Review

Event soil loss, runoff and the Universal Soil Loss Equation family of models: A review

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SUMMARY

The Universal Soil Loss Equation (USLE) is the most widely used and misused prediction equation in the world. Although it was designed to predict long-term average annual soil loss, it has the capacity to predict event soil losses reasonably well at some geographic locations and not well at others. Its lack of capacity to predict event erosion is highly influenced by the fact the event rainfall–runoff factor used in the USLE and its revisions (RUSLE, RUSLE2) does not consider runoff explicitly. While including direct consideration of runoff in the event rainfall–runoff factor improves the capacity to predict event erosion when runoff is measured, that capacity is reduced by inaccurate runoff prediction methods. Even so, the predictions may be better than when the traditional event rainfall–runoff factor is used if the rainfall–runoff model used to predict runoff works reasonably well. Direct consideration of runoff in the rainfall–runoff factor may improve the ability of the model to account for seasonal effects. It also enhances the ability of the model to account for the spatial variations in soil loss on hillslopes which result from spatial variations in soil and vegetation. However, the USLE model will not provide a capacity to account for deposition taking place on concave hillslopes unless it is coupled with an appropriate sediment transport model, as in done in RUSLE2. Changing the basis of the event rainfall–runoff factor has consequences on a number of the other factors used in the model, in particular new values of the soil erodibility factor need to be determined. Using runoff values from cropped areas is necessary to account for differences in infiltration capacities between vegetated and tilled bare fallow areas, but requires re-evaluation of the crop factors.

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Introduction

The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965, 1978) provides the most widely used, and misused, soil loss estimation equation in the world. The equation predicts the long-term average annual soil loss \( (A) \) associated with sheet and rill erosion using six factors that are associated with climate, soil, topography, vegetation and management. The USLE is often given as

\[
A = R K L S C P
\]

(1)

where \( A \) is average (mean) annual soil loss (mass/area/year) over the long term (e.g., 20 years), \( R \) is the rainfall-runoff "erosivity" factor, \( K \) is the soil "erodibility" factor, \( L \) and \( S \) are the topographic factors that depend on slope length and gradient, \( C \) is the crop and crop management factor, and \( P \) is the soil conservation practice factor. The USLE was originally developed to provide a method for estimating soil losses based on the results of more than 10,000 plot-years of data obtained from field experiments under natural rainfall in the USA, supplemented by data collected using rainfall simulators.

The USLE was originally applied to the prediction of soil losses from agriculture in the USA in order to preserve soil resources, but has been extended for use in numerous countries. In many cases, formulae used to determine the values of \( R, K, L, S, C \) and \( P \) in the USA have been adopted in other countries, although local experimental data have been used to develop local alternatives in some areas. The revised USLE (RUSLE) (Renard et al., 1997) was developed to take advantage of knowledge and data obtained in the 1980s and 1990s. It uses Eq. (1) with changes to the how some of the six factors are determined. In particular, a subfactor approach to the determination of \( C \) enables the model to be applied to crops and management systems not present in the original experiments used to develop the model. A computer program (RUSLE1) was developed to implement the RUSLE in the USA. The USLE was designed to apply to field sized areas. The RUSLE provided an approach that can be applied to one dimensional hill-slopes that do not produce deposition as a result of changes in slope gradient. RUSLE2 (Foster et al., 2003) provides an approach that does take into account deposition resulting from changes in slope gradient on one dimensional hillslopes.

Although Eq. (1) is commonly seen in the literature, the model actually works mathematically in two steps. The reason for this is that the USLE is based on the unit plot concept, where the unit plot is defined as tilled bare fallow area 22.1 m long on a 9% slope with

\[
A_{1} = R K
\]

(2)

and then multiply the result by appropriate values of \( L, S, C \) and \( P \) to account for the difference between the area of interest and the unit plot,

\[
A = A_{1} L S C P
\]

(3)

In effect, \( R \) is the independent variable in a regression model where the product of \( K, L, S, C \) and \( P \) combine to give the value of the regression coefficient. Originally, the values of \( K, L, S, C \) and \( P \) used to do this were associated with more than 10,000 plot-years of experiments undertaken in the USA. The fact that \( L, S, C \) and \( P \) are reduced variables mathematically forced to take on values of 1.0 for the unit plot has no physical significance. For example, when the formulae for \( K, L \), are modified appropriately, the model produces exactly the same value of \( A \) for a given non-unit plot sit-

![Fig. 1. The relationship between estimates of annual average soil losses produced by SOILLOSS, a local variant of the RUSLE, and observed values from runoff and soil loss plots in New South Wales, Australia. Redrawn from Rosewell (1993).](image-url)
Runoff and event erosivity

The relationships shown in Fig. 3 were obtained using all the events that produced soil loss from two plots considered at Holly Springs, MS and Morris, MN. In the USLE, a valid event in determining average annual values of \( E_{130} \) in the eastern part of the USA was considered to be one that had a rainfall amount that exceeded 13 mm or one where at least 6.5 mm fell in 15 min. The reason for this was that erosion from light rains was usually too small for practical significance and collectively, they had little effect on the distribution of the average annual value of \( E_{130} \). In addition, the cost of abstracting and analysing 4000 location-years of rainfall data in order to develop the initial \( R \)-factor map was greatly reduced by using the 13 mm threshold (Renard et al., 1997). However, in the subsequent analysis of rainfall data for the western part of the USA that restriction was removed (Renard et al., 1997) even though using the 13 mm restriction reduces the probability of the analysis including events that produce no runoff and hence erosion. In the approach adopted here, rainfall events that produce no erosion are not involved in the analyses.

Erosion is often perceived as a process in which soil particles are detached from within the surface of a cohesive soil matrix and subsequently moved downslope by one or more transport agents. In rainfall erosion, detachment may be caused by raindrops impacting the soil surface or by flow shear. Downslope transport may be associated with drop splash (splash erosion) or by the interaction between raindrop impact and flow (raindrop-induced saltation and rolling) or by flow alone (suspension, flow-driven saltation and rolling). In the context of the USLE/RUSLE model, soil loss is the mass of soil that passes across the downslope boundary of an area, divided by that area. Consequently, detachment may occur within an area but not contribute to soil loss during an event if the transport processes are slow. Similarly, soil loss during an event may have been caused by detachment that occurred during a previous event so that the USLE model is not directed at the prediction of erosion per se. Given that soil losses from the plots used to develop the USLE were essentially associated with runoff collected at the bottom edge of those plots, in the RUSLE, the term “sediment yield” is used rather than erosion (Renard et al., 1997).

As noted above, soil loss in of the USLE model is synonymous with sediment yield. Despite this, the USLE/RUSLE model does not give direct consideration to runoff in the so-called rainfall–runoff erosivity factor (\( R \)). However, an empirical rainfall–runoff model is embedded in the USLE/RUSLE because empirical relationships tend to exist between runoff amount and \( E \), and between peak runoff rate and \( I_{30} \). However, as is evident from data for Morris, MN (Fig. 3B) where the model efficiency associated with the \( E_{130} \) index is extremely low, the \( E_{130} \) is not able to deal with the effect of runoff on soil loss at all well at some locations. Foster et al. (1982) noted that without modification, the USLE is somewhat unsatisfactory for estimating soil loss from individual storms, and observed that erosivity factors that included rainfall amount, rainfall intensity and runoff amount were better predictors than \( E_{130} \). They also noted that erosivity factors with separate terms for rainfall and runoff erosivity were best.

