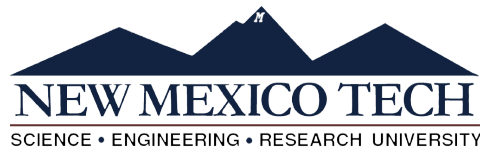


# **DEVELOPMENT OF WATERCOURSE AGGRADATION/DEGRADATION RISK INDEX FOR NEW MEXICO**

Project No. NM10DSN-01

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## **PREFACE**

This project serves to develop stream aggradation and degradation risk indexes and GIS maps for New Mexico. The primary objective of the project is to create field-verified aggradation and degradation risk indexes and accompanying GIS maps that will be used by Department personnel in the design of drainage structures on roads that cross waterways within the state's USGS hydrologic regions.

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## ABSTRACT

An *ArcGIS*<sup>®</sup> based methodology was employed to derive a bulking factor (*BF*) used to size for increased hydraulic capacity in culverts under sediment loading. Seventeen watersheds were studied across the State of New Mexico. By analyzing physiographic attributes for these sites related to soil erosion and sediment transport during a 100-yr, 24-hr design storm, a linear correlation was developed to estimate a watershed specific *BF* based on the product of a length-slope (*LS*) factor and soil erodibility (*K*-factor). This correlation was used to generate a statewide *BF* raster map. In addition, a soil erosion risk (*ER*) statewide raster map was produced using fuzzy logic together with the Universal Soil Loss Equation (*USLE*). Additional maps were prepared delineating the variation of *BF* and *ER* across the six NMDOT districts and within the seventeen watersheds studied as grouped into three relative classes, low, medium, and high. For the seventeen watersheds the *BF* ranged from 1.02 to 1.35. On a scale of 0 to 1, the statewide *ER* ranged from 0.05 to 0.87.

Although the statewide map provides a simple method to determine a *BF* for a delineated watershed, additional *ArcGIS*<sup>®</sup> procedures were implemented to derive specific watershed attributes and directly evaluate the *BF* for the watershed using a macro-based spreadsheet, independent of use of statewide map or linear regression.

Additional field verification is needed to validate and/or refine the procedures put forth herein. A field verified bulking factor and soil erosion map would allow for prediction of high-risk areas prone to sediment accumulation from upstream soil erosion and provides a means to adjust the hydraulic design capacity of new, potentially impacted, drainage structures.



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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 design of hydraulic structures, such as culverts that intersect a perennial or ephemeral waterway, requires the engineer to carefully consider the implications of such phenomena. A bulking factor (*BF*), or ratio of total flow with sediments to clean water flow, provides for an increased hydraulic capacity for culvert sizing under sediment load. Failure to properly assess a location in terms of sediment load may result undersized drainage structures.

In this study, seventeen small watersheds within New Mexico were characterized for various attributes related to drainage and sediment load using an *ArcGIS*<sup>®</sup> software-based approach. An in-depth terrain analysis based on a Digital Elevation Model (*DEM*) coupled with land cover and use, precipitation, soil, and hydrography raster datasets provided characterization of key watershed attributes, such as area, slope gradient, length-slope, channel slope, total flow length, drainage density, 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*<sup>®</sup> and the *NRCS TR-55* 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 was estimated using the Modified Universal Soil Loss Equation (*MUSLE*) and the procedures proposed by Mussetter Engineering, Inc. (MEI 2008). A preliminary statewide map of bulking factor was subsequently generated based on a linear regression of two key watershed attributes established for the study watersheds. A macro-based Excel<sup>®</sup> spreadsheet was also formulated to allow the user to estimate a watershed specific bulking factor using *ArcGIS*<sup>®</sup> derived watershed attributes of peak flow, runoff volume, channel slope, soil erodibility, vegetative cover, and a length-slope topographic factor. The *BF* ranged for 1.02 to 1.35 for the seventeen watersheds studied.

A soil erosion risk map was also developed for the State of New Mexico using an *ArcGIS*<sup>®</sup> software-based approach with application of *FuzzyCell*, a fuzzy logic-based Geographic Information System (*GIS*) tool. A 2-yr, 6-hr precipitation depth, slope gradient, Normalized Difference Vegetation Index (*NDVI*), and soil erodibility were used as surrogate metrics for the respective index parameters (*R*-factor, *LS*-factor, *C*-factor, and *K*-factor) of the *Universal Soil Loss Equation (USLE)*. A second iteration utilized a 1-dimensional length-slope (*LS* factor) in lieu of slope gradient. The fuzzy generated risk maps were virtually identical statewide. Risk varied between 0.05 and 0.87 on a color scale from 0 to 1, providing a visual perspective of potentially problematic areas. Areas of concern identified relative to culvert deposition and clogging were generally associated with regions of medium to high risk. A sensitivity analysis identified slope gradient as a dominate factor in overall soil erosion risk, followed by soil erodibility and *NDVI*, with precipitation depth being less important. The topographic *LS*-factor was also identified as a dominate factor in the magnitude of the *BF*.

## LITERATURE REVIEW

A characteristic of alluvial streams in the arid and semi-arid regions of the Southwest is that during rainfall events, large quantities of sediments are transported from upland regions and deposited into the lower reaches of the catchment. This phenomenon follows the proportionality developed by Lane (1):

$$QS \propto Q_s d_{50}$$

where,

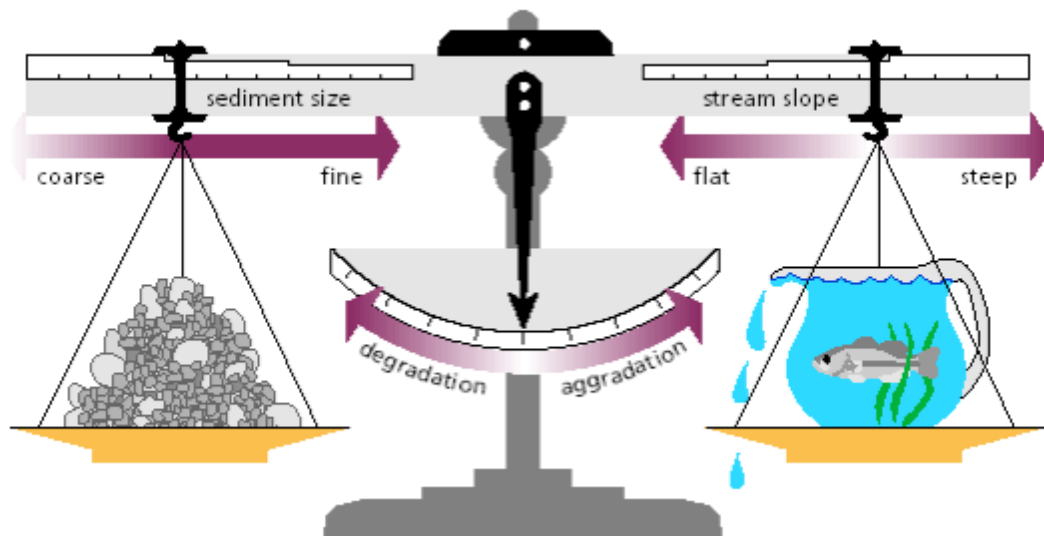
$Q$  = stream discharge

$S$  = stream slope

$Q_s$  = sediment transport capacity

$d_{50}$  = sediment median grain size

Figure 1 illustrates this relationship of how water volume, sediment volume and particle size, and stream slope (or energy grade) are naturally balanced. If the balance is tipped, the channel responds by either aggrading (building up sediment on the channel bed) or degrading (scouring down the channel bed). A change in any one of these parameters will cause adjustments of the other variables until the stream system is brought back into balance. For example, using the diagram below it can be seen that an increase in the stream water volume would tip the scale to the right. The system will respond by degrading until either the volume and/or size of sediment increases enough to bring the scale (stream channel) back into balance.



**FIGURE 1. Lane's Balance: Demonstrating a balance between: sediment supply, sediment size, stream slope, and stream discharge.**

In the simplest of terms, the design of a new or existing hydraulic structure (bridge or culvert) that intersects a perennial or ephemeral waterway requires the engineer to carefully consider the geomorphic implications embodied in Eq. 1. For example, the relationship predicts that for constant  $Q$  and  $d_{50}$  within a stream segment, a decrease in  $S$  will result in a decrease in  $Q_s$ , or an increase in aggradation potential within the segment. For culverts designed at a milder slope than the natural stream gradient, the potential for clogging is predicted by the Lane relationship (2). The *USDA*, in their methodology for risk assessment of road-stream crossing failure, indicated that a culvert having a slope less than 30% of the approaching stream bed slope was at a high risk for sediment plugging (3).

Sediment supply to a stream segment relative to sediment transport capacity of the stream dictates whether there will be aggradation or degradation. Sediment mobilization at the watershed scale is a stochastic process. The range of morphology and behavior of a stream network with respect to aggradation or degradation depends upon the power spectrum of sediment supply (texture and rates) and the sediment transport capacity of the reach (Benda *et al.*, 2004). The sediment supply and its storage are modulated by the drainage area for a given set of environmental conditions (4). According to the Langbein-Schumm rule, maximum sediment yield per unit area of catchment for the semi-arid southwest United States occurs at an annual precipitation of about 300-mm (12-in.) (5). For a given precipitation event, excess rainfall produces a runoff hydrograph ( $Q_w$  versus  $t$ ) at a fixed location within the catchment network. Simultaneously, a sedimentgraph of suspended solids ( $Q_s$  versus  $t$ ) results, although a direct relationship between the hydrograph and the sedimentgraph is rarely present (6).

At the network level, if the sediment supply exceeds the sediment transport capacity of the reach, the stream bed slope must increase in order to increase the transport rate to match the supply rate. The initial excess of sediment will result in aggradation at the upstream end of the reach until the downstream portion of the bed slope is steep enough to transport the incoming sediment load. Conversely, when the incoming sediment supply is less than the sediment transport capacity of the reach, the sediment deficit must be satisfied by the extraction of sediment through the reach until the bed slope is flattened enough to reduce the sediment transport capacity to the point that it matches the incoming sediment load. In each case, the reach dynamically tends towards establishing an equilibrium bed slope based on sediment supply.

As evident from the above qualitative description of sediment supply and sediment transport capacity, assessment of stream stability is complex. Factors that influence stream stability are actively occurring in time and space and are driven by hydrologic and hydraulic phenomena within a particular catchment and stream reach. Johnson *et al.* (1999) examined various methods to assess stream stability in the vicinity of road crossings and developed criteria and a procedure for rapid assessment thereof based on geomorphic and hydraulic processes (7). The procedure consisted of a mix of 13 regional and local stability indicators with a numerical rating scale and associated weighting factors. However, as the authors point out, the procedure only provides a relative ranking of stability rather than a quantitative evaluation of the magnitude of change.

The development and application of Geographical Information System (*GIS*) procedures has provided the scientific and engineering community a powerful tool to address complex problems on a more quantitative basis. For example, Wu (2006) used a *GIS* platform to integrate



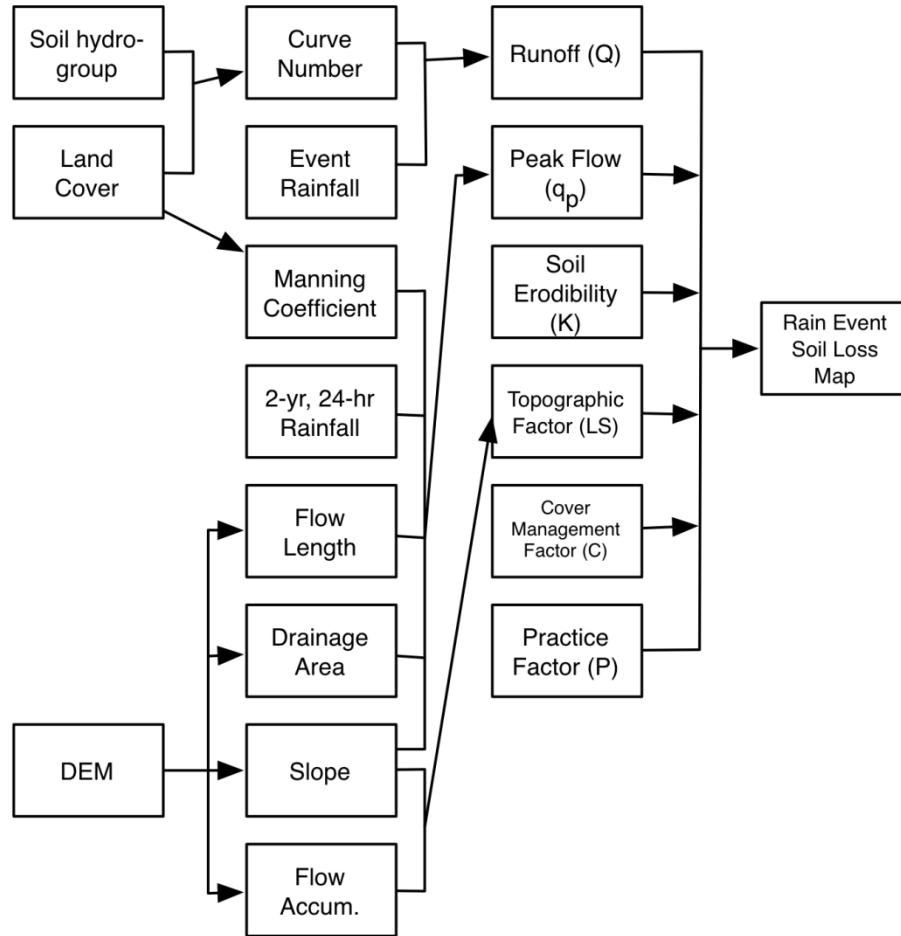
numerical data, spatial data, and embedded hydrologic and hydraulic models. Specifically, Hydrologic Engineering Center-Hydrologic Modeling System (*HEC-HMS*) and Hydrologic Engineering Center-River Analysis System (*HEC-RAS*) were used to generate design flows and water surface profiles for use in drainage design and flood management (8).

The *HEC-HMS* model is designed to simulate the precipitation-runoff processes of dendritic watershed systems, ranging from large river basins to small urban or natural catchments. It is now interfaced with the Geospatial Hydrologic Modeling Extension (*HEC-GeoHMS*) for use with *GIS*. Through a series of steps known collectively as terrain preprocessing, this extension transforms the drainage paths and watershed boundaries into a hydrologic data structure that represents the catchment area response to a storm event.

Pullar and Springer (2000) modeled the impact of non-point pollution in catchments using the Agricultural Non-point Source (*AGNPS*) model tightly coupled with *GIS* (9). The single-event distributed parameter model employed a hydrologic component to estimate runoff and flow based on the Natural Resources Conservation Service (*NRCS*) Curve Number (*CN*) method and a sediment transport component to estimate erosion based on the Universal Soil Loss Equation (*USLE*). Sediment was routed from cell to cell across the *GIS* configured catchment to determine where sediment was being deposited. A similar routing approach based on *USLE* output was used by Evans and Seamon (1997) to develop a *GIS* map of stream sediment loadings as a function of location along the path of main drainage (10). Kalin *et al.* (2003) used the *KINEROS* model with *GIS ArcView* interface to model direct runoff and sediment yield from two small *USDA* experimental watersheds with emphasis on geomorphologic resolution on the runoff hydrographs and sedimentgraphs (11).

A geospatial land degradation information system was developed for the State of Arizona by van Leeuwen and Sammons (2003) using the Revised Universal Soil Loss Equation (*RUSLE*) integrating remotely sensed data and *in-situ* data into a *GIS* platform (13). The *GIS* output displayed a distribution of annual soil loss and the degradation risk potential over the state.

Zhang *et al.* (2009) integrated the Modified Universal Soil Loss Equation (*MUSLE*) into a *GIS* framework to assess soil erosion risk for a given watershed (*Figure 2*) (12). Note that the *USLE* and *RUSLE* models estimate annual gross upland erosion as a function of rainfall energy, specified in terms of a rainfall erosivity factor. In *MUSLE*, rainfall energy is replaced with a runoff factor based on peak flow and runoff volume. This allows for prediction of soil erosion from individual storm events of a particular design frequency and duration.



**FIGURE 2: Flow Chart of *ArcMUSLE* Calculation Process.**

The above flow chart delineates key watershed attributes that are composited to estimate gross upland erosion. This was the starting point for the majority of project research effort to estimate a bulking factor for use in design of culverts.

The bulking factor ( $BF$ ) traditionally used in hydraulic structure design is based on total sediment concentration, or

$$BF = (1 + 2C_v)$$

where

$C_v$  = sediment concentration by volume (decimal fraction)

For example, a sediment concentration of 0.3 equals a  $BF$  of 1.6. This concentration is considered to be the critical state between sediment flow and mud flow (14). A study of the total sediment supply to the Rio Grande Canalization Project (15) indicated that three contributing arroyo basins had a total load concentration in excess of 20% (volume) with two basins in excess of 30% (volume). Traditionally, if a  $BF$  could be estimated the hydraulic structure design capacity was increased by the  $BF$  factor and clear water hydraulics applied using

an appropriate Manning's roughness coefficient of the conveyance structure. At high  $C_v$  beyond mud flow, however, application of a  $BF$  alone for design would be inadequate to pass the sediment load using on clear water roughness coefficient. The apparent roughness is considerably higher (16). To apply the bulking factor effectively the total sediment concentration must be estimated for a given design condition.

The *USLE*, *RUSLE*, and *MUSLE* models model only the wash load (upland erosion or overland sediment yield) within a catchment network. Sediment supply, however, consists of bed-material load and bed-material suspended load. The latter includes the wash load. Bed-material load describes particles in a flowing stream that are transported along the bed. This is in opposition to bed-material suspended load and wash load, which are carried entirely in suspension. There are a number of equations to estimate bed-material load, such as the Zeller-Fullerton equation, Meyer-Peter-Muller equation, Mussetter equation, etc. (15). The Zeller-Fullerton equation is a multiple regression sediment transport equation for a range of stream bed and alluvial floodplain conditions typical of arid regions in Pima County, Arizona. Others have been evaluated for use with ephemeral streams (5). A recent formulation for total load (excluding wash load) that appears promising for engineering design and analysis of hydraulic structures was proffered by Yang and Lim (2003) based on an equilibrium transport condition (sediment supply equals sediment transport) (17). The variables required to estimate the total sediment load at a control point within a catchment area are flow depth or hydraulic radius, mean flow velocity, energy slope, median sediment grain size, sediment density, and water temperature. The first three variables are obtained directly from a hydrologic/hydraulic evaluation. The later variables would be user-supplied.

Richards and Zeller (1999) used the Zeller-Fullerton equation for bed-load sediment transport rate along with a culvert sediment discharge rate equation by Graf and Acaroglu (1968) to estimate potential deposition in culverts (18,19). The authors noted that the culvert sediment discharge rate equation was developed for circular conduits. Unfortunately, the literature is rather sparse in addressing the sediment conveyance capacity of hydraulic structures. Minematsu and Arita (1987) applied sediment transport theory in a pipe to develop a design criterion for culverts, which incorporated sediment concentration ( $C_v$ ) (14). The resulting analytical equation satisfied two constraints: passage of maximum inflow from the catchment area based on the Rational Method and no sedimentation within the culvert. The latter condition was contingent upon the culvert slope. For a given slope, a larger diameter is required to safely pass a flow containing sediment compared to flow with no sediment. Similarly, for the same diameter pipe, a higher slope is required for sediment laden flows.

In summary, the *GIS* platform is well-suited to address and formulate a methodology to estimate a sediment concentration arriving a control point within a catchment area. A key to developing a risk index of aggradation/degradation for design of hydraulic structures, specifically a bulking factor ( $BF$ ), is sediment supply/sediment transport capacity at a control point. This is a more quantitative approach using integrated models and equations within *GIS* to estimate these parameters. Geomorphic factors that affect sediment yield and delivery are embodied within these models and equations, such as soil type, precipitation, topography, vegetative cover, and land use. On a larger scale, the same approach may be taken using more global attributes affecting sediment supply and sediment transport capacity.

## Drainage Area

Sediment yield from small drainage basins is typically supply-limited, meaning it is limited primarily by the supply of sediment, and sediment yield increases as a function of drainage basin area (Griffiths *et al.*, 2006) (21). As drainage basins increase in area and become more topographically complex, sediment yield often becomes transport-limited, meaning that sediment yield is restricted by the increasingly complex process of moving sediment down and out of the basin. Empirical sediment yield power-law equations have been developed for the semi-arid southwestern United States and, specifically, Arizona, New Mexico, and California (Yang *et al.*, 1998) that show this inverse relationship (22). The general form of the sediment yield ( $Q_s$ ) is

$$Q_s = aA_d^{-b}$$

where  $A_d$  is the drainage area and  $a$  and  $b$  are fitted coefficients.

Additionally, the sediment delivery ratio (*SDR*), defined as the ratio of sediment delivered at a given location to the gross erosion from the drainage area above that point, varies widely with drainage area, topography (slope), density of drainage network within the drainage area, annual precipitation, storm runoff volume, among other factors. Numerous empirical equations have been developed. In general, as the drainage area decreases logarithmically sediment delivery increases.

## Slope Steepness Factor and Slope Length Factor

Soil erosion depends upon drainage area topography in terms of slope gradient ( $\theta$ ) and slope length ( $\lambda$ ). Associated attributes, slope steepness factor ( $S$ ) and slope length factor ( $L$ ), can be derived from the *DEM*; however, the slope length factor (*LS*-factor) is the most difficult to compute when soil erosion spatially is to be considered (Patriche *et al.*, 2006) (23). Within *RUSLE* the *LS*-factor is quantified using the standardized slope length (slope segment) raised to an exponent ( $m$ ) that varies with slope angle, or

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

where  $\lambda$  is given in meters.

The slope steepness factor depends upon the slope angle as well, or

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

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

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

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

where  $\theta$  is the slope angle in degrees (23).

The slope steepness and slope length factor are multiplied to yield the *LS*-factor, also referred to as a Sediment Transport Capacity Index. A *GIS* compatible map of slope angle ( $\theta$ ) and slope length ( $\lambda$ ) can be generated for a defined watershed drainage associated with a given culvert. Using the raster calculator function in *ArcGIS*<sup>®</sup>, a watershed specific *LS*-factor can then be determined.

To account for the impact of flow accumulation convergence, Moore and Burch (1986) (29) proposed the following *LS*-factor equation:

$$LS = (m+1) \left( \frac{A}{22.13} \right)^m \times \left( \frac{\sin \theta}{0.0896} \right)^n$$

where  $A$  is the upslope contributing area per unit width ( $m^2/m$ ),  $\theta$  is the slope angle (degrees), and  $m$  and  $n$  are exponents for specific types of flow and soil conditions. It should be noted that  $m$  equal to 0.6 and  $n$  equal to 1.3 give results consistent with the *RUSLE* *LS*-factor for slope length less than 100-m and slope angles less than 14° (10). A 2-dimensional *LS* factor decreases when estimated with upslope contributing area as compared with the 1-dimensional *LS* (30). The resultant soil erosion estimate would decrease.

### Soil Type and 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 *K*-factor of the *RUSLE* and *MUSLE* soil loss equations. A stable soil may have a *K*-factor value of 0.01, whereas a highly fragile soil may have a *K*-factor of 0.70. A *GIS* compatible map of *K*-factors for the State of New Mexico is available from the *NRCS SSURGO* soil survey data. Additionally, a *GIS* compatible map of *NRCS* hydrologic soil group classifications (*A-D*) can be extracted from the same data set.

### Vegetation Cover

Normalized Differential Vegetation Index (*NDVI*) is a thematic image of estimate vegetation density derived using multi-spectral satellite imagery obtained from *MODIS*. *NDVI* statistics is a common tool for identifying and characterizing vegetation. *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, 2008) (24). The cover management factor (*C*-factor) in the *RUSLE* and *MUSLE* soil loss equations expresses the influence of vegetation upon soil erosion. It depends upon vegetation type, stage of growth, and cover percentage; its value ranges from 0 to 1. It has been linearly correlated with the *NDVI* (Patriche *et al.*, 2006; Karaburun, 2010) (23,25). Additionally, *NDVI* has been linearly correlated with percent ground cover (Shank, 2008) (24). A *GIS* compatible *NDVI* data for the State of New Mexico is available from the NASA *MODIS* website. Consideration, however, must be given to the use of satellite imagery as being momentary values representative of the time of image acquisition (Patriche *et al.*, 2006) (23). Hence, any extrapolation or correlation of *NDVI* data to the condition of watershed cover as per density, percent cover, etc. must be based on a mosaic of images taken throughout an annual cycle (Patriche *et al.*, 2006) (23). A similar methodology of weighted average monthly *NDVI* images was used to create a monthly *C*-factor for use in evaluating land degradation (van Leeuwen and Sammons, 2003) (26).

## **Precipitation**

Rainfall erosivity defines the aggressiveness of rain to cause soil erosion. The most common rainfall erosivity index is the *R*-factor in the *RUSLE* soil loss equation. It is a composite factor of rainfall kinetic energy and maximum 30 minute intensity of rain and represents a measure of the erosive force and intensity of rain in a normal year. A low resolution *GIS* compatible format of an isoerodent map for the State of New Mexico map is available (800-m x 800-m). However, Wischmeier and Smith (1978) reported that the *R*-factor could be approximated with reasonable accuracy by using the 2-yr, 6-hr ( ${}_2P_6$ ) rainfall frequency distribution (27). Correlations exist based on storm type, such as *Type II* storms typical of New Mexico. This 2-yr, 6-hr distribution is available for the State of New Mexico in *GIS* compatible format from *NOAA*, as well as average annual precipitation and other useful frequency-duration distributions, such as the 2-yr, 24-hr and 100-yr, 24-hr distributions used herein.

## METHODOLOGY

### Bulking Factor Procedure

A sediment-load bulking factor ( $BF$ ) for a given watershed may be estimated using the procedure developed by Mussetter Engineering, Inc. (MEI, 2008), or

$$BF = \frac{Q + Q_{total}}{Q}$$

where  $Q$  = clear water discharge

$Q_{total}$  = total sediment load (bed material and wash load)

or

$$BF = \frac{1}{1 - \frac{C_{total}/10^6}{s_g - (C_{total}/10^6)(s_g - 1)}}$$

where  $C_{total}$  = total sediment concentration by weight (ppm)

$s_g$  = specific gravity of sediment (unitless)

### Modified Universal Soil Loss Equation (*MUSLE*)

The *MUSLE* may be used to calculate the fine sediment (wash load) yield ( $Y_s$ ) in tons resulting from a single storm, or

$$Y_s = \alpha(V_r Q_p)^\beta K(LS)CP$$

where  $\alpha$  = region specific calibration factor

$\beta$  = region specific calibration factor

$V_r$  = runoff volume (acre-ft)

$Q_p$  = peak runoff flow (cfs)

$K$  = soil erodibility factor

$LS$  = Length-slope factor

$C$  = cropping factor

$P$  = erosion control factor

Based on watershed analysis of the middle and lower Rio Grande, an  $\alpha$  of 285 is recommended (MEI, 2008). A value for  $\beta$  is taken as 0.56 as standard default. The factors  $K$  and  $LS$  are taken as an average value, respectively, for the watershed as determined by raster grid databases and *ArcGIS*<sup>®</sup> spatial analyst. The  $LS$  factor is derived from a *DEM* of the watershed. A cropping factor of 0.3 may be specified to represent a relatively sparse vegetative cover condition throughout the watershed, or determined by other means. For undeveloped watersheds, the erosion control factor is set at 1. The hydraulic inputs of runoff volume and peak flow are 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 load concentration (ppm)

$W_w$  = weight of runoff volume (tons)

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

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

### **Transport Equation for High Suspended Solids Concentrations (MPN-Woo Equation)**

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)

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

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

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

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

$$Q_s = q_s W$$

where  $W$  = average channel width (ft)

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

$$Q_{total} = Q_f + Q_s$$

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

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

### **Implementation of the MEI (2008) Procedure to Specific Watersheds**

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 is 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 area, the dominate discharge has a recurrence interval of 5 to 10 years, wherein the 100 year peak discharge ( $Q_{100}$ ) for the area averages about five times the dominant discharge (MEI, 2008).

