

A GIS-based Hydraulic Bulking Factor Map for New Mexico

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Abstract In this study, sediment loading and clogging potential were evaluated based on a physiographic and hydrologic perspective for eight small semi-arid watersheds within New Mexico. Attributes related to drainage and sediment load were characterized using an *ArcGIS*[®] software-based approach. An in-depth terrain analysis coupled with land cover, precipitation, soil, and hydrography raster datasets provided characterization of key watershed attributes. Associated raster maps of derived attributes were generated in addition to watershed peak flow and runoff. With this composite data a bulking factor, or ratio of total flow with sediments to clean water flow, was estimated. For engineering design, the bulking factor provides for an increased hydraulic capacity for culvert sizing under sediment load. Significant trends and correlations were evident and supported by literature, thus offering the potential for the development and verification of a statewide bulking factor map and ultimately an engineering design factor for drainage structures.

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 design of hydraulic structures (bridge or culvert) that intersect a perennial or ephemeral waterway requires the engineer to carefully consider the implications of such phenomena. Failure to properly assess a location in terms of sediment load may result in poorly designed structures.

In this study, eight small watersheds within New Mexico were characterized for various attributes related to drainage and sediment load using an *ArcGIS*[®] software-based approach. An in-depth terrain analysis based on a Digital Elevation Model (*DEM*) coupled with land cover, precipitation, soil, and hydrography raster datasets provided characterization of key watershed attributes, such as area, slope gradient, slope-length, channel slope, total flow length, drainage density, drainage concavity, soil hydrologic group, soil erodibility, and cropping management factor.

Associated raster maps of derived attributes were generated. In addition, the Hydraulic Engineering Center-Hydrologic Modeling System (*HEC-HMS*) model coupled with *ArcGIS*[®] and the *TR-55 SCS* Curve Number method was used to estimate peak flow and runoff volume for a 100-yr, 24-hr design storm. With this composite data a bulking factor, or ratio of total flow with sediments to clean water flow, was estimated using the Modified Universal Soil Loss Equation (*MUSLE*) and the procedures proposed by Mussetter Engineering, Inc. (MEI 2008). Increased hydraulic capacity must be provided for culvert sizing under sediment load. Therefore, a preliminary statewide map of bulking factor was generated based on a multi-linear regressed correlation using various watershed attributes established for the eight study watersheds.

Soil Erosion Modeling via *MUSLE*

MUSLE was developed based on limited data for single storm sediment yield in Texas and the southwestern United States and is used only on small watersheds. The *MUSLE* equation is as follows (Williams 1975):

$$Y_s = \alpha(Qq)^\beta K L S C P \quad (\text{Eq.1})$$

where:

Y_s = single storm sediment yield (tons)

α = region specific calibration factor

β = region specific calibration factor

Q = storm runoff volume (acre-ft)

q = peak discharge (cfs)

K = soil erodibility factor

L = slope length factor

S = slope steepness factor

C = cover-management factor

P = support practice factor.

MUSLE in its simplicity has direct conceptual and physical relevance of its factors. However, the model is empirical and does not consider all physical factors affecting sediment yield (Williams, 1975).

Available *GIS*-based Watershed Attributes

In order to better understand sediment loading 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 slope, aspect, plan and profile curvature, flow-path length, and upslope contributing area.

Land Cover and Vegetative Index: Land cover (*LC*) composition and change are important aspects for investigation of sediment transport in relation to soil stability and erodibility. *LC* data is available through the *USGS* National Land Cover Database (*NLCD*). *NLCD* is a detailed land surface reference based on Landsat satellite images. It provides precise data rendering of spatial boundaries between 16 classified *LC* types.

Other *LC* related data includes the Normalized Difference Vegetation Index (*NDVI*), which 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) defined in Eq. 1, or

$$C = e^{-\alpha \left\{ \frac{NDVI}{\beta - NDVI} \right\}} \quad (\text{Eq.2})$$

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 Eq. 2.

Soil Erodibility and Hydrologic Group: 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 soil loss equations and the National Resources Conservation Service (*NRCS*) Hydrologic Soil Group (*HSG*) classifications. 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.

