16 Runoff and Predicting Erosion on Hillslopes within Catchments

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Introduction

Erosion on hillslopes within catchments contributes to a decline in agricultural productivity and produces pollutants that adversely affect the quality of water in rivers, reservoirs and lakes. In many places, sheet, rill and interrill erosion dominate erosion on hillslopes within catchments. 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. Four 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).

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 particles to saltate underwater. 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 loose particles travel with the flow without the aid of raindrop impact. Whether a particle detached by raindrop impact (RD) is transported by RIFT or FT depends on its size, density and the flow conditions. Rill erosion is dominated by Flow Detachment with transport by Flow (FD-FT). The RD-ST, RD-RIFT, RD-FT and FD-FT systems that operate on hillslopes within catchments result in sediment being discharged with flow. As a consequence, runoff is a factor in determining soil loss.

Erosion by Rain-impacted Flow

So-called process-based models like WEPP (Flanagan and Nearing, 1995) and EUROSEM (Morgan et al., 1998) attempt to model the detachment and transport processes explicitly and recognize that runoff is a factor in determining soil loss. In sheet and interrill erosion, RIFT is the major transport system. RD-RIFT tends to control the movement of silt and sand sized material, while RD-FT tends to control the movement of the finer material. Because erosion results from the discharge of this sediment, the equation

\[ q_s = q_w c \]  

(16.1)

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 the erosion rate. RIFT is the major transport system in sheet and interrill erosion.
system that operates in sheet and interrill erosion areas and Kinnell (1993) showed that when RIFT dominated transport of sediment

$$q_{R} = c_{R} f I_{d} u f[h, d]$$  \hspace{1cm} (16.2)$$

where \(q_{R}(p, d)\) is the mass of sediment of size \(p\) discharged per unit width of flow associated with the impacts of drops of size \(d\), \(c_{R}\) is an empirical 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 \((d)\).

As noted above, in rain-impacted flows, RIFT tends to control the movement of silt and sand sized material, while FT tends to control 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. With splash erosion, 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 \((k)\) is given by

$$k_{s} = (1 - H)k_{sm} + H k_{pdl}$$  \hspace{1cm} (16.3)$$

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. Consequently, the erodibility of such a surface is not given by a single value but may range between \(k_{sm,RIFT}\) 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 Predicting Erosion on Hillslopes within Catchments**

Process-based models like WEPP and EUROSEM require a considerable amount of data and it is common for erosion within catchments to be predicted using the Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1978) or the revised version of it (RUSLE, Renard et al., 1997) because they are less data and computationally intensive. While the USLE/RUSLE was not developed for predicting event erosion, it follows that

$$A_{e} = R_{e} K L S C P_{e}$$  \hspace{1cm} (16.5)$$

where \(A_{e}\) is the erosion that takes place during a rainfall event, \(R_{e} = E I_{30}\) (where \(E\) is event rainfall kinetic energy and \(I_{30}\) is the maximum 30-minute rainfall 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 \(P_{e}\) is the soil conservation protection factor that applies during the event. Figure 16.1 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.

As noted above, erosion on hillslopes results from sediment being discharged with flow. Equation 16.1 applies to all situations where sediment is discharged with flowing water. However, models like the 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 Eqn 16.1 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 $I_{E30}$ is a measure of event rainfall intensity. Thus

$$A_e = k \frac{Q_e I_{E30}}{\text{rainfall amount}}$$

(16.6)

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 ($Q_{Re}$) for the event. Consequently,

$$A_e = k \frac{Q_{Re} E_{E30}}{\text{rainfall amount}}$$

(16.7)

Figure 16.1 shows how Eqn 16.7 predicts event erosion for the bare fallow plot at Morris when event runoff is known. The variant of the USLE that uses $Q_{Re} E_{E30}$ 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 five events produced 177 t/ha. The USLE (Fig. 16.1) predicted 177 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 $E_{E30}$. However, it uses USLE factor values for $K$, $L$, $S$, $C$ and $P$ when these should only be used when $R_e = E_{E30}$. $K$, the soil erodibility factor, has units of soil loss per unit erosivity index and must be re-evaluated if $R_e$ is changed from $E_{E30}$. 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 determined for a vegetated area, 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 16.2 shows the relationship between that erosivity index and event soil losses from a cropped plot at Zanesville, OH. 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.

