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Soil Conservation: Principles of Erosion by Water

The study of soil erosion by water is dynamic, with many advances developing since the advent of digital computers. Although scientists and engineers have been investigating the factors affecting erosion for many decades, most of the early work was limited to storms or, even more commonly, seasonal phenomena. Efforts to incorporate known physical laws in such early work led to the solution of problems. Current computer capability allows solutions of known physical relationships that facilitate description of spatial and temporal variability.

The hydraulic principles involved in soil erosion by water were applied primarily to larger river systems where the flow depths are large relative to the roughness elements. Thus, the transfer of such technology to upland soil erosion problems must be made with complete understanding of the assumptions involved. Students of soil erosion problems, and practitioners, need to be aware that many technological improvements being made will require continual upgrading of the subject matter. The material presented subsequently is intended to provide an introduction to soil erosion theory and some of the strategies for the control of erosion.

11-1 WATER EROSION

Erosion and sedimentation by water involve processes of detachment, transport, and deposition of soil particles. The major forces are from raindrop impact and water flowing over the land surface. Erosion may be un-

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noticed on a smooth soil surface where raindrops are eroding large quantities of sediment, whereas it can be dramatic where concentrated flow creates an extensive rill and gully system. Factors affecting erosion can be expressed in an equation of the form

$$E_r = f(C_l, S_p, T_o, SS, M) \quad [1]$$

where

E_r = erosion,
f = function of ( ),
C_l = climate,
S_p = soil properties,
T_o = topography,
SS = soil surface conditions, and
M = Human activities.

Sediment yield should not be confused with erosion. Sediment yield is the amount of eroded sediment that is delivered to a point in the watershed remote from the origin of the detached particles. In a watershed, sediment yield includes the erosion from slopes and channels, mass wasting, and deposition of eroded sediment on both slopes and in channels.

The universal soil loss equation (USLE) is essentially an expression of the functional relationship shown in Eq. [1] (Wischmeier and Smith, 1965, 1978). It was developed from extensive field experimentation and has been widely accepted by conservation planners. The USLE, a product of six terms representing the major factors in Eq. [1], gives an estimate of the average annual erosion expected from a field-sized area. The USLE is

$$A = RKLSCP \quad [2]$$

where

A = the computed soil loss per unit area expressed in the units selected for K and for the time period selected for R. In practice, these are usually so selected that they compute A in metric tons per hectare per year, but other units can be selected.
R = the rainfall and runoff factor, which is the number of rainfall erosion index units for a given time period, usually a year, plus a factor for runoff from snowmelt or applied water where such runoff is significant.
K = the soil erodibility factor, which is the soil loss rate per erosion index unit for a specified soil as measured on a unit plot, defined as a 22.1-m length of uniform 9% slope continuously in clean-tilled fallow.
L = the slope-length factor, which is the ratio of soil loss from the field slope length to that from a 22.1-m length under identical conditions.
S = the slope-steepness factor, which is the ratio of soil loss from the field slope gradient to that from a 9% slope under otherwise identical conditions.

C = the cover and management factor, which is the ratio of soil loss from an area with specified cover and management to that from an identical area in tilled continuous fallow.

P = the support practice factor, which is the ratio of soil loss with a support practice such as contouring, stripcropping, or terracing to that with straight-row farming up and down the slope.

The material presented below is not intended to replace the detailed material in Agriculture Handbook no. 537 (Wischmeier and Smith, 1978). The details contained in the handbook must be familiar to the user of the USLE. The material we presented here is a general overview of the water erosion problem.

11-2 CLIMATE

Climate directly but obscurely influences erosion. For example, the semiarid western USA, with generally low rainfall, has high sediment yield per unit area (Langbein and Schumm, 1958), because the low rainfall generally supports a poor vegetative cover to protect the soil from raindrops and because erosion from channels is generally large. Similarly, land slopes are often greater in the mountainous areas of the West. Thus, climate interacts with other factors such as topography and soil cover. Climate is often described by annual rainfall in an area, although the seasonal distribution of the precipitation, the intensity of the precipitation, the form of precipitation, and temperature at critical periods are also important climatic indicators. Erosive rains are not uniformly distributed over a typical year except in some areas in the Southeast. In western Nebraska, 24% of the annual rainfall erosivity potential normally occurs in the 1-month period from 15 May to 15 June. Because this period coincides with seedbed preparation for crops such as corn, when there is little ground cover to protect against erosion, the hazard of erosion is usually severe. In contrast, a negligible amount of average annual rainfall erosivity occurs during the same period in the Palouse area of the Northwest.

The erosivity of precipitation coming as snow is less than that for an equivalent rainfall because there is no detachment by raindrops. However, warm rain on snow can produce large rates of runoff that may be quite erosive when coupled with a highly erodible soil produced by frequent freeze-thaw cycles. Rain on snow with frozen ground, although it produces large amounts of runoff, will not produce erosion.

The "concentration of energy" in rainstorms is also important. Large amounts of rainfall at low intensities (low energy concentration) may cause much less total erosion than small amounts of rainfall at high intensities (high energy concentration). Such high-energy rainfall is characteristic of Arizona, where a single 2-h thunderstorm commonly produces over 50% of the annual R value (Renard et al., 1974).

The rainfall erosivity term R in the USLE expresses the important characteristics of rainfall influencing erosion. Analysis of experimental data showed that erosion is highly correlated with rainfall energy, rainfall amount, and rainfall intensity. These factors may be combined as the product (*EI*) of a storm's total kinetic energy and its maximum 30-min intensity. Since erosion is linearly related to *EI,* values for the individual storms are summed for an annual erosivity R value. Average annual values for R range from a low in the West of 200 to almost 10 000 MJ mm(ha h y)$^{-1}$ (megajoule-millimeters per hectare hour per year) in the Southeast. If one assumes that all factors except R of the USLE are the same, erosion in the Southeast will be over 25 times that in the West. However, for undisturbed conditions, the high rainfall will produce very good ground cover, and thus little erosion, whereas ground cover will be poor in the low rainfall area, allowing very high erosion rates. Human activities that disturb the ground cover can greatly change this natural situation.

