Sediment delivery from hillslopes and the Universal Soil Loss Equation: Some perceptions and misconceptions

P.I.A. Kinnell
Institute of Applied Ecology
School of Resource, Environment and Heritage Sciences
University of Canberra
Canberra ACT 2601

This is a preprint of an article that has been accepted for publication in Hydrological Processes © (2007) John Wiley and Sons Ltd

ABSTRACT

The Universal Soil Loss Equation (USLE) or the Revised Universal Soil Loss Equation (RUSLE) are often used together with sediment delivery ratios in order to predict sediment delivery from hillslopes. In using sediment delivery ratios for this purpose, it is assumed that the sediment delivery ratio for a given hillslope does not vary with the amount of erosion occurring in the upslope area. This assumption is false. There is a perception that hillslope erosion is calculated on basis that hillslopes are, in effect, simply divided into 22.1 m long segments. This perception fails to recognize the fact the inclusion of 22.1 m length in the calculation has no physical significance but simply produces a value of 1.0 for the slope length factor when slopes have a length equal to that of the unit plot. There is a perception that the slope length factor is inappropriate because not all the dislodged sediment is discharged. This perception fails to recognize that the USLE and the RUSLE actually predict sediment yield from planar surfaces, not the total amount of soil material dislocated and removed some distance by erosion within an area. The application of the USLE/RUSLE to hillslopes also needs to take into account the fact that runoff may not be generated uniformly over that hillslope. This can be achieved by an equation for the slope length factor that takes account of spatial variations in upslope runoff on soil loss from a segment or grid cell. Several alternatives to the USLE event erosivity index have been proposed in order to predict event erosion better than can be achieved using the E10 index. Most ignore the consequences of changing the event erosivity index on the values for the soil, crop and soil conservation protection factors because there is a misconception that these factors are independent of one another.

Keywords: USLE; soil erosion; sediment yield

INTRODUCTION

At this time, sediment delivery to and from rivers and streams is a topic of interest with regard to the impact of land use on water quality. How much soil, nutrients and undesirable chemicals moves from hillslopes to these rivers and streams and then gets discharged in dams, lakes and sensitive marine environments is a matter of concern. The effects of current and alternative land uses needs to be investigated in order to determine appropriate land management strategies to maintain or obtain good water quality. Since measurement of erosion and sediment delivery to streams cannot be done on a wide scale, mathematical models are employed to do this task. Such models invariably depend on erosion measurements made at the small scale being extrapolated to the larger scale. A factor called the sediment delivery ratio, the ratio of the gross erosion upslope of a point to the sediment delivered, is often used to predict the amount of sediment delivered from the erosion estimated to occur on hillslopes as a result of this extrapolation.

As noted above, the estimates of erosion invariably depend on erosion measurements made at the small scale being extrapolated to the larger scale. Although not designed for this purpose, the Universal Soil Loss Equation (USLE: Wischmeier and Smith 1978), or the revised version of it (RUSLE: Renard et al, 1997), is commonly used to do this extrapolation. More process-based models such as WEPP (Lafren et al, 1991) and EUROSEM (Morgan et al., 1998) are too data and computationally intensive to use over large areas.

The USLE and the RUSLE are often given as

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

where \( A \) is average (mean) annual soil loss (mass/area) over the long term (eg 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. While 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 bare fallow area 22.1 m long on a 9 % slope with cultivation up and down the plot. Only \( R \) and \( K \) have units. \( L, S, C \) and \( P \) are reduced variables that are mathematically forced to take on values of 1.0 for the unit plot condition. As a consequence of this, the USLE and the RUSLE first predict erosion for the unit plot condition (\( A_1 \))

\[ A_1 = R K \]  

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,

\[ A = A_1 L S C P \]  

The values of \( K, L, S, C \) and \( P \) that can be used to do this are 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 that are mathematically forced to take values of 1.0 for the unit plot has no physical significance. For example, when appropriately parameterised, the model produces exactly the same value of \( A \) for a given non-unit plot situation no matter what value of slope length and gradient is chosen for the unit plot condition.
SOME PERCEPTIONS AND MISCONCEPTIONS

The USLE slope length factor

The slope length factor in the USLE and the RUSLE is calculated using the equation

