Soil Properties That Affect Erosion

William J. Veon and Arthur C. Miller, Department of Civil Engineering, Pennsylvania State University

It is well known that some soils erode more easily than others. The erodibility of soils has been related to such physical and chemical soil properties as texture, structure, organic content, pH, and permeability and to such engineering properties as the dispersion and surface-aggregation ratios. This paper reviews the pertinent literature on soil erosion, concludes that the nomograph model developed by Wischmeier and others gives the best estimate of soil-erodibility values for most soils, and suggests that the nomograph developed by Roth and others be used to predict erodibility values for appropriate subsoils.

It is well known that some soils erode easily whereas others, under the same conditions of climate, vegetation, and topography, erode very little. This phenomenon is directly attributed to basic differences in the physical and chemical properties of soils. The erodibility of a soil is usually determined on the basis of soil characteristics alone.

Kibler and Busby (1) defined soil erodibility as the inherent susceptibility of soil particles to detachment and transport by raindrops and runoff. The erodibility of soils has been related to such physical and chemical soil properties as texture, structure, organic content, pH, and permeability and to such engineering properties as dispersion and surface-aggregation ratios. These are only a few of the parameters with which engineers and scientists have tried to quantify erodibility.

Because the farmer was the first to be concerned with soil loss, earlier studies of erodibility involved agricultural lands. The higher the erodibility of a farm soil was, the greater was the potential loss of productivity and therefore of profits. Today, because of increased environmental awareness of stream pollution, studies are being initiated that deal with lands affected by construction activities. Stringent laws now limit the amounts of sediment pollution permitted in streams that border construction sites; erosion-control methods and measures are thus essential. Sometimes the costs of these control measures make up a sizable amount of the budget for a project. Adequate estimation of erodibility values can help cut these costs by increasing the accuracy of the erosion-prediction equations often used to design control structures, thus helping to eliminate excessive overdesign. The purpose of this paper is to review some of the pertinent literature on soil erosion and to conclude from the literature what is the best parameter to use in representing potential soil erodibility.

In 1930, Middleton (2) made one of the earliest attempts to analyze the properties of soil that influence soil erosion. He indicated that the dispersion ratio, the ratio of colloid to moisture equivalent, the erosion ratio, and the silica-sesquioxide ratio were the most significant soil parameters influencing erosion.

The dispersion ratio is the suspension percentage divided by the total silt plus clay and is a measure of the stability of soil aggregates when they are acted on by moving water. The suspension percentage is a function of the dry weight of the silts and clays and is obtained by pipetting a suspension of soil sample in water [the suspension and pipetting methods are explained by Middleton (2)]. Total silt plus clay is determined by standard mechanical analysis of the soil sample. The erosion ratio, which gives an indication of the erodibility of soils under similar field conditions, is the value obtained by dividing the dispersion ratio by the ratio of colloid (obtained by the water-vapor-absorption method) to moisture equivalent. Middleton gave dispersion ratio as the most valuable single criterion in distinguishing between erodible and nonerodible soils. Higher dispersion ratios corresponded to erodible soils and lower ratios to nonerodible soils.

Middleton pointed out other soil characteristics of some value: angle of repose, which was much greater for a nonerodible soil in a saturated condition than for an easily eroded soil; plasticity number, which was of more significance than the liquid lower limit; percolation rate; quantity of organic matter; total exchangeable bases (in both quantity and character); and determination of slaking value (Middleton suggested that some modification was needed in the determination method used).

In 1932 and 1934, Middleton, Slater, and Byers published reports on the determination of the physical and chemical properties of soils from the then-existing agricultural erosion experiment stations (3, 4). The percolation ratio, which was given as the ratio between the suspension percentage and the colloid to moisture equivalent value, gave an indication of permeability and depended on the fact that in the more easily dispersed soils the muddy percolation waters more effectively closed the naturally occurring water passageways with silt and colloid. The percolation ratio is applicable only in the comparison of surface soils. Other parameters cited for further study in relation to erosion were shrinkage and swelling characteristics, the acid contents of soils, and soil structure.