Two types of information are needed to represent the seasonal pattern of rainfall erosivity: (i) the average annual R value and (ii) its distribution throughout the year. This information is available in Agriculture Handbook no. 537 (Wischmeier and Smith, 1978), and a map of the annual R factor expressed by using the International System of Units (SI) was presented by Foster et al. (1981b).

The USLE estimates expected erosion over a long period. It must be modified to estimate erosion for individual storms. The modifications usually involve changing the R term to reflect the greater variability of erosion on a storm-by-storm basis. Foster et al. (1977) replaced R with a term defined as

$$E = (0.5\,R_{st} + 3.5\,V_u\,\sigma^{1/3}) \qquad [3]$$

where

E = storm erosivity from rainfall and runoff MJ mm(ha h)$^{-1}$
R_{st} = single storm *EI* erosivity value MJ mm(ha h)$^{-1}$
V_u = storm runoff (mm)
σ = storm peak runoff rate mm h^{-1}

In effect, Eq. [3] reflects the erosion contribution by both raindrop impact and runoff. In watersheds where significant deposition occurs, sediment yield is almost entirely related to flow characteristics, and the coefficient of R_{st} in Eq. [3] can be set to zero. Williams (1975) used this approach with the equation

$$Y = 90.5\,(Q\,q_p)^{0.56}\,K\,L\,S\,C\,P \qquad [4]$$

where

Y = computed soil loss (tonnes) for the runoff event,
Q = storm runoff (m^3), and
q_p = peak runoff rate for the storm (m^3 s^{-1}).

The variables Q and q_p are estimated using commonly available techniques for estimating runoff (SCS, 1972). Equation [4] has been used and widely tested for estimating sediment yield.

The USLE and a delivery ratio (Roehl, 1962) to account for deposition are often used to estimate sediment yield. Better ways of estimating sediment yield using a runoff-based equation such as Williams' modification of the USLE (Eq. [4]) or recent fundamental models that route sediment through the watershed system are being developed (Knisel et al., 1980). Such models are derived from more basic erosion relationships that consider continuity of mass and the processes of detachment, transport, and deposition by raindrop impact and the flow of water over the land surface and in the channels (see Appendix). The models also calculate erosion rates for individual storms. They can consider the spatial distribution of soils, the land use, and the topography in the field or watershed.

11-3 SOIL PROPERTIES

Some soils are much more susceptible to erosion than others. In fact, during the same rainfall, a highly erodible soil can erode 10 times faster than a nonerodible soil. Factors affecting a soil's resistance to erosion include its organic matter content, primary particle-size distribution, structure, iron and aluminum oxide content, electrochemical bonds, moisture content, and aggregation (Wischmeier et al., 1971; Grissinger, 1966; Partheniades, 1972). The *K* term in the USLE quantifies a soil's erodibility. The U.S. Department of Agriculture Soil Conservation Service and Agricultural Research Service have tabulated the values of *K* for most major soils found in the continental USA and have presented a nomograph for estimating a value where they are unavailable (Fig. 11-1).

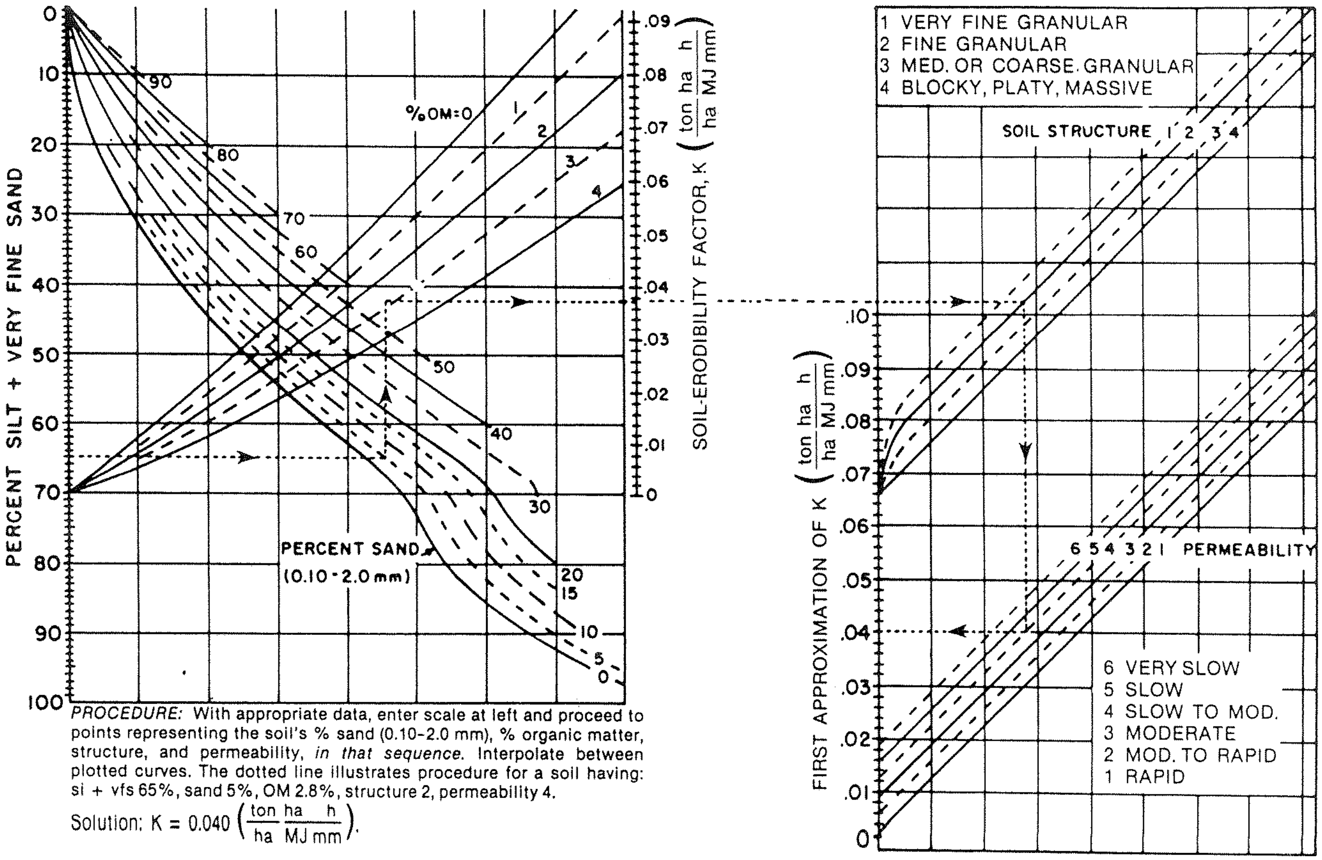
Good management practices (e.g., improving organic matter content, soil tilth, and soil structure) may decrease erodibility. Continuous tillage destroys soil structure and decreases organic matter content, thereby increasing erodibility. These management influences are described in other terms of the USLE. In concept, the *K* factor is a fixed soil property that remains constant over a long period. In practice, some soils are more susceptible to rill erosion than other soils. Since rill erosion is a function of runoff volume and rate (see Appendix), erosion control on these soils requires maintenance of high infiltration rates and prevention of large accumulation of runoff by, e.g., installing terraces and diversions.