The *HSG* classification is a *NRCS* generated classification system in which soils are categorized based on its runoff potential. The *NRCS* Curve Number Method (*CN*) uses *HSG* classes for computation of runoff. Hydrologic soil groups are based on estimates of runoff potential of fully saturated soils that are not protected by vegetation and subject to precipitation from long-duration storms. Soils in the United States are assigned to four groups (A, B, C, and D) and three dual classes (A/D, B/D, and C/D).

Precipitation: Rainfall intensity and amount defines the aggressiveness of rain to cause soil erosion. The National Oceanic and Atmospheric Administration (*NOAA*) National Weather Service (*NWC*) precipitation frequency estimates for the semiarid southwestern United States are available via the Precipitation Frequency Data Server

(*PFDS*). Based on specific storm durations the web server extracts frequency and confidence limit estimates and provides two basic types of output: Depth-Duration-Frequency (*DDF*) and Intensity-Duration-Frequency (*IDF*).

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. Nationwide seamless *NHD* data is available based on high resolution 1:24,000-scale topographic mapping and medium resolution 1:100,000-scale topographic mapping.

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 and Land Cover: *DEM* datasets for New Mexico including both 10-m and 30-m resolutions were uploaded from the *USGS* National Elevation Dataset (*NED*) website (<http://ned.usgs.gov/ned/>). The 30-m resolution *DEM* raster grid masked to fit the state boundaries was used for all statewide calculations. A 10-m resolution *DEM* raster for each county was acquired for watershed specific calculations. *LC* raster grid data was also obtained from the *USGS* National Map database. The raw data was then modified and reprojected to fit the needs of the project.

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 an average 16 years of accumulated data for New Mexico (Bulut, 2011) was utilized to evaluate the *C*-factor used in this study via Eq. 2. An α of 2 and β of 1 were used (van der Knijff *et al.* 2002). Even though the *NDVI* spectral formula has an output of -1.0 to 1.0, the *NDVI* process scales this output from 0 to 255. Note that the *NDVI* statewide map values ranged from 181 to 109. The resultant statewide map of cropping factor ranged between 0.09 and 0.82. A conditional statement was used to set the maximum *NDVI* to 155, resulting in a *C* = 0.09 (low soil loss potential). The minimum *NDVI* of 109 translates to a *C* = 0.82 (high soil loss potential).

Precipitation Data: Design storm 100-yr, 24-hr precipitation duration data was uploaded from the *NOAA NWC* via the *PFDS* (<http://weather.gov/>) and modified to fit the statewide boundaries. For this project per pixel *DDF* data was extracted site specifically with a resolution of approximately 90-m.

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 programs *Arc Hydro* and *HEC-GeoHMS*. 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. For more watershed specific attributes (longest flow path, stream slope, and sheet and rill flow) and linkage of the newly derived data (watershed, sub-watershed, streams, precipitation, and *CN* data) into a single dataset for easy viewing, exportation into other programs, and for time of concentration calculations, the *HEC-GeoHMS* extension coupled with *Excel*[®] was used. Data is generated as raster grids, shapefiles, and .hms formats.

Curve Number (CN): A *CN* raster grid for each respective watershed county was developed using *LC*, *SSURGO*, and *DEM* data, interfaced with the *ArcGIS*[®] extension *HEC-GeoHMS* program and coupled with the *NCRS TR-55 CN* methodology (Zhan and Huang 2004). A high *CN* refers to high runoff and low infiltration such as urban areas, whereas a low *CN* refers to low runoff and high infiltration found commonly in dry soils (Zhan and Huang 2004).

Peak Discharge and Runoff Volume: Using the *HEC-HMS v3.5* program coupled with the watershed attribute data previously generated, a peak flow (cfs) and runoff volume (ac-ft) were calculated for each respective watershed for a 100-yr, 24-hr storm event and a Type II *NRSCS* storm type.