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 a cell with coordinates i, j can be determined using the approach proposed by Desmet and Govers (1996):

$$L_{ij} = \frac{(A_{ij-in} + D^2)^{m+1} - A_{ij-in}^{m+1}}{D^{m+1} E_{E30}^m}$$

(16.8)
where $A_{ij-in}$ 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. Equation 16.8 is an adaptation equation for the $L$ factor for a slope segment developed by Foster and Wischmeier (1974) to the grid cell situation. However, the $L$ factor for a uniform rectangular slope is based on the distance from the onset of runoff (Wischmeier and Smith, 1978). Thus, if no runoff occurs from upslope then

$$L_{ij} = \frac{D^m}{(22.13)^m}$$

(16.9)

the USLE $L$ factor for an area $D$ metres long. Setting $A_{ij-in}$ to zero results in Eqn 16.8 producing the correct result. However, it follows that if the upslope area has a runoff coefficient that lies somewhere between zero and that for the grid cell, $L_{ij}$ should lie somewhere between that given by Eqn 16.8 when $A_{ij-in}$ is zero and $A_{ij-in}$ 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, $L_{ij}$ should be greater than that given when $A_{ij-in}$ is equal to the physical area upslope of the grid cell. This can be achieved by replacing $A_{ij-in}$ by an effective value of $A_{ij-in} (A_{ij-in\text{eff}})$ to give

$$L_{ij} = \frac{(A_{ij-in\text{eff}} + D^2)^{m+1} - A_{ij-in\text{eff}}^{m+1}}{D^{m+2} x_{ij}(22.13)^m}$$

(16.10)

where

$$A_{ij-in\text{eff}} = A_{ij-in} \frac{Q_{C,ij-in}}{Q_{C,ij-all}}$$

(16.11)

and $Q_{C,ij-in}$ is the runoff coefficient for the upslope area and $Q_{C,ij-all}$ is the runoff coefficient for the area including the cell. Figure 16.3 shows how $L_{ij}$ for the outlet cell to a 1 ha area varies with the upslope runoff coefficient when the cell size is 30 m.

The value of $L_{ij}$ produced using Eqn 16.10 only differs significantly from that produced by the Desmet and Govers (1998) approach (Eqn 16.8) when the runoff coefficient of the upslope area ($Q_{C,ij-in}$) is less than that of the cell. Basing the calculation of $A_{ij-in\text{eff}}$ on the runoff coefficient of the cell as an alternative using $Q_{C,ij-all}$ results in greater departures from Eqn 16.8, but produces a value of infinity when the cell is pervious enough to absorb all the rain that falls on it when some runoff enters the cell from upslope. Such rainfall–runoff conditions can occur, but obviously a value of infinity for $L_{ij}$ is inappropriate. Consequently, the combination of Eqns 16.10 and 16.11 has the appropriate characteristics to deal with this situation.
When the USLE-M is applied to grid cells,

\[ A_{e,i,j} = (Q_R E I_{30,i,j} K_{U M e,i,j} L_{U M e,i,j}) \times S C_{U M e,i,j} P_{U M e,i,j} \]  

(16.12)

where the subscript UM indicates factors whose values differ from those of the USLE and the subscript e indicates parameters that vary between rainfall events. When the whole area in which the grid cell occurs is uniform, the USLE-M L factor for the cell with coordinates i, j is given by (Kinnell, 2001)

\[ L_{U M e,i,j} = \frac{Q_{C e,i,j} [A_{i,j} - D^2 m + 1] - Q_{C e,i,j} [A_{i,j} - D^2 m + 1]}{Q_{R e,i,j} \times \text{cell} \ D^m + 2 x_{i,j} [22.13]^m} \]  

(16.13)