11-4 TOPOGRAPHY

Topography affects erosion on two scales—macro- and micro-. Slope steepness, length, and shape express the macroscale. Steepness and row side slopes and roughness configurations left by tillage implements are expressions of microtopography.

11-4.1 Macrotopography

Topography, as expressed by slope steepness, length, and shape, influences erosion. The energy of the eroding agents increases with slope steepness. Additional runoff accumulates with longer slope lengths, which in-



PROCEDURE: With appropriate data, enter scale at left and proceed to points representing the soil's % sand (0.10-2.0 mm), % organic matter, structure, and permeability, *in that sequence.* Interpolate between plotted curves. The dotted line illustrates procedure for a soil having: si + vfs 65%, sand 5%, OM 2.8%, structure 2, permeability 4.

Solution: $K = 0.040 \left(\frac{\text{ton}}{\text{ha}} \frac{\text{ha}}{\text{MJ}} \frac{\text{h}}{\text{mm}}\right)$.

Fig. 11-1. The soil erodibility nomograph in SI units (Wischmeier and Smith, 1978).

creases the capacity of flow to detach and transport soil particles. The effect of slope shape on erosion depends on the locations of steepest portions along the slope. Erosion is greatest when steep slopes occur at the end of the slope where maximum runoff has accumulated. The options available for modifying the macrotopography of a field or watershed are limited except for construction, mine reclamation, and similar sites where extensive land reshaping is possible.

In the USLE, *L* and *S* are dimensionless factors accounting for the effects of slope length and steepness. Their product is the topographic factor that is the expected ratio of soil losses from a given length and steepness of slope to corresponding losses from the standardized plot dimensions used in other terms of the USLE (22.1-m long plot with 9% gradient). Nomographs that assume uniform slopes are available for obtaining the *LS* term (e.g., Wischmeier, 1977; Wischmeier and Smith, 1978). The formula for computing the combined slope length-steepness factor is

$$LS = (\lambda/22.1)^m (65.41 \sin^2 \theta + 4.56 \sin \theta + 0.065) \qquad [5]$$

where λ = the slope length in meters; $m = 0.5$ if the slope is steeper than 5%, 0.4 on slopes of 3.5 to 4.5%, 0.3 for slopes of 1 to 3%, and 0.2 on uniform gradients of less than 1%; and θ = the angle of slope. The *LS* value can be modified to account for the effects of slope irregularities using the procedure detailed by Foster and Wischmeier (1974). An example of one such computation is given in Agriculture Handbook no. 537 (Wischmeier and Smith, 1978). Equation [5] has been modified somewhat for use in the Pacific Northwest (Chapt. 19).

Watershed topography and geomorphologic characteristics may greatly influence runoff and, hence, erosion. Watersheds with dense channel networks (i.e., a high proportion of channels per unit watershed area), steep channels, basin shapes, and geology that increase runoff volumes and rates all tend to increase erosion. Analytical and experimental results have shown the effect of slope shape on erosion (Fig. 11-2).

Slopes of the sediment load curves in the upper part of the figure indicate the rate of erosion as a function of position on the slope. Erosion losses from the convex slope increase very rapidly near the bottom of the slope, whereas the losses from the concave slopes are greater near the top, indicating deposition may occur at the bottom. The magnitude of the erosion and the location where deposition begins are functions of several factors, including the susceptibility of the soil to detachment by flow relative to detachment by raindrop impact, slope curvature, and runoff rate.

11-4.2 Microtopography

Microtopography scale refers to the roughness and surface configurations that remain after tillage. The microtopographic influence is described by the cover management and support practice factor of the USLE. The

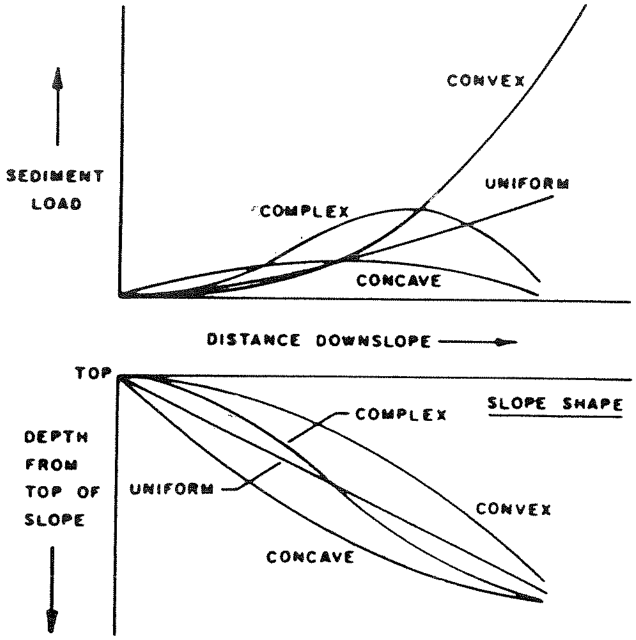


Fig. 11-2. Influence of slope shape on sediment load and rate of erosion. Steepness of sediment load curves indicates rate of erosion, and negative slope indicates deposition (from Meyer et al., 1975).

steep side slope of a row (microtopography) may produce large quantities of detached soil particles, but if the main slope gradient (macrotopography) is flat, little sediment may leave the field. On the other hand, if the main slope gradient is steep and rows run uphill and downhill, the steep side slopes of rows will increase erosion.