A 1933 study by Baver (5) stated that two factors affecting runoff and erosion were the capacity of the soil to absorb water (the rate being more important than the amount) and the permeability of the soil profile (the degree of permeability of the subsurface horizons being of great importance). Both of these parameters were related to the structure and texture of soil as well as to the amount of lime and organic matter in the soil, the presence of which leads to increased granulation.

Baver also proposed other factors that influence soil erosion: the ease of dispersion and the size of the soil particles and the degree of aggregation of the soil. The size of the soil particles and the aggregation of smaller particles into larger units affected the ease of dispersion, i.e., the ease with which soil particles can be suspended in runoff water. The degree of aggregation of the soil was the single most important parameter because all of the other factors mentioned were related to it in some way. An increase in the degree of aggregation increased porosity and, consequently, the rates of water absorption and percolation. It also decreased the ease of dispersion and increased the size of the particles.

In 1935, Lutz (6) indicated that the amount of soil erosion depended partly on the amount and the velocity of the runoff water and partly on the soil properties. Iredell sandy clay loam and Davidson clay were selected for a study of the physical soil properties that influence erosion. Field observations showed that the Iredell loam was an erodible soil and the Davidson clay a comparatively nonerosive one. A laboratory study of the physical properties of the two soils under the same environmental conditions showed that the difference in their erodibility resulted primarily from the degree of aggregation of the finer fraction. Because of this, and because of the results of further analysis, it was concluded that flocculation, hydration, and permeability of the Iredell and Davidson colloids at least partially explained the differences in their erodibility. The erodibility of the Iredell loam resulted from its ease of dispersion (in which hydration was an important factor) and the dense, impervious nature of the B horizon. The nonerodible nature of the Davidson clay was the result of its nonhydrated condition and the high degree of flocculation of the colloid fraction into large, porous, and stable aggregates.

In a preliminary investigation of the relation of the physical properties of Cecil sandy loam, Cecil clay loam, and Madison clay loam to their respective erodibilities, Peele (7) reported in 1937 that the rate at which water percolates through a soil is a much more accurate index of the susceptibility of a soil to erosion than is the water-holding capacity of that soil. He also indicated that Middleton's suspension percentage and dispersion ratio appeared to give a good index of relative erodibility. Peele suggested that other factors that should be taken into consideration in evaluating erodibility are the compactness of the soil, the presence of artificial channels (as a result of plant and animal life), and the thickness of the various soil horizons.

In 1945, after conducting various experiments, Peele, Latham, and Beale (8) concluded that no single value determination or ratio could be found that would adequately characterize the erodibility of all soils. They stressed that too many variables affected the relation of the physical properties of soil to erodibility for all of them to be expressed by a single value. The authors suggested that a workable, systematic soil classification based on erodibility might be developed by grouping soils according to their internal permeability and forming subgroups based on the mechanical composition of the surface soil. The soils in the subgroups would be further differentiated on the basis of the physical properties of the A horizon, such as the degree and stability of aggregation of the clays and silts and the degree of flocculation of the colloidal material.

In 1954, Anderson (9) found three soil variables to be of value in a study relating watershed characteristics to sediment discharge in Oregon. In arriving at the three variables, Anderson employed an analysis of variance technique to test the significance of differences, among soil types, in some physical characteristics expected to be related to erodibility. The physical characteristics used in the analysis, in decreasing order of significance, were the surface area of the particles coarser than 0.05 mm in diameter, aggregated silt plus clay, Middleton's dispersion ratio, ultimate silt clay (Middleton's total silt plus clay), and Middleton's suspension percentage.

Anderson singled out two processes in relating suspended sediment to soil characteristics: the supply process and the binding process. The supply process is represented by that component in the soil that produces the fraction of erosion that is caught and measured as suspended sediment (sediment yield). The ultimate silt plus clay was taken as an index of the supply process. The binding process is represented by the fraction of the soil that tends to bind the soil together versus the amount of soil surface in the nonbinding fraction that requires binding. The surface area of particles coarser than 0.05 mm in diameter divided by the aggregated silt plus clay was taken as an index of how effectively the soil was bound. This new parameter was called the surface-aggregation ratio.