Length-Slope Factor (LS-Factor): Both statewide and individual delineated watershed *LS*-factor raster grids were developed using the following *ArcGIS*[®] raster grids: *DEM*, stream flow length, and slope gradient. Slope steepness (*S*) factor and slope length (*L*) factor calculations are an integral part of many environmental analyses, particularly erosion models. Fundamentally, *L* represents the effect of slope length on erosion, where slope length (λ) is the distance from the origin of overland flow along a given flow path to the location of concentrated flow or sediment deposition. *S* represents the effect of slope steepness on erosion. In most cases, soil loss increases more rapidly with slope steepness than it does with slope length. These two attributes are usually considered together, expressed as a Length-Slope (*LS*) factor. *LS* a measure of the sediment transport capacity of overland flow (Moore and Wilson 1992).

Soil erosion depends upon drainage area topography in terms of slope gradient (θ) and slope length (λ). Associated attributes, *S*-factor and *L*-factor, are derived from *DEM* data. The *L*-factor is quantified using the standardized slope length (slope segment) raised to an exponent (*m*) that varies with slope angle:

$$L = \left(\frac{\lambda}{22.13} \right)^m$$

where

λ = slope length (m).

The m exponent may be determined with the following set of equations (Patriche *et al.* 2006):

$$m = \frac{\beta}{1 + \beta}$$

$$\beta = \frac{\left(\frac{\sin\theta}{0.0896}\right)}{[3(\sin\theta)^{0.8} + 0.56]}$$

where

θ = slope angle (degrees).

Exponents m and β were calculated specifically pixel by pixel for each watershed.

The S -factor depends upon the slope angle and may be described in the following equation:

$$S = 65.4\sin^2\theta + 4.56\sin\theta + 0.0654$$

Bulking Factor (BF): The bulking factor (BF), traditionally used in hydraulic structure design, is based on total sediment concentration, and given by

$$BF = (1 + (2 \times C_v)) = \frac{Q_p + Q_{s\text{total}}}{Q_p}$$

where

C_v = sediment concentration by volume (decimal fraction)

Q_p = clear-water peak discharge (cfs)

$Q_{s\text{total}}$ = total sediment load (cfs)

For structural design, if a BF can be estimated, a hydraulic structure design capacity can be increased over a clear-water hydraulic capacity. The latter capacity is evaluated using an appropriate Manning's roughness coefficient of the conveyance structure. To apply a BF effectively the total sediment concentration must be estimated for a given design condition. Mussetter Engineering, Inc. (MEI) conducted an investigation of sediment transport in the Albuquerque/Rio Rancho metropolitan area in New Mexico concluding that discharges estimated using standard rainfall-runoff procedures typically do not account for the presence of sediment flow. At high sediment loads, the total volume of sediment and water values can be significantly higher than clear water discharge calculations (Bohannon-Houston 2009). For estimates of sediment load, the MPM-Woo (Woo 1985) procedure was used for a typical rectangular cross section with width-depth ratio at a dominant discharge of 40, assuming critical flow conditions and a range of median (d_{50}) particle sizes (MEI 2008).

The *MUSLE* was used to calculate the fine sediment (wash load) yield (Y_s) in tons resulting from a single storm (Eq. 1). Based on watershed analysis of the middle and lower Rio Grande, an α of 285 is recommended (MEI 2008). A value for β was taken as 0.56 as a standard default. The K -factor and LS -factor were taken as an average value, respectively, for each watershed as determined by raster grid databases

and *ArcGIS*[®] Spatial Analyst. The *LS* factor was derived from a 10m *DEM* of the watershed. To account for the cropping factor, a watershed specific cropping factor was included in the above *MUSLE* equation for wash load. For undeveloped watersheds, the erosion control factor was set at 1. The hydraulic inputs of peak flow and runoff volume were determined using HEC-HMS coupled with the *NRCS TR-55* Curve Number method.

The fine sediment concentration is given by

$$C_f = 10^6 \left(\frac{Y_s}{W_w + Y_s} \right)$$

where

C_f = fine sediment (silt and clay) concentration (ppm)

W_w = weight of runoff volume (tons).

The associated wash load discharge (Q_f) in cfs is calculated by

$$Q_f = \left(\frac{Q_p}{S_g} \right) \left(\frac{C_f}{10^6 - C_f} \right)$$

where

S_g = specific gravity of the sediment (unitless).

