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**Integration of Modified Universal Soil Loss Equation
(MUSLE) into a GIS environment to assess soil erosion risk**

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Integration of Modified Universal Soil Loss Equation (MUSLE) into a GIS environment to assess soil erosion risk

Short title: Integration of MUSLE into GIS to assess soil erosion risk

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ABSTRACT

Soil erosion is an important economic and environmental concern throughout the world. In order to assess soil erosion risk and conserve water and soil resources, soil erosion modeling at the watershed scale is urgently needed. This study integrated the Modified Universal Soil Loss Equation (MUSLE) in a Geographic Information System (GIS) framework in the form of a tool called ArcMUSLE, an extension of ArcGIS[®] software, to assist soil and water conservation agencies in soil erosion risk assessment and prioritization of critical areas for soil erosion control practices. With widely available spatial data, this tool can be applied to determine curve numbers, to estimate runoff, peakflow, and soil loss for a rainfall event within a watershed. An application example for a watershed in Black Hawk County, Iowa, USA, is presented.

KEY WORDS: MUSLE; soil erosion; GIS; watershed

INTRODUCTION

Soil erosion is a serious world wide problem due to its adverse economic and environmental impacts. Soil loss in excess of soil production results in soil deterioration and reduced productivity. Sediment and attached pollutants such as nutrients, pesticides, and toxic metals can negatively impact water quality, aquatic habitat, and hydrologic system. As much as 90 percent of the total loss of nitrogen and phosphorus from agricultural watersheds is associated with sediment (Miller *et al.*, 1988). Jones *et al.* (1997) estimated that because of soil erosion the total productivity loss in United States is more than \$25 billion (US \$), and off site loss is more than \$17 billion, which totals about \$100 ha⁻¹ per year. Pimentel *et al.* (1995) estimated that 90% of US cropland is losing soil above the sustainable rate which generally is between 5-12 tons ha⁻¹ per year (metric ton). In Iowa, one of the main agricultural states in the US, with 89% of its land in cropland or pasture, half of the fertile topsoil has been lost during the last 150 years of cultivation and loss of topsoil continues at a rate of about 30 tons ha⁻¹ per year (Pimentel *et al.*, 1995). It is critical to manage soil erosion to protect water resources and maintain land productivity, and ideally, areas most prone to severe erosion should be prioritized for conservation practices or projects.

Soil erosion is a complex process that is related to soil properties, topography, land cover, and human activities. In order to estimate soil erosion and optimize soil conservation management, many soil erosion models have been developed. Lal (2001) and Merritt *et al.* (2003) summarized major soil erosion models such as the Universal Soil Loss Equation (USLE) and the Watershed Erosion Prediction Project (WEPP), and

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the erosion models in the Agricultural Non-Point Source model (AGNPS), the Areal Non-point Source Watershed Environment Response Simulation (ANSWERS) model, and the Chemical Runoff and Erosion from Agricultural Management System model (CREAMS). Within these models, USLE and its derivatives, Revised USLE (RUSLE) and Modified USLE (MUSLE), are the most widely used empirical models because of their minimal data and computation requirements (Lal, 2001; Merritt *et al.*, 2003; Lim *et al.*, 2005; Xu *et al.*, 2008). The USLE and RUSLE models estimate average annual gross erosion as a function of rainfall energy. In MUSLE, the rainfall energy factor is replaced with a runoff factor. This improves the sediment yield prediction, eliminates the need for delivery ratios, and allows the equation to be applied to individual storm events. Sediment yield prediction is improved because runoff is a function of antecedent moisture condition as well as rainfall energy (Williams, 1975a and 1975b; Williams and Berndt, 1977; Neitsch *et al.*, 2005; Kinnell, 2005). However, the application of MUSLE at a watershed scale is a sophisticated data processing procedure and requires professional GIS knowledge and technology. Therefore, we developed a user friendly ArcGIS® tool, named ArcMUSLE, to facilitate soil erosion modeling and soil erosion risk assessment work at watershed scale.

