A GIS-based Estimate of Net Erosion Rate for Semi-arid Watersheds in New Mexico

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Introduction

A characteristic of watersheds in southwest arid and semi-arid regions is that, during rainfall events, large quantities of sediments are transported from upland regions and deposited into the lower reaches of the drainage catchment. The quantity and size of material transported depends on the transport capacity of runoff water. However, if transport capacity is less than the amount of eroded soil material available, then the amount of sediment exceeding the transport capacity gets deposited. If the converse is true, then the amount of sediment load passing the outlet of a catchment is known as sediment yield.

Monitoring of source areas via erosion pins and suspended sediment sampling, and fingerprinting using physical, chemical, or radiological properties are two approaches to evaluating net erosion rates within a watershed. Erosion pins were used by Ludwig *et al*. (2000) along six transects within the Otero Mesa desert grasslands in southern New Mexico to evaluate soil erosion. From 1982-1995, soil surfaces along these transects eroded an average of 0.4 mm/yr. This equates to approximately 5.2 mt/ha/yr at a soil bulk density of 1.3 mt/m^3. Nearing *et al*. (2005) used ^{137}Cesium fallout fingerprinting to evaluate erosion and deposition rates within the 3.7 ha shrub-dominated Lucky Hills sub-watershed within the Walnut Gulch Experimental Watershed near Tombstone, Arizona. Rates ranged from a soil loss of 9.83 mt/ha/yr to a deposition gain of 5.74 mt/ha/yr with an average of 4.27 mt/ha/yr net soil loss for the total watershed. This latter average was similar to soil loss calculated from suspended sediment loads (5.8 mt/ha/yr) obtained via an instrumented fume.

Such studies provide insight into soil erosion and deposition as a phenomenon that directly impacts soil quality, water quality, and overall watershed condition and its subsequent management for beneficial use. *GIS*-based modeling and evaluation is another tool to evaluate and quantify potential soil erosion. A procedure is presented to estimate net soil erosion based on specification of a transport capacity coefficient, which reflects the impact of vegetative cover on eroded soil transport. The methodology is applied to reported soil loss data from the Volcano Hill Wash sub-basin of the Rio Puerco basin to the Rio Grande.

Objective

The objective of this work is to utilize a *GIS* platform to estimate total annual net erosion from a given watershed using available or derivable raster-based attributes. To facilitate this, the procedure and method by Jain *et al.* (2010) is utilized. The Universal Soil Loss Equation (*USLE*), introduced later, estimates gross annual soil loss and is based on five empirical input variables: rainfall erosivity (*R*-factor), soil erodibility (*K*-Factor), length slope (*LS*-factor), land use cropping factor (*C*-Factor), and erosion prevention practice (*P*-factor). *GIS* provides the means to compute soil erosion in individual grids based on the *USLE,* and to determine catchment sediment yield, or net erosion, by using the concept of transport limiting sediment delivery.

Available *GIS*-based Watershed Attributes

In order to better understand sediment transport within a given watershed, foundational information and data must be collected:

Terrain: A Digital Elevation Model (*DEM*) is the most commonly used tool for terrain investigation. The National Elevation Dataset (*NED*) is the primary elevation data product produced and distributed by the United States Geological Survey (*USGS*). The *NED* provides seamless raster elevation data of the conterminous United States. Primary attributes that can be generated from a *DEM* include, but not limited to, slope, flow-path length, flow direction, and upslope contributing area.

Rainfall Erosivity: This metric reflects the erosion capacity of rainfall and is the product of total rainfall energy and the highest 30-minute intensity (EI_{30}). Hastings *et al*. (2005) reported that sediment yield from four micro-watersheds near Los Alamos National Laboratory exhibited a stronger positive correlation to rainfall erosivity than rainfall depth for 14 convective thunderstorms.

Vegetative Index: The Normalized Difference Vegetation Index (*NDVI*) is a thematic image of estimated vegetation density derived using multi-spectral satellite imagery. *NDVI* values range between -1 and +1. Non-vegetated areas typically produce small or slightly negative values, while vegetated areas produce values starting around 0.4 and approaching 1.0 (Shank 2006). *NDVI*-images have been scaled to approximate the crop management factor (*C*-factor) as defined in Eq. 1, or

$$C = e^{-\alpha\left\{\frac{NDVI}{\beta - NDVI}\right\}} \tag{1}$$

where

α and β = unitless parameters that determine the shape of the curve.

The *C*-factor integrates a number of factors that affect erosion including vegetative cover, plant litter, soil surface, and land management. van der Knijff *et al*. (2002) found that an α of 2 and β of 1 gave the most reasonable results when applied to the above relationship.

