RUNOFF, SEDIMENT CONCENTRATION AND PREDICTING EROSION ON HILLSLOPES WITHIN CATCHMENTS

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Abstract

While both raindrop impact and flow are involved in the detachment and transport processes, most erosion by rain results from sediment moving in surface water flow. Thus one approach to modelling erosion involves considering sediment discharge in terms of the product of runoff and sediment concentration.

At the small scale, raindrop impact in rain impacted flows increase sediment concentration above that associated with unimpacted flows. The detachment-transport systems involved are transport-limiting systems which produce a layer of loose material on top of the surface of the soil matrix. The two layered surface exhibits variable erodibility depending on the depth and content of the loose material. Most erosion models do not consider this effect.

At a bigger scale, prediction models like the Universal Soil Loss Equation (USLE) do not consider runoff as a primary factor. This results in the USLE in overpredicting low levels of erosion and underpredicting high level of erosion. This problem can be overcome via the USLE-M which includes runoff as a factor in accounting for event erosivity. This is also important to the modelling of erosion within grid cells where factors such as infiltration, vegetation and crop management cause runoff to vary spatially.

Additional Keywords: rainfall erosion, Universal Soil Loss Equation variants

Introduction

Rainfall erosion results from the detachment of particles from within the soil surface followed by the transport of detached particles away from the site of detachment. 4 detachment and transport systems exist:

1. Raindrop Detachment with transport by Raindrop Splash (RD-ST)
2. Raindrop Detachment with transport by Raindrop Induced Flow Transport (RD-RIFT)
3. Raindrop Detachment with transport by Flow (RD-FT)
4. Flow Detachment with transport by Flow (FD-FT)

Raindrop Detachment with transport by Raindrop Splash (RD-ST) is the system that operates in what is commonly known as splash erosion. Raindrop Induced Flow Transport (RIFT) is a process where each drop impact causes soil material to be lifted into the flow and settle back to the bed some distance downstream. Flow transport (FT) occurs when lose particles travel with the flow without the aid of raindrop impact. Whether a particles detached by raindrop impact (RD) is transported by RIFT or FT depends on its size, density and the flow conditions. In sheet and interrill erosion, Raindrop Detachment with transport by Raindrop Induced Flow Transport (RD-RIFT) tends to control the movement of silt and sand sized material while Raindrop Detachment with transport by Flow (RD-FT) tends to control the movement of the finer material. Rill erosion is dominated by Flow Detachment with transport by Flow (FD-FT).

With splash erosion, raindrop detachment is the primary detachment agent and transport away from the site of detachment occurs by raindrop splash The tendency for raindrop splash to transport material radially from the point of impact means that on large level or near level surfaces, a layer of pre-detached material builds up on the surface over time. This is because the transport system is extremely inefficient. Any material splashed may come from this layer and from the soil surface beneath it. Also, because the pre-detached material sits on top of the soil surface, it provides a degree of protection (H) against detachment from that surface. Consequently, the erodibility of the surface (k_s) is given by

$$k_s = H\ k_{sm} + (1+H)\ k_{pdl} \qquad (1)$$

where k_{sm} is the erodibility of the surface of the soil matrix (sm) when no pre-detached particles are present, k_{pdl} is the erodibility of the pre-detached layer (pdl) of particles, and H has values of 0 to 1. On sloping surfaces, the transport efficiently increases because more material is splashed downslope than up but this also results in the layer of pre-detached material increasing in the downslope direction.

Erosion by rain-impacted flow

Erosion by rain-impacted flow dominates sheet and interrill erosion. Because erosion is associated with sediment being discharged with the flow, the equation

$q_s = q_w\ c$ (2)

where q_s is the sediment discharge (mass per unit width of flow), q_w is the water discharge (mass per unit width of flow), and c is the sediment concentration (mass of sediment per unit mass of water) is relevant to determining of the erosion rate. Kinnell (1993) showed that when Raindrop Induced Flow Transport dominated to transport of sediment

$q_{sR}(p,d) = a_p\ I_d\ u\ f[h,d]$ (3)

where a_p is a coefficient that is dependent on particle size and density, I_d is intensity of rain of drops of size d, u is flow velocity, and f[h,d] is a function that varies with flow depth (h) and drop size (d).

