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The USLE-M and Modeling Erosion Within Catchments

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ABSTRACT

The Universal Soil Loss Equation (USLE) is often used to predict erosion in grid cells. Unfortunately, it is not well suited to this task. A modification of the USLE called the USLE-M can do the task better. Given an adequate ability to predict runoff, the USLE-M predicts event erosion better than the USLE. It also provides a mechanism, which enables the impact of upslope runoff on erosion in grid cells to be modeled. These features are illustrated by data from runoff and soil loss plots and erosion predictions for grid cells in a subcatchment in the Rocky Creek catchment, Queensland, Australia.

INTRODUCTION

The spatial variation in erosion is of interest to land and water quality managers. Erosion occurring in a part of a catchment or watershed has both on site and off site impacts. Changing the land use in one particular area may have not only consequences in that area but in other areas downslope and on the materials carries by runoff to rivers, streams and impoundments (dams, lakes). The Universal Soils Loss Equation (USLE) (Wischmeier and Smith, 1965, 1978) is often used in estimating rainfall erosion within catchments. The Agricultural Non Source Pollution model (AGNPS) (Williams et al., 1975) is one example where this occurs. AGNPS uses the USLE to estimate the amount of sediment that is available to a sediment transport model, which is used to model the movement of sediment and associated pollutants from the sites of erosion across the land to gullies, streams and rivers and then to the outlet of the catchment during a rainfall event. Unfortunately, the USLE was not designed for this sort of use. A modification of the USLE, the USLE-M (Kinnell and Risse, 1998), is an event-based model that is better suited to this task.

The USLE-M

The primary difference between the USLE and the USLE-M is that no explicit consideration of runoff occurs within the USLE erosivity index where as there is an explicit consideration of runoff in the USLE-M erosivity term.

The theory behind the USLE-M erosivity index is based on the concept that event erosion (A_e) is given by the product of runoff amount (Q_e) and the bulk sediment concentration for the event (c_{be});

$$A_e = Q_e \, c_{be} \quad (1)$$

where

$$C_{be} = \frac{\sum_{t=1}^{T} q_t c_t}{Q_e} \quad (2)$$

where T is the total number of time units (e.g. minutes) in an event, q_t is the runoff amount and c_t the sediment concentration measured in each time unit. In the USLE-M it is assumed that c_{be} is dependent on (a) the kinetic energy per unit quantity of rain and (b) a measure of the peak rainfall intensity since the peak rainfall intensity tends to produce the highest sediment concentration and the highest runoff rate during a rainfall event. The USLE erosivity index for a rainfall event is EI_{30}, the product of the total amount of rainfall kinetic energy expended on the ground during the rainfall event and maximum rain intensity recorded using a 30-minute time base. The kinetic energy per unit quantity of rain is given by E divided by the amount of rain that falls during an event (B_e). Thus, if I_{30} is assumed to provide a measure of the impact of event rainfall intensity on c_{be}, the erosivity index for an event (R_e) is given by

$$R_e = Q_e \, I_{30} \, E/B_e \quad (3)$$

Because the runoff ratio (Q_R) is given by

$$Q_R = Q_e/B_e \quad (4)$$

Eq. 3 can be written as

$$R_e = Q_R \, EI_{30} \quad (5)$$

This is known as the $Q_R EI_{30}$ index (Kinnell, 1997). The USLE-M is the version of the USLE that uses the $Q_R EI_{30}$ index as its index of event erosivity:

$$R_{UMe} = Q_R \, EI_{30} \quad (6)$$

Figures 1 and 2 illustrate the gain in using the USLE-M rather than the USLE in predicting event erosion. In Figure 1, event soil losses from a 22.13 m long plot with a slope gradient of 19 % during 10 years (1935-1945) at Arnot (Ithaca), NY, are plotted against the EI_{30} index (Figure 1A) and the $Q_R EI_{30}$ index (Figure 1B) using logarithmic scales. Values for Z(log), the logarithmic form of the Nash-Sutcliffe (1970) model efficiency index (similar to the correlation coefficient) are also shown. In this particular example, the USLE operates at an efficiency of about 54%, the USLE-M at an efficiency of about 77 %.

