DIVISION S-6—SOIL & WATER MANAGEMENT & CONSERVATION

Prediction Technology for Soil Erosion by Water: Status and Research Needs

M. A. Nearing,* L. J. Lane, E. E. Alberts, and J. M. Laflen

ABSTRACT

This is a review of research related to soil-erosion prediction technology. The trend in erosion prediction technology in the USA, Australia, and Europe is toward the development of process-based simulation models. The emphasis in erosion research on strictly empirically based models, such as the Universal Soil Loss Equation, is declining. With the process-based technologies come a new array of research needs. In the USA, The USDA Water Erosion Prediction Project (WEPP) has produced a new generation of soil-erosion prediction technology based on fundamentals of hydrologic and erosion science. The development of the new computer-based WEPP erosion model for estimation of rill and interrill erosion required an extensive review and analysis of current knowledge of the science of soil erosion by water. Research needs were identified. The relative importances of identified research needs were evaluated using a sensitivity analysis of the WEPP model, which identified the more important of the input variables required to execute the model. The review of research reported here, along with a discussion of associated current needs for research, addresses four general areas: (i) fundamental erosion relationships, (ii) soil and plant parameters related to erosion, (iii) data bases, user interfaces, and conservation system design, and (iv) erosion model development and analysis.

THE USDA WATER EROSION PREDICTION PROJECT has developed a new generation of erosion prediction technology (Lane and Nearing, 1989). The technology is physically based on fundamentals of hydrologic and erosion science. Development of the WEPP continuous-simulation model required inclusion of components for climate, infiltration, soils, water balance, runoff routing, plant growth, residue decomposition, tillage, and erosion. Thus, each of these associated areas of research was carefully evaluated during the development of the WEPP erosion models. This new prediction technology is fundamentally different from the Universal Soil Loss Equation (USLE) and carries with it a new set of research needs. Also, the WEPP model can be used as an interactive tool for assessing research needs. Sensitivity and other analyses of the model, if used with discretion, can help the erosion research scientist to identify the aspects of the overall erosion process which most influence accurate prediction and control of erosion and sediment yields for different management practices.

The history of erosion science has been discussed by Meyer and Moldenhauer (1985) and by Meyer (1984). A national need to understand and control soil erosion was identified during the early 1900s. This resulted in a major thrust in the 1930s of federal- and state-supported natural-runoff and erosion-plot research. Synthesis of that information began in the 1940s by Zingg (1940) and Musgrave (1947) and culminated with development of the USLE (Wischmeier and Smith, 1965). The USLE is empirically-based erosion prediction technology.

Development of mathematical theory for describing erosion mechanics began in the late 1960s (Meyer and Wischmeier, 1969; Foster et al., 1977; Negev, 1967). The theory was tested and refined, using new equipment, including field rainfall simulators (Meyer and McCune, 1958; Mutchler and Moldenhauer, 1963; Bubenzer, 1979; Meyer and Harmon, 1979; Foster et al., 1982). This new theory led to the technology used in the Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) model (Foster et al., 1980), which served as the prototype for the WEPP erosion prediction technology (Lane and Nearing, 1989; Nearing et al., 1989a).

The new WEPP technology is an improvement over the empirically-based USLE for assessing erosion and sediment yield and for evaluating alternative conservation practices. A major step in synthesizing knowledge in the field of erosion science, the new technology is also a powerful tool for identifying research needs in the area of erosion science. In the process of developing the WEPP technology, gaps in knowledge have been identified. Sensitivity analysis of the model has been used to identify which factors in the overall erosion process are more important to predicting and controlling erosion, and which are relatively less important.

Some results from the sensitivity analysis by Nearing et al. (1990) were used to evaluate or confirm the relative importance of several research needs discussed below. The purpose of that study was to evaluate the response of the WEPP hillslope-profile erosion model relative to changes in input parameters. Sensitivity analyses were conducted on soil, plant, hydrologic, and slope-profile input parameters for the model. The approach was to use a linear sensitivity coefficient representing the change in model response relative to changes in the values of input parameters representing a wide range of possible environmental conditions.

The sensitivity analyses (Nearing et al., 1990) for the WEPP erosion model indicated that key factors affecting model response were hydrologic parameters (rainfall intensity and runoff amount), rill erodibility, residue cover in rills, and rill hydraulic-friction factor. The rill

---

M.A. Nearing, Dep. of Agricultural Engineering, Driftmier Engineering Center, Univ. of Georgia, Athens, GA 30602; L.J. Lane, USDA-ARS, Aridlands Watershed Management Research Unit, Tucson, AZ 85719; E.E. Alberts, USDA-ARS, Cropping Systems and Water Quality Research Unit, Univ. of Missouri, Columbia, MO 65211; J.M. Laflen, USDA-ARS, National Soil Erosion Research Lab., Purdue Univ., West Lafayette, IN 47907. Received 9 Jan. 1990. *Corresponding author.

Published in Soil Sci. Soc. Am. J. 54:1702–1711 (1990).

hydraulic-friction factor sensitivity was evident through the soil-texture terms, as discussed in detail by Nearing et al. (1990). Saturated hydraulic conductivity and interrill erodibility were moderately sensitive parameters. However, as discussed by Nearing et al. (1990), both of these factors play a greater or lesser role in the predictions, depending on conditions. Interrill erodibility was dominant only for short or flat slopes. Saturated conductivity was more important for shorter, less intense storms and less important for larger storms. Interrill cover, plant canopy cover, and canopy height were relatively less significant terms, but increased in importance when interrill sediment generation was dominant over rill erosion. Bulk density and saturation (terms related to the suction term of the Green–Ampt infiltration equation [Green and Ampt, 1911]) did not have a major influence on model output. Peak rainfall intensity, time to peak rainfall intensity, rill spacing and width, and sediment transportability also did not play a major role in the predictions of soil loss.

The purpose of this paper is to report and discuss in some detail current status of erosion science as it relates to the improvement of erosion prediction technology. In conjunction with this review, research needs are identified. These research needs were identified through the development and sensitivity analysis of the WEPP profile-version erosion model, which forms the fundamental basis for the overall WEPP technology. The model predicts rill and interrill soil loss and sediment delivery on a hillslope profile as a function of climate, soil, management, and topographic factors. Four general areas of research will be discussed: (i) fundamental erosion relationships, (ii) soil and plant parameters influencing erosion prediction, (iii) data bases and user interfaces, and (iv) erosion model development and analysis.