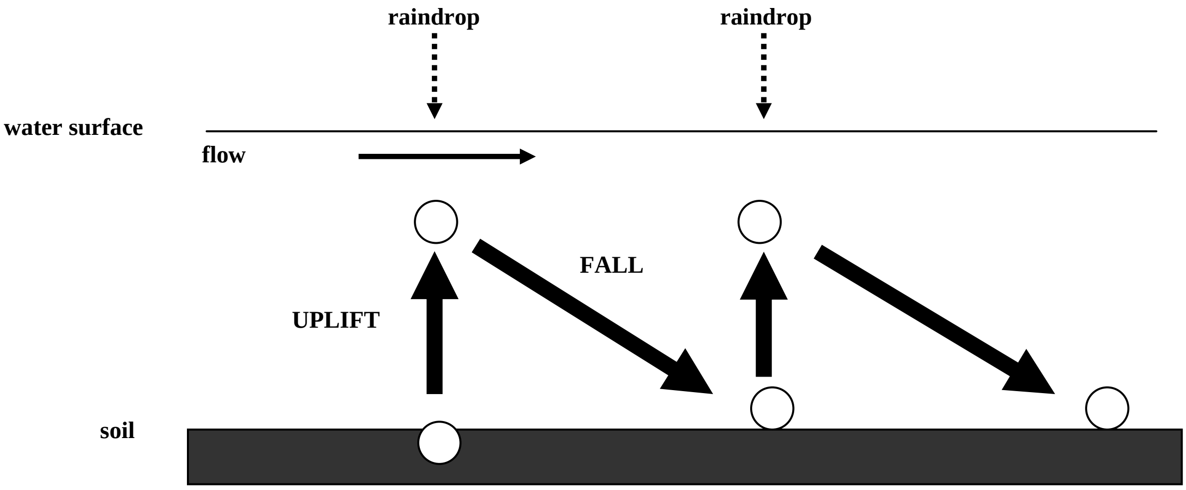

Figure 1. Schematic representation of particle up lift and fall with respect to Raindrop Detachment (RD) and Raindrop Induced Flow Transport (RIFT)

As noted above, in rain-impacted flows, Raindrop Induced Flow Transport (RIFT) controls the movement of silt and sand sized material while Flow Transport (FT) controls the movement of the finer material. In RIFT, particles are lifted into the flow by drop impacts but then fall back to the bed under the force of gravity. Downstream movement during fall occurs because the flow exerts a horizontal force on the falling particle (Figure 1). Like transport by splash, RIFT is transport system that produces a layer of pre-detached material sitting on the soil surface and consequently, the erodibility of the surface will vary depending on the depth and characteristics of this layer of pre-detached material. Thus, the erodibility of a surface eroding under a rain-impacted flow where raindrop induced flow transport dominates ($k_{s.RIFT}$) is given by

$k_{s.RIFT} = H\ k_{sm.RIFF} + (1+H)\ k_{pdl.RIFT}$ (4)

where $k_{sm.RIFT}$ is the erodibility of the surface of the soil matrix (sm) when no pre-detached particles are present, $k_{pdl.RIFY}$ is the erodibility of the pre-detached layer (pdl) of particles, and H has values of 0 to 1. Consequently, the erodibility of such a surface is not given by a single value but may range between $k_{sm.RIFF}$ and $k_{pdl.RIFT}$. Currently, so called process based models do not include any consideration of this and use a single experimentally derived erodibility factor which lies at some unknown point between the two extremes. This makes it difficult to relate these erodibility factors to measured soil physical and chemical factors because the physical and chemical properties of the two materials are quite different, and the dominance of one over the other is unknown.

