

**Development and Application of  
Modern Soil Erosion Prediction Technology  
— The USDA Experience**

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*Abstract*

Erosion prediction efforts are described to provide a synopsis of the USDA's experience in developing and applying soil erosion prediction technology in its research and development activities and its soil conservation programs. For almost five decades, equations to predict soil erosion by water have been useful in developing plans for controlling soil erosion and sedimentation. The Universal Soil Loss Equation (USLE) is the most widely known and used of the erosion prediction equations. The USLE presents a simply understood and easily applied technology which has been of incalculable benefit to soil conservation and land management. The Chemicals, Runoff, and Erosion from Agricultural Management Systems Model (CREAMS) contains a sophisticated erosion component based, in part, on the USLE and on flow hydraulics and the processes of sediment detachment, transport, and deposition. In 1985, the USDA in cooperation with BLM and several universities initiated a national project called the Water Erosion Prediction Project (WEPP) to develop a next generation water erosion prediction technology. The Revised Universal Soil Loss Equation (RUSLE) is an update of the USLE to improve erosion prediction in the interim before WEPP is adopted and to provide and adjunct technology thereafter.

*Keywords:* soil erosion, sedimentation, sediment yield, prediction models, soil conservation.

**Introduction**

Soil erosion science is very new compared with most of the agricultural sciences. Nearly all quantitative work has been done during the past half-century. New soil erosion research techniques incorporate a variety of technological skills developed during the past seventy years and have been aided by new scientific advances in related fields. These include improved or new measurement apparatus, laboratory procedures, electronics, mathematics, and the advent of computers and computer modelling.

Equipment and techniques have been developed to measure the rate of flowing water (runoff) from experimental plots and in streams in small watersheds. As

soil is eroded, it is transported as sediment by flowing water. The sediment concentration must be measured to determine sediment discharge rate. The product of sediment concentration (mass per unit volume of water) and flow rate (volume of water per unit time) gives sediment discharge rate in mass per unit time. By integrating sediment discharge rates throughout the period of flow or the duration of runoff, sediment yield is obtained from the experimental plot or the area above the point of measurement for a small watershed. Sediment yield is the net result of sediment detachment by impacting raindrops and flowing water, sediment transportation by raindrop splash and flowing water, and sediment deposition.

#### *Erosion Processes, Modelling and Erosion Prediction*

Our increased ability to conduct carefully controlled experiments and rapidly record data under a wide variety of soil, climate, and land use alternatives has provided a stimulus for research to develop new and better methods of interpreting, synthesizing, and generalizing data. These research efforts are needed to better understand the physical processes controlling soil erosion. The need to understand the processes and mechanisms governing erosion rates and amounts has led in turn to a scientific need to develop a predictive capability.

The ability to predict soil erosion impacts of various land uses and management practices before they are implemented allows land managers to select the most suitable alternatives for preventing or reducing soil erosion. A predictive capability is essential for erosion control and soil conservation because alternative management practices are numerous, expensive, and the results of a particular practice may take years or decades to exert a measurable influence on soil erosion. The prediction technology can be used to screen feasible alternatives and to eliminate those practices with the highest, unacceptable, erosion rates.

#### *Scope and Purpose*

Erosion prediction technologies discussed in this paper are limited to those used in the United States and to those developed and used by United States Department of Agriculture (USDA) agencies. The discussion is limited to soil erosion by water, although wind erosion specialists have developed similar technologies.

This paper provides a synopsis of the USDA's experience in developing and applying soil erosion prediction technology in its research and development activities and its soil conservation programs. Emphasis is on technology development with some discussion on application of erosion prediction technology in soil conservation planning.

#### *Brief History*

For almost five decades, equations to predict soil erosion by water have been useful in developing plans for controlling soil erosion and sedimentation. The Universal Soil Loss Equation (USLE) is the most widely known and used of the erosion equations. The USLE represents a simply understood and easily applied technology of incalculable benefit to soil conservation and land management.

The basis of the USLE can be traced to the erosion equation for sheet and rill erosion as affected by slope length and steepness (Zingg 1940) and subsequent modifications for climate, cropping and management (Smith and Whitt 1957). With this basis and a large body of experimental plot data, the USLE was completed and documented in 1965 and updated in 1978 (Wischmeier and Smith 1965, 1978). The USLE has many strengths but it also has limitations. One of the major limitation is the form of the equation—it is not process-based.

Erosion processes were described as early as the 1940's (see e.g. Ellison 1947) and represented in the form of useful equations by the 1960's (e.g. Meyer and Wischmeier 1969). Subsequent advances in hydrology and erosion science have provided the means of developing improved erosion prediction technology based on infiltration theory, hydrodynamics of overland flow, and interrill and rill erosion processes. The Chemical Runoff and Erosion from Agricultural Management Systems model (CREAMS) (Knisel 1980) contains a sophisticated erosion component based, in part, on the USLE and also on flow hydraulics and the processes of sediment detachment, transport and deposition. The CREAMS erosion component also calculates erosion by concentrated flow, the contributions of ephemeral gullies, and deposition in backwater and impoundments.

In 1985 the United States Department of Agriculture, in cooperation with the Bureau of Land Management and several universities, initiated a national project called the USDA Water Erosion Prediction Project (WEPP) to develop a new generation water erosion prediction technology (Foster 1987). As a practical, operational version of WEPP was not anticipated until 1995, an effort to revise the USLE was initiated at the same time (Renard *et al.* 1991).