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

(4)

where \( \lambda \) is the slope length in metres and \( m \) is a factor that varies with slope gradient in the USLE and the ratio of rill to interrill erosion in the RUSLE. The USLE was designed to predict soil loss from planar surfaces that are uniform with respect to soil, vegetation and management. As a result of this, the length of slope upon which the calculation of \( L \) is based is defined as the distance from the onset of overland flow to the point where deposition begins or where overland flow enters a channel bigger than a rill. This definition of slope length is also used in the RUSLE (Renard et al., 1997) but, in the RUSLE, provisions exist to deal with more complex slopes where vegetation and slope gradient vary. For nonuniform one dimensional hillslopes, the slope is broken into a number of planar segments, and the \( L \) factor for each segment \( i \) calculated using

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

(5)

where \( \lambda_i \) is the slope length to the bottom of segment \( i \), \( \lambda_{i-1} \) is the slope length to the bottom of the previous segment and \( m \) is determined by the slope gradient of segment \( i \). Eq. 5 results from an equation for sediment yield for the \( i \)th segment developed by Foster and Wischmeier (1974) and adopted in the RUSLE (Renard et al., 1997). 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 modelling spatial variations in soil loss given that 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 \( ij \), contributing area \( (\chi) \) divided by the width of the contour \( (w) \) over which the overflow flow from that area flows replaces \( \lambda \). This approach gives

\[ L_{ij} = \frac{(\chi_{ij}^{m+1} + D_i^{m+1} - \chi_{ij}^{m+1})}{\chi_{ij}^{m+1} (22.1)^m} \]  

(6)

where \( \chi_{ij} \) 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 \( x \) is a factor which accounts for variations in flow width that depend on the direction of flow relative to cell orientation (Desmet and Govers, 1996). Eqs 5 and 6 account for not just segment length or grid cell size but also the position of the segment or cell in the landscape.

Parsons et al (2006) contend that the USLE and the RUSLE simply predict erosion on a 22.1 m long area so that, in effect, hillslopes are simply divided into 22.1 m long plots and the value of erosion allocated to each one of them added together to give erosion on the hillslope. That perception is false. The value of 22.1 m appears in Eq. 4, 5 and 6 not because it has great physical significance but simply so that the value of \( L = 1.0 \) when \( \lambda = 22.1 \) m. Experiments that provided the data upon which the USLE was based contained a wide range of plot lengths (Risse et al., 1993). The designers of the USLE could have chosen some value other than 22.1 m for a standard. If they had done that, \( L \) for a 22.1 m long slope would not be 1.0 but that would have not had any impact on the value of \( A \) predicted for any given slope length – gradient combination because the value of \( K \) (Eq. 2) would be different from that used when the unit plot is 22.1 m.

The USLE and sediment delivery from hillslopes

Although Eqs. 5 and 6 exist to deal with complex hillslopes, neither the USLE nor the RUSLE deal with deposition that results from reductions in slope gradient such as occur on concave hillslopes. Because of this, it is common practice to predict gross soil loss from a hillslope \( (A_{gh}) \) using the USLE or the RUSLE ignoring the criteria for the slope length being limited to area where net deposition does not occur (Figure 1), and then multiply the result by the sediment delivery ratio to obtain the sediment yield \( (Y, \text{mass/area}) \) for the hillside,

\[ Y = A_{gh} DR_h \]  

(7)

where \( DR_h \) is the sediment delivery ratio for the hillside involved. When sediment yield for a whole watershed is the issue,

\[ Y = A_{gw} DR_w \]  

(8)
where \( A_{gw} \) is the gross soil loss over the whole area of the watershed and \( DR_w \) is the sediment delivery ratio for the watershed as a whole. As noted by Parsons et al. (2006), the sediment discharged from a watershed may contain substantial quantities of material eroded from river banks. Consequently, Eq. 8 may not provide a reasonably estimate of the amount of sediment leaving the watershed unless it includes predictions of erosion in the large channels.

Considerable attention has been given to the factors that influence \( DR_w \). The gross effect of watershed area \( (\text{Area}_w) \) has been considered using the equation

\[
DR_w = (\text{Area}_w)^b
\]

(9)

with \( b \) having a value less than 0 (Roehl, 1962; Renfro, 1975; Walling, 1983). The decline in \( DR_w \) with watershed area is usually associated with an increase the amount of deposition that occurs on concave slopes and flat areas as watershed area increases. Other factors observed to affect \( DR_w \) are, for example, particle size (the finer the material the less likely it is to be deposited), runoff, and the average gradient of the watershed.