The MEI (2008) procedure for bulking factor estimation uses the Woo relationship for computing suspended solids concentration coupled with the MPN bed-load equation to obtain a method for estimating bed-material load in streams carrying high concentrations of suspended sediment, or

$$q_s = aV^bY^c \left(1 - \frac{C_f}{10^6} \right)^d$$

where

q_s = unit width bed-material load (cfs/ft)

V = average cross-sectional velocity at peak flow (fps)

Y = hydraulic depth at peak flow (ft)

a , b , c , and d = Woo coefficients as a function of grain size (d_{50}).

The above formulation assumes a constant fine sediment yield during the storm.

Using the average channel width, the bed-material load discharge (Q_s) in cfs is given by:

$$Q_s = q_s W$$

where

W = average channel width (ft).

Total sediment discharge (Q_{stotal}) is, therefore, the sum of the wash load and a computed bed-material load, or.

$$Q_{stotal} = Q_f + Q_s \quad (\text{Eq.3})$$

Based on the specific gravity of the sediment, a bed-material load concentration may be determined, or

$$C_s = \frac{10^6 s_g Q_s}{Q_p + s_g Q_s}$$

where

C_s = bed-material load concentration (ppm).

Similarly, total sediment concentration may be determined as the following:

$$C_{stotal} = \frac{10^6 s_g Q_{stotal}}{Q_p + s_g Q_{stotal}}$$

The above methodology depends upon the hydraulic characterization of the watershed drainage with respect to average cross-sectional velocity (V), hydraulic depth (Y), and average channel width (W). The procedure used to estimate a bulking factor for each watershed follows the assumptions delineated by MEI (2008). A rectangular cross-section was assumed with a width to depth ratio of 40:1 at dominant discharge (Q_d), typical of naturally adjusted arroyos for stable sand-bed streams at or below critical flow (Froude number less or equal to 1). Here, dominant discharge is defined as the increment of flow that carries the most sediment over a long period of time. In the Albuquerque, NM area, the dominant discharge has a recurrence interval of 5 to 10 years, wherein the 100-yr peak discharge (Q_{100}) for the area averages about five times the dominant discharge (MEI 2008).

Implementing the procedure required that a dominant discharge be calculated by a 5:1 ratio from the peak discharge obtained from the *HEC-HMS* and *NCRS TR-55* analysis. A 24-hr design storm duration was assumed. Using an assumption of uniform flow via Manning's equation with a roughness coefficient of 0.03, typical of sand-bed arroyos, and a watershed flow length average slope obtained from the *DEM*, an average channel width (W) was estimated for the dominant discharge ($_{24}Q_d$). A second iteration of Manning's equation using this width and the $_{24}Q_{100}$ yields an average cross-sectional velocity (V) and hydraulic depth (Y) used in the unit width bed-material equation.

The last inputs required for the calculating of a bulking factor is the specification of the Woo coefficients and a specific gravity. A specific gravity of 2.65 was used for sand-bed arroyos. The Sediment and Erosion Design Guide (MEI 2008) provides a graph of the Woo coefficients a , b , c , and d as a function of average grain size in mm defined as d_{50} .

Drainage Delivery Ratio (DDR): A Drainage Density Ratio (DDR), or total flow length divided by the total drainage area, was estimated for each gridded watershed using the *TauDEM* (Terrain Analysis Using Digital Elevation Models) *ArcGIS*[®] extension.

Watershed Sediment Sieve Analysis: Random sediment sampling within the culvert proper (inlet, middle, and outlet) was performed for each watershed site. The collected samples were analyzed for grain size distribution based on *ASTM C 136-93* standard test method for sieve analysis of fine and coarse aggregates. A d_{50} sediment size was generated along with a grain-size distribution.

Results

Available statewide *GIS*-based raster grids were developed using the Albers Equal Area Conic (*AEAC*) projection (not shown). Watershed specific calculations that required gridded information was obtained by masking the respective statewide map. Estimates of watershed attributes so obtained are given in Table 1, providing a contrasting overview of the eight watersheds. Calculated bulking factors as determined by the MEI (2008) procedure are also provided.

