8 Universal Soil Loss Equation and Revised Universal Soil Loss Equation

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8.1 Introduction

8.1.1 History of the USLE (Universal Soil Loss Equation)

Conservation of soil and water requires both knowledge of the factors affecting these resources, and methods for controlling those factors to preserve those resources. Over the years, field, plot and small watershed studies have provided much valuable information regarding the complex factors and interactions involved in the environmental operations of land use and farming. These studies are the basis of the Universal Soil Loss Equation (USLE), which is a conservation planning tool that has been demonstrated to do a reasonably good job of estimating erosion for many disturbed-land uses. Predicting soil loss associated with modern land use is based on guidelines developed from research information in combination with additional experience from many sources. Information from empirical experiments and physically-based principles both assist in effective conservation planning.

The process of pulling together research results and experiences from agricultural practices began with Hugh Hammond Bennett (Helms, 2008), who was undoubtedly the most influential soil conservationist in the US. His early efforts led to his recognition as the 'father of soil conservation'. Bennett's early preaching against the menace of soil erosion led to Congressional action in 1929 establishing ten experimental stations, primarily in the cultivated agricultural areas of the US (Meyer & Moldenhauer, 1985; Renard, 1985). Later expansion of the research programmes included a large number of plots, crops, and management conditions that ultimately resulted in over 10,000 plot-years of data, collected over seven decades. Most of the plots involved the familiar dimensions 6.0 ft (1.8 m) wide by 72.6 ft (22.1 m) long, or a plot 35 ft (10.7 m) long used for some rainfall simulator studies. These plots simplified the computing of runoff and erosion on a per unit area basis (0.01 acre for the 6 × 72.6 ft or nominally 40 m^2 for the 1.8 × 22.1 m). Typical plot configurations were described in Brakensiek *et al*. (1979) and Laflen and Moldenhauer (2003).

In 1954, the National Runoff and Soil Loss Data Center was established by the US Department of Agriculture – Agricultural Research Service (USDA-ARS) at Purdue University in West Lafayette, Indiana. The Center was established to provide a central location for compiling and analysing soil erosion data collected from studies throughout the US. The Center, under the direction of W.H. Wischmeier, was responsible

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for summarizing and analysing the more than 10,000 plot-years of soil erosion and runoff data mentioned above, which resulted in the USLE (Wischmeier & Smith, 1965, 1978).

It has now been more than 50 years since the first releases of erosion prediction technology based on what have become widely known as the factors affecting sheet and rill erosion and, ultimately combining those in the USLE. Table 1 in Laflen and Moldenhauer (2003) gives an excellent synopsis of the published chronology of soil erosion prediction technology in the US.

The USLE and its predecessors were meant as field-level conservation planning rather than research tools, and were therefore structured to be 'user friendly' for USDA programmes in the Soil Conservation Service (SCS) (now the Natural Resources Conservation Service (NRCS)), and designed for tailoring erosion-control practices to the needs of specific fields and farms. The USLE was a 'paper-based' model where factors were found in printed tables and charts, and calculations were done by hand.

> "Had digital computers been available in the 1940s when erosion became recognized as a national problem, current prediction methods might more closely mimic the theory contained in Ellison's classic paper (1947) than the current empiricisms of the USLE." (Renard, 1985: 5)

What follows is a description of the evolution of the USLE–RUSLE effort, beginning with the improvements over the USLE leading to the RUSLE1 computer program and publication of the USDA Agriculture Handbook No. 703 (Renard *et al*., 1997). We will then describe the development of RUSLE2, leading to its release in 2004 and its continuing documentation. The final section of this chapter will examine continuing and possible future developments of the technology.

8.1.2 USLE/RUSLE factor values

The fundamental concept in establishing factor values in the USLE was the Unit Plot. This conceptual plot was composed of a land parcel 72.6 feet (22.1 m) in length with a 9% slope, maintained in a continuous, regularly tilled fallow condition with up-and-down hill tillage, thereby representing a condition very near the worst-case management. Such a plot was used as a base condition to which all other topographic, cropping, management and conservation practices were compared. Data from plots with different slopes, lengths and crops were adjusted to the unit plot, and compared across locations to establish reliable factor values. Benchmark soil erodibility and other terms (rainfall, slope length, slope steepness, cover-management and the support practice factors) used in the USLE/RUSLE have evolved over the years from data derived for varied conditions. Few if any unit plots were ever actually developed, but the concept was used to determine how the conditions of actual plots related to the unit plot.

The USLE soil loss equation is:

$$A = R\ K\ L\ S\ C\ P \tag{8.1}$$

where A is the computed soil loss per unit area, expressed in the units selected for K and for the period selected for R (in common practice these are usually selected such that they compute A, soil loss in US tons per acre per year); R, the rainfall and runoff factor, is the number of rainfall erosion index units, plus a factor for runoff from snowmelt or applied water where such runoff is significant; K, the soil erodibility factor, is the soil loss rate per rainfall erosion index unit for the specified soil under Unit Plot conditions; L and S are the slope length and steepness factors in relation to the conditions on a unit plot; C, the cover and management factor, is the ratio of soil loss from an area with specified cover and management to that from an identical area under the tilled continuous fallow Unit Plot conditions (C thus ranges from a value of zero for completely non-erodible conditions, to a value of 1.0 for the worst-case Unit Plot conditions); and P, the support practice factor, is the ratio of soil loss with a support practice like contouring, stripcropping, or terracing to that with straight-row farming up and down slope.

Because the USLE was based on empirical erosion data collected from relatively small plots or subwatersheds on relatively uniform hillslopes, the resulting erosion estimates were limited to similar situations. In essence, these results did not include any impact (either erosion or deposition) of the concentrated flow channels that form in the natural swales at the bottom of the roughly planar hillslopes, and certainly did not address classical gullying processes that often occur at steep boundaries such as headcuts and sidewall sloughing.

Use of the plot data to establish values for the factors above began with an analysis of rainfall erosivity by correlating the erosion measured under Unit Plot conditions with a whole series of measured rainfall values. A very strong correlation was found between this worst-case erosion and a combination of two rainfall factors, namely the total storm energy E and the maximum storm 30-minute intensity, or I_{30} (Wischmeier, 1959). The R factor was then calculated by summing over the calendar year the $E \cdot I_{30}$ values for all storms of over 12 mm (0.5 in.) or with more than 6.5 mm (0.25 in.) falling in 15 minutes, and taking the average of those annual values over all years of record. The soil erodibility (K) values were then determined for Unit Plot conditions ($C = P = LS = 1.0$) solving for K using measured A and R values. With the K values in hand, the values for C, P and LS could be determined by replicated plot studies on similar soils using different management practices or topographies.

Techniques for determining factor values to insert in the USLE (Equation (8.1)) were first presented for general use in the USDA's Agriculture Handbook No. 282 (Wischmeier & Smith, 1965). As use of this technology expanded and new studies were carried out to fill gaps and address weaknesses, new data were incorporated into the USLE, resulting in the second and most widely known release of the USLE technology in the USDA's Agriculture Handbook No. 537 (AH537) (Wischmeier & Smith, 1978). The values for the USLE factors as presented in AH537 were generally created to represent an average annual basis, although the form of the relationship does not demand that. The exception to this was the C factor, which was recognized as changing substantially through the year, leading to the cropping-period approach presented in AH537.

Following the release of AH537, the USLE became very widely used, both within the US and internationally. Perhaps its most common use was as one of the primary tools of the USDA Soil Conservation Service for conservation planning on agricultural lands. As use of the USLE expanded and it was applied in other situations, like disturbed forest lands (Dissmeyer & Foster, 1981, 1984), limitations of the technology became apparent. At the same time, continuing soil erosion research on both natural plots and under simulated rainfall led to improved understanding of the physical processes involved in hillslope sheet and rill erosion. Recognized limitations and advancements in erosion science pointed to the need for updating the USLE.

8.2 RUSLE

8.2.1 RUSLE1 development

In 1985, scientists and engineers from the USDA-ARS and the USDA Soil Conservation Service and affiliated academics with expertise in soil erosion assembled in West Lafayette, Indiana. At that workshop, two important decisions evolved, including the need to (1) develop technology to replace the USLE with a physically-based model (subsequently called the Water Erosion Prediction Project or WEPP); and (2) to computerize and update the 1978 version of the USLE with an improved model, subsequently called the Revised USLE or RUSLE. All subsequent material in this chapter is directed to a description and analysis of the various portions of the RUSLE effort, including both RUSLE1 and RUSLE2.

The first version of RUSLE1, a software program designed to operate in a DOS-based computer environment, was released in 1997. RUSLE1 was supported by USDA-ARS through Agriculture Handbook No. 703 (AH703) (Renard *et al*., 1997). The computer system soil erosion model described therein was a major conversion of the factor approach presented in AH537. Perhaps the most significant change was the subfactor approach to the calculation of the cover-management factor C, thereby allowing use of RUSLE1 for any land use that could be adequately addressed by these subfactors. This broke the previous bonds of the

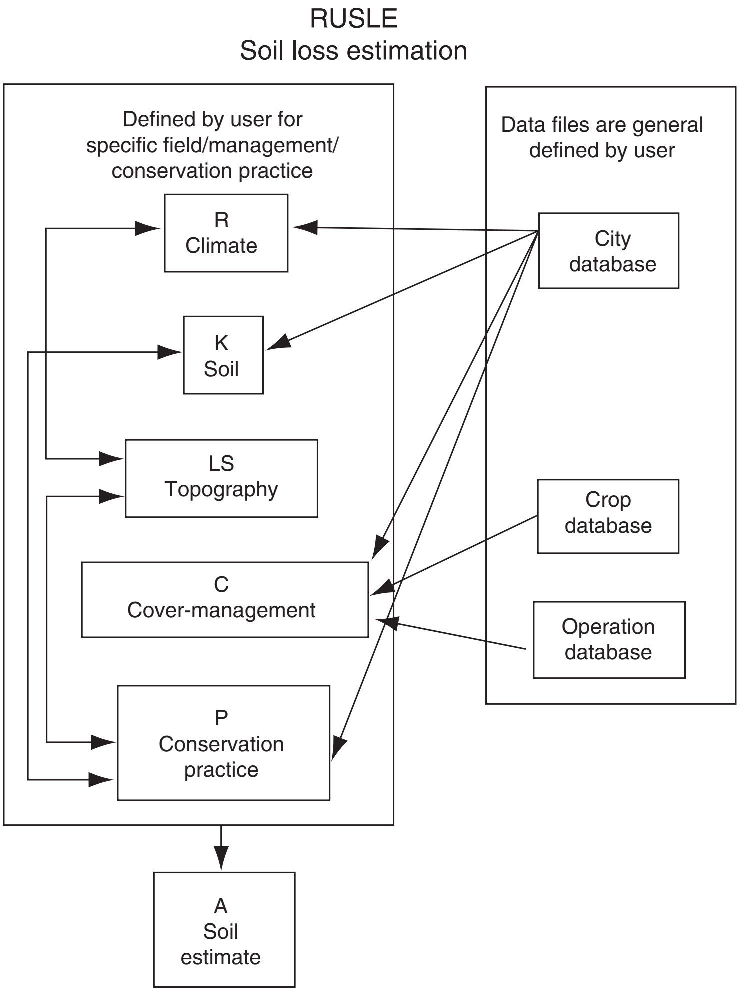

Fig. 8.1 RUSLE1 software flow chart (from AH703).

USLE to agricultural settings, as described in some detail below. The new AH703 development took an appreciable amount of effort involving scientists and engineers with experience in areas of knowledge representing each factor. It also involved a significant amount of testing by SCS-NRCS personnel in various locations, each having specific expertise in the crops, soils and climates involved. The DOS program developed for the 1997 RUSLE1 version permitted English unit calculations only. To input or output metric units required hand conversions of individual factor values using conversion factors (Foster *et al*., 1981) which were included in Appendix B of AH703.

