Estimating water erosion and sediment yield with GIS, RUSLE, and SEDD

C. Fernandez, J.Q. Wu, D.K. McCool, and C.O. Stöckle

ABSTRACT: A comprehensive methodology that integrates erosion models, Geographic Information System (GIS) techniques, and a sediment delivery concept for estimating water erosion and sediment delivery at the watershed scale was presented. The method was applied to a typical agricultural watershed in the state of Idaho, which is subject to increasing soil erosion and flooding problems. The Revised Universal Soil Loss Equation (RUSLE) was used to assess mean annual water erosion. The Sediment Delivery Distributed (SEDD) model was adapted to determine sediment transport to perennial streams. The spatial pattern of annual soil erosion and sediment yield was obtained by integrating RUSLE, SEDD, and a raster GIS (ArcView). Required GIS data layers included precipitation, soil characteristics, elevation, and land use. Current cropping and management practices and selected, feasible, future management practices were evaluated to determine their effects on average annual soil loss. Substantial reduction in water erosion can be achieved when future conservation support practices are applied. The integrated approach allows for relatively easy, fast, and cost-effective estimation of spatially distributed soil erosion and sediment delivery. It thus provides a useful and efficient tool for predicting long-term water erosion potential and assessing erosion impacts of various cropping systems and conservation support practices.

Keywords: ArcView GIS, RUSLE, SEDD, sediment delivery, sediment yield, soil erosion

Water erosion is a serious and continuous environmental problem. Rill and interrill erosion, two common forms of water erosion, involve detachment and transport of soil particles from top soil layers, degrading soil quality and reducing the productivity of affected lands. In addition, excessive sedimentation clogs stream channels and increases costs for maintaining water conveyances. Sediment delivered into water bodies may also be a source of contamination, adversely impacting the aquatic biota (Novotny and Olem, 1994). Consequently, the need to quantify the amount of erosion and sediment delivery in a spatially distributed form has become essential at the watershed scale and in the implementation of conservation efforts. Sediment yield from a watershed is an integrated result of all water erosion and transport processes occurring in the entire contributing area (Lane et al., 2000). The total sediment yield thus depends on both erosion at the various sediment sources such as crop, range, and forest lands, and the efficiency of the system to transport the eroded material out of the watershed (USDA-SCS, 1983). Sediment delivery ratio, the ratio of sediment delivered to the stream or watershed outlet to the total erosion from the contributing areas, is a commonly used indicator of the watershed sediment transport efficiency (Dickinson and Collins, 1998).

The potential for soil erosion varies from watershed to watershed depending on the configuration of the watershed (topography, shape), the soil characteristics, the local climatic conditions, and the land use and management practices implemented on the watershed. The Universal Soil Loss Equation (USLE), a plot- or field-scale model, incorporates most of these factors to estimate long-term water erosion from interrill and rill areas (Wischmeier and Smith, 1978). A revised version of this model (RUSLE) further enhanced its capability to predict water erosion by incorporating new information that has become available through the last 40 years of research (Renard et al., 1997). RUSLE, with great acceptance and wide use, is simple and easy to parameterize, and requires less data and time to run than most other models dealing with rill and interrill erosion (Jones et al., 1996).

The combined use of Geographic Information System (GIS) and erosion models has been shown to be an effective approach to estimating the magnitude and distribution of erosion (Mitasova et al., 1996; Molnar and Julien, 1998; Millward and Mersey, 1999; Yitayew et al., 1999). Erosion and spatially distributed sediment delivery in a watershed has been modeled by Ferro and Porto (2000) based on USLE and the travel time concept. This approach was incorporated into a GIS by Jain and Kothyari (2000). GIS facilitates efficient manipulation and display of a large amount of geo-referenced data. More importantly, it allows easy definition of spatial subunits of relatively uniform properties. Hence, with the aid of GIS, erosion and sediment yield modeling can be performed on the individual subunits. The identification of the spatially distributed sediment sources makes possible the implementation of special conservation efforts on these source areas.

The aim of this paper is (i) to present a methodology that combines GIS with RUSLE and a sediment delivery model to estimate the spatial distribution of soil erosion and sediment yield at a watershed scale, and (ii) to demonstrate the use of this methodology by applying it to Lawyers Creek Watershed, a typical watershed in the southern portion of the Idaho panhandle with predominant agricultural land use and subject to increasing soil erosion and flooding problems (U.S. Army Corps of Engineers, 2000).

Methods and Materials

Modeling soil erosion by RUSLE. RUSLE, a functional model derived from the analysis of intensive soil erosion data, has seen wide application in long-term water erosion prediction (Renard et al., 1997). Most efforts linking RUSLE and GIS have been carried

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out within raster GIS. Raster models are cell-based representations of map features, which offer analytical capabilities for continuous data and allow fast processing of map layer overlay operations (ESRI, 1996). In a raster GIS, the mean annual gross soil erosion is calculated at a cell level as the product of six factors

$$A_i = R_i\, K_i\, L_i\, S_i\, C_i\, P_i \tag{1}$$

where:
subscript i = i^{th} cell
A_i = the average annual soil loss per unit area within the cell (t/ha·yr)
R_i = the rainfall-runoff erosivity factor (MJ·mm/ha·h·yr)
K_i = the soil erodibility factor (t·ha·h/ha·MJ·mm)
L_i = the slope length factor
S_i = the slope steepness factor
C_i = the cover management factor
P_i = the conservation support practice factor

L_i, S_i, C_i, and P_i are all dimensionless.

