W. H. WISCHMEIER and L. D. MEYER, Purdue University,
West Lafayette, Indiana

SOIL ERODIBILITY ON CONSTRUCTION AREAS

Forty years of research in the U. S. Department of Agriculture has identified the major factors in soil erosion and established their functional relationships to soil loss. The relationships were combined in an empirical erosion equation that is now widely used on farmland and can be adapted to sediment prediction and erosion control planning on construction areas. Soil erodibility is one of the six major factors that determine soil-loss rate at a particular site. In this narrow sense, the term denotes the inherent susceptibility of a soil to detachment and transport by rainfall and runoff. Results of an intensive field, laboratory, and statistical study of the relations of soil properties and interactions to a soil's erodibility are briefly summarized in the report. Use of the soil-erodibility factor and the erosion equation to predict construction-site sediment yields is illustrated. The other factors in the equation evaluate effects of rainfall pattern, slope length, slope steepness and shape, cover and management, and conservation practices. They are interpreted relative to construction-site conditions, and sources of information for their locality evaluation are discussed. Recent tests of cover and management effects on construction sites are reviewed.

Soil erosion by water is a complex process that involves the interrelations of many factors. Some of these influence the capability of the erosive agents, rainfall and runoff, to detach and transport soil material. Others influence the ability of the soil to resist the forces of the erosive agents. Extensive research by the U. S. Department of Agriculture and land-grant universities has identified the major factors that influence soil erosion and has established functional relationships of soil, rainfall, topography, cover, and management to soil loss.

The term soil erodibility has several possible connotations. At the Agricultural Research Service (ARS), it has been used to denote the relative susceptibility of different soils to erosion when other factors are essentially equal. By this interpretation, erodibility is a function of soil properties only and, therefore, a soil parameter. On the other hand, expressions such as soil erodibility on a construction area are more likely to connote the expected soil-loss rate or sediment yield from a particular site. To predict erodibility in this broader sense requires that the effects of local rainfall pattern, slope length, slope steepness, land cover, and management practices be evaluated along with the soil factor.

This report will consider soil erodibility in the narrower sense, as a function of soil properties, but will also discuss its role as one of six major factors that combine to determine the amount of soil eroded from a particular site.

The factor relationships were derived from statistical analyses of soil loss and associated data obtained in 40 years of research by ARS and assembled at the ARS runoff and soil-loss data center at Purdue University (11). The data include more than a quarter-million runoff events at 48 research stations in 26 states, representing about 10,000 plot-years of erosion studies under natural rain. They also include supplemental data obtained with rainfall simulators (4) on field plots and from fundamental studies in the laboratory.

Several developments at the ARS data center have provided convenient working tools for farmland erosion control planning that can be adapted to conditions at the construction site as well. These developments include (a) a new rainfall-erosivity index EI, (b) a more informative parameter to describe soil particle-size distribution, (c) a soil-erodibility nomograph, (d) a slope-effect chart, (e) a technique for evaluating cover and management effects in relation to specific rainfall patterns, and (f) the universal soil-loss equation. The first five developments were incorporated in the sixth.

ERODIBILITY AS A SOIL PARAMETER

The dimensional soil factor K, derived for the universal soil-loss equation (17), is usually expressed in tons per acre per unit of rainfall EI, under conditions of 9 percent slope 72.6 ft long, continuously fallowed. (EI is defined later.) The K-value for a particular soil can be obtained directly from soil-loss data and is independent of geographic orientation. For the major soils on which the erosion plot studies were located, K ranged from 0.30 to 0.69. The more than 20-fold range in its magnitude emphasizes the importance of the soil factor in gross sediment prediction. Empirically determined, K combines the effects of the soil's water intake capacity and its susceptibility to detachment and transport by rainfall and runoff.