Recall that the previously discussed *MUSLE* equation for wash load (Y_s) (Eq. 1) is a function of the LS , K , and C factors. As a result of the MEI (2008) methodology, the calculated bulking factor must also depend on these variables. A sequential, multiple linear regression (*MLR*) of the calculated *BF* data was performed for LS and K , LS , K , and C , LS , K , C , and DDR . Statewide maps of bulking factor were then generated based on these regressions and previously generated LS -factor, K -factor, and C -factor state maps. Figure 1 shows a bulking factor map calculated with LS , K , and C using *MLR*. The shaded black areas are *no data* pixels for soil erodibility ($K = 0$) based on the *SSURGO* soil database. Other areas (high topographic relief) displayed unrealistic high bulking factors by virtue of a high LS factor for individual pixels. A conditional statement was used in the statewide raster calculation to set the maximum calculated bulking factor at a value of 2.0. Pixels with greater than this cutoff value were returned as *no data* and are shown as white areas.

For comparative purposes, statewide *BF* values were masked for the eight watershed locations. The calculated *BF*, however, did not correlate well with the average clipped *BF* for the candidate watersheds.

Discussion

Sediment yield: Calculated total sediment yield (Q_{stotal}) via Eq. 3 increased with watershed drainage area. This result follows the pattern of small drainage basins, wherein sediment yield is typically supply-limited and sediment yield increases as a function of drainage basin area (Griffiths *et al.* 2006). For large watersheds an inverse relationship has been observed; that is, a transport-limited regime exists.

Bulking Factor (*BF*): Calculated bulking factors, as determined by the MEI (2008) procedure and given in Table 1, show similar values for sites 1 through 5 ranging from 1.01 to 1.05. Sites 6, 7, and 8 have high bulking factors ranging from 1.32 to 1.53. These high value results for sites 7 and 8 paralleled field reconnaissance data that showed excessive sediment deposition and clogging of the associated culverts. High bulking factors in this range would be considered as mud-flows hydraulically; however, there is no field data to support this calculated magnitude. Based on a sieve analysis, the sediment grain size d_{50} for these high value sites was small. Also, the K

and *LS*-factors were high, collectively resulting in a high *BF*. A critical determinant in the calculation is a specification of d_{50} , which sets the magnitude of the Woo coefficients used in the bulking factor estimate. In general, as d_{50} decreases, the *BF* increases.

Bulking factors between 1.4 and 2.0 represent mud-flows (approximately 30 to 50% sediment concentration by volume). These flow regimes are a function of slope gradient and soil erodibility, but also include additional factors, such as slope consolidation, and loss of soil cohesion due to a high degree of saturation. Bulking factors less than 1.25 (approximately 20% or less sediment concentration by volume) represent water flood with conventional suspended sediment load and bed load.

With respect to *BF* and *DDR* one could also infer an asymptotic upper trend of *BF* with increased *DDR* based on the generally accepted relationship for homogeneous basins of an increased sediment delivery ratio (*SDR*) as drainage density increases. The physical definition of *SDR* is the ratio of sediment yield at the watershed outlet (point of interest) to gross erosion in the entire watershed. With more eroded sediment flow arriving at the culvert inlet, a higher *BF* would be expected. The calculated *DDR* for each watershed can be seen in Table 1. Note that the two sites with a low *BF* and high *DDR* (Sites 1 and 2) are areas that also have a low *K*-factor (soil erodibility), or resistive, stable soil. Additionally, for site 4 having a low *DDR* and low *K*-factor, the *BF* is the lowest. Site 3 also with a low *DDR* and moderate *K*-factor, the *BF* is the low. With the exception of sites 3 and 4, the remaining watersheds have approximately the same *DDR*.

Table 1: Watershed Attributes for the Project Culverts.