For both uniform and non uniform areas, it follows from Eqns 16.10 and 16.11 that

\[ L_{U M e,i,j} = \frac{Q_{C e,i,j} [A_{i,j} - D^2 m + 1] - Q_{C e,i,j} [A_{i,j} - D^2 m + 1]}{Q_{R e,i,j} \times \text{cell} \ D^m + 2 x_{i,j} [22.13]^m} \]  

(16.14)

where

\[ Q_{C e,i,j} \times \text{cell} = [(Q_{C e,i,j} \times D^2) + (Q_{C e,i,j} \times D^2)] / (A_{i,j} - D^2) \]  

(16.15)

Thus, when applied to grid cells or segments in a hillslope, the direct inclusion of runoff as a factor in the USLE-M results in an approach that takes account of temporal and spatial variations in runoff on erosion which is not possible using the USLE or the RUSLE.

**Discussion**

Although, in theory, the USLE-M has the capacity to predict event erosion better than the USLE, that capacity can only be realized if appropriate procedures exist for predicting runoff and values of determining \( K_{U M}, C_{U M} \) and \( P_{U M} \). There are a number of methods for predicting event runoff and it is up to the user to select an appropriate method. The USDA Curve Number approach (USDA, 1972) is commonly used to predict event runoff in water quality models and can be used with the USLE-M. At this time, procedures for determining \( K_{U M}, C_{U M} \) and \( P_{U M} \) have yet to be determined to the same degree as for the USLE. Alternatively, because they are ratios with respect to the soil loss from the bare fallow cultivation up and down the slope condition, it can be suggested that USLE parameter values for \( L, S, C \) and \( P \) can be used with an event erosivity factor other than \( E_{30} \) if the event erosivity factor is applied to predicting erosion from bare fallow with cultivation up and down the slope. Thus,

\[ A_{e} = [Q_R E I_{30} \times K_{U M e} L_{C e} P_{e}] \]  

(16.16)

where \( Q_{RI1} \) 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, may initially appear to be valid. However, although, as shown by Fig. 16.1, the approach takes advantage of predicting erosion better than the USLE on the bare fallow condition, it assumes that an erosion event will occur on a vegetated area whenever there is an erosion event on the bare fallow area and that assumption is not always correct. This can lead to erosion being predicted on vegetated areas for events when there is none (Fig. 16.4). Thus event

**Fig. 16.4.** Relationship between event soil losses predicted by multiplying event soil losses from a nearby bare fallow plot by RUSLE period Soil Loss Ratios (fortnightly C factor values) and event soil losses observed for conventional maize at Clarinda, IA plus 0.0001 t/acre to enable predicted losses to be displayed when observed losses are zero.
erosion can only be predicted appropriately if runoff for the area being eroded is determined and used to calculate the USLE-M event erosivity index in conjunction with the appropriate values of $K_e,UM, C_e,UM$ and $P_e,UM$. However, this is not the case when erosion is being predicted on an annual basis. Under these circumstances,

$$AA = R_{UM} A K_{UM} A L S C A P A \quad (16.17)$$

applies where $R_{UM} A$ is total value of $[Q_{R}EI_{30}]_k$ over the year, $K_{UM} A$ is the associate erodibility factor and $C_A$ and $P_A$ are annual values for the USLE $C$ and $P$ factors respectively. Equation 16.17 takes advantage of the ability of the product of $R_{UM} A$ and $K_{UM} A$ to predict to variation in annual soil better that can be achieved using the $EI_{30}$ index. Procedures exist for determining $K_{UM}$ Values from USLE $K_e$ (Kinnell and Risse, 1998).

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 RIFT is dominant. This is because particles travel 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 erodibilities. 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 USLE, a model that contains no direct consideration of runoff. There are variants of the USLE that do consider erosion to be directly dependent on runoff. One variant is 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-min 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 and procedures exist for determining annual values of $K_{UM}$. However, the approach where USLE $C$ and $P$ factors can be used because soil loss for the bare fallow up and down condition is being predicted using the $Q_{R}EI_{30}$ index only applies when erosion on the vegetated area occurs whenever erosion on the bare fallow also occurs. This condition does not apply on an event basis, but does at the annual time scale.

References