Anderson called the third soil variable in his study soil erosibility. This factor is the product of the dispersion ratio multiplied by the suspension percentage, which is multiplied by the ultimate silt plus clay, and then divided by 100 times the aggregated silt plus clay. Anderson also indicated the importance of parent material as a soil characteristic affecting erosion.

In 1963, Wischmeier and Olson (10) approximated absolute soil-erodibility factors for 20 agricultural soils by using the universal soil-loss equation of Wischmeier and Smith (11), which was originally determined for agricultural lands (the equation was formulated for U.S. customary units; therefore, values are not given in SI units):

$$A = RKLSCP \tag{1}$$

where A = estimated soil loss in tons per acre; R = rainfall erosion index (EI) (rainfall energy in hundreds of foot-tons force per acre per time unit for 1 in of rain times maximum 30-min intensity in inches per hour); K = soil loss in tons per acre per unit of rainfall erosion index (the soil-erodibility factor); L and S = length (in feet) and percent of slope parameters (both part of a dimensionless term); and C and P = ground cover and conservation practices. Wischmeier and Olson reported that, by using the equation in a transposed form (evaluating the equation for K), the effects of the inherent differences in erodibility of soils could be separated from the effects of differences in rainfall and management practices.

The accuracy with which the 20 soil-erodibility values could be approximated was dependent on the accuracy with which the other soil-loss data could be evaluated. Of the 20 soils studied, the 2 with the lowest K values were characterized as having a high percentage of coarse material on the surface. The remaining 18 soils fell roughly into a pattern in which the coarse-textured soils were the least erodible and the fine-textured soils were less erodible than the medium-textured soils.

In 1966, Bubenzer, Meyer, and Monke (12) evaluated the effect of particle roughness on erosion and sediment transport in a laboratory investigation. They used smooth sand, angular sand, and crushed glass cullet to simulate soil particles of different roughnesses. Major particle properties were size, shape (roughness), and specific gravity. In the investigation, particles of one size and roughness were studied at various combinations of slope length and steepness. It was found that particle roughness had little effect on the erosion rate of the larger particles but that the erosion rate for small particles increased as particle roughness increased. In addition, the erosion rate for all particles generally increased as the particle size decreased. Interestingly, on short, gentle slopes the larger particles for all degrees of roughness eroded more rapidly than the smaller particles. This reversal of expected erodibility due to particle size decreased as particle angularity increased.

In 1969, Wischmeier and Mannering (13) derived an empirical equation for calculating the soil-erodibility factor (K) (as found in the universal soil-loss equation) by applying multiple-regression analysis to specific soil properties. Properties that contributed significantly to soil-loss variances included percentages of sand, silt, clay, and organic matter; pH, structure, and bulk density of the plow layer and subsoil; steepness and concavity or convexity of slope; pore space filled by air; residual effects of sod crops; aggregation; parent material; and various interactions of these variables. Fifty-five widely differing corn-belt soils, most of which can be classified as medium-textured, were analyzed for specific physical and chemical properties. The resulting empirical equation is

$$K = 0.013(18.82 + 0.62X_1 + 0.043X_2 - 0.07X_3 + 0.0082X_4 - 0.10X_5 - 0.214X_6 + 1.73X_7 - 0.0062X_8 - 0.26X_9 - 2.42X_{10} + 0.30X_{11} - 0.024X_{12} - 21.5X_{13} - 0.18X_{14} + 1.0X_{15} + 5.4X_{16} + 4.4X_{17} + 0.65X_{18} - 0.39X_{19} + 0.043X_{20} - 2.82X_{21} + 3.3X_{22} + 3.29X_{23} - 1.38X_{24}) \quad (2)$$

The corresponding independent X-variables are given in Table 1. The equation combines the effects of primary and interaction terms and accounts for about 98 percent of the variability in the K-values of the 55 soils. Although Middleton's suspension percentage appeared to be the single variable most highly correlated with erodibility, the computer deleted it from the multiple-regression model because it was a function of other variables in the equation that, in the overall combination, had a greater capacity to decrease the error of estimation. The K-values calculated by using the equation were compared to 11 previously established benchmark K-values. This comparison indicated a high degree of technical accuracy in the equation.