This paper documents the development of the ArcMUSLE tool and its application to a watershed for the determination or prediction of curve number, topographic factor runoff, peak flow, sediment, and sediment delivery based on the input spatial information of elevation, soil, land cover, and rainfall from a given rainfall event. The following

sections are organized as methodology (calculation algorithms), ArcMUSLE development and interfaces introduction, and application example.

METHODOLOGY

Soil erosion is a hydrologically driven process and it depends on sediment being discharged with runoff (Kinnell, 2005). By including the runoff as an independent factor in modeling erosion, MUSLE has an improved accuracy of soil erosion prediction over USLE and RUSLE (Williams, 1975; Williams and Berndt, 1977; Erskine *et al.* 2002; Neitsch *et al.*, 2005; Sadeghi *et al.*, 2007). The MUSLE equation is applicable to the points where overland flow enters the streams and then all those points are summed up to give the total amount of sediment delivered to the stream network within a watershed. In general, MUSLE can be expressed as follows (Williams, 1975a and 1975b):

$$Y = 11.8 \times (Q \times q_p)^{0.56} \times K \times LS \times C \times P \quad (1)$$

where Y is the sediment yield to the stream network in metric tons, Q is the runoff volume from a given rainfall event in m³, q_p is the peak flow rate in m³ s⁻¹, K is the soil erodibility factor which is a soil property available from the Soil Survey Geographic (SSURGO) data, LS is the slope length and gradient factor, C is the cover management factor and can be derived from land cover data, and P is the erosion control practice factor which is a field specific value. The Q, q_p, and LS parameters can be derived from Digital Elevation Model (DEM), land cover, soil, and rainfall data. A detailed explanation of the calculation algorithms for Q, q_p, and LS follows.

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98 *Calculation of Runoff Q*

99 The runoff is calculated based on the widely used Soil Conservation Service (SCS, now
100 Natural Resources Conservation Service, NRCS) curve number method. This method was
101 developed and published in 1954 in the National Engineering Handbook Section 4:
102 Hydrology (NEH-4). Revisions of the book have been made in 1956, 1964, 1965, 1971,
103 1972, 1985, 1993, and 2004. As Ponce and Hawkins (1996) pointed out, the curve
104 number method owes its popularity among hydrology practitioners to its simplicity,
105 predictability, and stability. The theory of the curve number method is that for a given
106 rainfall event, the ratio of runoff depth to rainfall is equal to the ratio of actual retention
107 (the rain not converted to runoff) after runoff begins to the potential maximum retention
108 after runoff begins (NRCS, 2004). It is shown with equation 2.

109
$$\frac{Q_d}{R} = \frac{F}{S} \tag{2}$$

110 where Q_d is runoff depth in mm, R is the event rainfall in mm, F is the actual retention
111 after runoff begins (mm), and S is the potential retention parameter which is related to the
112 soil and land cover conditions of the watershed. When initial abstraction (I_a) is
113 considered, the amount of rainfall available for runoff is $(R - I_a)$. Actual retention is the
114 difference between rainfall and runoff depth ($F = R - Q_d$). An empirical relationship
115 between I_a and S was expressed as $I_a = 0.2S$. After substituting these three equations to
116 equation 2, runoff can be calculated from rainfall and potential maximum retention with
117 the equations:

118
$$Q_d = 25.4 \frac{(R/25.4 - 0.2S)^2}{(R/25.4 + 0.8S)} \quad (\text{if } R \geq 0.2S)$$

$$Q_d = 0 \quad (\text{if } R \leq 0.2S) \quad (3)$$

S is calculated from curve number (CN): $S = 1000/CN - 10$ in inches. In GIS, CN can be derived from soil HSG (hydrologic soil group) classification and land cover type (NRCS, 1986). In other words, equation 3 means that if rainfall is less than initial abstraction, there is no runoff, if rainfall is larger than initial abstraction, runoff depth can be calculated from the rainfall amount and the curve number. After the user specifies the rainfall amount, Q_d will be calculated, then multiplied by the area to get runoff volume Q for each cell.