County	Socorro		Lincoln	Otero	Catron	Rio Arriba		Dona Ana
Type	CMP	CMP	CBC	CBC X2	CMP	CMP	CMP X2	N/A
Watershed	US-380 MP10	I-25 MP127	US-54 MP103.4	US-54 MP97	HWY36 MP12.5	HWY96 MP14	US-285 MP340.1	Case Study
K Avg	0.13	0.18	0.19	0.24	0.28	0.39	0.31	0.25
LS Factor Avg	1.39	0.39	0.37	0.7	5.6	3.37	9.22	8.3
Sieve D ₅₀ (mm)	0.9	<0.6	1.5	<0.6	<0.6	<0.6	<0.6	0.5
Channel Slope (m/m)	0.03	0.018	0.02	0.018	0.032	0.06	0.04	0.029
²⁴ Q ₁₀₀ (cfs)	135.9	129.0	100.1	21.8	262.0	439.6	290.9	871.8
Runoff Volume (ac-ft)	15.2	21.1	21.8	4.9	28.2	43.2	50.5	144.4
DDR (L _i /A _i) (m/m ²)	0.126	0.132	0.048	0.035	0.119	0.117	0.147	0.117
BF	1.04	1.05	1.01	1.04	1.32	1.3	1.65	1.53
C Factor Avg	0.46	0.49	0.42	0.45	0.31	0.23	0.42	0.42
CN	82	55	69	57	75	73	71	69
¹⁰⁰ P ₂₄ (in)	3.44	3.44	3.28	3.29	2.98	3.08	3.03	3.55

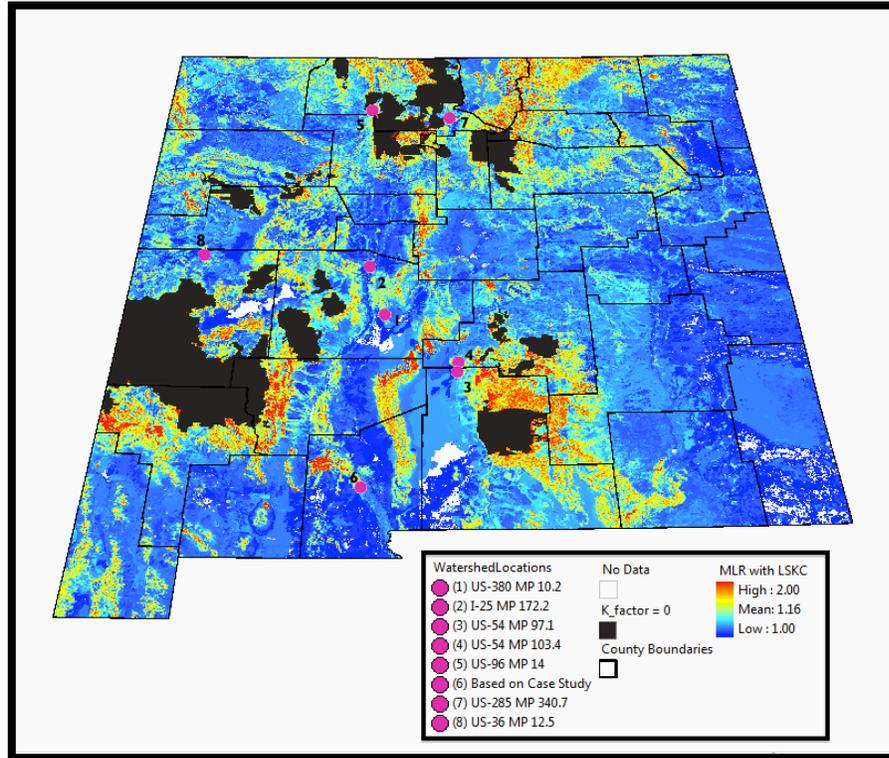


Figure 1: Statewide BF Estimated with $LSKC$ Multilinear Regression.

Regression Trends for BF : Multi-linear regressions were conducted for the watershed sites with an r^2 of 0.985 for LS and K , 0.991 for LS , K , and C (Figure 1), and 0.995 for LS , K , C , and DDR . For any multi-linear regression, the r^2 increases as the number of variables introduced increases. The r^2 can be described such that a given percentage (98.5, 99.1, or 99.5) of the variation of the dependent variable (BF_i) around its mean (BF_{mean}) is explained by the respective regressions (LS , K , C , and/or DDR). Statistically, the multi-linear coefficients for the LSK regression (intercept, LS , K) have p -values of $5.19e-5$, $3.38e-5$, and 0.06 and, therefore, are statistically significant at an $\alpha = 0.10$ since $p < 0.10$. For the LS , K , and C ; and LS , K , C , and DDR relationships, LS and K remain statistically significant ($\alpha = 0.10$); however, the added C and DDR attribute coefficients are greater than the designated cutoff α of 0.10 and would be considered statistically insignificant with relation to BF . However, C and DDR are physiographic-based attributes. The former is part of the $MUSLE$ equation; the latter is related to the sediment delivery ratio (SDR). Therefore, their inclusion may provide a better watershed bulking factor correlation with the availability of additional data. However, the data set herein is severely limited.