Runoff as a factor in prediction erosion with catchments

It is common for erosion within catchments to be predicted using the the Universal Soil Loss Equation (Wischmeier and Smith 1978) or the revised version of it (RUSLE, Renard et al. 1997). While the USLE/RUSLE was not developed for predicting event erosion, it follows that

$A_e = R_e\ K_e\ L\ S\ C_e\ P_e$ (5)

where A_e is the erosion that takes place during a rainfall event, $R_e = EI_{30}$ (where E is event rainfall kinetic energy and I_{30} is the maximum 30 minute intensity), L and S are the USLE topographic factors which vary in space but not time, C_e is the crop and crop management factor that is associated with the event, and P is the soil conservation protection factor that applies during the event. Figure 2 shows how the USLE predicts event erosion on a bare fallow plot at Morris, MN in the USA. In this case, low soil losses were severely overpredicted.

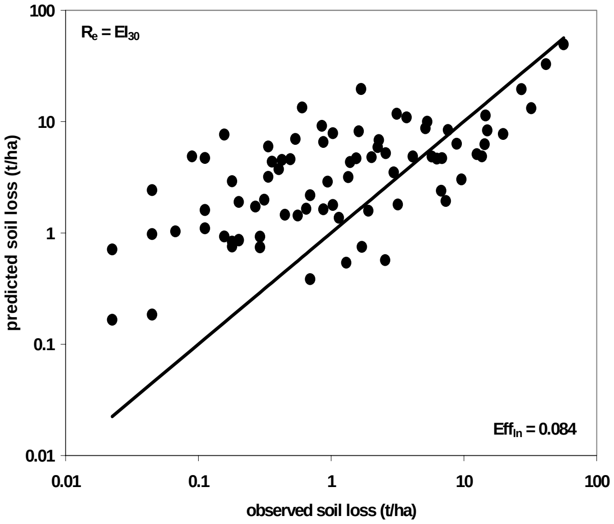

Figure 2. Relationships between observed and predicted event soil loss for plot 10 (bare fallow) in experiment 1 at Morris, MN when predicted = bR_e where R_e is EI_{30} Eff_{ln} is the Nash-Sutcliffe efficiency factor for the ln transforms of the data and reflects the amount of variation from the 1:1 lines shown in these figures. NB. This analysis takes no account of short term variations in K.

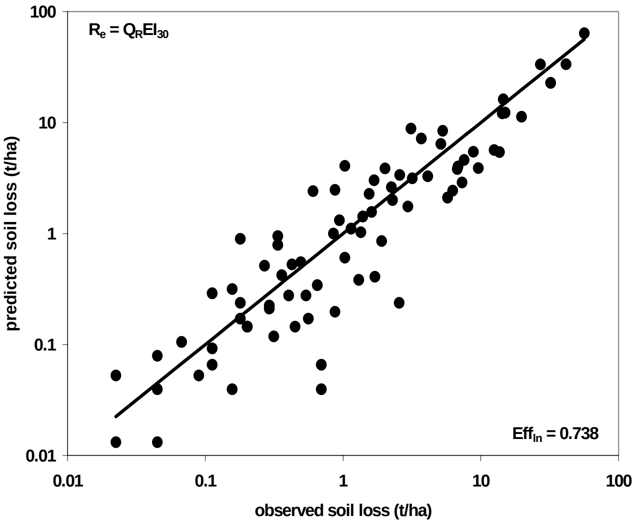

Figure 3. Relationships between observed and predicted event soil loss for plot 10 (bare fallow) in experiment 1 at Morris, MN when predicted = bR_e where R_e is $Q_R EI_{30}$ Eff_{ln} is the Nash-Sutcliffe efficiency factor for the ln transforms of the data and reflects the amount of variation from the 1:1 lines shown in these figures. NB. This analysis takes no account of short term variations in K.