In terms of predicting sediment delivery from hillslopes, Eq. 7 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 that results from a reduction of slope gradient results from the sediment entering that low gradient area being in excess of the capacity of the flow to transport sediment through the low gradient area. Consider the example shown in Figure 2 where, over some period of time, flow in the lowest segment has a capacity to transport only 5 tons of sediment through to its downslope boundary. If 20 tons of sediment enters the upslope boundary, 15 tons is deposited and so \( DR_h \) has a value of \( 5/20 = 0.25 \). If the supply of sediment drops so that 10 tons is delivered to the upslope boundary, 5 tons is deposited and so \( DR_h \) has a value of \( 5/10 = 0.5 \). The graph in Figure 2 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, Figure 2 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 with regard to the movement of soil material down a slope is not new. Figure 3 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 together with a sediment transport model to predict sediment delivery. In AGNPS 5.0, the USLE is directed to estimating detachment so that, in the context of Figure 2, the sediment transport capacity model controls not only sediment movement on the lower segment but also on the upper segment where there is no need to do so. A new version of the RUSLE, called RUSLE2 (Foster et al., 2003), also 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. However, AnnAGNPS (Bingner and Theurer, 2001), the replacement for AGNPS 5.0, uses the conventional approach where the RUSLE is used with sediment delivery ratios to predict sediment delivery.
One issue that raises concern about the use of the USLE and the RUSLE in predicting soil loss from hillslopes is the fact that detached particles are transported across the landscape at various rates. Parsons et al. (2006) point out that the USLE and the RUSLE do not deal with deposition resulting from cross-slope movements. Buffer strips and filter strips are not included in the calculations, and slope length, slope gradient, soil, vegetation and management vary spatially. The RUSLE (Renard et al., 1997), while not dealing with deposition resulting from cross-slope fluxes, provides a mechanism to deal with the P factor, which accounts for the effects of transport capacity on sediment delivery. The RUSLE focuses on effect of slope length on the long term sediment yield not erosion per se.

Conceptually, for a hillslope segment, Eq. 5 becomes

$$L_i = \frac{\lambda_i \sum_{j=1}^{m} \chi_{ij} \mathcal{D}_{ij} + \sum_{j=1}^{m} \chi_{ij}(\text{cell}^{m+1})}{\sum_{j=1}^{m} \chi_{ij}(\text{cell}^{m+1})}$$

where $L_i$ is the slope length of the $i$th segment, $\lambda_i$ is the slope length of the upslope area, and $\lambda_{ij}$ is the slope length of the $j$th upslope area. This equation, with $\lambda_{ij}$ equal to the segment, equal to $\lambda_{i+1}$ when the runoff coefficient for the upslope area is greater than $\lambda_{i-1}$, is analogous to Eq. 1 of this paper, which is used when discussing the impact of topography on soil loss from hillslope segments in the RUSLE. The RUSLE focuses on effect of slope length on the long term sediment yield, not erosion per se.

Although it is true that, no matter what the time frame, some detached particles will fail to cross the downslope boundary of erosion plots, the RUSLE focuses on effect of slope length on the long term sediment yield, not erosion per se. The RUSLE does not account for significant deposition and the term "sediment yield" not erosion is used in this context. The RUSLE is based on the assumption that in the downslope direction, as in the case illustrated in Figure 2, the failure to predict sediment delivery from concave hillslopes is due to the fact that, in the RUSLE, the downslope gradient is less than the upslope gradient. As a result, the RUSLE was designed to provide an appropriate means of dealing with the effect of topography on soil loss from hillslope segments. The RUSLE does not deal with deposition resulting from cross-slope movements. Buffer strips and filter strips are not included in the calculations, and slope length, slope gradient, soil, vegetation and management vary spatially. The RUSLE focuses on effect of slope length on the long term sediment yield, not erosion per se.