#### *The Institutional Basis of Erosion Prediction*

The erosion prediction technology described above is designed to address conservation activities for USDA enabling legislation such as the Soil and Water Resource Conservation Act of 1977 (PL 95-192, commonly referred to as RCA), the National Resource Inventory which is a component of RCA, the Forest and Rangeland Renewable Resources Planning Act of 1974 (PL 93-378, commonly called RPA), the Food Security Act of 1985 (PL 99-198), and the Renewable Resources Extension Act of 1978 (PL 95-306, called RREA). These legislative authorizations direct the activities of eight USDA agencies: Agricultural Research Service (ARS), Agricultural Stabilization and Conservation Service (ASCS), Cooperative State Research Service (CSRS), Economics Research Service (ERS), Extension Service (ES), Farmers Home Administration (FmHA), Forest Service (FS), and Soil Conservation Service (SCS). In addition, other agencies in other departments of American federal and state governments are expected to use this technology, as are consulting firms involved in environmental planning. Thus, provision must be made to ensure that the technology is available to the extensive list of users and that it is correctly applied and interpreted.

The soil loss tolerance concept is another important aspect of soil conservation planning that may be replaced by modern erosion prediction technology such as WEPP. This, in turn, may lead to new definitions of soil erodibility and highly erodible lands, definitions that are the basis of many agency programs within USDA. Hence, the importance of documenting the scientific basis, development, implementation, and application of erosion prediction technology is evident.

## The Universal Soil Loss Equation (USLE)

### *Description and Scientific Basis*

The statistically derived Universal Soil Loss Equation (Wischmeier and Smith 1978) is used to compute sheet and rill erosion as a function of factors representing climate, soil, topography, and land use. The USLE is

$$A = R K L S C P, \quad (1)$$

where  $A$  is the average annual soil loss,  $R$  is the erosivity factor,  $K$  is the soil erodibility factor,  $L$  and  $S$  are slope length and steepness factors, respectively,  $C$  is the cropping-management factor, and  $P$  is the supporting practices factor. The erosivity factor  $R$  represents the effect of rainfall and runoff, the soil erodibility factor  $K$  represents the effect of soil, the length and steepness factors  $L$  and  $S$  represent the effect of topography, and the cropping-management and supporting practices factors  $C$  and  $P$  represent the effect of land use and management.

The USLE was derived from more than 10 000 plot-years of data. Typical plots were 1.8 m wide and 22.1 m long (0.004 ha) and were located in all regions of the United States east of the Rocky Mountains. A variety of slope lengths and cropping and management practices were studied over a wide range of climatic conditions. Bare plots were included at several locations to evaluate soil erodibility. Supporting practices such as contouring, stripcropping, and terracing were evaluated on small watersheds approximately 0.8 hectares in size.

The USLE has two major components, the dimensional terms  $R$  and  $K$  and the nondimensional terms  $L$ ,  $S$ ,  $C$  and  $P$ . The product  $RK$  computes soil loss for the unit plot condition for a specific soil at a specific location. A unit plot is defined as 22.1 m long on a 9% slope maintained in a continuous up and down hill tillage condition. The  $L$ ,  $S$ ,  $C$  and  $P$  terms adjust the experimental field plot soil loss to unit plot conditions. For example, a  $C$ -factor value of 0.34 means that a particular cropping-management system is 34% as erodible as the unit plot condition.

### *Rainfall and runoff erosivity factor $R$*

An erosivity map for the Eastern United States was developed from  $R$  values calculated using weather data from 182 locations in the U.S. In the Western United States, where rainfall is highly variable in space, values for  $R$  were estimated using the 2-yr frequency, 6-h duration rainfall amount for a location.

### *Soil erodibility factor $K$*

The soil erodibility factor  $K$  is the rate of soil loss per unit erosion index as measured on a unit plot. Under unit plot conditions, with the  $LS$ ,  $C$  and  $P$  factors equal to 1.0, the value for the erodibility factor  $K$  is the slope of the regression line, through the origin, between erosion index and soil loss.

Initially, the  $K$ -factor was evaluated for a series of benchmark soils (Wischmeier and Smith 1978), and soil scientists assigned  $K$ -factor values to other soils by comparing their properties to those of the benchmark soils. Later Wischmeier and Mannering (1969) conducted field rainfall simulator experiments on approximately 55 soils to produce the data used to develop the USLE soil erodibility nomograph which relates  $K$  to soil properties (Wischmeier *et al.* 1971).

### *Topographic factors L and S*

Variations of slope length and steepness in the field from the unit plot conditions are accounted for in the *L* and *S* factors. The *L* and *S* factors vary among storms, soils, slope lengths and cropping-management conditions, but a single slope steepness relationship was chosen to represent the effect of steepness (McCool *et al.* 1987).

The USLE originally applied only to uniform slopes. Later, Foster and Wischmeier (1974) developed a method based on the sediment continuity equation for applying the USLE to slopes nonuniform in shape, soil, and cover-management. However, even with this method, the USLE does not apply to areas such as the toe of a concave slope beyond where deposition occurs. Thus the USLE cannot be used to compute sediment yield without applying a sediment delivery ratio or substituting a runoff erosivity factor for the *R*-factor (Williams 1975).

### *Cover-management factor C*

Crop stages were defined to consider the wide variation in erosion that results from varying cover during a crop growth cycle. The principal USLE crop stages are F, fallow; SB, seedbed; 1, early growth; 2, developing growth; 3, maturity; and 4, after harvest. Factors influencing erosion include canopy development, production of ground cover during harvest, loss of ground cover by tillage and decomposition, production or reduction of surface roughness by tillage, change in roughness by soil consolidation and rainfall, aggregate reduction by tillage, and variation of soil erodibility by season.