It is well known that sediment discharge is given by the product of flow discharge and sediment concentration. Consequently,

\[
A_e = q_e c_e \quad (6)
\]

where \( q_e \) is the runoff rate (volume/area/time) and \( c_e \) is the sediment concentration (mass/volume). However, none of the erosivity factors considered by Foster et al. (1982) were examined in the context of Eq. (6). Given Eq. (6), the USLE model implies that,

\[
c_e = b_I E_{130}/q_e \quad (7)
\]
where $b_1$ is an empirical coefficient. Consistent with differing abilities of Eq. (5) to account for event soil loss from bare fallow at Holly Springs, MS and Morris, MN, Eq. (7) is able to account for variations in sediment concentrations at Holly Springs, MS, better than at Morris, MN (Fig. 4). In fact, as indicated by the negative value of model efficiency factor ($Eff(ln)$), the ability of Eq. (7) to account for the variation in observed sediment concentrations is worse at Morris than if the mean sediment concentration for all the events is used.

Kinnell (1997) suggested that sediment concentrations for individual rainfall events were dependent on the kinetic energy per unit quantity of rain (given by $E$ divided by rainfall amount $r_e$) and $I_{30}$ so that

$$c_e = b_2 E_{I30}/r_e$$

where $b_2$ is an empirical coefficient. A parameter like $I_{30}$ influences $c_e$ because the peak rainfall intensity produces the highest runoff rate and tends to produce the highest sediment concentration during a rainfall event. Eq. (8) is effective in estimating sediment concentrations on bare fallow plots at Morris, MN (Fig. 5A), where the USLE/RUSLE model does not estimate event sediment concentrations well (Fig. 4B). At Holly Springs, MS, where the USLE/RUSLE model works reasonably well in predicting event soil losses from bare fallow plots, Eq. (8) ($r^2 = 0.555$) provides an improvement on the capacity of Eq. (7) ($r^2 = 0.348$) to account for the event sediment concentrations associated with plot 5 in experiment 3.

Because runoff divided by rainfall is the runoff ratio ($Q_e$), it follows from Eqs. (6) and (8) that

$$A_e = b_1 Q_e E_{I30}$$

where $b_3$ is an empirical coefficient. Given that

$$A_e = b_1 Q_e E_{I30} = b E_{I30}$$

$b_1$ has values that usually differ from those for $b$ because $Q_e$ usually does not equal 1.0. As shown in Fig. 5B, Eq. (9a) is more effective in estimating event soil loss from bare fallow at Morris, MN than when the $E_{I30}$ index is used (Fig. 3B). Also, the $Q_e E_{I30}$ index is more effective than the $E_{I30}$ index in accounting for event soil losses from a cracking clay at Gunnedah, NSW, Australia (Fig. 6). The $Q_e E_{I30}$ index is the event rainfall–runoff factor used in a modification of the USLE called the USLE-M (Kinnell and Risse, 1998).

It should be noted that some of the residual variation associated with Eqs. (5) and (9a) results from the fact that these equations make no provision for the possibility that soil erodibilities vary between rainfall events when, in reality, soil erodibilities in bare fallow areas vary in time as a result of factors such as cultivation and crusting of the soil, and in the case of Eq. (5), soil moisture.

The USLE-M is not the only variant of the USLE model using explicit consideration of runoff in the prediction of sediment yields. In the MUSLE (Williams, 1975), a version of the USLE that was designed to be applied at the watershed rather than the field scale, the $E_{I30}$ index is replaced by a power of the product of runoff amount and the peak runoff rate to give

$$S_Y = 11.8(Q_e q_{pe})^{0.56} K L S C_P e$$

where $S_Y$ is event sediment yield in tonnes, $Q_e$ is volume of runoff for the event in m$^3$ $q_{pe}$ is peak flow rate for the event in m$^3$ s$^{-1}$, $K$, $L$ and $S$ are the normal USLE factors for the soil and topographic effects, and $C_P$ and $P_e$ are event values for the USLE $C$ and $P$ factors (Williams and Berndt, 1977). In terms of accounting for event sediment concentrations, Eq. (10) gives

$$c_e = b_3 q_{pe}^{0.56}/q_e^{0.44}$$

Please cite this article in press as: Kinnell, P.I.A. Event soil loss, runoff and the Universal Soil Loss Equation family of models: A review. J. Hydrol. (2010), doi:10.1016/j.jhydrol.2010.01.024
where $b_1 = 11.8 \, K \, L S C \, P_e$. In EPIC, a model designed to assess the effect of soil erosion on productivity (Williams et al., 1984a,b), event sediment yield is predicted by

$$SY_e = X_e K L S C P_e [ROKF]$$

where ROKF is the coarse fragment factor as defined by Simanton et al. (1984), and $X_e$ is selected from a variety of rainfall–runoff “erosivity” factors. This approach has been extended to APEX (Williams et al., 2008) where $X_e$ can be selected from

$$X_e = EI_{30}$$

$$X_e = 1.586 (q_e q_{pe})^{0.56} DA^{0.12}$$

$$X_e = 0.65 EI_{30} + 0.45 (q_e q_{pe})^{0.33}$$

$$X_e = 2.5 (q_e q_{pe})^{0.5}$$

$$X_e = 0.79 (q_e q_{pe})^{0.65} DA^{0.009}$$

$$X_e = b_3 q_e^{b_6} q_{pe}^{b_5} DA^{b_8}$$

where $DA$ is drainage area expressed in ha, and $b_6$–$b_8$ are user-selected coefficients (Williams et al., 2008).

Williams et al. (1984a,b) indicated that Onstad and Foster (1975) was the source of Eq. (13c). However, the approach used by Onstad and Foster actually used the equation

$$R_e = 0.5 EI_{30} + 0.5 q_e (q_e q_{pe})^{0.33}$$

where $x$ was a factor that caused the average annual value of $R_e$ produced by Eq. (14) using $q_e$ and $q_{pe}$ values obtained for the unit plot to equal the average annual value of the $EI_{30}$ index. While the $EI_{30}$ index is applied in the USLE model to predict soil loss associated with sheet and rill erosion, detachment and transport processes in rills involve the expenditure of flow energy. Eq. (14) was developed to produce an index which was perceived by Onstad and Foster to be better account for this fact. Also, the value of $x$ was set so that the long-term average value of $R_e$ produced by Eq. (14) was the same as the long-term average value produced by $R_e = EI_{30}$. Given that, by definition, $K$ is the amount soil loss per unit of $R$ when $R_e = EI_{30}$, this enabled Eq. (14) to be used with $K$ to predict soil loss from bare fallow areas. There is no provision in EPIC or APEX to do the same. The consequences of this are discussed later.