Soil Erodibility: Soil erodibility depends on organic matter content, soil texture, soil permeability, profile structure, as well as other factors, and is embodied in the soil erodibility factor (*K*-factor) of the *USLE*. The *K*-factor is a measurement of the inherent susceptibility of soil particles to detachment and transport by rainfall and runoff. It typically ranges from 0.10 to 0.45 (Renard *et al.* 1991), wherein a lower value constitutes to a stable soil, and a higher value represents a highly fragile soil. A GIS compatible map of *K*-factors for the State of New Mexico is available from the *NRCS* Soil Survey Geographic (*SSURGO*) database and *NRCS* State Soil Geographic (*STATSGO*) database.

National Hydrography Dataset: The National Hydrography Dataset (*NHD*) is the surface water component of the *USGS* National Map. More specifically, the *NHD* contains a flow network (flow-lines) that allows for tracing water downstream or upstream.

Materials and Methods

Detailed and supplemental information for materials and methods described herein, including internet sources for downloads, may be found in Gallegos (2012).

Digital Elevation Models: *DEM* datasets for New Mexico were uploaded from the *USGS* National Elevation Dataset (*NED*) website (http://ned.usgs.gov/ned/). A 10-m resolution *DEM* raster for each county was acquired for watershed specific calculations.

Rainfall Erosivity: A raster grid of the *R*-factor is available based on a digitized USDA iso-erodent map of the US (http://invest.ecoinformatics.org/shared/Erosivity-US.zip/). A statewide raster for New Mexico was clipped from this grid. The resolution is low; however, it is currently the only available GIS-compatible dataset.

SSURGO and *STATSGO* Soil Datasets: *ArcGIS*® shapefile data was uploaded from the *NRCS* web site (http://soils.usda.gov/). With the uploaded soil data a complete countywide database was generated focusing primarily on the highly detailed *SSURGO* data and filling in the missing data locations with the less detailed *STATSGO* data. The result was a raster dataset of the *K*-factor.

NDVI: A *NDVI* raster layer based on a maximum seasonal *NDVI* average of 16 years of accumulated data for New Mexico (Bulut, 2011) was utilized to evaluate the *C*-factor used in the *USLE* via Eq. 1. An α of 2 and β of 1 were used (van der Knijff *et al*. 2002). The resultant statewide map of cropping factor ranged between 0.09 (low soil loss potential) and 0.82 (high soil loss potential).

National Hydrography Dataset: *NHD* high resolution (1:24,000-scale) topographic mapping data was uploaded from a specialized hydrography *USGS* portal (http://nhd.usgs.gov/).

Derived Watershed Attributes

All watershed characteristics calculations were performed using *ArcGIS*® coupled with the extensional program *Arc Hydro*. For basic characteristics such as delineating a given watershed boundary; calculating a watershed's area, slope, flow direction, flow accumulation, and stream linkage; and sub-watershed delineation, the *Arc Hydro* program extension calculates and generates raster grid and shapefile data.

Length-Slope Factor (*LS*-Factor): For a given watershed, a 2-dimensional *LS*-factor raster grid was developed using the TauDEM (Terrain Analysis Using Digital Elevation Models) *ArcGIS*® extension based on a *D-inflinity* flow direction and upland contributing area, or

$$LS = \left\{\frac{A}{22.13}\right\}^{0.4} \left\{\frac{S}{0.0896}\right\}^{0.6} \tag{2}$$

where A is the specific catchment area per contour length (m^2/m) and S is the slope (^{o}). A 2-dimensional *LS*-factor accounts for flow accumulation convergence (Moore and Burch, 1986).

Watershed Net Soil Erosion

The eroded sediment from each watershed follows a defined drainage path for a particular cell to the catchment outlet as shown in Figure 1. The sediment outflow from each cell is equal to the soil erosion in the cell plus the contribution from upstream cells, if transport capacity is greater than this sum. However, if transport capacity is less than the sum of soil erosion in the cell and the contribution from upstream cells, the amount of sediment exceeding the transport capacity gets deposited in the cell and the sediment load equal to transport capacity is discharged to next downstream cell.