ARS recently conducted an intensive study of the relation of a soil's erodibility to its physical and chemical properties. Rainfall simulators were used in three physiographic regions to apply identical rainstorms to identically prepared, fallowed field plots on widely differing soils. The experimental design allowed interactions between soil parameters to exert their normal influence on the measured erodibilities. Topographic and surface-condition variables were measured, and the soil profile was described at each test site. Physical and some chemical properties of each soil were determined by standard laboratory methods (16). Regression analyses were used to explore the relative predictive capabilities of numerous soil properties individually and collectively. Terms to evaluate the effects of various factor interactions were included in the regression models.

A 24-term equation, derived from data for 55 widely varying Corn Belt soils, accounted for 98 percent of the variance in observed K-values (16). The equation did not fully meet the requirements of a field working tool, but it showed some interesting factor interrelationships that influence the erodibility of a soil. Some of them will be discussed later. Further exploratory analyses, which included five additional soils, resulted in development of new relationships that were combined in the soil-erodibility nomograph shown in Figure 1 (15). The nomograph is a convenient tool for graphical computation of the erodibility of a specific topsoil or subsoil horizon.

Factor Relationships That Influence a Soil's Erodibility

Standard textural classes as defined in the USDA Soil Survey Manual (9) were poorly correlated with soil erodibility. Soils classified as silt loams, for example, ranged all the way from moderately to very highly erodible. Mechanical analysis data, based on the USDA classification system, accounted for less than 25 percent of the soil-loss variance for the fallowed plots. This system classifies particles smaller than 0.002 mm as clay, those from 0.002 to 0.05 mm as silt, and those from 0.05 to 2.0 mm as sand. In very general terms, the silt-size particles were eroded most easily, and soils became less erodible as either the sand fraction or the clay fraction increased. The rate of increase in erodibility with additional increments of silt-size material became less as either organic matter or the clay-to-sand ratio increased. The rate of decrease in erodibility with increased clay content declined with higher organic-matter content or higher aggregation index. Aggregates of appreciable size washed off.

Analyses of the rainulator and natural rain soil-erodibility data showed conclusively that particles classified by the USDA system as very fine sand (0.05 to 0.10 mm) behave more like silt than like larger sand. When silt was redefined to include particles from 0.002 to 0.10 mm and sand was redefined as 0.10 to 2.0 mm, the prediction values of the two parameters were substantially improved. This grouping approaches AASHO (1) and ASTM classifications but does not quite coincide with them.

Even with the improved mechanical analysis classification, the relation of erodibility to percentage of silt depended very much on the clay-to-sand ratio and associated levels of other properties of the particular soil. Development of a statistical parameter that adequately describes the whole particle-size distribution for a given soil greatly enhanced the predictive capability of mechanical analysis data. The new particle-size parameter (15), which was designated as M, is

$$M = (\text{percentage of } 0.002 \text{ to } 0.10 \text{ mm}) \times (\text{percentage of } 0.002 \text{ to } 2.0 \text{ mm}) \quad (1)$$

where the first group is percentage of silt and very fine sand and the second is percentage of silt plus sand (or 100 minus percentage of clay).

The parameter M accounted for 85 percent of the variance in observed K-values for the 55 rainulator-tested soils in a curvilinear relationship. Some of the individual soil predictions, however, still deviated rather widely from the observed values. Three more parameters were required to account for these deviations: soil organic-matter content, structure, and permeability.

Organic-matter content was inversely related to sediment content of the runoff and was directly related to the amount of rain needed to initiate runoff and to the final infiltration rate. The inverse relations of erodibility to organic-matter level and water-stable aggregation were strongest for silts, silt loams, loams, and sandy loams and declined significantly as clay content increased. Percentages of organic matter were determined by a modified Walkley-Black method (10). They are roughly 1.7 times the percentage of soil carbon.