Kinnell et al. (1994) suggested that the $I_e E_k$ index gave more direct consideration of hydrology than the $EI_{30}$ index in predicting short-term soil loss. This index is calculated by summing the product of values of the excess rainfall rate ($I_e$, the rainfall intensity minus average acceptance rate of the soil during the event) and the rate of expenditure of rainfall kinetic energy ($E_k$) during a rainstorm. $I_e$ is a surrogate for the runoff rate so that the model operates on the premise that the sediment concentration varies directly with the rate of expenditure of rainfall kinetic energy. While event soil losses for two bare plots at Holly Springs, MS were better correlated with this index than with the $EI_{30}$ index (Kinnell et al., 1994), this approach requires high resolution rainfall intensity data. As a general rule, high resolution rainfall intensity data are not available at most geographic locations and because the $Q_e EI_{30}$ index is less dependent on such data, it is more easily applied to predicting event soil losses than the $I_e E_k$ index.

As noted above, RUSLE2 operates on a daily time step, and consequently, RUSLE2 uses a mathematical equation that is similar in form to Eq. (4),

$$A_{d14} = R_e K$$

where $A_{d14}$ is the computed soil loss from the unit plot for the $d$th day and $R_e$ is computed average daily erosivity for that day. Average daily erosivity values are determined by disaggregating average monthly erosivity input values into daily values. The recommended procedure for the Continental US involves the use of erosivity density data. Erosivity density, which is the ratio of monthly erosivity to monthly precipitation, is multiplied by monthly precipitation to obtain monthly erosivity values. The first step in developing average monthly erosivity density values is to compute erosivity values for individual storms using measured weather data (USDA-ARS, 2008). Interestingly, if they were determined on an event rather than the monthly basis, erosivity density values could be used in modelling event sediment concentration through the approach adopted in USLE-M (Eq. (8)).

Bagarello et al. (2008, 2009) obtained data from bare plots in southern Italy and observed that event soil loss was related to powers of the $Q_e EI_{30}$ index that were close to 1.5 and 1.6. It would appear from Eq. (6) that, in the experiments undertaken by Bagarello et al., sediment concentrations not only increased with the energy of the storm per unit quantity of rain and $I_{30}$ but also runoff amount ($q_e$).

The impact of erosivity indices on other factors in the USLE model

As noted earlier, changing the event erosivity factor from $EI_{30}$ has impacts on other factors in the USLE/RUSLE model. The $K$ factor is one in particular because, by definition, it is the soil loss per unit of $R$ when $R_e = EI_{30}$.

The $K$ factor

Originally, the values of $K$ were determined by dividing values of $A$ determined from soil loss experiments under natural rainfall by $R$. Given a need to extend the USLE to soils other than used in the bare fallow experiments upon which the USLE was based, a nomograph was developed to determine $K$ values from soil properties (Wischmeier et al., 1971). The mathematical approximation of this nomograph for the cases where the silt fraction does not exceed 70% is

$$K = \frac{A}{R}$$

where $A$ is the amount of soil loss and $R$ is the runoff rate.
$K = [2.1 \times 10^{-4}(12 - OM)M^{1.14} + 3.2(s - 2) + 2.5(p - 3)]100^{-1}$

(16)

where $M$ is the product of primary particle size fractions, $s$ is the soil structure class, and $p$ is a permeability class (Wischmeier and Smith, 1978). The inclusion of permeability in Eq. (16) provides a factor that is designed to directly account for how different soils influence runoff but factors such as texture and structure also influence runoff. Eq. (16) has been used widely both in the USA and elsewhere. A number of other equations have been developed using other soil properties (Renard et al., 1997; Williams et al., 1984a,b; Shirzi and Boersma, 1984; Loch et al., 1998; Vaezi et al., 2008) and for specific types of soil, such as those of volcanic origin (El-Swaily and Dangler, 1976).

Work on determining $K$ in the USA included experiments using rainfall simulators experiments involving “dry, wet, and very wet” conditions with “dry, wet, and very wet” events. The inclusion of permeability in Eq. (16) provides a factor that is designed to directly account for how different soils influence runoff but factors such as texture and structure also influence runoff. Eq. (16) has been used widely both in the USA and elsewhere. A number of other equations have been developed using other soil properties (Renard et al., 1997; Williams et al., 1984a,b; Shirzi and Boersma, 1984; Loch et al., 1998; Vaezi et al., 2008) and for specific types of soil, such as those of volcanic origin (El-Swaily and Dangler, 1976).

**Table 1**

<table>
<thead>
<tr>
<th>Place</th>
<th>Presque Isle</th>
<th>Arnot (Ithaca)</th>
<th>Marceus</th>
<th>Morris</th>
<th>Castana</th>
<th>Bethany</th>
<th>McCredie</th>
</tr>
</thead>
<tbody>
<tr>
<td>State</td>
<td>Maine</td>
<td>New York</td>
<td>New York</td>
<td>Minnesota</td>
<td>Iowa</td>
<td>Missouri</td>
<td>Missouri</td>
</tr>
<tr>
<td>Soil name</td>
<td>Cardiob</td>
<td>Bath</td>
<td>Honeoye</td>
<td>Barnes</td>
<td>Minean</td>
<td>Shelby</td>
<td>Mexico</td>
</tr>
<tr>
<td>Plot Nos</td>
<td>1,3, 1-8, 1-18</td>
<td>1-8</td>
<td>1-2, 1-3</td>
<td>1-5, 1-10, 1-13</td>
<td>31/4-40/10</td>
<td>21-2, 1-18</td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>62/7-69/9</td>
<td>35/4-6/2</td>
<td>39/6-43/6</td>
<td>47/71-10</td>
<td>60/5-70/10</td>
<td>31/6-40/8</td>
<td></td>
</tr>
<tr>
<td>Mean obs. $K$</td>
<td>0.0162</td>
<td>0.0031</td>
<td>0.0390</td>
<td>0.0345</td>
<td>0.0262</td>
<td>0.0619</td>
<td>0.0327</td>
</tr>
<tr>
<td>Mean $K_{30}$</td>
<td>0.0536</td>
<td>0.0888</td>
<td>0.0836</td>
<td>0.1337</td>
<td>0.0737</td>
<td>0.1228</td>
<td>0.0728</td>
</tr>
</tbody>
</table>

The reason for this approach is that $K$ in the USLE model is defined as the mass of soil lost for the unit plot per unit of $R$ when $R = E_{30}$. The reason for this approach is that $K$ in the USLE model is defined as the mass of soil lost for the unit plot per unit of $R$ when $R = E_{30}$. As noted earlier, $K$ is, by definition, the ratio of the amount of soil lost per unit of $R$ when $R = E_{30}$. Consequently, the values of $K$ used in the EPIC and APEX should differ depending on whether Eq. (13a)-(13f) is used. Likewise, the MUSLE should not use USLE/RUSLE K values. The USLE, EPIC and APEX violate the mathematical rules that underlie the USLE/RUSLE model. The consequence of using USLE $K$ values when $R$ does not equal $E_{30}$ is illustrated by data presented in Table 1. Table 1 shows $K$ values for the USLE and $K_{30}$ values for the USLE-M ($R = Q_6E_{30}$) obtained by Kinnell and Risse (1998) for a number of soils in the USA using runoff and soil loss data from bare fallow plots contained in the USLE database. The ratios of $K_{30}$ to $K$ shown in Table 1 indicate the differences between the soils in terms of their capacity to infiltrate rain, something that depends on both the properties of the soil and the rain at the various locations. The ratios are determined by dividing the total value of $E_{30}$ obtained over an appropriate period of time by the total value of $Q_6E_{30}$ obtained for that soil over that same period. The soil at Holly Springs, MS, has the lowest infiltration capacity while the soil at Morris, MN, has the highest infiltration capacity, and the difference in these infiltration capacities is responsible for the better performance of the USLE-M over the USLE at Morris, MN. Given that $K_{30}$ is defined by $K_{30}$ multiplied by the ratio of $K_{30}$ to $K$, using the USLE $K$ when $R = Q_6E_{30}$ would result in underestimating soil loss by factors ranging from 1.4 at...
that as previous cropping and management, the protection offered to that soil loss. An approach based on the impacts of factors such as soil erodibility, soil consolidation, and residue cover are directed at variations in sediment concentration rather than soil loss per se.