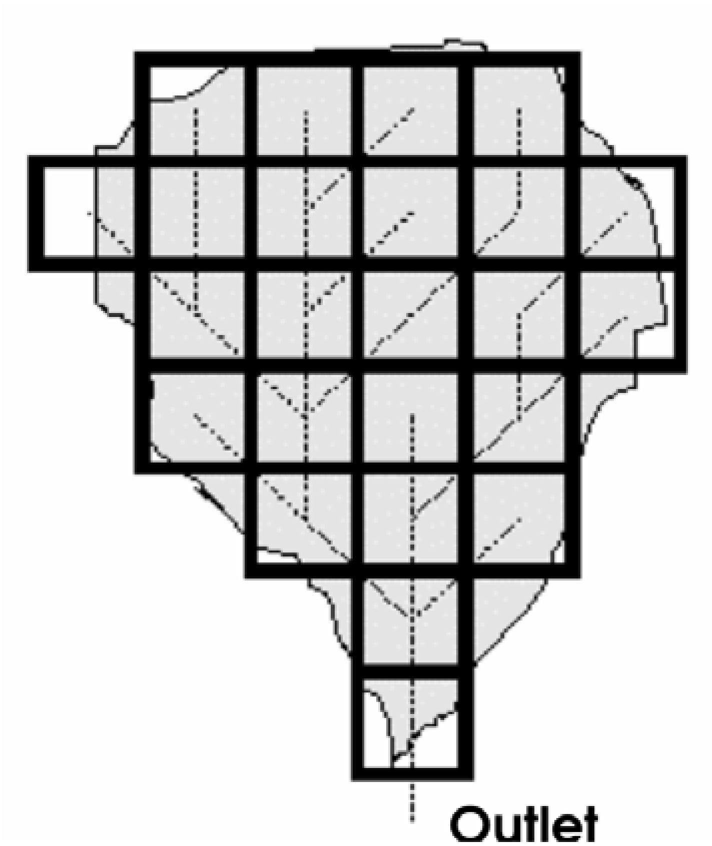

Figure 1: Schematic showing discretized grid cells in a catchment (Jain *et al.*, 2005).

The mean annual sediment transport capacity (*TC*) is computed using a relationship based on catchment physiographic parameters, such as soil erodibility, upslope contributing area, and slope gradient (Verstraeten *et al.*, 2007) as given below:

$$TC_i = K_{TC} R_i K_i A_i^m S_i^n \tag{3}$$

where TC_i is the transport capacity (Mt/ha/yr) of cell i, K_{TC} is the transport capacity coefficient (reflecting the vegetation impact on the transport capacity), R is the rainfall erosivity factor (MJ mm ha^{-1} hr^{-1} yr^{-1}), K_i is soil erodibility (Mt ha h ha^{-1} MJ^{-1} mm^{-1}), A_i is the upslope contributing area per unit of contour length for cell i (m^2/m), S_i is the slope gradient of cell i (m/m), and m and n are empirical or theoretical derived exponents. Prosser and Rustomji (2000) made a review of flume, laboratory plot, and field plot data and found that the median value is 1.4 for both exponents. Based on their review, values of $1.0 \leq m \leq 1.8$ and $0.9 \leq n \leq 1.8$ are recommended for use in sediment transport modeling. However, there was no strong evidence for one exponent to outweigh the other.

Eroded sediment is routed along the runoff paths towards the outlet taking into account the local transport capacity, TC_i of each pixel. If the local TC is smaller than the sediment flux, then sediment deposition occurs. This approach assumes that sediment transport is not necessarily restricted to a transport limited system. If TC is higher than the sediment flux, then sediment transport will be supply limited. For the grid-based discretization system adopted herein, transport limited accumulation can be computed as (Jain *et al.*, 2010):

$$T_{out_i} = min\left(SE_i + \sum T_{in_i}, TC_i\right) \tag{4}$$

$$D_i = SE_i + \sum T_{in_i} - T_{out_i} \tag{5}$$

where SE_i is the annual gross soil erosion in cell i, T_{in_i} is the sediment inflow in cell i from upstream cells, T_{out_i} is the sediment outflow from the cell i, and D_i is the deposition within cell i. All variables have units of Mt/ha/yr. An estimation of the annual gross soil erosion for a grid (or cell) is expressed by the *USLE* as

$$SE_i = R_i K_i LS_i C_i P_i \tag{6}$$

where R_i is the rainfall erosivity factor (MJ mm ha^{-1} hr^{-1} yr^{-1}), K_i is the soil erodibility factor (Mt ha h ha^{-1} MJ^{-1} mm^{-1}), LS_i represents a 2-dimensional length slope topographic factor (unitless), C_i is a cover-management factor (unitless), and P_i is the support practice factor (unitless). The latter factor is generally assumed to be unity for cell *i*.