FUNDAMENTAL EROSION RELATIONSHIPS

Rill Detachment Processes

The detailed description of the WEPP erosion model was presented by Nearing et al. (1989a). The model uses a steady-state sediment continuity equation of the form

$$dG/dx = D_r + D_i \qquad [1]$$

where G (kg m^{-1} s^{-1}) is sediment load, x (m) is distance down the hillslope, D_r (kg m^{-2} s^{-1}) is rill detachment or deposition, and D_i (kg m^{-2} s^{-1}) is the delivery rate of interrill sediment to the rills. The relationship for detachment in rills is given by

$$D_r = K_r(\tau - \tau_c)(1 - G/T_c) \qquad [2]$$

where K_r (s m^{-1}) is rill erodibility, τ (Pa) is shear stress in the rill, τ_c (Pa) is critical hydraulic shear stress of the soil, G (kg m^{-1} s^{-1}) is again sediment load, and T_c (kg m^{-1} s^{-1}) is the transport capacity of the flow in the rill. Rill detachment rate is zero when flow shear stress does not exceed the critical shear stress of the soil. The parameters K_r and τ_c are soil dependent (erodibility parameters) and τ and T_c are flow dependent.

Perhaps the greatest limitation to our current representation of the rill erosion process is that it is based on detachment by flow only. Other individual processes such as rill sidewall sloughing and headcutting are not explicitly accounted for in the equations, though they may be empirically lumped into the equation via the soil erodibility factor. It has been suggested (Elliot, 1988) that replacement of the flow shear model with a flow energy model would allow us to incorporate the effects of sloughing and headcutting. Since average shear stress is a direct function of energy for a given flow width, depth, and steepness (Elliot, 1988), it is difficult to envision how the use of an energy model alone could improve erosion predictions. This is particularly true for the case of sidewall sloughing, which is a function of potential energy of the sidewalls which is released when the soil adjacent to the sidewalls are scoured away. Explicit considerations of scour, sidewall sloughing, and headcutting in erosion equations could improve our erosion models.

The term $1 - G/T_c$ in Eq. [2] is a feedback term for rill detachment that reflects the fact that soil detachment rates in the rill are a function of the sediment load in the flow relative to the capacity of the flow to transport sediment. When the water is clear, the ratio G/T_c is zero and rill detachment is maximum for a given level of shear stress. Sediment transport capacity is defined as being the maximum capacity of the flow to transport sediment. When transport capacity is filled, net detachment rate in the rill becomes zero.

The basis for the sediment feedback relationship was discussed by Foster and Meyer (1972). Basically, the function used assumes a linear relationship between the two extreme cases of clear water ($G/T_c = 0$) and maximum sediment load ($G/T_c = 1$) for the detachment case. The general trend has been verified (Meyer and Monke, 1965; Willis, 1971), but there has never been experimental verification of the linear relation between the two known end points. This relationship plays a key role in the rill detachment relationship, and has a significant influence on the relative effects of interrill vs. rill erodibility values, surface cover effects in rill and interrill areas, slope lengths and gradients, buffer strips, and strip cropping on predicted soil losses.

The WEPP model predicts that spacing and width of rills can influence soil erosion rates on hillslopes significantly in certain cases (Page, 1988). However, the effects are not significant in many or most cases. The reader is referred to the discussion by Nearing et al. (1989a) for further information. The average sensitivities of soil loss to rill width and rill spacing for a range of conditions are low (Nearing et al., 1990).

Interrill Processes

The basic function used in the WEPP model for delivery of interrill sediment to rills, whereby the sediment becomes available for transport by rill flow, is

$$D_i = K_i I^2 \qquad [3]$$

where K_i (kg s m^{-4}) is the interrill erodibility term and I (m s^{-1}) is rainfall intensity (Meyer, 1981). Equation [3] is a sediment delivery relationship; it does not explicitly differentiate between detachment and transport processes on interrill areas. The WEPP model incorporates the effect of transport on interrill sediment delivery through the use of a sideslope-angle function (Foster, 1982). The hypothesis is that, at low slope angles, interrill erosion is a transport-limiting process whereby not all of the soil detached by impact of raindrops can be transported from the interrill area. At higher slopes, transport capacity is sufficient to carry all the sediment detached by rainfall.

The use of a power function of intensity for soil loss imposes limitations on the description of interrill erosion. One of the objectives of the process-based erosion models is to clearly delineate between hydrologic and erosion processes. For example, the rill erodibility term, K_r, relates soil detachment in rills to flow shear stress. Thus the rill erodibility parameter is entirely independent of infiltration rate for a soil. For the interrill case, the erodibility term, K_i, is not independent of infiltration and runoff, because the sediment delivery from the interrill area is a function of both detachment and transport.

The form of Eq. [3] also introduces difficulty in accounting for the effect of surface sealing on interrill erosion. The WEPP model does predict surface sealing on soils, but does not adjust the interrill erosion rate for the effect of surface sealing. The reason is that surface sealing affects both detachment rates and infiltration rates on a soil, and the relative effects are apparently different for different soils. This difference has led to inconsistencies in the scientific literature regarding the effect of surface sealing on interrill erosion. Brenneman (1988) measured interrill erodibility on two soils at two times, immediately after tillage and again one month later. The Clarion loam soil (fine-loamy, mixed, mesic Typic Hapludoll) showed a reduction in interrill erodibility with time and the Monona silt loam (fine-silty, mixed, mesic Typic Hapludoll) soil showed no measurable overall effect on interrill erodibility with time. Chaves (1987) showed an increase in interrill erodibility with time on a Russell silt loam soil (fine-silty, mixed, mesic Typic Hapludalf). West and Nearing (1988) showed no statistical effect on interrill erodibility with time for the Russell silt loam and the Oakdale fine sandy soil (coarse-loamy, mixed, thermic Mollic Haploxeralf). A fundamental approach and experimental verification is needed to improve the interrill sediment delivery function. This approach should explicitly delineate between detachment and transport processes on interrill areas. Some progress in this area has been made by Gilley et al. (1985) and Hairsine (1988).

A major deficiency in representing detachment processes is in terms of sediment size distributions. It is known that sediment particles detached from interrill areas are smaller, on the average, than those from rill areas. Separate predictive equations for sediment sizes from rill and interrill areas must be developed and those equations must be incorporated into our erosion models. Differentiation of sediment from rill and interrill areas will be very important in estimating chemical transport associated with sediment.