Table 1. Variables used in calculating soil-erodibility factor.

Variable	Definition	r[a]	F-Ratio[b]
X_1	Percentage silt × 1/percentage organic matter	0.66	48
X_2	Percentage silt × reaction[c]	0.53	13
X_3	Percentage silt × structure strength[c]	0.06	5.9
X_4	Percentage silt × percentage sand	-0.22	29.3
X_5	Percentage sand × percentage organic matter	-0.63	38
X_6	Percentage sand × aggregation index	-0.54	6.2
X_7	Clay ratio	-0.37	24.7
X_8	Clay ratio × percentage silt	0.0006	2.4
X_9	Clay ratio × percentage organic matter	-0.46	34.2
X_{10}	Clay ratio × 1/percentage organic matter	0.002	88.3
X_{11}	Clay ratio × aggregation	-0.44	4.3
X_{12}	Clay ratio × 1/aggregation index	0.15	7.4
X_{13}	Aggregation index	-0.37	17.5
X_{14}	Antecedent soil moisture	-0.02	2.8
X_{15}	Increase in acidity below plow zone[c]	0.52	18.2
X_{16}	Structure[c]	0.05	19.9
X_{17}	Structure strength	-0.03	6.9
X_{18}	Structure change below plow layer	0.13	12.7
X_{19}	Thickness of granular material	0.13	6.7
X_{20}	Depth from friable to firm	0.05	1.8
X_{21}	Loess = 1, other = 0	0.36	14.3
X_{22}	Over calcareous base = 1, other = 0	-0.30	21.6
X_{23}	Percentage organic matter × aggregation index	-0.49	6.7
X_{24}	Reaction × structure	0.05	22.6

[a]Coefficient of partial correlation.
[b]Significance according to a statistical F-distribution.
[c]Numerically coded from profile descriptions.

Standard soil-profile descriptions provided all the information needed for the erodibility model except specific data on particle-size distribution, organic matter content, and aggregation in the plow layer.

In 1971, Wischmeier, Johnson, and Cross (14) discovered a new statistical parameter that successfully reflected the influence of particle-size interrelations. This made possible a soil-erodibility model presented in the form of a nomograph (Figure 1). The new parameter, designated M, is the product of the percentage of silt and the percentage of silt and sand.

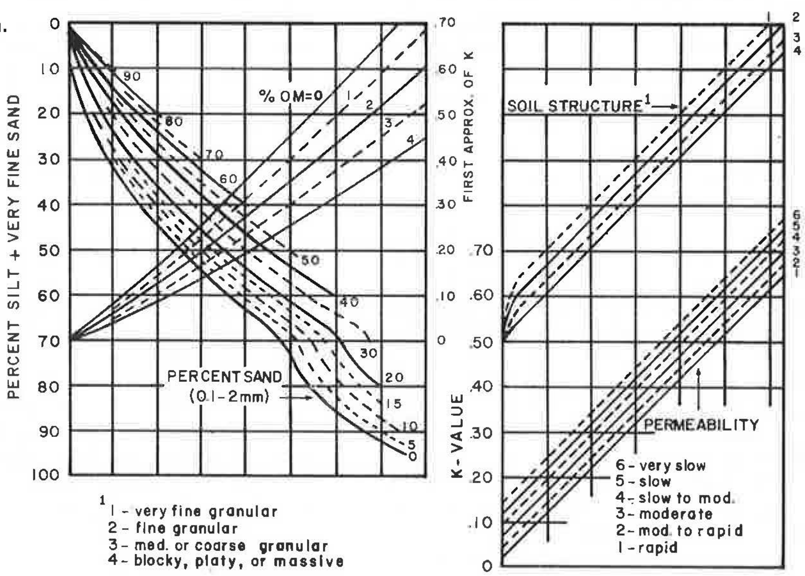
Wischmeier, Johnson, and Cross began their study by redefining the standard silt and sand classifications. The new silt classification included very fine sand (0.05 to 0.10 mm) because data showed conclusively that very fine sand behaved more like silt than like larger sand. Sand was therefore redefined as particles ranging from 0.10 to 2 mm in diameter. Use of the new classifications for silt and sand resulted in the M-value accounting for 85 percent of the variation in the observed K-values for 55 rainulator-tested soils.