An equivalent R factor (R_{eq}) has been developed for the unique climatic conditions of the Pacific Northwest (PNW) region featuring winter rainy season and cyclic freezing and thawing of soil (USDA-ARS, 2002). R_{eq}, in SI units, is related to the annual precipitation (Pr, mm) in a linear relationship

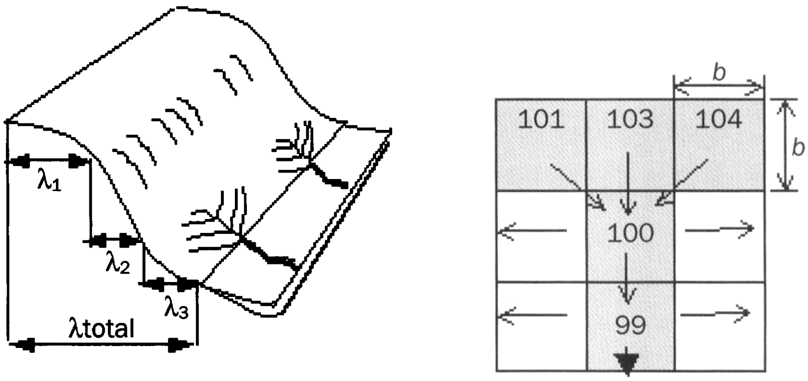
$$R_{eq} = -823.8 + 5.213\, Pr \tag{2}$$

The K factor accounts for the susceptibility of soil particles to detachment and movement by water (Römkens et al., 1997). K values have been estimated for all the vertical layers of the soil series surveyed by the Natural Resources Conservation Service (NRCS) and included in the attribute data file of soil maps (in 7.5-minute quadrangle units, scale 1:24,000) in the Soil Survey Geographic (SSURGO) Database. In SSURGO, K values are expressed as annual averages in English units, which are converted to SI metric units according to Foster et al. (1981).

The L and S factors in RUSLE reflect the effect of topography on erosion. Two automated approaches to estimating the L factor have been suggested by Desmet and Govers (1996) based on the original concepts of Foster and Wischmeier (1974). In the first approach, an irregular slope that may consist of a series of concave, convex, and uniform segments is discretized into uniform segments (Figure 1a). For any segment, e.g., segment j, the L factor, according to Foster and Wischmeier (1974), is

Figure 1

Soil detachment rate affected by a) slope length and b) upslope contributing area. Shown in a) is an irregular slope of length λ (adapted from Renard et al., 1997). In b), the upslope contributing area ($U_{i,j\text{-}in}$) varies from cell to cell, e.g., $U_{i,j\text{-}In} = b \times 4$ for the outlet cell.



a) Irregular slope

b) Upslope contributing area from a DEM

$$L_j = \frac{\lambda_j^{m+1} - \lambda_{j-1}^{m+1}}{(\lambda_j - \lambda_{j-1}) \cdot (22.13)^m} \tag{3}$$

where:
λ_j (m) = slope lengths of segment j
λ_{j-1} (m) = slope lengths of segment j-1
m = slope-length exponent

m values of 0.5 for the PNW region (McCool et al., 1993) and 0.4 to 0.6 for other areas (Moore and Wilson, 1992) have been suggested. 22.13 m (24.20 yd) is the length of a standard erosion plot defined in USLE and RUSLE. In implementing Equation 3 in a 2-D raster GIS, each grid cell is regarded as a slope segment with a uniform slope. The L factor for any cell is now related to its upslope contributing area, i.e., the upslope drainage area from which the water flows into this location (Moore and Wilson, 1992; Desmet and Govers, 1996; Mitasova et al., 1996). Consequently, the slope length λ in Equation 3 is replaced by the upslope contributing area per unit contour width (Figure 1b). For a grid cell with coordinates (i, j), the L factor becomes

$$L_{i,j} = \frac{U_{i,j-out}^{m+1} - U_{i,j-in}^{m+1}}{(U_{i,j-out} - U_{i,j-in}) \cdot (22.13)^m} \tag{4}$$

where:
$U_{i,j\text{-}in}$ = upslope contributing area per unit contour width at the inlet of a grid cell
$U_{i,j\text{-}out}$ = upslope contributing area per unit contour width at the outlet of the grid cell
$U_{i,j\text{-}out}$ = $U_{i,j\text{-}in}$ + a_i/b, where a_i is the area of cell i and b is the cell resolution, further explained after Equation 9.

In the second approach of Desmet and Govers (1996), the equation for soil detachment rate at any point along a slope, originally derived by Foster and Wischmeier (1974), was adapted to estimate the detachment rate of a grid cell in a raster GIS. If the detachment rate at the center of the cell is used, the L factor is

$$L_{i,j} = (m+1)\left(\frac{U_{i,j-out} + U_{i,j-in}}{2 \cdot (22.13)}\right)^m = (m+1)\left(\frac{2 \cdot U_{i,j-in} + b}{2 \cdot 22.13}\right)^m \tag{5}$$

The slope steepness factor S, developed by McCool et al. (1987), accounts for the effect of slope gradient on erosion Equation 6 and 7 calculate the S factor for different slope steepness conditions

$$S = 10.8 \sin\theta_i + 0.03 \qquad \theta_i < 5.14° \tag{6}$$

$$S = 16.8 \sin\theta_i - 0.50 \qquad \theta_i \geq 5.14° \tag{7}$$

where:
θ_i = slope angle (degree) of cell i
5.14° = the slope of a standard USLE plot (tan (5.14°) = 9%).

