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ESTIMATING SEDIMENT YIELD FROM CULTIVATED FIELDS

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ABSTRACT

The erosion/sediment yield component of CREAMS, a field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems, estimates erosion and sediment yield from agricultural fields. The model uses fundamental erosion concepts to describe erosion, deposition, and sediment transport by overland flow and concentrated flow, and deposition in small ponds. Sediment yield is computed for particle classes ranging from primary clay to large aggregates. An enrichment ratio is computed as the ratio of the specific surface area of the sediment to that for the residual soil. Use of tested relationships reduced the need for calibrating the model with site-specific data. Sediment yield computed without calibration of the model agreed well with observed values for several small watersheds. Model application was demonstrated with two field situations.

INTRODUCTION

Models can be useful in selecting management practices to control erosion and sediment yield from cultivated fields as demonstrated by two decades of use of the Universal Soil Loss Equation (USLE) by the USDA-Soil Conservation Service (SCS). The SCS works directly with farmers in applying the USLE to specific situations to evaluate practices, which generally results in a plan for adequately controlling erosion that is acceptable to the farmer. Similarly, practices to control sediment yield from farm fields can be evaluated with a model like CREAMS. An overview of the erosion/sediment yield component of the model, its validation, and its application to two examples are discussed. Complete details on the component are given by Foster et al. (3).

OVERVIEW OF EROSION/SEDIMENT COMPONENTS OF CREAMS

CREAMS is a field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems (7). It has components for hydrology and movement of nutrients and pesticides, in addition to the one for erosion/sediment yield.

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Requirements for Erosion/Sediment Yield Component:

(1) The model should apply to many practices, including conservation tillage, crop rotations, double cropping, contouring, stripcropping, terraces, and grassed waterways. Also, it should consider topographic factors like concave slopes, backwater at field outlets, and erosion in natural waterways. (2) Both absolute and relative estimates for a specific practice and site should be reasonably accurate. (3) Parameter values should require little or no calibration. (4) Selecting parameter values and running CREAMS should be relatively easy for the user. (5) The model should operate inexpensively for a 20-year storm record and compute monthly and annual totals from estimates for individual storms.

Basic Relationships:

The model computes detachment, sediment transport and deposition on a storm-by-storm basis using rainfall erosivity, runoff volume, and a characteristic runoff rate for each storm. Quasi-steady flow is assumed. Sediment is routed through overland flow and concentrated flow areas. Calculations are performed step by step, moving downstream segment by segment.

The basic equation in the model, which is for coninuity, is given by

$$dq_s/dx = D_L + D_F \tag{1}$$

where q_s = sediment discharge (mass/unit width/unit time), x = distance, D_L = rate of lateral inflow of sediment (mass/unit area/unit time), and D_F = rate of detachment or deposition by flow (mass/unit area/unit time). When Eq. 1 is applied to overland flow, D_L is the rate of interrill detachment, and D_F is the rate of detachment by rill erosion or the rate of deposition by overland flow. When Eq. 1 is applied to concentrated flow, D_L is the rate of inflow of sediment from overland flow, and D_F is the rate of detachment or deposition by the flow.

Rate of deposition is given by

$$D_d = \alpha\ (T_c - q_s) \tag{2}$$

where D_d = rate of deposition, α = a first-order reaction-coefficient (length^{-1}), and T_c = transport capacity of the flow (mass/unit width/unit time). The reaction coefficient α is given by

$$\alpha = a\ V_s/q \tag{3}$$

where a = 0.5 for overland flow and 1.0 for concentrated flow, V_s = fall velocity of a sediment particle class, and q = rate of runoff (volume/unit width/unit time). Rate of runoff is assumed to be directly proportional to upslope contributing area. Peak discharge, computed at the watershed outlet by the hydrology component of CREAMS, is used as the characteristic discharge for the storm.