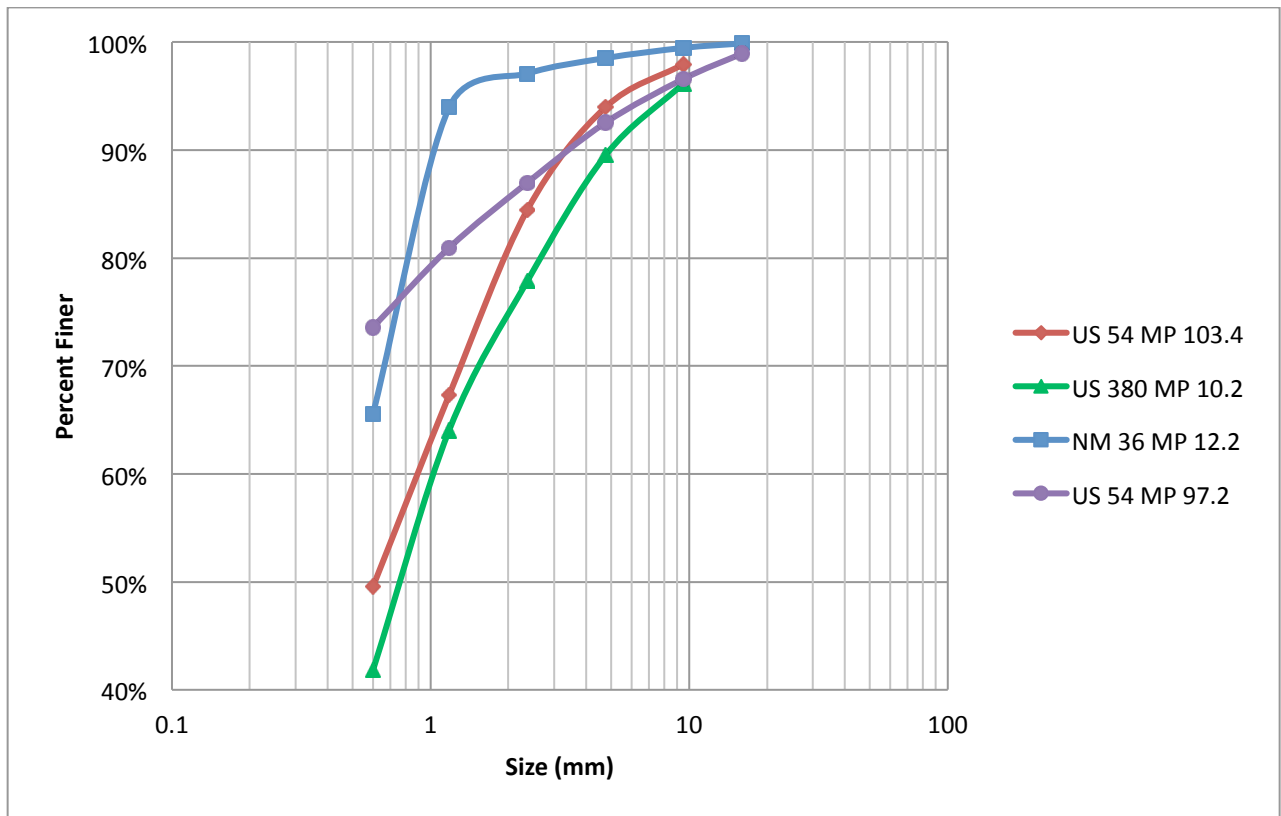
Implementing the procedure requires that a dominant discharge be calculated by 5:1 ratio from the peak discharge obtained from the *HEC-HMS* and *NCRS TR-55* analysis. A 24 hr design storm duration is assumed. Using an assumption of uniform flow via Manning's equation with a roughness coefficient of 0.03, typical of sand-bed arroyos, and a watershed flow length average slope obtained from the *DEM* and *HEC-GeoHMS* terrain processing, an average channel width ( $W$ ) is 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 may be used for sand-bed arroyos. The *Sediment and Erosion Design Guide* [MEI, 2008] (31) provides a figure of Woo coefficients  $a$ ,  $b$ ,  $c$ , and  $d$  as a function of average grain size in mm defined as  $d_{50}$ . Equations or tabular values to determine the respective coefficient for a given grain size are not available. However, the following set of coefficients was estimated based on scaling the appropriate coefficient y-axis at specific values of the grain size x-axis:

<u><b>D<sub>50</sub></b></u>	<u><b>a</b></u>	<u><b>b</b></u>	<u><b>c</b></u>	<u><b>d</b></u>
0.5	4.00E-04	3.8	0.34	-2.46
1	9.50E-06	5.35	-0.3	-2.5
1.5	2.30E-06	5.72	-0.62	-2.14
2	1.30E-06	5.8	-0.725	-1.85
2.5	1.20E-06	5.7	-0.765	-1.62
3	1.40E-06	5.6	-0.78	-1.41
3.5	1.50E-06	5.4	-0.775	-1.23
4	1.70E-06	5.3	-0.77	-1.08

### **Sieve Analysis**

Random sediment sampling within the culvert proper (inlet, middle, and outlet) was performed at selected candidate sites. The collected samples were then taken to the Civil Engineering laboratory at New Mexico Tech for sieve analysis based on *ASTM C 136-93* standard test method for sieve analysis of fine and coarse aggregates. The smallest sieve size used had a mesh size of 0.6 mm. Based on these procedures and the samples obtained for each site, a grain-size distribution was generated along with an estimated or extrapolated  $d_{50}$  value. The following figure shows the grain size distributions for US 54 MP 103.4 ( $BF = 1.02$ ), US 54 MP 97.2 ( $BF = 1.03$ ), US 380 MP 10.2 ( $BF = 1.05$ ), and NM 36 MP 12.2 ( $BF = 1.21$ ). A large fraction of the collected sediment lies below 1 mm (fine to coarse sand). A  $d_{50}$  of 0.6-mm was used in calculating a site-specific  $BF$  for the candidate watersheds.



**FIGURE 3: Sieve Analysis for Selected Culvert Sites.**

## Culvert Sediment Depths and Deposition

Measurements of sediment depth and accumulation were taken at selected sites during the course of investigation. Table 1 summarizes the data collected. Some culverts are visually problematic with high clogging potential as evident by the depths accumulated over the duration of study. Although the tonnage estimate of barrel deposition may seem high, it does not represent the actual sediment load passing through the culvert. Figure 4 is a Google Earth picture of the inlet of a culvert located in Rio Arriba County on US 285 MP 340.7. Figure 5 is a recent reconnaissance picture of the culvert outlet showing an expansive sediment fan.

**TABLE 1: Summary of Observed Sediment Depths and Deposition.**

County	Culvert	Size and Type	Depth <sup>a</sup> (in)	Duration (yr)	Tons <sup>b</sup>	BF <sup>c</sup>
Rio Arriba <sup>1</sup>	US 285 MP 340.7	2x 72 in CMP	29/30/31	~ 2	50	1.35
Catron <sup>2</sup>	NM 36 MP 12.2	120 in CMP	42/36/36	~ 2	132	1.21
Socorro <sup>3</sup>	US 380 MP 10.2	96 in CMP	17/13/4	~ 2	45	1.05
Rio Arriba <sup>4</sup>	NM 96 MP 14.0	60 in CMP	60	<sup>d</sup>	75	1.25
Socorro <sup>5</sup>	I-25 MP 172.2	8 ft x 8 ft CBC	22/10/3	<sup>d</sup>	60	1.03
Socorro <sup>6</sup>	I-25 MP 155.2	8 ft x 8 ft CBC	24/16/2	<sup>d</sup>	56	1.06
Lincoln <sup>7</sup>	US 54 MP 103.4	5 ft x 8 ft CBC	9/6/4	<sup>d</sup>	6	1.02
Otero <sup>8</sup>	US 54 MP 97.2	2x 4ft x 3 ft CBC	11 to 18	<sup>d</sup>	60	1.02
Mora <sup>9</sup>	NM 120 MP 48.5	60 in CMP	0 to ~2	<sup>d</sup>	<sup>e</sup>	1.08
DeBaca <sup>10</sup>	US 60 MP 340.6	54 in CMP	0 to ~6	<sup>d</sup>	<sup>e</sup>	1.06
Socorro <sup>11</sup>	Star Route 1	3x 6 ft x 8 ft CBC	negligible	<sup>d</sup>	<sup>e</sup>	1.21
Rio Arriba <sup>12</sup>	NM 96 MP 15.8	132 in CMP	42/36/36	<sup>d</sup>	70	<sup>f</sup>

<sup>a</sup> Observed sediment depths as per inlet/middle/outlet, or inlet to outlet

<sup>b</sup> Barrel deposition estimated based on culvert length, depth of sediment, and  $\rho_s = 110 \text{ lb}_m/\text{ft}^3$

<sup>c</sup> Based on MEI (2008) procedures using 2-D *LS*

<sup>d</sup> Duration of sediment deposition between maintenance cleaning is not known

<sup>e</sup> Negligible

<sup>f</sup> Non-candidate watershed not analyzed for *BF*

<sup>1</sup> Culvert barrels partially cleaned after project started.

<sup>2</sup> Cleaned as per project team request.

<sup>3</sup> Cleaned as per project team request.

<sup>4</sup> Completely clogged throughout project duration

<sup>5</sup> I-25 cleaning maintenance unknown relative to project duration (no cleaning requested).

<sup>6</sup> Inlet right-of-way cleaned sometime after project started; culvert barrel not cleaned.

<sup>7</sup> Cleaning requested; no cleaning provided after start of project.

<sup>8</sup> Cleaning requested; inlet and outlet right-of-way cleaned; culvert barrels not cleaned.

<sup>9</sup> No cleaning provided after start of project.

<sup>10</sup> No cleaning provided after start of project.

<sup>11</sup> No cleaning requested; sediment deposition minor, but not measured.

<sup>12</sup> Non-candidate site within 2 miles of NM 96 MP 14.0 culvert.



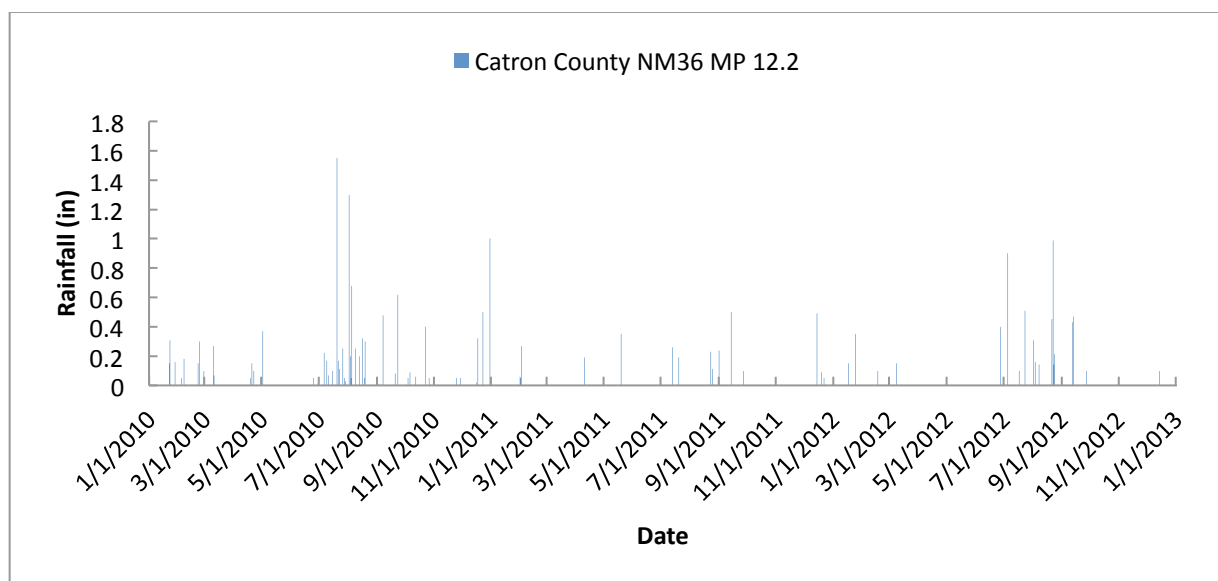
**FIGURE 4: Inlet to US 285 MP 340.7 Culvert.**



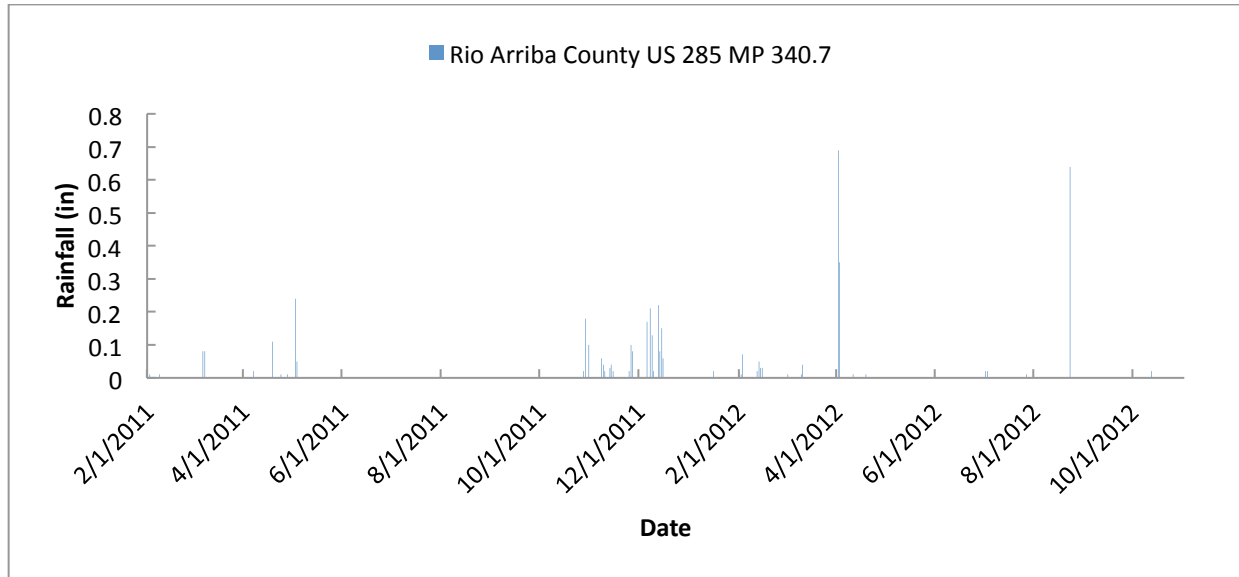
**FIGURE 5: Outlet from US 285 MP 340.7 Culvert.**

## Rainfall

Rainfall data for the seventeen watersheds were obtained from the New Mexico Climate Center (<http://weather.nmsu.edu/en/home/climate-new-mexico/>) using the nearest weather station based on watershed latitude and longitude. Daily precipitation was extracted for the project period. Figures 6 and 7 show the recorded daily precipitation depth for the NM 36, MP12.2 (Catron County) site and the US 285, MP 340.7 (Rio Arriba County site), respectively. These two watersheds were problematic relative to sediment loading to the respective culvert and subsequent sediment deposition. Significant rainfall events coincided with field verified additional deposition of sediment. For these two sites, the  $BF$  was 1.21 and 1.35, respectively. Similar correlation of sediment accumulation within the culvert barrel with rainfall was observed for the US 380, MP 10.2 (Socorro County) site ( $BF = 1.05$ ); however, other sites receiving significant rainfall over the project duration did not show appreciable sediment deposition, for example, the US 54, MP 103.4 site ( $BF = 1.03$ ). Rainfall duration and intensity are critical elements to soil erosion and sediment transport; however, other factors related to culvert design may be operative and control whether or not a given culvert is susceptible to sediment deposition and clogging.



**FIGURE 6: Precipitation Data for NM 36, MP 12.2 (Quemado Station).**



**FIGURE 7: Precipitation Data for US 28, MP 340.7 (Alcalde Station).**

## **Bulking Factor Calculation Methodologies**

### *Method 1*

The simplest method to get an estimate of the  $BF$  for the culvert site in question is to clip the delineated watershed from the statewide 1-Dimensional  $BF$  map. This map was generated using the linear correlation of  $LS_1K$  with  $BF$  calculated using the MEI (2008) methodology. The average  $BF$  for the watershed can then be extracted with the spatial analyst toolset.

### *Method 2*

This method is based on the linear correlation of  $LS_2K$  with  $BF$  calculated using the MEI (2008) methodology. With the delineated watershed established, the *Modelbuilder* algorithm is run to calculate the 2-Dimensional watershed pixel by pixel  $LS$ -factors. The average  $LS$ -factor for the watershed is then found by right clicking the watershed grid file in the map document: go to→ properties→ symbology→ classified→ classification statistics to view the mean. Additionally, the watershed  $K$ -factor raster is extracted by mask from the statewide raster using the delineated watershed. The average  $K$ -factor is found by the same selection procedure. The product of these values is used as input to the regression equation  $BF = 0.1878 * LS_2K + 1$  to yield the watershed  $BF$ .

### *Method 3*

Processing the watershed completely through the sequential *ArcHydro*, *HEC-GeoHMS*, and *HMS* toolsets yields values for channel slope (ft/ft), peak discharge (cfs), and runoff volume (ac-ft). In addition to using the average  $LS$ -factor and  $K$ -factor evaluated in *Method 2*, an average  $C$ -factor must be determined from the statewide  $C$ -factor raster using the extracted watershed and the same selection procedure used to view an average  $LS$ -factor and  $K$ -factor. Executing the macro-

based Excel spreadsheet developed for the MEI (2008) methodology with these six watershed-specific attributes results in an estimate of the *BF*.

#### *Method 4*

Traditional watershed analysis commonly used by drainage engineers may be implemented as an alternative means to estimate channel slope (ft/ft), peak discharge (cfs), and runoff volume (ac-ft) for the delineated watershed, in lieu of processing the watershed completely through an *ArcGIS*® platform. With these alternate values, the procedure to estimate the *BF* is the same as *Method 3*.

#### ***Modelbuilder and Calculation of a 2-Dimensional Length-Slope Factor***

*ModelBuilder* is a built-in application in *ArcGIS*® that works as both a stand-alone programming tool as well as an interface for *Python* and *Visual Basic* script languages. *ModelBuilder* provides the capability to automate a wide range of *ArcTools* and scripts appropriate for recurring calculations used in the bulking factor determination. This allows for minimal user input and rapid calculations of several attributes pertaining to the characterization of individual watersheds [Kraemer and Panda, 2009] (32). Automated calculations and extraction of needed attributes were implemented by the research team to calculate a 2-D *LS*-factor.

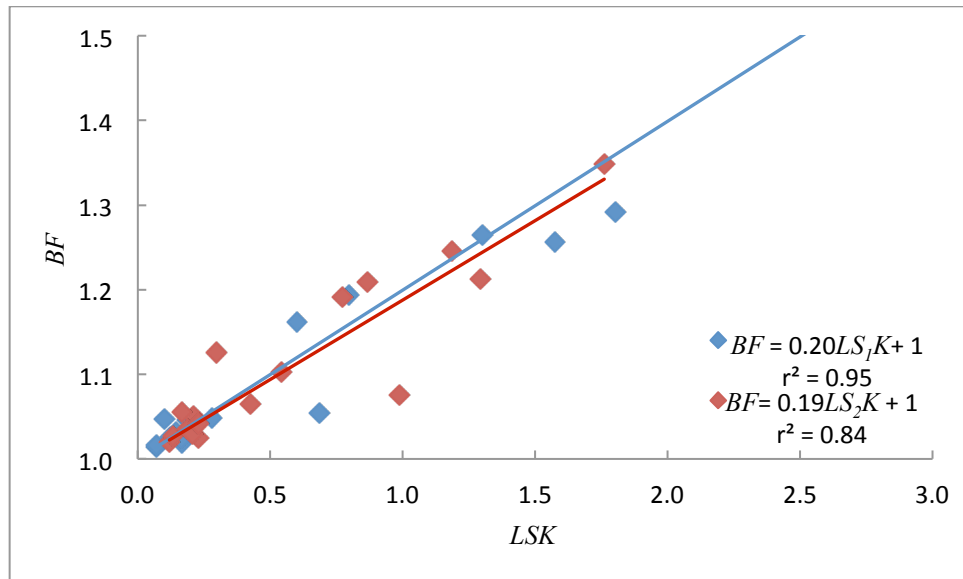
Specifically, given a masked *DEM* of the contributing watershed to a culvert, pixel by pixel *LS*-factors are automatically generated and stored in an appropriate folder location for subsequent user calculation of a bulking factor. A user-friendly step-by-step procedure was developed. The following figure represents the underlying *ModelBuilder* flow algorithm implemented in *ArcMap* for calculating the average 2-D *LS*-factor. Note that this algorithm is hidden from the user. Upon implementation, the algorithm requires user specification of the *DEM* file and a folder location for the results. The average 2-D *LS*-factor for the watershed can then be extracted with the spatial analyst toolset.





### Bulking Factor Relationships

Figure 9 contrasts bulking factors calculated using a 1-D and 2-D  $LS$  factor for the seventeen sites based on a linear regression upon the product  $LSK$ . Immediately obvious is the reduction in the magnitude of the bulking factor using the 2-D  $LS$  factor. The research team believes that the 2-D  $LS$  values are more appropriate, as they better approximate actual flow accumulation and convergence/divergence within a watershed. Similar linear correlations of bulking factor with the product  $LSKC$  were developed ( $BF = 0.52LS_1KC + 1$ ,  $r^2 = 0.94$ ; and  $BF = 0.54LS_2KC + 1$ ,  $r^2 = 0.88$ ).



**FIGURE 9: Bulking Factor Relationships.**

Statewide  $BF$  maps generated based on the linear regression relationships  $LS_1$  and  $K$ , and  $LS_1$ ,  $K$ , 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 lies in the mean values of each. Average values were extracted from the statewide  $BF$  maps for the watershed locations. Looking at the difference between  $LS_1K$  and  $LS_1KC$   $BF$  values, introducing the  $C$ -factor (incorporating vegetation) will increase or decrease the original  $LS_1K$   $BF$  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] (33). Introducing the  $C$ -factor provides a means for inhibiting or accelerating the distribution of erosion risk ( $BF$ ) in areas of high topographic relief.

Multi-linear regressions were also conducted for the watershed sites for  $LS_1$ ,  $K$ , and  $C$ . 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 of the variation of the dependent variable ( $BF_i$ ) around its mean ( $BF_{mean}$ ) is explained by the respective regressions ( $LS$ ,  $K$ , and/or  $C$ ). Statistically, the multi-linear coefficients for the  $LS_iK$  regression (intercept,  $LS$ ,  $K$ ) were statistically significant at an  $\alpha = 0.10$ . For the  $LS_i$ ,  $K$ , and  $C$  relationships,  $LS$  and  $K$  remain statistically significant ( $\alpha = 0.10$ ); however, the added  $C$  attribute coefficient was greater than the designated cutoff  $\alpha$  of 0.10 and would be considered statistically insignificant with relation to  $BF$ . However,  $C$  is a physiographic-based attribute and integral to  $MUSLE$  equation. Therefore, its inclusion may provide a better watershed bulking factor correlation with the availability of additional data.

In practice, when comparing which method would be best suited for calculating a statewide  $BF$ , a linear regression based solely on  $LS_i$  and  $K$  should provide a fairly accurate working map with minimal parameters required for a  $BF$  calculation. The research team chose to focus on a two-parameter approach.

### Estimating Uncertainty in a Calculated Bulking Factor

The MEI [2008] (31) methodology used by the research team to estimate a bulking factor has a number of variables and assumptions:

- Channel Width/Flow Depth Ratio ( $w/y$ ): 40:1
- Design Peak Flow/Dominant Flow Ratio ( $Q_{100}/Q_{dom}$ ): 5:1
- Channel Manning's Roughness Coefficient ( $n$ )
- Sediment Grain Size ( $d_{50}$ )
- Watershed Cropping Management Factor ( $C$ )
- Watershed Soil Erodibility ( $K$ )
- Watershed Length-Slope Factor ( $LS$ )
- Channel Slope (%)
- Runoff Volume ( $V$ )
- Peak Flow ( $_{24}Q_{100}$ )

The relative uncertainty in each of the above inputs to the bulking factor calculation can be propagated into a relative uncertainty in the bulking factor as follows:

$$u_{BF} = \left[ \left( \frac{x_1}{BF} \frac{\partial BF}{\partial x_1} u_1 \right)^2 + \left( \frac{x_2}{BF} \frac{\partial BF}{\partial x_2} u_2 \right)^2 + \dots + \left( \frac{x_n}{BF} \frac{\partial BF}{\partial x_n} u_n \right)^2 \right]^{1/2}$$

where

- $u_{BF}$  = relative uncertainty in bulking factor
- $x_i$  = independent variable or assumption  $i$
- $\partial BF / \partial x_i$  = derivative of bulking factor with respect to variable or assumption  $i$
- $u_i$  = relative uncertainty in variable or assumption  $i$

The  $\partial BF/\partial x_i$  may be estimated by plotting the change in  $BF$  with the change in variable or assumption  $i$  holding the other variables or assumptions constant.  $\partial BF/\partial x_i$  would be the slope of the resultant plot, and it represents the sensitivity of bulking factor to a given change in  $x_i$ .

This procedure was implemented with the ten inputs listed above over a range of  $\pm 20\%$  uncertainty for bulking factors between 1.05 and 1.35 based on the current data base. The percentage (%) uncertainty in the calculated bulking factor was linear given by the following equation ( $r^2 = 0.99$ ):

$$u_{BF} = 31.41 (BF - 1)$$

For example, the relative uncertainty in calculated bulking factors of 1.1, 1.2, and 1.3 is approximately 3.1, 6.3, and 9.4 % based on all variables and assumptions having a relative uncertainty of  $\pm 20\%$ . As the relative uncertainty of any one variable or assumption changes, the relative uncertainty in bulking factor will decrease or increase accordingly as its relative uncertainty is the combined effect of the relative uncertainties of all  $x_i$ s. For a 10% across the board relative uncertainty in variables and assumptions, the relative uncertainty in bulking factor is reduced by half.

### Bulking Factor and Length-Slope Factor (2D versus 1D)

During the course of project investigation, two length-slope ( $LS$ ) factors were evaluated for use in the MEI [2008] (31) bulking factor ( $BF$ ) methodology. A statewide one-dimensional  $LS_{1D}$  raster map was generated; however, the algorithm to generate a two-dimensional  $LS_{2D}$  was area-limited and could not be implemented on a statewide basis. Accordingly,  $LS_{2D}$  were calculated for each candidate watershed. For average watershed slopes less than approximately 6%, the  $LS_{2D}$  is less than  $LS_{1D}$  for the sites evaluated. Figure 10 shows the relationship between the two bulking factors and the length-slope factors upon which they were calculated.

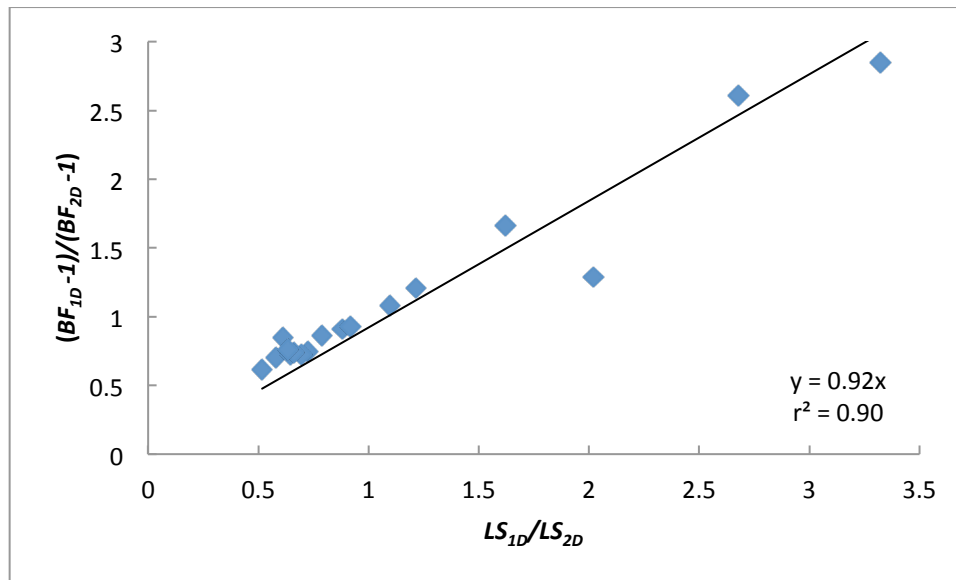
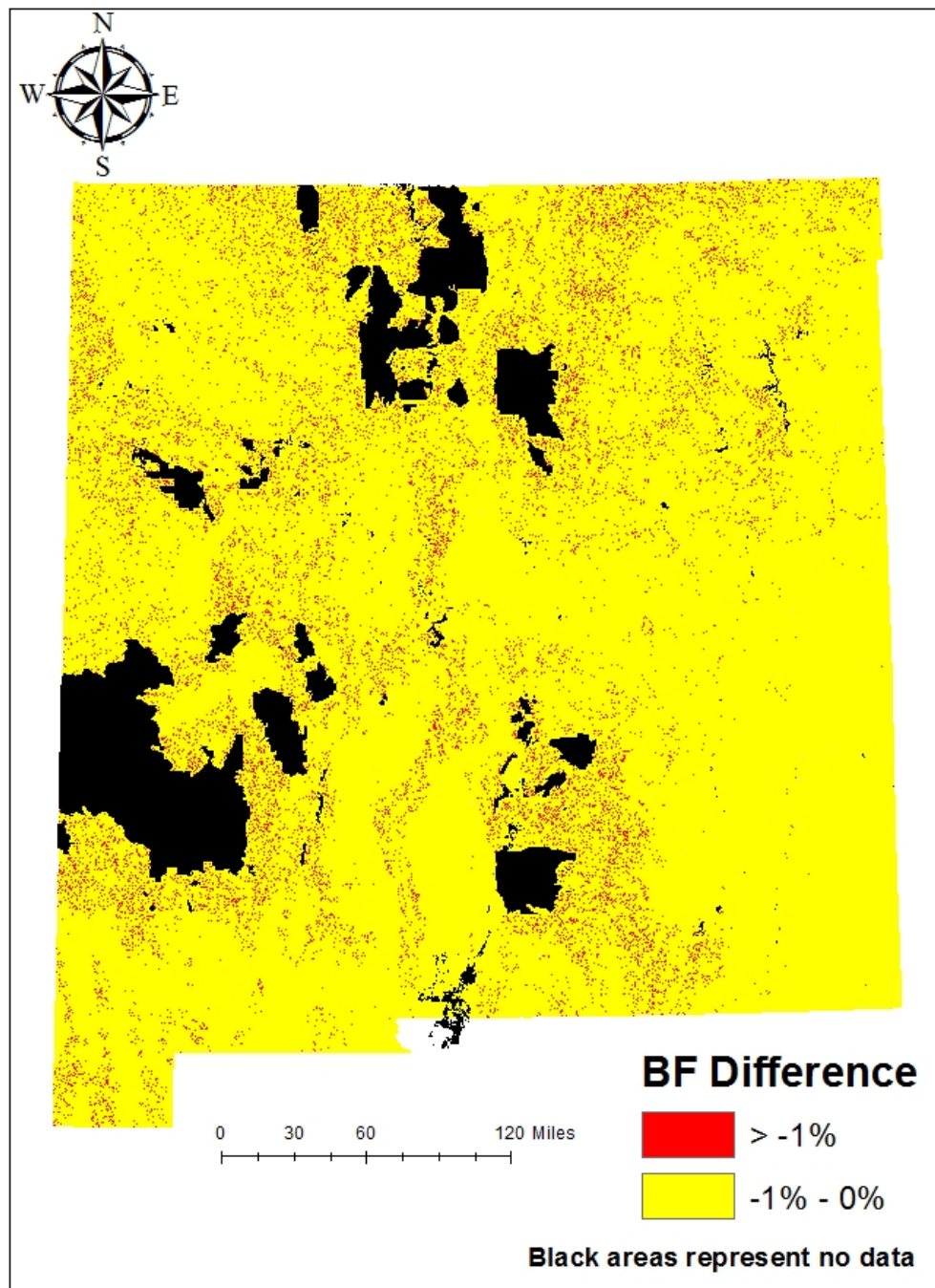


FIGURE 10: Bulking Factor and Length-Slope Factor (2D versus 1D).