Another change in the RUSLE1 approach was to begin grouping the expanded list of required user inputs into a crude database, defined as shown in Fig. 8.1. This allowed for saving and re-use of sets of inputs corresponding to, for example, a specific location. In addition to the computerization of the model, every USLE factor underwent significant changes in moving to RUSLE1. These changes are generally described in the paragraphs that follow.

(i) Rainfall erosivity factor (*R*) The most common way of presenting rainfall erosivity information in the US has been through the use of isoerodent maps, allowing the reader to interpolate the corresponding *R* value for a specific location. The isoerodent maps in AH703 were calculated using the same criteria as in AH537, namely summing the storm kinetic energy times the maximum 30-minute intensity for storms larger than 0.5 in (12 mm), unless at least 0.25 in (6.5 mm) fell in 15 min. These calculations were computed for all non-snow storms within a period of *N* years. Normally at least 22 years of storms were included for the calculations (see AH537 for details), but longer periods are advisable when the coefficient of variation of annual precipitation is large. A total of 181 key precipitation locations with 15-min data were used for the map in AH537, and a few additional locations to fill in gaps were added to produce Figure 2.1 in AH703. AH537 included very little erosivity information for the western US, with only 11 western station isoerodent values used to estimate the two-year 6-h precipitation amount. A power relationship developed by Wischmeier (1974) to fit those values provided some measure of the expected erosivity, but the results were not thought to be very accurate, or to reflect adequately the known intermontane climate variability. Through an agreement between Oregon State University, USDA-ARS, USDA-SCS and the National Weather Service, data from 713 stations with 15-min measurement intervals were used to calculate *EI* values, and thereby to construct new isoerodent maps for the western US in AH703, although all storms were included in the western erosivity calculations (excluding snow). Analysis of these records showed that 225 precipitation-measuring locations had records longer than 12 years and precipitation resolutions of 0.01 in. (0.25 mm). Values of the coefficient of determination (R^2) in excess of 0.8 were obtained with the model $EI_{15} = b(EI_{60})$. Values of the regression parameter *b* ranged from 1.08 to 3.16, varying widely among climate zones.

To supplement this work, 1082 hourly stations were used to calculate EI_{60}. Of these stations, 790 had record lengths of 20 years or longer. These data were adjusted to a 15-min measurement interval using the cited correction. *R* factors were also adjusted to equivalent break-point data using the Weiss (1964) relationship $R = 1.0667\ (R_{15})$. The isoerodent map was prepared by hand contouring on large-scale maps, reflecting the major topographic influences in mountain and range topography. The newer isoerodent maps (Figures 2-2, 2-3 and 2-4 of AH703) were thus felt to be a significant improvement over those in AH537.

In addition, seasonal *EI* distributions were developed for 84 climate zones in the western US (Fig. 2-7, AH703). The distributions were developed for calculating the time-varying *C* factor in RUSLE1, building on the crop growth stage approach found in AH537.

City database files were then developed in RUSLE1 to provide the climatic data needed for erosion calculations. This included the *R*-factor value, the *EI* distribution values for 24 bimonthly periods, and the 10-yr frequency storm maximum *EI* that was needed for calculating the *P* factor credit for contour farming. Maps of these values were calculated for precipitation gauge locations and are presented in Figures 2-9 to 2-12 in AH703.

Two additional modifications to the classical USLE *R*-factor approach were included in RUSLE1 to address specific geographical needs. In areas with very low relief and high rainfall intensities (such as in the Mississippi River delta), research has found that runoff ponds to substantial depths before running off, and that this ponded water absorbs some of the raindrop impact that could cause detachment (Mutchler, 1970). Based on these data, RUSLE1 included a term to adjust downwards the erosivity experienced by the soil, based on slope steepness and rainfall erosivity (taken as a surrogate for intensity). The other modification to the *R* factor was for frozen and thawing soils, encountered in the Pacific Northwest (Northwest Wheat and Range Region (Austin, 1981)), and in some of the southern plains of Canada. In these cases, a soil with much weakened structure exposed to even a low-erosivity event will experience high erosion rates, so an alternative means of selecting an equivalent *R* value for these conditions was included in RUSLE1.

(ii) Soil erodibility factor (*K*) The soil erodibility factor (*K*) represents the effect of soil properties and soil profile characteristics on soil loss (see Chapter 2 in Renard *et al*., 1997). In a practical sense, *K* is a lumped parameter representing an integrated annual average of the soil and profile reaction to erosion and hydrological processes. The processes consist of soil detachment and transport by raindrop impact and surface flow, deposition due to topography and tillage roughness and rain infiltration into the soil profile.

The best erodibility factors are obtained from long-term direct soil-loss measurement on natural plots. Rainfall simulation data has also been used, but is recognized as being less accurate (Römkens, 1985). Only inherent soil properties are considered determinants of the USLE soil erodibility factor, which means that soil erodibility must be measured under the Unit Plot conditions described earlier. The minimum adequacy of the observation period for soil erodibility was usually taken as two years, but longer periods provide better results due to the likelihood of experiencing a broader range of climatic and soil conditions. Most of the plots used in measuring soil erodibility were in the Midwestern cropping areas of the US (see Table 3.1 in Renard *et al*., 1997).

In most cases, US RUSLE1 users will have little trouble in selecting specific *K* values, because NRCS has identified values for most major soil mapping units. Site-specific values can be obtained from the widely available NRCS soil surveys, or directly from USDA soil databases. If such data are not available, the erodibility nomograph (Fig. 8.2), based on a relationship fitting the data as described above, is the most commonly used tool to estimate *K*, although there are some soils where it does not apply, and one of the site-specific relationships for specific soils (Renard *et al*., 1997: 75) may be a better choice in the US. Users should contact their NRCS state soil scientist or other local soil specialist to certify the value to be used for their location. In other areas of the world, users may have to resort to soil sampling and the use of Fig. 8.2.

(iii) Topography factors (*LS*) There are more questions and concerns about the *LS* topographic factor than for any other term in RUSLE. The primary reason for these concerns is that the choice of slope length involves substantial judgment; different users choose different slope lengths for similar situations. The two primary questions here are what hillslope (downslope runoff path) to use to represent an area, and how then to define that hillslope in terms of specific length and steepness values. The first question is really one of policy rather than science (do we choose the worst-case hillslope, or the median slope, or some other?), while the second question is a more technical yet qualitative one of how to define where runoff begins, the path it takes down the slope and when it reaches a concentrated flow channel, thus ending the hillslope. The attention given to slope length is not always warranted because soil loss is often less sensitive to slope length than to any other USLE/RUSLE factor. For typical slope conditions, a 10% error in slope length results in a 5% error in computed soil loss. In contrast, soil loss is much more sensitive to changes in slope steepness than to errors in slope length. In the USLE, for example, a 10% error in slope steepness will usually give about a 20% error in computed soil loss. RUSLE has a more linear slope steepness relationship than did the USLE. Improvements in the relationship for steep slopes mean that computed soil loss for slopes less than 20% are similar in RUSLE and USLE, but on steep slopes, computed soil loss in RUSLE is just over half that predicted by the USLE, whose relationship did not include data for steep slopes. In addition, RUSLE makes more explicit the reliance of the length relationship on the susceptibility of the soil to rilling, which may be influenced by the slope steepness, soil characteristics, and management impacts. Finally, RUSLE includes a slope relationship specifically for the frozen soil region of the Northwest Wheat and Range Region (Austin

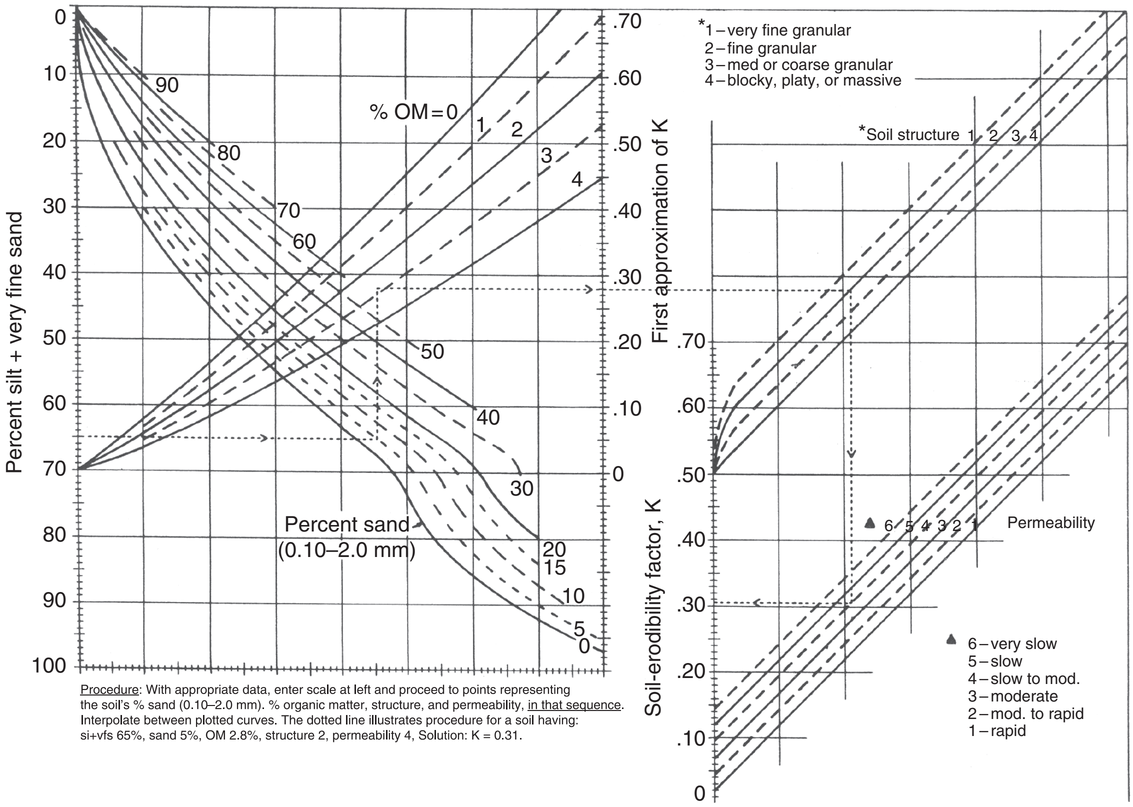

Fig. 8.2 The soil erodibility nomograph that gives *K* in US Customary Units (see Wischmeier & Smith, 1978).

1981). Detailed information on the selection of slope calculations is given in AH703 Chapter 4.

The difficulty in defining slope length is, however, substantial enough to have served as the primary impediment for employing GIS-based systems in using RUSLE. The topographic data available to populate GIS databases generally does not have the spatial resolution necessary to pick out the small concentrated flow channels commonly found at the bottom of a USLE/RUSLE hillslope. As a result, slope lengths computed using these data are almost always far too long. In fact, most attempts to use GIS with USLE/RUSLE recognize this and simply cut off the slope lengths at some arbitrary value. This poor resolution also causes the GIS system to miss the flat floodplains often found at the bottom of a hillslope, where substantial deposition may occur. This may change as higher-resolution topographic data (such as those collected using Lidar) become available, although how best to use these extensive datasets must still be decided.

In using the USLE, the slope length was defined as beginning at the top of the hillslope where runoff starts, and extending down to where the sheet and rill flow reaches either a concentrated flow channel or a depositional area. This limit of the depositional area was required because such deposition rarely occurred on the plots used to collect USLE data. Deposition can be caused by anything that slows the runoff and causes sediment to deposit, such as an increase in roughness caused by a management change (e.g. a strip of dense vegetation), or a decrease in slope grade.

In RUSLE1, this definition was expanded slightly to include areas of deposition caused by management changes on the hillslope, which was accomplished by including some of the more process-based routines used in CREAMS (Foster *et al*., 1980).