Examination of the M-value showed that it was quite descriptive. For soils with a low or medium silt fraction, the M-factor increase for each additional percentage of silt increase depended very much on the sand-to-clay ratio of the soil. As the sand content got higher, the silt content decreased and the M-factor declined in value but remained a function of the silt-to-clay ratio. When the clay content was high, the M-factor assumed a low value that was a function of the sand-to-silt ratio.

Although the M-value is not directly identified on the nomograph in Figure 1, the left-hand portion of the graph is based on the relation of M to K. This relation changes when the silt content approaches 70 percent; the percent sand curves are therefore "bent" near the 70 percent silt line.

The five parameters needed to read numerical soil-erodibility values directly from the nomograph were obtained from routine laboratory determinations and standard soil-profile descriptions. These five parameters are percentage of silt plus very fine sand, percentage of sand greater than 0.1 mm, organic matter content,

Figure 1. Soil-erodibility nomograph.



Procedure: With appropriate data, enter scale at left and proceed to points representing the soils % sand (0.10-2.0mm), % organic matter, structure and permeability, in that sequence. Interpolate between plotted curves.

structure, and permeability. The soil-structure parameter refers to structure type and size as coded from a standard soil profile. The permeability factor refers to the soil profile as a whole and is classified according to the U.S. Department of Agriculture Soil Survey Manual (15). Whether the soil is original topsoil or "scalped" subsoil, all factors except permeability are taken from the upper 15 to 18 cm (6 to 7 in). One soil parameter that could be significant—percentage of coarse fragments—was not included in the nomograph. Limited data indicated that the K-value read from the scale may be reduced by 10 percent for soils with stratified subsoils that include layers of small stones or gravel that do not have a seriously impeding layer above them.

Comparison of the soil-erodibility values of benchmark soils to K-values obtained for these soils from the nomograph indicated the high accuracy of this study. The nomograph can be applied to agricultural lands as well as to lands affected by construction.

In 1973, in a state-of-the-art report on the causes and mechanisms of cohesive soil erosion, Paaswell (16) presented a number of soil parameters that are used in evaluating the erosion of cohesive soils. These parameters, which were placed in four categories, are listed in the table below.

Category	Parameter
Physical properties	Soil type (clay mineral)
	Percentage of clay
	Liquid and plastic limits and activity
	Specific gravity
Physicochemical properties	Base exchange capacity
	Sodium absorption ratio
	Pore-fluid quality
	Pore-fluid environment
Mechanical properties	Shear strength (surface and body)
	Cohesion and thixotropy
	Swelling and shrinkage properties
Environmental conditions	Weathering (wetness and dryness)
	Freezing and thawing
	Prestress history

Paaswell also included a good summary of selected studies on cohesive soil erosion.

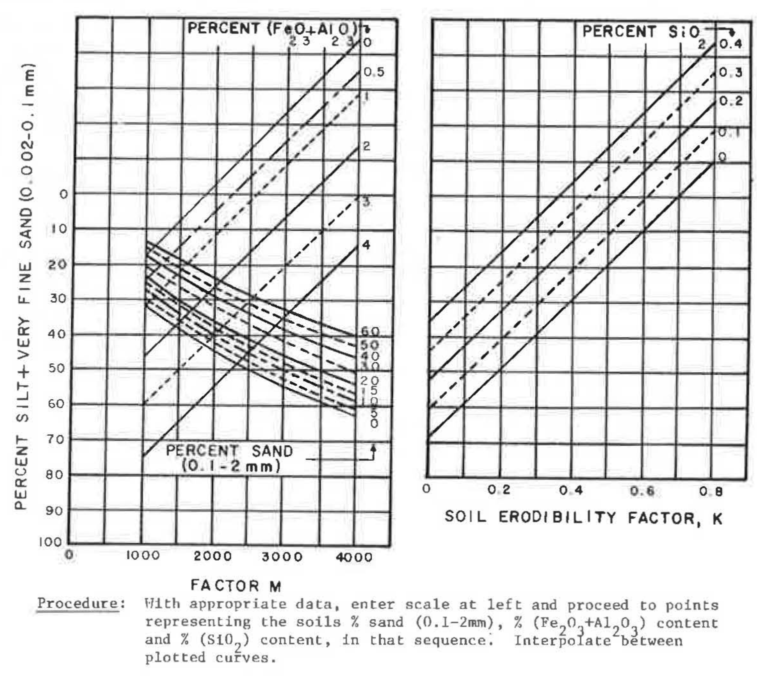
In 1974, Roth, Nelson, and Romkens (17) used multiple-regression techniques to determine a model of subsoil erodibility. Using the nomograph model of Wischmeier, Johnson, and Cross (14) as a starting point, the authors set out to (a) test the model on specific subsoils; (b) determine various chemical, physical, and mineralogical characteristics of both surface soils and subsoils and relate these to the soil-erodibility factor (K); and (c) improve the existing model, if necessary, so that subsoils would be included.