A visual comparison of statewide raster maps of  $BF_{1D}$  and  $BF_{2D}$  based on the respective linear correlations of  $BF$  versus  $LSK$  was virtually indistinguishable. A normalized difference map calculated as the quantity

$$\Delta BF(\%) = 100 \left( \frac{BF_{2D} - BF_{1D}}{BF_{2D}} \right)$$

is given in Figure 11. The maximum normalized difference over the range of watershed  $LSKs$  is less than 2%. Therefore, it is recommended that the one-dimensional statewide map be used as a screening tool to identify potential problem areas and that the watershed specific bulking factor be evaluated using the MEI (2008) methodology based on implementing the two-dimensional length-slope factor.



**FIGURE 11: Normalized Difference Between  $BF_{2D}$  and  $BF_{1D}$ .**

## RESULTS

### Summary of Watershed Attributes

#### *Sediment yield*

The calculated sediment yield via the method of MEI (2008) *versus* drainage area showed an upward linear trend and followed the pattern common observed in 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] (35).

#### *K-factor*

The *K*-factor represents both susceptibility of soil to erosion and the amount and rate of runoff. The range of values for the eight watersheds was from 0.13 to 0.39 (Table 2). This range is associated with a coarse-textured sandy soil to medium-textured loamy soil having a low to moderate erodibility. Thus, the respective watershed soils may be classified as moderately susceptible to detachment, producing moderate runoff potential [Renard *et al.* 1991] (36).

**TABLE 2: Summary of Derived Attributes for the Watersheds.**

County	Type	Watershed	K Factor Avg	C Factor Avg	2d LS Factor Avg	LS Factor Avg	Channel Slope (ft/ft)	Q Peak (CFS) 100yr	Runoff Volume (AC FT) 100yr
Socorro	1- 8'CMP	US 380 MP 10.2	0.133	0.46	1.57	1.39	0.030	135.9	15.2
Lincoln	1-CBC 5x8	US 54 MP 103.4	0.186	0.42	0.64	0.37	0.020	100.1	21.8
Otero	2- CBC 3x4	US 54 MP 97.2	0.236	0.45	0.97	0.70	0.018	21.8	4.9
Catron	1-10' CMP	NM 36 MP 12.2	0.281	0.31	4.61	5.60	0.032	262.0	28.2
Rio Arriba	N/A CMP	NM 96 MP 14.0	0.386	0.23	3.07	3.37	0.060	439.6	43.2
Rio Arriba	2-72" CMP	US 285 MP 340.7	0.310	0.42	5.68	9.22	0.040	290.9	50.5
Socorro	CMP	I-25 MP 172.2	0.175	0.49	0.76	0.39	0.018	129.0	21.1
Dona Ana	N/A	Dona Ana Case Study	0.249	0.42	3.10	8.30	0.029	871.8	144.4
Sandoval	N/A	Sandoval CaseStudy	0.233	0.45	1.07	0.70	0.010	5280.1	2075.3
Sandoval	3CBC 10X11	I-25 Site B MP 241.2	0.315	0.15	12.02	27.57	0.100	1845.3	199.2
Sandoval	3CBC 6X8	I-25 Site A MP 241.5	0.248	0.39	2.19	7.26	0.040	287.2	65.9
Socorro	3-CBC	Star Route 1	0.360	0.39	2.41	2.21	0.038	804.7	159.0
DeBaca	54" CMP	US 60 MP 340.6	0.370	0.35	0.51	0.33	0.020	179.6	19.4
Mora	1-60" CMP	NM 120 MP 48.5	0.366	0.15	2.70	1.88	0.028	72.8	4.9
Torrance	1 4X3 CBC	US 285 MP 245.6	0.308	0.24	0.54	0.33	0.021	2736.8	506.7
Rio Arriba	1-48" CMP	US 64 MP 146.98	0.340	0.09	8.33	12.30	0.090	176.7	11.5
Socorro	1CBC 8X8	I-25 MP 155.2	0.350	0.32	1.21	0.80	0.028	254.2	45.0

### *LS-Factor*

The *LS* factor includes a slope length factor *L* and a slope steepness factor *S*, incorporating the effect of slope length and slope steepness on erosion, respectively. Values of *L* and *S* are relative and represent how erodible the particular slope length and steepness is relative to a unit plot [Renard *et al.* 1997] (37). Within each watershed a large range of gridded *LS* values was seen. Visually each watershed can be characterized by the gradation of *LS* across its drainage; extreme values (highs and lows) are present in specific parts of the watershed and do not provide an overall perspective. Although, it is valuable to know where higher or lower erosion/sediment transport/sediment deposition potentials are located in a given watershed, for this study it is most useful to view the *LS*-factor as an average with respect to each watershed (Table 2).

The candidate watersheds have average 1-D and 2-D *LS* factors ranging from 0.33 to 12.3 and 0.51 to 8.33, respectively. The calculated bulking factor (*BF*) is highly sensitive to the magnitude of the *LS*-factor. It is worth noting that the Catron County NM 36, MP 12.2 and Rio Arriba County US 285, MP 340.1 culvert sites are both problematic locations with respect to field verified culvert clogging. These sites had a high average *LS*-factor. The statewide average 1-D *LS* value is 4.6; however, high *LS* values can be observed in high topographic relief areas (mountainous regions) with lower values in areas of mild to minimal topographic features (plains). Development of a statewide 2-D *LS*-factor map was not possible given the processing limit of the *TauDem* software. However, an average 2-D *LS*-factor was determined for each watershed using *Modelbuilder*. Subsequent correlations were developed with the calculated *BF* values using average *LS*-factors determined from a clipped statewide map 1-D *LS*-Factor map and the *Modelbuilder* 2-D *LS*-Factor algorithm, respectively.

### *C-factor*

The *C*-factor, or cropping management factor, is a ratio of the soil eroded from a specific type of cover to that from clean-tilled fallow under identical slope and rainfall. With higher vegetative cover the potential for sediment transport is decreased. A cropping factor raster map was developed based on a statewide *NDVI* raster. The derived *C*-factor for the watershed sites are reasonably similar and range from 0.09 to 0.49 (Table 2), classifying them as low cover vegetation by definition, providing little cover from intense precipitation. One could infer that the study areas fall between a medium to low erosivity potential. This data parallels common vegetation seen in the arid southwest [Dick-Peddie *et al.* 2000] (34).

### *Particle Size ( $d_{50}$ )*

The  $d_{50}$  particle size for the study watersheds that were analyzed for sediment size gradation ranged between 0.6-1.5 mm, typical of semi-coarse to coarse sand.

### *Curve Number (CN)*

The watershed sites have a Hydrologic Soil Groups (*HSG*) rating of B, B/D, or D, with a predominance of B. This makes them moderately low potential for runoff due to moderate infiltration. Similarly, when looking strictly at land cover (*LC*), all sites consist of scrub to



barren *LC* classification. A *CN* raster grid for each respective watershed county was developed using *LC*, *NRCS* Soil Survey Geographic (*SSURGO*), *HSG*, and *DEM* data, interfaced with the *ArcGIS*® extension *HEC-GeoHMS* program and coupled with the *NRCS TR-55 CN* methodology. The range of calculated *CN* values for the eight watersheds was from 69 through 82, indicating a medium to high potential for runoff with minimal infiltration.

#### *Peak Discharge and Runoff Volume*

Based on a short duration, high intensity *Type II* storm (typical of the semi-arid southwest), a 100-yr, 24-hr design precipitation depth, and the Curve Number (*CN*) lag method, peak flows ( ${}_{24}Q_{100}$ ) ranged from 21.8-5280 cfs with runoff volumes ranging from 4.9-2070 ac-ft (Table 2). Runoff volume increased with increasing watershed area. The calculated total sediment flow ( $Q_{total}$ ) also increased with drainage area. Since this calculated value is based on peak flow ( ${}_{24}Q_{100}$ ), the observed upward linear trend would be expected based on the procedure (MEI 2008) used to estimate total sediment flow (31).

#### *Bulking Factor (BF)*

For many sites the *BF* was at low-end spectrum, i.e. less than 1.10. Sites with high *BF* values, greater than 1.20, paralleled field reconnaissance data that showed excessive sediment deposition and clogging of the associated culverts. Based on the 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.

#### **Alternative Bulking Factor Relationship**

The following equation may be used to relate sediment discharge ( $Q_s$ ) to clear water discharge ( $Q_w$ ), or

$$Q_s = aQ_w^n$$

where *a* and *n* are bulking constants fixed throughout the storm hydrograph. The value of *n* is between 2 and 3 for most sand bed streams [Vanoni, 2006] (38). For most of the candidate watersheds observed during field reconnaissance, this textural classification would be appropriate. The coefficient *a* may be estimated by integration of the storm hydrograph based on a total sediment yield. The method assumes that the peak sediment discharge coincides with the peak hydrograph discharge. In reality, there may be a significant lag time between  $Q_w$  peak and  $Q_s$  peak.

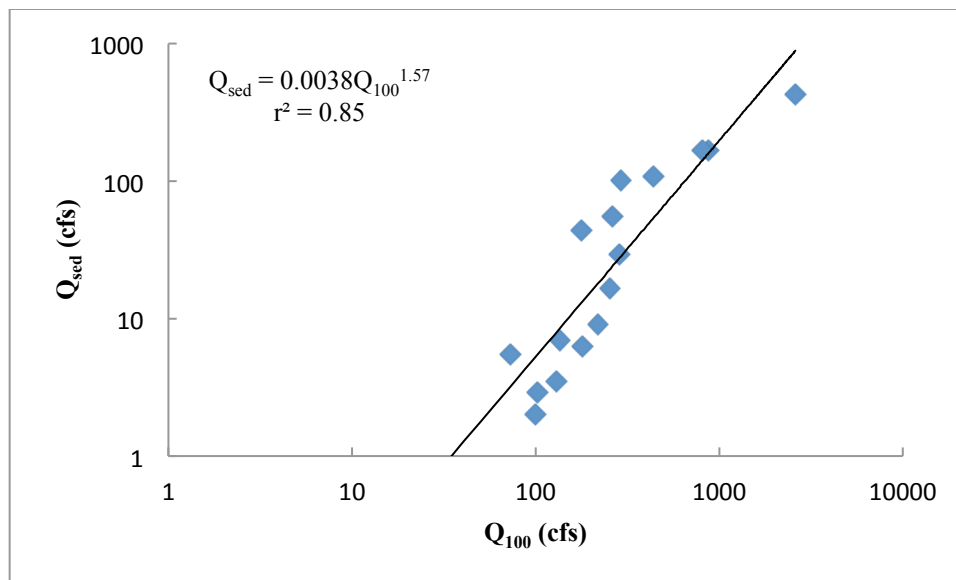
Combining the above equation with the definition of bulking factor ( $BF$ ), or

$$BF = \frac{Q_s + Q_w}{Q_w}$$

yields an alternative expression for  $BF$  in terms of clear water flow:

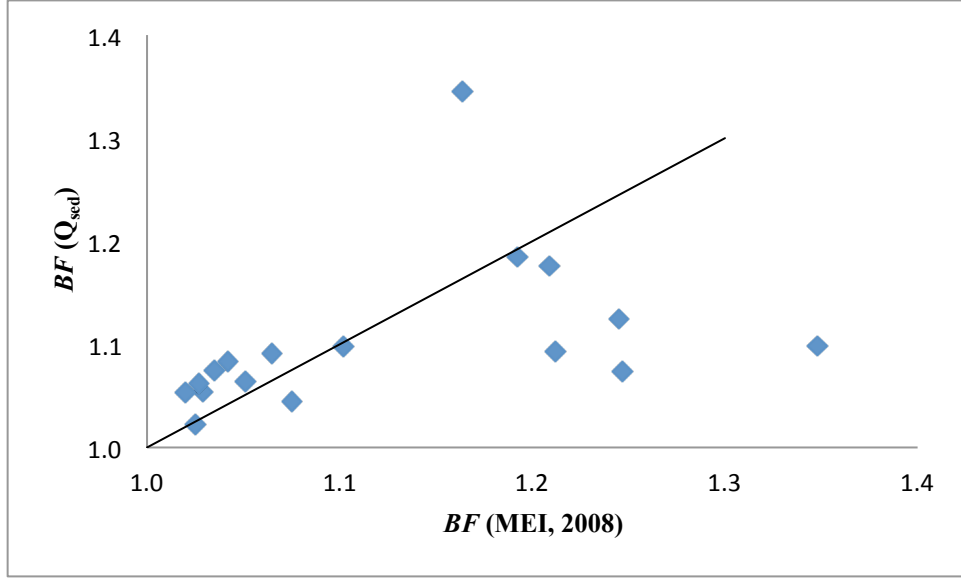
$$BF = 1 + aQ_w^{n-1}$$

The relationship between  $Q_s$  and  $Q_w$  for the watersheds analyzed is shown in Figure 12 based on the MEI (2008) methodology for  $BF$  (31). Although the regression coefficient is high, the exponent  $n$  does not lie between 2 and 3; however, the *MUSLE* does not account for concentrated flow erosion, only sheet and rill erosion, and does not include other potential sources of sediment, such as gully erosion, and channel bed and bank erosion. In addition, the coefficient  $a$  is storm and watershed specific and not a constant as determined herein for the suite of watersheds. However, with the assumption of a constant coefficient  $a$ , one may compare  $BF$  results.



**FIGURE 12: Sediment Discharge versus Clear Water Discharge.**

Figure 13 contrasts the  $BF$  values estimated by the MEI (2008) method with those determined using the above regression equation and the alternative expression for  $BF$  given in terms of  $Q_w$  as evaluated by *HEC-HMS*. The diagonal line represents a 1:1 correlation. The correlation is poor; thus, estimating a  $BF$  strictly in terms of  $Q_w$  would not be advised as both  $a$  and  $n$  are storm and watershed specific. Further, these coefficients may be time-dependent, and not fixed as assumed.

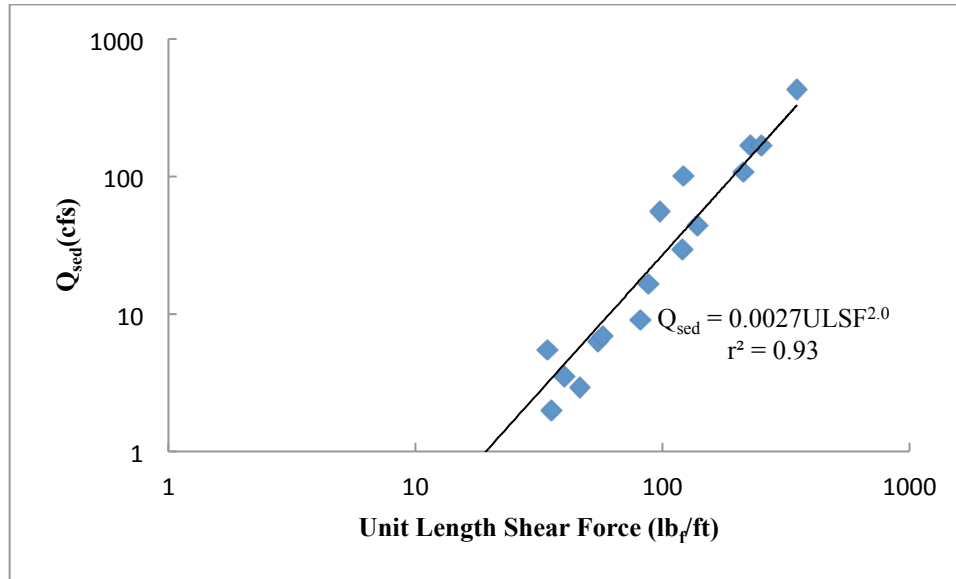


**FIGURE 13: Comparison of BF Values.**

Concentrated flow erosion is considered a threshold phenomenon, wherein incision occurs when a threshold of soil resistance is exceeded. The critical threshold may be related to the hydraulics of flow (Knapen, *et al.*, 2007). A number of these predictor variables were evaluated based on the hydraulic information derived from the MEI (2008) procedure. These included shear stress, unit length shear force, stream power, and effective steam power. Interestingly, a strong correlation was observed between the calculated  $Q_s$  and unit length shear force ( $\Gamma$ ), defined as

$$\Gamma = \tau W_p = \gamma R_h S W_p$$

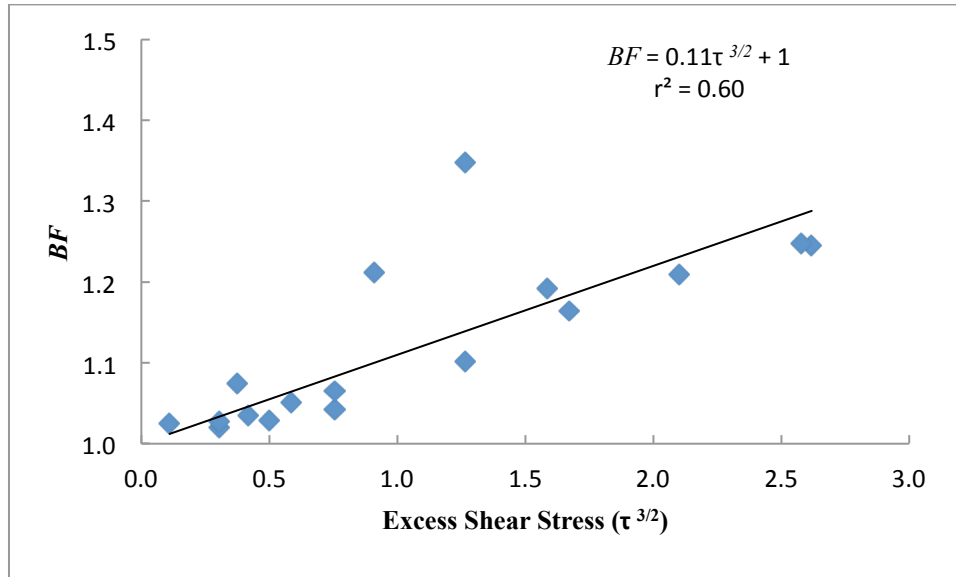
where  $\tau$ ,  $W_p$ ,  $\gamma$ ,  $R_h$ , and  $S$  equals the bed shear stress, channel wetted perimeter, unit weight of water, channel hydraulic radius, and average bed slope, respectively. Figure 14 depicts this relationship.



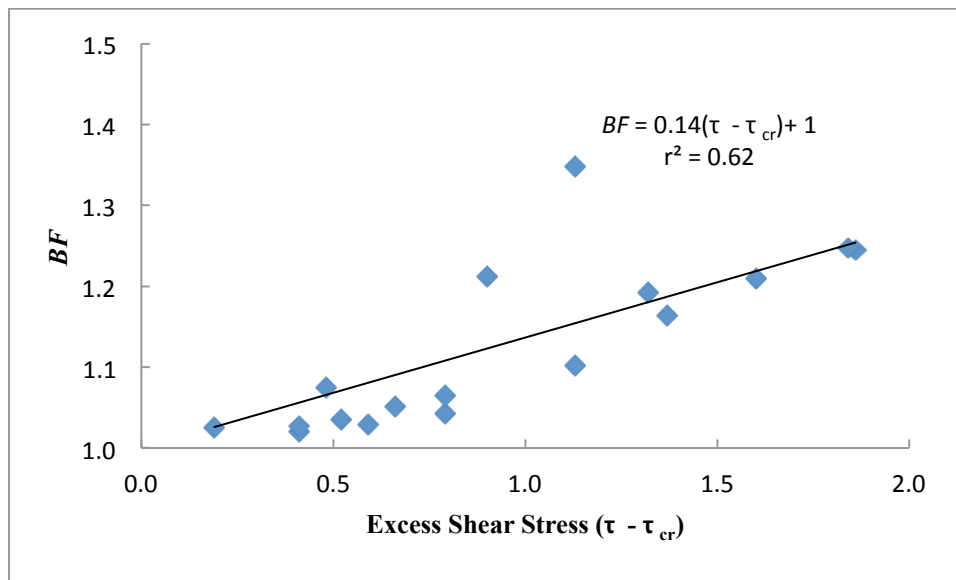
**FIGURE 14: Total Sediment Flow as a Function of Unit Length Shear Force.**

Excess shear stress models have been used to evaluate concentrated flow soil erosion (Knapen, *et al.*, 2007). A simplified version for soil detachment capacity is proportional to flow shear stress raised to the  $^{3/2}$  power, or  $\tau^{3/2}$ . A linear excess shear model assumes the soil detachment capacity is proportional to the difference between  $\tau$  and  $\tau_{cr}$ , where  $\tau_{cr}$  is a critical shear stress below which no detachment occurs. The proportionality coefficient is termed the soil erodibility, not to be confused with the soil erodibility  $K$ -factor. Actual soil detachment rate is a function of sediment load and water flow sediment transport capacity; furthermore, no consensus exists about the nature of the relation (linear or non-linear) between detachment rate and shear stress (Knapen, *et al.*, 2007). However, assuming that a bulked water flow is physically manifested by some level of soil detachment capacity, a  $BF$ , albeit determined analytically or experimentally, may be somewhat correlated with these excess shear stress metrics. For high shear stress and long slopes, the linear form may be acceptable and  $\tau_{cr}$  can be omitted when flow shear stress is large [Knapen, *et al.*, 2007] (39).

Figures 15 and 16 provide the correlations between  $BF$  and  $\tau^{3/2}$  and  $BF$  and  $\tau - \tau_{cr}$ , respectively. Based on a review of soil texture data conducted by Knapen, *et al.* (2007), the value for  $\tau_{cr}$  for sandy soil was estimated to around  $0.04 \text{ lb}_f/\text{ft}^2$  or  $2 \text{ Pa}$ .  $BF$  increases with an increase of the respective excess shear metric. The correlation is not high; however, if firmly established, such relationships are simple to use as the flow regime shear stress can be estimated for a particular channel bed based on the peak flow discharge, channel slope, cross-sectional flow, and assumed soil texture.



**FIGURE 15:  $BF$  versus Excess Shear Stress (Non-Linear).**



**FIGURE 16:  $BF$  versus Excess Shear Stress (Linear).**

### **Culvert Sites—Outlet Below Existing Ground Topography**

Throughout the conduct of field reconnaissance, several culverts were observed to be constructed with the outlet invert below the existing ground topography. A prime example is a 36-in corrugated metal pipe (CMP) culvert located in Lincoln County on Hwy 380, MP 81.5. This culvert was one of the initial culverts identified by the NMDOT as a potential candidate for study. It was, however, not selected based on this outlet feature. At the time of the visit, the

culvert barrel was approximately three-quarters full of sediment at the inlet and over half full at the outlet. The top of the culvert barrel is just visible in Figure 17.



**FIGURE 17: Hwy. 380 CMP Culvert, MP 81.5 (outlet).**

Another non-candidate double 8 ft x 8 ft rectangular concrete box (RCB) culvert that was visited recently is located on I-25 at MP 199.1 in Valencia County. Figure 18a below clearly indicates the historical remnants of severe inlet clogging to the full interior height. The culvert outlet is shown in Figures 18b. Additional evidence of sediment clogging approximately halfway up the interior height is noted in this figure. A mild, yet adverse terrain slope beyond the culvert outlet is depicted in Figure 18c. This feature was visually quite evident during the site visit. Figure 19 is a street view image from Google Earth showing the large mounds of excavated sediment adjacent to the culvert outlet.





**FIGURE 18a,b, and c: I-25 RCB Culvert, MP 199.1 (inlet, outlet, and outlet topography).**



**FIGURE 19: Excavated Sediment from I-25 MP 199.1 Culvert.**

The candidate culvert site located in Catron County on Hwy. 36, MP 12.2 was visited four times. This culvert was observed to be fully clogged during the initial visit. The estimated bulking factor ( $BF$ ) for the contributing watershed is 1.21 based on a 2-D length-slope factor ( $LS_{2D}$ ). A sequence of photographs taken of the outlet at different times before and after cleaning is provided as Figures 20a-d. After cleaning, a noticeable positive elevation gradient in the downstream drainage at the culvert outlet exists. This is evident in the two outlet photographs taken after cleaning (Figures 20b and c), showing a filling-in of the downstream drainage area over time following two storm events. The latter picture clearly shows the sediment fan that developed at the outlet. The adverse slope exacerbates the sediment deposition problem and will

lead to the eventual complete clogging of the culvert, as was initially witnessed prior to cleaning. Thus, the combination of a high bulking factor and an adverse culvert invert relative to natural outlet drainage will precipitate rapid clogging of the culvert barrel for this site.



**FIGURE 20a, and b: Hwy. 36 CMP Culvert, MP 12.2 Outlet Showing Adverse Grade, MP 12.5 (5/26/2012 before cleaning, 10/6/2011 immediately after cleaning).**



**FIGURE 20c, and d: Hwy. 36 CMP Culvert, MP 12.2 Outlet Showing Adverse Grade, MP 12.5 (6/22/2012 and 10/23/2012 sediment deposition following storm events).**

A final example of a structure with an adverse outlet gradient is a 30-in CMP culvert located in Rio Arriba County on US285, MP 340.1 as shown in Figure 21 (photograph taken 11/13/2012). The figure indicates a recent cleaning of the downstream drainage to the right-of-way; however, the culvert outlet invert lies below ground level. A sediment dam now exists at the right-of-way boundary. This non-candidate culvert lies within 0.6 mi of a candidate culvert site (MP 340.7) that has an estimated bulking factor of 1.35. The culvert outlet was substantially filled to the crown at 24-in sediment depth; the inlet had approximately 9-in of sediment deposition.





**FIGURE 21: US285, MP 340.1 Culvert Outlet.**

A Google Earth street image of the inlet to this culvert is given in Figure 22. The channel shows evidence of aggressive incision near the inlet. This particular watershed is small, but is topographically dominated by nearby regions of high slope which funnels the excess runoff to the culvert.



**FIGURE 22: Inlet to US 285 MP 340.1 Culvert.**

### **Erosion Risk Using Fuzzy Cell**

Fuzzy set theory formalized by Zadeh (1965) provides a methodology for handling subjective and linguistically expressed variables and represents uncertainty in the absence of complete and precise data (40). The logical processing using fuzzy set theory is known as fuzzy logic. Mitra *et al.* (1998) developed a fuzzy logic model to predict soil erosion in a relatively large watershed using inputs of slope angle, soil erodibility, etc. expressed as linguistic variables. The objective was to provide macro-level soil erosion risk zone maps. A similar approach was used by Guesgen *et al.* (2000) to predict soil erosion potential, which included input variables of slope, annual precipitation, and vegetation (41). For the research described herein, a fuzzy logic knowledge-based methodology was implemented within a *GIS* environment using *FuzzyCell* software to evaluate relative soil erosion risk for the State of New Mexico.

A general fuzzy inference system has the components of fuzzification, fuzzy rule base, fuzzy output inference engine, and defuzzification. Fuzzification converts each piece of input data within a raster data set to degrees of membership via a given membership function, which assumes values between 0 (no membership) to 1 (full membership). Fuzzy membership can take on several forms of classification, e.g. triangular, trapezoidal, and Gaussian.

A fuzzy rule base contains fuzzy rules that include all possible fuzzy relations between inputs and outputs. These rules are expressed in logical a *if-then* format using expert knowledge-based judgment supplied by the project investigators or from a literature review. For relative levels of soil erosion, the model uncertainties are included within the fuzzy logic rule set in the form of simple *if-then* statements using linguistic variables, e.g. high, medium and low.