Figure 2 shows how the efficiency of the two models varies with the hydraulic characteristics of the soil as measured by the gross infiltration ratio for runoff producing events (GIR_{rope}) at 14 locations in the USA and one in Australia. GIR_{rope} is calculated by:

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$$GIR_{rope} = 1 - \frac{\sum_{n=1}^{N} (Q_e)_n}{\sum_{n=1}^{N} (B_e)_n}, Q_e > 0 \quad (7)$$

where N is the number of rainfall events where runoff occurred during the period of measurement. Because this measure ignores events where rain falls but no runoff is produced, it has a lower value than the gross runoff ratio that is based on all rainfall events. Figure 2 shows that the USLE-M operates at an efficiency of about 80 % irrespective of the hydraulic characteristics of the soil at many geographic locations, where as the efficiency of the USLE falls as GIR_{rope} increases. Consequently, there is a gain in efficiency in using the USLE-M in most cases, particularly when the soil can absorb a considerable proportion of the rainfall.

Because the USLE uses empirically derived parameters, changing the basis of the erosivity index means that the values for the soil (K), crop and crop management (C), and the conservation practice (P) factors used in the USLE cannot be used directly in the USLE-M. The equations for determining the soil (K_{UM}) and crop and crop management (C_{UM}) factors from runoff and soil loss plot experiments are:

$$K_{UM} = \frac{\sum_{n=1}^{N} (A_e)_n}{\sum_{n=1}^{N} (Q_R EI_{30})_n} \quad (8)$$

when $L = S = C_{UM} = P_{UM} = 1.0$, and

$$C_{UM} = \frac{\sum_{n=1}^{N} (A_e)_n}{K_{UM} \sum_{n=1}^{N} (Q_R EI_{30})_n} \quad (9)$$

when $L = S = P_{UM} = 1.0$ and $C \neq 1.0$. A similar expression is used to determine P_{UM}. As with the USLE, $C_{UM} = 1.0$ for bare fallow , and $P_{UM} = 1.0$ for cultivation up and down the slope. Since variations in slope length have, in theory, no appreciable impact on runoff, and S values have been developed through observation that variations in slope gradient have no significant impact on runoff when L is held constant (Renard et al, 1997), arguable, the topographic factors used in the USLE (L, S) still apply to USLE-M.

Table 1. Examples of K_{UM} values for soils in the USA

Soil	K_{UM}	K_U	K_{UM}/K_U
Bath	0.0088	0.0031 (1)	2.7
Caribou	0.0536	0.0162 (2)	3.3
Mexico	0.0728	0.0327 (4)	2.2
Monona	0.0737	0.0262 (3)	2.8
Honeye	0.0836	0.0390 (6)	2.1
Grenada	0.0933	0.0667 (8)	1.4
Shelby	0.1228	0.0619 (7)	2.1
Barnes	0.1337	0.0345 (5)	3.8

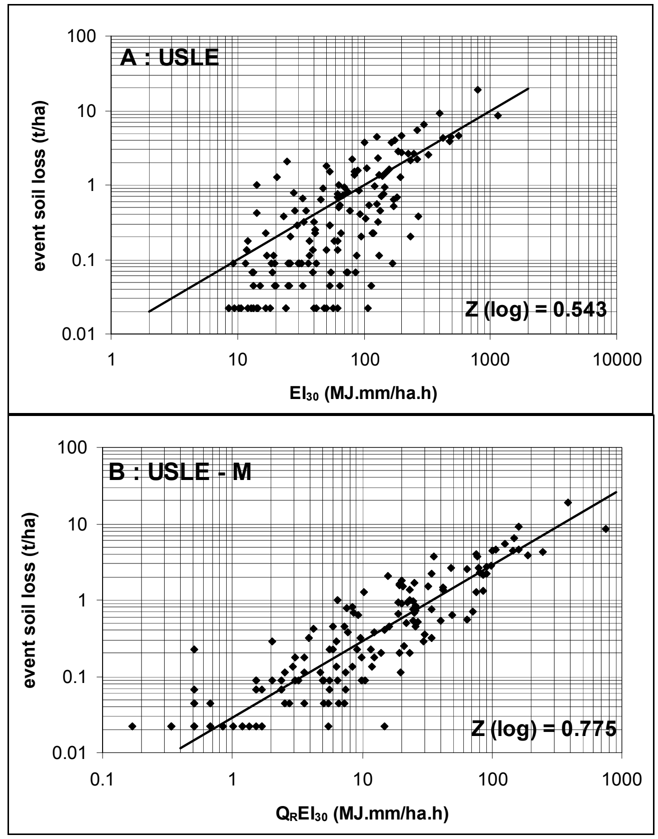

Figure 1. Relationships between event soil losses for plot 8 in experiment 1 at Arnot (Ithaca), NY and the EI_{30} and $Q_R EI_{30}$ indices. The lines represent the relationships generated by (A) the USLE and (B) USLE-M. From Kinnell and Risse (1998).