Soil structure apparently bears a close relation to several soil properties that influence erodibility. When a soil-structure index (9) was included with the particle-size parameter M and organic-matter content, it significantly improved the accuracy of individual erodibility predictions. Structure codes shown in Figure 1 are as follows:

Structure Index	Definition
1	Very fine granular
2	Fine granular
3	Medium or coarse granular
4	Blocky, platy, or massive

The only additional parameter needed to obtain prediction accuracy within the range of practical needs was the standard permeability classification (9). The six permeability classes are as follows:

Permeability Class	Definition
1	Rapid
2	Moderate to rapid
3	Moderate
4	Slow to moderate
5	Slow
6	Very slow

Many other parameters were tested. Water-stable aggregation was inversely related to erodibility and, in simple regressions, accounted for about 6 percent of the soil-loss variance. Because of its interrelation with particle-size distribution and organic-matter content, however, the aggregation index proved of no additional value in the multiple-term relationship on which the erodibility nomograph is based. Bulk density and the dispersion ratio proposed by Middleton (7, 8) were omitted from the final equation for the same reason. The relation of pH to erodibility seemed to depend on the soil's structure and silt content. The data were not adequate to establish dependable relationships between phosphorus and potassium contents and erodibility.

Nomograph

The soil-erodibility nomograph (15) shown in Figure 1 graphically solves an abridged equation that incorporates the new particle-size distribution parameter M and the revised definitions of silt and sand. The parameter M appears in the nomograph as the unidentified horizontal scale in the left section. The scale does not need identification because M is computed in the first step of the nomograph solution.

The five moves in the graphic solution are shown in Figure 1. All entry values, except permeability, apply to the upper 6 or 7 in. of soil, regardless of whether it happens to be an original topsoil or a scalped subsoil.

For soils with silt (0.002 to 0.10 mm) fractions less than 70 percent, the nomograph solves the equation:

$$2.1(10^{-4})(12 - O)M^{1.14} + 3.25(S - 2) + 2.5(P - 3) \quad (2)$$

where O is percentage of organic matter, M is the particle-size parameter, S is the structure index, and P is the permeability class. Changes in the relationships of Eq. 2 when the silt fraction exceeds about 70 percent are introduced by the inflections in the curves of percentage of sand.

The error of estimate based on the data used for derivation of the nomograph indicates that, of 100 K-values obtained by its solution, 68 would be within 6.4 percent of the true values, 90 within 11 percent, and 99 within 17 percent. When the nomograph was applied to descriptive data for bench-mark soils on the erosion research stations, all the solutions were well within accuracy requirements for practical use.

Because the soil surface is often unprotected during construction periods, the soil factor assumes even greater relative importance. C horizon subsoils exposed by bulldozing were tested with a rainulator on two construction sites: a Miami loam subsoil and a compacted, calcareous loam till underlying a Wingate silt loam. In each case, the measured K-value was within 0.02 of the value predicted by the nomograph. Soil-loss data from mechanically desurfaced plots in erosion studies of the 1930s and 1940s on Shelby loam in Missouri and Marshall silty clay loam in Iowa were equally reassuring. Also, nomograph readings for wide range of hypothetical subsoils, including textural extremes, predicted K-values that appear quite realistic. However, further studies are under way at Purdue University to explore possible influences of chemical properties and to test the validity of the nomograph for subsoils extremely high in clay content.

The erodibility nomograph can be especially helpful for sediment prediction and erosion control planning on construction sites because it can predict the changes in erodibility when different subsoil horizons are exposed in the reshaping process. For example, assume that a residential development is being planned on an eroded rolling phase of Enon silt loam in Fairfax County, Virginia. From soil classification data, the planner obtains a detailed description of his soil (except the K-values) as given in Table 1. Using first the information for the A_p horizon, he enters the left scale of Figure 1 with the 71 percent silt + vfs (0.002 to 0.10 mm), moves horizontally to the curve for 15 percent sand, vertically to the OM = 2 percent curve, horizontally to structure = 2, and vertically to permeability = 4. On the scale to the left of this point he reads K = 0.45. Following a similar procedure for each soil horizon, he obtains the other four K-values given in Table 1.