The soil loss ratio (SLR) is the ratio of soil loss during crop stage to soil loss from the unit plot during the same period. Soil loss ratios also take into account the residual effects of previous crops on soil erodibility. Because the USLE does not include explicit infiltration and runoff terms, soil loss ratios partially account for variation in infiltration and runoff among seasons and cover and management conditions. Soil loss ratios also account for the variation of soil erodibility with level of production since increased biomass affects erodibility.

Soil loss ratios for agricultural conditions were derived from a large, experimentally obtained data base. However, a similar data base did not exist for uncultivated land such as rangelands. In the absence of a data base, the subfactor method (Wischmeier 1975) was used to estimate soil loss ratios for uncultivated land. The subfactor method represented three major effects of canopy, ground cover, and within soil. Dissmeyer and Foster (1981) extended this approach to disturbed forest lands.

Values for *C*-factors can be computed 'once and for all' for specific cropping-management practices on specific regions. Thus, tables of site-specific *C*-factor values were produced to greatly facilitate application of the USLE.

### *Support practice factor P*

The *P*-factor represents the effect of supporting structural conservation practices such as contouring, terraces and stripcropping on erosion. The *P*-factor values were obtained by comparing the sediment yield from small watersheds with supporting practices to the sediment yield from watersheds or plots with up-and-down hill tillage. In some of the watersheds studied, ephemeral gully erosion, which does not occur on plots, was found to produce much sediment in addition to the

contribution by sheet and rill erosion (Foster and Ferreira 1981). The computed soil losses do not include gully or streambank erosion.

### *Applications*

The USLE was initially developed as a tool to assist in conservation planning on cropland. However, the USLE has been used and sometimes misused (Wischmeier 1976) for many other conditions including rangelands, disturbed forestlands, construction sites, and surface mine reclamation sites. Typically, a soil loss is computed for a set of proposed practices. Practices having computed soil loss values less than a soil loss tolerance assigned to the specific soil or site are considered acceptable.

Soil loss tolerance values are usually set by considering the soil factors of texture, moisture holding capacity, depth, nutrient loss by erosion, soil formation rates, off-site detrimental effects of sediment yield, and tendency for gullies to develop (Soil Loss Tolerance Workshop 1956; McCormack and Young 1981). Values are chosen so that long-term productivity and land value can be maintained while allowing practical farming practices. Annual soil loss tolerance values for cropland typically range from approximately 7 to 11 t ha<sup>-1</sup>. In contrast to the USLE which has a large data base as its scientific basis, soil loss tolerance values are largely based on judgment.

A major USLE application that emerged during the 1970's was the inventory of erosion rates. During the last 20 years, several national inventories on non-federal U.S. lands were conducted to estimate sheet and rill erosion and other variables that affect land quality (National Research Council 1986). One extensive survey used the USLE to compute erosion at more than one million sample points. Results from these inventories were used by Congress and other public agencies to develop soil conservation policies. Generally, these policies have identified lands that are highly susceptible to erosion and have targeted resources to these lands, rather than distributing resources regardless of erosion rate.

Federal legislation in 1985 and again in 1990 required that farmers control erosion below a certain level to be eligible to participate in certain farm programs (Cohen *et al.* 1991). The USLE is being used to help farmers determine acceptable practices and by agencies to determine if farmers have complied with the legislation. Several states also have erosion and sediment control laws where the USLE is used to implement the laws.

### **The Chemicals, Runoff, and Erosion from Agricultural Management Systems Model (CREAMS)**

#### *Description and Scientific Basis*

During the 1970's, the impact of agricultural practices on off-site water quality became a major concern. The CREAMS model (Knisel 1980) was developed as a tool to evaluate the relative effects of agricultural practices on pollutants in surface runoff and in soil water below the root zone. Because sediment is a major pollutant and a carrier of contaminants, the CREAMS model included an erosion component (Foster *et al.* 1981). The CREAMS model applies to field-sized watersheds that are typically less than 40 ha but may be as large as about 400 ha. The watershed is assumed to be uniform in soil, topography, and land use.

Because of the concern for off-site water quality, sediment yield and characteristics of the sediment leaving the watershed are the main erosion-related variables computed by CREAMS. The amount of sediment leaving a field is limited by either transport capacity or detachment. Therefore, a process-based approach was used in CREAMS rather than either the USLE (Wischmeier and Smith 1978) or the Modified USLE (MUSLE) (Williams 1975). The erosion/sedimentation component of CREAMS is used to compute soil loss on a storm-by-storm basis to be compatible with the continuous simulation model chosen to compute the movement of nutrient and pesticide chemicals. To minimize computer run time, storm erosivity  $EI_{30}$  and peak runoff rate were used to compute an 'average' sediment concentration in the runoff for each storm. This approach was judged adequate because CREAMS was intended to be used principally to evaluate relative differences among practices.

Runoff concentrates in a few major channels before leaving most farm fields (Foster 1986). The profile along these channels is often concave such that major scour, termed ephemeral gully erosion, can occur along the upper reach of these channels and deposition may occur along the lower reach of the channels. This erosion, not estimated by the USLE, can be as great as that produced by sheet and rill erosion.

Many fields also have concave slopes that foster deposition and reduce sediment yield, thereby increasing the fraction of fines in the remaining sediment. Impoundment terraces and gradient terraces also can reduce sediment yield while increasing the proportion of fines in the sediment. The USLE does not estimate this deposition nor does it compute the enrichment of fines caused by deposition.