The C factor

The C factor is the ratio of the long-term soil loss from a vegetated area to the long-term soil loss from a bare fallow area on the same soil cultivated up and down a 22 m long slope with a gradient of 9%. Originally determined from long-term erosion experiments with natural rainfall, it was later recognised that the protective effect of crops varied during the year in a manner that could be determined through the use of subfactors. In the RUSLE, the impacts of factors such as previous cropping and management, the protection offered to the soil surface by the vegetative canopy, and the erosion reduction due to surface cover and surface roughness and soil moisture are all considered (Renard et al., 1997). Short-term values of C are referred to as Soil Loss Ratios (SLR) so that

\[ C = \frac{SLR_{E1} + SLR_{E2} + \cdots + SLR_{En}}{E1} \]

where \( E1 \) is the sum of the \( Ei \) values for period \( i \) with \( n \) periods occurring over the total time \( t \) being examined.

In the USLE/RUSLE, the C factor accounts for how crops and crop management cause soil losses to vary from those losses that occur on bare fallow areas. Consequently, if runoff is explicitly considered as a factor in determining \( R \), then factor values for the USLE can only be used if the runoff used to determine \( R \) is associated with the bare fallow condition. As illustrated by Eq. (18),

\[ A_{veg} = C_{UM}Q_{AB}E30 + C_{UM}Q_{AB}E30C_{UM} \]

where \( A_{veg} \) is the event soil loss from a vegetated area, \( Q_{AB} \) is the runoff ratio for the bare fallow condition, \( C_{um} \) is the USLE C factor for the event, and \( C_{UM} \) is the C factor that applies when the runoff coefficient for the vegetated condition \( (Q_{AV}) \) is used instead of \( Q_{AB} \). A different crop factor \( (C_{UM}) \) is required when \( Q \) is determined by runoff from the cropped area but not if the runoff from the bare fallow condition is used. Table 2 illustrates this when the \( Q_{E30} \) index is used and \( Q \) is determined for the cropped condition on plots at a number of locations in the USA. \( C_{UM} \) differs from \( C \) simply because values of \( Q_{AB} \) differ from the values of \( Q_{AV} \). Consequently, the \( C_{UM} \) to \( C \) ratio reflects the effect of the crop and crop management on the capacity of the surface to infiltrate rain. In most cases, corn has little effect on that capacity. In contrast, Bermuda grass had a major effect on the capacity to infiltrate rain at Guthrie, OK.

The values of \( C_{UM} \) and \( C \) shown in Table 2 were determined by using the long term runoff ratios for the bare fallow and cropped conditions at the locations considered. In the case of C, a subfactor approach was developed to compute the effect of prior land use, crop canopy, surface cover and soil moisture on \( C \) over time (Renard et al., 1997). An approach based on the impacts of factors such as previous cropping and management, the protection offered to the soil surface by the vegetative canopy, and the erosion reduction due to surface cover and surface roughness has yet to be developed for determining \( C_{UM} \). Given that in the USLE-M, runoff is directly considered in the \( Q_{E30} \) index, the effects of such factors on \( C_{UM} \) are directed at variations in sediment concentration rather than soil loss per se.

The P factor

As in the case of the C factor, if runoff is explicitly considered as a factor in determining \( R \), then \( P \) factor values for the USLE cannot be used if the runoff used to determine \( R \) is not for cultivation up and down the slope. Currently, \( P_{UM} \) values are determined using long term runoff ratios for the cultivation up and down the slope condition in a similar way as used to calculate the \( C_{UM} \) values presented above associated with experiments designed specifically to evaluate \( P \) factor values. Procedures exist in the RUSLE to determine \( P \) values based on erosion theory and analysis of experimental data. Given sufficient data collected from appropriate experiments, it should be possible to develop similar procedures to calculated \( P_{UM} \) values.

The L and S factors

In the USLE/RUSLE model, the L factor is given by

\[ L = \left( \frac{\lambda}{22.1} \right)^m \]

where \( \lambda \) is the distance from the onset of overland flow to the point where deposition occurs or when runoff enters a channel that is bigger than a rill. It is measured on the horizontal projection, not parallel to the slope. The value of 22.1 m appears in this equation so that \( L = 1.0 \) when \( \lambda = 22.1 \) m.

In the USLE, \( m \) varies with slope gradient. It has a value of 0.2 for gradients of less than 1% and increases to a value of 0.5 for gradients greater than 5% (Wischmeier and Smith, 1978). In the RUSLE (Renard et al., 1997), \( m \) is recognised as varying with the ratio of rill erosion to interrill erosion \( (\beta) \),

\[ m = \beta / (1 + \beta) \]

For soils moderately susceptible to rilling, \( \beta \) varies with slope gradient according to the equation

\[ \beta = \frac{\sin \theta / 0.0896}{[3.0 \sin \theta]^{0.8} + 0.56} \]

where \( \theta \) is the slope angle (Renard et al., 1997). In RUSLE2, factors such as soil erodibility, soil consolidation, and residue cover are

Table 2

Average annual crop factor values associated with \( R_c = Q_{EV30} \) and \( R_r = E30 \) for a number of crops at a number of locations in the USLE data base obtained by Kinnell and Risse (1998). \( C_{IM} \) is the crop factor when \( R_c = Q_{EV30} \) and \( C \) is the crop factor when \( R_r = E30 \).

<table>
<thead>
<tr>
<th>Location</th>
<th>Crop</th>
<th>( C_{UM} )</th>
<th>( C )</th>
<th>( C_{UM}C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bethany, MO</td>
<td>Alfalfa</td>
<td>0.008</td>
<td>0.002</td>
<td>4.00</td>
</tr>
<tr>
<td></td>
<td>Corn</td>
<td>0.674</td>
<td>0.628</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>Corn–meadow–wheat</td>
<td>0.188</td>
<td>0.106</td>
<td>1.77</td>
</tr>
<tr>
<td>Clarinda, IA</td>
<td>Corn</td>
<td>0.634</td>
<td>0.316</td>
<td>2.01</td>
</tr>
<tr>
<td></td>
<td>Corn–oat–meadow</td>
<td>0.424</td>
<td>0.168</td>
<td>2.52</td>
</tr>
<tr>
<td>Guthrie, OK</td>
<td>Cotton</td>
<td>2.435</td>
<td>1.357</td>
<td>1.79</td>
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<tr>
<td></td>
<td>Bermuda grass</td>
<td>0.064</td>
<td>0.002</td>
<td>32.00</td>
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<tr>
<td></td>
<td>Wheat–clover–cotton</td>
<td>0.913</td>
<td>0.344</td>
<td>2.65</td>
</tr>
<tr>
<td>La Crosse, WI</td>
<td>Corn</td>
<td>0.527</td>
<td>0.469</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>Deere</td>
<td>0.486</td>
<td>0.337</td>
<td>1.44</td>
</tr>
<tr>
<td></td>
<td>Corn (mulch till)</td>
<td>0.384</td>
<td>0.250</td>
<td>1.54</td>
</tr>
<tr>
<td>Morris, MN</td>
<td>Corn</td>
<td>0.520</td>
<td>0.434</td>
<td>1.20</td>
</tr>
<tr>
<td></td>
<td>Meadow–corn–oat</td>
<td>0.040</td>
<td>0.010</td>
<td>4.60</td>
</tr>
<tr>
<td>Presque Isle, ME</td>
<td>Potato</td>
<td>0.634</td>
<td>0.316</td>
<td>2.01</td>
</tr>
</tbody>
</table>