By definition of K, soil losses from the respective soil horizons, if exposed on similar slopes and under similar rainfall, would be directly proportional to the K-values. On this site, a 3-ft cut would expose a C horizon that is nearly twice as erodible as the B_3 horizon exposed by a 2-ft cut. On other soils, the B horizon may be substantially more erodible than the topsoil or the C horizon. Information on the subsoil K-values not only shows the depths of cut that would result in the most or the least sediment yield potential but also shows whether return of stockpiled topsoil on the exposed subsoil would be profitable on the particular site.

The nomograph solution, although quantitative, reflects only the effect of the soil on gross erosion. The universal soil-loss equation combines this soil parameter with effects of five other factors to predict gross sediment from specific farm or construction-site areas.

The soil-loss equation, A = KRLSCP, computes average annual soil loss A as the product of the soil factor K discussed above, a rainfall factor R, and dimensionless factors for the effects of slope length L, slope steepness S, cover and management C, and conservation practices P (18). The factors R, L, and S combine to describe the potential of the erosive agents to detach and transport soil material; K reflects the susceptibility of the soil to detachment and transport by the forces of the erosive agents; C and P describe the effectiveness of land cover, management techniques, and conservation practices for protecting the soil's surface against the erosive agents.

The factor R is the rainfall-erosivity index EI. For a given rainstorm, EI is the product of the storm's rainfall energy and maximum 30-min intensity (12). For a season or year, it is the sum of the individual storm values. This product appears to evaluate satisfactorily the combination of rainfall kinetic energy available for detachment of soil particles and associated runoff available to transport them and to detach others.

On the basis of published drop size and terminal velocity data, the kinetic energy of rainfall is related to rainfall intensity by the following formula:

$$Y = 9.16 + 3.31 \log_{10} I \tag{3}$$

where Y is energy in hundreds of foot-tons per acre-inch and I is intensity in inches per hour (17). The rainstorm is divided into increments of approximately uniform intensity, and the energy for each increment is computed using Eq. 3 or the published energy-intensity chart (17) derived from it. The sum of these incremental values is the E-component of the EI parameter. The I-component is maximum 30-min intensity, in inches per hour.

Locational values of EI (factor R) throughout the 37 states east of the Rocky Mountains may be obtained from a published iso-erodent map (13, 18) derived from 22-year rainfall records. This map, with the county lines omitted, is shown in Figure 2.

Topographic factors L and S adjust the soil-loss prediction for effects of differences in length and steepness of land slope. The capability of runoff to detach and transport soil material increases rapidly with increases in runoff velocity. Runoff velocity increases as runoff rate increases, as the flow concentrates, or as the slope steepens. Therefore, the erosive potential of runoff increases substantially as slope length or steepness increases. On slopes not exceeding 20 percent and of moderate length, average slope effect is expressed by

$$A = C \lambda^{0.5} \tag{4}$$

$$A = 0.43 + 0.30s + 0.043s^2 \tag{5}$$

where

A = soil loss,
λ = slope length, in feet,
s = percentage of slope, and
C = a function of soil, rainfall, and land use.

Dimensionless factors L and S of the soil-loss equation are obtained by expressing Eqs. 4 and 5 relative to their solutions for the basic plot dimensions of 9 percent slope, 72.6 ft long. The topographic factor LS is then expressed as

$$LS = \lambda^{0.5}(0.0076 + 0.0053s + 0.00076s^2) \tag{6}$$

In practice, the applicable LS-value may be conveniently obtained from a published slope-effect chart (18) derived by this formula.

When a slope is concave, convex, or irregular, the average steepness does not accurately predict the slope effect. The soil-loss rate near the toe of a convex slope (steepening toward the bottom) is greater than on a uniform slope of equal elevation change (3, 20). On a concave slope it is less. These relationships are shown in Figure 3 and can be very significant in reducing sediment yields from reshaped land at construction sites. The magnitude of the effect of the curvilinearity can be approximated by dividing the slope into segments.