A hydrologic element approach was used in CREAMS to consider a variety of topographies and management and structural practices. The three hydrologic elements in CREAMS are overland flow, channel and impoundment. A 'field-sized' area is represented by choosing a collection of these elements.

The main equation governing both the overland flow and channel elements is the steady-state continuity equation for sediment transport (Foster *et al.* 1981)

$$dG/dx = D_f + D_s, \quad (2)$$

where  $G$  is the sediment load (mass/width-time),  $x$  is distance,  $D_f$  is the detachment or deposition rate by flow (mass/area-time), and  $D_s$  is the rate that sediment is added to the flow from lateral areas (mass/area-time). Equation (2) accounts for sediment detachment, transport, deposition, and thus sediment yield. The erosion component used for CREAMS was a major advance in expressing soil erosion as a process-based phenomenon.

#### *Overland flow*

The overland flow hydrologic element in CREAMS represents the area where sheet and rill erosion occur. An overland flow element is described by distance and steepness along a representative landscape profile. The shape of this profile can be uniform, simple concave or convex, or complex, which is a combination of convex-concave or concave-convex. The landscape profile can be short, such as 0.5 m to represent the sideslope of a ridge-furrow system in a cotton field,

or long, such as the flow path from the watershed divide to a concentrated flow area, typically from 30 to 180 m.

A modification of the USLE (Foster *et al.* 1977) is used to compute interrill erosion, primarily caused by raindrop impact, which is separate from rill erosion, primarily caused by flowing water. Values for the various USLE factors are chosen from standard USLE tables.

In situations such as decreasing slope steepness, sediment load can exceed transport capacity even if no rill erosion occurs. Deposition occurs in such a situation and is computed by (Einstein 1968)

$$D_p = 0.5V_f(T_c - G), \quad (3)$$

where  $D_p$  is deposition rate (mass/area-time),  $T_c$  is transport capacity (mass/width-time), and  $V_f$  is the fall velocity of a particle class. The 0.5 factor accounts for the tendency of raindrop impact to keep sediment suspended in shallow flow (Renard and Foster 1983). A value of 1 is used for the channel element because raindrop impact is assumed to have minimal effect in keeping sediment suspended in the channel flow. Equation (3), which is solved by particle class, is the principal means by which CREAMS computes enrichment of the sediment in fines when deposition occurs.

The Yalin (1963) equation is used to compute transport capacity. This equation was chosen because previous research and evaluations during the development of CREAMS showed it to be the best equation available (Foster and Meyer 1972; Alonso *et al.* 1981). The Yalin equation was modified to consider up to 10 particle classes and to shift transport capacity among particles classes when transport capacity for one class was greater than load for that class and load exceeded transport capacity for another class (Foster 1982).

An important CREAMS development was to allow sediment to be aggregated. Sediment eroded from most agricultural fields is a mixture of primary particles and aggregates (Foster *et al.* 1985). The aggregates are often much larger than the primary particles making up the aggregates. Aggregates are thus readily deposited even though they may have a high clay content, although clay is not easily deposited in a dispersed state. Because chemical pollution potential of clay sediment is much higher than that for silt and sand, the composition of the sediment and its enrichment by deposition is very important in computing the contaminant load carried by sediment.

#### *Channel element*

Sediment is routed through the channel element using the same method as in the overland flow element with two exceptions. Lateral inflow of sediment is from the overland flow element or from another channel element if two channel elements are in series. The other exception is that detachment by flow,  $D_f$ , is computed from

$$D_f = K_c(\tau_s - \tau_c), \quad (4)$$

where  $K_c$  is a soil erodibility factor for detachment by flow,  $\tau_s$  is shear stress acting on the soil and  $\tau_c$  is critical shear stress of the soil. Parameter values



were determined from rill erosion experiments and from the literature (Foster and Lane 1983). Experiments showed that detachment by flow is strongly related to the recency of tillage. Immediately after tillage, some soils are highly susceptible to detachment by flow, but over a period of about four months, resistance to erosion increases significantly.

Because untilled soil is generally much more resistant to rill erosion by flowing water than is tilled soil, untilled soil immediately beneath the tilled surface layer often acts as a less erodible layer (Foster and Lane 1983). When an eroding channel scours to a resistant layer, channel widening dominates and erosion rate decreases. If flow continues for a sufficiently long period of time, erosion may almost cease. Thus, erosion in such a channel depends on the size of the storm relative to the size of the channel eroded by previous storms. Equations were derived to compute these phases. The equations for the initial phase before the channel reaches the less erodible layer describe a channel geometry that is a function of the flow hydraulics and the critical shear stress of the soil (Foster and Lane 1983). In the second phase, the equations compute erosion at the intersection of the channel sidewall and the less erodible layer. The general form of the equation for erosion rate as it decreases with time is an exponential decay function (Foster and Lane 1983).

An important feature of CREAMS is the ability to analyse the effect of backwater at the edge of a field. Restrictions such as culverts, ridges around fields, and dense vegetation around fields retard runoff causing as much as 70% of the sediment load to be deposited in these backwater areas within the field (Foster 1986). The user specifies characteristics of the outlet control and, if backwater exists, the model computes a reduced slope of the energy gradeline for the flow, which reduces the transport capacity of the runoff at the edge of the field.