Please cite this article in press as: Kinnell, P.A. Event soil loss, runoff and the Universal Soil Loss Equation family of models: A review. J. Hydrol. (2010), doi:10.1016/j.jhydrol.2010.01.024
considered in determining the ratio of rill to interrill erosion (USDA-ARS, 2008).

Although A is the average amount of soil lost per unit area over a slope of length \( L \), the amount of soil lost per unit area varies spatially. Table 3 shows how L varies as slope length increases by 50-m increments. Because L increases as \( L \) increases, the L factor value for each 50-m segment increases in the downslope direction. The value of L for segment \( i \) is given by (Renard et al., 1997).

\[
L_i = \frac{(\lambda_{m+1} - \lambda_{i+1})}{(\lambda_{i} - \lambda_{i-1})22.1^m} 
\]

(22)

The S factor in the USLE is given by

\[
S = 65.41 \sin^2 \theta + 4.56 \sin \theta + 0.065 
\]

(23)

Because Eq. (23) over-predicts soil losses from high-gradient slopes, in the RUSLE it has been replaced by (Renard et al., 1997).

\[
S = 10.8 \sin \theta + 0.03 \text{, gradient } < 9\% 
\]

(24a)

\[
S = (\sin \theta/0.0896)^{0.6} \text{, gradient } \geq 9\% 
\]

(24b)

The USLE was designed to estimate soil losses from planar slopes with uniform characteristics. Under these conditions, runoff is produced uniformly over the whole area, and there is a physical basis to the product of L and S when this is the case (Moore and Burch, 1986; Moore and Wilson, 1992). Eq. (22) enables the model to be applied to hillslopes that are not uniform through partitioning the hillslope into segments which have uniform soil, topographic and vegetation characteristics. In reality, surface water flows converge and diverge in two dimensions on hillslopes because slopes usually have both a vertical and a lateral direction. Grid cell representations of landscapes in catchments provide a common vehicle for modeling spatial variations in soil loss when each grid cell is considered to be uniform in terms of soil, slope length and gradient, and vegetation and management. In the L factor equation for grid cell \( i, j, k \), \( \lambda \) is replaced by the contributing area (\( \lambda' \)) divided by the width of the contour (\( w \)) over which the runoff from that area flows. This approach gives

\[
L_{ij} = \frac{(\lambda_{ij, in} + D^2)_{m+1} - \lambda_{ij, in}^{m+1}}{D^{m+2} \lambda_{ij, in}^{m+1}(22.1)^m} 
\]

(25)

where \( \lambda_{ij, in} \) is the contributing area for overland flow into the cell, \( D \) is the size of the cell (length of the sides of the cell) and \( \lambda \) is a factor which accounts for variations in flow in width that depend on the direction of flow relative to cell orientation (Desmet and Govers, 1996). The replacement of \( \lambda \) by contributing area divided by the width of the contour over which the runoff from that area flows operates on the assumption that the quantity of water flowing over the surface of a cell controls erosion, rather than the distance the overland flows travel.

Non uniform runoff production

Eqs. (22) and (25) account for not just segment length or grid cell size, but also for the position of the segment or cell in the landscape. However, spatial variations in soil and vegetation affect the way runoff is produced so that runoff may not be produced uniformly over the whole of the eroding area as assumed by the USLE/RUSLE model. Disparities between the runoff coefficient for a segment or cell and that for the upslope area occlude, leading to errors when Eqs. (22) and (25) are used. Kinnell (2007) has proposed a modification of these equations to deal with the fact that, in many cases, runoff generation varies spatially. Conceptually, for a hillside segment, Eq. (22) becomes

\[
L_i = \frac{(\lambda_{i-1, eff} + \lambda_{i, seg})^{m+1} - (\lambda_{i, eff})^{m+1}}{\lambda_{i, seg}(22.1)^m} 
\]

(26)

where \( \lambda_{i-1, eff} \) is the length of the up slope area that would exist if the whole area produced runoff uniformly, and \( \lambda_{i, seg} \) is the slope length of the segment \( (\lambda_{i, seg} = \lambda_i - \lambda_{i-1}) \). Consequently, \( \lambda_{i-1, eff} \) will be less than \( \lambda_{i-1} \) when the runoff coefficient for the upslope area is less than that for the current segment, equal to \( \lambda_{i-1} \) when the runoff coefficient for the upslope area is equal to that of the segment, and greater than \( \lambda_{i-1} \) when the runoff coefficient for the upslope area is greater than that for the segment. Similarly, for a grid cell, Eq. (25) becomes

\[
L_{ij} = \frac{(\lambda_{ij, in, eff} + D^2)^{m+1} - (\lambda_{ij, in, eff})^{m+1}}{D^{m+2} \lambda_{ij, in, eff}^m(22.1)^m} 
\]

(27)

where \( \lambda_{ij, in, eff} \), the effective area of upslope area, is less than \( \lambda_{ij, in} \) when the runoff coefficient for the upslope area is less than that for the current segment, equal to \( \lambda_{ij, in} \) when the runoff coefficient for the upslope area is equal to that of the segment, and greater than \( \lambda_{ij, in} \) when the runoff coefficient for the upslope area is greater than that for the segment.

As noted above, the values of \( \lambda_{i-1, eff} \) and \( \lambda_{ij, in, eff} \) vary from \( \lambda_{i-1} \) and \( \lambda_{ij, in} \) depending on the values of the runoff ratios in the upslope area (\( QC_{up} \)) and the segment (\( QC_{seg} \) or cell (\( QC_{cell} \)). As a result, Kinnell (2007) proposed

\[
\lambda_{i-1, eff} = \lambda_{i-1} QC_{up}/QC_{cell} \]

(28)

\[
\lambda_{ij, in, eff} = \lambda_{ij, in} QC_{up}/QC_{cell} \]

(29)

where \( QC_{seg} \) is the runoff coefficient for the area that includes both the upslope area and either the cell or segment. Fig. 7 shows how the ratio of \( QC_{up} \) to \( QC_{cell} \) varies as \( QC_{seg} \) varies from 0 to 1 when \( QC_{cell} \) is dependent on an upslope area that is 3 times that of the segment and \( QC_{seg} = 0.5 \). As indicated earlier, with the USLE, there is an assumption that runoff production is spatially uniform. Eqs. (28) and (29) are consistent with the concept that the adjustment must deal with the fact that the upslope area is not producing runoff as it would if the whole area had the same runoff ratio, the condition

\[ QC_{seg} = 0.5 \]

\[ QC_{up} = 3QC_{seg} \]
that is central to operation of the USLE/RUSLE model as it was originally developed.