Information is not available to evaluate the factor LS on very steep slopes, such as 2:1 or 3:1 roadbank slopes, in relation to soil and rainstorm characteristics. Use of Eq. 6 or the published slope-effect chart on slopes steeper than 5:1 would be speculative and is not recommended. Beyond some critical steepness, not yet identified, the formula would probably overpredict soil loss.

Practice factor P, on farmland, reflects the runoff control and erosion-reducing effects of superimposed practices such as contour farming, terracing, or contour strip-cropping. The effectiveness of terraces or diversions, which reduce effective slope length and runoff concentration, should be similar on construction sites. Benefits derived from denuding only alternate strips along a construction area slope at any one time or from contoured mulch strips should be comparable to those from strip-cropping.

The cover and management factor C, on farmland, is the ratio of soil loss from land cropped under specified conditions to the corresponding loss from tilled, continuous fallow (which is the basic condition on which the soil factor K is evaluated). C ranges in value from near zero for excellent sod to 1.0 for continuous fallow. On construction sites, C reflects the influences of various types and rates of mulch, methods of revegetation, chemical soil stabilizers and loose and compacted fills. Some of these effects have been studied by operating a rainfall simulator on construction site conditions. Others can be estimated from field plot data.

The graph in Figure 4 shows how soil loss was influenced by various rates of straw mulch on several soils and slopes (2, 5, 6). The data are from rainulator storms applied at 2.5 in./hour for 1 hour on 2 successive days on 35-ft slope lengths. The study on Fox loam of 15 percent slope was on untilled oat land from which all residue had been removed with a scraper. The Xenia and Wea soils had been plowed and disked. The Wingate and Miami subsoils had been mechanically denuded prior to mulching. The Wingate subsoil on 20 percent slope was highly erodible, and substantial rilling occurred beneath the 2.3 tons of straw mulch per acre. The studies showed that even small rates of mulch may greatly reduce soil loss but that larger rates are required for adequate erosion control. They also showed that the mulch rate required for control increases as the erosion hazard increases and that in some situations even a heavy straw mulch would not adequately control erosion.

Figure 5 shows the results of a study of stone and wood-chip mulches for erosion control on construction sites (2). This study was on the 20 percent Wingate subsoil. Surface mulches of crushed stone, gravel, and wood chips showed great potential for erosion control on short, denuded slopes.

After 5 in. of rain had been applied in standard tests, inflow was added at the upper ends of the plots to obtain runoff rates equivalent to those from slope lengths of 75, 115, and 150 ft respectively. Figure 6 shows the results for several of the treatments. With the added inflow, soil losses from the poor treatments were extremely high. However, the stone mulch treatments at 240 and 375 tons/acre, and wood chips at 25 tons, had nearly clear runoff. Even at 135 tons/acre, a depth of less than 1 in., the stone mulch treatment lost only 10 percent as much soil as the 2.3-ton straw mulch treatment at an equivalent length of 150 ft on this 5:1 slope. Stone mulch at 135 tons/acre can be delivered and spread for about 1 cent/sq ft, and wood chips are becoming a common waste material because of restrictions on burning.

Broadcast seeding of grass after the tests gave excellent stands on the plots mulched with 240 or 375 tons of stone, 12 tons of wood chips, or 2.3 tons of straw per acre. Stands were very poor on the no mulch and on the 15-ton rate of stone mulch.

Figure 1. Soil-erodibility nomograph.