The shear stress acting on the soil is responsible for sediment transport by overland and concentrated flow and detachment by concentrated flow. The distribution of total shear stress between cover, such as mulch or vegetation, and the soil is estimated using sediment transport theory (6). Flow velocity and depth is estimated with Manning's equation. Yalin's (19) equation was modified to estimate sediment transport capacity for nonuniform sediment. The modified equation distributes transport capacity according to particle size and density, hydraulics of flow, and availability of each particle class in the sediment load (2). If transport capacity for a particle class exceeds its load, the excess shifts to other classes where transport capacity is less than sediment load. The model accommodates up to ten particle classes.

Sediment detached from agricultural soils is usually composed of both aggregates and primary particles. Aggregates, conglomerates of primary particles and organic matter, have specific gravities less than 2.65 and may be much larger than the primary particles composing them. Particle distribution at detachment depends on soil properties and previous management. The particle relationships in CREAMS were developed from data and analysis provided by R. A. Young, USDA-SEA-AR, Morris, Minnesota.

Particle specifications are for the sediment as it is detached. When deposition occurs, the model computes redistribution of the particle classes and enrichment of fines. An enrichment ratio is computed as the ratio of specific surface area of the sediment and organic matter to that of the residual soil.

Representation of Hydrologic Elements:

Hydrologic elements of overland flow, concentrated flow, and impoundments represent the watershed, as illustrated in Fig. 1. A single element or a combination of elements is selected that best fits the specific situation.

Overland Flow. Slope length, average steepness, steepness at the upper and lower ends, and coordinates of a miduniform section are used by the model to construct a representative concave, convex, or complex slope shape. Uniform sections of a slope are a single segment. Convex and concave sections are divided into three and ten segments, respectively. Greater resolution is required where deposition might occur.

Interrill detachment rate D_i (mass/unit area/unit time) is given by

$$D_i = 4.57\ EI\ (s + 0.014)\ KCP\ (\sigma_p/V_u) \qquad (4)$$

where EI = storm erosivity (energy times maximum 30-minute intensity), s = sine of the angle of the slope, K = soil erodibility factor, C = soil loss ratio, P = contouring factor, σ_p = characteristic runoff rate (volume/unit area/unit time), and V_u = volume of runoff per unit area. The parameters K, C, and P are from the USLE (18).

The equation for rill detachment rate D_r (mass/unit area/unit time) is

$$D_r = (6.86 \times 10^6) m\ V_u\ \sigma_p^{1/3} (x/\lambda_u)^{m-1} s^2\ KCP\ (\sigma_p/V_u) \qquad (5)$$

where m = slope length exponent, x = distance downslope from the origin of overland flow, and λ_u = length of the USLE unit plot. The ratio (σ_p/V_u) converts an amount of detachment for a storm to an average detachment rate for the storm.