Conceptually, for a hillslope segment, Eq. 5 becomes

$$L_i = \frac{\lambda_i \sum_{j=1}^{m} \chi_{ij} \mathcal{D}_{ij} + \sum_{j=1}^{m} \chi_{ij}(\text{cell}^{m+1})}{\sum_{j=1}^{m} \chi_{ij}(\text{cell}^{m+1})}$$

where $L_i$ is the slope length of the $i$th segment, $\lambda_i$ is the slope length of the upslope area, and $\lambda_{ij}$ is the slope length of the $j$th upslope area. This equation, with $\lambda_{ij}$ equal to the segment, equal to $\lambda_{i+1}$ when the runoff coefficient for the upslope area is greater than $\lambda_{i-1}$, is analogous to Eq. 1 of this paper, which is used when discussing the impact of topography on soil loss from hillslope segments in the RUSLE. The RUSLE focuses on effect of slope length on the long term sediment yield, not erosion per se.
Figure 4 shows how the ratio of $Q_{C,up}$ to $Q_{C,all}$ varies as $Q_{C,up}$ varies from 0 to 1 when $Q_{C,all}$ is dependent on an upslope area that is 3 times that of the segment and $Q_{C,seg} = 0.5$. Since $Q_{C,all}$ can only take on a value of zero when both $Q_{C,up}$ and $Q_{C,seg}$ or $Q_{C,cell}$ are zero, the $Q_{C,up}$ to $Q_{C,all}$ ratio will not tend to infinity in the same way as the $Q_{C,up}$ to $Q_{C,seg}$ or $Q_{C,cell}$ ratio. Also, Eqs 12 and 13 are consistent with the concept that the adjustment has to 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 that, as noted above, is central to operation of the USLE/RUSLE model as it was originally developed.

![Figure 4: The effect of $Q_{C,up}$ on the ratio of $Q_{C,up}$ to $Q_{C,all}$ for the case where $Q_{C,seg} = 0.5$ and the length of the upslope area is 3 times that of the segment being considered](image)

Predicting annual soil loss and soil loss from individual events

Although the USLE and the RUSLE were not designed to do so (Wischmeier, 1976; Renard et al, 1997), they have been applied to predict year by year variations in soil loss and, as noted earlier, soil loss from individual rainfall events in the case of AGNPS 5.0. Risse et al (1993) observed that the USLE over predicted low soil losses and under predicted high soil losses when it was applied at both the long term average annual time scale (Figure 5) and the annual time scale. Kinnell and Risse (1998) observed that the event version of Eq. 2,

$$\lambda_{1,e} = R_e K$$

where $A_{1,e}$ is the soil loss generated by a rainstorm on the unit plot and $R_e$ is the product of the total storm kinetic energy ($E$) and the maximum 30-minute rainfall intensity ($I_{30}$), over predicted low erosion amounts and under predicted high erosion amounts at some locations (Figure 6)

![Figure 5: Measured average annual erosion in USLE runoff and soil loss plots in the USA and the values predicted by Risse et al (1993) using the USLE with best available parameter values for $R$, $K$, $L$, $S$, $C$ and $P$. The line indicates the perfect fit.](image)

![Figure 6: Relationships between observed event soil loss for plot 5 (bare fallow) in experiment 1 at Morris, MN and predicted event soil loss when $R_e$ is $E I_{30}$. Eff is the Nash – Sutcliffe (1970) efficiency factor for logarithmic transforms of the data. A value zero indicates that the model is no better at predicting the observed data than using the mean.](image)
They observed that replacing the EI30 index by the product of that index and the runoff ratio (Qe) to give,

$$ A_{Le} = Qe \times EI_{30} \quad (15) $$

where Qe is the runoff ratio for the unit plot and KLM is a soil factor that has a value that differs from K in the USLE and the RUSLE, decreased the tendency to over predict low event soil losses and under predict high event soil losses substantially (Figure 7). In a gross sense, there is an empirical relationship between rainfall and runoff embedded in the USLE that works best when the eroding area is impervious. Consequently, it could be perceived that the runoff ratio provides a correction for situations where the eroding surface is pervious. However, in reality, the product of the runoff ratio and the EI30 index is based on the observation that the sediment concentration for an event is dependent on the kinetic energy per unit quantity of rain and a factor that is related to the peak rainfall intensity. Because of this, factors such as KLM, CUMe and PUMe are directed at accounting for variations in event sediment concentration rather than both runoff and sediment concentration as is the case in the USLE.

$$ A_{Le} = Qe \times EI_{30} \quad (16) $$

tended to predict soil loss to occur on vegetated areas when, on many occasions, none actually occurred. To avoid this problem, the USLE-M (Kinnell and Risse, 1998) used runoff from vegetated areas in the determination of the QeEI30 index with the consequence that

$$ A_e = Q_e \times EI_{30} \times C_{UMe} \times P_{UMe} \quad (17) $$

where Qe is the runoff ratio for the vegetated area, and CUMe and PUMe differ in value from C and P because of that.