*FuzzyCell* is an output inference engine designed and implemented to enhance conventional GIS software (ArcMap<sup>®</sup>) with fuzzy set theory (Yanar and Akyürek, 2006) (42). The procedure internalized within this software consists of four steps: 1) computing compatibilities; 2) truncating or scaling conclusions; 3) aggregating truncated or scaled conclusions; and 4) defuzzification. As an example of this procedure, consider the following *if-then* rule:

**IF** *A* is low and *B* is low and *C* is high, **THEN** *D* is medium

**Compatibility** — For given values of *A*, *B*, and *C* (i.e. 5.6, 20.1, and 103.6) and a linguistic designation (i.e. low, medium, and high) via their respective membership function, a compatible fuzzy value (0 to 1) is assigned for each fact (i.e. 0.87, 0.92, and 0.56, respectively). For example, the fact of *A* being 5.6 with a linguistic designation of low yields a fuzzy value of 0.87 from its assigned membership. Use of a *t-norm* operator “product” makes the conclusion sensitive to every input *versus* a *t-norm* operator “min” in which only one input controls the conclusion. For the “product” operator, the compatibility with the above *if-then* rule would be  $0.87 \times 0.92 \times 0.56$  or 0.45. For the “min” operator, the compatibility is 0.56. The compatibilities for other rules are similarly evaluated. The result of computing compatibility is that the degree to which the antecedents (i.e. the *ifs*) have been satisfied is known (Liu *et al.*, 2007) (43).

**Truncation or Scaling** — An implication operator is used to shape the consequence (i.e. the *then*) of the rule via a truncation (“min”) or scaling (“product”) of each conclusion. For a set of *if-then* rules, *D* is also assigned a fuzzy membership function (i.e. triangular or trapezoidal) with linguistic designations (i.e. low, medium, and high). For the above rule, a “min” implication operator truncates the *D* medium membership function at either 0.45 or 0.56 depending upon the type of compatibility operator specified. A “product” implication operator simply scales down the membership function by the specified compatibility operator, retaining the original triangular or trapezoidal membership shape.

**Aggregation** — Next, the inferred conclusions about *D* having the same linguistic variable (i.e. low, medium, and high) are aggregated, or combined into a single fuzzy set, typically using the union of all truncated or scaled conclusions via the “or” operator. The “or” operator uses the maximum value of all conclusions for a given linguistic variable of *D*.

**Defuzzification** — Defuzzification is a means to convert the aggregated fuzzy set into a precise value, or crisp conclusion. Several methods are available, including weighted average, maximum membership, average membership, and center-of-gravity method. The latter takes the center of the area under the aggregated fuzzy set as the answer. Defuzzification results in a unique number for each pixel within the output raster set.

### Relative Soil Erosion Risk via Fuzzy Inference System

Annual soil loss may be modeled empirically using the Revised Universal Soil Loss Equation (*RUSLE*) and a *GIS* Raster-based approach. The topography is represented as gridded cells with the assumption that each cell is internally uniform with respect to controlling factors such as soil type, rainfall, slope gradient, vegetative cover, etc. The average annual soil erosion (*A*) for any given cell may be estimated from six factors:

$$A = R K L S C P$$

where,  $R$  is the long-term annual average rainfall erosivity,  $K$  is the soil erodibility factor,  $L$  is the slope length factor,  $S$  is the slope gradient factor,  $C$  is the crop management factor, and  $P$  is the conservation support factor. Instead of obtaining a value for annual soil loss using the *RUSLE* method, a fuzzy logic approach was implemented to estimate a relative macro-scale erosion risk based on fuzzification of soil erodibility, slope gradient, 2-yr, 6-hr precipitation ( ${}_2P_6$ ), and a normalized difference vegetative index ( $NDVI$ ). The latter two variables are surrogates for the rainfall erosivity ( $R$ ) and crop management factor ( $C$ ), respectively.

The selected soil erosion variables ( ${}_2P_6$ ,  $K$ ,  $S$ , and  $NDVI$ ), represented as raster maps of *NM* data, were assigned a trapezoidal membership function with classes of low, medium, and high soil erosion risk. Assignment and delineation of fuzzy membership is best based on expert opinion (the project investigators or a literature review). A search of the literature provided some insight into the specification of each variable, for example slope (Mitra, *et al.*, 1998; Tayfur, *et al.*, 2003) (44,45), soil erodibility (Mitra, *et al.*, 1998; Ahamed, *et al.*, 2000) (44,46), and precipitation (Guesgen *et al.*, 2000) (41).

Wischmeier and Smith (1978) reported that the  $R$  factor could be approximated with reasonable accuracy using the 2-yr, 6-hr rainfall frequency distribution (47). The relationship for the western states is as follows:

$$R = 27.38P^{2.17}$$

where,  $P$  is the 2-yr, 6-hr precipitation (in) and  $R$  equals the rainfall erosivity (hundreds ft ton/ac-yr). The statewide 2-yr, 6-hr precipitation for New Mexico ranged from a maximum of 2.20 in to a minimum of 0.7 in with an average of 1.38 in. Using the above equation and cutoff values of 10, 50, and 90 as being low, medium, and high rainfall erosivity, membership classes for the 2-yr, 6-hr precipitation were specified as 0.63, 1.32, and 1.73 in, respectively, for low, moderate, and high erosion risk based on a trapezoidal membership function.

A trapezoidal membership function was also implemented for both soil erodibility and slope gradient with cutoff values of 0.10, 0.30, and 0.5 and 5, 10, and 15%, respectively, for low, moderate, and high erosion risk, respectively. These cutoff values were selected based a review of soil erosion literature that utilized a fuzzy inference approach (soil erodibility (Mitra, *et al.*, 1998; Ahamed, *et al.*, 2000) (44,46) and slope (Mitra, *et al.*, 1998; Tayfur, *et al.*, 2003)) (44,45).

The membership classes for  $NDVI$  were based on the reverse scaling of  $C$  values using the following formula:

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

where,  $\alpha$  and  $\beta$  are parameters that determine the shape of the  $NDVI$ - $C$  curve. An  $\alpha$  of 2 and  $\beta$  of 1 were used (van der Knijff *et al.*, 1999) (48). Values of  $C$  equal to 0.8, 0.5, and 0.2, respectively, were selected as cutoffs for high, medium, and low soil loss via a fuzzy inference for the *RUSLE*. Using the above formula with the stated fitting parameters, gave  $NDVI$  inputs of 110, 125, and 145, respectively, for the cutoff values. These values were then used to assign fuzzy memberships for high, moderate, and low erosion risk based on a trapezoidal membership function.

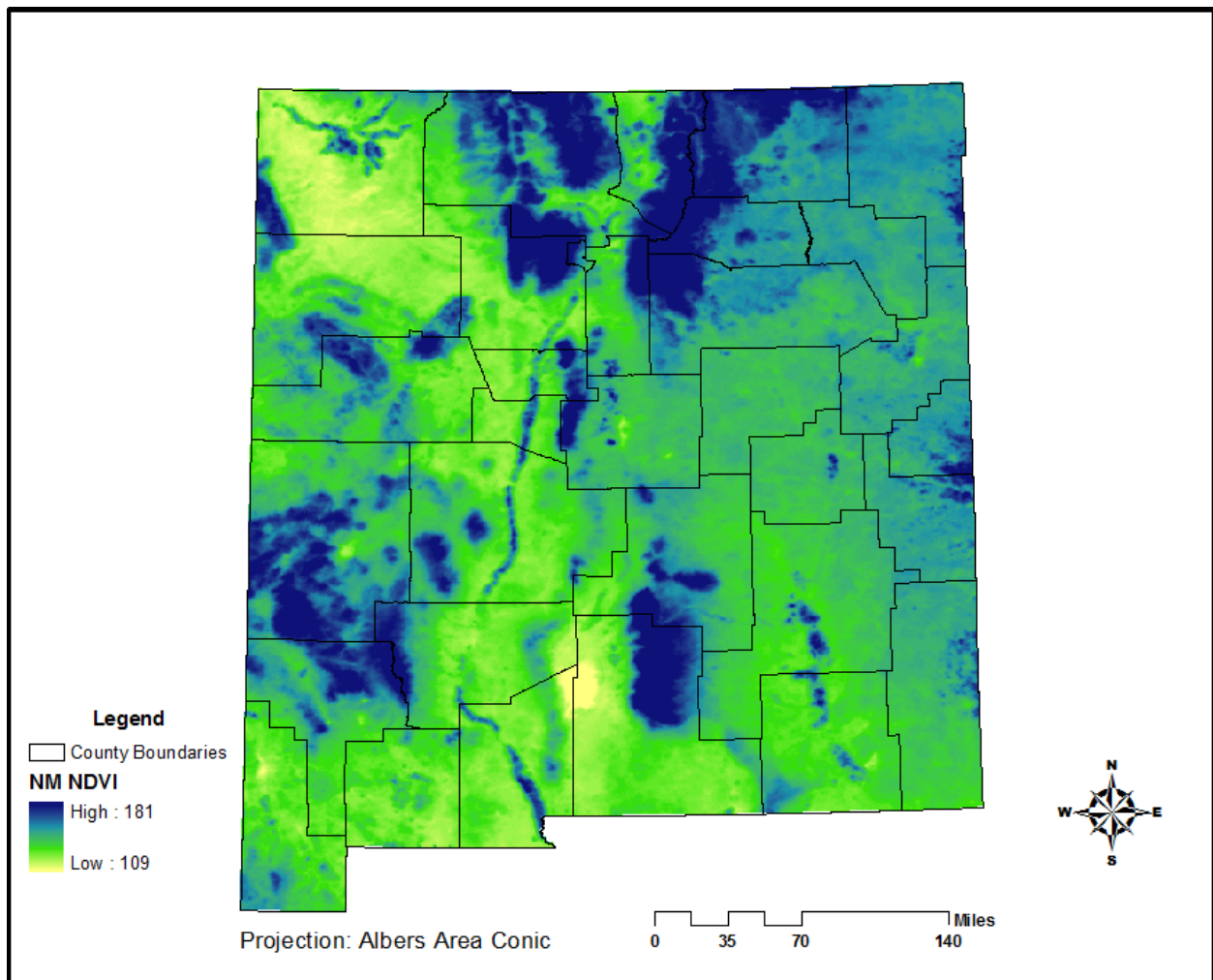


In all four input variables, partially overlapping membership classes were used. The respective raster data sets and memberships with associated cutoffs are depicted in Figures 23 through 30 for *NDVI*,  ${}_2P_6$ , *K*, and *S*, respectively. The *NDVI* raster in Figure 23 represents an average maximum annual NDVI value from 1995-2009.

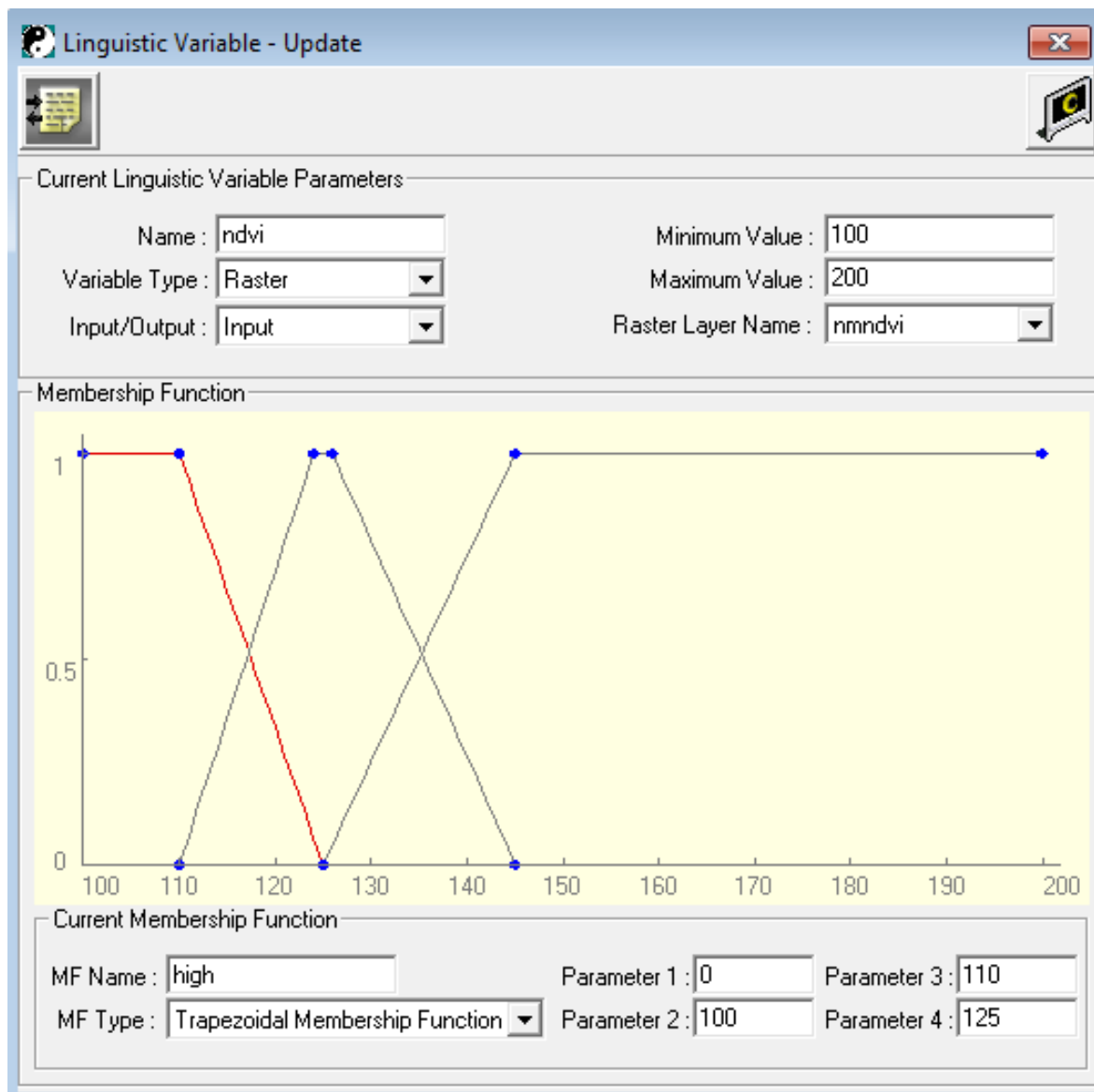
Having four input variables ( ${}_2P_6$ , *K*, *NDVI*, and *S*) and three linguistic classes (low, moderate, and high) requires  $3^4$  or 81 *if-then* rules. A partial list of these rules is given in Figure 31. These rules are comprised of an *if-then* premise and a consequence; for example, if *x* is *A* and *y* is *B*, then *z* is *C*. The consequence is also given in terms of a linguistic variable, such as low, medium, or high soil erosion risk. For this analysis, a partially overlapping triangular membership function was used for relative soil erosion with seven levels of consequence (aka significance) as given in Figure 32.

*FuzzyCell* software was used herein as the fuzzy inference system. Compatibility was computed using the *t-norm* “product” operator. The *t-norm* “min” operator was specified as the implication operator with the inferred conclusions aggregated via the “or” operator. The center-of gravity defuzzification was used to obtain distinct values of relative soil erosion risk from 0 (low risk) to 1 (high risk). If desired, the raster calculator may be used to convert these values into a project risk scale from 1 to 10.

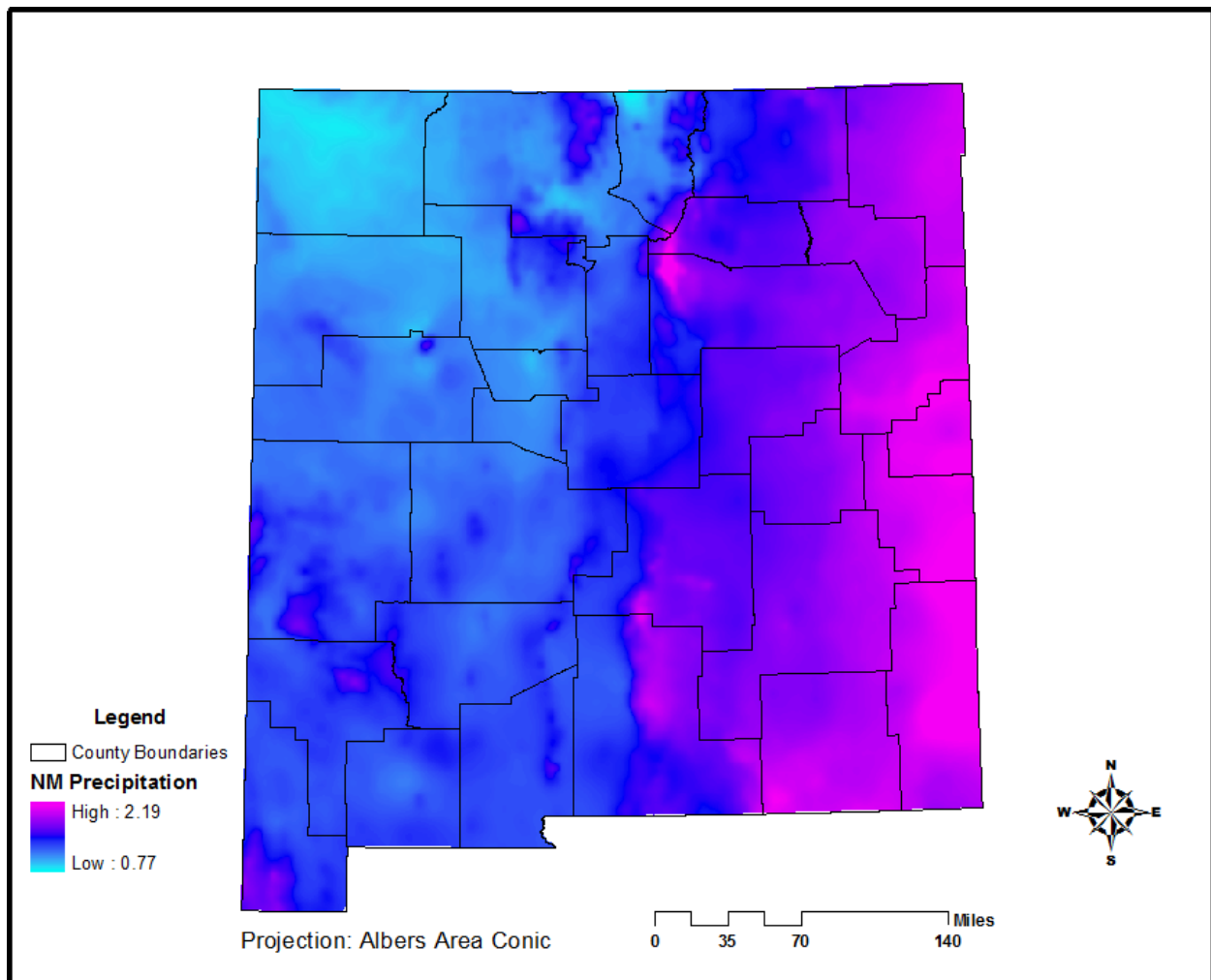
Upon implementing the model with 81 rules and a 30-m *DEM*, it was quickly observed that *FuzzyCell* is limited in the amount of information that can be processed without obtaining a fatal error (crashing the software). Running the model using all of the the statewide raster data sets at one time was not possible. Masking of the smaller irregular-shaped HUCs (hydrologic uniform code) also produced the same result. The model does run on smaller rectangular-shaped masked areas. This necessitated repeated runs of the model and the merging of output raster sets to produce the statewide erosion map shown in Figure 33.