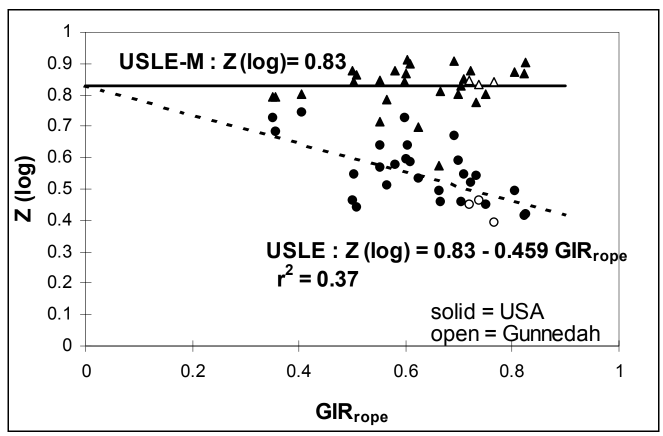

Figure 2. The relationships between Z(log) for the USLE and USLE-M and the gross infiltration ratio for runoff producing events (GIR_{rope}) for bare fallow plots at the 14 USA locations and Gunnedah in Australia. Z(log) values for USLE-M are represented by triangles, those for the USLE by circles. The relationship between Z(log) and GIR_{rope} for USLE-M is indicated by the solid line, that for the USLE by the dashed line. From Kinnell and Risse (1998).

Table 1 provides some examples of K_{UM} values obtained by Kinnell and Risse (1998) when Eq. 8 was used with historic plot data in the USA. Table 2 shows examples of C_{UM} values obtained when Eq. 9 was used. USLE K (K_U) and C (C_U) values are also shown in Tables 1 and 2 respectively. The soils in Table 1 are ordered in increasing value of K_{UM}. Because runoff is a term that appears explicitly in the USLE-M erosivity index (R_{UMe}), the ordering of the soils differs from that for K_U (indicated in the brackets). The K_{UM}/K_U comparison reflects the differences in soil hydraulic properties. A value of 1.0 for the K_{UM}/K_U ratio occurs with an impervious soil. The higher the K_{UM}/K_U ratio, the greater proportion of the rain absorbed by the soil. In the case of the C_{UM} to C_U comparison, the C_{UM}/C_U ratio reflects the impact of the crop on runoff. Corn has little impact on runoff ($C_{UM}/C_U \approx 1.3$) where as grass has a major impact on runoff in some cases (e.g. Bermuda grass at Guthrie, $C_{UM}/C_U = 32$).

The USLE-M and erosion in grid cells

Models like AGNPS use the USLE to predict the spatial variation of erosion in a catchment for an erosion event. Obviously, it follows from Figures 1 and 2 that some gain in accuracy can be achieved by replacing the USLE by the USLE-M in such models if runoff is predicted well. Also, in some cases where AGNPS is linked to a GIS, each cell is considered as a separate hydrologic unit in the context of modelling erosion although it is not considered this way in the context of the sediment transport model. This is not realistic because runoff and erosion tend to increase in the downslope direction. However, the alternative, the L factor based on contributing area (Desmet and Govers, 1996), also has shortcomings. Because it considers runoff directly, it follows that the USLE-M contains a mechanism for addressing the problem.