Slope length factor (L) Plot data used to derive slope length (L) show that erosion for slope length λ (ft) varies as:

$$L = (\lambda/72.6)^m \tag{8.2}$$

where 72.6 = the RUSLE unit plot length (ft) and m is a variable slope length exponent. The slope length λ is the horizontal projection. The value for m can be found from $m = \beta/(1 + \beta)$, where the slope-length exponent β is related to the ratio of rill erosion (caused by overland flow) to inter-rill erosion (principally caused by raindrop impact). The ratio of rill to inter-rill erosion when the soil is susceptible to both rill and inter-rill erosion is:

$$\beta = (\sin\theta/0.0896)/[3.0(\sin\theta)^{0.8} + 0.56] \tag{8.3}$$

where θ is the slope angle. For a value of β, the slope-length exponent m is calculated using the relation above. When runoff, soil, cover, and management conditions indicate that the soil is highly susceptible to rill erosion, the exponent should be increased (see AH703, Chapter 4). These conditions are expected, for example, for steep, freshly prepared construction slopes. In such cases where the soil is highly susceptible to rilling, AH703 recommended doubling the value of β resulting from Equation (8.3). When conditions favour more inter-rill and less rill erosion, as in cases of consolidated soils like those found in no-till agriculture, m should be decreased by halving the β value. A low rill to inter-rill erosion ratio is typical of conditions on rangelands. With thawing, and cultivated soils dominated by surface flow, a constant value of 0.5 should be used (McCool *et al*., 1989, 1993). In RUSLE1 the choice between these alternatives was made by selecting a general land-use category; in RUSLE2 the program automatically and continuously adjusts the m value based on slope steepness, soil type and management impacts.

Slope steepness factor (S) Soil loss increases more with steepness than with slope length. In RUSLE, the slope steepness has changed from that used by the USLE, and is evaluated with the relationship (McCool *et al*., 1987):

$$S = 10.8\sin\theta + 0.03 \quad S<9\% \tag{8.4}$$

$$S = 16.8\sin\theta - 0.50 \quad S>9\% \tag{8.5}$$

The relationship is based on the assumption that runoff is not a function of slope steepness for slopes greater than 9%. Slope effect on runoff and erosion as a result of mechanical disturbance, cover and vegetation is considered in the cover-management (C) or support practice factor (P). For slopes shorter than 4.6 m (15 ft), use:

$$S = 3.0(\sin\theta)^{0.8} + 0.56 \tag{8.6}$$

Equation (8.6) applies to conditions where the water drains freely from the slope end. For the slope steepness factor above, it is assumed that rill erosion is insignificant on slopes shorter than 4.6 m (15 ft), and that inter-rill erosion is independent of slope length.

When freshly tilled soil is thawing, in a weakened state and primarily subjected to surface flow, use the following (McCool *et al*., 1993):

$$S = 10.8\sin\theta + 0.03 \quad S<9\% \tag{8.7}$$

$$S = (\sin\theta/0.0896)^{0.6} \quad S>9\% \tag{8.8}$$

In most practical applications, a single plane or uniform slope can be a poor representation of the hillslope topography, and erosion can vary greatly between concave or convex slopes of equal average steepness. Users are cautioned and encouraged to use the complex slope calculations, because differences can be significant when contrasted with a uniform plane.

Actual selection of the hillslope used to represent a field can be a complicated choice, and is best done through examples rather than verbiage. Additional detail and guidance for field measurement of the *LS* factor for varying field scenarios is given in AH703.

Cover-management Factor (C) The cover-management factor, *C*, is possibly the most important of the RUSLE/USLE factors because it represents the most readily managed condition for reducing erosion. In the USLE, the *C* factor was described as providing a measure of how erosion from the current condition compares with that for the Unit Plot condition, which is considered as nearly worst-case. The individual values of *C* vary between 0 for a completely non-erodible condition, to a value somewhat greater than 1.0. Values greater than 1.0 imply conditions more erodible than those normally experienced under Unit Plot conditions, which can occur for conditions with very extensive tillage (e.g. roto-tilling), leaving a very smooth surface that produces much runoff and makes the soil especially susceptible to erosion. *C* values are weighted average soil-loss ratios (SLRs), each of which represents the ratio of soil loss under current conditions for a short period of time to the expected soil loss under Unit Plot conditions during that same period. The SLRs vary throughout the year as soil and cover conditions change with soil disturbance and plant growth. The *C* value then represents the average of the time-varying SLR values, each weighted by the portion of rainfall erosivity during that same time period.

In contrast to the tables of *C* factors presented in AH282 and AH537, RUSLE1 uses a subfactor method to compute SLRs as a function of five factors:

$$C = PLU \cdot CC \cdot SC \cdot SR \cdot SM \qquad (8.9)$$

where *C* is the overall cover-management factor, *PLU* is the prior landuse subfactor, *CC* is the canopy cover subfactor, *SC* is the surface cover subfactor, *SR* is the surface roughness subfactor, and *SM* is the soil moisture subfactor (used only in the Northwest Wheat and Range Region area (Austin, 1981), otherwise unity). Expanded details for evaluating *C* factors are presented in AH703.

Although ground cover is known to affect erosion more than the other subfactors, it is wrong to give it exclusive attention without considering within-soil effects such as those associated with root mass and tillage. A 30% surface cover after planting is the criterion frequently used for conservation tillage; the USLE relationships predict that this 30% cover will reduce soil loss by about 72%. By comparison, the soil loss for a freshly ploughed meadow is reduced by about 75% from that for Unit Plot conditions, showing that within-soil effects can have a substantial impact. Although the effects are not as pronounced, the impacts of canopy cover and surface roughness can also provide substantial benefits, especially in the absence of surface cover.

The structure of Equation (8.9) implies that the effects of subfactors in reducing erosion are multiplicative. For example, if there is a canopy cover that reduces erosion by 45% from Unit Plot conditions, this means that $CC = 0.55$. If there is also enough surface cover to reduce erosion by 60% from Unit Plot conditions ($SC = 0.4$), then assuming all other factors are under Unit Plot conditions ($PLU = SR = SM = 1.0$), the overall factor value would be $C = 0.55 \times 0.4 = 0.22$, or a 78% reduction in erosion from Unit Plot conditions.

The subfactor approach in RUSLE1 was designed to break the dependence of the USLE structure on specific land-use data. Without this break, calculations would require separate complete and expensive datasets for each possible combination of land uses. The subfactor analytical approach was carried out under the basic assumption that the erosion impact of various factors such as surface cover and roughness is really independent of the type of land management controlling that factor. For example, the impact of covering the surface with straw mulch and of growing grass should be relatively independent of whether this is done as part of normal agricultural field operations or to control erosion on construction sites. Under this assumption, we start with the relationships to estimate erosion based on the parameters that control the subfactors for surface cover, biomass and roots in the soil, surface roughness, vegetative canopy cover, and soil moisture. Once those relationships are developed using field data, if the RUSLE1 program can model the effect of any field management operation on those parameters (soil, vegetation, biomass), it should be able to model the resulting erosion.

The subfactor approach and the equations controlling it are described in great detail in AH703. What follows is a brief introduction to the subfactors included in RUSLE1.

Prior land-use subfactor (PLU) The *PLU* subfactor is calculated in RUSLE as the product of soil consolidation and soil biomass effects:

$$PLU = C_f \cdot C_b \cdot \exp\text{-}[(c_{ur} \cdot B_{ur}) + (c_{us} \cdot B_{us}/C_f^{\,cuf})] \qquad (8.10)$$

where *PLU* is the prior land-use subfactor (ranging from 0 to 1), C_f is a surface-soil-consolidation factor, C_b represents the relative effectiveness of subsurface residue in consolidation, B_{ur} is the mass density of live and dead roots in the upper 100 mm (lb acre^{-1} in^{-1}), B_{us} is the mass density of incorporated surface residue in the upper 100 mm of soil (lb acre^{-1} in^{-1}), C_{uf} represents the soil consolidation impact on the effectiveness of incorporated residue, and c_{ur} and c_{us} are calibration coefficients indicating subsurface residue impacts.

The B_u variables calculate the impact on erosion rates of live and dead roots and incorporated residue. The effectiveness of such materials can take two forms. Firstly, roots and residue can control erosion directly by physically binding soil particles together and acting as mechanical barriers to soil and water movement. Secondly, roots and residue exude binding agents and serve as a food source for micro-organisms that produce other organic binding agents. These serve to increase soil aggregation and thereby reduce susceptibility to erosion. The RUSLE software keeps track of the biomass in each layer, continuously adjusting the rootmass and subsurface residue to account for residue additions or losses by decomposition.

Canopy cover subfactor (CC) The canopy-cover subfactor indicates the effectiveness of the vegetative canopy in reducing the energy of rainfall striking the soil surface. Although most of the rainfall intercepted by canopy eventually reaches the soil surface, it usually does so with much less energy than rainfall directly striking the ground. The intercepted drops fracture into smaller drops, or drip from leaf edges, or travel down crop stems to the ground. The canopy-cover effect is given as:

$$CC = 1 - F_c \cdot \exp(-0.1 \cdot H) \qquad (8.11)$$

where *CC* is the canopy-cover subfactor ranging from 0 to 1, F_c is the fraction of land surface covered by canopy, and *H* (ft) is the distance that raindrops fall after striking the canopy.

Surface cover subfactor (SC) Surface cover affects erosion by reducing the transport capacity of runoff, by causing deposition in ponded areas, and by decreasing the surface area susceptible to raindrop impact. This is perhaps the single most important factor in lowering SLR values. Surface cover includes crop residue, rocks, cryptogams, and other non-erodible and non-mobile material in direct contact with the soil surface. The effect of surface cover on soil erosion is given as:

$$SC = \exp[-b \cdot S_p\,(0.24 / R_u)^{0.08}] \qquad (8.12)$$

where *SC* is the surface cover subfactor, *b* is a coefficient, S_p is the percentage of land area covered by surface cover, and R_u is the surface roughness, as will be defined later.

Land area percentage covered by residue can be estimated from residue weight by the relationship of Gregory (1982):

$$S_p = [1 - \exp(-\alpha \cdot B_s)] \cdot 100 \qquad (8.13)$$

where S_p is percentage residue cover, α is the ratio of the area covered by a piece of residue to its mass (acre lb^{-1}), and B_s is the dry weight of crop residue on the surface (lb ac^{-1}). If more than one type of residue is present, the resulting total surface area cover is calculated as:

$$S_p = \{1 - \exp[-\Sigma (\alpha_i \cdot B_{si})]\} \cdot 100 \qquad (8.14)$$

where α_i is the ratio of area covered to the mass of that residue for each type encountered. The summation is for each type of residue, as each residue type may have a unique α_i value.

Surface roughness subfactor (SR) Surface roughness has been shown to affect soil erosion directly, and also to affect it indirectly through the impact of residue effectiveness as controlled by the *b* value in Equation (8.12). The surface roughness subfactor is a function of the surface random roughness, which is defined as the standard deviation of surface elevations across the slope, when changes due to land slope or non-random tillage marks (such as dead furrows, traffic marks, and/or disk marks) are removed from consideration. A rough surface has many depressions and barriers. During a precipitation event, these trap water and sediment, causing rough surfaces to erode at lower rates than do smooth surfaces under similar conditions. Increasing surface roughness decreases transport capacity and runoff detachment by reducing flow velocity.

Roughness and cloddiness of soils also affect the degree and rate of soil sealing from raindrop impact. Soils that are left rough and cloddy typically have greater infiltration rates. Soils that are finely pulverized are usually smooth, seal rapidly, and have low infiltration rates. RUSLE assumes that roughness decreases with the time since tillage by the relationship:

$$D_r = \exp[\, ½(-0.14\, P_t) + 1/2(-0.012 \cdot EI_t)] \qquad (8.15)$$

where D_r is the dimensionless roughness decay coefficient, P_t is the total inches of rainfall since the most recent soil-disturbing surface operation, and EI_t is the total *EI* amount since that operation.

