream tubes
41	Water and Sediment Routing using 4 stream tubes
42	Water and Sediment Routing using 5 stream tubes
*3 stream tubes condition used as a base condition, using Yang's equation and Manning's coefficient of 0.02	

The results of sensitivity analysis are presented in Figures 1 through 4. Figure 1 demonstrates the effects of varying roughness coefficients and sediment transport equations. In this analysis for each of the three sediment transport functions available in the model, 9 runs were performed for a total of 27 computer runs. The Manning's roughness coefficients were altered from 0.005 to 0.05. The base condition for the computer runs was chosen as n = 0.020. Sediment routing computations were conducted using three stream tubes and a single sediment size group of 0.125 mm - 0.250 mm. In Figure 1, the scour/deposition of cross sections 6,000 ft, 7000 ft, 8000 ft, and 10000 ft downstream

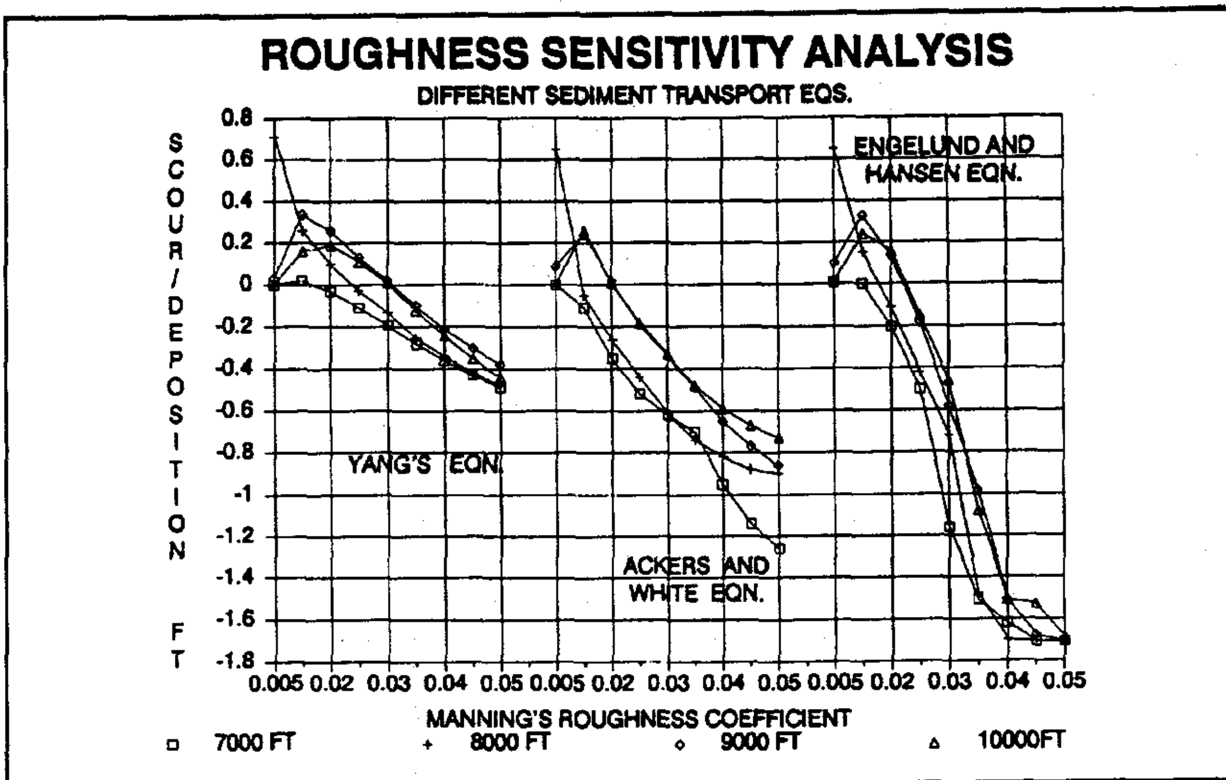

Figure 1 - Roughness sensitivity analysis

from the canal entrance were plotted for various roughness values. These scour/deposition values correspond to computations utilizing 60 time steps of one-day duration. Results from the analysis are summarized as:

- Varying the channel roughness coefficient alters the computed scour and deposition significantly.
- Selecting different sediment transport equations for simulations has a significant effect on model results.