Equation 2 applies to all situations where sediment is discharged with flowing water. However, models like the Universal Soil Loss Equation (USLE) and the RUSLE do not consider runoff as a primary independent factor in the prediction of erosion from field sized areas. It follows from Equation 2 that if runoff is considered as a primary independent term in predicting erosion, then event sediment concentrations on a bare fallow area will vary between soils and with rainfall kinetic energy level of the rainfall and some measure of event rainfall intensity. The kinetic energy level of the rainfall is given by dividing E by the rainfall amount and I_{30} is a measure of event rainfall intensity. Thus

$$A_e = k\ Q_e\ I_{30}\ E/\text{rainfall amount} \qquad (6)$$

where k is an empirical coefficient that is dependent in part on the soil, and Q_e is event runoff. Q_e divided by rainfall amount is the runoff coefficient (Q_R). Consequently,

$$A_e = k\ Q_{Re}\ E\ I_{30} \qquad (7)$$

Figure 3 shows how Eq. 7 predicts event erosion on a bare fallow plot at Morris, MN in the USA when event runoff is known. The variant of the USLE that uses Q_{Re} E I_{30} as its event erosivity index is known as the USLE-M (Kinnell and Risse, 1998).The total loss from the plot was 374 t/ha from 80 events over 10 years. The top 5 events produced 177 t/ha. The USLE (Figure 2) predicted 123 t/ha (-31% error) while the USLE-M predicted 164 t/ha (-7% error). The 10 events producing the lowest soil loss contributed 0.83 t/ha. The USLE predicted 25 t/ha for these events, the USLE-M 1.12 t/ha.

The USLE-M is not the only USLE variant to include runoff as a parameter in the event erosivity factor. The MUSLE (Williams, 1975) uses the product of event runoff (Q_e) and peak runoff ($q_{p.e}$) in place of EI_{30}. However, it uses USLE factor values for K, L, S, C and P when these should only be used when $R_e = EI_{30}$. K, the soil erodibilty factor has units of soil loss per unit erosivity index and must be re-evaluated if R_e is changed from EI_{30}. Also, even if this is done, C and P values cannot be applied if the values of Q_e and $q_{p.e}$ are determined for anything but bare fallow and cultivation up and down the slope. If they are, then the effect of runoff is considered twice. In addition, the MUSLE event erosivity index does not account for erosion at the plot scale well. Figure 4 shows the relationship between that erosivity index and event soil losses from a cropped plot at Zanesville, Ohio. The Nash-Sutcliffe efficiency factor for the index in this case is 0.283, assuming that C is constant with time. The efficiency factor value for the USLE-M was 0.619.

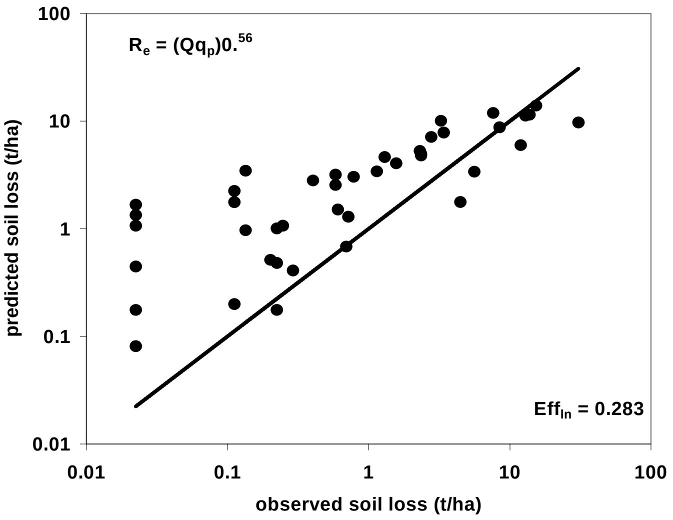

Figure 4. Relationships between observed and predicted event soil loss for plot 1 in experiment 1 with corn at Zanesville, Ohio when predicted = b R_e where $R_e = (Qq_p)^{0.56}$ and b is a fitted parameter. NB. This analysis takes no account of short term variations in C. Eff_{ln} for $R_e = Q_R EI_{30} = 0.619$.