**FIGURE 23: NM Normalized Difference Vegetative Index (NDVI) Distribution.**

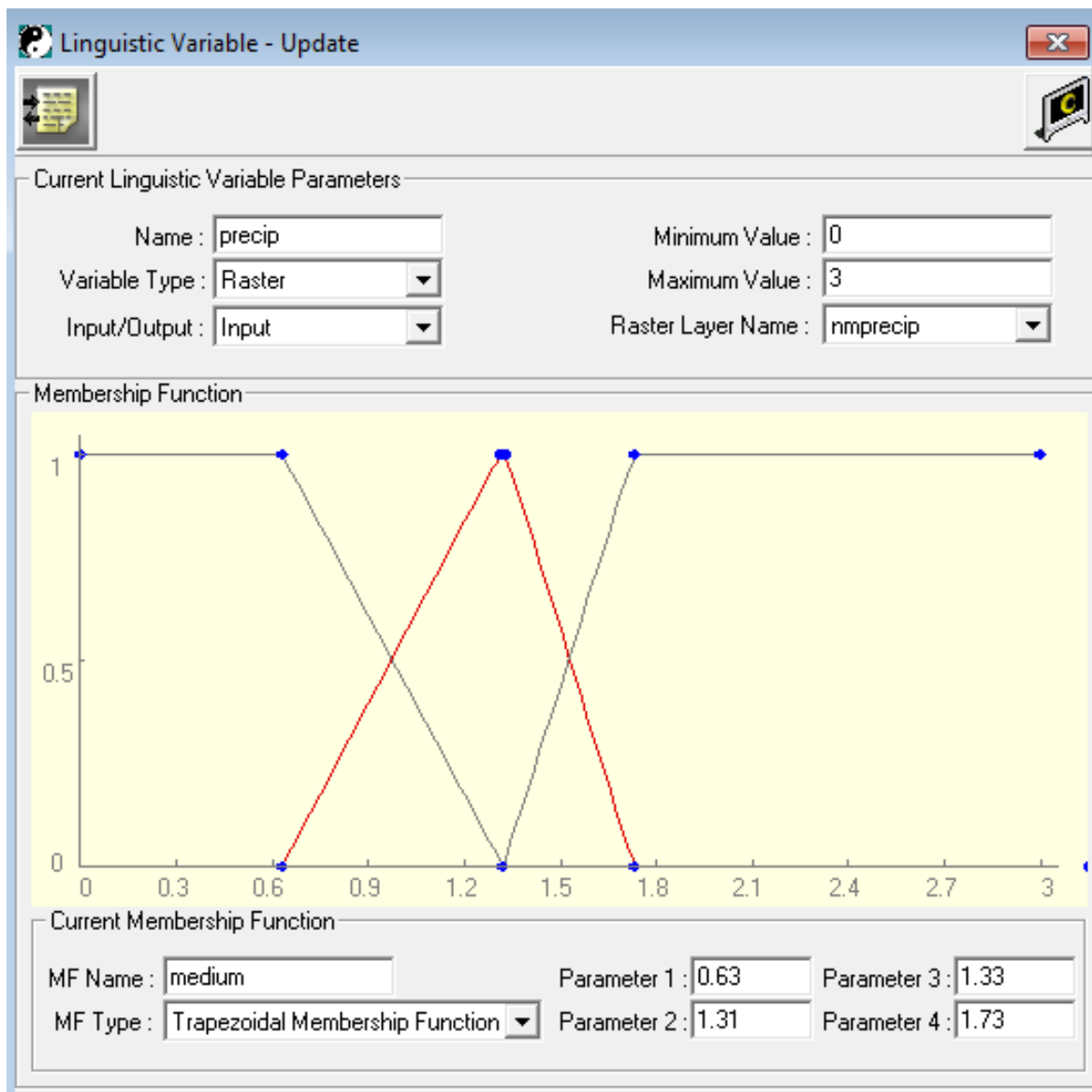


**FIGURE 24: *NDVI* as a Linguistic Variable Input.**

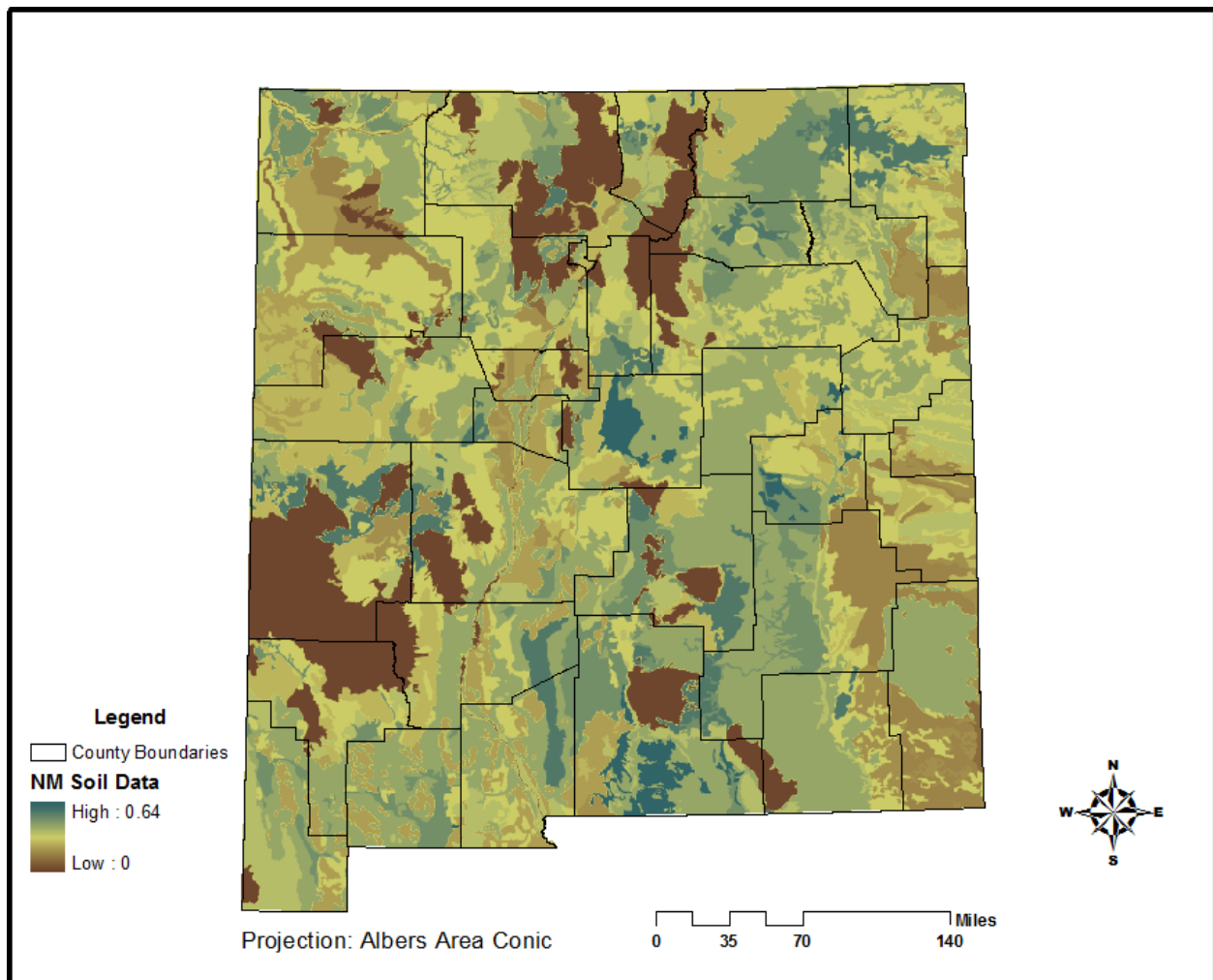


**FIGURE 25: NM 2-yr, 6-hr ( $2P_6$ ) Precipitation Distribution.**

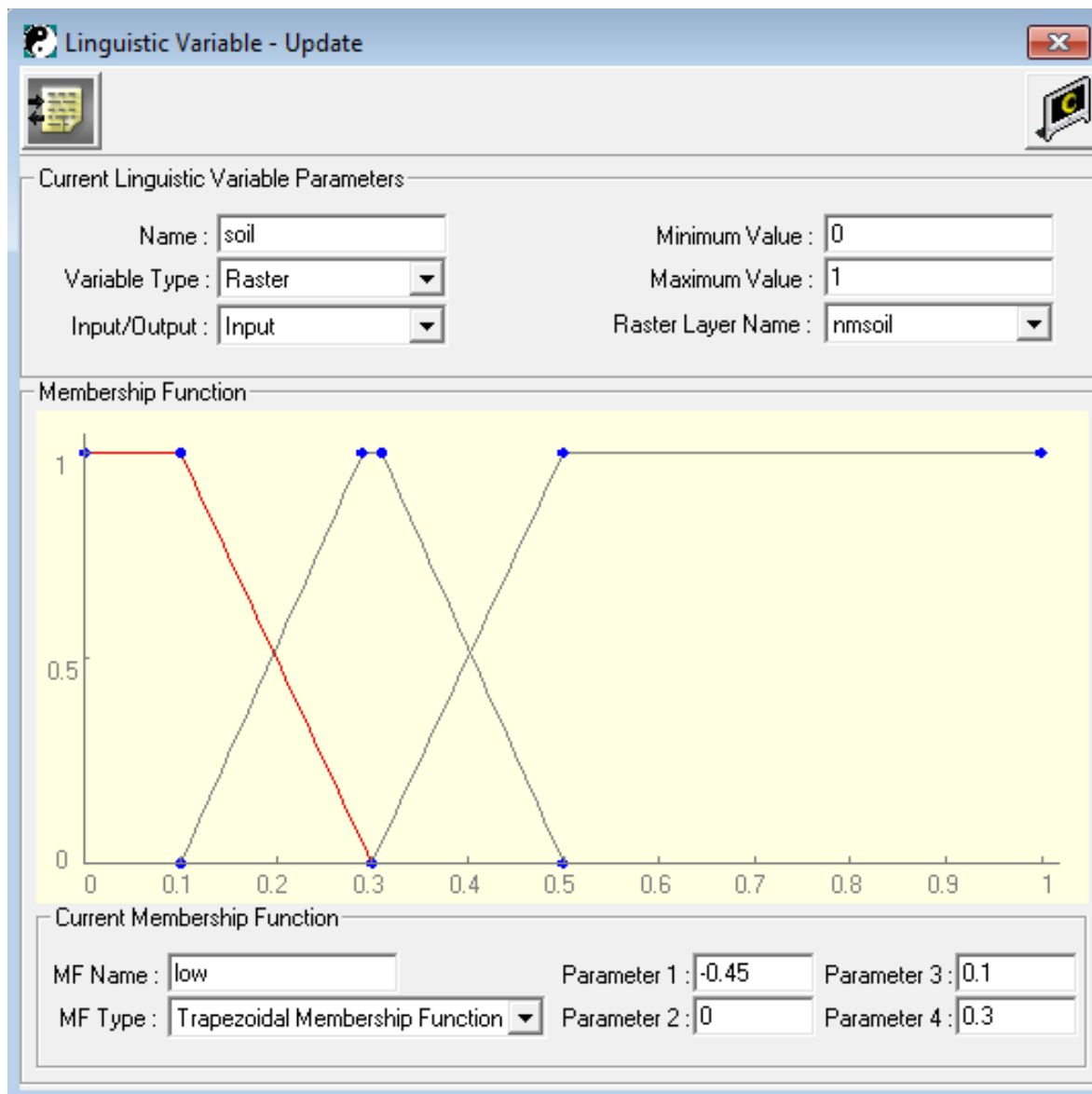




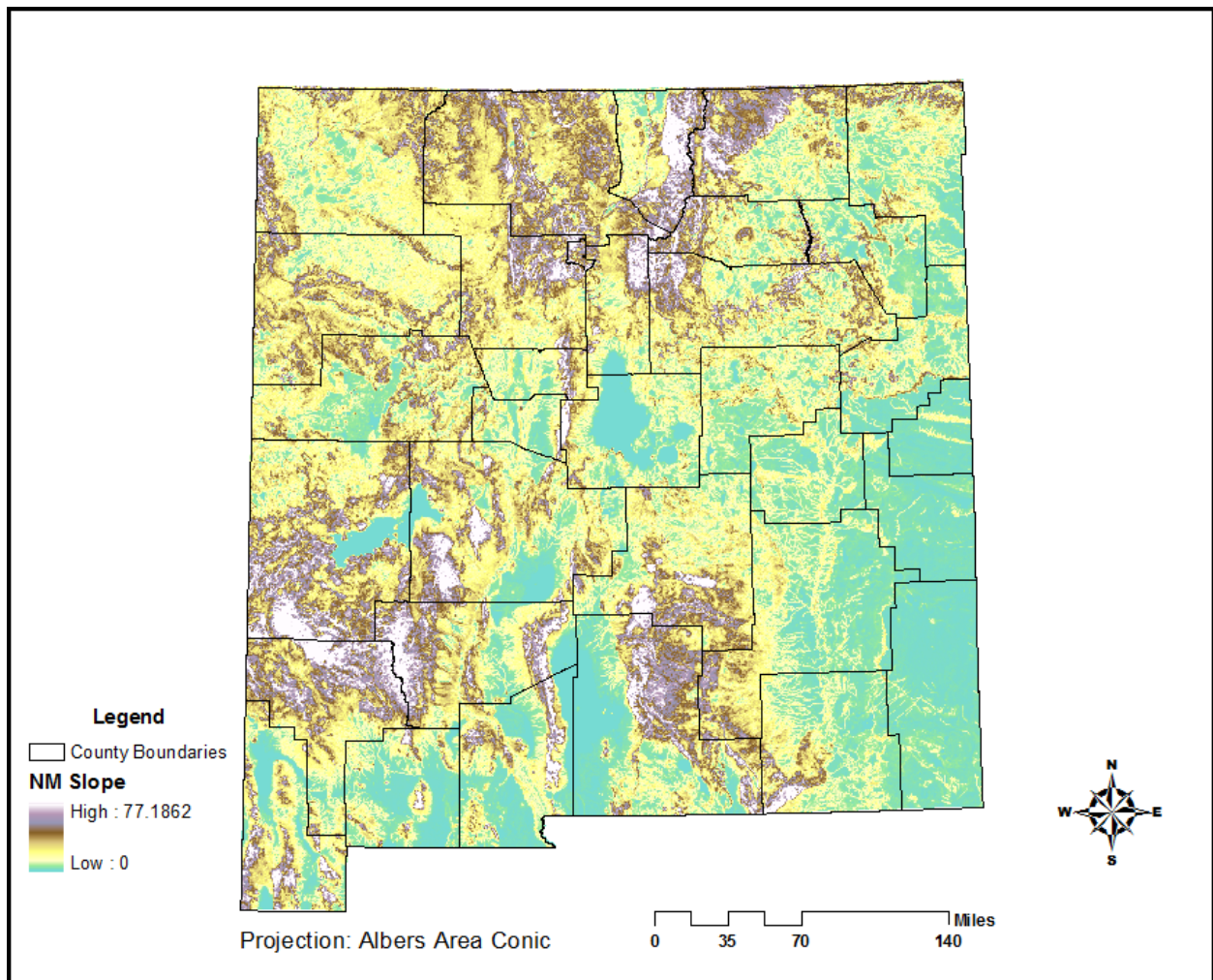
**FIGURE 26: Precipitation as a Linguistic Variable Input.**



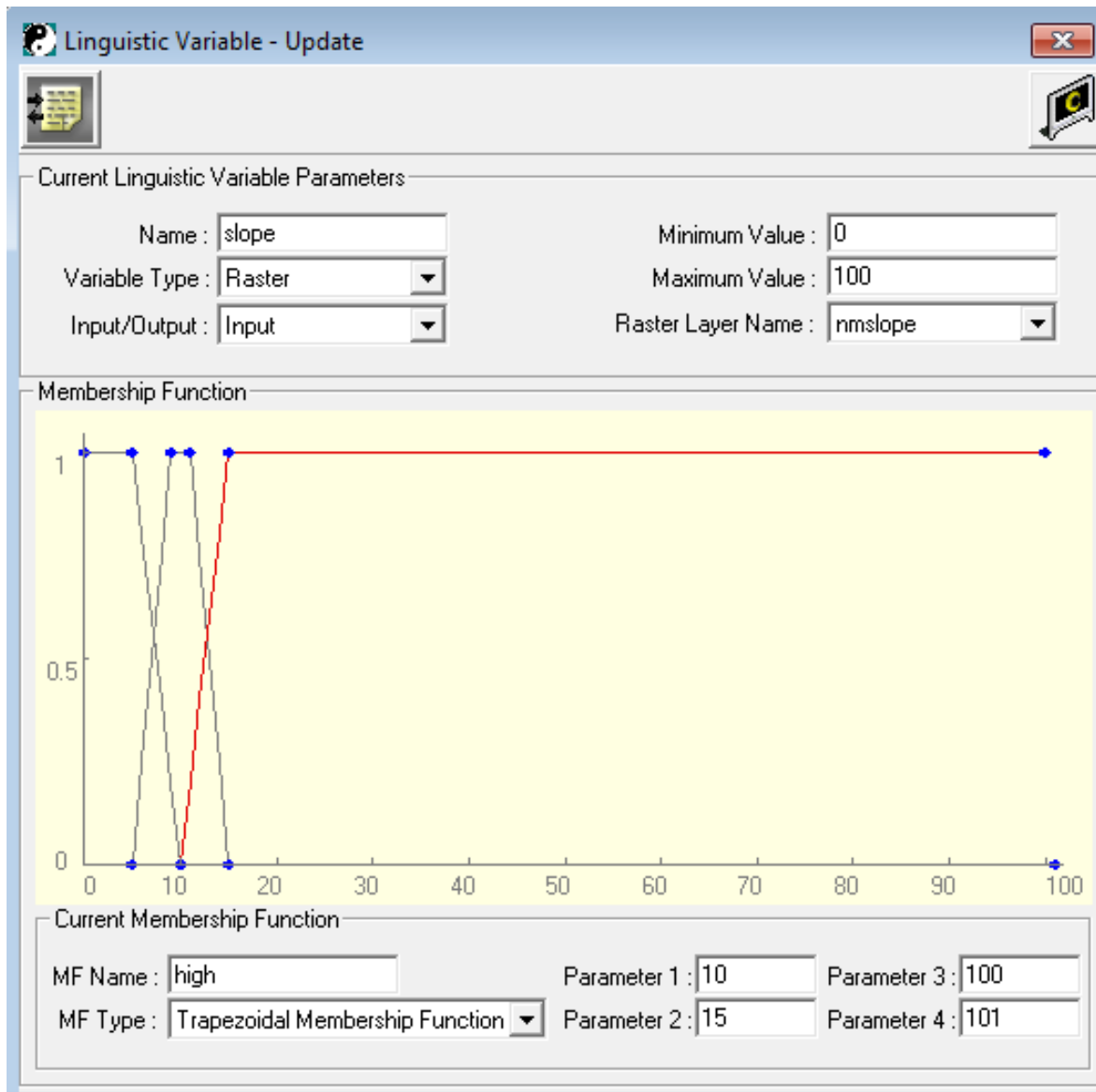
**FIGURE 27: NM Soil Erodibility.**



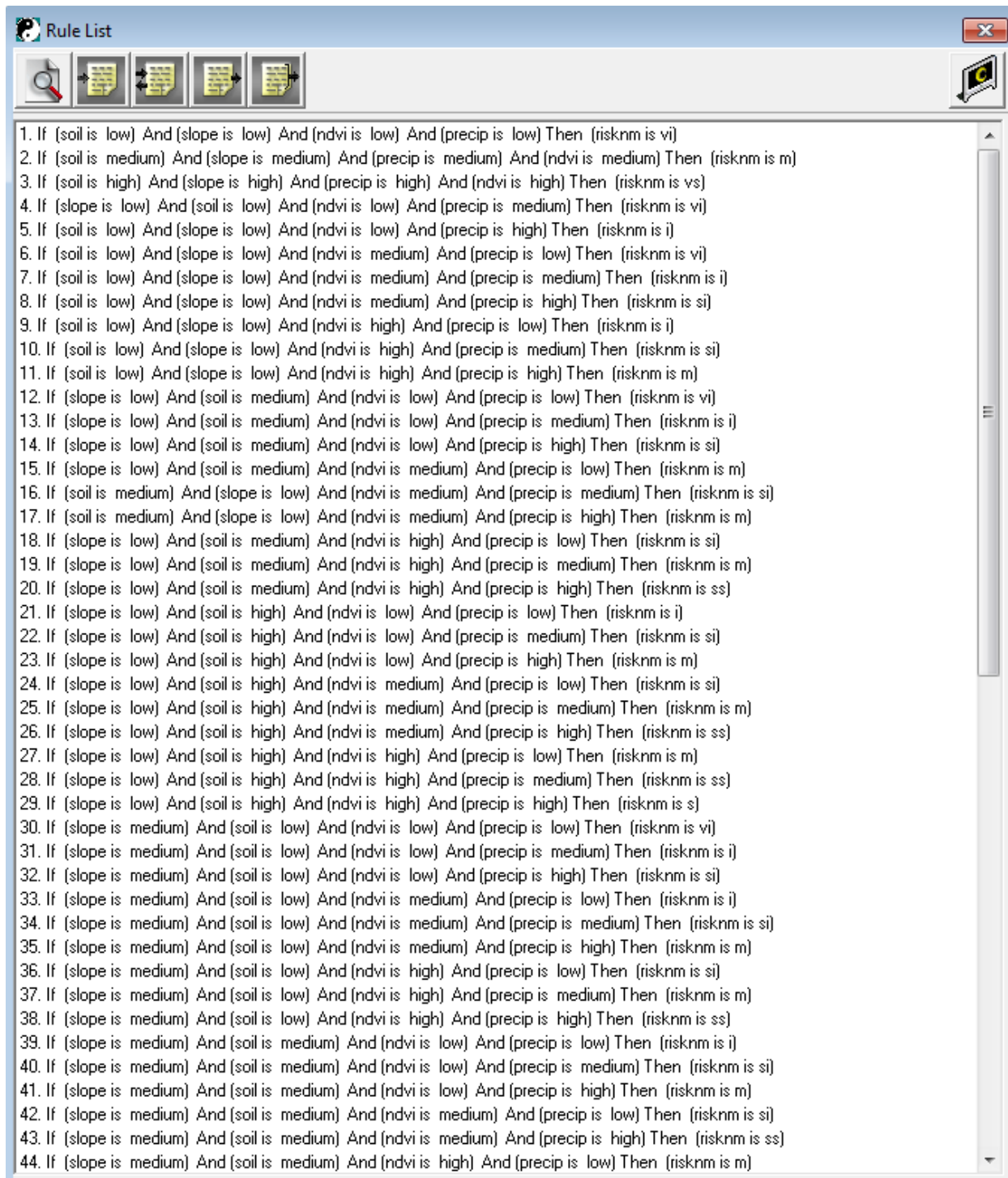
**FIGURE 28: Soil Erodibility as a Linguistic Variable Input.**



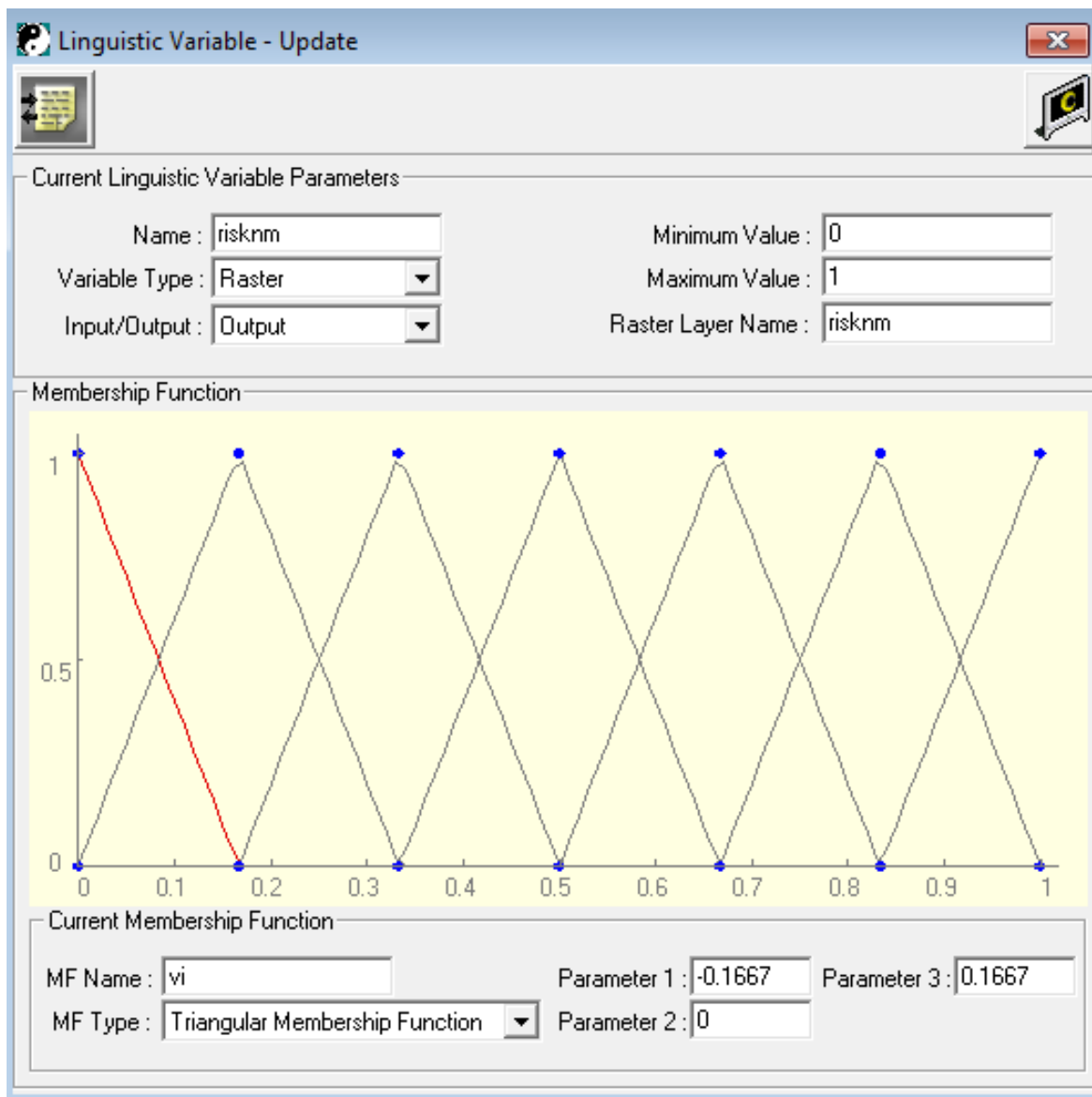
**FIGURE 29: NM Slope Distribution.**



**FIGURE 30: Slope as a Linguistic Variable Input.**

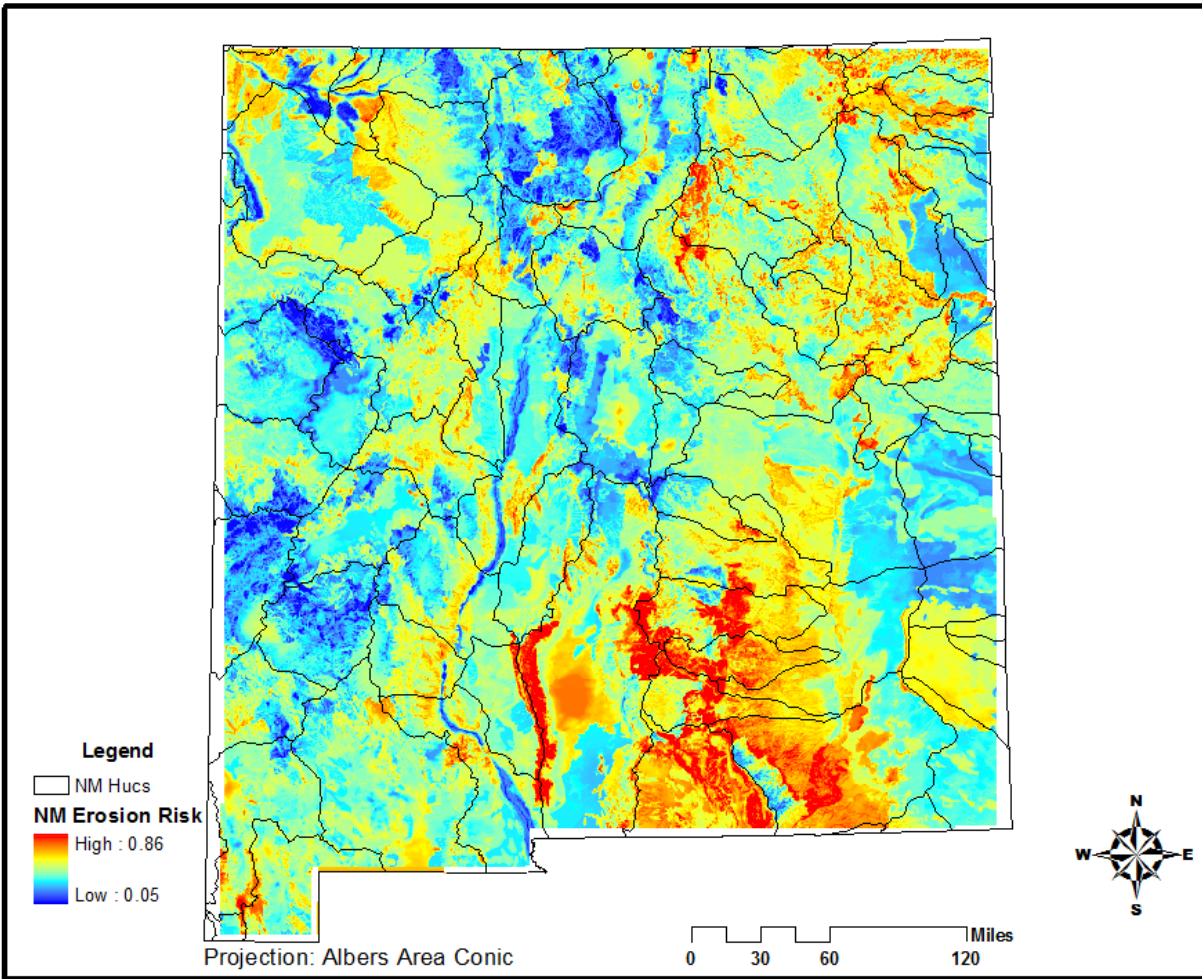


**FIGURE 31: FuzzyCell If-Then Rule List.**



**FIGURE 32: Erosion Risk as a Linguistic Variable Output.**



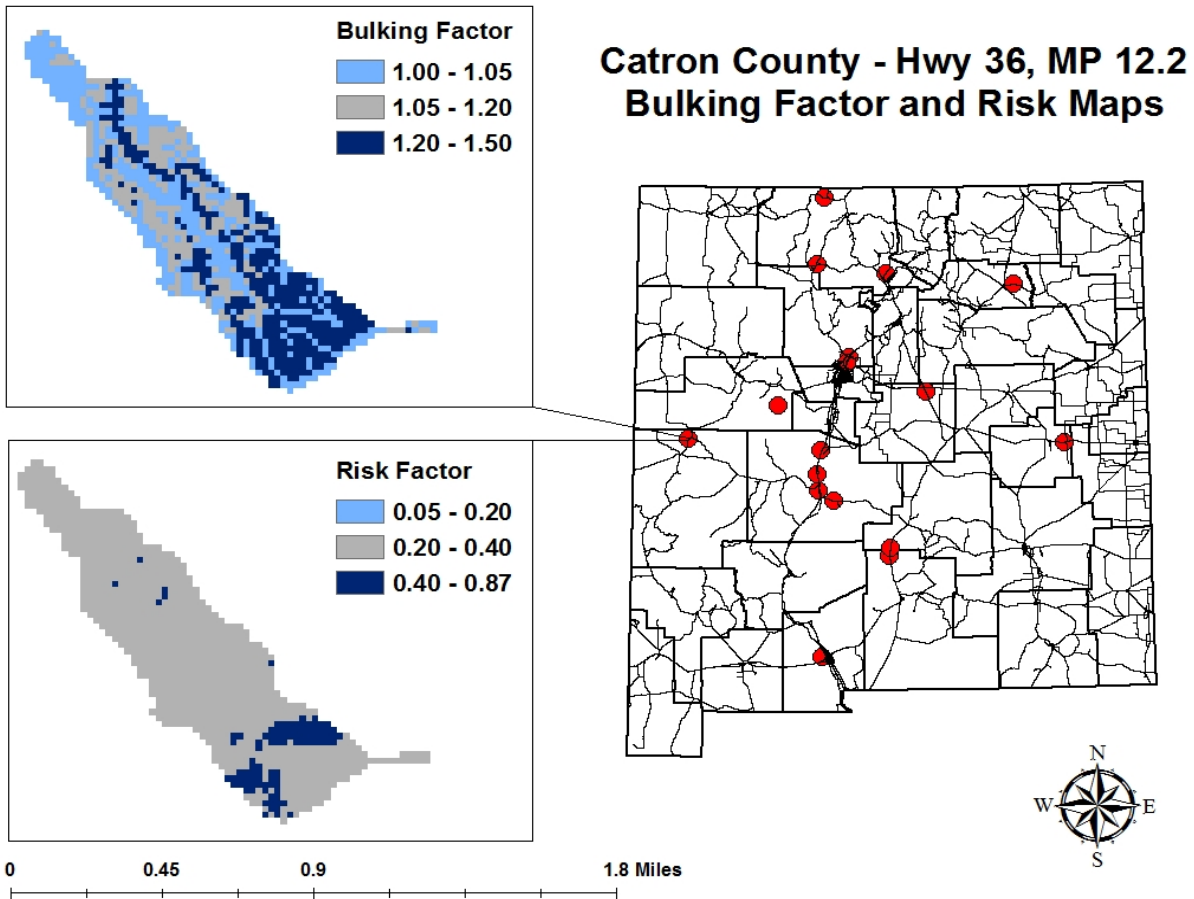


**Figure 33: NM Erosion Risk Distribution using *FuzzyCell*.**

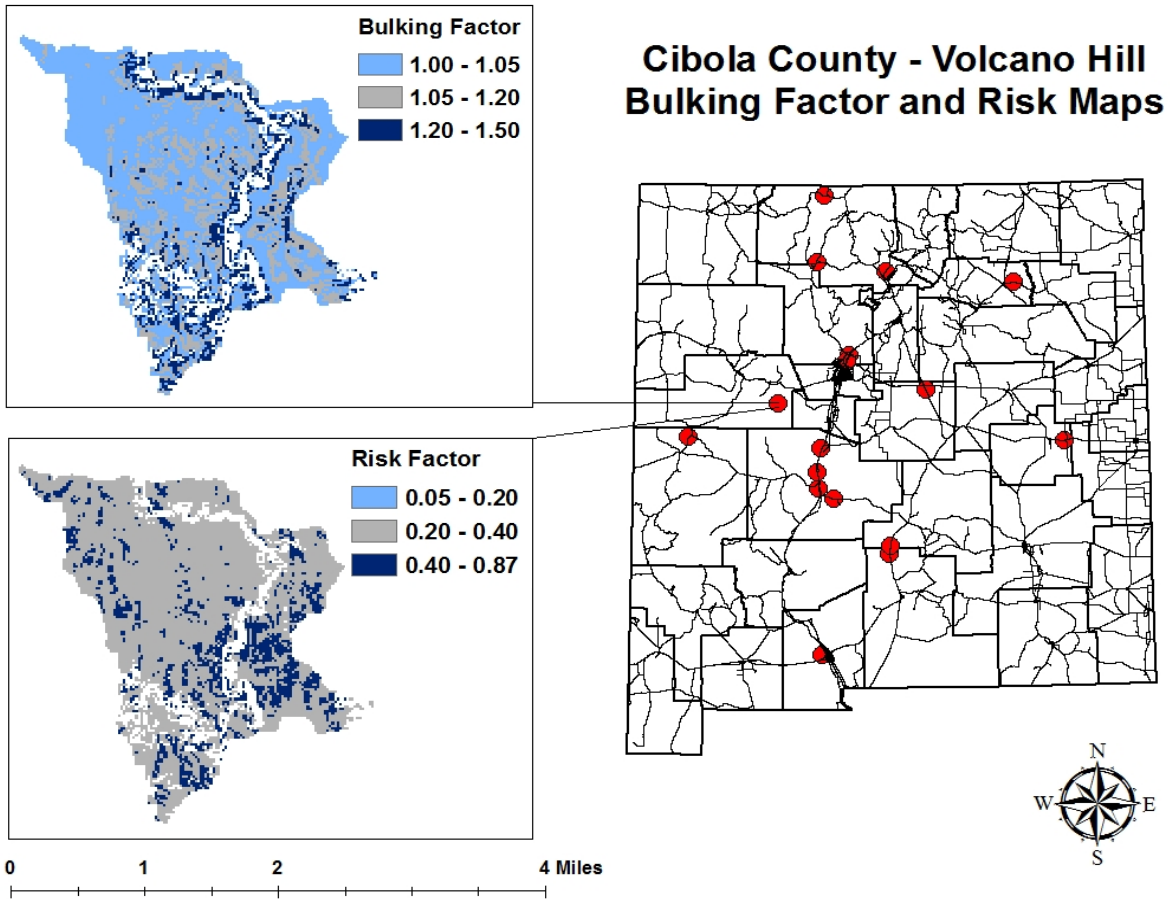


### **Bulking Factor and Risk Maps for Selected New Mexico Watersheds**

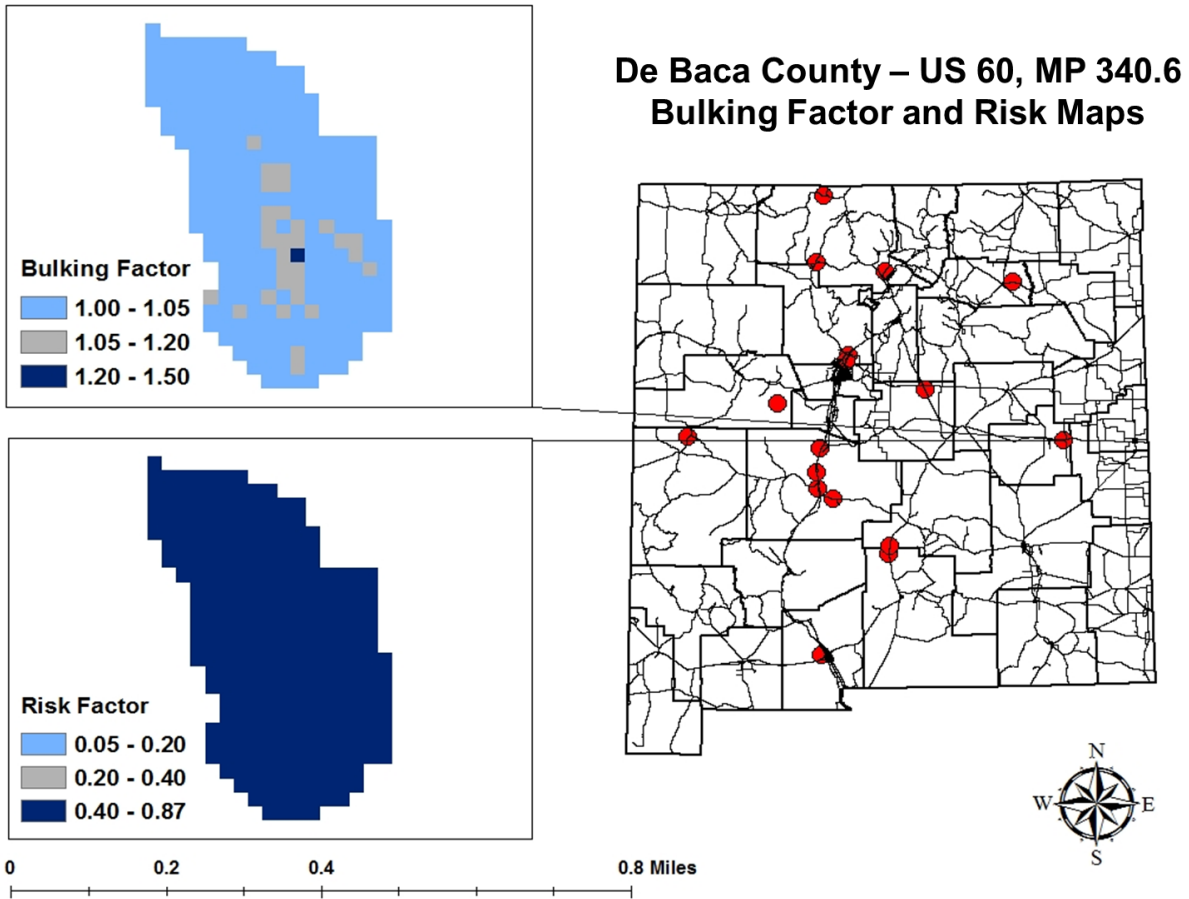
Figures 34-50 provide a visual view of the gradation of estimated bulking factor ( $BF$ ) and soil erosion risk ( $ER$ ) within the respective watersheds. The  $BF$  was calculated pixel by pixel for the respective watershed using the linear regression equation developed for  $BF$  regressed against  $LS_2K$  (Figure 9). The respective  $ER$  plot was extracted from the statewide raster map of soil erosion risk (Figure 33).