These conclusions are illustrated in Figure 1 by the significant variance of the computed scour/deposition with respect to the selection of the sediment transport equation. While Manning's roughness coefficient n was kept constant at $n = 0.02$, at Station 8000 ft the Ackers & White equation predicts 0.27 ft of scour and the Engelund & Hansen equation predicts 0.15 ft of scour. On the other hand, Yang's equation predicts 0.1 ft of deposition. Similar results can be obtained throughout the entire range of roughness values. For sensitivity analysis of other computational parameters, Yang's sediment transport equation was used for the computations.

Figure 2 demonstrates the sensitivity of sediment routing computations to the duration of the time step utilized in numerical computations. The conclusions from this figure are:

- Proper selection of length of computational time step is necessary for the convergence of results. For time steps of between 0 and 3 days, computed results are almost identical to the base run with a time step of 1 day. For time step durations larger than 10 days, the discrepancies with the base condition of a one-day time step increase significantly.
- Since the finite difference scheme used for approximating the sediment continuity equation is an approximation method, the accuracy of the results rely on the duration of time step even within the stable range.
- Proper selection of simulation time step should be made following a sensitivity analysis.

Figure 3 demonstrates the sensitivity of computed results to the number of stream tubes selected for the GSTARS simulation. The computer runs for studying the stream tube sensitivity were performed using one-day time steps and a single sediment size. The scour depths shown in Figure 3 pertain to thalweg elevations. The analysis presented in this paper was based on point values rather than total sediment volume removed from the study reach. Figure 3 demonstrates the computed scour depths at various locations along the study reach for one, two, three, four, and five stream tubes. Figure 3 shows that the number of stream tube selected is not a factor in scour depth computations. This is highly desirable since the stream tubes are merely utilized to obtain the variation of flow conditions across the channel for higher model output resolution. Figure 4 shows the variation of execution times with the number of stream tubes selected for the GSTARS simulation. For a single sediment size, the computation times are only 8 percent higher for simulations using five stream tubes than simulation runs with only one stream tube. This indicates the computational efficiency of the GSTARS' stream tube computations.