It is common to model erosion in catchments using grid cells. When a hillslope is uniform with respect to soil and vegetation, the effect of slope length for cell with co-ordinates i,j can be determined using the approach proposed by Desment and Govers (1996):

$$L_{i,j} = \frac{(A_{i,j\text{-}in} + D^2)^{m+1} - A_{i,j\text{-}in}^{m+1}}{D^{m+2}\, x_{i,j}^{m}\ (22.13)^m} \qquad (8)$$

where $A_{i,j\text{-}in}$ is the contributing area (m^2) upslope of the cell, D is cell size (m), m is the USLE slope length exponent (Renard et al 1997), and x is a factor that depends on the direction of flow with respect to grid orientation. If no runoff occurs from upslope then

$$L_{i,j} = \frac{D^m}{(22.13)^m} \qquad (9)$$

the USLE L factor for an area D metres long. Setting $A_{i,j\text{-}in}$ to zero results in Eq. 8 producing the correct result.

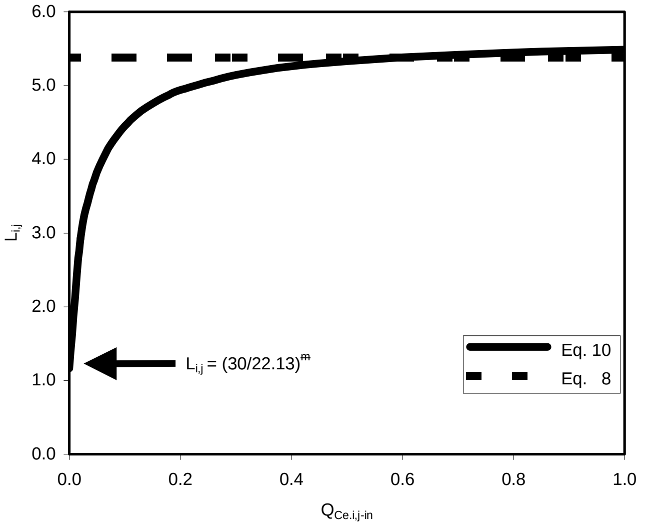

Figure 5. The effect of $Q_{Ce.i,j\text{-}in}$ on $L_{i,j}$ for the outlet cell to a 0.9 ha area when D = 30 m and the runoff coefficient for the cell = 0.6.

However, it follows that if the upslope area has a runoff coefficient that lies somewhere between zero and that for the grid cell, $L_{i,j}$ should lie somewhere between that given by Eq. 8 when $A_{i,j\text{-}in}$ is zero and $A_{i,j\text{-}in}$ is equal to the physical area upslope of the grid cell. Similarly, if the runoff coefficient of the upslope area is greater than that of the cell, $L_{i,j}$ should be greater than that given when $A_{i,j\text{-}in}$ is equal to the physical area upslope of the grid cell. This can be achieved by replacing $A_{i,j\text{-}in}$ by an effective value of $A_{i,j\text{-}in}$ ($A_{i,j\text{-}in.eff}$) to give

$$L_{i,j} = \frac{(A_{i,j\text{-in.eff}} + D^2)^{m+1} - A_{i,j\text{-in.eff}}^{m+1}}{D^{m+2}\,{}_{i,j}^{m}\,(22.13)^m} \qquad (10)$$

where

$$A_{i,j\text{-in.eff}} = A_{i.j\text{-in}}\, Q_{Ce.i,j\text{-in}} / Q_{Ce.i,j\text{-all}} \qquad (11)$$

and $Q_{Ce.i,j\text{-in}}$ is the runoff coefficient for the upslope area and $Q_{Ce.i,j\text{-all}}$ is the runoff coefficient for the area including the cell. Figure 5 shows how $L_{i,j}$ for the outlet cell to a 0.9 ha area varies with the upslope runoff coefficient when the cell size is 30 m.