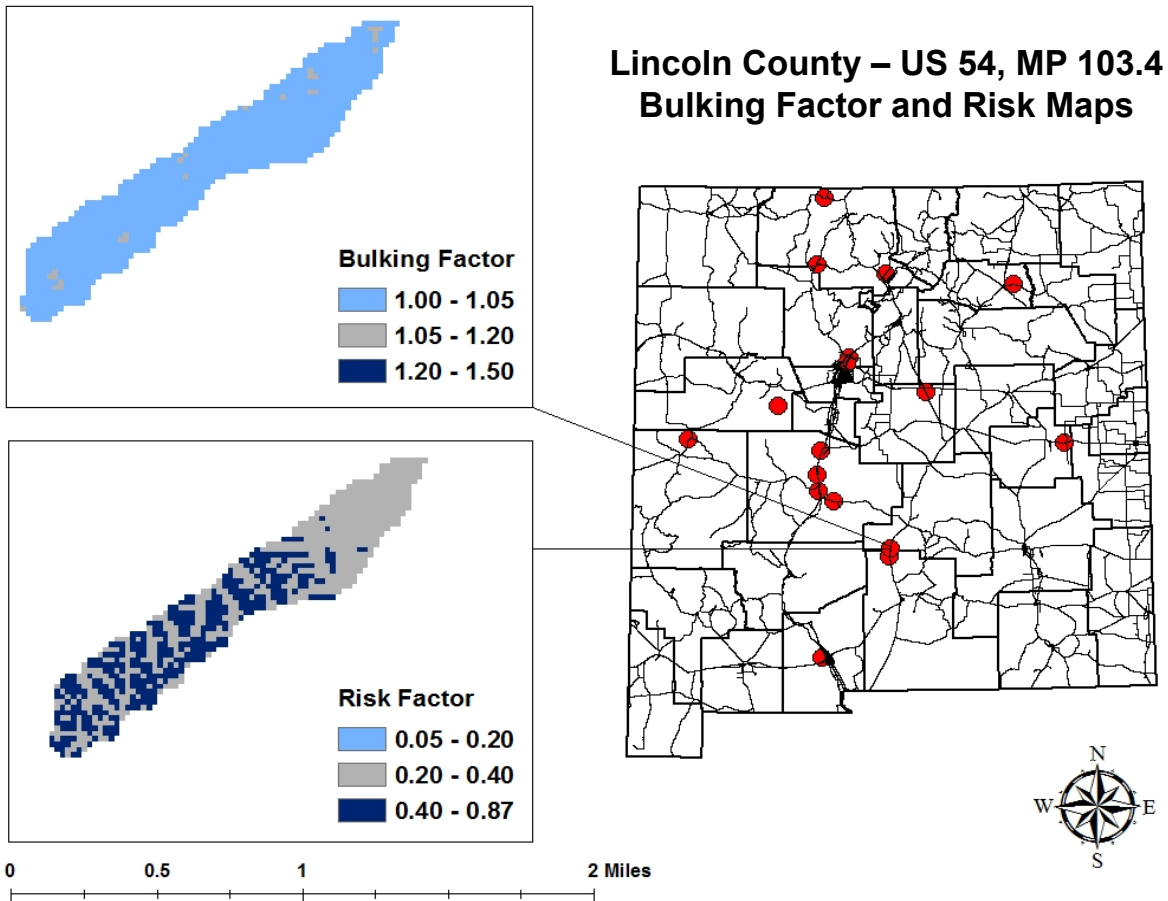
**FIGURE 34: Bulking Factor and Risk Maps for Catron County, NM 36.**



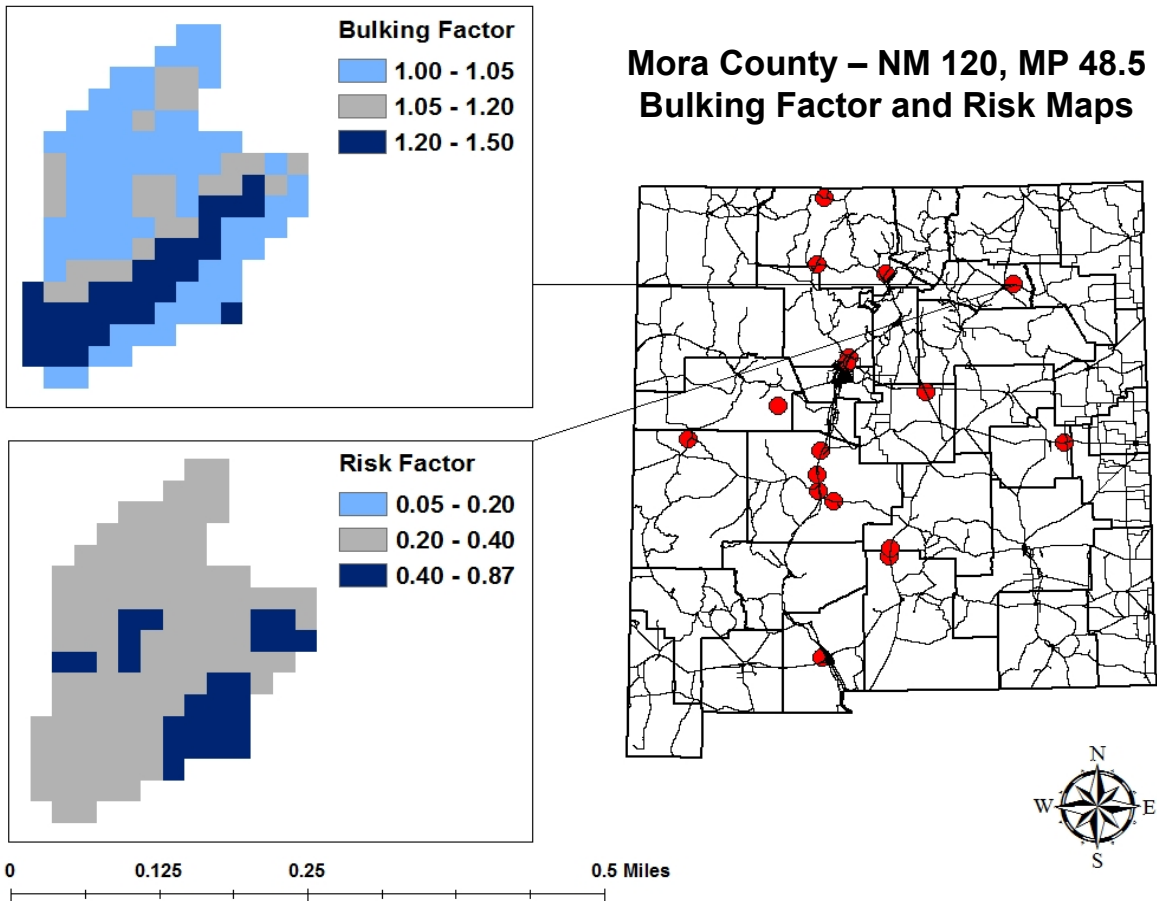
**FIGURE 35: Bulking Factor and Risk Maps for Cibola County-Volcano Hill.**



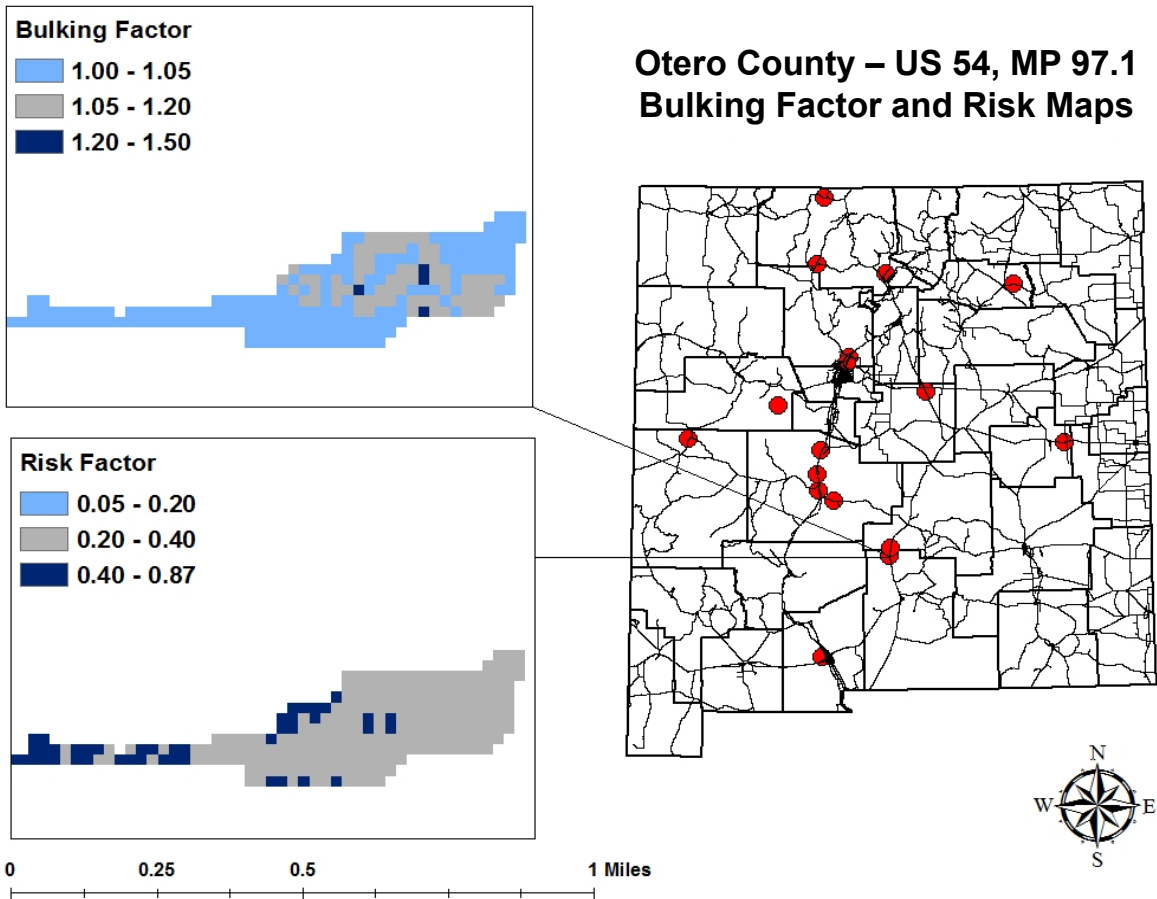
**FIGURE 36: Bulking Factor and Risk Maps for De Baca County, US 60, MP 340.6.**



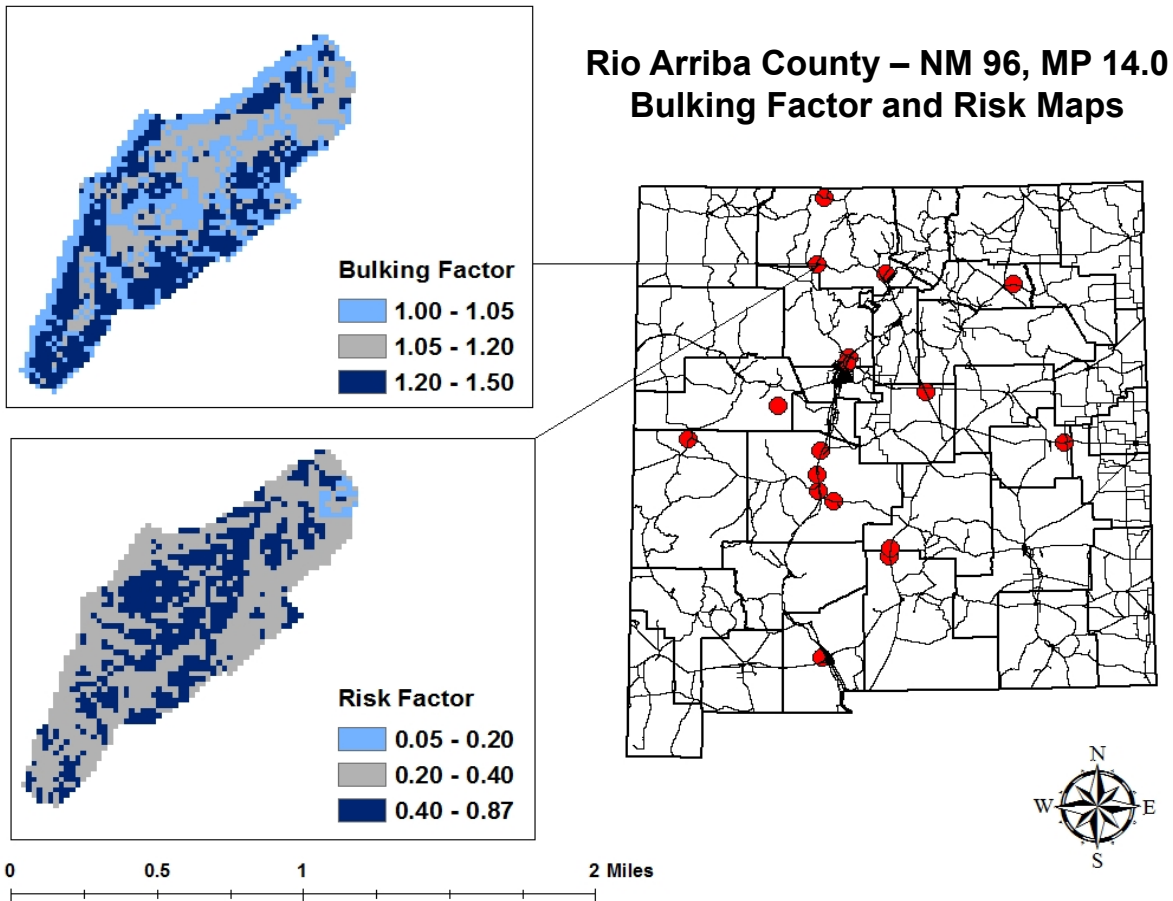
**FIGURE 37: Bulking Factor and Risk Maps for Lincoln County, US 54, MP 103.4.**



**FIGURE 38: Bulking Factor and Risk Maps for Mora County, NM 120, MP 48.5.**

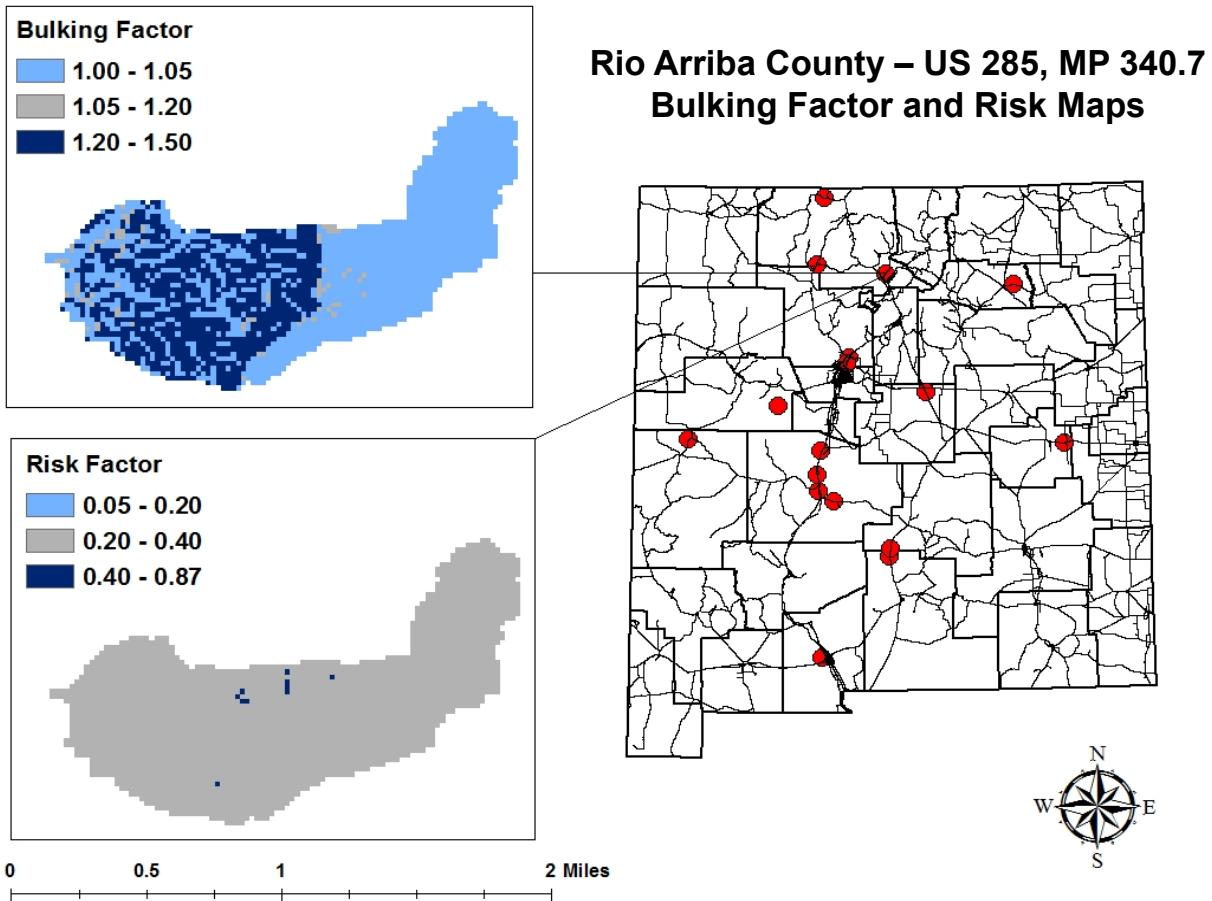


**FIGURE 39: Bulking Factor and Risk Maps for Otero County, US 54, MP 97.1.**

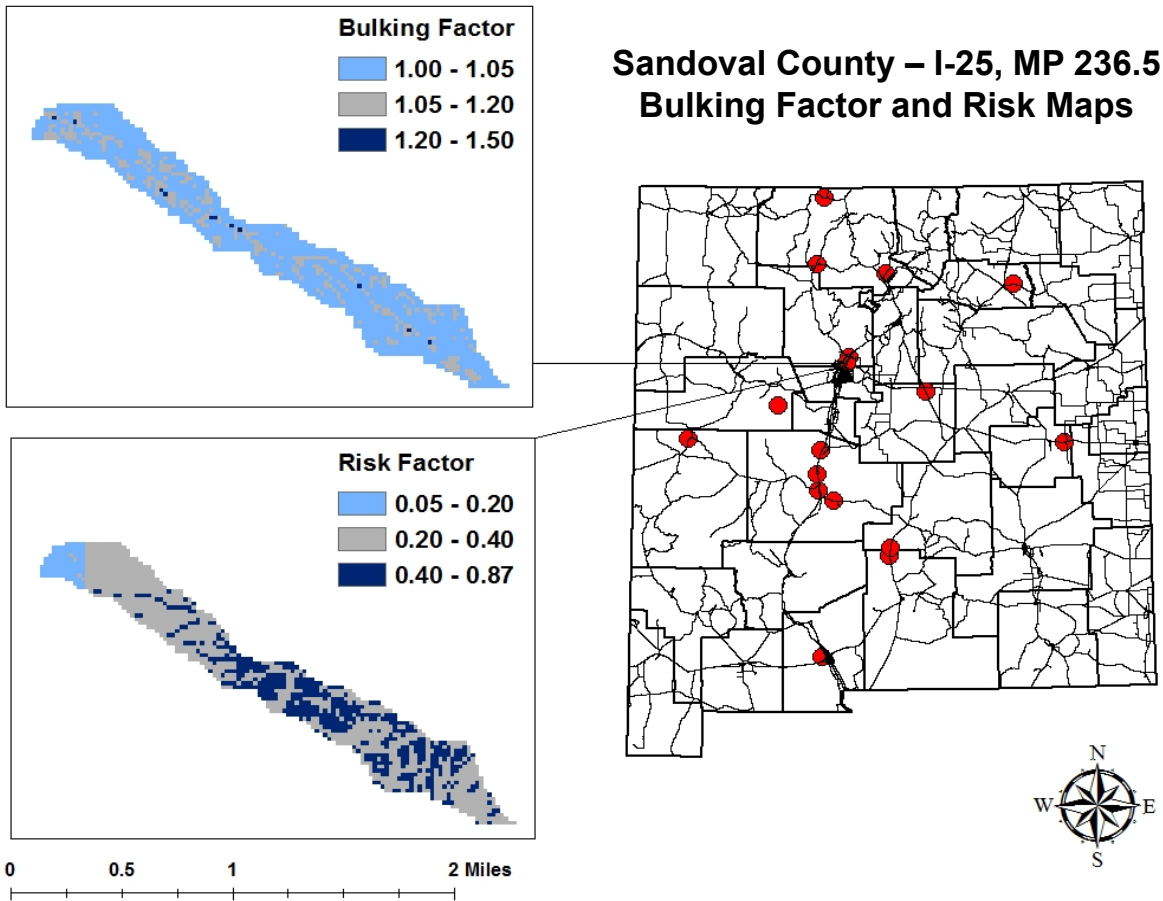


**FIGURE 40: Bulking Factor and Risk Maps for Rio Arriba County, NM 96, MP 14.0.**

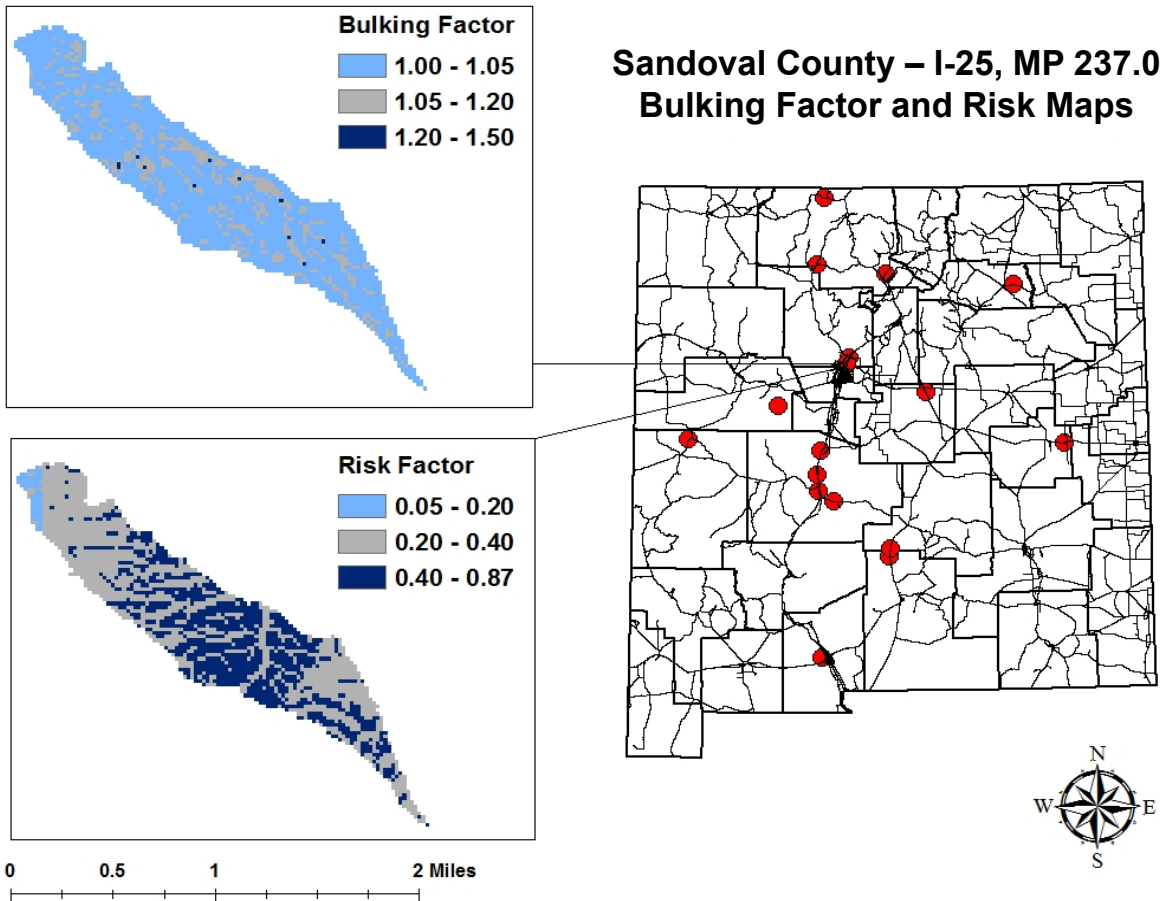




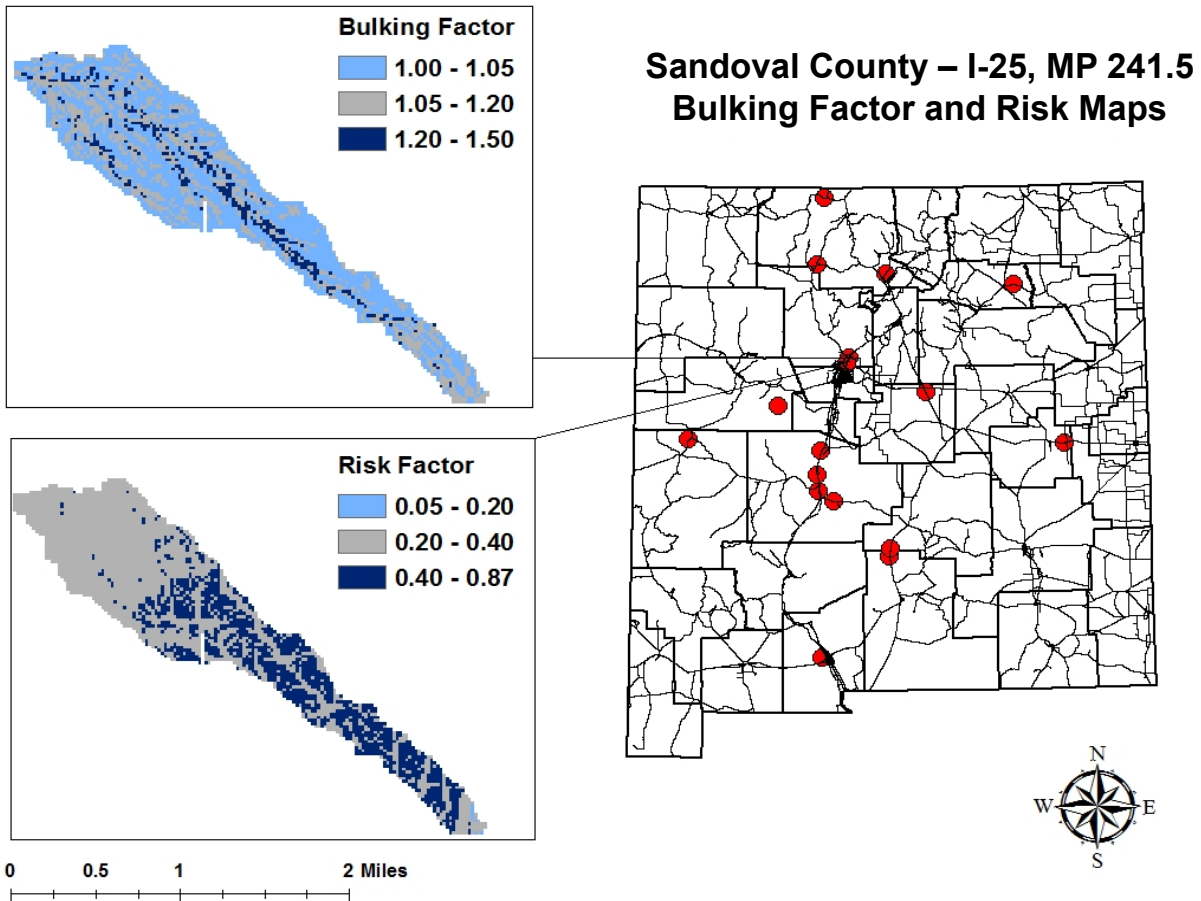
**FIGURE 41: Bulking Factor and Risk Maps for Rio Arriba County, US 285.**