A number of other rainfall-runoff factors have been proposed. For example, in EPIC, a model designed to assess the effect of soil erosion on productivity (Williams et al., 1984), event sediment yield is predicted by

$$ SY_e = X_e \times K \times L \times C \times P \times [ROKF] \quad (18) $$

where ROKF is the coarse fragment factor as defined by Simanton et al (1984), K, L and S are the normal USLE factors for the soil and topographic effects, C and P are event values for the USLE-C and P factors, and Xe, the rainfall-runoff “erosivity” factor, is selected from

$$ X_e = E I_{30} \quad (19a) $$

$$ X_e = 1.586 (Q_e q_{pe})^{0.56} DA^{0.12} \quad (19b) $$

$$ X_e = 0.65 E I_{30} + 0.45 (Q_e q_{pe})^{0.33} \quad (19c) $$

where DA is drainage area expressed in ha, Qe is runoff expressed in mm, qpe is peak runoff rate expressed in mm/h, E I30 in MJ mm ha ha.h and SYe is the sediment yield for the event in t/ha (Williams and Arnold, 1997). However, given that K is the sum of event soil loss from the unit plot divided by the sum of event values of the EI30 index, K can only be used when Xe = E I30. Also, as with the USLE-M, if, as is the case with EPIC, runoff from the area of interest and not the unit plot is used for Qe, then C and P cannot be used when Xe is given by either Eq. 19b or 19c. Thus the combination of Eq. 18 and either Eq. 19b or Eq. 19c is not valid.

Williams et al (1984) indicated that Onstad and Foster (1975) was the source of Eq. 15c. However, the approach used by Onstad and Foster gave an equation that had the form

$$ R_o = a \times E I_{30} + b \times Q (q_{pe})^{0.33} \quad (20) $$

rather than

$$ R_o = a \times E I_{30} + b (Q_{pe})^{0.33} \quad (21) $$

In addition, Foster et al. (1977) used a = 0.5 and b = 0.5 α where α was a factor that caused the average annual value of Ro produced by Eq. 20 using Q and qpe values obtained for the unit plot to equal the average annual value of Ro when R0 = E I30. Because of this, Eq. 20 can be used with USLE K, C and P values while Eq. 19c cannot. In applying Eq. 20 to the data of Piest et al (1975), Foster et al (1977) were fortunate that the crop in the Treynor watersheds was corn and corn has little impact on runoff generation when compared to bare fallow (Kinnell and Risse, 1998).
amount of sediment discharged per unit area, soil loss from an area is sediment yield. Given that the objective of the USLE and the RUSLE is to predict the long-term average annual soil loss, the distinction is academic but the fact that the USLE and the RUSLE do not account for deposition resulting from slope gradient is not.

Although neither the USLE nor the RUSLE were designed to do so, they have been used to predict event sediment yield from hillslopes. The USLE and the RUSLE do not include a factor for the change in the erosivity index due to change in the slope gradient. However, simply replacing the erosivity factor by another which accounts for variations in the slope gradient is not an invalid modification of the USLE and RUSLE. Nevertheless, if the soil loss predicted by the USLE or the RUSLE is expressed as a specific area rate of sediment delivery to a stream, the USLE and RUSLE formulae can be emulated to other areas which differ significantly in terms of climate, soil, topography or vegetation.

CONCLUSION

The USLE was originally designed to predict the long-term average annual soil loss from uniform areas and values of the K, L, C, and P factors were determined from data collected from small and hillslopes. The USLE was not specifically designed to predict the deposition on concave hillslopes. The USLE-M, as with the USLE or the RUSLE, does not account for the effect of deposition on concave hillslopes. To do so, the USLE-M must operate in conjunction with an approach that deals appropriately with deposition when the sediment supply is increased by rainfall on a concave hillslope.

References