**Hillslope form**

As noted above, slope length in the USLE model is limited by the occurrence of either a channel bigger than a rill or the onset of deposition, in particular deposition associated with a change in slope gradient such as that illustrated in Fig. 8. When applied to whole hillslopes that include a change in slope causing deposition, this criteria is often ignored and the sediment yield for the hillslope ($SY_h$) estimated by multiplying the gross soil loss estimated using the USLE or the RUSLE for the whole hillslope length ($A_h$) by the sediment delivery ratio ($DR_h$).

$$SY_h = A_h DR_h$$  \hspace{1cm} (30)

By definition, $DR_h$ is the ratio of the gross soil loss for the area upslope of a point to the sediment yield associated with that point. Consequently, $DR_h$ is basically a correction factor for extending the USLE/RUSLE model beyond its design criteria. However, Eq. (30) depends on the assumption that $DR_h$ does not vary with the amount of gross soil loss predicted to occur on the hillslope. This assumption is severely challenged by the fact that the deposition resulting from a reduction of slope gradient is due to the amount of sediment entering that low-gradient area being in excess of the flow’s transport capacity. In the example shown in Fig. 9, flow in the lowest segment has a capacity to transport only 5 tonnes of sediment through to its downslope boundary over some period. If 20 tonnes of sediment enters the upslope boundary during that period, 15 tonnes is deposited, so $DR_h = 5/20 = 0.25$. If the supply of sediment then drops so that 10 tonnes is delivered to the upslope boundary, 5 tonnes is deposited, so $DR_h$ then becomes $5/10 = 0.5$. The graph in Fig. 8 shows how $DR_h$ varies over other values of sediment input. The only time that $DR_h$ is constant is when there is no deposition and $DR_h = 1.0$ (Kinnell, 2004). Arguably, Fig. 8 illustrates a situation that may not occur much in practice because there are situations where both the sediment input and the transport capacity vary together. However, there is no guarantee that when this does happen the variation in the transport capacity will hold the sediment delivery ratio to a constant value.

The need to consider sediment transport capacity of overland flow with regard to the movement of soil material down a slope is not new. Fig. 9 is reproduced from Meyer and Wischmeier (1969), and models like AGNPS 5.0 (Young et al., 1989) and ANSWERS (Beasley et al., 1980; Beasley and Huggins, 1991) use the USLE/RUSLE model together with a sediment transport model to predict sediment delivery when deposition occurs due to changes in slope gradient. As noted earlier, RUSLE2 (Foster et al., 2003), predicts sediment delivery using the sediment transport capacity approach. RUSLE2 also adjusts the composition of the sediment for the preferential deposition of coarse particles with respect to fine. Details of the approach are provided in USDA-ARS (2008) but RUSLE2 assumes that all sediment regardless of composition is equally transportable. Given that coarse particles are less transportable than fine this assumption is questionable (USDA-ARS, 2008). Consequently, the manner by which RUSLE2 applies the transport capacity approach in determining sediment delivery may not be as robust scientifically as some would desire.
Event erosion and the unit plot approach

As noted above, the USLE model works in two steps. The first step is the prediction of soil loss from the so called “unit” plot using Eq. (2), then this value of soil loss is multiplied by appropriate values of L, S, C and P (Eq. (3)) to predict the soil loss for the situation of interest. Applying this approach to predicting soil losses for individual rainfall events results in

$$A_e = A_t L S C_p P_e$$

(31)

However, the unit plot approach does not work well with individual rainfall events. Fig. 10 show the result of applying Eq. (31) to the prediction of event soil losses from conventional corn at Clarinda, IA when the $A_t$ values were obtained from a nearby bare fallow plot. There are a number of events where soil loss is predicted but none observed. Eq. (31) predicts that soil loss will occur on a cropped plot whenever soil loss occurs on the bare fallow plot. However, because the presence of vegetation influences the infiltration capacity of the soil, there are events where soil loss occurs from the bare fallow plot but no soil loss occurs from the cropped plot. The two staged mathematical approach used in the USLE/RUSLE model is one of the reason why the model does not predict event erosion well on vegetated areas. Consequently, when changing the event erosivity index to one which predicts event erosion well on vegetated areas. From the bare fallow plot but no soil loss occurs from the cropped plot. The two staged mathematical approach used in the USLE/RUSLE model is one of the reason why the model does not predict event erosion well on vegetated areas. Consequently, when changing the event erosivity index to one which predicts event erosion on bare fallow areas better than the $E_{30}$ index, there is a need to give direct consideration of the effect of vegetation on runoff in order to overcome errors associated with the prediction of event erosion when none occurs. As indicated by Eq. (18), $C_{UM}$ values provide the mechanism to do this when $Q_bE_{30}$ index is used as the event erosivity index.

Model predictive capacity

The accuracy of any prediction depends on (a) the ability of the model to account for effects of the physical phenomena causing the output and (b) the accuracy to which the parameters have been determined. As indicated above, and as often found in the literature, factors such as cultivation, surface crusting, and cracking cause variation between rainfall events in the susceptibility of soil surfaces to erosion. Conceptually, the best modelled soil losses for a plot are the soil losses produced by a statistical replicate, since both the plot and the replicate should be equally affected by such factors. However, when event soil losses from 40 fallow plots at the same location near Kingdom City, MO were compared, Wednt et al. (1986) observed that coefficients of variation for both runoff and soil loss increased markedly from values of about 20% consistently observed at high runoff and soil loss values when runoff and soil loss values were small. The USLE data base contains duplicate plots for various soils, plot lengths, gradients and crops, and Nearing et al. (1999) undertook an analysis based on determining two values of an index of the relative difference between each pair,

$$R_{diff A} = (A_b - A_c)/(A_b + A_c)$$

(32)

$$R_{diff B} = (A_b - A_c)/(A_b + A_c)$$

(33)

plotting $R_{diff A}$ against $A_b$ and $R_{diff B}$ against $A_b$ without discriminat-ing plot A from plot B. With this approach, if $A_b > A_c$ then $R_{diff A}$ varies from a maximum of 1 to a minimum of 0 and while $R_{diff B}$ takes on negative values. Eqs. (32) and (33) are based on

$$R_{diff} = (Y_p - Y_m)/(Y_p + Y_m)$$

(34)

where $Y_p$ is the value predicted by a model and $Y_m$ is the measured value, assuming that each plot acts as a model in regard to the other plot. Nearing et al. concluded from their analysis that the accuracy of the soil loss predicted from a replicate decreased as the value of the predicted loss decreased.