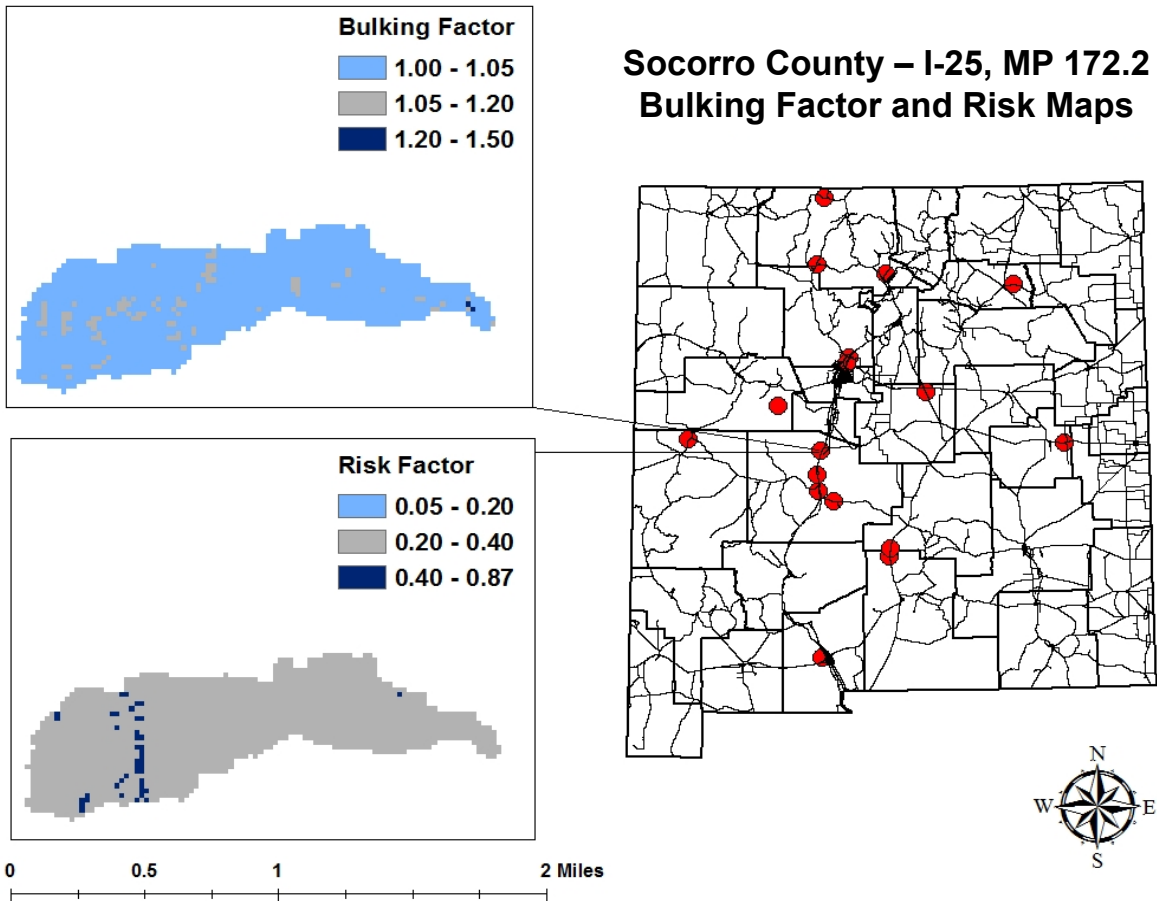
**FIGURE 42: Bulking Factor and Risk Maps for Sandoval County, I-25, MP 236.5.**



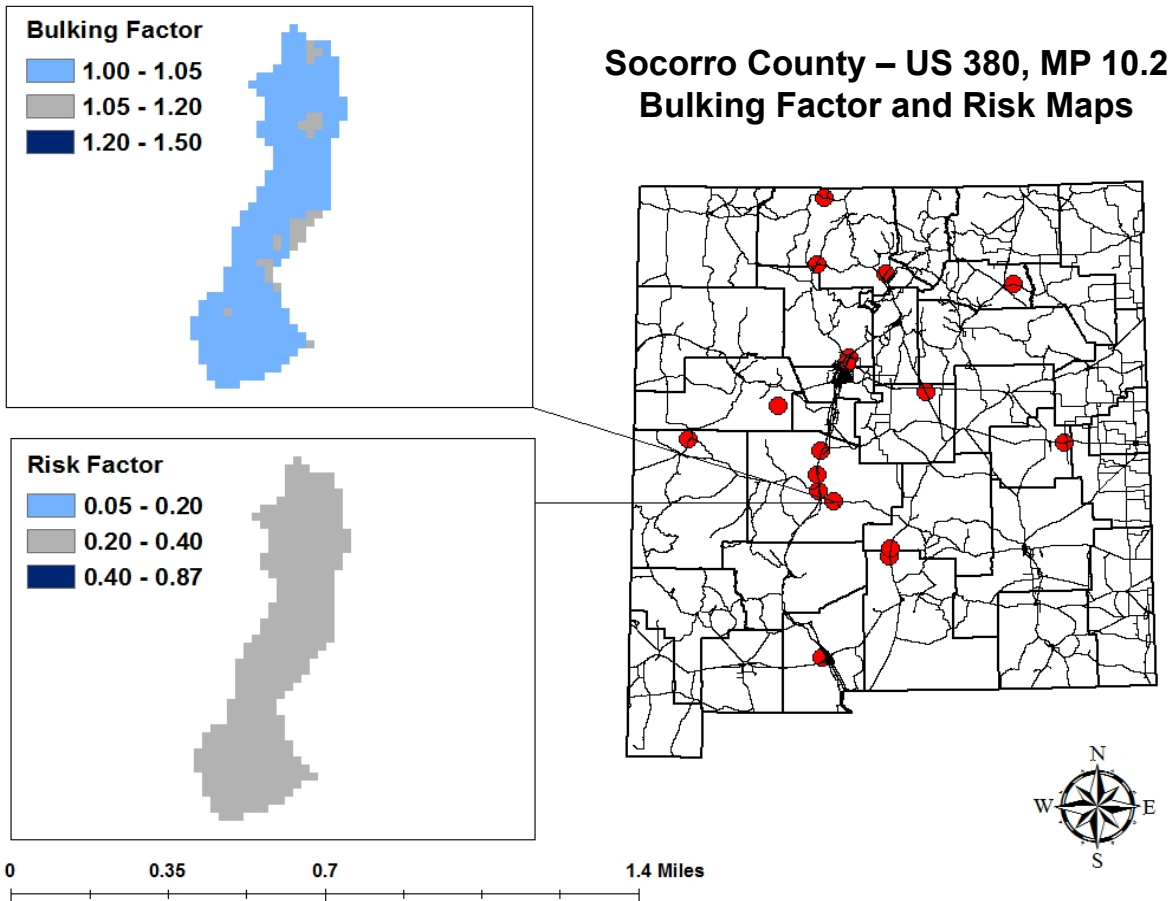
**FIGURE 43: Bulking Factor and Risk Maps for Sandoval County, I-25, MP 237.**



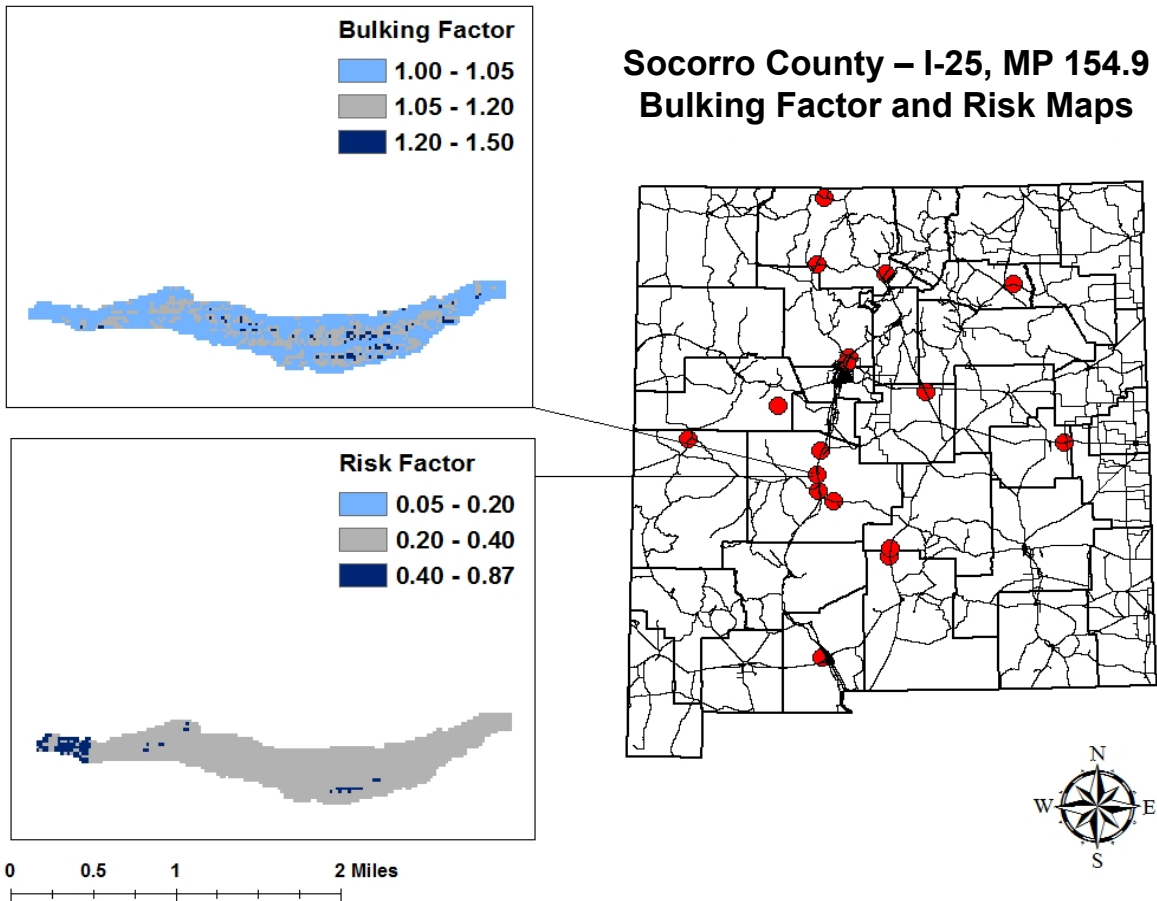
**FIGURE 44: Bulking Factor and Risk Maps for Sandoval County, I-25, MP 241.5.**



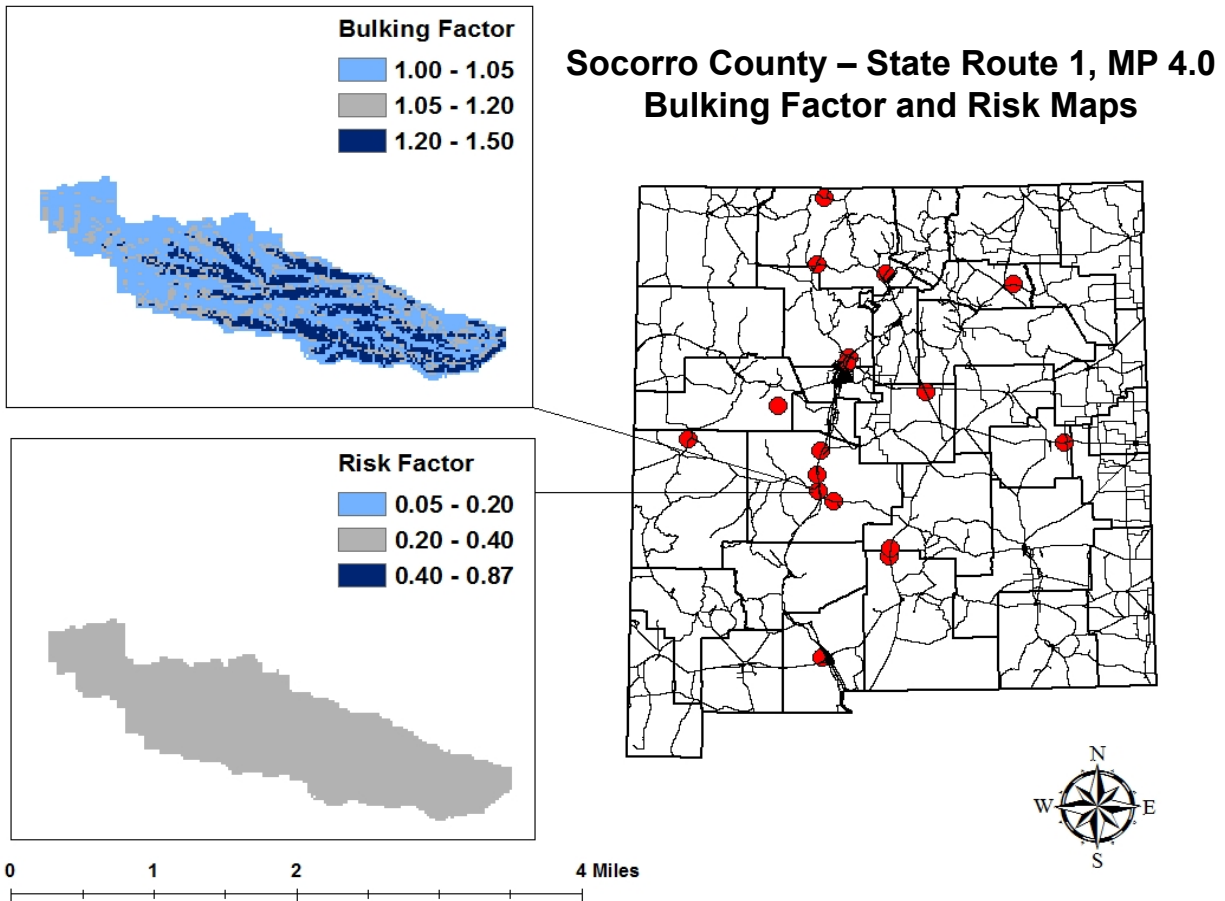
**FIGURE 45: Bulking Factor and Risk Maps for Socorro County, I-25, MP 172.2.**



**FIGURE 46: Bulking Factor and Risk Maps for Socorro County, US 380, MP 10.2.**

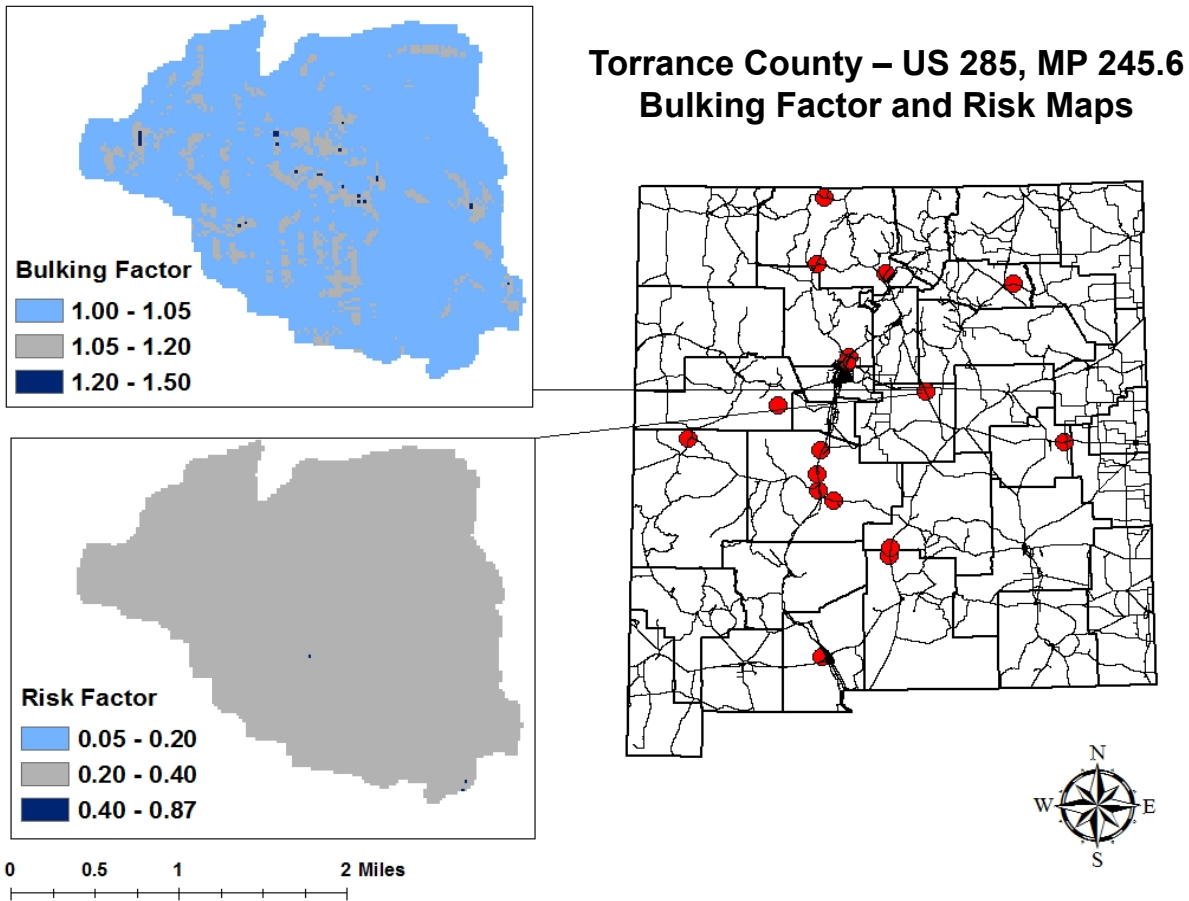


**FIGURE 47: Bulking Factor and Risk Maps for Socorro County, I-25, MP 154.9.**

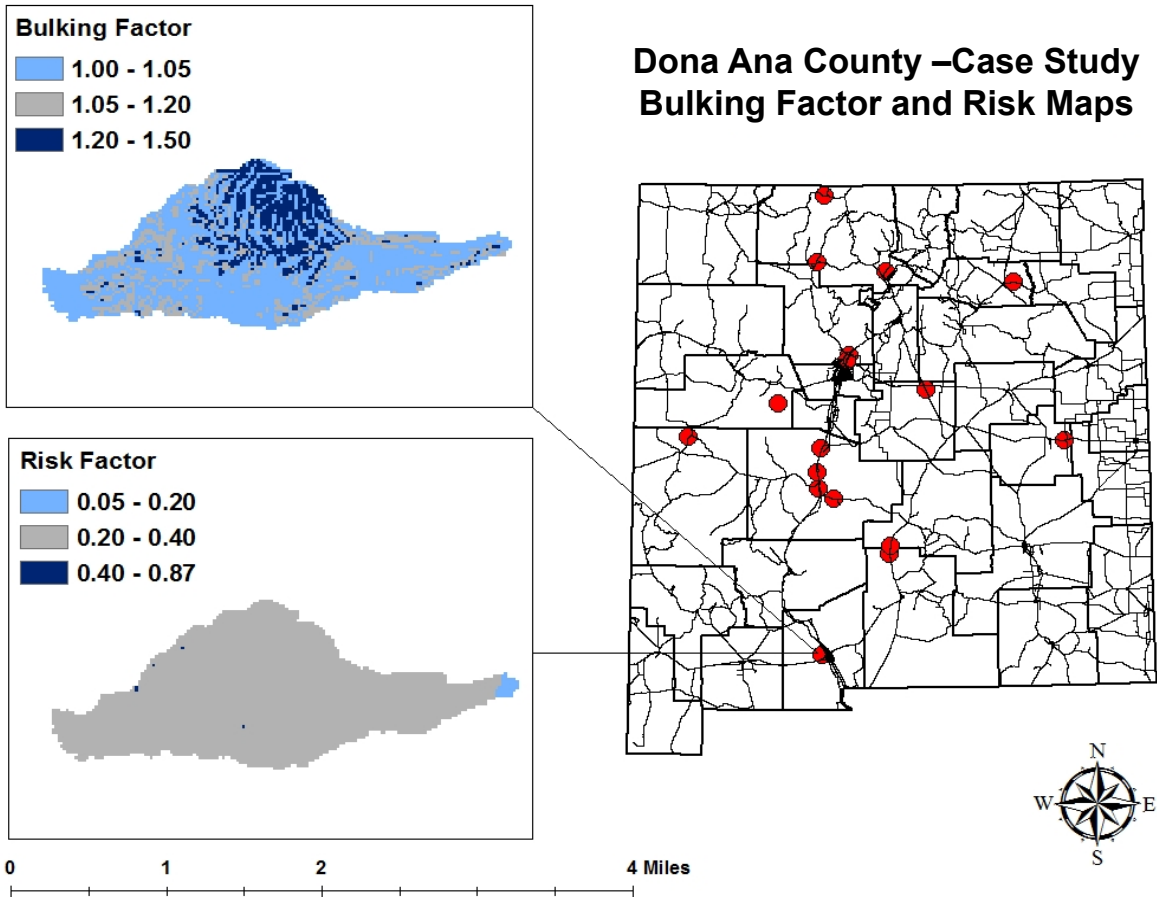


**FIGURE 48: Bulking Factor and Risk Maps for Socorro County, State Route 1, MP 4.0.**





**FIGURE 49: Bulking Factor and Risk Maps for Torrance County, US 285, MP 245.6.**



**FIGURE 50: Bulking Factor and Risk Maps for Dona Ana County.**

### **Bulking Factor and Risk Maps for NMDOT Districts**

Figure 51 shows the statewide *BF* map generated using the 1-D LS-factor and K-factor linear relationship. Figures 52-57 provide a visual view of the gradation of estimated bulking factor (*BF*) and soil erosion risk (*ER*) with respect to the six NMDOT districts. The respective *BF* plot was extracted from the statewide raster map of *BF*, whereas the respective *ER* plot was extracted from the statewide raster map of soil erosion risk (Figure 33).

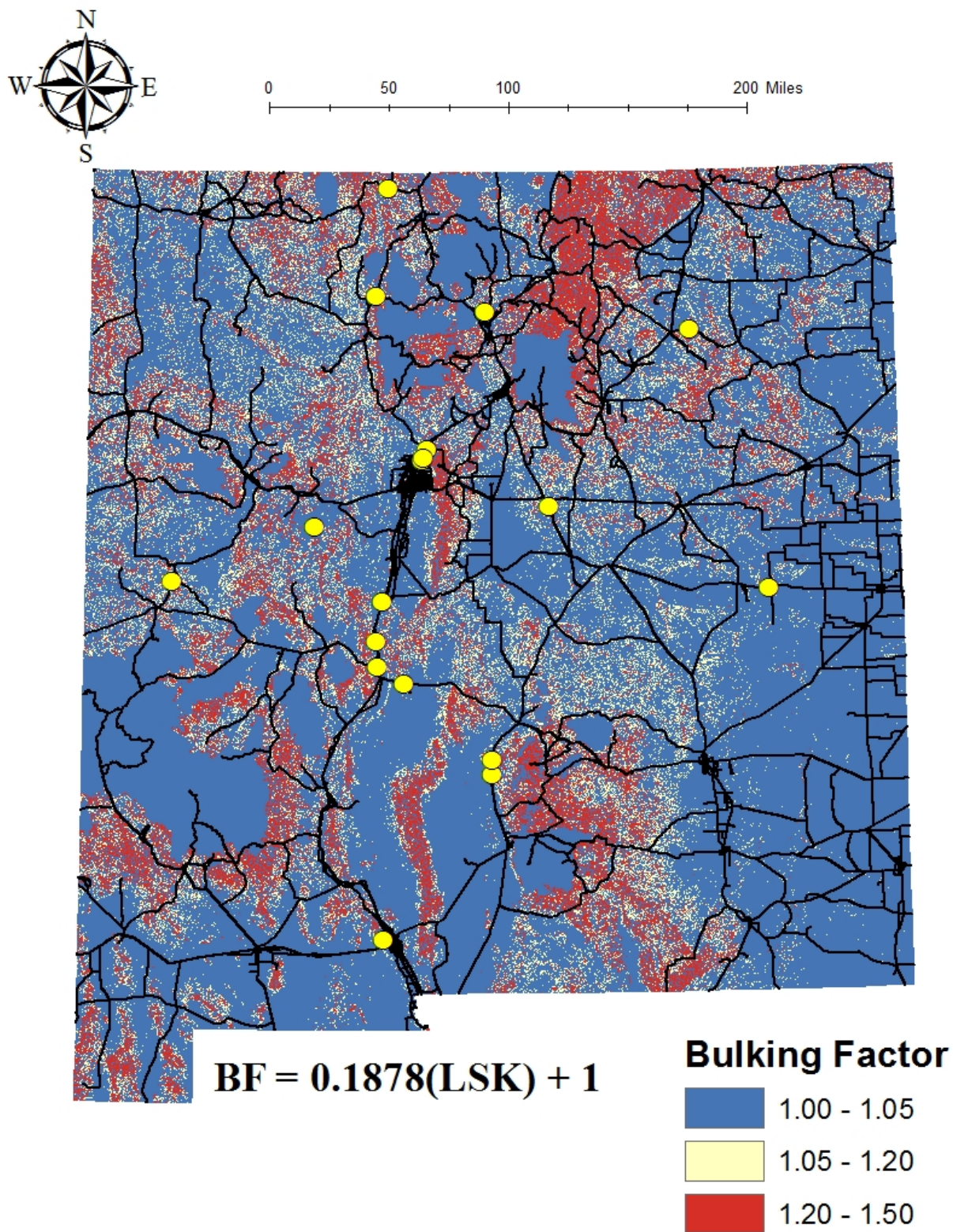
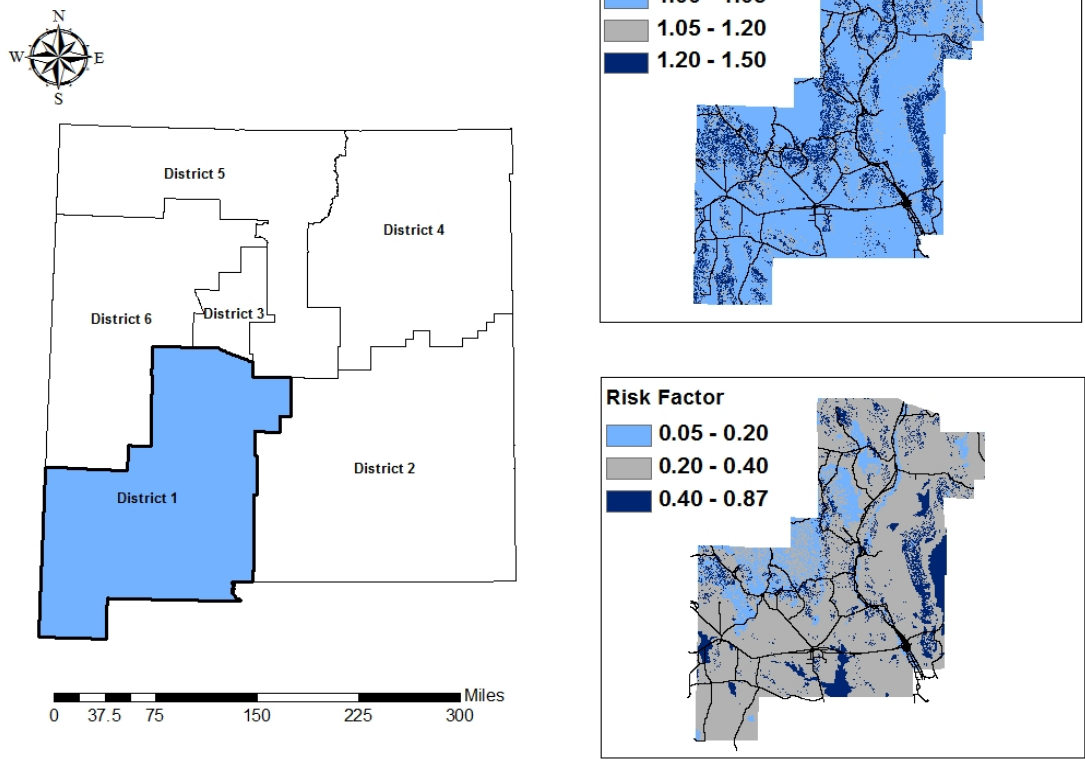
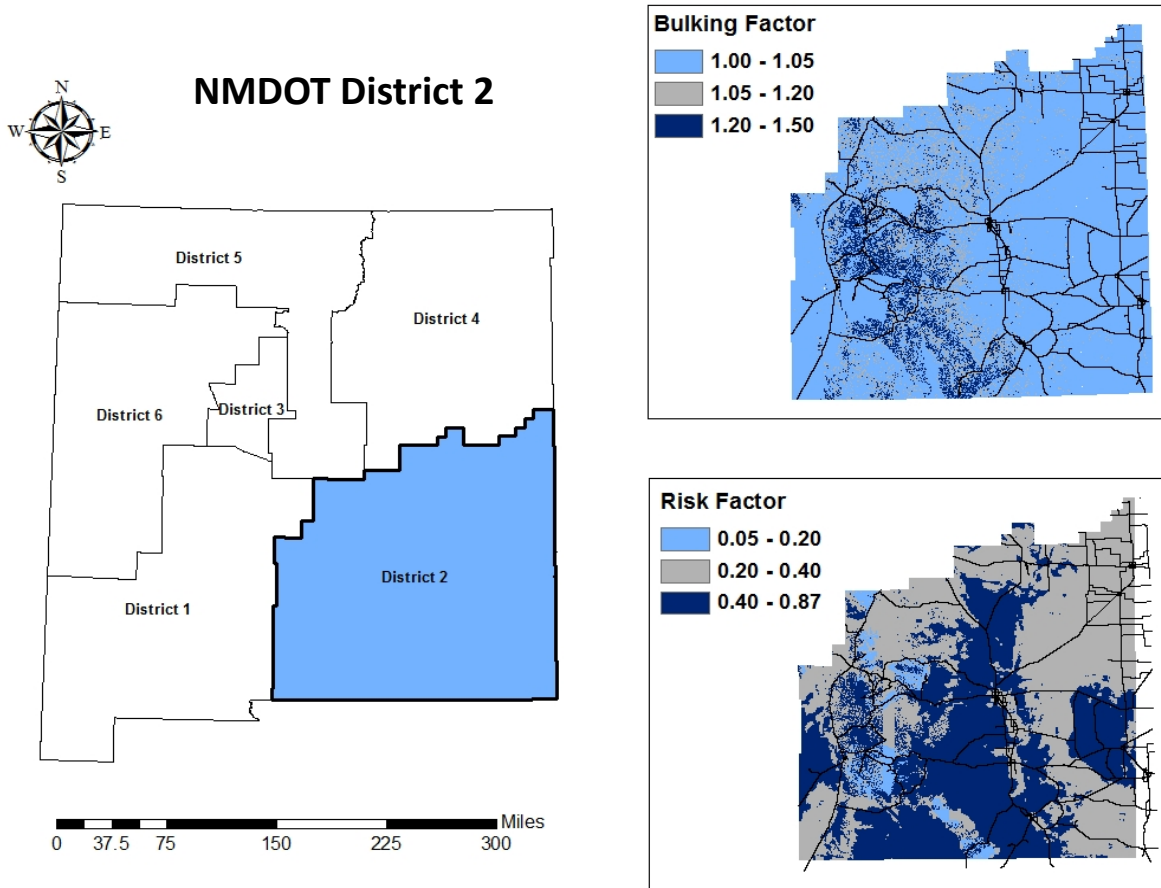


Figure 51: Bulking Factor Map (Linear Correlation with 1-D *LS* Factor).