If the initial roughness is defined as R_i, then surface roughness just before a new tillage operation (R_u) can be defined as:

$$R_u = 0.24 + [D_r (R_i - 0.24)] \qquad (8.16)$$

where R_u is in inches. Since many field operations affect only a portion of the surface, R_u is also the roughness of that field portion left undisturbed by the current operation.

For that surface portion affected by the field operation, the resulting roughness has been found to be a function of subsurface biomass present in the top 4 in. of soil. The relationship is:

$$R_a = 0.24 + (R_t - 0.24) \{0.8\, [1 - \exp\,(-0.0012\, B_u)] + 0.2\} \qquad (8.17)$$

where R_a is the roughness after biomass adjustment (in.), R_t is the original roughness based on the assumption of ample subsurface biomass such as is found with high-yielding US-type corn, and B_u is total subsurface biomass density in the top inch of soil (lb ac^{-1} in^{-1}), with $B_u = B_{ur} + B_{us}$ as used in Equation (8.10).

The adjusted tillage roughness is then combined with that of the undisturbed portion of the surface as follows:

$$R_n = R_a\, F_d + R_u\, F_u \qquad (8.18)$$

where R_n is the net roughness following the field operation (in.) and F_d and F_u are respectively the fractions of the surface disturbed and undisturbed, such that their sum equals one.

Similarly, the roughness decay coefficient must be adjusted to reflect that only a portion of the field is disturbed using the relation:

$$D_e = D_r\, F_u + 1.0\, F_d \qquad (8.19)$$

where D_e is the equivalent roughness decay coefficient. RUSLE then reorganizes the relationships described above to calculate the R_t, P_t and EI_t values corresponding to the equivalent roughness decay coefficients, under the assumption of a constant EI_t/P_t ratio. If a site is clean-tilled and left without human intervention, two things will happen: (1) the tillage roughness will decrease as defined previously; and (2) as time passes, vegetation will tend towards its climax community, with attendant roughness caused by protruding roots, soil pushing up around old basal areas, rocks, and so on. RUSLE assumes that the formation of this vegetative roughness follows a typical sigmoidal growth curve, increasing from the minimum roughness (r_{min} with a default of 0.24 in.) to the total roughness when soil is consolidated (r_{max}) over the time required for consolidation (t_{con}).

Once the current roughness R_u has been defined based on the tillage roughness and all the roughness decay calculations described above, the surface roughness subfactor for this time period is then:

$$SR = \exp\left[-0.66\,(R_u - 0.24)\right] \qquad (8.20)$$

Soil moisture subfactor (SM) In non-irrigated portions of the Northwest Wheat and Range Region (NWRR; Austin, 1981), soil moisture during critical crop periods depends upon crop rotation and management. In such cases, the addition of a soil-moisture subfactor (*SM*) is suggested. *SM* reflects dry fall conditions and increasing soil moisture over winter. The soil moisture decrease during the growing season depends upon crop rooting depth and soil depth, and the soil moisture replenishment during the winter and spring depends upon precipitation amount and soil depth. Research to make such a correction is needed. In most instances this factor is assumed to be unity, which means that there is no substantial impact of soil moisture extraction by the vegetation on erosion. This assumption of $SM = 1.0$ is probably valid for all areas except those experiencing erosion caused by light rains on frozen-thawing soils.

(iv) Conservation practice factor (*P*) It is not always clear how the conservation practice factor (*P*) differs from the cover management factor (*C*), because both are meant to indicate the impact of management practices on erosion. In general terms, the basic difference is that the *C* factor reflects the positive impact over the larger portion of the management area, through factors like vegetation, biomass on the surface or within the soil, and roughness. The *P* factor is generally seen as reflecting the positive impacts of management through the control of runoff, with special emphasis on how the management changes the direction and speed of that runoff, but also reflecting to some degree management practices that control the amount of runoff. Traditionally the *P* factor has been used to reflect the impact of agricultural practices such as the various forms of strip-cropping (buffer strips, filter strips, rotational strip-cropping), terraces, contour tillage, and subsurface drainage. In other land uses, *P* would reflect the impact of analogous practices, such as filter strips for water quality control, or the use of diversions on construction sites. RUSLE1 brought to the USLE structure a subfactor approach for the *P* factor as well as the *C* factor, with separate subfactors for contouring, strips, terraces, and subsurface drainage. As with the *C* factor, these subfactor values are multiplied together to give the overall *P* factor.

Contouring subfactor Data on the effect of contouring show a tremendous amount of scatter, but there are some trends, as shown in Figure 6-2 of AH703. These indicate that higher ridges give more benefit than lower ridges, that contouring is more effective for areas with lower rainfall intensities, and that the effectiveness reaches a peak at about 9% slope, losing effectiveness at lower slopes due to less inherent erosion, and at higher slopes due to potential breakover of the ridges by ponded runoff. In addition, contouring is most effective when the ridges are perfectly on the contour, with its impact decreasing rapidly as the furrows have more grade.

RUSLE1 fits the scattered contouring data with a series of equations used to describe the base contouring *P* value for different slope steepnesses. It then adjusts these for climate and storm intensity using a runoff scaling factor based on the 10-year storm *EI* compared with a value for the central part of the US, and finally adjusts the results based on the contour furrow grade, using the relationship (AH703 eqn. 6-11):

$$P_g = P_o + (1 - P_o)(s_f / s_l)^{1/2} \qquad (8.21)$$

where P_g is the P factor for off-grade contouring, P_o is the P factor for on-grade contouring calculated using the sequence described above, s_f is the grade along the contour furrow, and s_l is the slope grade.

As reflected in the data summarized in tables in AH537, contouring tends to lose effectiveness on very long slopes, as runoff tends to build up behind the contour ridges and cause breakover of the ridges, which can be assumed to make the lower contour ridges ineffective. RUSLE estimates the maximum slope length over which contouring is effective (called the 'critical slope length' in AH703) using a variation on a relationship developed by Foster *et al*. (1982) for mulch stability. Once again, this relationship depends on slope steepness and runoff, and it is calibrated against the critical slope lengths shown in the tables in AH537. RUSLE then gives *P*-factor credit (i.e. reduces the erosion estimate) for the area upslope of the critical length, but not for the downslope area.

Strip-cropping subfactor The impact of management on runoff and its ability to carry sediment is probably the single factor that has changed most in the USLE/RUSLE evolutionary process. As described above, this has included substantial changes in how the hillslope is defined. RUSLE1 included a process-based approach to estimating the amount of deposition caused by changes in management and the resulting slowing of runoff. This started with the definition of a slope segment as being a portion of the topography with constant soil, management, and steepness. The approach taken was a simplified version of the CREAMS approach (Foster *et al*., 1980), which looks at four possible cases for each slope segment, where a segment is defined: (1) where there is no runoff leaving the segment, so all incoming sediment is deposited; (2) where there is erosion throughout the segment; (3) where there is deposition throughout the segment; and (4) where deposition occurs at the top of the segment and erosion at the bottom. These four cases are examined by calculating the increase in transport capacity within the segment, and comparing that with the amount of additional sediment added by erosion within the segment. This requires estimation of a runoff rate, which in RUSLE1 is based on the ten-year *EI* storm erosivity.

The impact of the deposited sediment on the P factor is somewhat subjective, as the P factor is meant primarily as a measure of soil resource conservation, while the primary effect of deposition is on sediment delivery. Because sediment deposition does not preserve the soil resource as much as preventing erosion in the first place, RUSLE1 does not give as much conservation credit for practices that cause sediment deposition as for practices that prevent soil erosion. RUSLE1 gives credit for deposition that occurs based on its location on the slope, using the relationship:

$$B = M\,(1 - x^{1.5}) \qquad (8.22)$$

where B is the benefit, M is the mass of sediment deposited, and x is the location of the deposition as a fraction of the total distance downslope. This benefit is calculated into the P factor as:

$$P_s = (g_p - B)/g_p \qquad (8.23)$$

where P_s is the P factor for strip-cropping, and g_p is the potential sediment load that would occur if there was no deposition.

Terracing subfactor Within RUSLE, terraces (or diversions on construction sites) provide two benefits: (1) they break the hillslope profile into a combination of multiple shorter profiles, thereby reducing erosion; and (2) they cause some deposition to occur up on the hillslope, thereby providing some benefit in conserving the soil resource. The first of these benefits is taken into account through the *LS* topographic factor described above. For the second benefit, RUSLE uses sediment yield data collected on watersheds with terraces to estimate the amount of sediment deposition that will take place, then gives that a credit benefit identical to that described above for the benefit of deposition in strip-cropping.

Subsurface drainage subfactor There are some data that suggest subsurface drainage can be effective in reducing erosion, presumably by reducing soil moisture and thereby decreasing runoff during a storm event (Formanek *et al*., 1987; Bengtson & Sabbage, 1988). These data show substantial scatter, but indicate an average erosion reduction of about 40% for a subfactor $P = 0.6$.

Sediment delivery estimate As the first step in the evolution from the USLE, RUSLE1 is still primarily geared towards planning based on soil conservation. In spite of this, using the techniques described above for strip-cropping, it does provide a crude sediment delivery estimate. This is done by using a value of $B = M$ in Equation (8.22), providing the ratio of sediment delivered over sediment eroded, or essentially a sediment delivery ratio. Multiplying this P factor for sediment delivery by the other factors then provides the hillslope sediment delivery for evaluating off-site impacts.

8.2.2 RUSLE1 program implementation

The RUSLE1 computer code was written in the C programming language. Chapter 7 in AH703 included a fairly detailed description of the RUSLE1 program layout and operation. This was deemed necessary because as dissemination of and training in RUSLE1 proceeded, it quickly became apparent that a program with this level of complexity could not be assumed to be intuitive to a first-time user. Part of this complexity was inherent in the level of input information required from the user, while an additional portion was due to the program structure. This structure was based on the USLE 'paper' implementation, and hid nothing from the user.

8.2.3 RUSLE1 implementation history and experience

Perhaps the two primary lessons learned from the USDA-NRCS implementation of RUSLE1 were: (1) the importance of an iterative feedback process in developing the program; and (2) the sheer scale of the effort necessary to implement such a model on the national scale. Although these lessons were partially due to the specifics of the situation, they are also broad enough to be instructive to other individuals and groups within or outside the US who are implementing a program like RUSLE. One of the key elements in the development of the RUSLE1 computer program was the close contact between the program developers and a variety of user representatives. Although the development began with defined user requirements, these underwent substantial changes as the program was presented to users through a variety of feedback and training sessions, involving a mixture of skilled and novice users. Only through that iterative feedback process did the program begin to meet the true user needs, as these needs often only became apparent when users were exposed to the program. Based on the RUSLE experience, it simply does not work to introduce a new model under the presumed process of setting initial user requirements and declaring success once those are met.

Although the RUSLE1 computer program itself was first deemed ready for full review and delivery in 1991, the process of developing the database information necessary to allow full implementation took an additional 4–5 years. This included a strong collaborative research effort sponsored by USDA-NRCS and carried out by researchers at North Carolina A&T University, Alcorn State University, and Alabama A&M University to collect the data required for the vegetation descriptions, including especially time-varying data on vegetative canopy cover, rootmass and biomass.

Substantial effort also went into determining exactly how the program would be implemented in the USDA-NRCS field offices, with special attention paid to consistency of results across political boundaries, and consistency of use patterns. One of the important concepts developed during this period was the development of C-Factor Zones, which recognized that climatic differences rather than political boundaries controlled the possible management scenarios, leading to shared management descriptions across state lines. National, state and regional NRCS personnel developed the required management descriptions to describe the bulk of schemes used in these areas, which in turn defined the operation and vegetation descriptions that had to be developed. In other words, broad implementation required both local expertise and substantial cooperation and oversight.

In spite of all the work that needed to be done and all the decisions that needed to be made (and remade!), full NRCS implementation of RUSLE1 began in 1993, using version 1.04 of the program, which is the version represented and documented in far more detail in AH703. This was actively used for conservation planning throughout the US, and for the Conservation Compliance portion of NRCS responsibilities associated with the 1985 and 1990 US Farm Bills.