Depression roughness can store large quantities of detached sediment, greatly reducing the amount of sediment leaving a field. However, as the depressions fill, sediment delivery increases to a rate comparable to that from a relatively smooth surface.

Roughness can often eliminate or greatly reduce runoff from small to moderate rainstorms. Preventing runoff from a storm completely eliminates erosion for that storm. Large storms with high runoff water can cut rills through the depression storage areas, reducing or even eliminating such storage capacity. Thus, roughness must be reestablished periodically to maintain its effectiveness.

11-5 SURFACE COVER

Surface cover includes vegetative canopies and material in contact with the ground surface. A vegetative canopy intercepts raindrops above the soil surface and ground surface covers (mulches, plant residue, and erosion pavement), and tends to dissipate some of the raindrop energy and reduce runoff velocity.

The number of raindrops intercepted by a canopy depends on its density. Some of the intercepted water reforms drops, which then fall to the soil surface or ground cover. The energy of the reformed drops is usually much less than that of the nonintercepted drops because their height of fall from the canopy is usually too low for them to regain terminal velocity. Some of the intercepted water becomes stemflow. Consequently, a canopy does not reduce runoff erosivity so much as it reduces rainfall erosivity, especially during larger storms. Material in contact with the soil surface is more effective than a canopy in reducing erosion. The energy of raindrops striking this cover is completely dissipated, whereas drops falling from a canopy regain some energy. Furthermore, material in contact with the soil slows the runoff, which increases the flow depth, providing a greater buffer for reducing the hydrodynamic impact forces of the raindrop (Mutchler and Young, 1975). Also, slowing the flow increases infiltration and reduces runoff erosivity.

Wischmeier and Smith (1978) used a cover management term *C* in the USLE to account for the effects of surface cover. Values of *C* presented in Agriculture Handbook no. 537 (Wischmeier and Smith, 1978) consider different canopy heights, densities, and different ground surface cover rates. Relationships are also available for various rangeland and woodland conditions (Wischmeier, 1975; Dissmeyer and Foster, 1981). Because cover varies greatly throughout the year, *C* values that reflect the crop growth stage must be used. At planting time, the seedbed for a conventionally planted corn is three times as susceptible to erosion as it is just before harvest with a full canopy. The distribution of cover interacts with the distribution of rainfall erosivity over the year. Erosion may be reduced by planting crops or managing land use so that soil-disturbing activities are performed during periods of less erosive rains.

Agriculture Handbook no. 537 (Wischmeier and Smith, 1978) gives the procedure for deriving local *C* factors in the USLE. A weighted *C* value is developed that reflects the distribution of the crop stages, the crop rotation, and the distribution of the average annual *EI* at the specific location where erosion is being estimated. Such a computation is illustrated in Table 8 of the handbook.

Erosion pavements reduce erosion under desertlike conditions. Where plant cover is limited, gravel-covered surfaces are very effective in absorbing the impact energy of raindrops. Renard et al. (1974) suggested that the percentage of the soil surface covered by gravel or larger material should be included with the plant cover in determining a *C* value for use in the USLE.

11-6 HUMAN ACTIVITIES

Human activity affects erosion by use of the land and installation of supporting erosion control practices. Adequate erosion control on land that is especially susceptible to erosion may restrict land use to forestry or grass-land. Land having fewer restrictions may be cropped, but may require special care, including the use of crop rotations. In many modern agricultural systems, continuous corn and soybean have replaced rotations of meadow, small grain, and corn. Adequate erosion control for continuous row cropping often requires use of conservation tillage systems. Most conversation tillage systems control erosion by leaving all or a part of the previous year's crop residue on the surface. Management practices that incorporate crop residues to improve soil tilth and structure are effective in increasing infiltration and therefore in decreasing runoff and erosion. Removing too much of the crop residue for energy production, animal feed, or building materials can greatly reduce the effectiveness of these systems.

These types of management effects are described by the USLE *C* factor. Supporting practices such as contouring, stripcropping, terraces, diversions, and detention ponds are accounted for in the *P* factor of the USLE.

11-7 SUPPORT PRACTICES

Most support practices control erosion by reducing the erosivity and transport capacity of runoff. Often the gradient and flow velocity along the runoff path are reduced enough that erosion by flow in rills and waterways is eliminated. The reduction in runoff erosivity is often great enough that deposition occurs, which reduces sediment yield from the field.

The sedimentation processes usually involved are detachment from areas where runoff erosivity has not been reduced and deposition in the area where it has been reduced. The sediment load entering this area must exceed the transport capacity of the flow for deposition to occur. The ratio of sediment leaving the deposition area to that entering depends on the relationship between the amount of sediment entering the area and the transport capacity of flow in the area (Neibling and Foster, 1977). This ratio is the *P* factor of the USLE.

11-7.1 Contouring, Graded Furrows, and Contour Ridges

Flow may travel along the contour before breaking over the row ridges, depending on the ridge height and the runoff characteristics. Flow along the contour is on a gradient considerably less than the direct downslope gradient. If the gradient along the row middles—the low area between higher plant row ridges—is steep, rill erosion may occur. If the gradient along the row is flat, deposition will occur in row middles. Where the flow breaks over the row ridges at low points, considerable rill erosion may occur. If the rows run vertically on the slope, transport capacity of flow in the middles increases rapidly as slope increases. On steep slopes where no deposition occurs, erosion from the ridges could be much greater than if the field were not ridged (Mutchler and Murphree, 1980).

11-7.2 Grass Strips

Detachment occurs on tilled areas upslope from the strips of close-growing vegetation, so that the sediment load at the upper edge of the vegetative strip is relatively high. The upper edge of the strip slows the runoff and reduces its transport capacity. If the transport capacity is reduced to less than the incoming sediment load, deposition occurs, which reduces the sediment load. Dense vegetation also eliminates most erosion within the strip.

11-7.3 Terraces

Terraces reduce rill erosion on overland flow areas by reducing slope length, but the total reduction in erosion is not great because interrill erosion per unit area is unaffected. For example, reducing slope length to one fourth of its original value cuts soil loss only in half according to the USLE. The greatest benefit of properly designed terraces is safe conveyance of concentrated surface runoff from the field without channel erosion.

If the sediment load reaching the terrace channel from the interterrace area is greater than the transport capacity of flow in the terrace channel, deposition occurs in the channel at a rate dependent on grade and other factors (Foster and Ferreira, 1981). If terrace channels are steep, they may erode with no deposition.