#### *Impoundment element*

The impoundment element in CREAMS is used to compute the deposition in impoundment terraces that drain through an underground tile. Discharge from these terraces is controlled by an orifice in the standpipe that drains the terrace. The impoundment component is based on analyses of output from detailed simulations (Laffen *et al.* 1978) and on measured data from impoundment terraces (Laffen *et al.* 1972).

#### *Applications*

The erosion component of CREAMS has principally been used to compute loss of pollutants from field-sized agricultural areas. However, the CREAMS erosion component can also be used as an erosion model on its own if estimates are available on an individual storm basis for storm erosivity, volume of runoff, and peak runoff rate.

A typical application for a field is to use the overland flow-channel element sequence. The overland flow element is used to compute sheet and rill erosion and the channel element is used to compute ephemeral gully erosion and deposition in the backwater at the field outlet. The effectiveness of a grass waterway can be analysed using the channel element in this application. The model can also analyse a waterway having sections of differing covers.

With the CREAMS erosion component, the user is able to identify where in the field system major erosion and deposition rates are occurring. Thus, the user is able to evaluate the effect of alternative practices on localized erosion and deposition rates, sediment yield and sediment characteristics from each hydrologic element used in the sequence describing a particular field system. The model computes an enrichment ratio, which is the ratio of specific surface area of the sediment to the specific surface area of the soil. Summation of the product of the enrichment ratio and the sediment yield for each storm indicates the pollution potential of the sediment itself and as a carrier of chemicals.

### **The Revised Universal Soil Loss Equation (RUSLE)**

#### *Description and Scientific Basis*

The effort to upgrade the Universal Soil Loss Equation was precipitated by recognition that the knowledge acquired since the 1978 update of the USLE needed to be incorporated to improve erosion prediction. Thus, the Revised Universal Soil Loss Equation effort was initiated in April 1985 and is now available to users.

Although the RUSLE maintains the basic six-factor product form of the USLE, all equations used to arrive at the factor values have been modified. The technology is computerized so it is possible to evaluate conditions not possible with the USLE. For example, crops for which soil loss ratios were not available in the USLE can now be simulated based on some fundamental crop measurements.

#### *Rainfall and runoff erosivity factor $R$*

The procedure used for extrapolating  $R$ -factor values for the Western U.S. by using the 2-yr frequency, 6-h duration precipitation values has proven to provide poor estimates.

The RUSLE incorporates hourly precipitation data collected from more than 1000 National Weather Service (NWS) rain gauges to calculate point values of  $R$ . Available records varied from as short as 5 years to more than 20 years. A linear correction was used to adjust the hourly recorded amounts to those which might be obtained in a more conventional short-interval hyetograph. The new method produced point estimates of  $R$  that are as much as seven times as large as those in The USLE User's Manual, Agricultural Handbook 537 (Wischmeier and Smith 1978).

In the Pacific Northwest, where much of the erosion occurs from melting snow on partially frozen soil, an equivalent  $R$ -factor value was calculated.

Some minor changes were also made in the Eastern U.S., for example, a correction factor was developed to reduce  $R$ -factor values where flat slopes are found in regions of long, intense thunderstorms. Pondered water on the soil reduces the erosivity of raindrop impact.

#### *Soil erodibility factor $K$*

The RUSLE contains a soil erodibility nomograph for estimating  $K$ -factor values. If the nomograph does not apply, an equation based on 'average diameter' of the soil particles can be used to estimate  $K$ . An algorithm that includes a term for aggregate stability can be used to estimate  $K$  for volcanic soils such as those found in Hawaii.

Another change incorporated in the RUSLE accounts for rock fragments on the soil surface and in the soil profile. Rock fragments on the soil surface (e.g., erosion pavement) are treated like mulch in the  $C$ -factor, and the  $K$ -factor value (from the nomograph) is adjusted to reflect the effects of rock on permeability and, in turn, runoff. The profile rock is assumed to reduce permeability and thereby increase runoff and the soil erodibility.

In the RUSLE,  $K$  varies seasonally. Experimental data have shown that  $K$ -factor values vary with season and are highest in spring when freeze-thaw actions cause soil fluffing. The lowest values are observed in mid-autumn following rain compaction and in winter because of frozen soil. The seasonal variability is addressed by the RUSLE with estimates of  $K$  weighted in proportion to 15-day interval EI estimates. The  $K$  estimates are obtained with equations that relate  $K$  to the frost-free period and to the annual  $R$ -factor.

#### *Topographic factors $L$ and $S$*

The RUSLE uses three separate slope length relationships which include (a) a function of slope steepness, as in the USLE, (b) a function of the soil's susceptibility to rill erosion relative to interrill erosion, and (c) a slope length relationship specifically for the Palouse region in the Pacific Northwest. Guides in the computer program and the user handbook help the user identify the appropriate relationship for the particular field condition encountered.

The RUSLE uses a more nearly linear slope steepness relationship than the USLE. The RUSLE and the USLE generate similar soil loss values for slopes less than about 20%, however, on steep slopes, computed soil loss is significantly less with RUSLE. Use of the USLE quadratic relationship for steep slopes is not supported by experimental data and field observations. The RUSLE also provides a slope steepness relationship for short slopes subject primarily to interrill erosion, such as might be experienced on bedded fields and on the cuts associated with road construction. Another slope steepness relationship was developed for the Palouse region of the Pacific Northwest.

#### *Cover-management factor $C$*

As in the USLE, the soil loss ratios used to calculate the  $C$ -factor values are perhaps the most important components in the RUSLE because they represent conditions that can be managed most easily to reduce erosion. Furthermore, values of  $C$  can vary from near zero for a very well protected soil to about 1.5 for a finely tilled, ridge surface that results from much runoff and leaves the soil susceptible to rill erosion.