It follows from above that the capacity of a good model to predict observed soil loss for any given event tends to increase as the magnitude of the soil loss increases. However, arguably, before Nearing (2000b), no method existed to determine what constituted an acceptable prediction. Using Eqs. (32) and (33), Nearing (2000b) analysed 2061 paired event soil loss values from replicated plots at seven sites in the USA, and 797 paired annual soil loss values to determine the boundaries marking the limits to the envelope containing 90% and 95% of the observed data. He determined that

$$R_{diff acc} = m_1 log_{10}(M) + b_3$$

(35)

where $M$ is the measured value, and $m_1$ and $b_3$ are empirical coefficients that varied with the occurrence interval and boundary (upper, lower). Fig. 11 shows the values of $R_{diff A}$ and $R_{diff B}$ obtained for two bare fallow plots at Ginninderra, Australia (Kinnell, 1983) together with the boundary lines for the 90% occurrence. The envelopes are not symmetrical. This is because, although from any given event, $R_{diff A} = -R_{diff B}$, the negative value is always plotted at a lower soil loss than the positive one. The two grey data points in Fig. 11 illustrate this in an experiment where, as a general rule, one of the duplicate plots systematically produced less soil loss than the other. Fig. 12 shows $R_{diff}$ values obtained when the $Q_bE_{30}$ index is used with the soil loss data obtained for plot 5 in experiment 1 at Morris, MN. Fig. 12 shows that 90% of event soil losses estimated by using the $Q_bE_{30}$ index on plot 5 in experiment 1 at Morris, MN
This would not be the case using the USLE/RUSLE event erosivity ported by Kinnell (1983) were dominated by sheet erosion and the to better account for this fact. The soil losses in the experiments re-
Eq. (14) was developed to produce an index which was perceived
occurs are higher than when sheet erosion occurs. As noted earlier,
plots were often cultivated to eliminate rilling, but as a general rule no record of the occurrence of rilling is avail-
plots were cultivated only once a year in order to minimise tempo-
Rdiff values for soil losses estimated using the QREI30 index on plot 5 (bare
fallow) in experiment 1 at Morris, MN and the 90% occurrence intervals determined by Nearing (2000b).

It is generally observed that soil losses that occur when rilling
occurs are higher than when sheet erosion occurs. As noted earlier,
Kinnell (1983) were dominated by sheet erosion and the
plots were cultivated only once a year in order to minimise temporal variations in erodibility. In the experiments upon which the USLE was based, the plots were often cultivated to eliminate rilling, but as a general rule no record of the occurrence of rilling is available in the publicly available USLE database. However, for a period of time, surface condition was observed after each event on the 41-
m long plot on the cracking clay soil at Gunnedah, NSW (Kinnell et al., 1994). The data obtained during this period indicated that the value of \( b_3 \) (Eq. (8)) associated with events where plots surfaces were rilled was, for the conditions at this location, about twice those for events associated with sheet erosion (Fig. 14). Even so, rather frequent cultivation and the cracking nature of the soil contribute to high variability in sediment concentrations associated with any given value of \( EI_{30} \) per unit rainfall and, as a result, the difference between the values of \( b_3 \) observed for the experiment is not statistically significant. However, following the approach that led to Eq. (14) and including a term directed more specifically at sediment concentrations generated by rill erosion through an event erosivity index such as

\[
R = q_i(b_3EI_{30}/R_e + b_6QREI_{30})
\]

where \( b_3 \) and \( a \) are empirical coefficients, may better account for soil losses than the \( QREI_{30} \) index on areas where rill erosion occurs. Arguably, the values of \( b_3 \) and \( b_6 \) may vary between segments as the power of runoff to cause rilling increases down along a hillslope.

**Determining \( EI_{30} \) and the R factor**

As a general rule, the kinetic energy of rainfall is not determined routinely in most geographic locations. As a result, the \( E \) factor is calculated from rainfall intensity–kinetic energy relationships that have been derived from the collection of raindrop size data at certain geographic locations over some period of time. In the USLE, the relationship between the kinetic energy per unit quantity of rain and rainfall intensity is expressed by

\[ e = 916 + 331\log_{10}i \quad \text{for} \quad i \leq 3 \text{ in./h} \]

\[ e = 1074 \quad \text{for} \quad i > 3 \text{ in./h} \]

where \( e \) is in ft ton/acre/in. and \( i \) is in in./h, following analysis of drop size data collected by Laws and Parsons (1943). In the RUSLE, Eq. (37) is replaced by

\[ e = 1099[1 - 0.72\exp(-1.27i)] \]

whose metric equivalent is

\[ e_m = 0.29[1 - 0.72\exp(-0.05i_m)] \]

where \( e_m \) has units of MJ/ha/mm and \( i_m \) has units of mm/h. Eqs. (38) and (39) use the mathematical form proposed by Kinnell (1981, 1987). A number of other mathematical equations have been proposed, many of which were reviewed by van Dijk et al. (2002). Some of these produce negative values of \( e_m \) at low rainfall intensities, Eq. (37) included (for \( i < 0.00171 \) in./h, \( i_m < 0.043 \) mm/h). Technically,
$e_m = 0$ when $i_m = 0$, but becomes positive immediately when a single raindrop falls to the ground. While Eqs. (38) and (39) do not produce a value of zero when $i_m = 0$, they can be perceived to meet the condition that $e_m > 0$ when $i_m > 0$ in a suitable manner as well the tendency of $e_m$ to be constant at high rainfall intensities.

Eqs. (38) and (39) imply that the kinetic energy flux (kinetic energy/area/time) increases non-linearly at low rainfall intensities before increasing in a nearly linear manner at moderate to high rainfall intensities. However, in the short term, $e_m$ values vary markedly in space and time from the predicted values because of rainfall spatial and temporal heterogeneities. Also, average raindrop sizes often vary depending on synoptic conditions. For example, thunderstorm rains tend to produce larger drops at low intensities than do other types of rain. Consequently, storm kinetic energy may differ appreciably from predicted values in some circumstances. Also, experiments with replicate treatments on plots with different aspects indicate that the orientation of the eroding area with regard to wind direction can influence soil loss (Agassi and Ben-Hur, 1991). Accurate determination of rainfall–runoff erosivities based on the $EI_{30}$ index at both long (many years) and short (annual, monthly, weekly, daily) time scales require appropriate rainfall intensity data. In many cases, $EI_{30}$ values have been obtained using rainfall intensities that have been determined using pluvographs, but in many geographic regions only daily rainfall amounts are recorded. Consequently, a number of approaches have been adopted to estimate average annual $R$ and short-term values for rainfall–runoff erosivity, including annual ($R_m$), seasonal ($R_s$), monthly ($R_u$), event ($R_e$) erosivities. Extrapolation of average annual $R$ values from locations where $EI_{30}$ values have been appropriately determined may be based on factors such as the 2 year frequency 6 h rainfall amount (Renard et al. (1997)) or the modified Fournier Index, which is the sum of the ratio of monthly rainfall squared to annual rainfall over the year (Arnoldus, 1980; Munka et al., 2007).