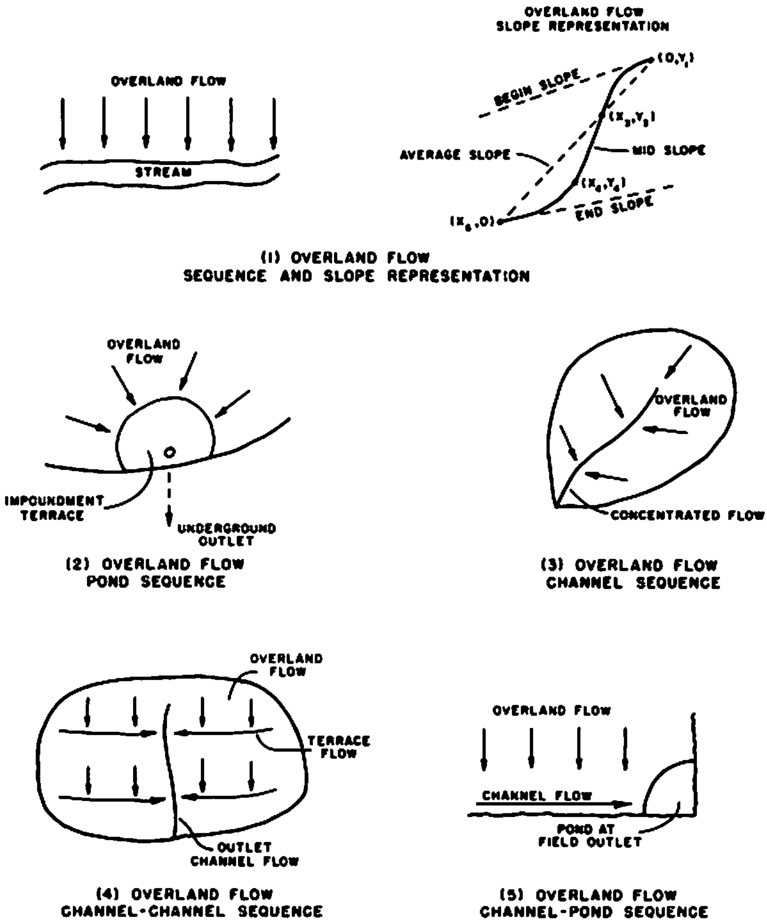

FIG. 1.—SELECTION OF HYDROLOGIC ELEMENTS TO REPRESENT TYPICAL FIELD SYSTEMS

Concentrated Flow. The concentrated flow element describes erosion and sediment transport in natural and grassed waterways, terrace channels, and diversions. Obstructions at field outlets can cause backwater and subsequent deposition. The spatially varied flow equation for increasing discharge was normalized and solved for a range of discharge rates, channel slopes, Manning's n, and outlet control depths. Third-order polynomials were fitted to give friction slope as a function of distance along the channel.

Runoff on a recently prepared seedbed with tillage across natural waterways may cause much erosion in the waterways. Detachment rate for this erosion is given by

$$e_{ch} = K_{ch} (\tau - \tau_{cr})^{1.05} \quad (6)$$

where e_{ch}= detachment rate at a point around the wetted perimeter of the channel (mass/unit area/unit time), K_{ch} = soil erodibility factor for erosion of tilled soils by flow, τ = shear stress at a point around the wetted perimeter of the channel, and τ_{cr} = critical shear stress.

Once the channel erodes to a nonerodible layer which may be at the depth of secondary or primary tillage, the channel stops eroding downward and begins to widen. As the channel widens, erosion rate decreases. Therefore, erosion by concentrated flow is a function of the amount of previous erosion after the channel reaches a nonerodible layer. Erosion rate is given by an exponential function of the difference between current channel width and the final channel width that the channel reaches for continuous discharge at the given slope, roughness, and critical shear stress. Tillage resets the channel to its original condition.

Variation in slope, Manning's n, critical shear stress, and depth to a nonerodible layer along the channel and variation of critical shear stress over the year can be considered. Critical shear stress is lowest right after tillage at planting and increases as the soil consolidates over time without tillage.

Impoundment. The impoundment element describes deposition behind impoundment terraces and similar structures that drain after each storm through a pipe where discharge rate is controlled by an orifice. Deposition behind ridges and other weir-like structures is estimated with the backwater relationships for concentrated flow. The fraction of a given particle type discharged from the impoundment is given by

$$f_i = Ae^{-Bd_i} \quad (7)$$

where f_i= fraction discharged of particle type i, and d_i = sedimentation diameter of particle type i. Coefficients A and B are related to geometry of the impoundment, orifice coefficient, infiltration rate through the impoundment boundary, and runoff volume (3).

VALIDATION

Validity of the model was studied by comparing output from the model with observed data for several situations.

Overland Flow:

The equations for detachment on overland flow areas were tested for runoff plots under natural rainfall (12) and for a 30-ha watershed in continuous corn at Treynor, Iowa (4, 15). The Yalin equation was selected to compute transport capacity of overland flow after testing several sediment transport equations (14). The model accurately computed the particle distribution of sediment from simulated rainfall on concave plots and plots with mulch and grass strips at their ends (5).

Erosion by Concentrated Flow:

The concentrated flow relationships adequately described erosion rate and widths of rills when they were restricted by a nonerodible layer (10). The relationships also accurately estimated widths for stream channels, an indication that they are good estimators of final channel widths. Therefore, when channels erode to their final widths, estimates of total erosion should be reasonably accurate. Estimates of the soil loss for individual storms are less accurate.