Transport Relationships

Most erosion models rely on the concept of transport capacity, which is defined as the maximum amount of sediment that a flow can carry without deposition occurring. Sediment transport capacity is very important in predicting soil erosion on hillslopes, but our current understanding allows us to estimate transport capacity generally only within an order of magnitude. Clearly, significant improvements in erosion prediction technology will come as a result of improved sediment-transport estimation techniques. Most sediment transport relationships for upland erosion models are taken from those which were developed for stream flow. The WEPP model uses a Yalin (1963) relationship as modified by Foster et al. (1980) for nonuniform sediment. It is doubtful that significant progress in this area can be made simply by use of a different existing formula (Lane et al., 1982). Theory must be developed and experiments conducted specifically related to developing new transport equations for shallow rill and interrill type flows. Significant advances have been made recently in characterizing turbulent flows using flow visualization and other techniques (Kline et al., 1967; Grass, 1971; Praturi and Brodkey, 1978), but those studies have not been extended to the shallow flow conditions common to areas of rill and interrill erosion.

More important than which sediment transport equation to use in predicting soil erosion is the issue of what transport capacity means and how it is used. Transport capacity is basically a balance between entrainment and deposition rates of the already detached sediment in the flow. The description of the entrainment process does not include a factor for cohesive soil forces, but considers only the gravity forces of the sediment that must be overcome for the particle to be lifted into the flow. The implicit assumption, then, for erosion of cohesive soils is that cohesive forces are negligible once the soil has been initially detached from the in situ soil mass.

Another implicit assumption when using a sediment-transport equation to describe erosion is that deposition is a continual process. When we refer to *detachment* in describing soil loss we mean the process of removing in situ soil particles from the bulk soil mass. The term *net detachment* refers to a balance between detachment, entrainment of previously detached particles, and deposition for the case when net movement of particles is from the soil surface into the flow. Some recent erosion models have avoided the explicit use of an existing sediment-transport equation entirely (Hairsine, 1988).

Deposition Relationships

Deposition calculations are very important for estimating the sediment delivery from a slope profile. Good deposition relationships are critical to providing accurate predictions of off-site sediment problems. The WEPP model uses different forms of the sediment continuity equation (Eq. [1]) for the deposition and detachment cases. Deposition in rills is calculated using the equation

$$D_r = V_f/q\,(T_c - G) \qquad [4]$$

where V_f (m/s) is effective fall velocity of the detached sediment and q (m^2/s) is runoff rate per unit width. Deposition is calculated when sediment load, G, is greater than sediment transport capacity, T_c. The effective fall velocity term acts mathematically as a first-order decay coefficient that predicts the rate at which sediment load approaches transport capacity during deposition. In WEPP, this coefficient is calculated based on the log average of the three smallest of the five size classes used in the model. There is little justification for this assumption, other than that such calculation appears to give reasonable results.

Much work is needed in the area of predicting deposition on complex slope profiles. This work may be classified into three general areas.

1. If a single effective-fall-velocity term is to be used to calculate net deposition, improved methods of calculating an effective fall velocity must be developed.
2. Reliable deposition data for nonuniform slopes in the field is nonexistent. Collection of such data will require innovative techniques and careful experimental procedures. Exact slope-profile descriptions will be essential to interpreting the data. Also, the rate of sediment delivery to the area of net deposition must be accurately measured as a function of time through the experiments.
3. More basic, theoretical work needs to be performed to provide better estimates of transport and deposition rates for mixtures of particle-size classes. Both the CREAMS and WEPP models allow for transport capacity to be shifted between particle-size classes. Until more and better data are available, it is difficult to assess the validity of those procedures or to test alternatives.

Dynamic to Steady-State Conversions

The WEPP model uses a dynamic hydrology model to drive a steady-state erosion model. The procedure for making the dynamic to steady-state conversion was reported in Lane and Nearing (1989) and Nearing et al. (1989a). Runoff volume predicted by the hydrology model is used in the erosion model. The steady-state runoff rate is set at the peak runoff rate given by the hydrology model and duration of runoff is adjusted accordingly to maintain the same total runoff volume. The influence of this assumption on predictions of total erosion is not entirely clear and should be investigated. Undoubtedly the conversion from dynamic to steady-state causes some distortion in the predictions of relative proportions of total rill and interrill soil loss. A goal for erosion scientists should be to develop better and more usable dynamic erosion models.

Climate Selection

The most important overall variable for accurate soil-loss predictions with the WEPP model is total precipitation (Nearing et al., 1989b). Erosion at a location is highly variable from year to year. Wischmeier (1962) reported that, on the average, three quarters of average annual soil loss was caused by only four storms per year. Thomas and Snyder (1986) analyzed a 40-yr erosion-index (EI) record from Watkinsville, GA, and determined that a 10-yr planning period is necessary for making management decisions for design of conservation systems. The total soil loss for a year can be highly dependent on one or two storm events, and the estimated soil loss from any one storm can vary greatly, depending on factors such as the recency of tillage. Total soil loss for any time period is a function of two distributions, one for the resistance of the system, which includes cover and soil factors that change daily, and one for the distribution of the rainfall events for the time period. Guidelines have not yet been established for determining the number of years of simulation necessary to obtain accurate long-term predictions of soil loss and sediment yield, nor has any reliable methodology been developed for selecting representative years or storm events to obtain reasonable long-term averages of erosion.

Several factors must be considered when developing criteria for estimating long-term erosion averages. Any method must incorporate differences for different climates. Arid climates obviously have fewer runoff events per year and will require longer simulations than humid locations. One management system may require different selections of climate years than another. Winter crops, for example, cause a very different distribution of erosion resistance than do summer crops. Also, the method that produces good long-term estimates of soil loss may not also produce good long-term estimates of sediment yield on complex slopes with deposition on the toe slope. The ratio of net soil loss to total sediment yield leaving a field is a function of storm intensity, runoff amounts, and peak runoff for a given storm event. This last factor is of particular concern for developing a method of identifying characteristic storm events that accurately represent increments of the year. A series of representative storms for a year that gives reasonable estimates of average on-site soil loss may not give reasonable estimates of off-site sediment delivery.

Landscape Surface Descriptions

Process-based erosion models represent a major advance in predicting soil movement on complex hillslope profiles. The next generation of technology should be able to represent complex landscape surfaces and the movement of sediment on those surfaces. Digital terrain models can be used to describe landscape surface elevations (Moore et al., 1987). Methods for calculating overland routing of flow on complex surfaces will need to be developed and then linked to process-based erosion equations (Moore and Burch, 1986). Data input for soil, topography, crop management, and climate could be accessed through a Geographical Information System.