In the Algarve region of Portugal, $R_m$ was observed to be better related to multiple linear regression involving monthly rainfall for days with rain $>10$ mm and the monthly number of days with rainfall $>10$ mm than with monthly rainfall (de Santos Loureiro and de Azevedo Coutinho, 2001). One approach that has been used in a number of geographic areas such as Canada (Bullock et al., 1989), Finland (Posch and Rekolainen, 1993), Italy (Bagarello and D’Asaro, 1994), and Australia (Yu and Rosewell, 1996) considers that $EI_{30}$ is related to a power of event rainfall amount, ($X_p$)

$$EI_{30} = x_1 X_p^{x_2}$$

where $x_1$ and $x_2$ are empirical constants. The value of $x_1$ may show seasonal variation (Richardson et al., 1983; Posch and Rekolainen, 1993). Given that, in the context of the criteria associated with the USLE/RUSLE model, daily rainfall provides a reasonable proxy for storm rainfall amount (Hoyes et al., 2005), Eq. (40) using daily rainfall amount provides a practical approach to extending observed $EI_{30}$ values to areas where appropriate rainfall intensity data are lacking. Also, as noted above, the erosion density approach used in RUSLE2 provides a method of obtaining daily erosivity values from daily rainfall and, because they are the ratio of erosivity to rainfall values, monthly average erosivity density values stabilize with fewer years of data than do erosivity values themselves (USDA-ARS, 2008).

**Accuracy of runoff predictions**

As noted above, the USLE does not include direct consideration of runoff in determining the $R$ factor but it has an empirical rainfall–runoff model imbedded in it that relies on the relationship between storm rainfall energy ($E$) and runoff. Relationships between storm rainfall energy and runoff are not particularly bad at locations like Holly Springs, MS, (Fig. 15A) but not particularly good at locations like Morris, MN (Fig. 15B). Despite Foster et al. (1982) observing that including runoff as a factor in the event erosivity index increased the ability of the event erosivity factor to account for variations in event soil loss, the $EI_{30}$ index remains the event erosivity factor in the RUSLE and RUSLE2. The results shown in Figs. 5 and 6, and by Foster et al., result from indices calculated using measured values of runoff. However, it has been argued (Nearing, 2000a) that the level of accuracy by which runoff can be predicted is not sufficient for event erosivity indices used in models like the USLE-M to be used in place of the $EI_{30}$ index in the determination of the time based erosivity values used in USLE and the RUSLE. Even so, when used in predicting soil losses within watershed models where spatial variations in runoff are predicted, the USLE and the RUSLE do not enable these models to determine the impacts of the hydrology of the landscape on soil losses within the watershed. As noted above, spatial variations in the production of runoff on hillslopes are not currently accommodated well in the USLE or the RUSLE. Neither are temporal variations such as those resulting from rain falling on wet rather than dry watersheds. Often, in watershed models, the empirical SCS Curve Number approach is used to predict runoff because the available data on rainfall is limited to only daily or event amount. While the accuracy of this approach is often questioned, using it with the USLE-M may perhaps provide more realistic results in watershed models than associated with using the $EI_{30}$ index. In addition, there are other methods that can produce relatively good predictions of runoff in some circumstances (Fentie et al., 2002). Although the accuracy of runoff predictions may be a matter for debate, the fact remains that the failure to consider runoff explicitly in the USLE model is a factor in causing the USLE and the RUSLE to produce systematic errors in the prediction of event erosion. The failure of the USLE/RUSLE has been well demonstrated at Morris, MN. Certainly, the ability of $Q_0 EI_{30}$ index to predict event erosion will depend on the accuracy by which runoff can be predicted but unless direct...
consideration is given to the effect of runoff on erosion within the USLE/RUSLE, the ability of the USLE/RUSLE to predict event soil loss is questionable unless the eroding area has a high runoff coefficient.

**Accuracy of predictions of soil loss by more process-based models**

More process-based models such as WEPP (Flanagan and Nearing, 1995) and EUROSEM (Morgan et al., 1998) were developed to predict event erosion better than the USLE/RUSLE and to facilitate the prediction of erosion for situations outside those experienced in the database used to develop the USLE/RUSLE. An advantage perceived by this approach was the ability to parameterise the impacts of soils in models like WEPP from experiments using artificial rainfall and controlled runoff such as that reported by Elliot et al. (1989). WEPP ignores any variation in the kinetic energy per unit quantity of rain such as that used in determining \( E_{30} \) (Eqs. (38) and (39)), but is dependent on rainfall intensity data. These intensities are generated by a stochastic daily parameter weather generator, CLIGEN (Nicks et al., 1995). The meteorological data required to parameterise CLIGEN are not available in many countries outside the USA. Also, the ability of WEPP to predict soil losses in the USA has been shown to not be better than either the USLE or the RUSLE. Using more than 1600 plot years of data from natural rainfall–runoff plots in the USA, Tiwari et al. (2000) observed that, for average annual soil losses, the model efficiency of WEPP determined using the Nash and Sutcliffe (1970) factor (\( Eff \)) defined as

\[
Eff = \frac{\sum (Y_o - Y_m)}{\sum (Y_o - Y_m^*)}
\]

(41)

where \( Y_o \) is the observed value, \( Y_m^* \) is the modelled value and \( Y_m \) is the mean of the observed value, was 0.40, whereas it was 0.58 and 0.60 for the USLE and the RUSLE, respectively. Also, like the USLE and the RUSLE, WEPP was observed to over-predict low annual soil losses and under-predict high annual soil losses. The value of \( Eff \) is positive when the model predicts soil loss better than just using \( Y_m \), and negative when the model predicts soil loss worse than using \( Y_m \). For annual soil loss, the USLE produced negative values at four locations, the RUSLE at 2. WEPP produced negative values of \( Eff \) for annual soil losses at six of the 20 locations. Arguably, the lower efficiency demonstrated by WEPP can be attributed to the availability of more refined and site specific input parameters for the USLE and the RUSLE (Tiwari et al., 2000).

**Conclusion**

As noted above, the accuracy of any prediction depends on (a) the ability of the model to account for effects of the physical phenomena causing the output, and (b) the accuracy by which the parameters have been determined. One of the major constraints to using so-called process-based models is the difficulty in parameterising them. Although, as indicated above, parameterising the USLE model is not all that simple if good results are to be achieved in many geographic locations, process-based models require considerable effort to obtain appropriate parameter values in order to run them. This, and their failure to produce better results than achieved using the USLE/RUSLE model (Tiwari et al., 2000), encourages the use of the USLE/RUSLE model in roles for which it was not designed. In particular, it is widely used in watersheds models designed to examine the impact of landuse on water quality. In this role, the USLE/RUSLE model is used to extrapolate data collected at the plot scale to area much larger area than the field sized areas for which it was originally designed. At the hillslope scale, spatial variability in soil and vegetation result in spatial variations in runoff within the area for which soil loss estimates are required, so that the modelling approach required to produce those estimates needs to be sensitive to those spatial variations in runoff. Models like WEPP and EUROSEM have an advantage over the USLE, RUSLE and RUSLE2 because they include explicit consideration of runoff in determining the erosive stresses being applied to the land surface. Including direct consideration of runoff in the event rainfall–runoff factor of the USLE/RUSLE model enhances the capacity of that model to account for variations in event erosion when runoff is measured or predicted reasonably well, and produces a model that has a better capacity to react to the spatial variations in runoff that occur at the hillslope scale. However, unless the consequences of including that direct consideration of runoff in the rainfall–runoff factor on the other factors in the model are taken into account, the result will break fundamental mathematical rules that should be adhered to when developing mathematical models.

**References**