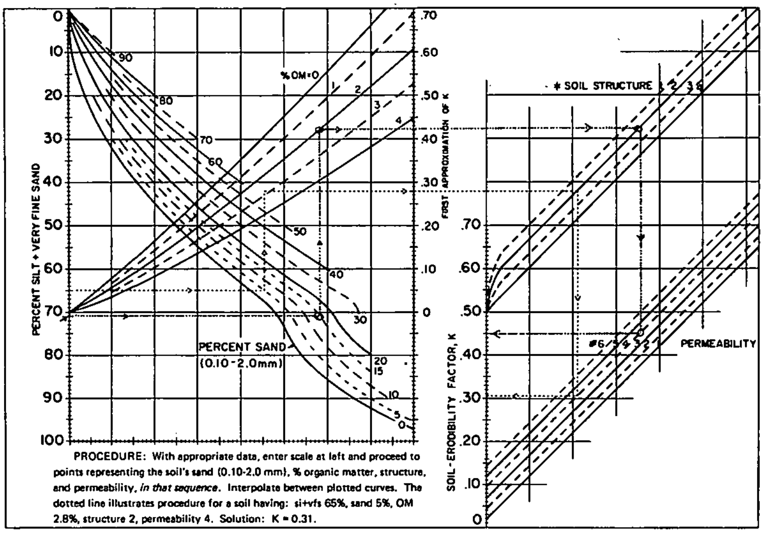


Table 1. Soil horizon data for deriving K-values.

Soil Horizon	Depth (in.)	Texture Class	Particle Size (mm) 0.002-0.10 (percent)	Particle Size (mm) 0.10-2.0 (percent)	Organic Matter (percent)	Structure Index	Permeability Class	K
A_p	0 to 6	sil	71	15	2.0	2	4	0.45
B_1	6 to 9	sicl	60	7	0.6	4	4	0.42
B_2	9 to 20	sic	51	7	0.4	4	4	0.33
B_3	20 to 32	c	38	5	0.3	4	4	0.22
C	32 to 42	sicl	61	9	0.2	4	3	0.43

Figure 2. Average annual values of rainfall intensity (17).

Figure 3. Influence of land slope shape on sediment load.

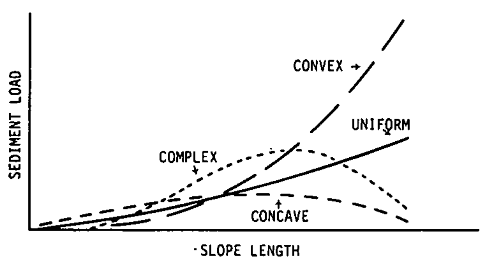


Figure 4. Soil losses from 5 in. of intense simulated rain, as affected by straw mulch cover (intensity = 2.5 in./hour; slope length = 35 ft).

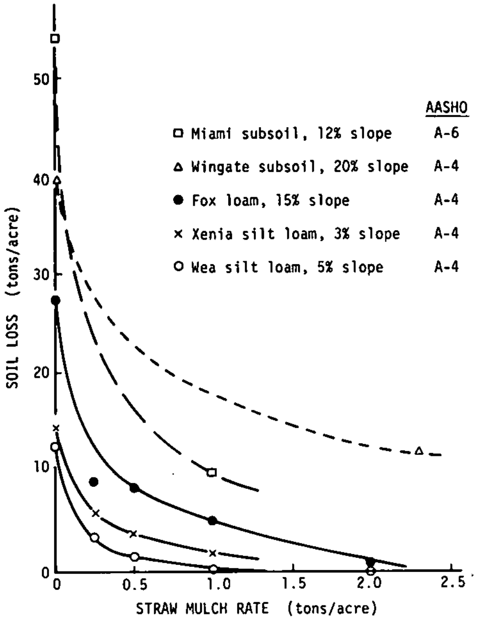


Figure 5. Influence of several mulch types and rates on soil loss from 5:1 construction side-slope (rain intensity = 2.5 in./hour; total applied = 5 in.; slope length = 35 ft).