SOIL AND PLANT PARAMETERS

Baseline Soil Erodibility

Soil erodibility for the WEPP model, or any process-based erosion model, is conceptually different from soil erodibility as defined for the USLE. In the USLE, infiltration and soil resistance to detachment are not treated distinctly; therefore, the erodibility value in the USLE represents a lumping of those two factors. The erodibility value in the USLE is also a time-averaged value, intended to represent a long-term value with respect to soil loss. The WEPP hillslope model, on the other hand, is a process-based continuous-simulation model. Being process-based, it represents infiltration and soil resistance to detachment as separate processes, with distinct parameters for each. Since it is a continuous-simulation model, the parameters for both infiltration and erosion are adjusted by the model to account for temporal changes in soil properties and plant parameters (e.g., residue cover and canopy) that influence soil loss and sediment transport.

The WEPP erosion model has three erodibility terms: one for interrill erosion, K_i, and two for rill erosion, K_r and τ_c. These terms represent the coefficients for the rill (Eq. [2]) and interrill (Eq. [3]) erosion equations that provide the best fit between measured and predicted detachment rates for a soil. This is an important point. The soil erodibilities used in the WEPP model are not fundamental soil properties in any sense, but are dependent on the form of the detachment equations used in the model.

Soil erodibility research conducted during the 4-yr model-development phase of WEPP focused on measuring and evaluating differences among soils in the three erodibility parameters. Accomplishing this objective required that soils be tested in a standard state, which was a seedbed prepared by moldboard plowing and disking (Nearing et al., 1989b). Corn was specified as the antecedent crop, and all surface residue was removed prior to tillage. Each soil was tilled in an optimum or near-optimum soil-water state. The purpose of these and other restraints was to minimize, as much as possible, extraneous sources of variation that might influence the measured parameters. From analysis of the erodibility and other soil property data, regression relationships were developed to predict baseline erodibility values from time-invariant soil properties, including physical, chemical, mechanical and mineralogical (Alberts et al., 1989).

The WEPP model shows a high sensitivity of response to the erodibility parameters, particularly to rill erodibility (Nearing et al., 1990). Though sensitivity to rill erodibility is generally greater than sensitivity to interrill erodibility, interrill erodibility can be the dominant factor under conditions where rill detachment is small, such as for low slope angles, short slope lengths, no-till management systems, and most rangeland conditions. Nevertheless, there is basis for the argument that greater research attention should be focused on rill erodibility. First, the overall sensitivity of soil loss is greatest to rill erodibility, and under the conditions where interrill erosion is dominant soil losses are generally lower. Also, variation in rill erodibility between cropland soils is less than for interrill erodibility (Elliot et al., 1989). While rill erodibilities on 36 cropland soils ranged from about 0.001 to 0.025 s m^{-1} (a factor of 25), interrill erodibilities on the same cropland soils ranged from about 800 000 to 4 300 000 kg s m^{-4} (a factor of about 5).

A fundamental approach to predicting baseline soil erodibility is needed. The approach to predicting baseline soil erodibility has been to measure soil properties on many soils and to use multiple regression techniques to relate erodibility to soil properties. However, under conditions of high variability in measurements, as is the case with erosion measurements, coefficients selected by stepwise linear regression techniques are biased. Lane and Dietrich (1976) showed that, for relatively small sample sizes and moderate to high variability, stepwise regression rarely was able to derive equations that even contained all of the important independent variables. Furthermore, the estimated coefficients for the variables selected were biased, in that the absolute values of the coefficients were too high. A fundamental approach to soil erodibility must rely on an understanding of the basic processes of detachment, the hydrodynamic forces induced by raindrop impact and surface flow, and the interparticle bonding forces within soils. The approach could include predictive equations based on fundamental soil properties, on-site field tests, or some combination of the two approaches.

Temporal Changes in Soil Erodibility

Prediction of baseline erodibility values obviously represents a major step in developing erosion prediction technology. Most soils, however, exhibit large variations in erodibility with time, because of climatic and cropping and management influences. Research designed to evaluate within-soil variation in erodibility has lagged behind the more traditional research that has evaluated among-soil sources of variation in erodibility. Understanding and predicting within-soil variation in erodibility requires knowledge of how key soil and plant parameters change within and among years, and how these changes influence soil erodibility. Developing this understanding will be a challenging task, because of the number and interrelatedness of the soil and plant parameters that influence erodibility, and differences in the level of influence of the soil and plant parameters on rill vs. interrill erosion.

Erodibility parameters change as a recently tilled, loose, unconsolidated soil slakes and disperses into a consolidated mass with stronger, more continuous fabric (Nearing et al., 1988b). Responsible mechanisms relate to the wetting and slaking of clods and aggregates and to subsequent drying. Drying induces internal water stresses that force soil particles into greater surface contact, creating more surface area for bonding (Nearing et al., 1988a). There is a need to develop better understanding of the soil consolidation processes and their relation to erodibility. Existing consolidation models for erodibility (Nearing et al., 1988b) should be better verified and parameterized for a greater number of soil types. Also, there is a need to develop a better understanding of how cropping differences influence aggregate slaking and changes in soil strength. Consolidation also affects the spacing and geometry of rills, but these effects need to be quantified for a range of soil types and environmental conditions.

Soil consolidation has a more dramatic effect on rill erodibility than on interrill erodibility. This is evident from comparisons of erodibility values between cropland (disturbed) and rangeland (consolidated) field data (Elliot et al., 1989; Simanton, 1989). Rill erodibilities are ~29 times greater on croplands than on rangelands; for interrill erodibilities, the differences are on the order of four times. These data indicate that research focused on changes in rill erodibility due to soil consolidation may be more important than changes in interrill erodibility due to consolidation.

For many soils and climates, freezing and thawing of soils complicate our understanding of soil erosion. The effects of soil freezing and thawing on rill and interrill erodibilities are not well understood. Research needs in this area include (i) developing a better understanding of how the water content of frozen and thawing soil affects erodibility, and (ii) determining if the number of freezing and thawing cycles affects soil erodibility during the next cropping season.

Cropping and Management Effects on Erosion

Cropping and management effects on soil structural parameters, like wet-aggregate stability, have been measured for many years. Heavy emphasis has been placed on wet-aggregate stability for several reasons, including: (i) it expresses the resistance of the soil to slaking and dispersion by wetting, (ii) slaking and dispersion are key processes involved in the development of a surface seal or crust, (iii) the measurement is relatively sensitive to cropping and management influence, and (iv) it is a relatively easy and inexpensive measurement to make in the laboratory. Much of the cropping and management focus has been on measuring relative differences in wet-aggregate stability among different cropping systems and tillage practices once or twice a year. Interrill sediment yield and measures of wet-aggregate stability have generally been inversely correlated, but the statistical significance of the associations have ranged from insignificant (Bradford et al., 1987) to highly significant (Luk, 1979). One basic reason for the inconsistency in research results relates to the lumping of sealing and crusting effects on both runoff and soil detachment. In the WEPP model, most of the cropping and management effects on rill and interrill erosion losses are accounted for by making temporal adjustments in the respective erodibility parameters. These temporal adjustments generally take the form of a 0-to-1 adjustment to the baseline erodibility values, based on predicted plant parameters such as live root mass, dead root mass, and mass of buried residue.