Values for  $C$  are weighted average soil loss ratios (SLRs) that represent the predicted soil loss for a given condition at a given time to that for a unit plot (see section on The Universal Soil Loss Equation, Description and Scientific Basis, for definition of a unit plot). The SLRs vary during the year as soil and plant conditions (cover) change. The RUSLE computes  $C$ -factor values by weighing the 15-day SLRs according to the seasonal distribution of EI.

In RUSLE, the SLRs are computed as a function of five subfactors: prior land use, canopy cover, surface cover, surface roughness and soil moisture. One

reason for the subfactor approach in the RUSLE is for applications where SLR values are not available from experimental research.

Grazing effects on rangeland, pasture and meadow are reflected in the effect of canopy height, ground cover and root biomass. Finally, in the USLE, ground cover reflected vegetation and litter; in the RUSLE, ground cover is given as 1.0 minus the amount of bare soil to reflect the addition of litter in the form of rock and stone to the conventional vegetative litter.

#### *Support practice factor P*

Of all the USLE factors, values for the support practice *P*-factor are the least well defined. The *P*-factor mainly represents how surface conditions affect runoff paths and hydraulics. For example, with contouring, tillage marks are credited with directing runoff around the slope at much reduced grades. However, slight changes in grade can change runoff erosivity greatly.

In experimental field studies, small changes in such features as row grade, and their effect on erosion, are difficult to document leading to appreciable scatter in measured data. For example, the contouring effectiveness in field studies conducted on a given slope have ranged from no reduction in soil loss to a 90% reduction. Thus, *P*-factor values represent broad, general effects of such practices as contouring.

In the RUSLE, extensive data have been analysed to re-evaluate the effect of contouring. Furthermore, simulation studies have been conducted using the CREAMS model (Knisel 1980). The results have been interpreted to give factor values for contouring as a function of ridge height, furrow grade and climatic erosivity. New *P*-factor values for the effect of terracing account for grade along the terrace, while a broader array of stripcropping conditions are considered in the RUSLE.

Finally, *P*-factors have been developed to reflect conservation practices on rangeland. The practices require estimates of surface roughness and runoff reduction as with the stripcropping option for croplands.

#### *Applications*

Although the RUSLE maintains the same structural limitation form inherent to the USLE (the multiplicative product of six factors), the equations used to evaluate individual factors are significantly different.

Of greatest significance is that *C*-factor values can be estimated with the RUSLE for crops and management and tillage systems where SLRs were not available. Given that users can obtain data to develop a crop file for their conditions, SLRs with which to calculate a *C*-factor can be made for any crop. Also, new tillage implements can be added to the operations file to cover a range of tillage activities.

Furthermore, data gaps for estimating *R*-factors, the time varying *K*-factor, the new algorithms for the topographic factor, and the new technology developed for estimating support practices greatly enhance RUSLE and permit its application to modern farming practices used throughout the U.S. The technology also shows promise for use in other parts of the world including developing countries.

## The USDA Water Erosion Prediction Project (WEPP)

### *Description and Scientific Basis*

The Water Erosion Prediction Project (WEPP) resulted from a 1985 workshop held at Lafayette, Indiana. There it was concluded that the technology existed, with the addition of some well targeted research, to develop a process-based soil erosion prediction technology. Subsequently, a series of meetings was held with various users to define the requirements of such a technology and to establish a plan to develop the technology. These requirements and plans are embodied in a set of User's Requirements (Foster 1987).

The WEPP model is a daily time-step simulation model which uses the rill-interrill concept of soil erosion (Foster 1982). The WEPP model simulates the processes that occur on a piece of land that determine the status of its soil, plant, residue and water. The status of these characteristics determines the response to a hydrologic event, whether it is rain, snow, snowmelt or frost accumulation.

The WEPP model is intended to apply to all situations where water erosion occurs, including that resulting from rainfall, snowmelt and irrigation. However, the WEPP model is limited to water erosion occurring from sheet, rill, and ephemeral gully erosion processes. The erosion occurring in large gullies and perennial streams is not considered, nor is streambank erosion or erosion from wave action. The WEPP technology is to apply to cropland, pastureland, rangeland, forestlands and lands disturbed by construction and mining.

Major milestones in the project to date have been the development of a set of user requirements (Foster 1987), documentation of the project (Lane *et al.* 1988; Lane *et al.* 1989; Elliot *et al.* 1989), and the delivery of a version for field testing in August 1989 (Lane and Nearing 1989). The technology is to be ready for use by action agencies in 1993, and is expected to be fully implemented by the Soil Conservation Service by 1995.

### *Versions of WEPP*

Three versions of WEPP will be developed, namely profile, watershed and grid. The profile version is a direct replacement of the Universal Soil Loss Equation and is an integral part of the watershed and grid versions.

The profile version computes detachment and transport by raindrop impact, and detachment, transport and deposition by flowing water. It is applied to a hillslope where sheet and rill erosion can occur, as with the USLE, except the WEPP profile version also considers sediment deposition. It is applicable from the edge of a watershed to a channel.

Sediment delivery from a small watershed is estimated using the WEPP watershed version. The watershed version includes the WEPP profile version to estimate sediment delivery to channels from one or more profiles within a watershed. The watershed version will compute sediment transport, deposition and detachment in small channels and impoundments within a watershed. The watershed version simulates erosion in small ephemeral channels, but not the erosion occurring in classical gullies.