Using Eqs. 3-6 results in different maps of erosion, sediment transport, and sediment deposition rates, whereby a distinction can be made between gross erosion, net erosion, and sediment deposition. With additional *ArcGIS*® processing within spatial analyst, different values of total gross and net erosion and total sediment deposition can be defined as follows:

$$Total\ Gross\ Erosion = \sum SE_i \tag{7}$$

$$Net\ Erosion\ (NE_i) = SE_i - D_i \tag{8}$$

$$Total\ Net\ Erosion = \sum NE_i \tag{9}$$

A low value of the transport coefficient, K_{TC}, indicates a strong influence of vegetative cover on reduction of transport capacity (Jain *et al.*, 2010); thus, resulting in lower total net erosion flux within a given watershed. Jain and Das (2010) coupled the transport coefficient, K_{TC}, to the vegetative status in a watershed by hypothesizing it as an exponential function of the *NDVI*, or

$$K_{TC} = \beta * exp\left[\frac{-NDVI}{1-NDVI}\right] \tag{10}$$

where β is a scaling factor determined through calibration of observed sediment yield.

Application of Method

To use the concept of transport limited accumulation to evaluate annual net soil erosion for a given watershed requires that a transport coefficient, K_{TC}, be specified, based on calibration of observed data or simply an engineering assumption based on professional judgment. Specific watershed soil erosion data for the State of New Mexico is limited. However, the Volcano Hill Wash sub-basin of the Rio Puerco basin to the Rio Grande was evaluated for erosion and sediment yield over a period of three years by Gellis *et al.* (2001). Figure 2 delineates the location of this 930 ha watershed. Note that while the Rio Puerco does not contribute significantly to the average annual runoff of the Rio Grande at its confluence, it does heavily impact the sediment burden to the Rio Grande due to its high average annual suspended sediment concentration.

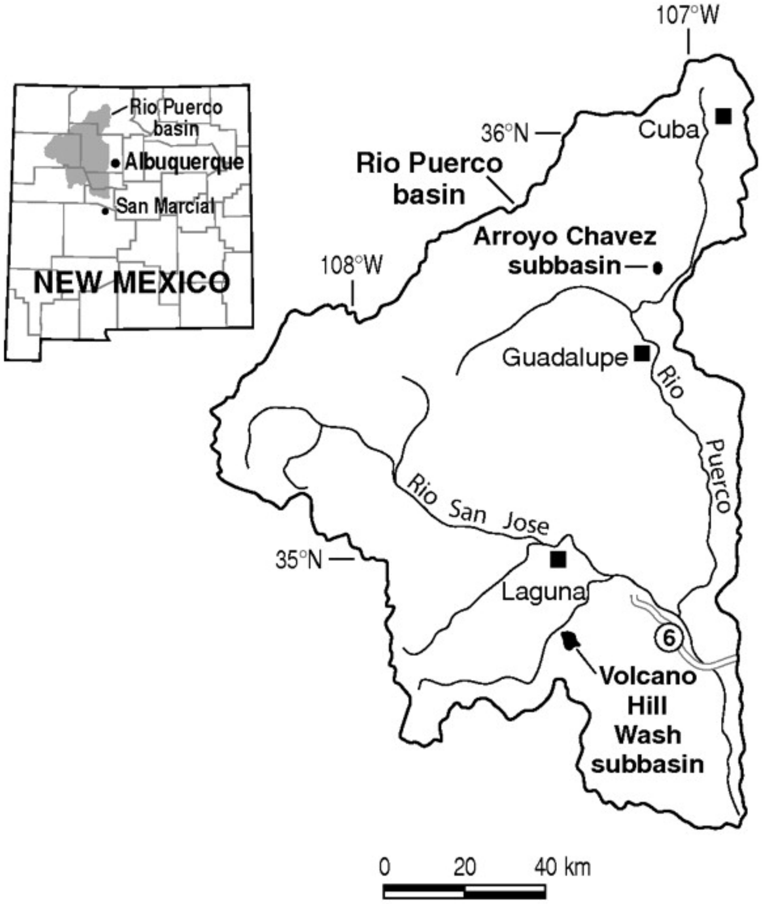

Figure 2: Volcano Hill Wash Sub-basin (Gellis *et al.* (2001).

The average annual sediment yield based on streamflow and suspended sediment measurements at gaging stations for water years 1996-1998 was 4.05 Mt/ha/yr. Upland erosion from sediment dams and traps throughout the basin's five geomorphic surfaces collected over a period of 797 days totaled 3630 Mt. This equates to an upland erosion of 1.79 Mt/ha/yr based on the reported total contributing area of the geomorphic units and duration of study. As the authors point out, the difference between measured estimates of sediment yield and upland erosion (unaccounted sediment) may be contributions of sediment from bed erosion and bank erosion, or sources of upland erosion not measured by sediment traps and dams.