11-7.4 Waterways

Many farm fields contain natural or constructed waterways that convey runoff from the field. Tillage can significantly increase the erodibility of the soil in the waterway (Foster et al., 1980a). If an intense storm with large runoff rates occurs soon after tillage, erosion may be severe. These tilled waterways may erode downward to a relatively nonerodible layer at the depth of secondary or primary tillage; after reaching the nonerodible layer, they will widen. While they widen, erosion rate decreases. Erosion may be low during a storm if a previous, more intense storm has formed a wide channel.

Eroding waterways may be protected by reshaping to a broader, shallower channel and establishing grass. A good grass stand can almost completely eliminate erosion, and depending on the amount of incoming sediment and flow hydraulics, can cause deposition in the waterway. This deposition may reduce sediment yield at the edge of the field, but deposition in waterways frequently causes maintenance problems. Much of the deposition will be along the edge of the waterway, hampering the entrance of runoff into the waterway. The flow will move along the edges of a poorly maintained waterway, causing serious erosion problems.

11-7.5 Impoundments

Natural impoundments such as backwater at field outlets and constructed impoundments such as tile outlet terraces can trap large amounts of sediment by deposition and significantly reduce sediment yield at the edge of the field. Impoundment deposition depends on the opportunity for the sediment to settle to the bottom before runoff carries it away. Therefore, fewer fine particles than coarse particles are trapped. Likewise, impoundments that drain rapidly are less efficient sediment traps. Simple models, based on the settling velocity of particles, are available for estimating deposition and amount of sediment leaving impoundments (Laflen et al., 1978; Ward et al., 1977).

11-8 SEDIMENT CHARACTERISTICS

Sediment yield refers to delivery of sediment to a point in the watershed remote from the origin of the detached particles. The quantity of sediment yield and the sediment's size characteristics are important in analyses of nonpoint source pollution where the effectiveness of best management practices (those practices that minimize off-site pollution) is being evaluated. Sediment delivery is a transport process. When sediment available from the detachment processes exceeds the flow's transport capacity, deposition results. The USLE and a delivery ratio to account for deposition are often used to estimate sediment yield.

Fine soil particles cause the greatest water quality problems, yet these are the most difficult particles to remove from the flow. Practices that control sediment yield by inducing deposition remove the coarse particles first, leaving the fine ones. Therefore, the most effective sediment control for water quality maintenance is prevention of most erosion in the first place, thus eliminating the need for removal of sediment from the flow by deposition. Furthermore, control of sediment yield by control of erosion helps to maintain soil productivity.

Rates and amounts of deposition depend on the diameter and the density of the sediment particles. Sediment is typically a mixture of primary particles and aggregates. Diameters range from that for primary clay (0.002 mm) to that for coarse sand and aggregates (1.0 mm). Specific gravity ranges from 2.65 for primary particles to 1.6 for aggregates (Foster, 1982).

The distribution of sizes and densities of sediment particles depends on soil properties, previous management, tillage, and upslope deposition. On poorly aggregated soils the size distribution of the sediment at the point of detachment may be almost that of the primary particles of the soil mass. On other soils, most of the sediment may be eroded as aggregates. For example, a soil of 20% clay may yield sediment that is only 5% primary clay (Foster, 1982).

11-9 EROSION CONTROL STRATEGIES

Erosion is controlled in one or both of two ways: (i) reduce the erosive agents' energy (i.e., raindrop impact and runoff) or (ii) increase the soil's resistance to detachment. The second way is long term and highly desirable, but its impact is usually less than that of the first. Maintenance of cover in contact with soil is the most effective single factor for reducing erosion; a 90% mulch cover will cut erosion by 93% (Wischmeier and Smith, 1978). This type of soil cover reduces the energy of both raindrop impact and runoff. Often, it increases infiltration and reduces evaporation as well. Canopy, especially that near the soil surface, can reduce erosion caused by raindrop impact if the cover is dense. Minimizing the degree of soil disturbances leaves more crop residue on the soil surface and produces few soil particles that are easily detached and transported. Maintenance of soil roughness and contour tillage store detached soil particles and reduce runoff for small to moderate rainstorms. Shortening of slope length with terraces and diversions reduces rill erosion but not erosion by raindrop impact. Terraces and detention structures control sediment yield more effectively than they control erosion.

Good management practices such as crop rotations and incorporation of organic matter from crop residue and manure improve soil structure and soil tilth. These practices increase the soil's resistance to detachment, increase infiltration, and reduce runoff. Over the long term, the net result is a significant reduction in erosion. Meadow rotations are effective in the short run. Obviously, erosion is greatly reduced during the rotation period with the meadow. Moreover, a residual effect from the period with the meadow lasts for about 2 years for subsequent crops, such as corn.

11-10 SUMMARY

Soil erosion by water occurs when raindrops impact on bare soil or when water moves over the soil surface creating a shearing force. Erosion exceeding the natural regeneration rate may reduce the capacity of a soil to produce crops. Excessive erosion by surface runoff causes gully erosion that inconveniences farming operations and reduces land value. Climate, soil, topography, cover, and human activities on the land all affect erosion. Empirical equations based on field experiments are used to plan conservation practices to adequately control erosion.

Runoff transports the eroded sediment from the fields. If the transport capacity of the runoff is less than the sediment detached upslope, deposition that reduces the amount of sediment leaving the field occurs. Large and dense particles are the first to deposit during a storm event, leaving an enriched amount of fine sediment in the flow. These fine sediments are the carriers of many agricultural chemicals. Sediment may cause considerable off-site damage by filling water conveyance and storage structures, being a pollutant itself, and being a carrier of pollutants such as some fertilizer and pesticide compounds. Sediment yield estimates are required in water quality analysis to assess the importance of on-farm erosion to downstream degradation of water quality.

To date, most erosion and sediment yield prediction techniques have been empirical, but fundamentally based equations and models are being developed that will significantly improve prediction accuracy and will apply to a broad range of conditions.