The value of $L_{i,j}$ produced using Eq. 10 only differs significantly from that produced by the Desmet and Govers approach (Eq. 8) when the runoff coefficient of the upslope area ($Q_{Ce.i,j\text{-in}}$) is less than that of the cell. Basing the calculation of $A_{i,j\text{-in.eff}}$ on the runoff coefficient of the cell as an alternative using $Q_{Ce.i,j\text{-all}}$ results in greater departures from Eq. 8 but produces a value of infinity when the cell in pervious enough to absorb all the rain that fall on it when some runoff enters the cell from upslope. Such rainfall-runoff conditions can occur but obviously a value of infinity for $L_{i.j}$ is inappropriate. Consequently, the combination of Eq. 10 and 11 has the appropriate characteristics to deal with this situation.

Discussion

The Universal Soil Loss Equation (USLE) has been widely used to model erosion in catchments in connection with non-point source (NPS) pollution. Because of observations that prediction of the amounts of sediment delivered from hillslopes is less than predicted using the USLE or the revised USLE (RUSLE), a common approach to modelling NPS pollution involves multiplying the USLE predicted erosion by sediment delivery ratios (SDRs). The sediment delivery ratio can be defined as the ratio of the total erosion upslope of a point to the sediment delivered from that point. Williams (1975) contended that the use of SDRs was not necessary if the rainfall energy factor in the USLE is replaced by a runoff rate factor because watershed characteristics such as drainage area, slope, and watershed shape influence runoff rates and delivery ratios in a similar manner. The MUSLE was the result of this, and is used in SWAT (Soil and Water Assessment Tool, Arnold et al., 1998), an water quality model popular in the USA. However, as indicated above, the MUSLE lacks mathematical integrity. The MUSLE, and hence SWAT, uses the USLE K, C and P factors inappropriately. The USLE K factor can only be used when the event erosivity index is EI_{30}. Using the USLE C and P factors can will account for the effect of runoff twice if the event erosivity factor is based on runoff from anything but bare fallow and cultivation up and down the slope. Consequently, the event erosion equation for the MUSLE should be

$$A_e = R_{e.MUSLE}\, K_{e.MUSLE}\, L\, S\, C_{e.MUSLE}\, P_{e.MUSLE} \qquad (12)$$

where the subscript “MUSLE” indicates factors which have values that differ from the USLE. The runoff effect issue also apply to the USLE-M. Consequently, the USLE-M is represented by (Kinnell and Risse 1998)

$$A_e = R_{e.UM}\, K_{e.UM}\, L\, S\, C_{e.UM}\, P_{e.UM} \qquad (13)$$

where the subscript “UM” indicates factors which have values that differ from the USLE. Kinnell and Risse (1998) presented procedures for determining annual average values of the USLE-M soil erodibility factor (K_{UM}), and the crop factor (C_{UM}) and the erosion protection factor (P_{UM}) but equivalent procedures have not been developed for K_{MUSLE}, C_{MUSLE}, P_{MUSLE}.. Also, the MUSLE event erosivity factor is entirely empirical while the USLE-M index has some physical basis.

Although the USLE-M has appropriate credentials for prediction erosion in hillslopes given an appropriate capacity to predict runoff, procedures for determining $K_{e.UM}$, $C_{e.UM}$, and $P_{e.UM}$ have yet to be determined to the same degree as for the USLE. However, USLE parameter values can be used with an event erosivity factor other than EI_{30} if the event erosivity factor is applied to predicting erosion from bare fallow with cultivation up and down the slope. Thus,

$$A_e = [Q_{R1} EI_{30}]_e\, K_{eUM}\, L\, S\, C_e\, P_e \qquad (14)$$

where Q_{R1} is the runoff coefficient for the bare fallow cultivation up and down the slope condition and C_e and P_e are event values for the USLE C and P factors respectively, is valid. The model represented by Eq. 14 is called the “USLE-M lite” Kinnell (in review). As shown by Figures 2 and 3, the USLE-M lite has the advantage of predicting erosion better than the USLE on the bare fallow condition but can use existing USLE procedures for determining the values for all the other factors except soil erodibility. However, since temporal variations in soil erodibility are often incorporated in C rather than considered directly, K_{eUM} can be taken as K_{UM} which, as noted above, can be determined from USLE K. Thus, the USLE-M lite provides a practical approach to predicting event erosion in catchments provided that runoff can be predicted adequately. The USDA Curve Number approach is an approach commonly used to predict event runoff from event rainfall and can be used with the USLE-M.