Calculation of Peak Discharge q_p

The graphical peak discharge method is used to compute peak discharge q_p ($\text{m}^3 \text{s}^{-1}$) (NRCS, 1986):

$$q_p = q_u A Q_d F_p \quad (4)$$

where q_u is the unit peak discharge in $\text{m}^3 \text{s}^{-1} \text{km}^{-2} \text{mm}^{-1}$, A is the drainage area in km^2 , Q_d is the runoff depth in mm, and F_p is the pond and swamp adjustment factor which is the percentage of pond and swamp area over the watershed area. The time of concentration, T_c , is required for the calculation of q_u and is developed by calculating a travel time for sheet flow and a travel time for shallow concentrated flow. Sheet flow is flow over plane surfaces and usually occurs in the headwater of streams. The time of travel for sheet flow (T_{sheet}) of less than 91.4 m is calculated using Manning's kinematic solution:

$$T_{\text{sheet}} = \frac{0.091(nL)^{0.8}}{J^{0.5} S^{0.4}} \quad (5)$$

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where the travel time is in hours, n is the Manning's roughness coefficient, L is the flow path length in meters, s is the slope in percentage and J is the 2-yr, 24-hr rainfall (typical 24-hour duration precipitation with a 2-year return period) in mm which is published by the National Weather Service (NWS). After a maximum of 91.4 m, sheet flow usually becomes shallow concentrated flow and the time of travel for shallow concentrated flow ($T_{shallow}$) is calculated using the following equation for the remainder of the flow path until it flows into a defined channel:

$$T_{shallow} = \frac{3.281 \times L}{3600 \times 16.1345 \times s^{0.5}} \tag{6}$$

where L is the flow path length in meter. This equation is based on Manning's equation and two assumptions for Manning's roughness coefficient (0.05) and hydraulic radius (0.4). Now the two times of travel calculations can be added together to come up with the time of concentration (T) where each drainage way discharges into a stream.

$$T = T_{sheet} + T_{shallow} \tag{7}$$

The unit peak discharge can then be calculated using the following equation:

$$q_u = 10^{(C_0 + C_1 \log T + C_2 (\log T)^2)} \tag{8}$$

Coefficients C_0 , C_1 , and C_2 are available from the Urban Hydrology for Small Watersheds manual (NRCS, 1986). They are determined by rainfall type and the ratio of initial abstraction (I_a) and 2-yr 24-hr rainfall (P).

The peak discharge can then be calculated with eq. 4 as Q_d is available from the previous section and A can be derived directly from DEM data.

Determining LS Factor

The LS factor reflects the effect of topography on soil erosion. Within it, L represents the effect of slope length on erosion and S reflects the influence of slope gradient on erosion (Williams, 1975a; Williams and Berndt, 1977; Lu *et al.*, 2004). The equation (eq. 9) developed by Moore and Burch (1986 a, b) is used to calculate the LS factor in ArcMusle:

$$LS = \left(\frac{A}{22.13}\right)^{0.4} \times \left(\frac{\sin \theta}{0.0896}\right)^{1.3} \quad (9)$$

where A is the product of flow accumulation and cell size, θ is the slope in degrees, both of which are derived from the DEM directly.