A different S factor equation in RUSLE was developed for slopes greater than 5.14° in the PNW region based on rill erosion data collected from small grain fields (McCool et al., 1993) as shown in Equation 8. For slopes less than 5.14° in this region, Equation 6 is applicable.

$$S = (\sin \theta_i / \sin [5.14°])^{0.6} = (\sin \theta_i / 0.0896)^{0.6} \quad \theta_i \geq 5.14° \tag{8}$$

GIS technology allows for relatively easy calculation of the S factor based on Digital Elevation Models (DEM). It also allows the calculation of the L factor for rill and interrill erosion through the estimation of the upslope contributing area per unit contour width $U_{i,j\text{-}in}$ by computing flow direction and accumulation. Generally, $U_{i,j\text{-}in}$ is taken as the sum of the grid cells from which water flows into the cell of interest (Mitasova et al., 1996)

$$U_{i,j-in} = \frac{1}{b} \sum_{i=1}^{n_i} \mu_i a_i \tag{9}$$

where:

a_i = area of cell i

n_i = number of cells draining into the cell

μ_i = weight depending on the runoff and infiltration rates of individual cells

b = contour width approximated by the cell resolution.

Mitasova et al. (1996) found it appropriate to use the upslope contributing area approach when cell resolution ranges from 2 to 20 m (6.6 ft to 65.6 ft). If μ_i =1 and $a_i = b^2$, $U_{i,j\text{-}in}$ becomes $n_i \times b$. Figure 1b illustrates how $U_{i,j\text{-}in}$ is estimated in a raster GIS.

In reality, a zone of deposition or concentrated flow would generally occur when a slope becomes long (~120 to 150 m or ~131.2 yd to 164.0 yd). Accordingly, a slope length limit should be imposed to appropriately represent the interrill and rill erosion processes in erosion modeling (McCool et al., 1997). Similarly, in calculating $U_{i,j\text{-}in}$ in a GIS, a limit in the number of cells draining into a given cell should be assumed depending on the cell resolution. For example, for a 30 m × 30 m grid (32.8 yd x 32.8 yd), the limit in the number of cells draining into a given cell may be conservatively set to four (30 m × 4 = 120 m).

The C factor for cultivated lands is calculated primarily based on the information on crop rotations. The calculation can be tedious and is most efficiently performed by the RUSLE software program (version SWCS1.06b Win32, USDA-ARS, 2002). Values of the C factor for other land uses such as rangeland and forest are available from the literature (Haan et al., 1994), which are generally lower than those values for croplands. The P factor for cultivated lands is also calculated with the RUSLE software. P values are determined by the extent of individual conservation practices, such as contouring, strip cropping and terracing, which can also be used in combination. These practices generally decrease the erosive impact of rainfall and runoff (Renard et al., 1997).

Modeling sediment yield using the sediment delivery distributed (SEDD) model. The SEDD model discretizes a watershed into morphological units (areas of defined aspect, length, and steepness) and determines a sediment delivery ratio (SDR) for each unit (Ferro and Porto, 2000). SDR_i, the fraction of the gross soil loss from cell i that actually reaches a continuous stream system, is estimated following Ferro and Minacapilli (1995) as a function of travel time

$$SDR_i = \exp(-\beta\, t_i) \tag{10}$$

where:

t_i = travel time (hr) for cell i

β = basin-specific parameter.

The time for runoff water to travel from one point to another in a watershed is determined by the flow distance and velocity along the flow path (USDA-SCS, 1975; Bao et al., 1997). If the flow path from cell i to the nearest channel traverses N_p cells, then the travel time from that cell is calculated by adding the travel time for each of the N_p cells located along the flow path (Jain and Kothyari, 2000)

$$t_i = \sum_{i=1}^{N_p} \frac{l_i}{v_i} \tag{11}$$

where:

l_i = length of segment i in the flow path (m) and is equal to the length of the side or diagonal of a cell depending on the flow direction in the cell

v_i = flow velocity for the cell (m/s).

Flow velocity of overland flow and shallow channel flow can be estimated from the relationship (Haan et al., 1994, based on information in USDA-SCS-TR-55, 1975)

$$v_i = d_i\, s_i^{1/2} \tag{12}$$

where:

s_i = slope of cell i (m/m)

d_i = a coefficient for cell i dependent on surface roughness characteristics (m/s).

Table 1. Values of d_i (Adapted from Table 3.20, Haan et al., 1994).

Surface	d_i (m/s)
Overland flow	
Forest	0.76
Contour, strip cropped	1.56
Short grass	2.13
Straight row cultivation	2.62
Paved	6.19
Shallow concentrated flow	
Alluvial fans	3.08
Grassed waterways	4.91
Small upland gullies	6.19

The values of coefficient d_i are given in Table 1. To ensure the proper use of Equation 11, a lower limit of velocity for the watershed is generally established by setting the minimum cell slope to a small value (e.g., 0.3% in this study) (Smith and Maidment, 1995).

The basin-specific parameter β depends primarily on watershed morphological data (Ferro, 1997) and can be estimated with an inverse modeling approach. SDR_w, the sediment delivery ratio for a watershed is related to β as a weighted mean of SDR_i values by the following equation

$$SDR_w = \frac{\sum_{i=1}^{N} \exp\left[-\beta\, t_i\right] l_i^{0.5}\, s_i^2\, a_i}{\sum_{i=1}^{N} l_i^{0.5}\, s_i^2\, a_i} \tag{13}$$

where:

N = total number of cells over the watershed

l_i = length of cell i along the flow path

s_i = slope of the cell

a_i = area of the cell.

