Integration of Modified Universal Soil Loss Equation (MUSLE) into a GIS Framework 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 worldwide 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
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):

\[ Y = 11.8 \times (Q \times q_p^{0.56}) \times K \times LS \times C \times P \]  

where \( Y \) is the sediment yield to the stream network in metric tons, \( Q \) is the runoff
volume from a given rainfall event in \( m^3 \), \( q_p \) is the peak flow rate in \( m^3 \ \text{s}^{-1} \), \( K \) 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.
Calculation of Runoff $Q$

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

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

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

$$Q_d = 25.4 \frac{(R/25.4 - 0.2S)^2}{(R/25.4 + 0.8S)} \quad \text{(if } R \geq 0.2S\text{)}$$
\[ Q_d = 0 \quad \text{(if } R \leq 0.2S) \quad (3) \]

S is calculated from curve number (CN): 
\[ S = \frac{1000}{CN} - 10 \] 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 \( q_p \) \( (m^3 \text{s}^{-1}) \) (NRCS, 1986):

\[ q_p = q_u A Q_d F_p \quad (4) \]

where \( q_u \) is the unit peak discharge in \( m^3 \text{s}^{-1} \text{km}^2 \text{mm}^{-1} \), \( A \) is the drainage area in \( \text{km}^2 \), \( Q_d \) 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, \( T \), 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:

\[ T_{sheet} = \frac{0.091(nL)^{0.8}}{J^{0.5}S^{0.4}} \quad (5) \]
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 (\( T_{\text{shallow}} \)) is calculated using the following equation for the remainder of the flow path until it flows into a defined channel:

\[
T_{\text{shallow}} = \frac{3.281 \times L}{3600 \times 16.1345 \times s^{0.5}} 
\]

(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.

\[
T = T_{\text{sheet}} + T_{\text{shallow}} 
\]

(7)

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

\[
q_u = 10^{(C_0 + C_1 \log T + C_2 (\log T)^2)} 
\]

(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:

\[ LS = \left( \frac{A}{22.13} \right)^{0.4} \times \left( \frac{\sin \theta}{0.0896} \right)^{1.3} \]  

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

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

ArcMUSLE was not compared with measured data for validation purpose in this paper because MUSLE has been widely used and validated in many countries (Williams 1975b; Johnson et al. 1985; Loch et al. 2000; Erskine et al. 2002; Blaszczynski 2003; Lim et al. 2005; Sadeghi et al. 2007). Other equations or algorithms including the curve number method are from NRCS official documents (1986, 2004) and have been used since 1975 (Ponce and Hawkins 1996; Blaszczynski 2003; Zhan and Huang 2004; Mishra 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 run off. 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
higher curve number values and higher runoff depth for corn and soybean land. Lands
with hydrologic group D soil have the highest curve number values and highest runoff
depth. Peak flow is derived from six parameters including runoff depth, land cover, 2-
year 24-hour rainfall, flow length, drainage area, and slope. The sediment map shows
where soil sediment is eroded, the darker areas indicate larger amount of sediment
created. When comparing the sediment map with LS factor and runoff depth, in general,
the areas with the highest sediment yield are those having high LS factor values and
deeper runoff. There are areas that have high LS factor values, such as in the upper third
of the watershed, which have shallow runoff depth as the result of having hydrologic soil
group B and grass as the land cover. After field verification, corresponding Best
Management Practices (BMPs) such as contour farming, filter strips, or conservation
tillage can be applied to those areas. The sediment delivery map shows the amount of
sediment entering waterbodies, the darker areas indicate larger amount. BMPs such as
sediment ponds or wetland restoration to trap sediment before the overland flow enters
waterbodies can be applied in these areas. As a conclusion, soil erosion critical areas are
identified in the sediment map and sediment delivery maps. The application of suitable
BMPs to these areas will improve the efficiency of soil and water conservation projects.

SUMMARY

The newly developed ArcMUSLE soil erosion modeling tool and its application to a
watershed in Iowa are reported to introduce this tool to the water and soil conservation
community. ArcMUSLE applies the MUSLE equation, curve number, and graphical peak
discharge methods within an advanced GIS analysis environment. Outputs of the tool
include curve number, runoff, peakflow, and soil loss for a rainfall event within a watershed. It can assist the prioritization of critical soil erosion areas and the improvement of water and soil conservation efforts. The ArcMUSLE toolset was originally designed for use in Iowa but with proper input data preprocessing it could be applied in other areas. Further development will include improvement of functionality, such as a curve number setting model that allows the user to specify CN’s for different land cover categories.

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Figure Captions

Figure 1 Flow chart of the ArcMUSLE calculation process

Figure 2 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).
Figure 1 Flow chart of the ArcMUSLE calculation process
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MUSLE Calculation: 1. Analysis Property Setting

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

Cancel  Back  Next  Analyze

MUSLE Calculation: 2. Input layers selection

DEM

DEM layer

DEM Z unit

meter  foot

Rainfall

Rainfall layer

2 year 24 hour event

Soil

Soil layer

Midslope

K factor

HSG

Land cover / use

Land cover layer

LC code

C factor

Mannings n

Cancel  Back  Next  Analyze
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.
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