8.2.4 Science problems with RUSLE1

As the USLE came into general use, it quickly became apparent that the impact of management on erosion could vary greatly among periods within a year or among years within a rotation. This was recognized by the later USLE methods, with AH537 using a time-varying SLR based on cropping periods. RUSLE1 carried this further, using a daily time-step for the *C*-factor calculations, and also for some of the *P*-factor calculations. However, due to user requirements that the structure of RUSLE1 reflect that of a 'paper implementation' of the USLE, this was not carried to its logical extreme. The time-varying values of each of the individual factors were aggregated over the year, and the resulting annual values were multiplied as shown in Equation (8.1). Unfortunately, this aggregated approach is not correct, as the sum of products is not equal to the product of sums, which can be seen in the simple calculation $(2 + 3) \times (4 + 5) = 45 \neq (2 \times 4) + (3 \times 5) = 23$. Clearly, the proper approach was to take any time-varying values and multiply these for each day or period, then add the daily products to get the total erosion. This was recognized as a problem early in RUSLE1 development, but it could not be dealt with while retaining the 'paper implementation' capability. Calculations showed that the erosion results could vary by up to 30% between the two approaches.

8.2.5 RUSLE1 program weaknesses

In addition to the weaknesses inherent in the RUSLE1 science development, some more general weaknesses in the program operation became apparent during implementation.

The first program weakness was that the RUSLE1 structure was based on science rather than on how the user saw things. For example, one parameter used in the *LS* calculations is the soil texture, which affects the susceptibility of the soil to develop rills, thereby impacting the *LS* β value (Equation (8.2)). In spite of this, the user will clearly think of texture as a soil property, and not as something related to topography. This is one of many examples in RUSLE1 where there was a need to approach things more from the user's viewpoint, and not from the modelling viewpoint.

Another weakness of the RUSLE1 approach is that any user could change any database value. Although NRCS had put substantial effort into developing specific databases for climates and vegetations, any user could change the values, either intentionally or by accident. This resulted in many implementation headaches, such that two users using the same inputs would get very different results because one of the underlying database files had been modified.

Finally, the DOS-based interface used in RUSLE1 was already dated at the time of its delivery, and users repeatedly asked for a Windows®-based or similar graphical user interface, with which they were becoming increasingly familiar.

8.3 RUSLE2

As RUSLE1 developed, it quickly became apparent that there were some scientific weaknesses with the approach taken that were primarily caused by its close linkage to the methodology used in the USLE. In addition, through the training and implementation process, some lessons were learned about how the general program could be improved. Work began to address these issues in 1996, culminating in the release of a first RUSLE2 version in 2001 and the beginning of a US-wide NRCS implementation with actual distribution of the program to the field offices beginning in 2004. Based on some of the lessons learned in RUSLE1 implementation, this included a much earlier push to begin establishing the required databases, as well as to begin the iterative process of developing and modifying the program based on user feedback.

A primary change in the RUSLE2 implementation of the USLE relationships could be described as downplaying the importance of the individual factors. In the original USLE concept, these factors (except perhaps for C and P) were generally considered to be independent. This was clearly no longer the case in RUSLE1, as exemplified by the dependence of the β term in the LS relationship (Equation (8.3)) on various soil and management factors, which also impact the K and LS values. The factor-based RUSLE1 implementation caused both science and user problems. Inconsistent values could be entered in the various factors (a science error) and the program required the user to jump back and forth between factors in order to enter relevant and related data.

Implementation of RUSLE1 also made clear many places where the science was not specifically in error, but could be greatly enhanced. The most obvious of these was in full implementation within RUSLE2 of the CREAMS (Foster *et al*., 1980) sediment transport and deposition approach, allowing the definition of the RUSLE2 hillslope to include depositional zones all the way down to the concentrated flow channel, and making RUSLE2 much more applicable to water quality problems. Other places where it was thought that the science could be enhanced by smaller improvements were many, especially in reducing the need for user selection of values by developing ways for the program to calculate needed values from information already available in databases. For example, in RUSLE1 the user needed to describe in several places the susceptibility of the soil to rilling; but this would vary with time, and can be estimated using parameters such as the soil texture, slope steepness, and management parameters already calculated within RUSLE2.

As with RUSLE1, many scientists and engineers were involved in producing and delivering the RUSLE2 technology, including those involved in data collection and preparation for analysis. Most of these individuals are acknowledged in the references for the corresponding documents.

8.3.1 General approach to RUSLE2 science problems

The following summary brings up to date earlier and more extensive summaries of science improvements in RUSLE2 (Foster *et al*. 2000, 2003; USDA-ARS, 2008a,b). In this treatment, distinctions are drawn between RUSLE2 and RUSLE1 version 1.04, as documented in AH703. Some of the science enhancements in RUSLE2 exist in later versions of RUSLE1, specifically in RUSLE1.05 and RUSLE1.06, which were developed with the support of the US Department of Interior Office of Surface Mining (Foster *et al*., 2003).

RUSLE2 retains the conceptual use of the USLE factors, makes computations that are based on soil loss estimates referenced to unit plot conditions, and uses ratios to adjust predictions to other conditions. However, RUSLE2 goes beyond the USLE. It uses process-based equations derived from fundamental erosion science and professional judgment to make RUSLE2 applicable to situations beyond the scope of USLE or RUSLE1. As scientific approaches improved, RUSLE2 was calibrated to reproduce the core SLRs for different cropping systems and crop growth stages listed in Table 5 of Agriculture Handbook 537 (Wischmeier & Smith, 1978). This calibration ensured that RUSLE2 erosion estimates for common situations would be similar to the established and accepted values that have been used for decades in the US for conservation compliance assessment.

A major change in RUSLE2 was the de-emphasis of the USLE factors, and the organization of information into 'objects'. This object-oriented organization applies to both the computer programming and the way that data are input by the user. The RUSLE2 developers made an effort to group and consolidate information needed by RUSLE2 into objects or descriptions that reflected how users think about the USLE factors. In the example mentioned above, with RUSLE1 the user had to use soil-related information not only in determining the *K* factor, but also in determining the *LS* factor, where the user chose among soil classes differing in their relative susceptibility to rill or inter-rill erosion (Table 4-5, Renard *et al.*, 1997). In RUSLE2, all soil-related information is included in a soil description, and all management information is contained in a management description. RUSLE2 combines these descriptions with the topographic description to define another description, that of a hillslope profile object, and extracts the information it needs from the descriptions to make erosion computations based on climate information contained in a location description.

Databases are maintained at the object level. Objects may contain other objects and subobjects. For example, a management object is composed of the dates of occurrence of operation objects (like tillage, planting, or other soil-disturbing operations) and vegetation objects. Vegetation objects contain descriptions of growth patterns, and canopy and residue characteristics needed by RUSLE2 to compute the vegetation's influence on erosion. RUSLE2 does not simulate the growth of vegetation, but rather takes the information contained in the vegetation description and accounts for its effect on the *L*, *C* and *P* factors through numerous influences on variables tracked or calculated internally by RUSLE2, including soil biomass, surface residue cover, surface roughness, canopy cover, Manning's roughness, and the runoff curve number. In the USLE, all the factors were independent of each other; the *K*, *L*, *S* and *P* factors were annual constants, while the *R* and *C* factors were broken down into crop growth phases. In RUSLE1, the *R*, *K* and *C* factors varied among 24 half-month periods but remained largely independent of each other, although the *LS* and ground-cover effects varied with the ratio of rill to inter-rill erosion, which in turn varied with soil texture, slope steepness and cover-management variables. In RUSLE2, all factors except *S* vary on a daily basis, and there are numerous interactions among the factors (USDA-ARS, 2008a). Annual averages of the RUSLE2 factors can be calculated, but the products of these averages will not equal the average annual erosion predicted by RUSLE2.

A major improvement in RUSLE2 is that the user can now define any number of steepness, soil, or management breaks along the slope, and the program will accordingly break the slope into segments representing each combination, and complete the calculations on those. RUSLE2 overcame limitations in describing complex hillslopes that existed in USLE and RUSLE1 by conceiving of hillslopes as being composed of three layers: topography, soil, and management. Each of these layers can be segmented independently to represent any complex one-dimensional hillslope situation. RUSLE2 then defines slope segments as each unique combination of topography, soil, and management layers. Because of the inclusion of deposition routines that were not part of the USLE or RUSLE1, RUSLE2 applies to hillslopes that include concave areas where sediment deposition occurs. Also, channels at the slope bottom, terraces with channels within hillslopes, impoundments, and sediment basins may all be described. These features allow RUSLE2 to compute sediment deposition and fine-particle enrichment of delivered sediment using process-based equations. Currently RUSLE2 does not simulate erosion in channels.

This ability to consider slope segments has also enabled RUSLE2 to deal nicely with the application of terraces or diversions as a management alternative. From a USLE/RUSLE perspective, the terrace channel becomes the concentrated flow channel defining the bottom of an upper hillslope profile, while the top of the terrace itself defines the beginning of a new lower profile. Within RUSLE2 this is handled automatically, defining not only the profiles, but allowing the user to specify the type of concentrated flow channel transferring water down from the terrace/diversion to the hillslope bottom. This channel can currently be modelled to cause deposition, but cannot currently be modelled as experiencing erosion. The ability to easily add or remove terraces for the hillslope description is important because it allows these to be approached as another management alternative, rather than requiring redefinition by the user of the hillslope profile itself.

(i) Changes in the climate description The climate data required to calculate soil loss in RUSLE2 are monthly averages for precipitation, temperature and erosivity, plus the desired location's ten-year 24-h precipitation amount ($P_{10y,24h}$). Climate description changes from RUSLE1 to RUSLE2 include: specification of $P_{10y,24h}$ rather than the ten-year *EI* event; updating the underlying record to the period from 1960 to 1989 (1960 to 1999 in many cases); and development of the erosivity density concept. Specification of monthly average precipitation and monthly average erosivity density is the preferred way of describing monthly erosivity in RUSLE2, and these values are contained in all the NRCS location climate files (USDA-NRCS, 2008). Erosivity density is defined as the amount of rainfall erosivity per unit of precipitation. Erosivity density has units of energy per unit area per unit time (e.g. MJ ha^{-1} h^{-1}), and when multiplied by the depth of precipitation over an interval (event, day, month, year) yields the appropriate average erosivity value. Using erosivity density has several advantages over directly calculated rainfall erosivity: (1) because it is the ratio of storm erosivity to storm precipitation, missing data have less impact on monthly means; (2) a shorter period of record is needed to arrive at a stable value of this ratio than a stable absolute value of erosivity; (3) because erosivity density was found to be relatively independent of elevation up to 3000 m, it was possible to interpolate a smoothly-varying erosivity density surface for the entire nation, making it possible to calculate erosivity for each county (common use in the US) or each precipitation zone (USDA-ARS, 2008a,b). The effect of elevation on erosivity was reflected by defining precipitation zones within counties of 11 mountainous western US states. The erosivity density approach allows geographically consistent erosion predictions needed for a conservation/erosion planning tool, and maximizes information that can be extracted from available 15-min precipitation data.

(ii) Changes in the soil description Changes in the soil description and *K*-factor computations include the development of a modified nomograph for highly disturbed soils, the development of new routines to describe time-variation in the *K* factor based on location temperature and precipitation data, and the ability to reflect the impact of subsurface drainage by specifying a soil hydrological class. RUSLE2 contains equations representing both the standard nomograph (Fig. 8.2) and a modified nomograph that applies to disturbed soils such as construction sites or reclaimed mine soils. The modified nomograph is the same as the standard nomograph for fine granular soils ($S = 2$), but the structural trend in erodibility is reversed in the modified nomograph, so that erodibility decreases as structure varies from very fine granular to massive. In the modified nomograph, the labels for class 1 and 3 structures would be exchanged and the line for class 4 structure would be to the left of all structure lines shown in Fig. 8.2. The modified nomograph is recommended for highly disturbed lands such as reclaimed mined land and construction sites, whereas the standard nomograph is recommended for agricultural soils because of its empirical support. For equivalent soil properties, both the standard and modified nomograph return a base *K* factor for Columbia, MO, which is a reference location and the centre of the RUSLE2 domain.