11-11 APPENDIX

11-11.1 Basic Mechanics of Erosion by Water

Concepts of basic erosion mechanics were understood by the 1930's (Cook, 1936). Although equations describing these concepts had been formulated by the 1940's (Ellison, 1947), empiricism rather than theory yielded the universal soil loss equation (USLE) (Wischmeier and Smith, 1978). More recently, applied erosion models based on fundamental concepts and theory have been developed (Foster, 1982, Foster et al., 1980a). An understanding of basic erosion mechanics is useful for application of fundamental models as well as the USLE and extension of the USLE to new situations where data are limited.

11-11.2 Basic Principles

Erosion of soil by water is a process of detachment of particles (sediment) from the soil mass by the erosive agents rainfall and runoff. Detachment, the removal of sediment from the soil mass at a point, adds particles to the sediment load transported downslope by runoff. Deposition, the reverse of detachment, is the removal of soil particles from the sediment load in the runoff and their addition to the soil mass at a location remote from where the sediment originated. Deposition occurs where the transport capacity of the runoff is less than the sediment load in the runoff (Foster and Meyer, 1977).

For illustration, consider a concave slope. On the steep upper end of the slope, transport capacity often exceeds the sediment load (Fig. 11-3). Downslope, sediment load has increased due to detachment. Transport capacity tends to increase as runoff accumulates along the slope and tends to decrease with the steady decrease in steepness along the slope. The net effect is that transport capacity increases to a point part way down the slope and then decreases. If the slope becomes flat enough, transport capacity will become less than the sediment load, and deposition will begin.

Runoff as overland flow on many soils tends to concentrate in many small channels. Erosion occurring in these channels is defined as rill erosion (Fig. 11-4). Erosion occurring on areas between the rills is defined as interrill erosion (Foster and Meyer, 1977). Flow in rills transports the sediment downslope, and flow on interrill areas moves sediment laterally toward the rills. Interrill flow is generally along the microslopes, whereas flow in rills is along the macroslope.

As previously mentioned, erosion is dynamic, it varies with time within a storm and varies from storm to storm. Since erosion dynamics are complex, we have assumed a quasi-steady state to simplify this analysis. The main governing equation is continuity expressed by (Foster and Meyer, 1975):

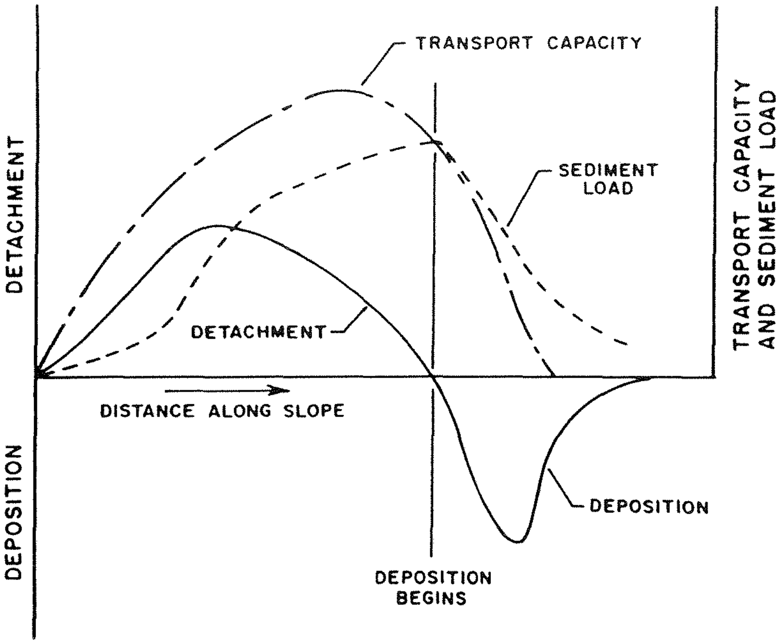


Fig. 11-3. Detachment, transport, and deposition processes along a concave slope that flattens enough to cause deposition.

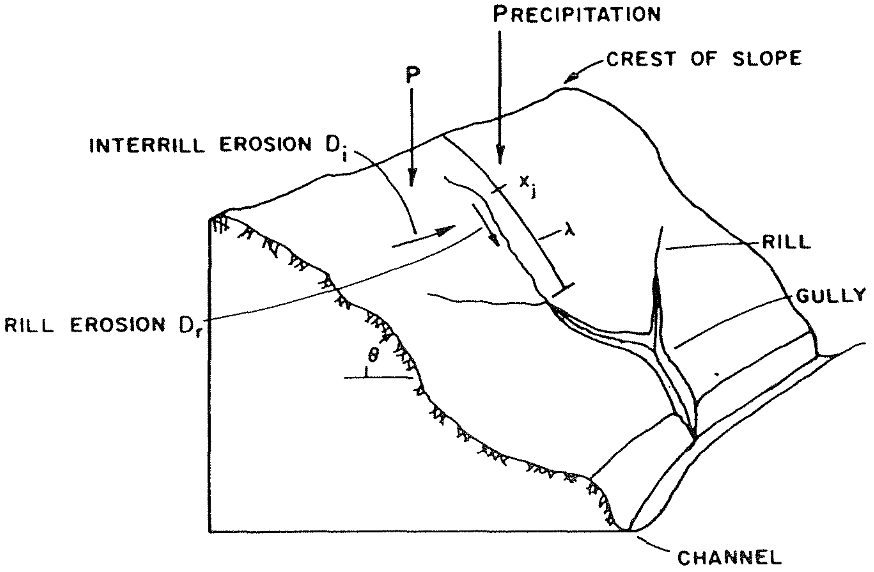


Fig. 11-4. Erosion on interrill areas, rills, gullies, and channels.

$$dg/dx = D_f + D_i \qquad [6]$$

where g = sediment load (mass per unit width per unit time), D_f = rate of detachment or deposition by flow in rills (mass per unit area per unit time), D_i = rate of delivery of sediment to rills by interrill erosion (mass per unit area per unit time), and x = distance downslope. Equation [6] is integrated to give sediment load at the location λ as

$$g = \int_0^{\lambda} (D_f + D_i)dx. \qquad [7]$$

The next step is to write relationships for D_f and D_i.