The SDR_w can be estimated by analyzing field data or through developed relationships for different watersheds or areas. Some of these relationships relate SDR_w to stream order, drainage density, soil type, and the size of watershed (Corbitt, 1990). An example is the simple relationship proposed by Vanoni (1975), which suggests a reduction in sediment delivery ratio (SDR) when drainage area increases, i.e.,

$$SDR_w = k\ (a_w)^{-c} \tag{14}$$

where:

k and c are empirical coefficients, both dimensionless

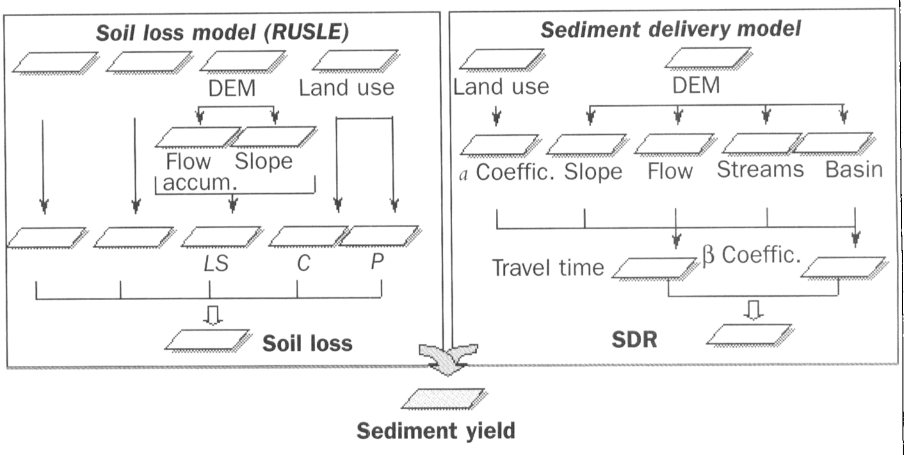
a_w = watershed area (m^2).

Once SDR_w is known, β can be estimated from Equation 13 with a recursive fitting algorithm. After β is determined, SDR_i can be readily computed following Equation 10. Finally, to identify the major source areas of sediment reaching the stream network, the soil erosion and sediment delivery ratio coverages are overlaid. The sediment yield from each grid cell (Y_i, t/yr) is computed as

$$Y_i = SDR_i \cdot A_i \cdot a_i \tag{15}$$

A conceptual diagram showing the integration of all the major procedures described above for estimating the spatially distributed soil loss and sediment delivery is presented in Figure 2.

Figure 2
Integrated procedures to estimate spatially distributed soil erosion and sediment delivery using Geographic Information Systems (GIS).



Application to Lawyers Creek Watershed

Study Site. The Lawyers Creek Watershed covers an area of approximately 544 km^2, 44-km long, and 15-km wide (210 mi^2, 27.34 mi long, and 9.32 mi wide). It is located in the southern portion of the Idaho panhandle, including parts of Lewis and Idaho counties (Figure 3). The watershed comprises a gently rolling plateau bisected by deep narrow canyons (U.S. Army Corps of Engineers, 2000). Land use and channel features have changed compared to historical patterns. More meanders were present in the Lawyers Creek in its natural state than currently. Channel straightening and realignment, and thus the loss of riparian habitat, have occurred through time to gain additional agricultural lands (Fuhrman et al., 1999). Such changes generally increase flood peak discharges and decrease the time to peak, which may in turn lead to significant increase in sediment discharge due to the exponential relationship of sediment transport capacity to water discharge (Fuhrman et al., 1999). Elevated sedimentation tends to reduce the stream channel depth and further increase the flood potential downstream, particularly at the watershed outlet where the city of Kamiah is located (Fuhrman et al., 1999). Kamiah is a rural community within the historical boundaries of the Nez Perce Indian Reservation. Excessive sedimentation during the past has dramatically increased the risk for the city to be severely damaged by future flood events (Fuhrman et al., 1999). The community of Kamiah has been a focus in several previous investigations including a preliminary Federal Interest Study (U.S. Army Corps of Engineers, 2000) and a flood mitigation and river enhancement planning effort (Fuhrman et al., 1999).

The Lawyers Creek watershed is currently dominated by croplands that account for 56% of the total area. Coniferous woodlands cover much of the uppermost watershed and account for 16% of the whole area, while grass and brush are found in the remaining areas (28%) along the main channel and its tributaries. The climate of the area is influenced by westerly winds that bring moist maritime air from the northern Pacific Ocean. Maximum and minimum tempera-

Figure 3
Land use in the Lawyers Creek Watershed.

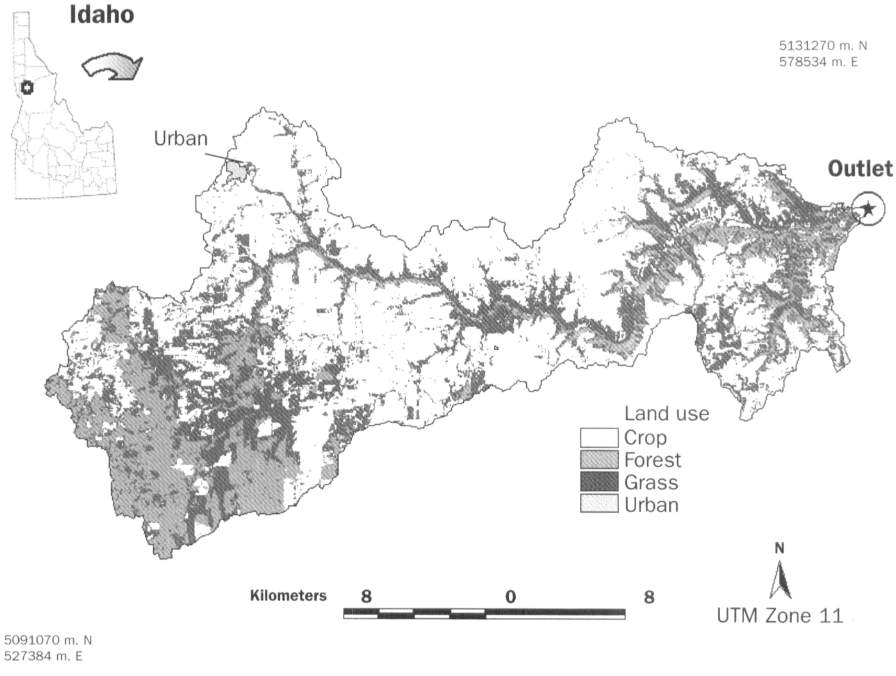


Table 2. Common crop rotations and the *C* values for the Lawyers Creek Watershed.