Sediment Yield from Terraces:

Sediment yield was simulated without calibration of the model for eight years of data from four small, single-terrace watersheds at Guthrie, Oklahoma (1). Sediment yield from the terraces was a function of both erosion on the overland flow area and erosion and deposition in the terrace channel. The model performed adequately, as Table 1 shows.

TABLE 1.—COMPARISON OF SIMULATED SEDIMENT YIELD FROM SINGLE TERRACE WATERSHEDS WITH MEASURED VALUES

Terrace	Grade	Sediment Yield Observed (kg/m^2)	Sediment Yield Simulated (kg/m^2)
2B	Variable, 0.0033 at outlet to 0 at upper end.	12.2	6.4
3B	Variable, 0.005 at outlet to 0 at upper end.	13.8	11.9
3C	Constant, 0.005	12.1	10.6
5C	Constant, 0.0017	4.8	4.6

Sediment Yield from Impoundment Terraces:

The equations for deposition in impoundment terraces were developed from extensive field tests and modeling studies (8, 9). CREAMS was used to simulate erosion on overland flow areas draining into and sediment yield leaving impoundment terraces at three locations in Iowa. The simulation results shown in Table 2 were without calibration for several widely varying storms. The results were considered acceptable because the means of the observed and simulated data were close if storm 70147 is ignored at Charles City even though individual values differed significantly for several storms. J. M. Laflen, USDA-Science and Education Administration, Ames, Iowa provided field data and assisted with these simulations.

Sediment Yield from a Small Agricultural Watershed:

Simulations were made without calibration for 30 months of data for a 1.3-ha watershed at Watkinsville, Georgia in conservation tillage for corn (16). The computed sediment yield passing through the flume for the period of record was 1.5 kg/m^2, whereas 1.8 kg/m^2 was measured. Measured deposition in backwater at the flume nearly equaled measured sediment yield that passed through the flume on a similar nearby watershed (11). The model adequately represented deposition in backwater as well as erosion upslope in the concentrated flow area and on the overland flow areas.

TABLE 2.—SUMMARY OF OBSERVED AND SIMULATED SEDIMENT YIELD FROM IMPOUNDMENT TERRACES IN IOWA

Watershed	Area	Julian Date	Sediment Yield	
			Observed	Simulated
	(ha)	(Yr-Day)	(kg)	(kg)
Charles City	1.9	70147	542	24
		70152	33	6
		70244	2	72
		70323	26	2
		71151	127	133
		71157	95	72
Eldora	0.73	68198	128	68
		68220	26	25
		69187	479	251
		69232	56	103
		71163	152	63
Guthrie Center	0.57	69207	116	124
		69249	10	40
		70144	55	29
		70162	90	56
		70167	10	13
		70229	5	24

APPLICATION

Application of the model is illustrated with two examples. Universal effectiveness or acceptability of particular practices is not implied, because both absolute and relative effectiveness are site specific.

The first example is a 1.3-ha Georgia Piedmont watershed typical of within-field watersheds. The second, a Mississippi Delta field, represents a special application of the model. Storm EI, runoff volume, and peak rate of runoff were estimated from daily rainfall using the hydrology component of CREAMS (17). Rainfall and other required hydrologic data were measured by the USDA-Science and Education Administration at Watkinsville, Georgia for the Georgia Piedmont example and at Clarksdale, Mississippi for the Mississippi Delta example.

Georgia Piedmont:

The first step in applying the model is to identify the watershed boundary and concentrated flow area from a contour map (Fig. 2). An overland flow element and a concentrated flow element were used to represent the watershed. Parameter values for ten overland flow paths around the watershed were averaged for a representative overland flow path. Flow at the watershed outlet was assumed to be restricted,