L factor for applying the USLE-M in grid cells

In the USLE, the L factor for a slope is given by:

$$L = (\lambda/22.13)^m \qquad (10)$$

where λ is the length of the slope as measured along the horizontal projection and m varies with factors such as slope gradient (Wischmeier and Smith, 1965). In the approach adopted in AGNPS, a grid cell may, as noted earlier, be considered to be a single hydrologic unit in the context of predicting soil erosion so that for a cell with coordinates i,j

$$L_{i,j} = (D / 22.13)^m \qquad (11)$$

where D is the length of the cell. In contrast to this, Desmet and Govers (1996) proposed a L factor for use when applying the USLE in grid cells that was based on the specific catchment area concept of Moore and Burch (1986a, b). The specific catchment area is given by the contributing area above a line over which water flows divided by the length of the line. By using this measure in place of slope length in the determination of the slope length factor for irregular hillslopes by Foster and Wischmeier (1974), Desmet and Govers proposed that the L factor for the grid cell with co-ordinates i, j could be described by:

$$L_{i,j} = \frac{(A_{i,j-in} + D^2)^{m+1} - A_{i,j-in}{}^{m+1}}{D^{m+2} x_{i,j}^m (22.13)^m} \qquad (12)$$

where $A_{i,j\text{-}in}$ is the area contributing to flow into the cell with co-ordinates i,j, D is the length of the sides of the grid cell, and $x_{i,j}$ is the width of the contour over which the flow is discharged. $x_{i,j}$ is dependent on flow direction relative to grid cell orientation.

The concept behind Eq. 12 is that the erosion in a grid cell can be determined by subtracting the sediment discharged (erosion per unit area multiplied by area) for the area upslope of the grid cell from the sediment discharged for the area that includes the cell and dividing the result by the area of the cell. If this concept is applied when the USLE-M is used, then

$$L'_{UM_{ei,j}} = \frac{Q_{e.i,j}(A_{i,j-in} D^2)^{m+1} - Q_{e.i,j-in} A_{i,j-in}^{m+1}}{B_e D^{m+2} x_{i,j}^m (22.13)^m} \qquad (13)$$

in

$$A_{e.i,j} = E\, I_{30}\, K_{UMe.i,j}\, L'_{UMe.i,j}\, S_{i,j}\, C_{UMe.i,j}\, P_{UMe.i,j} \qquad (14)$$

where $Q_{e.i,j}$ is the runoff (in units of depth) passing across the lower boundary of the cell i,j and $Q_{e.i,j\text{-}in}$ is the runoff passing across the upper boundary of the cell during an event. Because the erosivity index for a cell when the USLE-M is used is given by the product of E, $I_{30,}$ and the runoff ratio for the cell ($Q_{Re.i,j\text{-}cell}$), not just the product of E and I_{30},

Table 2. Examples of C_{UM} values for crops at various USA locations.

Location	Crop	C_{UM}	C_U	C_{UM}/C_U
Bethany, Missouri	Alfalfa	0.008	0.002	4.0
	Corn	0.674	0.628	1.1
	corn/meadow/wheat	0.188	0.106	1.8
Clarinda, Iowa	Corn	0.634	0.316	2.0
	corn/oats/meadow	0.424	0.168	2.5
Guthrie, Oklahoma	Cotton	2.435	1.357	1.8
	Bermuda grass	0.064	0.002	32.3
	wheat/clover/cotton	0.913	0.344	2.7
LaCrosse, Wisconsin	Corn	0.527	0.469	1.1
Madison, S.Dakota	corn(ploughed)	0.486	0.337	1.4
	corn(mulch till)	0.384	0.250	1.5
Morris, Minnesota	Corn	0.520	0.434	1.2
	meadow/corn/oats	0.046	0.010	4.6

$$A_{e.i,j} = [Q_{Re.ij\text{-}cell} EI_{30}] K_{UMe.i,j}\, LUM_{e.i,j}\, S_{i,j}\, C_{UMe.ij}\, P_{UMe.ij} \quad (15)$$

so that

$$L_{UM\,e.i,j} = \frac{L'_{UM\,e.i,j}}{Q_{Re.i,j\text{-}cell}} \quad (16)$$

Consequently,

$$L_{UM_{e.i,j}} = \frac{Q_{Ce.i,j}(A_{i,j\text{-}in} + D^2)^{m+1} - Q_{Ce.i,j\text{-}in} A_{i,j\text{-}in}^{m+1}}{Q_{Re.i,j\text{-}cell} D^{m+2} x_{i,j}^m (22.13)^m} \quad (17)$$

where $Q_{Ce.i,j} = Q_{e.i,j} / B_e$ and $Q_{Ce.i,j\text{-}in} = Q_{e.i,j\text{-}in} / B_e$. It should be noted that $Q_{Re.i,j\text{-}cell}$ is the ratio of the runoff volume from the cell divided by the volume of rain that falls on the area of the cell. Since runoff from upslope contributes to the volume of runoff from the cell, $Q_{Re.i,j\text{-}cell}$ can take on values greater than 1.0. In contrast, $Q_{Ce.i,j}$ and $Q_{Ce.i,j\text{-}in}$ normally have values that are less than 1.0.