Rotation	Crop	Year	*C* Value†
1	Winter Wheat	1	0.234
	Spring Barley	2	0.049
	Winter Wheat	3	0.112
	Lentils or Peas	4	0.045
	Rotation C factor		**0.110**
2	Winter Wheat	1	0.259
	Spring Barley or Spring Wheat	2	0.050
	Summer Fallow	3	0.024
	Winter Wheat	4	0.455
	Spring Barley or Spring Wheat	5	0.050
	Spring Canola	6	0.030
	Rotation C factor		**0.145**

† The average *C* value over the entire croplands is 0.128, with an equal weight (50%) assumed for each of the two common rotations.

tures range from -4.4 to 33°C (24.08°F to 91.4°F) (OCS, 2001). Precipitation within the basin ranges from 533 to 737 mm (21.0 to 29.0 in) in accordance with elevation that varies from 358 to 1,742 m (391.5 to 1,905.1 yd).

Soil erosion and sediment delivery modeling. Spatially distributed soil erosion and sediment delivery for current land use and different potential conservation practices were estimated following the integrated RUSLE and SEDD modeling approach described earlier. The watershed was discretized into 30 m by 30 m (resolution of the digital elevation models) grid cells, which were presumed to exhibit homogeneous properties. Spatial data was analyzed using the ArcView raster GIS software (ESRI, 1996). GIS data required to create inputs for RUSLE and the sediment delivery model included digital elevation models, soil characteristics, precipitation, and land use cover. The data files were geo-referenced to the Universal Transverse Mercator (UTM) Zone 11 projection coordinate system according to NAD27. The 1:24,000 digital elevation models data files, derived from standard U.S. Geological Survey (USGS) topographic quadrangle map series, were available through the web site of the Idaho Department of Lands (2001). Soil maps for the Lewis and Idaho Counties were obtained from the SSURGO Database. A digital LANDSAT Thematic Mapper image for July 2000 was used to provide the watershed's current land use information. The digital precipitation data for the study site, generated by using Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al., 1994) was obtained from the PRISM internet web page (OCS, 2001). The precipitation corresponded to the average annual precipitation for the period of 1961-1990, which was regarded as representative of the long-term mean precipitation of the study area.

The *L* factor for each grid cell in the Lawyers Creek Watershed was determined using Equation 5 with the upslope contributing area being calculated for the center position of each cell. The *S* factor was obtained from Equation 6 and 8. To determine the effect of the present cropping and management practices, namely the *C* factor, two most commonly practiced crop rotations at the Lawyers Creek Watershed were modeled with equal weight (Table 2).

In determining the effect of erosion control practices, or the *P* factor, two hypothetical scenarios, contouring alone and contouring in combination with strip-cropping, were compared to the cross-slope farming currently implemented in the Lawyers Creek Watershed. Cross-slope farming involves conducting tillage operations at some slope gradient that is less stringent than contour farming requirements. In general it provides an erosion reduction intermediate to contouring up and down hill operations. Contour farming and strip-cropping are the most feasible practices to be adopted in this area (R. Fredericksen, USDA-NRCS, personal communication, 2001). The *P* factor for the cultivated lands was adjusted according to actual field slopes and a relatively conservative, low ridge height (1.3 to 5.1 cm or 0.51 to 2.01 in) (Table 3). In estimating the *P* factor, RUSLE treats a complex slope consisting of concave and convex segments as an equivalent uniform slope by using a weighted average of the slopes of all the segments. Thus, the same overall *LS* value would be obtained as for the original, complex slope. In this study, all slopes were discretized into equal-length segments (cells) in raster representation, the *P* factor for each cell was therefore estimated with the assumption that the cell is a segment of a uniform slope (the slope of the cell) with a length of 120 m (131.2 yd) (the maximum slope length). In essence, this approach was intended to approximate the *P* factor over an area by the arithmetic average of the *P* values of the individual cells included in the area. A major reason for making such an approximation was that the RUSLE software does not allow automated runs, making it practically impossible to compute the *P* value for all individual cells (roughly 342,600 for the agriculture lands in this study) each with a unique slope. Consequently, the cell slopes were divided

Table 3. *P* values (categorized by hill slope) for the croplands in Lawyers Creek Watershed.

Up-down hill slope	Cross-slope farming†		Contour farming 20% up-down hill slope		Contouring and strip-cropping 10% up-down hill slope	
(%)	Furrow grade	*P* values	Furrow grade	*P* values	Furrow grade	*P* values
0-4	4	1.000	0.6	0.548	0.3	0.440
5-9	5	0.852	1.5	0.544	0.7	0.440
10-14	6	0.828	2.5	0.601	1.2	0.440
15-19	7	0.897	3.5	0.843	1.7	0.550
20-24	8	0.935	4.4	0.910	2.2	0.730
25-29	9	0.961	5.5	0.946	2.7	0.830
30-39	10	0.984	7.2	0.987	3.6	0.920
> 40	12	1.000	9.0	1.000	4.5	0.970

† For cross-slope farming, the furrow grade values were recommended by the USDA-NRCS personnel (T. Ingersoll and R. Sandlund, personal communication, 2002). Ideally, for contouring, and contouring in combination with strip-cropping, the furrows should follow exactly the contour and their grades should be close to zero. In reality, however, furrows could rarely completely conform to the contour. In this study, we assumed a furrow grade of 20% and 10% of the up-down hill slope in the cropland areas for contouring, and contouring and strip-cropping, respectively. All furrow grades are in percent slope.