RUSLE1 included a time-varying *K* factor that was based on a few data points collected in the central US that indicated a time-varying change in Unit Plot erosion from storms with similar erosivity. New relationships in RUSLE2 capture the effect of temperature and precipitation on the likelihood of runoff and hence the *K* factor. For example, during cool and wet periods, higher antecedent soil water is likely to increase runoff and soil erosion, thus K should be higher. Similarly, increased temperature is expected to increase evapotranspiration, leading to lower antecedent soil moisture, lower runoff, and reduced K values. Relationships in RUSLE2 capture the main effects of seasonal variation in K at each location based on the ratio of temperature and precipitation values at each location to the average annual values at the reference location (Columbia, MO). For identical soil descriptions, these adjustments will increase the annual effective K at locations that are cooler and wetter than Columbia, MO, while average K values will be lower than the nomograph value at locations that are hotter and drier than Columbia, MO.

In RUSLE2, inclusion of the CREAMS (Foster *et al.*, 1980) sediment transport and deposition relationships requires knowledge of the sediment size distribution at the point of detachment, so the diameter, specific gravity, and primary particle composition of each of five size classes is calculated as a function of soil clay using equations similar to those in CREAMS (Foster *et al.*, 1985). The effect of drainage on runoff and sediment transport is discussed below with regard to the P factor.

(iii) Changes to the topographic description Whereas the rill to inter-rill erosion ratio in RUSLE1 was selected by the user, in RUSLE2 this ratio is calculated internally based on soil texture, prior land use (soil biomass and soil consolidation) effects, ground cover and slope steepness. This ratio determines the slope length exponent, m, in Equation (8.2), which controls the sensitivity of sheet and rill erosion to slope length. Instead of using Equation (8.3), the ratio of rill to inter-rill erosion in RUSLE2 is computed from (USDA-ARS, 2008a):

$$\beta = \left(\frac{K_r}{K_i}\right)\left(\frac{c_{pr}}{c_{pi}}\right)\left(\frac{\exp(-b_r f_g)}{\exp(-0.025 f_g)}\right)\left(\frac{s/0.0896}{3s^{0.8}+0.56}\right) \tag{8.24}$$

where the ratio K_r/K_i is the inherent rill to inter-rill soil erodibility ratio computed as a function of soil texture (as discussed in the text following Equation (8.3)); the term c_{pr}/c_{pi} reflects the effect of prior land use on the rill to inter-rill erosion ratio; the ratio $\exp(-b_r f_g)/\exp(-0.025 f_g)$ reflects how ground cover affects rill erosion more than it affects inter-rill erosion, b_r and 0.025 are coefficients ($\%^{-1}$) that express the relative effectiveness of ground cover for reducing rill erosion and inter-rill erosion, and f_g is ground cover expressed as a percentage. The last term is the same as Equation (8.3). Equation (8.24) shows how RUSLE2 takes the information stored in the topographic, management, and soil objects and uses it to calculate needed coefficients, thus reducing the need for users to specify unfamiliar parameters. The fact that the rill to inter-rill erosion ratio, as calculated from Equation (8.24), is independent of slope length (when it really is not) illustrates the price that RUSLE2 pays for the ability to retain the simple and familiar USLE equation structure.

Complex slopes can be represented in RUSLE2 to provide a better approximation of topography. A broad range of process-based routines allows for calculation of deposition caused by either management or topographic changes. This means that, for RUSLE2, the hillslope is defined as from where runoff begins until it enters a concentrated flow channel, which is the same definition as for WEPP.

(iv) Changes to the management description One significant change from RUSLE1 to RUSLE2 was the grouping of field operations and vegetations into a separate management object or description. Management objects comprise descriptions of field operations (their dates of occurrence, and their effects on surface cover and surface roughness) with vegetation descriptions whose growth is begun by the operation (if any) and the yield expected for that vegetation, and the amount and type of external residue added to the surface if a mulching operation. Management descriptions result in daily tracking of an extensive suite of variables that affect sheet and rill erosion, including canopy cover, standing residue, surface residue, surface roughness, ridge height, and the depth distribution of buried residue and soil biomass. Some of these, like standing stubble and ridge height, are variables that did not exist as USLE or RUSLE1 subfactors, but even the more familiar variables have received new and more detailed treatment in RUSLE2. In addition to surface and standing residue, RUSLE2 tracks dead biomass in 24 2.5-cm-thick soil layers in the soil profile. By default, standing residue decays at a rate that is a fraction of that of the surface residue, buried residue, or dead roots, which all decay at a rate controlled by climatic and residue variables using the same relationships as in RUSLE1. Mechanical tillage operations are described much more fully in RUSLE2 database files than in RUSLE1, in terms of the impact they have on flattening standing residues, disturbing the soil, or affecting the growth of vegetation. Soil disturbance is described in terms of the fraction of the soil disturbed, the intensity and depth of soil disturbance, the creation of ridges and random roughness, and the effect on burying, redistributing, or re-surfacing residues.

In a vegetation description, users define the base crop yield, the time course of canopy and root mass development (a 'growth chart'), and the characteristics of the residue produced when the crop dies. RUSLE2 uses this information once a 'begin growth' operation in a management description calls for that vegetation. The growth of the vegetation in RUSLE2 is independent of the location's climate data, so it must be properly described by the user for the situation being analysed. Several 'wizards' are available in the RUSLE2 interface to help users to develop vegetation descriptions, to define canopy/biomass relationships, canopy shape and intercepted raindrop fall height, and yield/flow retardance relationships. A new portion of the program specifically designed to help the database developer and program user properly to account for residue and root production in perennial vegetation systems is being developed, and is discussed subsequently.

One key feature added to the vegetation/operation/management descriptions in RUSLE2 is the ability of the user to vary crop yield. Vegetation is described for a specific assumed base yield, but when the vegetation is actually used within a management regime, the user can specify a higher or lower yield value. The vegetation description includes how the biomass varies with yield, allowing adjustment of all of the vegetation parameters by the program.

(v) Changes to the support practice factor Whereas the RUSLE1 user selects a cover management condition that, together with the soil hydrological group, defines a 'runoff index' analogous to the runoff curve number (*CN*), RUSLE2 calculates a *CN* internally as a function of soil hydraulic class, soil biomass, soil consolidation, soil roughness, and soil residue cover, thus reflecting the combined effects of soil, management and climate. RUSLE2 calculates runoff for the $P_{10y,24h}$ rainfall event every day. It also calculates sheet and rill erosion for this index event, and uses process-based equations to determine sediment transport, deposition, and fines enrichment. 'Infiltration' is calculated on slope segments with a low *CN* as the difference between $P_{10y,24h}$ precipitation depth and the 'initial abstraction', taken as 0.2 times the 'maximum retention' parameter, a transform of the *CN* (USDA-ARS, 2008a). The RUSLE2 equations for sediment transport capacity and deposition, and robust simplifications of the equations used in CREAMS, give RUSLE2 the ability to reflect the effects of spatial variation of soil erodibility, slope steepness, and cover management along a slope on detachment, transport and deposition. This approach results in estimates of the long-term average sediment production, erosion rate, transport capacity, deposition, and sediment characteristics along the slope, as well as the sediment amount and characteristics of sediment leaving the slope (Foster *et al*., 2000). In fact, RUSLE2 goes further than other 'process-based' models, in that it approximates backwater effects when it determines the effectiveness of dense narrow vegetative buffers on sediment trapping (USDA-ARS, 2008a). RUSLE2 also includes the ability to approximate the effect of simple impoundments and channels on sediment delivery and fines enrichment.

8.3.2 RUSLE2 implementation and lessons learned

(i) RUSLE2 websites There are two 'official' RUSLE2 web sites: an ARS site, http://www.ars.usda.gov/Research/docs.htm?docid=6010, and an NRCS site, http://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm. Both sites offer the same model, but with different databases, permission (access) levels, and templates. The ARS site provides a minimal database and access levels that allow scientists and engineers to see and change more parameters. The NRCS site includes much more extensive databases, and templates including a wide variety of additional tools, but the permissions for database manipulation are more restricted. The USDA-NRCS website is the single national point of delivery for the NRCS-approved RUSLE2 management templates and database components. Both websites contain documentation and training materials.

The NRCS website is remotely maintained and kept current by the NRCS database manager, who posts frequent database updates, revised soils data in RUSLE2 format, and updates to the 24,000+ management templates. Although the current version installer is posted for downloading and installation by private sector users, the NRCS has recently begun using an automatic software installation process for new releases of RUSLE2. This minimizes the amount of support time necessary to remove and install RUSLE2 on NRCS field office computers.

(ii) RUSLE2 interface: plasticity and security An internal NRCS oversight and evaluation review of RUSLE1 implementation uncovered significant differences in soil loss estimates from RUSLE1 across county lines in adjacent states and regions due to a lack of consistent RUSLE1 databases within NRCS. With this past experience in mind, RUSLE2 was implemented with a hierarchical approach that allows users to see and change only those factors they fully understand. In RUSLE1, any user could change any parameter, sometimes leading to a very unlikely combination of inputs that gave them the output they desired. In RUSLE2 inappropriate changes are controlled by three mechanisms. The first is the user interface, which is very user-configurable. This allows more complicated inputs or outputs to be removed from the visible set, simplifying the model to a degree matching the user's interests and abilities. Since in the RUSLE2 calculation engine a parameter that is not needed is not calculated, removing unnecessary parameters also accelerates calculations. The second control mechanism is called access control, which limits what the user is allowed to see or edit. Access must be granted to the user by a higher-level user, providing a very flexible control structure that can be modified as a user is trained and needs greater control over the program. The third control mechanism is protection of specific records or groups of records within the database. For example, records created by a user with a high access level can only be edited and re-saved by a user with that access level or a higher one in the same access chain. Other users can edit the record, but can only save it as another record, over which they can exert control. As a result, once NRCS creates and locks a record, they can distribute it with the confidence that it cannot be modified by less knowledgeable users.

(iii) RUSLE2 database development and management RUSLE2 is supported by databases that store factor data and data entered by users. The climatic data are held in a location/climate description stored in the database, as are the soil data in their own separate description. These can then be accessed for re-use simply by calling for them by name. The most extreme example of this approach is in the management descriptions. A management description is a list of the field operations and associated dates, including what vegetation is planted or residue added (if any). These field operation, vegetation, and residue descriptions are each stored in their own named database descriptions for potential re-use by other managements, which in turn can also be stored.

Database development began in early 2000 with the designation of a USDA-NRCS National Database Manager or 'czar' who was given the task of expanding the initial minimal core vegetation and operation descriptions for NRCS use on cropland and pastureland, as well as assisting with the development of detailed climate descriptions, and directing and managing the importing of soils data for all available soil surveys. Working with many colleagues, the database czar populated a single nationally-coordinated database of climate, soils, operations, vegetations, residue and support practice descriptions. For consistency, field office users were 'locked out' of editing the data in these parts of the database.

Because the national database was vast, it was organized into sections that could be downloaded from the NRCS website for use in local conservation planning. Soils data were organized by state and county or soil survey area. Thus, only the soils data that a particular field office or user needed would be contained in the local database, although another soils description could be imported as needed. Climate data were organized by state for use in the same way. Management records were organized by Crop Management Zones (CMZs), 75 regions of the country with similar crops and tillage systems.

Climate records. Climate data were populated for the entire US, including Alaska, Hawaii and the Pacific islands, Puerto Rico and the Virgin Islands. The effort included extraction of the monthly parameters from the national 1960–1989 dataset (1960–1999 in some cases), with calculation of monthly *EI* values for stations with recording intervals of 15 min or shorter. These data were smoothed using several routines and visual inspection to provide a relatively smooth erosivity density 'surface', which was then used to provide point values or, more commonly, an average value over a county.