ArcMUSLE DEVELOPMENT AND APPLICATION

ArcMUSLE was developed with C# and ArcObjects® as a distributable ArcGIS® extension. It is an integration of the MUSLE algorithm with up-to-date GIS technology. An overview of the data analysis process is shown in Figure 1. It is a raster based spatial analysis applying all the mathematic equations presented in the Algorithms section. Runoff is derived from soil data, land cover, and event rainfall. Peak flow is derived from data on land cover, DEM, and the previously calculated runoff. The LS factor is derived from the DEM. Soil erodibility is a soil property available in SSURGO soil data. The cover management factor is set based on land cover. The practice factor is a field specific value. MUSLE is finally applied to spatially calculate the soil erosion amount for a given rainfall event. User friendly interfaces were designed to facilitate ArcMUSLE usage and Figure 2 shows the three consecutive interfaces. In the first interface, the user needs to define the analysis environment which includes the watershed boundary, analysis

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181 resolution, and working directory. The second user interface is used to choose input
182 spatial data layers such as the DEM, soil, land cover, and 2-year, 24-hour rainfall data
183 and corresponding attribute fields. On the last user interface which is for parameters
184 setting, the user can designate the antecedent soil condition (dry, normal, or wet), the
185 amount of analysis rainfall, and drainage network size. As the P factor value is field
186 specific, a P factor raster layer can be used or a default value of one will be used if field
187 specific data are not available.

188 As mentioned previously, DEM, land cover, soil K factor, soil hydrologic group, and
189 2-year, 24-hour rainfall data are the necessary spatial input data for the model. The Iowa
190 Department of Natural Resources (DNR) compiled all of these spatial data in raster data
191 format for the entire state with a resolution of 30 meters and provided them to the public.
192 Land cover data include attributes on land cover category, C factor, and Manning
193 roughness coefficient n. The C factor value is derived from land cover type. Soil data
194 include attributes on slope, K factor, and HGC. For Iowa soil erosion analysis, users only
195 need to define a watershed boundary and the model can be easily run within ArcGIS®.

196 ArcMUSLE was not compared with measured data for validation purpose in this
197 paper because MUSLE has been widely used and validated in many countries (Williams
198 1975b; Johnson *et al.* 1985; Loch *et al.* 2000; Erskine *et al.* 2002; Blaszczyński 2003;
199 Lim *et al.* 2005; Sadeghi *et al.* 2007). Other equations or algorithms including the curve
200 number method are from NRCS official documents (1986, 2004) and have been used
201 since 1975 (Ponce and Hawkins 1996; Blaszczyński 2003; Zhan and Huang 2004; Mishra
202 *et al.* 2006). Instead, ArcMUSLE was applied to a watershed located in Black Hawk

County, Iowa, with an area of 24.2 km², to demonstrate how the tool can be easily used for effective soil erosion management. According to the Iowa DNR land cover classification of 2002, the majority of the watershed is agriculture land (30% hay, 63% corn or bean production). The Iowa DNR has listed the watershed as an impaired water resource. In order to assist soil and water conservation projects within the watershed, it is necessary to analyze the soil erosion risk and identify critical areas. All the input spatial data are shown in Figure 3. Soil antecedent moisture condition was set as average and the rainfall was set to the typical 24-hour precipitation for two year return period, i.e., 80.3 mm (3.16 inches). After running the model using this specified rainfall amount, the total amount of predicted sediment delivered to waterbodies was 6,669 tons and the total runoff volume was 765,370 m³ for the whole watershed.

Figure 4 illustrates the intermediate data products and analysis results (LS factor, curve number, runoff depth, peak flow, sediment, and sediment delivery) for this hypothetical precipitation event. The relatively steep areas, in the upper part of the watershed, have high LS values. The curve number is based on land cover and hydrologic soil group. When compared with forest and grass lands, lands in corn and soybean production generally have less evapotranspiration and water storage, and thus more runoff. Generally, runoff potential increases from hydrologic soil group A (sand, loamy sand, sandy loam) to D (clay loam, silty clay loam, sandy clay, silty clay or clay). The runoff depth map shows the overland flow which is calculated from the curve number and rainfall amount. The rainfall amount is a constant in this analysis. The pattern in the curve number and runoff depth maps match well with land cover and soil maps. There are