Six midwestern subsoils, with clay contents varying from 33.9 to 66.5 percent, were chosen to test the model. The existing erodibilities of these soils were measured for each of three land treatments: scalped soil, tilled soil, and semicompacted fill. Comparison of the erodibility values to those obtained by using Wischmeier's nomograph indicated that the nomograph was inadequate for estimating soil erodibilities for subsoils with high clay contents. As a result, and in fulfillment of the second objective of the study, various physical, chemical, and mineralogical parameters were determined for 46 surface soils (43 of which were used by Wischmeier, Johnson, and Cross in deriving their nomograph) and for 7 subsoils so that a better soil-erodibility model might be found. Some of the parameters used as independent X-variables in the multiple-regression analyses were the same as those used by Wischmeier and Mannering (13), and some of the terms used were new. Evaluating the independent factors for the surface soils only, by a backward elimination technique, resulted in the derivation of the following predictive equation:

$$K_{PRED} = 0.1357 + (6.710)(10^{-5}) X_{12} + 0.034\,48 X_{13} + 0.038\,47 X_{14} - 0.1732 X_{16} \quad (3)$$

where K_{PRED} = predicted K-value, X_{12} = M-value (14), X_{13} = soil structure, X_{14} = permeability, and X_{16} = percentage C-Na pyrophosphate. (Similar results were obtained by using a forward selection technique.) According to the authors, the four most significant variables in their equation were essentially the same four variables

Figure 2. Subsoil-erodibility nomograph.



Procedure: With appropriate data, enter scale at left and proceed to points representing the soils % sand (0.1-2mm), % (Fe_2O_3+Al_2O_3) content and % (SiO_2) content, in that sequence. Interpolate between plotted curves.

with which Wischmeier, Johnson, and Cross constructed their 1971 nomograph for predicting K-factors. The only difference was that sodium pyrophosphate extractable carbon was found in the new equation instead of the organic matter percentage. With a correlation coefficient of 0.866, however, the two parameters are highly correlated.

A weighted regression analysis had to be used in establishing a model for the prediction of subsoil erodibilities because there were only seven sets of subsoil data available. Therefore, each of the 46 surface soils was weighted $\frac{1}{46}$ and each of the 7 subsoils was weighted $\frac{1}{7}$ to increase the amount of data. The equation obtained for the prediction of soil erodibilities for subsoils with high clay contents (such as those considered in the study) was then

$$K_{PRED} = 0.321\,14 + (20.167)(10^{-5})\,X_{12} - 0.144\,40\,X_{31} - 0.836\,86\,X_{21} \qquad (4)$$

where

X_{31} = sum of the Fe_2O_3 and Al_2O_3 contents and
X_{21} = SiO_2 content.

This equation was found to be statistically significant at the 0.05 level. To further facilitate the use of this model, a nomograph was constructed from the equation (Figure 2). The layout of the nomograph is similar to that of the nomograph of Wischmeier, Johnson, and Cross (14).