The total net erosion rate was estimated for the Volcano Hill Wash sub-basin using the limited accumulation-based algorithms outlined in Eqs. 3-9 and clipped statewide rasters developed for R, K, C, and S. The upland contributing area raster and 2-dimensional LS-factor raster were evaluated based on the watershed *DEM*. Watershed *USLE* average attributes were as follows: R = 340 MJ mm ha^{-1} hr^{-1} yr^{-1}, K = 0.31 Mt ha hr ha^{-1} MJ^{-1} mm^{-1}, C = 0.46, and LS = 0.94. The average watershed slope was S = 0.13 m/m. The support practice factor (P) was taken as 1.0. The transport coefficient, K_{TC}, was then manually adjusted until a reasonable match of the Gellis *et al.* (2001) upland erosion data was realized. A K_{TC} of 2.0 x 10^{-8} gave a net soil erosion of 1.69 Mt/ha/yr.

Discussion

The calculated net soil erosion rate depends upon a number of inputs.

NDVI: The *NDVI* metric upon which the *C*-factor raster is estimated via Eq. 1 was based on a sixteen-year average of the maximum growing season vegetative index. Selection of an appropriate *C*-factor raster directly impacts the cell i gross soil erosion rate via Eq. 6 and indirectly the cell *i* net soil erosion through the transport limited accumulation of Eqs. 4, 5, and 8. The maximum NDVI, or lowest erosive potential, was selected to correspond with the monsoonal precipitation period of high rainfall erosivity, or high erosive potential. However, the available *R*-factor raster employed herein is an annual average and of low resolution.

LS-factor: The *LS*-factor decreases when estimated with upslope contributing area as compared with the 1-dimensional *LS*-factor (Rodriguez and Suárez, 2010). The resultant annual upland soil erosion estimate would decrease based on Eq.6. The choice of topographic factor would affect the magnitude of the estimated K_{TC}. This effect was not evaluated herein.

K-factor: The *NRCS* soil data sets specify two soil erodibility factors for each soil component layer: *KFFACT* and *KFACT*. The latter is described as a soil erodibility factor which is adjusted for the effect of rock fragments. Interspersed rock fragments provide armoring and significantly reduce soil detachment. The *K*-factor raster used herein was developed from the un-adjusted *KFFACT* data.

Ogungbade (2012) implemented this method for eight sub-watersheds within the Walnut Gulch Experimental Watershed (*WGEW*) in southeastern Arizona. A 1-dimensional LS factor, however, was used along with a constant value for the *R*-factor and *C*-factor for all sub-watersheds (*versus* pixel by pixel values based on raster grids). Final estimates of K_{TC} were evaluated by calibrating the modeled sediment yield with reported average annual sediment yield determined from stock pond sediment accumulation (Nichols, 2006). Although these sub-watersheds had similar vegetation cover characteristics, a single value of K_{TC} could not be determined for the set of 8 sub-watersheds. Calibrated K_{TC} ranged from approximately 10^{-5} to 10^{-3}.

Recall that this coefficient reflects the impact of vegetative cover on reduction of transport capacity within the watershed. The analysis herein does show that an order of magnitude increase in the specification of K_{TC} does result in an order of magnitude increase in calculated net soil erosion. Ritchie *et al.* (2005) observed, however, that vegetative cover was not related to soil redistribution at the aforementioned Lucky Hills sub-watershed within the *WGEW*. Cover within the shrub-dominated landscape was estimated at 26%; such low coverage did not appear to influence or capture transporting soils. Additionally, soil erosion rates were significantly correlated to the percent of rock fragments in the surface soil layer, with erosion decreasing as rock fragments increased.

In summary, careful specification and selection of the input variables based on the specifics of each watershed are needed as the calculated net erosion rate may be highly sensitive to one or more variables expressed in Eqs. 3 and 6. A sensitivity analysis is currently ongoing for selected watersheds.

Conclusion

Although only one example is provided herein, the method used is easily applied within an *ArcGIS*® environment to analyze similar sediment transport data, where available, and develop a database of K_{TC} values for semi-arid watersheds. Evaluation of K_{TC} may lead to better understanding of sediment transport data, where available, for rangeland watersheds with similar characteristics to that of the Volcano Hill Wash sub-basin and the *WGEW*. Additionally, an analysis of soil erosion risk as formulated by Bulut (2011) coupled with a net erosion estimate, based on the concepts and framework presented, could provide valuable information for local Natural Resources Conservation Service (*NRCS*) districts within the State of New Mexico involved in soil erosion management issues.

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