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225 higher curve number values and higher runoff depth for corn and soybean land. Lands
226 with hydrologic group D soil have the highest curve number values and highest runoff
227 depth. Peak flow is derived from six parameters including runoff depth, land cover, 2-
228 year 24-hour rainfall, flow length, drainage area, and slope. The sediment map shows
229 where soil sediment is eroded, the darker areas indicate larger amount of sediment
230 created. When comparing the sediment map with LS factor and runoff depth, in general,
231 the areas with the highest sediment yield are those having high LS factor values and
232 deeper runoff. There are areas that have high LS factor values, such as in the upper third
233 of the watershed, which have shallow runoff depth as the result of having hydrologic soil
234 group B and grass as the land cover. After field verification, corresponding Best
235 Management Practices (BMPs) such as contour farming, filter strips, or conservation
236 tillage can be applied to those areas. The sediment delivery map shows the amount of
237 sediment entering waterbodies, the darker areas indicate larger amount. BMPs such as
238 sediment ponds or wetland restoration to trap sediment before the overland flow enters
239 waterbodies can be applied in these areas. As a conclusion, soil erosion critical areas are
240 identified in the sediment map and sediment delivery maps. The application of suitable
241 BMPs to these areas will improve the efficiency of soil and water conservation projects.

SUMMARY

243 The newly developed ArcMUSLE soil erosion modeling tool and its application to a
244 watershed in Iowa are reported to introduce this tool to the water and soil conservation
245 community. ArcMUSLE applies the MUSLE equation, curve number, and graphical peak
246 discharge methods within an advanced GIS analysis environment. Outputs of the tool

247 include curve number, runoff, peakflow, and soil loss for a rainfall event within a
248 watershed. It can assist the prioritization of critical soil erosion areas and the
249 improvement of water and soil conservation efforts. The ArcMUSLE toolset was
250 originally designed for use in Iowa but with proper input data preprocessing it could be
251 applied in other areas. Further development will include improvement of functionality,
252 such as a curve number setting model that allows the user to specify CN's for different
253 land cover categories.

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326 **Figure Captions**

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328 Figure 1 Flow chart of the ArcMUSLE calculation process

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330 Figure 2 ArcMUSLE's graphical user interfaces. The first is used to set the analysis

331 environment, the second is used to set input layers, and the third one is used to set

332 analysis parameters.

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334 Figure 3 Study watershed location and input data. (Clockwise: location map, land cover,

335 2-year, 24-hour rainfall, hydrologic soil group (HSG), soil K factor, and DEM.

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337 Figure 4 Intermediate data products and analysis results of ArcMUSLE (clockwise: LS

338 factor, CN, runoff depth, peakflow, sediment, and sediment delivery).

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Figure 1 Flow chart of the ArcMUSLE calculation process

ArcMUSLE

Environment | **Inputs** | Parameters | Help

MUSLE Calculation: 1. Analysis Property Setting

$$\text{MUSLE: } Y = 95 \times (Q \times q_p)^{0.56} \times K \times LS \times C \times P$$

(English Unit)

Working directory:

Watershed boundary:

Cell size layer:

Cell size: meters

A

ArcMUSLE

Environment | **Inputs** | Parameters | Help

MUSLE Calculation: 2. Input layers selection

DEM

DEM layer

DEM Z unit: ☐ meter ☒ foot

Rainfall

Rainfall layer

2 year 24 hours event:

Soil

Soil layer

Midslope:

K factor:

HSG:

Land cover / use

land cover layer

LC code:

C factor:

Mannings n:

B

Figure 1 ArcMUSLE’s graphical user interfaces. The first is used to set the analysis environment, the second is used to set input layers, and the third one is used to set analysis parameters.

Figure 3 Study watershed location and input data. Clockwise: location map, land cover, 2-year, 24-hour rainfall, hydrologic soil group (HSG), soil K factor, and DEM.

Figure 4 Intermediate data products and analysis results of ArcMUSLE (clockwise: LS factor, CN, runoff depth, peakflow, sediment, and sediment delivery).