Conclusions

Erosion resulting from sediment moving with runoff is directly related to the product of runoff and sediment concentration.

At the small scale, variations in flow depth in rain-impacted flows influence sediment concentrations because the surface water absorbs raindrop energy. However, variations in flow velocity in rain-impacted flows do not cause variations in sediment concentration when Raindrop Induced Flow Transport (RIFT) is dominant. This is because particles travel a limited distances in the flow following each drop impact, and those distances vary directly with flow velocity. The deposition of detached particles between drop impacts results in a layer of pre-detached material sitting on the surface of the soil matrix. Raindrop impact lifts soil material into the flow from this layer and from the underlying surface if the protective effect of the layer of pre-detached material is not too great. The erodibility of the pre-detached material differs from that of the surface of the soil matrix with the consequence that the erodibility of the eroding area lies somewhere between the two erodibilites. The physico-chemical differences between the two materials, and the lack of knowledge about where between the two erodibilities the actual erodibility of an eroding area lies, makes for difficulties when attempting to relate soil erodibility to measurable soil properties.

At the larger scale, erosion is often modelled using the Universal Soil Loss Equation (USLE) which contains no direct consideration of runoff. There variants of the USLE that do consider erosion to be directly dependent on runoff. One variant is known as the MUSLE, another the USLE-M. Both models use event erosivity indices that differ from that used by the USLE but the MUSLE uses the USLE factors for K, L, S, C and P inappropriately. The USLE-M does not and has been observed to account for event soil loss better than both the USLE and the MUSLE at the plot scale. The need to use factor values other than the ones for the USLE when the event erosivity index is changed from EI_{30}, the product of event kinetic energy and the maximum 30 minute intensity, to the $Q_R EI_{30}$ index (where Q_R is the runoff ratio) used in the USLE-M can be reduced if the runoff ratio for bare fallow with cultivation up and down the slope is used in the calculation of the index. In this case only the soil erodibility factor has to be changed from that used with the USLE. Procedures exist for determining annual values of K_{UM}. To the extent that short term variations in soil erodibility from the annual value are often ignored when modelling event erosion using the USLE, the version of the USLE-M that uses this approach, the USLE-M lite, provides a practical approach to predicting event erosion in catchments provided that runoff can be predicted adequately.

References

Arnold, J.G., Srinivasan, R., Muttiah, R.S., and Williams, J.R. (1998). Large area hydrologic modelling and assessment – part I: model development. *Journal of the American Water Resources Association* 34, 73-89.

Desmet, P.J.J., and Govers, G. 1996. A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. *Journal Soil and Water Conservation* 51, 427-433, 1996

Kinnell, P.I.A. (1993). Sediment concentrations resulting from flow depth/drop size interactions in shallow overland flow. *Transactions American Society Agricultural Engineers* 36, 1099-1103.

Kinnell, P.I.A. (in review). The USLE-M lite - A USLE-M variant using Universal Soil Loss Equation factors. *Soil Science Society America Journal.*

Kinnell, P.I.A., and Risse, L.M. (1998). USLE-M: Empirical modeling rainfall erosion through runoff and sediment concentration. *Soil Science Society America Journal* 62, 1667-1672.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., and Yoder, D.C. (1997). Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). *Agric. Hbk.* No. 703. US Dept Agric., Washington, DC.

Williams, J.R. (1975). Sediment-yield prediction with universal equation using runoff energy factor. In “Present and Prospective Technology for Predicting Sediment Yield and Sources”. ARS.S-40, US Gov. Print Office, Washington, D.C., 244-252

Wischmeier,W.C., and Smith, D.D. 1978. Predicting rainfall erosion losses – a guide to conservation planning. *Agric. Hbk.* No. 537. US Dept Agric., Washington, DC.