Live Roots

Roots, as they grow and proliferate, tend to take the path of least resistance, which is generally through the larger pores found among aggregates or peds (interaggregate pores). This mechanical process, with associated microbial activity, is thought to decrease both rill and interrill soil erodibility. Limited research has been conducted on live-root effects on interrill erodibility, and no research has been conducted on live-root effects on rill erodibility. Erodibility research on live roots will have to be carefully approached, since roots help to consolidate the soil by removing water and decreasing the soil matric potential, a process which draws soil particles together and decreases soil erodibility. Consolidation by water stresses acting on the soil is already represented in the WEPP model for the rill erodibility parameters, but more research is needed to better understand the effect of live roots on erodibility parameters.

Dead Roots

Large amounts of dead roots often occur in cropland soils when an established pasture or meadow is returned to row-crop production. Soil losses measured from standard erosion plots for this condition, relative to that for continuous row cropping, are generally much lower. The effect of dead roots on rill erosion is not, to our knowledge, documented. The effect of dead roots on interrill erosion is thought to be due to small roots and root hairs, which are able to proliferate readily in the larger pores within aggregates or peds (intraaggregate pores). This binding in three dimensions has been shown to increase aggregate stability and resistance to slaking and dispersion by rapid wetting and raindrop impact. Greater amounts of organic matter in the surface soil under and after pasture may also have an effect on soil loss. This is probably through the effects of organic carbon on microbial activity. Only one known study conducted on a Mexico silt loam (fine, montmorillonitic, mesic Udollic Ochraqualf) has directly evaluated the effect of deadroots on K_i (E.E. Alberts, 1989, unpublished data). More research is needed in this area as well as for evaluating the effect of dead roots on rill erodibility.

Buried Residue

Several recent studies have shown that buried residue reduces soil detachment by rill flow (Dedecek, 1984; Brown, 1988; Van Liew and Saxton, 1983). Two options are available for representing this effect. The preferred approach is to partition the total shear stress into that acting on the soil and that acting on residue cover on the rill perimeter. The shear stress acting directly on the soil can then be calculated. The fraction of residue cover in the rill is difficult to predict, because equation parameters that relate rill residue cover to buried residue mass are not currently available, and because the process of residue removal by concentrated flow is not currently represented in the WEPP model. The other option is to account for the buried-residue effect by decreasing the baseline erodibility value with an adjustment calculated from buried-residue mass. More research in this area is warranted, particularly for a wider range of soil types.

Long-Range Research Needs

Predicting erodibility adjustments directly from plant parameters such as live and dead root biomass, or perhaps root length density, bypasses the effect of the plant parameters on soil properties that should be related directly to the erodibility parameters. One problem is the identification of measurable soil properties that are sensitive to temporal changes in cropping and management factors. As discussed above, wet-aggregate stability has been the soil property usually measured to characterize relative effects of different cropping and management systems. Another problem is that many erosion studies are not designed to evaluate the influence of a particular cropping and management treatment on both infiltration and erodibility parameters. This usually causes some confounding and makes interpretation of the results difficult. More process-based research on temporal changes in soil properties is needed if significant improvements in process-based erosion models are to be made.

Soil Infiltration Parameters

The WEPP model uses a Green-Ampt infiltration equation to calculate runoff volumes from storm events. The two parameters required for the Green-Ampt equation are saturated hydraulic conductivity and a wetting-front suction parameter. These parameters are treated in the WEPP erosion model similar to the erodibility parameters. The basic approach used to make the parameter estimates was discussed by Rawls and Brakensiek (1983). Baseline values are adjusted within the model to account for temporal changes due to environmental and management conditions. The regression approach has been traditionally applied to relate soil properties to the infiltration parameters. As is the case for the erodibility parameters, a fundamental approach to developing predictive equations might result in an improved method for estimating infiltration parameters. The reader is referred to Warrick (1983) for a detailed discussion of current research needs for estimating infiltration parameters.

One area that certainly deserves attention is the effect of surface sealing on infiltration. The WEPP erosion model does take into account surface sealing and its effect on infiltration; however, the effect is considered to be the same on all soils. Methods are needed for predicting which soils seal and crust and to what degree the sealing affects infiltration rates for different soils. Changes in crusts and their effects on infiltration after drying and cracking must also be addressed.

The effects of roots on the infiltration process is not represented in the WEPP model, and the scientific basis and mathematical relationships necessary for inclusion of such is not available. It is known that previous cropping has an effect on infiltration and erosion. The USLE contains a subfactor for residual effects of turned sod (Wischmeier and Smith, 1978). While the effect of previous cropping on total soil loss is well documented, the processes responsible are not. This makes it difficult to represent the effects of previous cropping in a process-based simulation model. More research is needed to determine and mathematically describe the effects of previous cropping, and live and dead roots in particular, on soil properties and infiltration.

It is also known that soil compaction affects infiltration. Research is needed to allow us to incorporate the effects of wheel compaction into the new erosion-prediction technology. The WEPP hillslope-profile model currently does not include a mechanism for accounting for nonhomogeneity of soil properties across slope, or on the scale necessary to describe tracked vs. nontracked soil.

Soil and Hydraulic Roughness

Soil surface roughness affects erosion processes primarily as it affects runoff processes and shear stress partitioning in rills (Foster, 1982). The effects of roughness on surface runoff processes are well established both for flow depth and velocities (Huggins and Burney, 1982) and for depressional storage (Onstad, 1984). The effects of roughness on soil detachment and transport are less well defined. Hydraulic roughness in rills can be partitioned between soil grain roughness, soil form roughness, and roughness due to surface cover. Theory shows that the shear stress acting in the rill, which acts both to detach soil and to transport sediment, can be partitioned according to the hydraulic roughness coefficients associated with the soil and surface cover (Foster, 1982). Some work is underway to relate soil surface roughness to hydraulic roughness, but more needs to be done.

It is not clear how form roughness, associated with soil microrelief, and grain roughness, associated with individual soil particles, influence the detachment process in rills. The WEPP model does not currently partition between grain and form roughness in rills, although it does so for interrill areas. One hypothesis which should be tested is that the flow shear stress, or energy, acting to detach soil particles from the in situ soil mass is related to the grain roughness. If that hypothesis were correct, a portion of the differences of rill erodibility between soils could be explained, since soils which are rougher (the clays) also tend to be those which have lower rill erodibilities. This is not to imply that the cohesion of the clays is not a factor in erodibility, but just that clod roughness may also be a factor.