11-11.3 Relationships for Detachment and Deposition

Sediment delivery after detachment from interrill areas is closely related to raindrop impact and may be written as (Foster et al., 1977)

$$D_i = K_i i^2 (as + b)\phi_i \qquad [8]$$

where D_i = rate of delivery of sediment from interrill areas, K_i = soil erodibility factor for interrill erosion, i = rainfall intensity, s = sine of slope angle θ, a and b = coefficients, and ϕ_i = soil loss ratio for interrill erosion. Soil loss ratio expresses the effect of such factors as vegetative canopy, surface cover in direct contact with the soil, tillage, residue incorporation, roughness, and previous land use. Soil loss ratio is the ratio of soil loss with the given condition to that of a base or unit condition where the soil loss ratio is defined as 1.0. Clean tilled, continuous fallow soil is the unit condition used here and in the USLE (Wischmeier and Smith, 1978).

Detachment by rill erosion, which is closely related to flow hydraulics, may be written as (Foster et al., 1977)

$$D_r = 2K_r \sigma x (cs^2)\phi_r \qquad [9]$$

where D_r = rate of detachment by rill erosion, K_r = soil erodibility factor for rill erosion, σ = rate of runoff per unit area, c = a coefficient, and ϕ_r = a soil loss ratio for rill erosion. Equation [9], based on the concept that detachment by rill erosion is a function of shear stress of the runoff as it flows over the soil surface, was derived using hydraulic relationships for shear stress as a function of flow depth and slope steepness (Foster et al., 1977).

Rate of deposition is a function of the flow hydraulics, the diameter and density of sediment particles, and the sediment load. It is expressed by (Foster and Meyer, 1975) as

$$D_d = \alpha (T_c - g) \qquad [10]$$

where D_d = rate of deposition and T_c = transport capacity of the flow. The deposition coefficient α for overland flow is given by (Foster et al., 1980b) as

$$\alpha = 0.5\ V_f/\sigma x \qquad [11]$$

where V_f = fall velocity of sediment particles. The coefficient α is large for large and dense particles, expressing the rapid deposition of these particles when transport capacity becomes less than sediment load. The coefficient α is small for small and light particles expressing their slow rate of deposition and distant travel before deposition once transport capacity becomes less than sediment load.

11-11.4 Derivation of Erosion Equations

Erosion equations can be derived for uniform slopes where the independent variables can be assumed to be constant along the slope.

11-11.4.1 Detachment Along Entire Slope

The equation for this case is obtained by substitution of Eq. [8] and [9] into Eq. [7] to give

$$g = i^2 K_i(as + b)\phi_i \lambda + \sigma K_r(cs^2)\phi_r \lambda^2. \qquad [12]$$

The average soil loss A for the slope length is

$$A = g/\lambda \qquad [13]$$

or

$$A = i^2 K_i(as + b)\phi_i + \sigma K_r(cs^2)\phi_r\lambda. \qquad [14]$$

Erosion equations are usually written for soil loss A for the storm. Equation [14] is intergrated with respect to time to obtain (Foster et al., 1977)

$$A = E_i K_i(as + b)\phi_i + E_r K_r(cs^2)\phi_r\lambda \qquad [15]$$

where E_i and E_r = interrill and rill erosivity factors, respectively.

11-11.4.2 Deposition Along Entire Slope

One example of deposition along the length of a uniform slope is when interrill erosion on row side slopes exceeds the transport capacity of runoff in the row middles. Another example is deposition of sediment eroded from soil projecting above the flow in depressions of a rough surface. Deposition rate along the slope is given by (Foster et al., 1980b) as

$$D = [\psi/(1 + \psi)](dT_c/dx - D_i) \qquad [16]$$

where dT_c/dx = the change of transport capacity with respect to distance and may be taken as a constant for uniform slopes and

$$\psi = 0.5V_f/\sigma. \qquad [17]$$

The sediment load at λ is

$$g=(\psi dT_c/dx+D_i)[\lambda/(1+\psi)] \qquad [18]$$

and soil loss is

$$A=(\psi dT_c/dx+D_i)/(1+\psi) \qquad [19]$$

For a storm, T_c, D_i, and ψ are averages for the storm. The interpretation of Eq. [19] is as follows. If ψ is large, as for particles that are readily deposited, soil loss is approximately equal to dT_c/dx, the change in transport capacity with distance, and sediment load is approximately equal to transport capacity at the end of the slope. If ψ is small, as for particles that are not readily deposited, soil loss is approximately equal to the interrill erosion rate D_i, with sediment load approximately equal to $D_i\lambda$.

Since the equations describing deposition are nonlinear, a typical diameter and density for the sediment cannot be assumed. The sediment distribution is broken into classes, and the governing equations are applied to each class separately. However, interaction between the classes is required in the computation of transport capacity (Foster, 1982).

11-11.5 Universal Soil Loss Equation

The USLE is given by Foster and Wischmeier (1974) as

$$A_{st} = R_{st} K (\lambda/\lambda_u)^m [65.41 \sin^2 \theta + 4.56 \sin \theta + 0.0654]\phi \qquad [20]$$

where A_{st} = soil loss for a storm, R_{st} = storm erosivity factor, K = soil erodibility factor, m = slope length exponent, λ_u = length of unit plot (22.1 m), θ = angle of the slope, and ϕ = soil loss ratio. The USLE in Eq. [20] is on a storm basis, which is its most basic form. In practice, the USLE is intended to estimate average soil loss for many storm occurrences over an extended time, e.g., a crop stage or a year. The average value for erosivity R for the period, the average sum of R_{st}, is used in such calculations. Soil loss ratio is replaced by a cover management factor C, which is soil loss ratio weighted according to the interaction of nonuniform distributions of R_{st} and ϕ.

11-11.5.1 Theoretical Interpretation of USLE Factors

11-11.5.1.1 Equation Form. The USLE, like most empirical erosion equations, is of the form

$$A \propto \lambda^m. \qquad [21]$$

Equations [20] and [21], as approximations to Eq. [14], lump rill and interrill erosion together. Equations [20] and [21] estimate no soil loss at a zero slope length, whereas Eq. [14] gives some soil loss, which can be quite large. There is a limit to the shortness of a slope length to which the USLE applies. The USLE may not apply to slopes shorter than 5 m (Foster et al., 1981b) and certainly does not apply to slopes as short as 1 m, such as row side slopes. Soil loss at a zero slope length is from interrill erosion, which is assumed to be constant over a uniform slope.