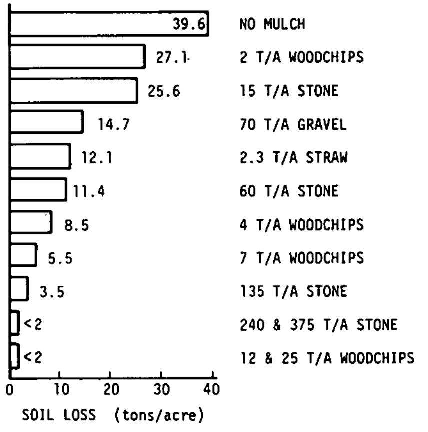
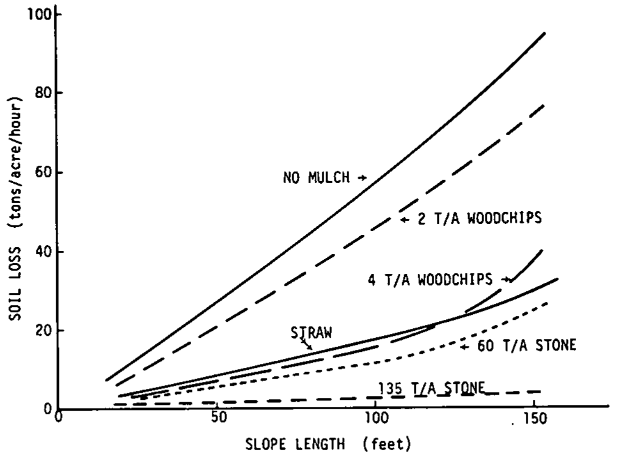


Figure 6. Influence of slope length on erosion rate for several mulch types and rates (5:1 slope).



Predicting Specific-Site Erosion

Effects of the six major factors discussed above are methodically combined in the universal soil loss equation to predict gross erosion from specific sites and in relation to specific planning alternatives. For illustration of the procedure, assume the construction-site situation used earlier to demonstrate application of the erodibility nomograph, and assume that the site is on a 10 percent slope about 200 ft long.

Consulting the detailed iso-erodent map (18) shows that, in Fairfax County, R = 200. For a 10 percent slope 200 ft long, Eq. 6 indicates that LS = 1.93. The erosive potential of the expected annual rainfall and associated runoff is R times LS, or 200 x 1.93 = 386 RLS units.

In the nomograph illustration, the planner found that for the A_p horizon of his soil K = 0.45. This means that he should expect 0.45 ton of soil loss per acre for each RLS unit or an annual total of 386 x 0.45 = 174 tons, if the surface were continuously in a condition equivalent to bare fallow. If the soil were scalped so as to expose the B_2 horizon, the estimated loss would be 386 x 0.33 = 127 tons and so on for the other horizons.

EI probability tables (18) show that at this site the planner faces a 5 percent probability of an R-value equal to or greater than 136 for a single rain event and an annual total of 336 or more in any 1 year. Using these values for R, he finds that he has a 5 percent likelihood of at least 118 tons of soil loss per acre from a single rain or 292 tons in 1 year. The latter would be about 200,000 cu yd of sediment per square mile.

If the topography were shaped to a convex slope, he could expect gross erosion from the area to exceed these estimates; if finished to a concave shape, it should be less. The amount of deviation expected would depend on the degree of slope curvature and the relative erodibilities of the subsoil horizons involved.

The potential sediment predicted by the RLS combination could be reduced by application of one or more of the practices discussed under factor C. For example, a straw or hay mulch at the rate of 3,000 lb/acre would have a C-value of about 0.10. The expected sediment yield from the A_p horizon, mulched at this rate but without use of diversions, would be RLSKCP = 200 x 1.93 x 0.45 x 0.10 x 1.0 = 17.4 tons/acre. The results of each of many alternative management decisions could be similarly predicted. The technique has been described more fully in other publications (14, 18).

ACKNOWLEDGMENT

The authors gratefully acknowledge contributions to this paper from Soil, Water, and Air Sciences, Agricultural Research Service, U.S. Department of Agriculture in cooperation with the Agricultural Research Station, Purdue University.

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