Roughness in rills due to residue cover is a dominant factor in predicting soil loss (Foster, 1982; Nearing et al., 1990), yet there are no definitive data relating surface residue in rills or small channels to hydraulic roughness coefficients (at least one such study is currently in progress; J.E. Gilley, 1989, personal communication). The next step after relating cover to hydraulic roughness would be to test the basic hypotheses related to shear-stress partitioning and effects of hydraulic roughness on both flow-detachment capacity and sediment-transport capacity.

Another problem related to soil surface roughness is its effect on interrill erosion processes. It is suspected, for example, that surface random roughness influences hydraulic roughness more at lower-flow Reynolds numbers, i.e., at lower depth of flow. It would be expected, therefore, that roughness on interrill ares could have a major influence on the transport mechanisms in interrill areas, where flow depths are very shallow. Improved instrumentation and analytical techniques should be developed to characterize soil surface roughness and its relationships to rill and interrill detachment and transport processes.

In our current erosion models, the effect of residue on erosion and sediment transport is reflected primarily through the hydraulic roughness factor. Another effect of residue, which is not usually accounted for, is flow spreading. Surface residue tends to spread the flow over wide areas and generally reduce flow depths and hence hydraulic shear stresses. Flow spreading also reduces the Reynolds number of the flow, which increases the effect of the residue in reducing flow energy and shear acting on the soil. These examples show that the interactions of soil roughness, residue cover, and flow depth on detachment and sediment transport capacity are complex and have not been adequately delineated.

DATA BASES, USER INTERFACING, AND CONSERVATION SYSTEM DESIGN

Erosion prediction technology must be usable by technicians at the field level. To meet that objective, the technology must encompass an integrated system of tools on three levels: data base generation, user interface, and simulation models. Development on all three levels is a research function. The WEPP landscape-profile-version erosion model requires four input data files to execute; a soil file, a slope profile file, a crop management file, and a climate file. The user must have file-building tools and access to appropriate soil, tillage implement, plant, and climate data bases in order to build the four data files. One approach which should be investigated for both data base and user interface development aspects of the prediction technology is expert systems. Engel (1988) developed an expert system to interface with an early, single-storm version of the WEPP technology, but such development has not continued. Expert systems are a logical choice to act as the interface between the user, the data bases, and the simulation model so that the user can provide the necessary input and obtain the desired output from the model.

Climate data bases and file-building tools required to use the WEPP models within the USA are available and will be distributed with the computer model. Likewise, all of the soils information necessary to build the soils data files for within the USA will be available when the model is distributed to the user. Plant-growth and residue-decay parameters for the model are available for only a few crop types. An expert system or some related tool should be developed that is able to communicate with an agronomist who is knowledgeable about a specific crop. The expert system would then translate that knowledge from the agronomist's terminology to the crop parameters required in the crop-growth component of the erosion prediction technology. The same approach could be used to build data bases for new tillage implements, each of which will have a different effect on soil disturbance, random roughness, and burial of surface residue.

If computer-based erosion prediction technology is to be usable worldwide, it must be an integrated system of tools. A potential user should have the tools to use regional information and expert knowledge (not necessarily in the form of research data) to build climate, plant, tillage implement, and soils data bases. The user interface should be flexible enough for the user to apply it in the new environment with the new data bases for the region—or, alternatively, technology must be available to readily adapt the interface to the new environment. Obviously, the process of data base development and user interfacing must include a major research component, along with aspects of training and technology transfer.

The WEPP prediction technology can be used as an interactive tool for designing conservation systems. Output for the model provides specific information concerning how must soil loss is occurring at each point along the hillslope profile and the monthly distribution of soil loss. That information allows the user then to experiment with alternative management systems, based on the spatial and temporal soil loss distribution estimates, and quickly assess the impact of the proposed systems for the site-specific information. Changes in tillage dates, different tillage implements, new crop rotations, strip cropping, contour farming, buffer strips, terraces, and reduced tillage can all be evaluated for their potential in controlling erosion and reducing off-site sediment delivery. Research is needed to provide guidelines and methods for using the technology as an interactive systems-design tool for soil conservationists and project planners.

MODEL ANALYSIS

The WEPP profile model is a continuous-simulation model that incorporates a large number of components. Analysis of the output from the erosion models could provide considerable insight into soil erosion processes and evaluation of environmental systems and their relationships to soil loss and generation of sediment. Model analysis falls into three general categories: validation, sensitivity analysis, and evaluation of confidence limits.

Validation entails comparisons between model predictions and measured field data. Such comparisons can help the research community identify those important aspects of the erosion process which are not accurately considered in the technology. It should be recognized that erosion data are by nature highly variable, and that poor correlation between measured and predicted soil loss for an individual site is not in itself justification for modification to the prediction technology. A systematic analysis of a number of data sets must be used to evaluate the need for incorporation of a new set of information into the process-based technology.

Sensitivity analysis of model inputs and internal parameters can aid the research community in assessing the relative importance of individual processes to the net impact on soil loss and sediment yield. Sensitivity analysis can act as a guide in identifying research needs for developing new, improved conservation and erosion-control practices as well as improved prediction technology. Such analysis must be used with care, for two reasons. The power of the prediction model is that it integrates a wide range of known information and simulates the interactions of a large number of processes, but the fact remains that current knowledge dictates the model relationships. There is, therefore, an inherent bias in models toward the current scientific knowledge base. Secondly, results of sensitivity analysis for a given variable, or set of variables, are dependent on the values of the remaining variables. For example, sensitivity of soil loss to interrill erodibility may be moderate across a wide range of conditions, but for short slopes or rangeland conditions it is the dominant factor for predicting soil loss. With awareness of these limitations, sensitivity analysis can be a powerful tool for gaining insight into the overall erosion problem.

Natural processes are inherently highly variable. A deterministic model, such as the WEPP model, does not provide the user with information on the reliability of its output. Research is needed to assess the confidence limits for the erosion estimates generated by the WEPP erosion model. Methods such as Monte Carlo simulation or the point-estimate method (Rosenblueth, 1975) can be used to provide confidence limit information. Questions should be addressed concerning the probability of meeting specified soil-loss tolerance levels with a given management system on a given field. In designing and evaluating soil conservation alternatives for a site, the user should know, for example, the probability that a proposed change in management practice will reduce soil loss by 50%. This information will provide the user a more realistic means of making management decisions and performing cost-benefit analysis.