The grid version is designed to be used for areas not satisfactorily represented by the watershed version. This might be because a field under evaluation is in several different watersheds, only part of the watershed is under study, or perhaps

only a portion of an area is receiving irrigation water. Such an area might be broken up into several smaller areas, called elements, and within each element the profile version applied. The grid version would also deal with sediment transport from element to element, and with delivery of sediment from the area through one or more discharge points.

#### *Soil erosion*

Soil erosion is a process of detachment, transport (Ellison 1947) and deposition. The WEPP model considers rill and interrill erosion processes and deposition in the profile version. Interrill erosion is the detachment and transport by raindrops and very shallow flows. Rill erosion is the detachment by concentrated runoff.

Interrill erosion is modelled as a function of an interrill erodibility factor, interrill slope and the square of rainfall intensity. The interrill erodibility factor is a function of soil texture and surface and crop canopy cover.

Rill detachment on bare soil is estimated as a linear function of excess hydraulic shear. The slope of the linear function is defined as rill erodibility, the hydraulic shear that must be exceeded before rill detachment occurs is the critical hydraulic shear. Rill erosion rates on an area are affected by sediment in runoff water and residue and plants that affect hydraulic shear.

Sediment transport in rills and channels is computed using the Yalin sediment transport equation (Yalin 1963). Sediment load and the fall velocity of transported sediment, along with the Yalin sediment transport equation, are needed to compute deposition in runoff. Deposition in impoundments is computed similarly to that in CREAMS (Knisel 1980).

#### *Hydrology*

The WEPP model contains three major components related to hydrology, namely a climate component, an infiltration-runoff component, and a winter component for snow accumulation, snow melt and soil frost.

Generated or measured climate variables, including storm rainfall amount and duration, ratio of peak rainfall intensity to average rainfall intensity, time when peak intensity occurs, daily maximum and minimum temperature, wind velocity and direction, and solar radiation are used in WEPP. These are used in the plant growth and residue decomposition components, in estimating soil water content of soil layers, and in estimating duration, peak rate and total amount of runoff.

The Green and Ampt equation with ponding considered is used in WEPP to compute infiltration. Rainfall excess is the difference between rainfall intensity and infiltration rate. The peak runoff rate is based on the kinematic wave model for a single plane.

Soil frost, snowmelt and accumulation are computed in the winter component. When frost is present, frost and thaw depth, water balance and infiltration capacity are computed. If snow is present, snowmelt, infiltration and surface runoff are computed. These are also used in the water balance and deep percolation components.

#### *Plant growth and crop residue*

The status of plants and crop residue are vital to the accurate estimation of soil detachment and transport. The direct and interactive effects of plants, including

amounts of below- and above-ground biomass, must be estimated accurately to evaluate the effects of various management practices on soil erosion.

WEPP estimates plant growth on a daily basis using a version of the EPIC model (Williams *et al.* 1983) and the accumulation and decomposition of residue and litter for both cropland and rangeland. Important plant growth characteristics include canopy cover and height, mass of live and dead below- and above-ground biomass, leaf area index and basal area, and residue cover. Information about dates and kinds of various tillage operations are input to the model. Many annual and perennial crops, management systems and operations that may occur on cropland, rangeland, forestlands, pastures and vineyards and gardens have been parameterized. Major efforts are underway to parameterize additional cropping-management systems.

#### *Water use and percolation*

The daily water balance is essential to estimate infiltration and runoff. The water balance and percolation component uses the climate, plant growth and infiltration components to compute the status of the soil water at each layer of interest in the soil, and to compute percolation from the root zone. Daily potential evapotranspiration and soil and plant evaporation are computed in this component. This component also receives the estimates of infiltration of melted snow from the winter component.

#### *Hydraulics*

The WEPP hydraulic component computes the hydraulic shearing forces required to compute rill erosion. These computations require information about runoff volumes, duration and peak rate, as well as hydraulic roughness, to apply the kinematic wave equations.

The WEPP model can be applied to several different areas down a slope. These areas may well have different crops, soils and topography. In some cases, such as for a small runoff event and stripcropping, runoff might occur on an upper strip and be infiltrated in the next lower strip. To satisfactorily simulate this possibility and to consider transitions down a slope, several approximations to the kinematic wave equation for overland flow were required.

Information about the rills and the flow conditions are required to compute rill erosion. Rill spacing and geometry are estimated by the WEPP model using results developed by Gilley *et al.* (1990) and Elliot *et al.* (1989).

#### *Soil processes*

The soil component of WEPP deals with temporal changes in soil properties important to soil erosion. These properties are important in estimating infiltration, percolation, runoff volume and runoff rates. In this component the effects of land use on soil and surface variables are quantified. These variables include random roughness, ridge height, bulk density, saturated hydraulic conductivity and soil erodibility parameters; rill and interrill erodibility and critical hydraulic shear. The WEPP model computes the status of these variables on a daily basis.

Past efforts to model erosion processes have used USLE relationships for estimating soil erodibility. A major WEPP effort has been extensive field studies

(Simanton *et al.* 1987; Elliot *et al.* 1989) to develop the technology to predict erodibility values for WEPP from soil properties.