There are two extremes to consider with respect to Eq. 17. The first is when the whole of the eroding area is impervious. In this case, $Q_{Ce.i,j} = Q_{Ce.i,j\text{-}in} = 1$ and $L_{UM.e.i,j}$ equals $L_{i,j}$ as calculated by Eq. 12. The other extreme is when no runoff enters the cell from upslope. Under these circumstances,

$$L_{UM_{e.i,j}} = \frac{Q_{Ce.i,j}(A_{i,j\text{-}in} + D^2)^{m+1}}{Q_{Re.i,j\text{-}cell} D^{m+2} x_{i,j}^m (22.13)^m} \quad (18)$$

while it follows from Eq. 11 that

$$L_{UM_{e.i,j}} = \left(\frac{D}{22.13}\right)^m \quad (19)$$

However, the values of $L_{UMe.i,j}$ generated by Eqs 18 and 19 are not equal and the difference between them increases as the number of cells in the upslope contributing area increases. The discrepancy is eliminated by

$$L_{UM_{e.i,j}} = F \frac{Q_{Ce.i,j}(A_{i,j\text{-}in} + D^2)^{m+1} - Q_{Ce.i,j\text{-}in} A_{i,j\text{-}in}^{m+1}}{Q_{Re.i,j\text{-}cell} D^{m+2} x_{i,j}^m (22.13)^m} \quad (20)$$

when

$$F = Q_{Ce.i,j\text{-}in} + \frac{1 - Q_{Ce.i,j\text{-}in}}{\left(\frac{1 + A_{i,j\text{-}in}}{D^2}\right)^m} \quad (21)$$

Comparison of the USLE and the USLE-M in predicting grid cell erosion

In terms of illustrating of the impact of using the USLE-M in place of the USLE in predicting erosion in grid cells, consider the yellow shaded cells in gridded subscathment shown in Figure 3. This area contains a non-converging westerly flow, which meets with a northerly flow that results from convergence of the flows from the south and southeast. The westerly flow starts in pasture on a 4 % slope before entering an area of wheat. Runoff amounts from the 1 ha

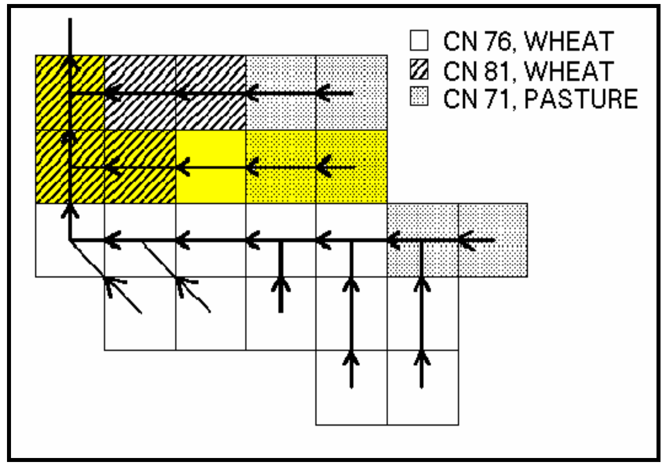

Figure 3. Grid cell representation of a subcatchment in the Rocky Creek catchment, Queensland, Australia, showing flow pathways, areas covered by pasture and wheat, and curve numbers (CN) allocated to particular areas. The catchment outlet is in the northwest corner of the subcatchment and water flows from it in a northerly direction.

cells are modeled using the Curve Number (CN) method. In this case, the pasture is allocated a CN of 71, while most of the wheat area is allocated a CN of 76. The overall shape of the catchment is concave and the zone near the subcatchment outlet is wetter than the rest. This zone is allocated a CN of 81. These CN values reflect the hydrologic nature of the clay soil that exists in the Rocky Creek catchment in Queensland, Australia.