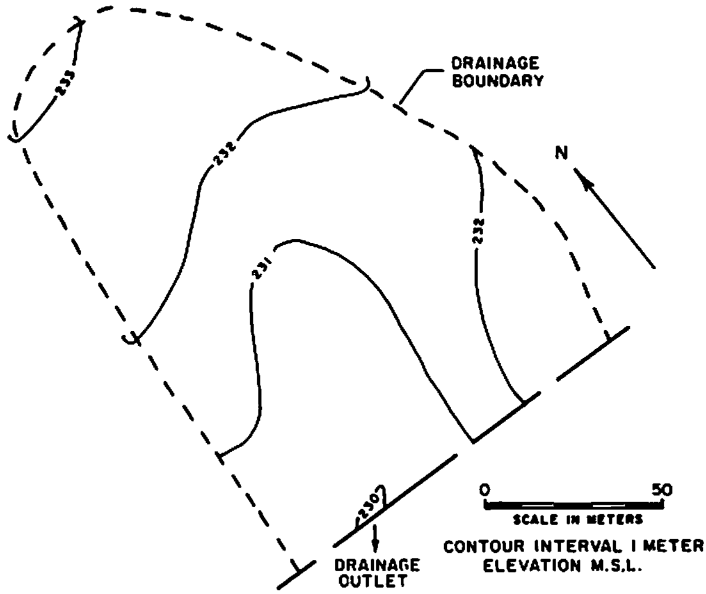

FIG. 2.—CONTOUR MAP FOR WATERSHED IN THE GEORGIA PIEDMONT EXAMPLE

causing backwater. A stage-discharge relationship (rating curve), was assumed for the outlet control.

Five practices for continuous corn were analyzed. Normally, a wide variety of practices would be analyzed so that the farmer can select from several, one practice that he prefers and that controls sediment yield.

Simulation results shown in Table 3 indicate the factors affecting erosion and sediment yield at this site. Deposition occurred with Practice 1 since the enrichment ratio, ER, of 1.8 is greater than 1.0. If the model computes no deposition, ER is 1.0. Deposition was on the toe of the concave overland flow slope, but most was in backwater immediately above the watershed outlet. Upstream from the backwater, the natural waterway eroded.

A grassed waterway, Practice 2, eliminated erosion by concentrated flow in the previously unprotected waterway, and caused deposition of some of the sediment eroded on the overland flow area. The increase in ER from 1.8 to 2.7 resulted from increased deposition. Fines were not reduced in the same proportion as sediment yield (SY), because ER increased. The product of SY and ER, a relative measure of both sediment yield and specific surface area, indicated sediment's carrying capacity for soil-adsorbed chemicals.

Deposition in and at the edges of the grassed waterway would cause maintenance problems and should be reduced by reducing erosion on the overland flow area. The chisel plow conservation tillage system, Practice 3, provided that reduction, which would also help to maintain soil productivity.

TABLE 3.—ANALYSIS OF SEVERAL FARMING PRACTICES FOR THE EXAMPLE GEORGIA PIEDMONT WATERSHED

Practice	Sediment Yield (SY)[a]	Enrichment Ratio (ER) Based on Specific Surface Area	Product SY·ER
	(kg/m^2)		(kg/m^2)
1. Continuous corn, moldboard plow, disk, cultivate, unprotected waterway.	1.55	1.8	2.8
2. Same as (1), except grassed waterway.	0.54	2.7	1.4
3. Same as (1), except chisel plow, no cultivation, and a grassed waterway.	0.27	2.3	0.6
4. Same as (1), except terraces on a 0.2% grade, and a grassed outlet channel.	0.38	2.8	1.1
5. Same as (1), except impoundment at lower end of unprotected waterway.	0.16	4.2	0.7

[a]Total for approximately 20 months of record.

Instead of conservation tillage, the farmer may prefer conventional tillage with conventional terraces, Practice 4, and a grassed outlet channel. Sediment yield was reduced by 75%, but ER increased because of considerable deposition in the terrace channels and in the grassed outlet channel. Another possibility was an impoundment terrace, Practice 5, which further reduced sediment yield, but greatly increased ER. The resulting SY·ER was as high as that for Practice 3 where SY was 1.7 times that of Practice 5.

As expected, enrichment ratio increased as sediment yield decreased, but in a scattered fashion. Furthermore, the relationship may be quite different for other situations, as the other example will show.