#### *Applications*

Applications of the WEPP models will include all those of the USLE as well as many additional applications beyond the scope of USLE. Some of the applications include:

- (1) Location of sediment detachment on a slope, either for individual storms or for long-time averages.
- (2) Evaluation of complete land treatment, including waterways, terraces, tillage systems and management on soil detachment within a field, delivery from a field and delivery from a farm.
- (3) Evaluation of range management and treatment alternatives on soil erosion and sediment delivery from rangeland areas.
- (4) Effect of road design and construction in forests on sediment delivery from forest lands.
- (5) Effect of ridge height on sediment delivery from a field.
- (6) Evaluation of grassed waterways.
- (7) Appraisal of Natural Resource Inventory (NRI) sites for estimates of sediment delivery from fields and farms.
- (8) Use of NRI sites and real-time weather to make same-day estimates of soil loss, perhaps at county or state levels.
- (9) Effect of autumn stubble management on the capture of snow and its consequent effects on soil erosion. These effects would include those due to increased soil moisture, altered hydraulics because of crop residue, and increased runoff during thawing periods.

As stated in a recent *Journal of Soil and Water Conservation* (Lafren *et al.* 1991, p. 37), 'WEPP will have the capability to provide answers important to new and old natural resource issues. It will be able to give farmers and conservationists better information on where to locate conservation practices on specific fields to achieve one or more goals. These goals might be a reduction of soil erosion, reduction of soil loss, or a reduction of sediment deposition at the foot of a slope'.

An additional model calculation which will be of great use in evaluating offsite effects of land treatment is the size distribution and specific surface area of the sediment delivered to the bottom of the slope or the watershed outlet. This information is vital to predicting the downstream transport of sediment, and in computing chemical loss from farm fields for pollution analyses.

#### **Future Considerations**

The above material describes past and current development and application of the main erosion prediction technology used by the USDA and its agencies. We now briefly discuss the implications of some possible future applications of the modern erosion prediction technology in USDA natural resource programs.

#### *Implications of Computer-based Prediction Technology*

Movement from the USLE to the modern water erosion prediction technology requires computers to implement the erosion models (CREAMS, RUSLE and



WEPP). This, in turn, forces new responsibilities and methods of operation on both the technology developers and the technology users.

Individuals and organizations developing erosion prediction technology will need to adopt modern methods of model development, computer program design, development, validation, verification and documentation. Organizations developing new technology will need to allocate resources to support its maintenance and modification throughout its 'lifetime' of use.

Individuals and organizations using the new erosion prediction technology will need to adopt modern methods of model maintenance, training, quality assurance and quality control in application of the new technology. Moreover, their hiring and training programs must recognize, accept and plan for computer implementation of soil erosion prediction.

In summary, technology development and technology application should be planned, designed, developed, documented, verified, validated, maintained and monitored as one 'life-cycle' project. Both developers and users should be directly involved in all phases from conception to implementation to eventual replacement of the old with the new technology.

#### *The Role of National Data Bases*

National data bases, such as climate, soils, topography, land use, management practices, economics, and regulations and policies governing erosion, will enable technology users at the local, county, state, and national levels access to common data and information. This common access together with a nationally uniform methodology will allow users at all levels to repeat the calculations and duplicate the erosion predictions. If erosion predictions can be duplicated and are documented, they meet the test of scientific defensibility.

Application of standardized handbook procedures allowed technology users this repeatability and defensibility in the past. National data bases and nationally uniform erosion prediction technology will bring a similar repeatability and defensibility to the computer-based erosion predictions.

#### *Implications of Predicting Sediment Yield*

In the past, the USLE was used to predict erosion on the parts of the landscape where erosion was occurring. Hereafter, we refer to this as 'onsite erosion'. This gave soil conservationists and planners a powerful tool for evaluation of alternative land uses, conservation practices, and management practices in terms of their relative onsite erosion. Positions on the landscape where sediment deposition occurred could not be adequately addressed with USLE-type technology. Nor could the USLE technology provide any information about sediment properties or sediment yield downstream of the eroding portions of the upland areas. Although RUSLE is improved in many ways over the USLE, it still shares these weaknesses.

The CREAMS and WEPP technology are designed to deal with sediment detachment, transportation and deposition. Thus, they are specifically designed to deal with onsite erosion, with transportation and depositional processes, and thus to compute sediment yield. This allows sediment yield predictions to be made onsite (as in the USLE) and 'offsite' (as in sediment deposited and sediment transported downstream).

With technology that can predict onsite and offsite erosion and sediment yield, broader objectives for soil erosion, soil conservation, farm planning, and resource inventory and protection are possible. These broader objectives can directly bring onsite damages and benefits together with the offsite damages and benefits of alternative land use and management practices.

Broader objectives involving soil erosion will require a broader-based concept of acceptable onsite erosion and offsite sediment yield. The soil loss tolerance concept (directly tied to onsite erosion and the USLE) will no longer be appropriate in defining acceptable rates of onsite erosion. The soil loss tolerance concept must be expanded or replaced to explicitly include onsite erosion and offsite sediment yield.

#### *Use of Erosion Prediction in Multiobjective Decision Making*

Increasingly in the future, land use and management decisions will be made by utilizing multiobjective decision-making. Considerations of soil erosion and soil protection will need to be made together with consideration of water supply, surface water and groundwater quality, local and regional economic factors, biodiversity, wildlife habitat, recreation, aesthetics, and other factors of specific concern.

If the long-range problems of soil protection and sustainable agriculture are to receive equitable consideration in these multiobjective analyses, then the limiting concept of soil loss tolerance must be expanded to include onsite erosion and offsite sediment yield.

Therefore, improved erosion prediction technology such as CREAMS and WEPP must ultimately replace the USLE and the RUSLE in USDA programs and planning. Only the improved technology will be compatible with the improved concepts of onsite erosion and offsite sediment yield which will extend or replace the soil loss tolerance concept.

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