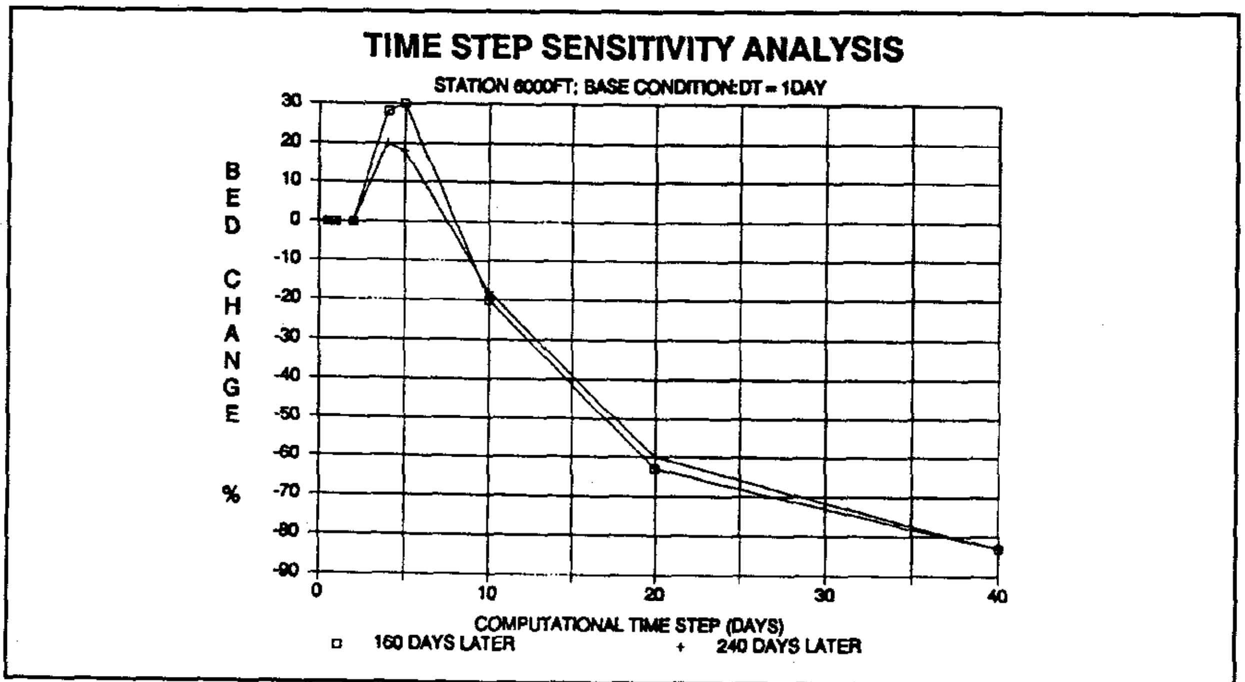

Figure 2 - Time step sensitivity analysis at Station 6000

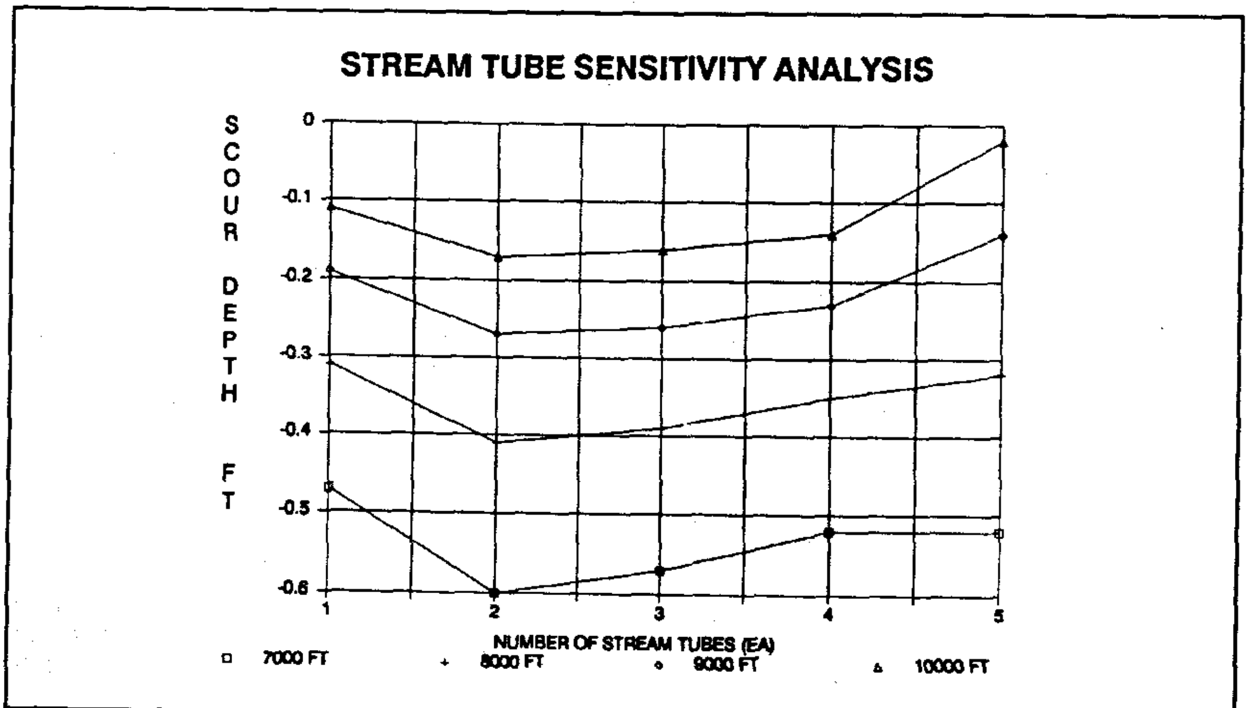

Figure 3 - Scour/deposition versus number of stream tubes

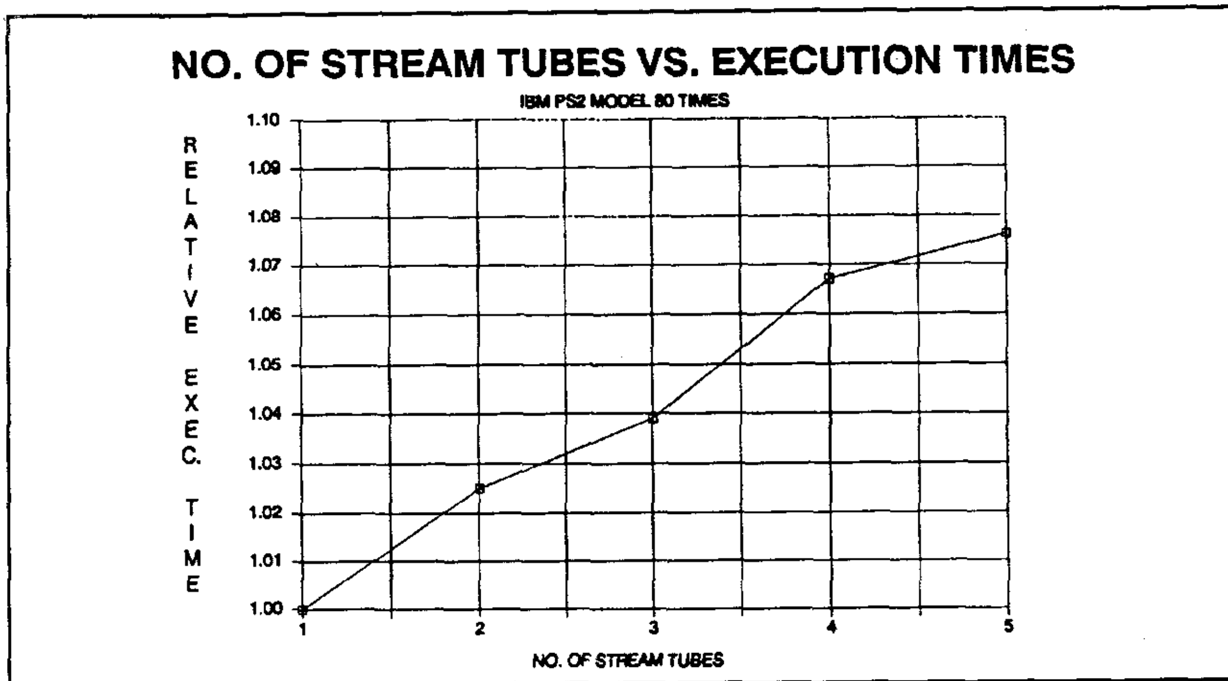

Figure 4 - Execution times versus number of stream tubes

CONCLUSIONS

The sensitivity analyses of the parameters used in the GSTARS for simulation of a stable uniform reach of the Rangpur Canal in Pakistan reached the following conclusions:

1. The magnitude of scour or deposition at a given cross-section is sensitive to the selection of sediment transport equation and Manning's roughness coefficient.
2. Proper selection of computation time step based on sensitivity analyses is important to the accuracy and convergence of the computational results.
3. The computed average depth of scour is not sensitive to the selection of number of stream tubes.
4. The increase of number of stream tubes used in the computation does not increase the computational time significantly.

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