Soil records. Creation of soil descriptions in RUSLE2 was eased by making direct use of the NRCS NASIS/SURGO soil database and tools, available online at http://soils.usda.gov/technical/nasis/. This is based on an NRCS soils expert (usually the State Agronomist) downloading from NASIS all of the necessary soil descriptions, then running those through a RUSLE2 utility that extracts the necessary information, tests it for consistency, and puts it into the required RUSLE2 format. Most RUSLE2 soils databases include some generic soil descriptions based on soil texture, and these are often more appropriate for use with highly disturbed and mixed soils like those on construction sites and mine reclamation projects.

Management records. The RUSLE1 experience used the approach of organizing the US by *C* factor or *EI* distribution zones in order to develop and coordinate the issuance of *C*-factor sets for common single crop and crop rotation scenarios. With RUSLE2 implementation, this cropping region concept was built upon with the creation of 75 Crop Management Zones (CMZs), in which common crops and tillage systems were described in detail and saved as 'locked' RUSLE2 management templates. CMZs are zones in which the climate and other factors thought to control management are assumed to be constant and unaffected by political boundaries. In other words, within a CMZ the crops are likely to be grown with very similar planting and harvest dates, as well as similar tillage systems, and so on. For example, one CMZ representing the central Corn Belt stretches east from the southeastern corner of Nebraska and northwestern corner of Kansas through northern Missouri, and across central Illinois, Indiana and Ohio. Another CMZ stretches south along the eastern side of the Appalachian range from Maryland into Alabama.

With national coordination, this effort involved significant coordination among NRCS state agronomists in setting typical dates of operations and creating these management templates to represent the typical tillage systems used in growing the important crops in each CMZ. Once a set of crop management template descriptions was created by a CMZ coordinator, it was submitted to the database manager for inclusion in the national NRCS RUSLE2 database. Each CMZ set was contained in a separate RUSLE2 export file so it could be imported into the local RUSLE2 database in each field office located within the boundaries of that CMZ. This provided a starting point for field offices as they implemented RUSLE2, and also provided consistency in the use of RUSLE2 since the locked management templates were based on typical dates and typical tillage systems used in the CMZ. Internally, the vegetations, operations and residues used by these managements all came from the same national NRCS RUSLE2 database. Users could copy templates into a local management file and change or edit the tillage system details, yields, crops and dates of operations to tailor them for use locally in specific runs, whereas the locked templates remained unedited for future use.

(iv) RUSLE2 database status Although the data developed for RUSLE1 (especially the vegetation and operation descriptions) proved invaluable in the NRCS database development efforts, development of the RUSLE2 database was still a tremendous effort. The USDA-NRCS, with initial guidance from ARS and aided by university and other cooperators, has compiled a database that includes (as of 21 July 2008): (1) 105 residues, describing how much cover each provides and how fast it decomposes; (2) 917 vegetations, from asparagus to zucchini, with each describing how the vegetation grows in terms of providing canopy cover and biomass; (3) 438 field operations, describing what happens to the soil, residue and vegetation as a result of the operation; (4) 10,976 climate descriptions; (5) 1,048,659 soil component descriptions, representing 649,032 soil map units in 3100 soil survey areas; (6) 467 special descriptions describing saved descriptions of strip-cropping, contouring, terracing, and sediment control basin practices; and (7) 26,361 managements for 75 CMZs, describing how the field operations, vegetations and residues fit together into management schemes.

8.3.3 Implementation needs and training requirements

(i) Preliminary training Initial RUSLE2 training was conducted by NRCS with assistance from the RUSLE2 development team in regional testing sessions during the period from 1999 to 2000. A minimal database, which included generic soils and only a few major crops and operations, was used for testing RUSLE2. As the training sessions progressed, it became clear that there were several background requirements that would be required of the trainees prior to full-scale training, including:

- enough background in the underlying USLE/RUSLE science to allow the trainee to understand the conceptual approach, the use of the inputs, and the meaning of the results; and
- a general understanding of how the computer program organizes information and reflects the 'conceptual model' behind RUSLE. This was enhanced by the flexibility of the program in developing very simple user interface templates, which allowed the program to be introduced at a rather basic level.

In addition, a fuller database adequately reflecting the broad range of situations that users would need to address was required for full-scale training.

(ii) NRCS RUSLE2 training Beginning in the summer of 2001, USDA-NRCS conducted regional 'train the trainer' sessions for NRCS state and area agronomists and others with erosion prediction responsibilities. These sessions were conducted by the NRCS Water Erosion cooperating scientist, national database manager, and the RUSLE2 development team. Training focused on the erosion science on which RUSLE2 is based, how to navigate the user interface, how the database structure is organized, the content of records in the various parts of the database, and hands-on experience in creating management scenarios and making simple RUSLE2 runs. One or two individuals from each state attended and began learning the model as well as learning how to train field office employees within their states. Each of these trainers then went back and conducted a series of 1–2 day RUSLE2 model training sessions to allow field office staff to develop sufficient skills such that they could make soil loss estimates using a relatively simple user template.

The regional 'train the trainer' sessions proved very valuable not only to the NRCS state personnel but also to the RUSLE2 development team, in that several NRCS user needs were identified that eventually led to enhancements and modifications to the RUSLE2 user interface. One enhancement was the development of a rotation builder module to allow creation of multi-year and multi-crop rotations from concatenation of single-year management scenarios. This also allows rapid substitution of individual tillage system years as treatment alternatives are explored during conservation planning with producers. NRCS users also expressed a need to group RUSLE2 runs for these different alternative treatments into a 'worksheet screen', and to assemble the worksheets for multiple fields within RUSLE2, thereby representing an entire farm. This need was addressed through the development of the 'plan view' in the interface. As states began to conduct field office training sessions, an NRCS User Guide for the RUSLE2 interface was developed and distributed. Additional 'how to' guides and references were prepared for specific tasks, such as importing and exporting database components, importing soils data from NASIS soils descriptions, installing new versions, and performing database updates.

As implementation and use of RUSLE2 expanded, and as NRCS and private sector users gained experience in the model, regional advanced RUSLE2 training sessions were conducted in all regions of the US. These sessions built on the initial training and provided more in-depth training, resulting in a deeper understanding of operations, vegetations, and support practice records, of modelling erosion and sediment deposition on complex slopes, of database management, of more complex screen views, and of organizing outputs and dealing with complex management scenarios. Additionally, as users became more sophisticated, more complicated screen views and printing templates that included more detailed outputs and analysis were developed and released.

(iii) Day-to-day support A significant amount of day-to-day support was provided to states and field offices by the NRCS water erosion cooperating scientist and the national database manager during the implementation years of 2001 through to the present. This was provided through a combination of telephone and e-mail support, and direct computer-to-computer sharing of software applications. Several 1–3 hour training sessions were conducted via this latter method to provide training to multiple states on new enhancements and timely topics. Support personnel also processed hundreds or even thousands of individual requests for additional vegetations, operations and support practices, as RUSLE2 use expanded across the US.

As various other applications were being developed, access to the 24,000 + RUSLE2 crop management templates became necessary. A common file exchange format was used so that these files could be exported and utilized by the Wind Erosion Prediction System (WEPS) model (Hagen, 1996). Several other applications have used this file exchange format to utilize all subsets of the RUSLE2 management templates.

8.3.4 Most significant application enhancements

RUSLE2 includes a user convenience called the 'worksheet view' that allows comparisons or combinations of a series of hillslope profiles, each of which represents a single RUSLE2 erosion/delivery calculation. For example, the management alternative worksheet uses a single climate, soil and topographic description, but below that shows a table of management alternatives and resulting erosion and sediment delivery (Plate 4). Each line in the table represents a single RUSLE2 calculation, and all lines share the common climate, soil and topography. The idea is that each worksheet in this case represents a field, with a list of likely management options and resulting erosion values. A group of worksheets can then be combined/compared in a 'plan', which can represent a farm, with each worksheet representing a field within that farm or land parcel. Within the worksheet, the user can control which management alternatives are brought into the plan for each field, allowing for comparison of all the alternatives. Once the planning decision is made, yes/no toggles can be set to display only the scenarios representing the 'before' and 'after' management alternatives. Thus they provide documentation of the 'before' and 'after' soil losses.

As indicated earlier, a feature added to the RUSLE2 program that greatly eased the database development effort was the inclusion of the Rotation Builder. This allowed the management scenarios to be developed as single crops, allowing the user within the program to 'paste' these together into the desired sequence. For example, the long growing seasons in the southeast US allows for multiple vegetable crops to be grown in sequence, resulting in a huge number of permutations requiring a large number of database descriptions. The Rotation Builder allows for limiting the descriptions to the single vegetations, which the RUSLE2 user can then combine within the program run as desired. If a specific combination is used frequently, the program allows users to save the combination as a single management, allowing for easy re-use.

Another RUSLE2 enhancement, developed with the support of the Wisconsin Department of Natural Resources and Dane County Land Conservation, is that the erosion and sediment delivery no longer need to be summed for the year. Conservationists working on construction sites are often interested in what happens only during some accounting period, over which the site operator is liable for erosion and sediment control. For example, the Wisconsin project defined a successful management plan as that which would keep the total sediment delivered from the site under 11 Mg ha^{-1} (5 US t ac^{-1}) during the period from the time of first soil disturbance until either placement of some non-erodible cover, or 60 days of growth of a permanent perennial vegetation. RUSLE2 allows for flexible definition of the accounting period, and of the target that must be achieved.

RUSLE2 also allows for printing a report describing the inputs and outputs of a RUSLE2 calculation. The form of the report is user-configurable, allowing users to define what they would like to see and in what form in a Microsoft Word® document. The resulting document can then be locked so that the user cannot change the results, and the associated RUSLE2 inputs can be saved into the document, allowing for a regulator to inspect the underlying information.

8.3.5 NRCS tools added to the NRCS RUSLE2 interface

Several additional calculations have been added to the NRCS RUSLE2 interface. The most prominent of these is calculation of the Soil Conditioning Index (SCI) (USDA-NRCS, 2002, examined by Zobeck *et al*., 2007), which provides a rough estimate of whether a specific location/management/soil combination will tend to cause an increase or decrease in soil organic matter. One component of the SCI that has also proved useful is the Soil Tillage Intensity Rating (STIR), which makes use of the tillage type, tillage depth, operation speed, and percentage surface disturbance as a rough estimate of the soil disturbance cause by the operation. The STIR value is used as a criterion for NRCS's National Residue Management Practice Standards (available for download at http://www.nrcs.usda.gov/Technical/Standards/nhcp.html, accessed 3 September 2008). The STIR and SCI calculations have no impact on the RUSLE2 erosion/delivery calculations, but make use of the management operation and erosion results.

NRCS has added a calculation of management fuel usage based on the sequence of operations to the RUSLE2 interface. Several state phosphorus index calculations have also been added to the interface. Other tools were added to the NRCS RUSLE2 interface to compute a Nitrogen Leaching Index and an Energy and Fuel Use Calculator based on the tillage operations. Examples of the SCI and the Fuel Use Calculator results are shown in Plate 4.

8.3.6 Future of the technology

The science supporting RUSLE2 continues to advance and will be incorporated into future releases of the model. Two active areas of research include (1) residue production in perennial systems, and (2) ephemeral gully erosion estimation.