Table 3 shows the L factors for the USLE at the two extremes, L via cell size (Eq. 11) being for the case when the area upslope of the cell contributes no runoff, L via contributing area (Eq. 12) being for the case when the area upslope of the cell is completely impervious. Cell numbering in Table 3 is restricted to the yellow area and is based on a left to right, top to bottom scheme. Consequently, 1 is the outlet cell, 2 is the cell immediately south of it while cells 3 to 6 make up the westerly flow area. In the case of L via cell size (Eq. 11), two values of L occur because of the change in m associated with the change in slope gradient from 3 % to 4 % between cells 3 and 4. L via contributing area (Eq. 12) tends to increase in the westerly direction but the change in m again influences on values of L between the cells 3 and 4. Values for L for the USLE-M (Eq. 20) are also shown in Table 3. These values decrease along the line of flow as a result of Q_R increasing as the flow concentrates in the westerly and northerly directions and the inverse relationship between L_{UMe} and Q_R (Eq. 20). The values shown result from a 55 mm rainfall event.

Table 3 also shows the amounts erosion predicted using the L factor values shown in Table 3. These amounts are associated with the 55 mm rainfall event having an EI_{30} value of 286 MJ.mm $ha^{-1}h^{-1}$, a K_{UM} to K_U ratio of 1.7, and C_{UM} to C_U ratios of 2.0 and 3.0 for wheat and pasture respectively. These values are associated with a clay soil that tends to produce runoff readily and sheep grazed wheat and pastures that do not show major differences in their soil

Table 3. Parameter values for cells in Figure 3.

Cell	1	2	3	4	5	6
slope gradient (%)	3	2	3	4	4	4
m	0.3	0.3	0.3	0.4	0.4	0.4
slope shape	uniform	uniform	concave	convex	concave	convex
crop	wheat	wheat	wheat	wheat	pasture	pasture
curve number (CN)	81	81	81	76	71	71
L_{ij} via Eq. 11	1.57	1.57	1.57	1.83	1.83	1.83
L_{ij} via Eq. 12	5.27	4.90	2.97	3.69	3.00	1.83
$L_{UMe.ij}$ via Eq. 20	0.15	0.18	0.73	1.01	1.19	1.83
$A_{e.ij}$ (L_{ij} via Eq. 11) (t/ha)	0.43	0.30	0.37	0.87	0.53	0.79
$A_{e.ij}$ (L_{ij} via Eq. 12) (t/ha)	1.43	0.93	0.71	1.75	0.88	0.79
$A_{UMe.ij}$ ($L_{UMe.ij}$ via Eq. 20) (t/ha)	0.75	0.50	0.50	0.86	0.52	0.59

hydraulic characteristics.

The erosion amounts associated with L values via Eq. 11 largely reflect variations in slope gradient. The erosion amounts associated with L values via Eq. 12 increase along the line of flow except where m changes between cells 4 and 3. Erosion amounts associated with the USLE-M (L via Eq. 20) show more subtle changes, which are driven by low Q_{R-cell} values in cells 5 and 6 and higher Q_{R-cell} values in cells 1 to 3 in conjunction with the slope gradient effects. This results in the USLE-M predicting lower erosion amounts than associated with L values via Eq. 11 in cells 4 to 6 and higher amounts in cells 1 to 3. Any change in the antecedent soil moisture conditions will alter the erosion predicted via the USLE-M but not the USLE. Consequently, the USLE-M provides an improved modeling capability that is not available with the USLE.

SUMMARY AND CONCLUSION

The USLE is often used to predict erosion in grid cells. It was not designed for this task. As indicated by Eq. 1, runoff is a primary factor in determining rainfall erosion. The failure of the USLE to include direct consideration of runoff in the erosivity index results in an inability to account for the impact of runoff on event erosion and the impact of upslope runoff in erosion in grid cells when the USLE is used within models like AGNPS. A modification of the USLE, the USLE-M (Kinnell and Risse, 1998), includes runoff as a factor in the erosivity index and this enables a L factor (Eq. 20) that depends on runoff from upslope not just area to be used in predicting erosion in grid cells. A comparison of the erosion predicted by the USLE-M using this L factor with the USLE using a L factor based on cell size (Eq. 11), and the L factor proposed by Desmet and Govers (1996) (Eq. 12) illustrates this. Given adequate capacity to predict runoff, the USLE-M approach provides an improved modeling capability that is not available when the USLE is used.

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