Statewide BF : The statewide BF maps generated based on the multi-linear regression relationships LS and K , and LS , K , and C showed similarities and differences. When the C -factor is introduced the resulting statewide BF map was almost indistinguishable to the BF map calculated with LS and K . The difference resides in the mean values of each. Average values were extracted from the statewide BF maps for the eight watershed locations. Looking at the difference between LSK and $LSKC$

BF values, introducing the *C*-factor (incorporating vegetation) will increase or decrease the original *LSK BF* value. This phenomenon is due to the fact that lands having low *C* values are naturally better protected from erosion by overland flow as opposed to barren lands with higher *C* values that are less resistant to erosion. The overall effect of this would be a decreased sediment transport capacity in areas that are well protected by the vegetation cover and to increase it in areas that are poorly protected by an established root system. Including the *C* factor will alter the distribution of areas of high sediment transport rate, making the topographic influence less pronounced and highlighting those areas of low protective vegetation cover. Vegetation, thus, can work as an inhibitor and an accelerator on the distribution of erosion risk in areas of high topographic relief (Pricope 2009). Introducing the *C*-factor provides a means for inhibiting or accelerating the distribution of erosion risk (*BF*) in areas of high topographic relief.

In practice when comparing which method would be best suited for calculating a statewide *BF* one could infer that a multi-linear regression based solely on *LS* and *K* would provide a fairly accurate map with minimal parameters required for calculations. However, knowing that the *C*-factor plays a role when determining a *BF* via the *MUSLE* equation, it may be worth including even though statistically the value is considered insignificant based on this limited dataset. Just as importantly the linear trends observed (*LSK versus BF* and *LSKC versus BF*) with high r^2 values (data not shown) cannot be ignored having produced similar results to the multi-linear regression data. Overall, more sample points are needed for determining which method would be best suited for the generation of a statewide *BF* map. Statistically, *DDR* appears to be insignificant when correlating a *BF*; however, its use may provide additional site-specific information and characteristics of watersheds with respect to sediment load. Note that this relationship is catchment specific, since a *DDR* value cannot be generated statewide.

Summary and Conclusion

Use of *ArcGIS*[®] is indispensable for this type of study, providing a large variety of toolsets necessary to combine and relate extensive amounts of data. Collectively, the data obtained and/or generated can be used for investigation, calculation, and the ultimate characterization of a wide range of attributes pertaining to soil erosion and sediment transport and deposition phenomena. Virtually any given watershed location with assessable and/or derivable GIS data can be analyzed physiographically using the procedural methodologies used and/or developed herein (Gallegos, 2012). These methodologies were applied to a limited dataset of eight small semi-arid watersheds.

The various *GIS*-based attributes (available or derived) provide their own unique informational characteristics of a watershed. Combining selected data with a sediment characteristic grain size (d_{50}) and using the methodology proposed by MEI (2008) watershed total sediment flow (Q_{total}) was determined, leading to an estimated bulking factor (*BF*) for each watershed investigated. Correlations between the calculated bulking factor and various watershed attributes were investigated. Based on watershed attributes of *LS* and *K*, or *LS*, *K*, and *C*, linear and multi-linear regression were evaluated. These provided sets of equations that could prove useful

for development of a statewide bulking factor map based on field-verified data. An example of a derived *BF* map was presented.