SUMMARY

This report reviews our current understanding of erosion science as it relates specifically to the development of soil erosion prediction technology. Research in four general categories are discussed: (i) fundamental erosion relationships, (ii) soil and plant parameters and their effects on erosion, (iii) data bases, user interfaces, and conservation system design, and (iv) model development and analysis. This review of research is based on experience through the development of the WEPP hillslope-profile erosion model, which is computer-based technology for estimating rill and interrill soil losses on hillslopes.

Development of process-based erosion prediction technology has required the delineation and description of fundamental erosion processes and their interactions. Further improvement in prediction technology will require further delineation and mathematical descriptions. Some key topics for study include (i) describing headcutting and sidewall sloughing in rills, (ii) replacing or better describing the concept of sediment-transport capacity and its relationships to detachment and deposition processes, (iii) developing theory and data sets to better predict deposition and sediment enrichment on complex slope profiles, and (iv) developing criteria for climate selection to obtain long-term average estimates of soil loss. New technology for describing erosion and sediment movement on complex hillslope profiles is also needed.

Research on soil and plant parameters related to erosion can be divided into that focused on baseline conditions and on temporal changes. Statistical relationships for estimating baseline soil erodibility as a function of time-invariant soil properties exist. A fundamental approach to prediction is needed to further improve baseline erodibility estimation. Fundamental approaches are also needed to predict temporal changes in soil erodibility in response to climatic and cropping and management influences. Our understanding of and ability to characterize temporal changes in soil properties needs much improvement. Two specific areas that deserve attention are surface-roughness effects on erosion and the effects of surface sealing on infiltration.

New process-based erosion prediction technology will require an extensive data base to be effective. Innovative techniques for developing model parameters will be required, including expert systems. The new technology also opens new opportunities for refining existing and developing new erosion-control practices. Methods for using the technology as an interactive tool for conservation systems design are needed.

To apply the new process-based technology, we need additional research directed toward developing techniques for modeling natural-resource systems. Validation and sensitivity analysis of the new erosion models must be done. We know erosion is highly variable in time and space. With the new simulation models, we can begin to address more fully temporal and spatial distributions of soil loss and sediment yield, confidence limits for our erosion estimates, and probabilities of meeting conservation goals with given management systems.

REFERENCES

Alberts, E.E., J.M. Laflen, W.J. Rawls, J.R. Simpson, and M.A. Nearing. 1989. Soil Component. p. 6.1–6.15 *In* L.J. Lane and M.A. Nearing (ed.) 1989. Water Erosion Prediction Project landscape profile model documentation. NSERL Rep. 2. Natl. Soil Erosion Res. Lab., USDA-ARS, Purdue Univ., W. Lafayette, IN.

Bradford, J.M., J.E. Ferris, and P.A. Remley. 1987. Interrill soil erosion processes: II. Relationship of splash detachment to soil properties. Soil Sci. Soc. Am. J. 51:1571–1575.

Brenneman, L.G. 1988. The effect of previous crops and time after tillage on rill and interrill soil erodibility. Ph.D. diss. Iowa State Univ., Ames (Diss. Abstr. 88-26 447).

Brown, L.C. 1988. Effect of incorporated crop residue on rill erosion. Ph.D. diss. Purdue Univ., West Lafayette, IN (Diss. Abstr. 88-25511).

Bubenzer, G.D. 1979. Rainfall characteristics important for simulation. p. 22–34. *In* Proc. Rainfall Simulator Workshop, Tucson, AZ. 14–15 Jan. 1985. USDA-SEA ARM-W-10. Soc. Range. Manage., Denver, CO.

Chaves, H.M.L. 1987. Influence of incorporated crop residue on interrill erosion. M.S. thesis. Purdue Univ., West Lafayette, IN.

Dedecek, R.A. 1984. Mechanical effects of incorporated residues and mulch on soil erosion by water. Ph.D. diss. Purdue Univ., West Lafayette, IN (Diss. Abstr. 84-23352).

Elliot, W.J. 1988. A process-based rill erosion model. Ph.D. diss. Iowa State Univ., Ames (Diss. Abstr. 88-25912).

Elliot, W.J., A.M. Liebenow, J.M. Laflen, and K.D. Kohl. 1989. A compendium of soil erodibility data from WEPP cropland soil field erodibility experiments 1987 & 88. NSERL Rep. 3. Natl. Soil Erosion Res. Lab., USDA-ARS, Purdue Univ., West Lafayette, IN.

Engel, B.A. 1988. Knowledge engineering in soil erosion. Ph.D. diss. Purdue Univ., West Lafayette, IN (Diss. Abstr. 88-74426).

Foster, G.R. 1982. Modeling the erosion process. p. 295–380. *In* C.T. Haan et al. (ed.) Hydrologic modeling of small watersheds. ASAE Monogr. 5. ASAE, St. Joseph, MI.

Foster, G.R., L.J. Lane, J.D. Nowlin, J.M. Laflen, and R.A. Young. 1980. A model to estimate sediment yield from field sized areas: Development of model. p. 36–64. *In* CREAMS—Vol. I. Model documentation. USDA-SEA Conserv. Rep. 26.

Foster, G.R., and L.D. Meyer. 1972. A closed-form soil erosion equation for upland areas. Ch. 12. *In* H.W. Shen (ed.) Sedimentation (Einstein). Colorado State Univ. Fort Collins.

Foster, G.R., L.D. Meyer, and C.A. Onstad. 1977. An erosion equation derived from basic erosion principles. Trans. ASAE 20:678–682.

Foster, G.R., W.H. Neibling, and R.A. Natterman. 1982. A programmable rainfall simulator. Paper 82-2570. ASAE, St. Joseph, MI.

Gilley, J.E., D.A. Woolhiser, and D.B. McWhorter. 1985. Interrill soil erosion: Part I. Development of model equations. ASAE 28:147–153.

Grass, A.J. 1971. Structural features of turbulent flow over smooth and rough boundaries. J. Fluid Mech. 50:233–255.

Green, W.H., and G.A. Ampt. 1911. Studies in soil physics. I. The flow of air and water through soils. J. Agric. Sci. (Cambridge) 4:1–24.

Hairsine, P.B. 1988. A physically based model of the erosion of cohesive soils. Ph.D. diss. Griffith Univ., Brisbane, Australia.

Huggins, L.F., and J.R. Burney. 1982. Surface runoff, storage and routing. p. 167–226. *In* C.T. Haan et al. (ed.) Hydrologic modeling of small watersheds. ASAE Monogr. 5. ASAE, St. Joseph, MI.

Kline, S.J., W.C. Reynolds, F.A. Schraub, and P.W. Runstadler. 1967. The structure of turbulent boundary layers. J. Fluid Mech.