Mississippi Delta:

Row ridges and furrows from bedding direct runoff along the rows to a field drain (Fig. 3). Each furrow is a small channel, and the side slopes of the row on either side of the furrow are the overland flow areas for a small watershed. Hydrologic elements of overland flow and concentrated flow were selected to represent these small watersheds, and a concentrated flow element was used to represent the field drain. Having separate equations for rill and interrill detachment permitted analysis of the row side slopes as overland flow areas, which would have been impossible with an equation having rill and interrill erosion combined.

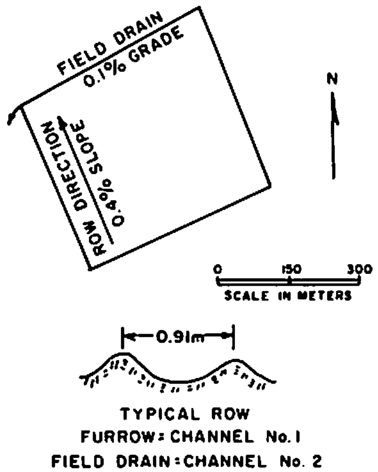

FIG. 3.—REPRESENTATIVE FIELD, MISSISSIPPI DELTA

Sediment yield was significant with conventional management, Practice 1 (Table 4). The estimated sediment yield for the first year of record was 2.8 kg/m^2 compared with 2.9 kg/m^2 measured by Murphree and Mutchler (13) for a similar rainfall on a similar watershed. Enrichment ratio was high because of deposition in the row furrows. Little deposition occurred in the field drain because sediment reaching the ditch was fine and not easily deposited.

Practice 2, no fall tillage with winter cover and a grass buffer strip at the end of the rows, reduced sediment yield by about 38%. The buffer strip did not greatly reduce sediment yield because most of the sediment reaching the strip was fines; however, the increase in ER from 2.5 to 2.7 reflected some deposition in the strip. Winter cover reduced detachment over the winter months, but the soil was still bare between the start of repeated spring tillage which buried winter cover and the development of a plant canopy.

Limited spring tillage, Practice 3, did not reduce sediment yield much further. Complete destruction of soil cover by spring tillage left the soil critically exposed to raindrop impact for a period before a plant canopy developed.

TABLE 4.—ANALYSIS OF THREE FARMING PRACTICES FOR THE EXAMPLE MISSISSIPPI DELTA WATERSHED

Practice	Sediment Yield (SY)[a]	Enrichment Ratio (ER) Based on Specific Surface Area	Product SY·ER
	(kg/m^2)		(kg/m^2)
1. Continuous cotton, fall tillage, multiple spring tillage, and grassed field ditch.	3.55	2.5	8.9
2. Same as (1), except no fall tillage, winter cover, and 6 m grass buffer strip along edge of field.	2.20	2.7	5.9
3. Same as (2), except limited spring tillage.	1.95	2.8	5.5

[a]Total for 36 months of record.

SUMMARY AND CONCLUSIONS

An erosion/sediment yield model for agricultural fields was developed with components for overland flow, concentrated flow, and small impoundments. It operates on a storm-by-storm basis using rainfall erosivity, runoff volume, and a characteristic runoff rate. Sediment is routed downslope using equations for continuity, detachment or deposition, and sediment transport capacity. Sediment is assumed to be composed of both primary particles and aggregates. The model computes an enrichment ratio based on specific surface area of primary particles and organic matter, composition of the aggregates, and computed particle distribution of the sediment load.

Use of tested relationships reduced calibration requirements for the model. Estimated sediment yield compared favorably with measured values.

Application of the model was demonstrated by two examples. For specific situations, the model identifies important erosion processes, provides information on total sediment yield, yield of particular sediment fractions, and enrichment ratio, and it can guide the selection of management practices to control erosion and sediment yield. The model applies to many practices including conservation tillage, crop rotations, conventional and impoundment terraces, stripcropping, and grassed waterways. Also, the model can consider slope shape, backwater at field outlets, and erosion in natural waterways. Selection of parameter values is straightforward.

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