Table 4. Values of the Revised Universal Soil Loss Equation (RUSLE) factors and predicted soil loss and sediment yield averaged by land use. The P factor for croplands is for cross-slope farming.

Land use	Area (ha)	*R*	*K*	*LS*	*C*	*P*	Soil loss (t/ha·yr)	*SDR*‡	Sediment yield (t/ha·yr)	% total
Forest	9,069	2400	0.050	3.37	0.001	1.00	0.39	0.32	0.18	0.68
Crop	30,833	2200	0.045	1.86	0.128	0.92	21.50	0.26	6.60	94.80
Grass	15,561	2300	0.047	3.43	0.003	1.00	1.10	0.45	0.62	4.50
Urban	109	2220	0.045	1.20	0.030	1.00	3.60	0.14	0.46	0.02
Average†	—	**2280**	**0.046**	**2.54**	**0.072**	**0.96**	**12.30**	**0.32**	**3.87**	—

† **Area-weighted**
‡ **Sediment delivery ratio**

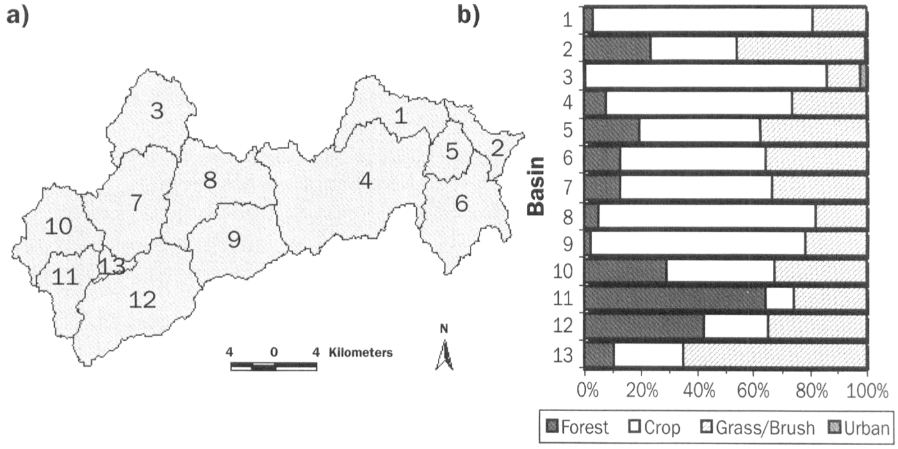
into groups and the *P* values for each group were estimated (Table 3). The values of the *C* and *P* factors for different current land uses are also shown in Table 4.

The standard procedure for delineating stream network and sub-basins from a raster digital elevation models in ArcView (ESRI, 1996), which is based on the eight pour-point algorithm (Jenson and Domingue, 1988), was used. This algorithm identifies the grid cell, out of the eight surrounding cells, towards which water will flow if driven by gravity. Thirteen sub-basins for the Lawyers Creek Watershed were identified (Figure 4). The delineated channel systems were compared to those on the USGS topographic maps as well as those described in the U.S. Army Corps of Engineers (2000) documentation to ensure that they adequately reflect reality.

In order to estimate the β coefficient for each sub-basin, the SDR_w values for these sub-basins were first estimated following Vanoni (1975). An application program (in Borland C++ Builder version 5) was then developed to determine the β values for each sub-basin by approximating the weighted mean of SDR_i to SDR_w. Subsequently, the SDR_i for individual cells (Equation 12) were calculated using the sub-basin-specific β values.

Figure 4

a) Lawyers Creek Watershed discretized into sub-basins and b) land use by sub-basin.



Results and Discussion

Gross soil loss. The average soil erosion in the watershed predicted by RUSLE was 12.3 t/ha·yr, corresponding to 21.5 t/ha·yr for croplands and 0.39 t/ha·yr for forestlands. The spatial distribution of the gross soil erosion is shown in Figure 5a. Based on the severity of erosion, the Lawyers Creek Watershed was divided into three regions: Region 1, low erosion (0-1 t/ha·yr), Region 2, moderate erosion (1-5 t/ha·yr), and Region 3, high erosion (> 5 t/ha·yr). Region 1 includes mostly urban and forested areas located at the higher elevations in the upper Lawyers Creek Watershed. These areas account for 18% of the entire watershed but the RUSLE-predicted soil loss accounts for only 1% of the total amount. Urban areas represent less than 0.2% of the total area of the watershed and have insignificant impact on the total soil erosion (Table 4). Region 2 consists of the deep canyon zone along the lower Lawyers Creek covered mainly by grass and brush. In this region, extensive gully erosion may occur. This area accounts for 29% of the total area and contributes to 2% of the total soil loss. Region 3 includes most of the agricultural zones along both sides of the Lawyers Creek. The area and soil loss account for 53% and 97% of the totals, respectively.