CONCLUSIONS

As a result of an intensive literature review conducted to determine an adequate soil-erodibility factor, the authors have concluded that the nomograph model developed by Wischmeier, Johnson, and Cross (14) gives the best estimate of soil-erodibility factors. The nomograph of Roth, Nelson, and Rumkens (17) should be used to predict erodibility values for subsoils with blocky or massive structure, very low permeability, and high clay content. The nomograph of Wischmeier, Johnson, and Cross is well documented and appears to be far superior to all other parameters and methods reported in the literature for predicting soil-erodibility values.

ACKNOWLEDGMENTS

This paper is part of a literature review being conducted for the research project, "Implementing a Procedure to Predict Sediment Flow From Highway Construction Sites," sponsored by the Pennsylvania Department of Transportation. The opinions, findings, and conclusions expressed are ours and not necessarily those of the Federal Highway Administration, U.S. Department of Transportation, or the Pennsylvania Department of Transportation.

REFERENCES

1. D. F. Kibler and C. E. Busby. A Guide to the Development of an Air Force Erosion Manual. Water Resources Engineers, Inc., Nov. 1970, 238 pp.
2. H. E. Middleton. Properties of Soils Which Influence Soil Erosion. U.S. Department of Agriculture, Technical Bulletin 178, 1930, 16 pp.
3. H. E. Middleton, C. S. Slater, and H. G. Byers. Physical and Chemical Characteristics of the Soils From the Erosion Experiment Stations. U.S. Department of Agriculture, Technical Bulletin 316, 1932, 51 pp.
4. H. E. Middleton, C. S. Slater, and H. G. Byers. Physical and Chemical Characteristics of the Soils From the Erosion Experiment Stations. U.S. Department of Agriculture, Technical Bulletin 430, 1934, 62 pp.
5. L. D. Baver. Some Soil Factors Affecting Erosion. Agricultural Engineering, Vol. 14, 1933.
6. J. F. Lutz. The Relation of Soil Erosion to Certain Inherent Soil Properties. Soil Science, Vol. 40, 1935.
7. T. C. Peele. The Relation of Certain Physical Characteristics to the Erodibility of Soils. Proc., Soil Science Society of America, Vol. 2, 1937, pp. 97-100.
8. T. C. Peele, E. E. Latham, and O. W. Beale. Relation of the Physical Properties of Different Soil Types of Erodibility. South Carolina Agricultural Experiment Station, Bulletin 357, 1945, 31 pp.
9. H. W. Anderson. Suspended Sediment Discharge as Related to Streamflow, Topography, Soil and Land Use. Trans., American Geophysical Union, Vol. 35, 1945, pp. 268-281.
10. W. H. Wischmeier and T. C. Olson. Soil-Erodibility Evaluations for Soils on the Runoff and Erosion Stations. Proc., Soil Science Society of America, Vol. 27, 1963, pp. 590-592.
11. W. H. Wischmeier and D. D. Smith. A Universal Soil-Loss Equation to Guide Conservation Farm Planning. Trans., 7th International Congress of Soil Science, Madison, Wisc., Vol. 1, Paper 2, 1961.
12. G. D. Bubenzer, L. D. Meyer, and E. J. Monke. Effect of Particle Roughness on Soil Erosion by Surface Runoff. Trans., American Society of Agricultural Engineers, Vol. 9, No. 4, 1966.
13. W. H. Wischmeier and J. V. Mannering. Relation of Soil Properties to Its Erodibility. Proc., Soil Science Society of America, Vol. 33, No. 1, 1969, pp. 131-137.
14. W. H. Wischmeier, C. B. Johnson, and V. Cross. Erodibility Nomograph for Farmland and Construction Sites. Journal of Soil and Water Conservation, Vol. 26, No. 5, 1971, pp. 189-193.
15. Soil Survey Manual. U.S. Department of Agriculture, Agriculture Handbook 18, U.S. Government Printing Office, 1951.
16. R. E. Paaswell. Causes and Mechanisms of Cohesive Soil Erosion: The State of the Art. HRB, Special Rept. 135, 1973, pp. 52-74.
17. C. B. Roth, D. W. Nelson, and M. J. M. Rumkens. Prediction of Subsoil Erodibility Using Chemical, Mineralogical and Physical Parameters. Technical Services, U.S. Environmental Protection Agency, June 1974.

Publication of this paper sponsored by Committee on Environmental Factors Except Frost.