In most USDA erosion models (e.g. WEPP, WEPS, RUSLE1), residue production occurs only during senescence of a crop and is calculated from the decline in live biomass. This is equivalent to the assumption that there is no dead biomass production during periods of increasing biomass, and no additional growth after the peak biomass is reached. This is probably a reasonable and acceptable assumption for the treatment of annual crops. However, in perennial vegetation and in mixed stands where different components mature at different times, death and growth usually occur simultaneously. A new type of vegetation description is being developed for RUSLE2 in which residue production is more continuous, based on the assumption that live biomass has an effective life span. In the absence of forage harvest or biomass removal, the daily change in live biomass amount is calculated as the difference between new growth and the death of old growth. Live biomass that is not harvested is added to a dead biomass pool after its lifespan is reached, thereby providing the soil the benefits of additional residue cover. Users input monthly potential growth patterns and shoot and root life-spans, and RUSLE2 calculates corresponding residue production patterns. Growth patterns are altered in response to management operations involving biomass removal. Daily changes in residue biomass are then calculated as the difference between death and decomposition or residue harvest. RUSLE2's new routines will simplify the creation of vegetation descriptions for perennial systems, providing more realistic estimates of residue creation throughout the year, and thereby improving runoff and erosion estimation for pastures, hay fields, and other systems dominated by perennial vegetation.

To predict average annual ephemeral gully erosion is challenging because there is no existing long-term database of ephemeral gully erosion rates comparable to the plot database underlying the USLE, which in turn underlies RUSLE. Ephemeral gully erosion is a process inherently driven by larger-than-average runoff events (see Chapter 19). Many process-based models have developed climate-generators (e.g. CREAMS: Knisel, 1980) that reproduce the stochasticity of weather. Applying these long-term weather records to an ideal runoff and erosion model would create a distribution of runoff and erosion events. Taking the monthly means of this population of ephemeral gully erosion events would represent the long-term average values needed to complement RUSLE2 sheet and rill erosion estimates and to estimate long-term average ephemeral gully erosion. The RUSLE2 developers proposed that modelling the correct storm amount and sequence of storms could reproduce the mean values. Toward this end, techniques to predict a sequence of index storms for any combination of soil and management anywhere within the continental US (and elsewhere, with appropriate calibration) have been developed, and require only RUSLE2 climate and profile-level information. The results approximate the mean monthly runoff, annual runoff event frequency, and a gamma distribution function scale parameter that characterizes 30-year stochastic runoff predictions generated using the AnnAGNPS (annualized Agricultural Non-Point Source) model (Bingner & Theurer, 2001).

By taking the largest in a series of runoff events as a 6-month return period event, and scaling the magnitudes of the periodic runoff events proportional to the long-term average disaggregated daily runoff amounts on event days, these parameters allow estimation of the date and size of a series of index runoff events that are proposed as the basis for an ephemeral gully calculation capability within RUSLE2. Index event RUSLE2 hillslope runoff, sediment yield, and sediment size distribution will be coupled with a physically-based ephemeral gully erosion model, possibly that used in CREAMS, to predict annual average ephemeral gully erosion.

8.3.7 RUSLE2 examples

RUSLE2 is so flexible that it is very difficult to decide which capabilities to show in a few examples, and in which form to display those. In narrowing the possibilities, it was decided to concentrate on three examples. The first example is included especially to dispel the notion that RUSLE2 is difficult and complicated to use. The other examples represent two common uses of RUSLE2. The second example compares management alternatives on a single field, as would probably be done by a conservation planner working with an agricultural producer. The third example demonstrates planning to meet a specific sediment delivery target on a construction site. In both of these latter cases the figure will appear relatively complex, but this complexity was added so that specific features could be highlighted.

(i) Example 1. Very simple view One of the complaints sometimes lodged against RUSLE2 is that it is too complex and difficult for a novice user. As described in the sections above, the complexity the user sees in RUSLE2 is totally controlled by what the user asks to see and how they ask to see it. The calculations are exactly the same for a simple view (Plate 5) as for a more complex one, except that fewer calculations may be needed because fewer outputs are requested. The user views are completely user-configurable, so there is an infinite number of possible views, not just some pre-specified simple, medium and complex views. The RUSLE2 screen capture (Plate 5) shows one of the simpler views, which could be used by someone with a minimal understanding of soil erosion. In order to get an erosion and sediment delivery result, the user need only select a location (climate), a soil, and a management from pre-existing lists in the database. They then enter a slope length and steepness (which assumes a uniform slope), and can immediately see the resulting erosion and sediment delivery. If desired, this view also allows the user to select from pre-defined contour or cross-slope tillage systems, to put in pre-defined vegetated barriers on or at the bottom of the slope, or to see what happens if pre-defined terrace systems are installed. If the trainer or program supplier believes that even these few conservation practices will not be understood by the target user, even these entries associated with Step 5 in the view above may be easily removed.

In this access level and view, the user has no way of directly modifying any of the inputs except slope length and steepness. Everything else must be selected from pre-defined descriptions in the database, presumably placed there by someone with the training and knowledge to do so. Most users are not long satisfied with so little flexibility. For example, they may want to be able to see the impact of a complex slope shape rather than being forced to assume a uniform slope. This increased power comes at the cost of increased complexity, as the user must now be faced with a user template allowing them to enter length and steepness values for the slope segments. This constant desire for more power and flexibility results in what the RUSLE2 development team calls 'template creep', which is the tendency of user templates to become increasingly complex over time in order to provide additional power. The RUSLE2 complexity that some users complain of is not built into the RUSLE2 program, but rather exists because other users who developed that user template thought those entries and outputs were necessary.

Finally, notice that Plate 5 shows the inputs and results in metric units, while the values shown in Plate 4 were in Imperial units. This demonstrates some of the additional flexibility of the RUSLE2 interface, which allows for any desired mixing and matching of units, and also for selecting the desired units within a system (e.g. cm or mm for height).

(ii) Example 2. Agricultural conservation planning The RUSLE2 screen capture shown earlier in Plate 4 presents the results of conservation planning on a hypothetical field. In this view the field is defined as having a single climate, soil, and uniform slope. Each line in the table then represents a single RUSLE2 erosion calculation, using the climate, soil and topography defined above, and combining it with a unique combination of contouring, terraces and cropping sequence to yield erosion, fuel use, and Soil Conditioning Index (SCI) results. In order from the top of the table, the lines represent: (1) corn with moldboard ploughing in the fall and disking in the spring, tilled and planted up-and-down the slope; (2) the same tillage, but close to the contour; (3) the same as (2), but with a single terrace in the middle of the slope; (4) fall chisel ploughing up-and-down the slope; (5) fall chisel ploughing, but close to the contour; and (6) fall strip tillage, where in the fall only a narrow strip is disturbed in knifing in nitrogen. The results for each line show the planner not only the erosion and sediment yield associated with each alternative, but also the estimated fuel cost and the SCI value for that option, with values > 0 indicating a net increase in soil organic carbon over time. These generally show the expected results, with the reduced tillage option resulting in the lowest erosion, fuel cost, and highest SCI values.

The graphs shown in Plate 4 indicate some of RUSLE2's capability in graphically representing results. In this case the graphs are of the percentage of soil surface covered by crop residue, with the graph on the left for the fall moldboard plough scenario, and that on the right for the strip till management. In addition, although it is not displayed here, the crop yields for each of the management alternatives can be set by the user, if it is thought that the management sequence has an effect on those.

(iii) Example 3. Construction site sediment control As described above, although the RUSLE2 calculations for estimating erosion and sediment yield for construction sites are no different from those for agricultural settings, the RUSLE2 flexibility allows for a substantially different look and feel, which makes it easier to use in construction settings. Several of these differences are shown in Plate 6.

One primary difference seen here is that for construction sites the primary output of interest is not the soil erosion on the hillslope, but rather the sediment delivery to the receiving channel, representing the off-site impact. In fact, it is often comparison of this value to some defined standard rather than comparison of average annual soil loss with the soil loss tolerance (T) (Johnson, 1987) that indicates the success or failure of a construction plan.

Another difference is the look and feel of the screen itself, including especially the visible icons and the text. These can be things as trivial as using a bulldozer icon instead of a tractor to represent field operations, or as substantial as completely different text shown on the screen for the same parameter, reflecting differences in terminology. For example, in agricultural settings we generally speak of crops and of crop residues added to the surface, while in construction settings we would use the more generic vegetation and surface cover materials, including synthetic blankets and added mulches as well as residues from the vegetation grown on the site.

Another difference mentioned above is the ability of RUSLE2 to aggregate results not only on an average annual basis, but over a user-defined accounting period. For example, in the situation shown here, the accounting period is defined as beginning from the time of the first soil disturbance until either the application of some non-erodible permanent material (e.g. pavement, sod, or landscaping materials) or 60 days of growth of perennial vegetation, with days whose average temperature falls below 35°F not counted. In Plate 6, the two bottommost results in the lower left-hand corner indicate whether the system meets the definition of the accounting period, and a green or red colour in the rectangle indicates whether the system did or did not meet the allowable sediment delivery threshold, in this case set by the regulatory body as a total of no more than 5 Mg ha^{-1} (2 US t ac^{-1}) over the entire accounting period.

Users indicated that for construction site use – unlike for agricultural use – there would be little need for the capability to save and re-use management descriptions, as the timing of field operations would vary tremendously due to many factors. Because of this, the view in Plate 6 shows the management scenario description (dates and descriptions of field operations) directly within the general RUSLE2 profile view, rather than named and stored as a separate database record.

These users also indicated a need to define complex slope topography, as they wanted to be able to account for the deposition occurring on the flatter portion at the bottom of an S-shaped slope: thus the complexity of Step 3 in Plate 6, which in the previous views was shown simply as single uniform slope length and steepness. The slope schematic in the upper-right corner of the view displays this complexity. The upper (management) layer of this schematic shows a management break about 55 ft (16.8 m) down the slope. This is caused by the selection in Step 5 of a pre-defined strip-barrier system, which in this case puts a single 20-ft strip of poor stand cool-season grass at the bottom of the slope. In addition, Step 5 sets that the runoff from the bottom of the slope feeds to a sediment basin, which is pre-defined as having an 80% settling efficiency for a silt loam soil that has not experienced previous deposition. This last clause is important because any deposition occurring before the runoff hits the sediment basin will cause the coarse material to settle out, thereby reducing the actual efficiency of the basin. In the specific case shown here, there will be deposition at the bottom of the slope caused by both the decreased slope steepness and the grass strip, so the basin will not provide 80% efficiency. If they had so desired, the users could have added additional complexity to the view to show where the deposition actually occurred, but this was not deemed worthwhile.

8.4 Summary

Soil erosion has long been recognized as a serious problem. Considerable efforts have been expended to address this problem, beginning in Missouri in 1923 and supported by the US Congress in a 1929 appropriation that initiated intensive soil erosion research. Early efforts to preserve soil and prevent erosion through the work of pioneers like H.H. Bennett led to an early period of plot scale conservation research at sites representing the ten major farming regions in the US. The 6 ft (1.8 m) wide by 72.6 ft (22.1 m) long (0.01 acre, 40 m^2) research plots were constructed to represent various crops and rotations. Primary measurements included precipitation, runoff and soil loss (erosion). The results from this research, in combination with additional crops and cultural practices data, ultimately provided a repository of data widely used by engineers and scientists to evaluate conservation practices. These data were the foundation of the empirical erosion prediction technologies and ultimately the Universal Soil Loss Equation (USLE).

The USLE was developed at Purdue University under the direction of Walter Wischmeier, with able assistance from Dwight Smith, and was published in 1965 and 1978 in two handbooks (AH282 and AH537). The handbooks became widely accepted for conservation farming (and especially soil erosion by water) in the US. In the early 1980s a program to develop technology to replace the USLE was initiated. The computer-based RUSLE (Revised Universal Soil Loss Equation) model was published in 1997. RUSLE incorporated significant advances over the USLE and permitted application of soil erosion estimation for a greater variety of crops and management practices beyond those in the original USLE database.

RUSLE was subsequently revised to include advanced scientific and interface technology and subsequently delivered as RUSLE2, along with expanded databases and more control over the parameters that specific users could see and change. The USDA-NRCS has accepted responsibility for the underlying databases within the US, which include descriptions of climates, vegetations and soils, along with extensive files describing common management practices. RUSLE2 is widely recognized as a major advance in erosion prediction and conservation technology, and provides a very flexible tool allowing resource conservationists, managers and developers to compare a broad range of management alternatives in deciding on an optimum resource use.

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