30:741-773.

Lane, L.J., H.H. Chang, W.L. Graf, E.H. Grissinger, H.P. Guy, W.R. Osterkamp, G. Parker, and S.W. Trimble. 1982. Relationships between morphology of small streams and sediment yield. J. Hydraul. Div., Am. Soc. Civ. Eng. 108:1328-1365.

Lane, L.J.,and D.L. Dietrich. 1976. Bias of selected coefficients in stepwise regression. p. 196-200. *In* Stat. Comput. Sect. Proc. Am. Stat. Assoc., Washington, DC.

Lane, L.J., and M.A. Nearing (ed.) 1989. Water Erosion Prediction Project landscape profile model documentation. NSERL Rep. 2. Natl. Soil Erosion Res. Lab., USDA-ARS, Purdue Univ., West Lafayette, IN.

Luk, S.H. 1979. Effect of soil properties on erosion by wash and splash. Earth Surf. Processes 4:241-255.

Meyer, L.D. 1981. How rain intensity affects interrill erosion. Trans. ASAE 24:1472-1475.

Meyer, L.D. 1984. Evolution of the universal soil loss equation. Soil Water Conserv. 39:99-104.

Meyer, L.D., and W.C. Harmon. 1979. Multiple-intensity rainfall simulator for erosion research on row sideslopes. ASAE 22:100-103.

Meyer, L.D. and D.L. McCune. 1958. Rainfall simulator for runoff plots. Agric. Eng. 39:644-648.

Meyer, L.D., and W.C. Moldenhauer. 1985. Soil erosion by water: The research experience. Agric. Hist. 59:192-204.

Meyer, L.D. and E.J. Monke. 1965. Mechanics of soil erosion by rainfall and overland flow. Trans. ASAE 8:572-577, 580.

Meyer, L.D., and W.H. Wischmeier. 1969. Mathematical simulation of the processes of erosion by water. Trans. ASAE 12:754-758, 762.

Moore, I.D., and G.J. Burch. 1986. Modelling erosion and deposition: Topographic effects. ASAE 29:1624-1630.

Moore, I.D., O'Loughlin, E.M., and G.J. Burch. 1987. A three-dimensional digital topographic model. Earth Surf. Processes Landforms.

Musgrave, G.W. 1947. The quantitative evaluation of factors in soil erosion: A first approximation. J. Soil Water Conserv. 2(3):133-138.

Mutchler, C.K., and W.C. Moldenhauer. 1963. Applicator for laboratory rainfall simulation. ASAE 6:220-222.

Nearing, M.A., L.T. West, and J.M. Bradford. 1988a. Consolidation of an unsaturated illitic clay soil. Soil Sci. Soc. Am. J. 52:929-934.

Nearing, M.A., L.T. West, and L.C. Brown. 1988b. A consolidation model for estimating changes in rill erodibility. Trans. ASAE 31:696-700.

Nearing, M.A., L.Deer-Ascough, and J.M. Laflen. 1990. Sensitivity analysis of the WEPP hillslope profile erosion model. Trans. ASAE (in press).

Nearing, M.A., G.R. Foster, L.J. Lane, and S.C. Finkner. 1989a. A process-based soil erosion model for USDA Water Erosion Prediction Project technology. Trans. ASAE 32:1587-1593.

Nearing, M.A., M.A. Weltz, S.C. Finkner, J.J. Stone, and L.T. West. 1989b. Parameter identification from plot data. p. 11.1-11.15. *In* L.J. Lane and M.A. Nearing (ed.). Water Erosion Prediction Project landscape profile model documentation. NSERL Rep. 2. USDA-ARS Natl. Soil Erosion Res. Lab., Purdue Univ., West Lafayette, IN.

Negev, M. 1967. A sediment model on a digital computer. Tech. Rep. 76. Dep. of Civil Engineering. Stanford Univ., Stanford, CA.

Onstad, C.A. 1984. Depressional storage on tilled soil surfaces. Trans. ASAE 27:729-732.

Page, D.I. 1988. Overland flow partitioning for rill and interrill erosion modeling. M.S. thesis. Univ. of Arizona, Tucson.

Praturi, A.K., and R.S. Brodkey. 1978. A stereoscopic visual study of coherent structures in turbulent shear flow. J. Fluid Mech. 89:251-272.

Rawls, W.J., and D.L. Brakensiek. 1983. A procedure to predict Green and Ampt infiltration parameters. p. 102-112. *In* D.C. Slack (ed.) Advances in infiltration. Proc. Natl. Conf. on Adv. in Infiltration, Chicago, IL. 12-13 Dec. 1983. ASAE, St. Joseph, MI.

Rosenblueth, E. 1975. Point estimates for probability moments. Proc. Natl. Acad. Sci. (USA) 72:3812-3814.

Simanton, R.J. 1989. Water Erosion Prediction Project rangeland field studies. USDA-ARS Rep., Tucson, AZ.

Thomas, A.W., and W.M. Snyder. 1986. Stochastic impacts of farming: Simulation of seasonal variation of climatic risk. Trans. ASAE 29:1026-1031.

Van Liew, M.W., and K.E. Saxton. 1983. Slope steepness and incorporated residue effects on rill erosion. Trans. ASAE 26:1738-1743.

Warrick, A.W. 1983. Parameters in infiltration equations. p. 69-81. *In* D.C. Slack (ed.) Advances in infiltration. Proc. Natl. Conf. on Adv. in Infiltration, Chicago, IL. 12-13 Dec. 1983. ASAE, St. Joseph, MI.

West, L.T., and M.A. Nearing. 1988. Soil consolidation effects on rill and interrill soil loss. p. 289. *In* Agronomy abstracts. ASA, Madison, WI.

Willis, J.C. 1971. Erosion by concentrated flow. USDA-ARS 41-179. U.S. Gov. Print. Office, Washington, DC.

Wischmeier, W.H. 1962. Storms and soil conservation. J. Soil Water Conserv. 17(2):55-59.

Wischmeier, W.H., and D.D. Smith. 1965. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains—Guide for selection of practices for soil and water conservation. USDA Agric. Hand. 282. U.S. Gov. Print. Office, Washington, DC.

Wischmeier, W.H., and D.D. Smith. 1978. Predicting rainfall erosion losses: A guide for conservation planning. USDA Agric. Handb. 537. U.S. Gov. Print. Office, Washington, DC.

Yalin, Y.S. 1963. An expression for bed-load transportation. J. Hydraul. Div., Am. Soc. Civ. Eng. 89:221-250.

Zingg, R.W. 1940. Degree and length of land slope as it affects soil loss in runoff. Agric. Eng. 21:59-64.