As a whole, this step-by-step physiographic-based methodology provides the means necessary to extract and determine a wide range of watershed attributes directly or indirectly pertaining to potential clogging of drainage structures. Moreover, even though the sample size was limited, significant trends and correlations were evident and supported by literature, thus offering the potential for the development of a statewide bulking factor map. Given time and effort, more watershed sites can be easily investigated using this methodology. With additional data and proper field verification, use of a statewide bulking factor map could become standard practice for design of drainage structures. This provides a physiographic-based approach to account for the effects of upland soil erosion, sediment transport and deposition, and sediment clogging potential for a given watershed and corresponding drainage structure.

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References

- Bohannon and Houston. (2009). Old Picacho Drainage Master Plan. Prepared for the Doña Ana County Flood Commission.
- Bulut, G.G. (2011). Potential Soil Erosion Risk for New Mexico and Sensitivity Analysis of Contributing Factors, MS Thesis, New Mexico Institute of Mining and Technology.
- Dick-Peddie, W.A., Moir, W.H., & Spellenberg, R. (2000). New Mexico Vegetation: Past, Present, and Future. Albuquerque: University of New Mexico Press.
- Gallegos, J.B. (2012). A *GIS*-based Characterization of Eight Small Watersheds in New Mexico with Emphasis on Development and Correlation of a Sediment Load Hydraulic Bulking Factor, MS Thesis, New Mexico Institute of Mining and Technology.
- Griffiths, P.G., Hereford, R., Webb, R.H., Geological Survey. (2006). Sediment Yield and Runoff Frequency of Small Drainage Basins in the Mojave Desert, California, and Nevada. Retrieved June 5, 2011, from <http://pubs.usgs.gov/fs/2006/3007/>
- MEI. (2008). Sediment and Erosion Design Guide, Prepared for the Southern Sandoval County Arroyo Flood Control Authority. Received August 23, 2011, from http://www.ssfca.com/development/documents/sediment_design_guide/Sediment_Design_Guide_12-30-08.pdf
- Moore, I.D., Wilson, J.P. (1992). Length-Slope Factors for the Revised Universal Soil Loss Equation: Simplified Method of Estimation. *J. Soil and Water Cons.*, 47(5). 423-428.

- Patriche, C.V., Căpățână, V., Stoica, D.L. (2006). Aspects Regarding soil erosion spatial modeling using the USLE / RUSLE within GIS. *Geographia Technica*, No. 2, 2006.
- Pricope, N.G. (2009). Assessment of Spatial Patterns of Sediment Transport and Delivery for Soil and Water Conservation Programs. *J. of Spatial Hydrology*, 9(1), 21-46.
- Renard, K.G., Foster G.R., Weesies, G.A., McCool, D.K., Yoder D.C. (1997). Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). Vol. 703. USDA. Washington, DC, USA.
- Renard, K.G., Foster, G.R., Weesies, G.A., Porter, J.P. (1991). "RUSLE: Revised Universal Soil Loss Equation". *J. Soil and Water Cons.*, 46(1), 30-33.
- Renard, K.G., Freimund, J.R. (1994). "Using Monthly Precipitation Data to Estimate the R-factor in the Revised USLE". *Journal of Hydrology*, 157(1-4), 287-306.
- Shank, M. (2009), "Mapping Vegetation Change on a Reclaimed Surface Mine Using Quickbird", Revitalizing the Environment: Proven Solutions and Innovative Approaches, 2009 National Meeting of the American Society of Mining and Reclamation, May 30-June 5, Lexington, Kentucky.
- Van der Knijff, J., Jones, R.J.A., Montanarella, L., (2002). "Soil Erosion Risk Assessment in Italy". *Preceedings of the Third International Congress Man and Soil at the Third Millennium. Geoforma Ediciones*, Logrono, Italy. 1903-1913
- Williams, J.R. (1975). "Sediment Routing for Agricultural Watersheds". *JAWRA Journal of the American Water Resources Association*, 11(5), 965-974.
- Woo, H.S. (1985). Sediment Transport in Hyper Concentrated Flows. Ph.D. Dissertation, Colorado State University, Fort Collins, CO.
- Zhan, X., Huang, M.-L. (2004). "ArcCN-runoff: An ArcGIS Tool for Generating Curve Number and Runoff Maps". *Environmental Modeling & Software*, 19(10), 875-879.