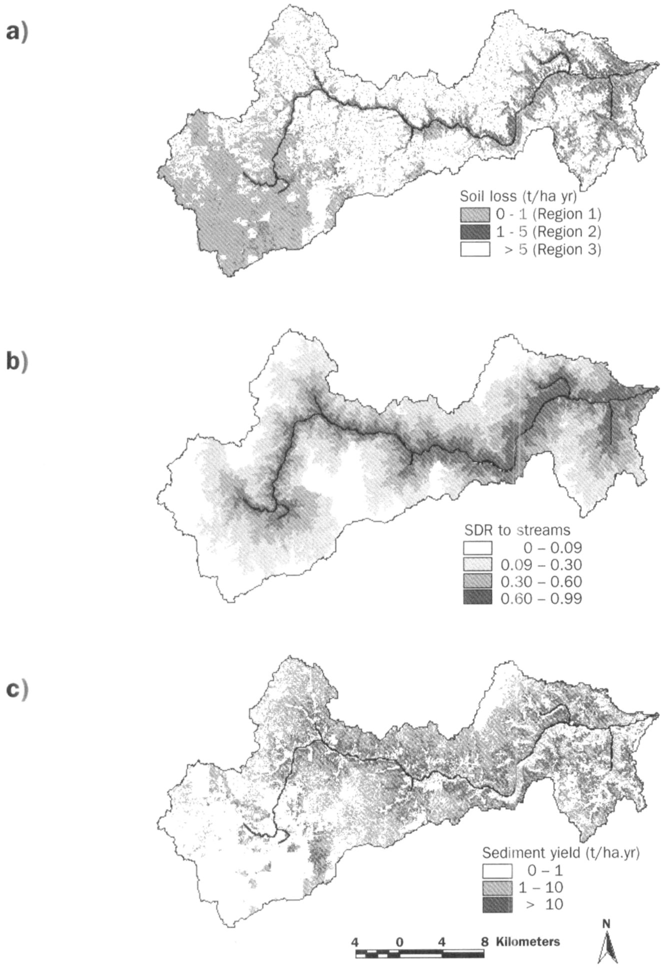
In typical RUSLE applications, gullies, net depositional zones, and areas of vertical walls are eliminated from the study area because RUSLE was not developed for such conditions (Renard et al., 1997). However, the areas of concentrated flow often generate much higher soil loss than estimated for regular slopes by RUSLE, and therefore it may be necessary to include these areas since they reflect a realistic increase in erosion (Mitasova et al., 1999). In fact, it has been a common practice in previous GIS applications to include these special areas for erosion estimation using RUSLE. This approach was also adopted in this study, although the estimated soil loss still represents an underestimate for those special areas in the Lawyers Creek Watershed. The classification of the erosion regions allows a comparison of soil losses from different areas as a result of different land uses and management practices. Millward and Mersey (1999) pointed out that, even though the estimation of erosion tends to be less accurate in locations of high soil loss potential, the identification of these areas where conservation practices are critically needed is of vital importance.

Considering the different scenarios, substantial reduction in soil loss can be achieved when contouring and combined contouring and strip-cropping practices are applied to the croplands, as expected. These scenarios lead to an average erosion reduction in the cultivated lands by 26% and 40%, resulting in annual average soil losses of 15.9 t/ha·yr and

12.8 t/ha·yr, respectively. From the SSURGO database, the soil tolerance limit (T) for the different soil series in the Lawyers Creek Watershed ranges from 2.2 to 11.2 t/ha·yr, averaging 9.7 t/ha·yr for the cultivated lands. The soil tolerance limit represents the maximum rate of annual soil erosion that will permit indefinite maintenance of soil productivity (OTA, 1982). For Lawyers Creek Watershed, even under the best scenario condition (contouring and strip cropping practices), the estimated mean erosion of 12.8 t/ha·yr for the cultivated lands under the best-scenario condition still exceeds the tolerance limits. The erosion results obtained under different scenarios clearly reveal the effectiveness and importance of conservation practices, and also suggest that practices other than those evaluated in this study may be incorporated in the watershed in order to further reduce erosion and sediment delivery. Conservation support practices typically affect erosion by redirecting runoff around the slope (Endale et al., 2000). In the past two decades, farmers in other regions have attempted to control erosion by using cover crops to stabilize the soil from precipitation, and by using reduced-tillage methods to protect bare soil with crop residue. Adopting additional, feasible cropping management and erosion control practices (including reduced-tillage and channel control) and targeting areas with high water erosion potentials should help to further reduce soil loss and sediment yield from the Lawyers Creek Watershed.

Figure 5

a) Gross soil loss predicted by Revised Universal Soil Loss Equation (RUSLE), b) Sediment Delivery Ratio (SDR) determined in relation to the permanent channels by using SEDD, c) Sediment yield obtained by multiplying soil erosion and SDR.



Sediment delivery ratio. The sediment delivery ratio averaged for all grid cells in the Lawyers Creek Watershed was 0.32 (Table 4). Average sediment delivery ratio values were also calculated at the outlets for several sub-basins, which were in good agreement with the sediment delivery ratio values estimated for each sub-basin as a whole by using Vanoni's equation (R^2 = 0.83). The estimation of sediment delivery ratio in a spatially distributed (cell-based) form allows the identification of critical sediment source and delivery areas as well as the site-specific implementation of proper management practices within a watershed. Dai and Tan (1996) note that the sediment delivery ratio values imply the integrated capability of a basin for storing and transporting the eroded soil. An increase in sediment supply at one location in a certain period may be compensated by a decline in other places and times and vice versa. Equation 10 states that the logarithm of SDR_i is inversely proportional to travel time, which is a function of both flow distance and flow velocity. Hence, the further away an area is from the stream, the longer the travel time and the lower the SDR_i; the greater the flow velocity along the flow path the shorter the travel time and the higher the SDR_i, as reflected in the results (Figure 5b, Table 5). It should also be emphasized that any two locations that are equidistant from the outlet may not have the same travel time, i.e., travel time distribution does not follow concentric zones. Flow velocity in reality is controlled by conditions such as surface vegetation type and roughness, and elevation changes over the drainage area. Randhir et al. (2001) found from their field study that longer travel times tended to occur in areas with rougher surfaces (vegetated areas) compared to areas with impervious and open land surfaces.

Unlike soil loss, the SDR_i values obtained for the Lawyers Creek Watershed did not exhibit a clear relation with land uses (Figure 5b). This result may be explained by the argument that sediment delivery ratio (SDR) tends to be affected more by the character of the drainage system than by land uses (Novotny and Chesters, 1989).