If Eq. [20] and [21] are fitted to Eq. [14], the exponent m varies for different conditions. The exponent equals (Foster et al., 1977)

$$m = 1/(1 + \beta) \qquad [22]$$

where

$$\beta = [E_i K_i (as + b)\phi_i]/[E_r K_r (cs^2)\phi_r \lambda]. \qquad [23]$$

In this equation, the numerator is soil loss caused by interrill erosion, and the denominator is soil loss caused by rill erosion. Equations [22] and [23] show that the slope length exponent increases toward a maximum of 1 as rill erosion increases. This qualitatively agrees with Wischmeier and Smith's (1978) recommendation for an increase in m for slopes up to 5% such as was used in Eq. [5]. Other factors affecting the slope length exponent are the rate and amount of runoff relative to rainfall, interrill erodibility relative to rill erodibility, interrill soil loss ratio relative to that for rill erosion, and slope length (Meyer et al., 1975). Experimental data have indicated variability in m but have not been adequate to define the relationship (Wischmeier et al., 1958).

11–11.5.1.2 Irregular Slopes. Theory permits application of the USLE to irregular slopes where deposition does not occur and runoff rate per unit area is relatively uniform along the slope (Foster and Wischmeier, 1974). Detachment at a point, as described by the USLE, is

$$D = (1 + m)\, R\, K\, (x/\lambda_u)^m\, S\, C\, P \qquad [24]$$

where S = the USLE slope factor given by

$$S = (65.4s^2 + 4.56s + 0.0654). \qquad [25]$$

The factors K, S, C, and P are based on conditions at x. Note that erosion rate at λ is $(1 + m)$ times the soil loss for the slope length λ.

Irregular slopes may be analyzed by dividing the slope into segments so that the uniformity of K, S, C, and P is maintained with a segment but variability from segment to segment can be asumed. By Eq. [7], the sediment ΔG_j produced on a segment is

$$\Delta G_j = \int_{x_{j-1}}^{x_j} D\, dx \qquad [26]$$

or

$$\Delta G_j = (R/\lambda_u{}^m) K_j\, S_j\, C_j\, P_j (x_j^{m+1} - x_{j-1}^{m+1}) \qquad [27]$$

where Δx_j = the segment length.

The total sediment produced on the slope composed of k segments is

$$G = \sum_{j=1}^{k} \Delta G_j. \qquad [28]$$

The average soil loss for the entire slope is given by

$$A = G/\lambda. \qquad [29]$$

If the slope segments are of equal length,

$$x_j = j\lambda/k \qquad [30]$$

average soil loss for the slope is

$$A = R \sum_{j=1}^{k} (\lambda/\lambda_u)^m\, S_j\, K_j\, C_j\, P_j\, \omega_j \qquad [31]$$

where

$$\omega_j = (j/k)^{m+1} - [(j-1)/k]^{m+1}. \qquad [32]$$

Equations [31] and [32] are the algorithm given by Wischmeier and Smith (1978) for analyzing irregular slopes. Note that $(\lambda/\lambda_u)^m\, S_j$ is the LS factor for the entire slope length using the slope of the j^{th} segment. Average soil loss on the j^{th} segment is given by

$$A_j = R\, K_j\, C_j\, P_j\, (\lambda/\lambda_u)^m\, S_j\, \omega_j\, k. \qquad [33]$$

Average soil loss A_j on a particular segment may be several times the average for the entire slope.

11-11.5.1.3 Erosivity. Since the USLE lumps interrill and rill erosion together, the USLE factor for rainfall erosivity, R_{st}, represents rainfall erosivity for both interrill and rill areas.

Erosivity R_{st} is

$$R_{st} = EI \qquad [34]$$

where E = storm energy and I = maximum 30-min intensity. Total storm energy is obtained by integrating energy concentration e over the total rainfall duration as

$$E = \int_o^T e\, i\, dt \qquad [35]$$

where T = duration of rainfall, i = rainfall rate, and dt = differential of time. In application, Eq. [35] is usually written in discrete form as

$$E = \sum_{k=1}^{n} e_k\, \Delta V \qquad [36]$$

where ΔV = an incremental depth of rainfall, and e_k = rainfall energy per unit of rainfall for the k^{th} increment of rain and is given by

$$e_k = 0.119 + 0.0873 \log_{10} i_k \qquad [37]$$

where e = unit rainfall energy in megajoules per hectare per millimeter [MJ(ha mm)$^{-1}$] of rain, and i_k = intensity in millimeters per hour for the k^{th} increment. Since e varies little with i, especially above 100 mm/h,

$$E = a_e\, V\, i_{ch} \qquad [38]$$

where a_e = a coefficient, V = depth of rainfall, and i_{ch} = a characteristic rainfall rate. Assuming that maximum 30-min intensity I is a good measure of i_{ch} gives

$$EI = a_e\, T\, I^2 \qquad [39]$$

where T is a rainfall duration defined by $T = V/I$. Note that I^2 is similar to i^2 in Eq. [8] for interrill erosion. The i_{ch} term gives a rate of interrill erosion per unit of rainfall, which, multiplied by volume of rainfall, gives total interrill erosion for the storm.

For runoff, characteristic runoff rate (σ_{ch}), is related to I by $\sigma_{ch} = I - f_{ch}$ where f_{ch} is a characteristic infiltration rate. Likewise, depth of runoff is related to depth of rainfall. The I term can be viewed as giving a rate of rill erosion per unit of runoff for a characteristic runoff rate, which, multiplied by the depth of rainfall corresponding to the depth of runoff, gives total detachment for rill erosion for the storm. The factor EI, although originally derived empirically (Wischmeier and Smith, 1958), is a simple variable for erosivity that contains the important variables that should be in an erosivity factor. These variables are the intensity and volume of rainfall and the rate and volume of runoff.

11-11.6 Fundamental Models

Detailed models based on fundamental concepts of erosion mechanics and sediment transport are being developed that give the user power beyond the USLE (Foster, 1982). However, they typically require a computer and may require considerable effort to assemble input data. Also, some require measured data to calibrate model parameters. These models calculate erosion and sediment yield on a storm-by-storm basis, which is necessary where both detachment and deposition processes are important. Analysis of complex, spatially varied areas requires detailed models of this type. Also, these models more accurately consider hydrologic processes than simple relationships like the USLE. They will be used more and more in the future.

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