Sediment yield. The average annual sediment yield for the Lawyers Creek Watershed, calculated as an average of the sediment yields

Table 5. Values of the Revised Universal Soil Loss Equation (RUSLE) factors, travel time, and predicted soil loss and sediment yield by sub-basin. Within each sub-basin the P factor for croplands is for cross-slope farming.

Sub-basin†	Area (ha)	*R*	*K*	*LS*	*C*	*P*	Travel time (h)	Soil loss (t/ha·yr)	*SDR*‡	Sediment yield (t/ha·yr)	CV (%)
1	3,220	2247	0.045	2.54	0.099	0.93	1.27	16.2	0.25	3.80	262
2	1,560	2340	0.047	4.23	0.041	0.97	0.32	10.5	0.59	5.47	215
3	4,020	2229	0.046	1.36	0.109	0.94	1.31	13.0	0.19	2.44	183
4	11,400	2085	0.046	3.20	0.085	0.94	0.44	14.5	0.48	6.49	191
5	1,530	2367	0.047	4.96	0.057	0.97	0.25	17.7	0.49	7.97	186
6	4,780	2535	0.047	3.90	0.067	0.95	0.66	19.1	0.35	5.33	191
7	5,330	2229	0.046	2.07	0.069	0.96	0.52	9.6	0.35	3.10	224
8	5,350	2214	0.044	2.15	0.098	0.94	0.53	14.3	0.38	5.41	173
9	4,590	2215	0.045	2.17	0.098	0.93	1.27	16.4	0.18	2.82	199
10	3,630	2462	0.046	1.42	0.050	0.98	2.03	6.2	0.13	0.74	284
11	2,600	2415	0.050	1.44	0.014	0.99	1.49	1.8	0.14	0.32	501
12	7,050	2409	0.050	2.25	0.030	0.98	1.20	6.5	0.23	1.34	238
13	520	2229	0.045	1.96	0.033	0.99	0.17	3.9	0.62	2.35	261

† Sub-basin delineation shown in Figure 4.
‡ Sediment delivery ratio.

from all the cells, was 3.9 t/ha·yr (Table 4). Channel erosion was not included in this study. The spatial variation of the sediment yield across the entire watershed is shown in Figure 5c. The sources of sediment in the basin coincide well with agricultural and steep areas. About 95% of the sediments reaching the main channel were produced in the croplands.

Similar patterns of soil loss and sediment delivery could be observed from the analysis made on sub-basins (Table 5). Note that there exist high variations in the predicted sediment yield within each sub-basin. Such high variations are a result of the diverse land uses and the wide range of land slopes and distances to channels within the individual sub-basins. Those sub-basins in which forest and grass are the principal land uses tend to produce both low soil erosion and sediment yield, although some of these sub-basins have a relatively high sediment delivery ratio value. For instance, sub-basin 13, a very small, non-cultivated basin, has a sediment delivery ratio as high as 0.60, and consequently 60% of the detached material is expected to reach the stream. However, because of its very low soil loss rate, this sub-basin has a sediment yield lower than many other sub-basins. Small watersheds generally have less area to accommodate sediment deposition compared to large watersheds. FitzHugh and Mackay (2001) differentiate between transport-limited and source-limited basins. In the former more material can be detached than can be carried away by transport processes, while in the latter the opposite is observed. Sub-basin 13, for example, may be classified as source-limited.

Among all the factors affecting soil loss, the *R*, *K* and *P* factors have relatively uniform values across the whole watershed and their impacts are similar among the sub-basins. However, the *LS* and *C* factors vary considerably among sub-basins and display a positive relation with soil erosion. The major sources generating high erosion are sub-basins 1, 3, 4, 5, 6, 8, and 9 (averaging 16 t/ha·yr) for which either the *LS* or *C* or both factors have high values. On the other hand, in contrast to, e.g., sub-basin 13, basins 3 and 9 have a high soil loss rate and a low sediment delivery ratio (0.18 and 0.19 vs. 0.60). Offsetting of high sediment delivery ratio and low erosion (or low sediment delivery ratio and high erosion) rendered to these sub-basins to produce similar amount of sediment yield.

Summary and Conclusion

A comprehensive approach that combines GIS with RUSLE and SEDD for estimating spatial distributions of soil erosion and sediment delivery at a watershed scale was presented. This method was applied to the Lawyers Creek Watershed, a typical watershed in the southern portion of the Idaho panhandle with predominantly cultivated croplands and subject to increasing erosion and flooding problems.

The proposed method allows for the identification of primary sediment source areas, the spatially varying sediment transport capacity, and ultimately, the sediment yield from each area. As opposed to the traditional "black-box" SDR_w for an entire watershed, the distributed SDR_i values, based on the travel time from individual cells and a basin-specific coefficient, help to clarify those critical areas with high potential for sediment transport. The integrated approach also facilitates fast and efficient assessment of different management alternatives, and thus can serve as a useful tool in natural resources management and planning.

In the case study of the Lawyers Creek Watershed, the croplands exhibit much greater erosion rates and sediment yield than the non-cultivated lands. They contribute 95% of the total sediment load while accounting for only 56% of the total area. A reduction in soil erosion up to 40% can be expected when combined erosion control practices are implemented.

Acknowledgements

We thank Dr. Darin Saul, director of the Center for Environmental Education at Washington State University (WSU), for his effort to help initiate and financially support this study. We also thank the office of USDA-NRCS, Nez Perce, Idaho, for providing pertinent information on the Lawyers Creek Watershed, Roger Nelson from the Biological Systems Department at WSU for his valuable work in developing an optimization code to determine the β coefficient, and the staff in the Remote Sensing and GIS Laboratory at University of Idaho for their help in processing the digital LANDSAT Thematic Mapper image.

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