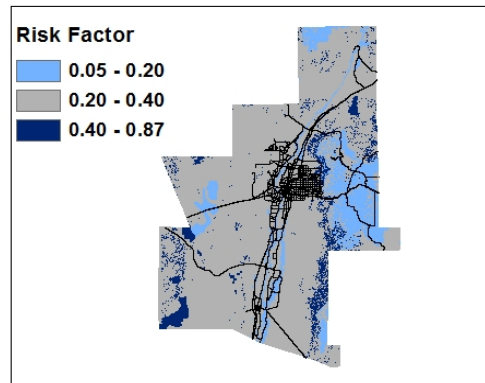
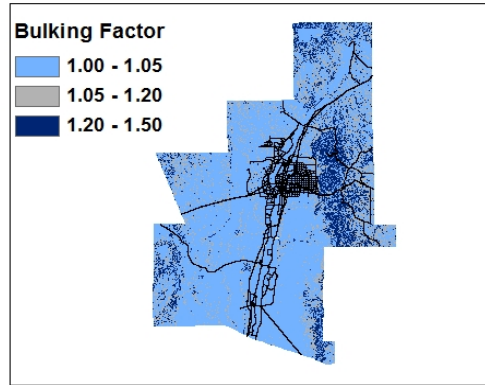
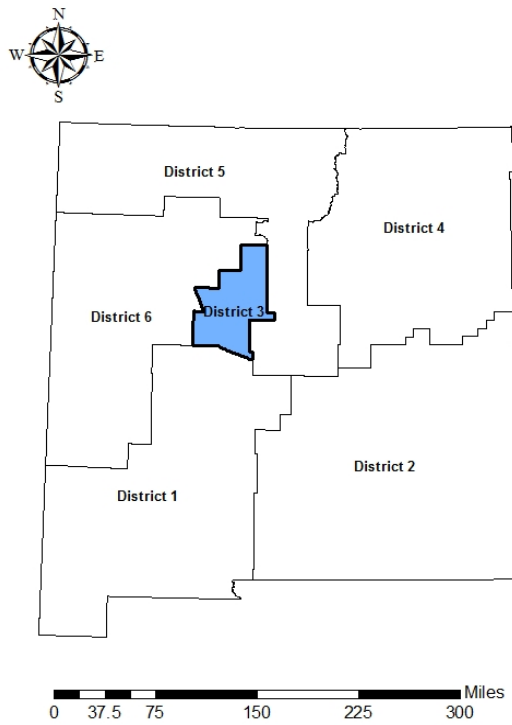


**FIGURE 52: Bulking Factor and Risk Maps for NMDOT District 1.**

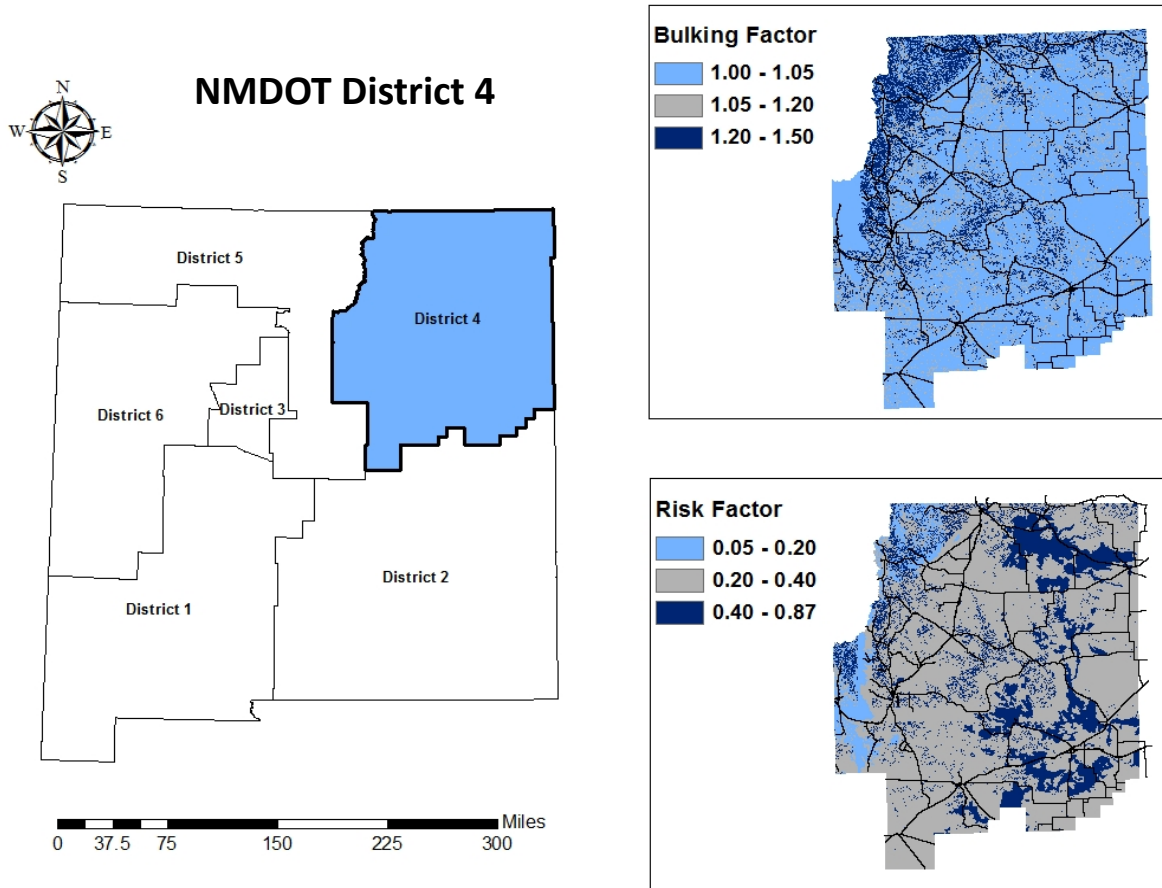


**FIGURE 53: Bulking Factor and Risk Maps for NMDOT District 2.**



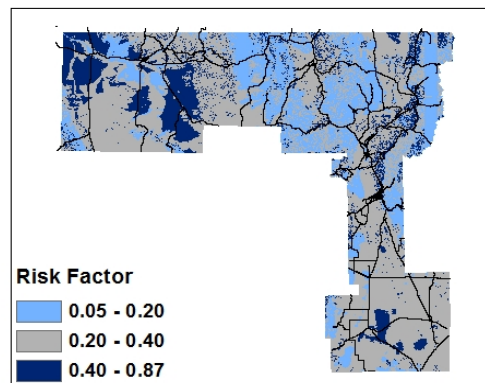
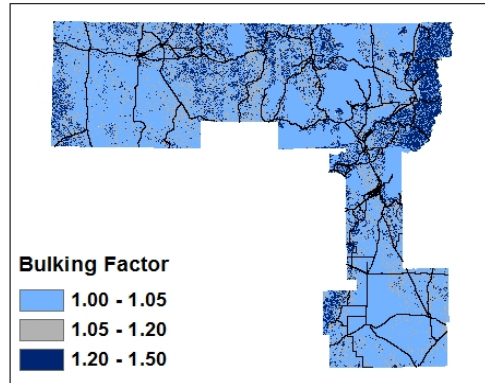
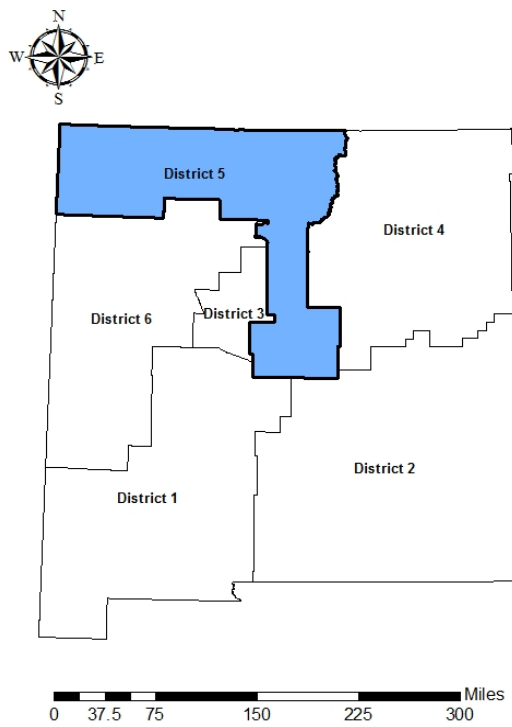


**FIGURE 54: Bulking Factor and Risk Maps for NMDOT District 3.**

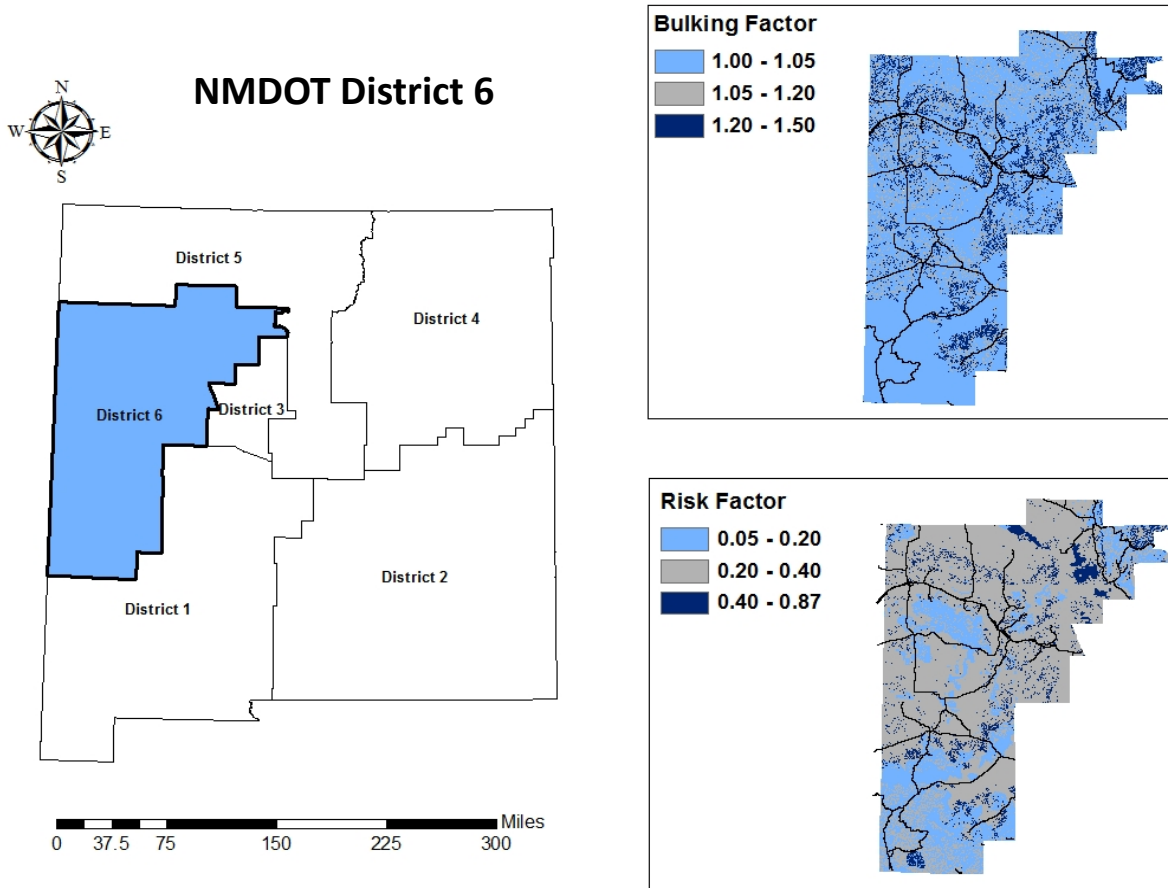


**FIGURE 55: Bulking Factor and Risk Maps for NMDOT District 4.**





**FIGURE 56: Bulking Factor and Risk Maps for NMDOT District 5.**



**FIGURE 57: Bulking Factor and Risk Maps for NMDOT District 6.**

## CONCLUSIONS AND RECOMMENDATIONS

Use of *ArcGIS*<sup>®</sup> 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 watershed attributes pertaining to soil erosion, sediment transport, and deposition phenomena. Virtually any given watershed location with assessable and/or derivable *GIS* data can be analyzed physiographically using the methodologies employed and/or developed herein.

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), a watershed total sediment flow ( $Q_{total}$ ) was determined, leading to an estimated bulking factor ( $BF$ ) for each watershed investigated (31). Correlations between the calculated bulking factor and various watershed attributes were investigated. Based on average watershed attributes of  $LS$  and  $K$ , a linear regression equation was developed and a statewide raster map of  $BF$  generated. With a watershed appropriately delineated, the statewide map may be extracted and a  $BF$  determined using *ArcGIS*<sup>®</sup> toolsets. Alternately, the generated statewide raster maps of a 1-D  $LS$ -factor and  $K$  factor may be likewise extracted for average values for the delineated watershed and the linear correlation used to estimate a  $BF$ . With field verification such regression could prove useful for refinement of a statewide bulking factor map. Both approaches represent a simplified engineering tool to estimate a watershed specific  $BF$ . Lastly, a rigorous procedure is detailed to obtain the necessary input to apply the MEI (2008) procedure for estimating a watershed specific  $BF$  using a macro-based spreadsheet.

As a whole, this step-by-step physiographic-based methodology provides a means to extract and determine a wide range of watershed attributes directly or indirectly pertaining to hydraulic capacity and potential clogging of drainage structures. Moreover, even though the sample size was limited, significant trends and correlations were evident and supported by literature. 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 based on a physiographic approach could become standard practice for design of drainage structures.

A larger watershed dataset, however, is required to verify the trends and correlations observed herein. The preliminary bulking factor map and other statewide *GIS* attributes should be used to identify additional watershed sites for evaluation based on the magnitude of  $BF$ ,  $LS$ ,  $K$ , and perhaps  $C$ , instead of using random watershed selection. Coupling watersheds that have been field verified as being problematic for culvert clogging with calculated bulking factors will provide not only a means to establish trends and correlations, but also a way to assess and verify this methodology.

With respect to generated attributes, higher resolution (3-m) *DEM* data would provide a more realistic scenario for each watershed evaluated and should be incorporated into the methodology as it becomes available. Other attributes and factors not investigated in this study could be explored. Certainly, coupling of the soil erosion risk methodology employed herein in tandem with the bulking factor procedure provides additional insight into potential problem areas for culvert sizing.

With more data points, extensive field verification, higher resolution data, and additional investigation of sediment transport and deposition related trends and attributes, a deeper understanding of factors directly and indirectly contributing to drainage structure clogging may be realized. A field verified bulking factor and soil erosion map would allow for prediction of high-risk areas prone to sediment accumulation from upstream soil erosion and provides a means to adjust the hydraulic design capacity of new, potentially impacted, drainage structures.

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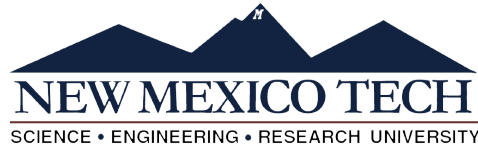


# **DEVELOPMENT OF WATERCOURSE AGGRADATION/DEGRADATION RISK INDEX FOR NEW MEXICO**

## **IMPLEMENTATION PLAN**

Project No. NM10DSN-01

Prepared by



Dr. Mark P. Cal, P.E.  
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May 9, 2013

Prepared for

NMDOT Research Bureau  
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Albuquerque, NM 87199-4690  
(505) 841-9145

# **Section 1**

## **Website Downloads**

## Require Software Downloads

1. ArcGIS 10.1
2. Service Pack 1 (ArcGIS 10.1 SP1 for Desktop), <http://support.esri.com/en/downloads/patches-servicepacks/view/productid/160/metaid/1913>
3. ArcHydro Tools 10.1 x64
4. HecGeoHMS 10.1.msi, <https://mft.esri.com/EFTClient/Account/Login.htm>, Login: ADSRiverHydraulics, Password: ADSRiver.2012
5. Hec-HMS 3.5 for Windows, <http://www.hec.usace.army.mil/software/hec-hms/downloads.aspx>
6. TauDEM Toolset 5.1 64 bit Install Package
7. MPICH2 found in Installation Instructions x86\_64, <http://hydrology.usu.edu/taudem/taudem5.0/downloads.html>

## **Section 2**

# **Watershed and Stream Delineation Procedure**

# Watershed and Stream Network Delineation using ArcHydro Tools

Prepared by  
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August  
2012

Modified by C. Richardson, M. Cal, and J. Ealey for the NMDOT training module  
April 2013

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## Introduction

The first step in doing any kind of hydrologic modeling involves delineating streams and watersheds, and getting some basic watershed properties such as area, slope, flow length, stream network density, etc. With the availability of digital elevation models (DEM) and GIS tools, watershed properties can be extracted by using automated procedures. The processing of DEM to delineate watersheds is referred to as *terrain pre-processing*. In this exercise, you will use ArcHydro tools to process a DEM to delineate watershed, subwatersheds, stream network and some other watershed characteristics that collectively describe the drainage patterns of a basin. The results from this exercise can be used to create input files for many hydrologic models. An exercise on how to use these results to create a *HEC-HMS* model is provided as a follow-up to this exercise.

## Computer Requirements

You must have a computer with windows operating system, and the following programs installed:

1. ArcGIS 10.1
2. ArcHydro tools (version that works with 10.1)

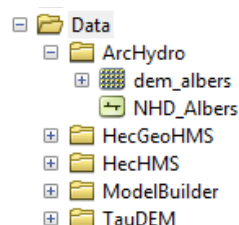
## Data Requirements and Description

The data files used in the exercise consist of a DEM grid for *Otero Mesa* in southern New Mexico and the associated hydrography data. Although the data are provided with this exercise, the steps involved in downloading the NED and NHD data from the USGS website are described in the following document.

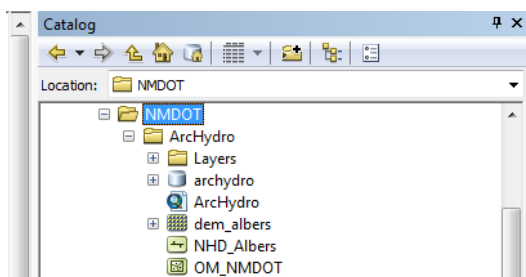
[http://web.ics.purdue.edu/~vmerwade/education/ned\\_nhd.pdf](http://web.ics.purdue.edu/~vmerwade/education/ned_nhd.pdf)

Note that specific screenshots are provided for key input of data relative to the *Otero Mesa* watershed. Other screenshots from the *Cedar Creek* watershed in Indiana, as developed originally for this tutorial by Dr. Venkatesh Merwade, are retained for illustrative purposes of processed output.

The ArcCatalog-view of the *Otero Mesa* data folder is shown below:



A second folder called *NMDOT* is provided as well for this tutorial as a guide. It contains all ArcHydro data generated for the *Otero Mesa* watershed. Below is the screenshot of this folder.

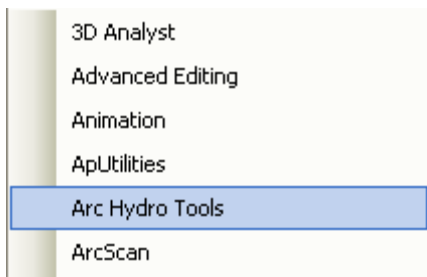


*dem\_albers* is the raw 10 m DEM for *Otero Mesa* obtained from USGS and extracted for the study watershed area. The second dataset, *NHD\_Albers*, is a shapefile containing stream network for the study watershed area. *NHD\_Albers* is extracted from the national hydrography dataset (this is done by selecting the stream network for the watershed and exporting it to a shape file). Both rasters are already assigned a projected coordinate system (NAD\_1988\_Albers).

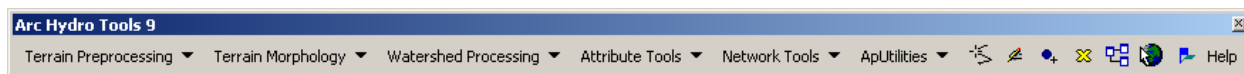
**Note:** It is critical to assign and use consistent coordinate system for all the datasets used in delineating watersheds by using any pre-processing tool.

## Getting Started

**Open** ArcMap. Create a new empty map, and save it as *ArcHydro.mxd* for this exercise (or any other name for future projects). **Right click** on the menu bar to pop up the context menu showing available tools as shown below.



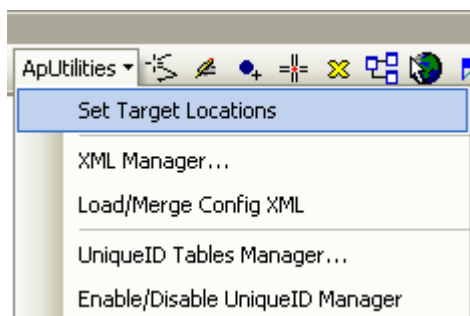
**Check** the ArcHydro Tools to add the toolbar to the map document. You should now see the ArcHydro tools added to ArcMap as shown below. You can leave it floating or you may dock it in ArcMap.



**Note:** It is not necessary to load the Spatial Analyst, Utility Network Analyst, or Editor tools because ArcHydro Tools will automatically use their functionality on as needed basis. These toolbars need to be loaded though if you want to use any general functionality that they provide (such as general editing functionality or network tracing). However, the Spatial Analyst Extension needs to be activated, by clicking Customize→ Extensions..., and checking the box next to Spatial Analyst.


## Dataset Setup

All vector data created with the ArcHydro tools will be stored in a new geodatabase that has the same name as the stored project or ArcMap document (unless pointed to an existing geodatabase) and in the same directory where the project has been saved (your working folder). By default, the new raster data are stored in a subdirectory with the same name as the dataset or Data Frame in the ArcMap document (called Layers by default and under the directory where the project is stored). The location of the vector, raster, and time series data can be explicitly specified using the function *ApUtilities*→ *Set Target Locations*.



You can leave the default settings if they are pointing to the same directory where the ArcMap document is saved.

## Load the data to ArcMap

**Click** on the Add icon  to add the raster data. In the dialog box, **navigate** to the location of the data; **select** the raster file *dem\_albers* containing the DEM for *Otero Mesa* and **click** on the Add button. The added file will then be listed in the Arc Map Table of contents. Similarly **add** the *NHD\_Albers* shapefile, and **save** the map document.

## Terrain Preprocessing

ArcHydro Terrain Preprocessing should be performed in sequential order. All of the preprocessing must be completed before Watershed Processing functions can be used. DEM reconditioning and filling sinks might not be required depending on the quality of the initial

DEM. DEM reconditioning involves modifying the elevation data to be more consistent with the input vector stream network. This implies an assumption that the stream network data are more reliable than the DEM data, so you need to use knowledge of the accuracy and reliability of the data sources when deciding whether to do DEM reconditioning. By doing the DEM reconditioning you can increase the degree of agreement between stream networks delineated from the DEM and the input vector stream networks.

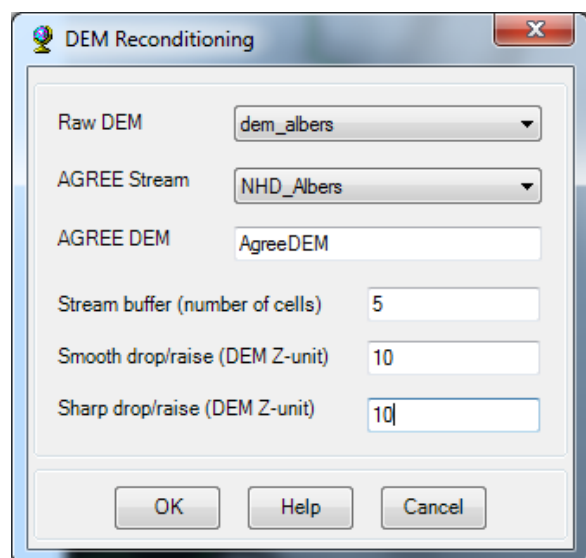
**Note:** Depending on the size of the datasets, processes like DEM Reconditioning, Filling Sinks and Flow accumulation can take from few minutes to up to one hour or more. Therefore, if you are using this tutorial as a guide for another larger dataset, be patient!

## 1. DEM Reconditioning

This function modifies a DEM by imposing linear features onto it (burning/fencing). The function needs as input a raw dem and a linear feature class (like the river network) that both have to be present in the map document.

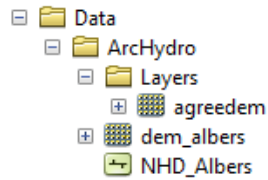
On the ArcHydro toolbar, **select** *Terrain Preprocessing* → *DEM Manipulation* → *DEM Reconditioning*.

Select the appropriate Raw DEM (*dem\_albers*) and AGREE stream feature (*stream*). **Set** the Agree parameters as shown. You should **reduce** the *Sharp drop/raise* parameter to 10 from its default 1000. The output is a reconditioned Agree DEM (default name AgreeDEM).



This process takes about 2 to 3 minutes! **Click OK** on the “...processing successfully completed” message box. Examine the folder where you are working you will notice that a folder named Layers has been created. This is where ArcHydro will store its grid results. A personal geodatabase with the same name as your ArcMap document has also been created as shown in the following ArcCatalog view:





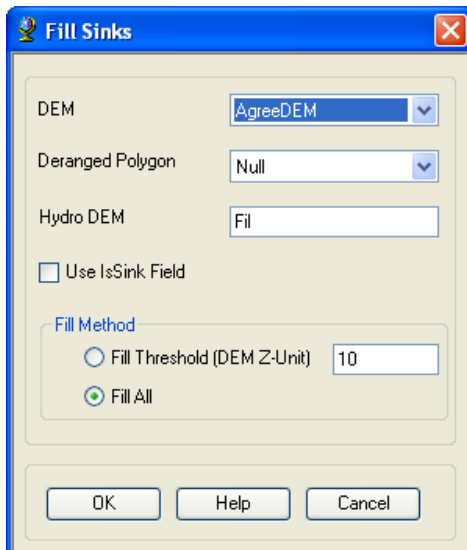
What AgreeDEM (or DEM reconditioning) does is pushes the raw DEM along the stream to create a distinct profile along the streams which otherwise does not exist in raw DEMs. This is mainly due to lack of elevation data along streams in raw DEMs.

## 2. Fill Sinks

This function fills the sinks in a grid. If cells with higher elevation surround a cell, the water is trapped in that cell and cannot flow. The Fill Sinks function modifies the elevation value to eliminate these problems.

On the ArcHydro Toolbar, **select** *Terrain Preprocessing* → *Data Manipulation* → *Fill Sinks*.

**Confirm** that the input for DEM is *AgreeDEM* (or your original DEM if Reconditioning was not implemented). The output is the Hydro DEM layer, named by default *Fil*. This default name can be overwritten. **Leave** the other options **unchanged**.



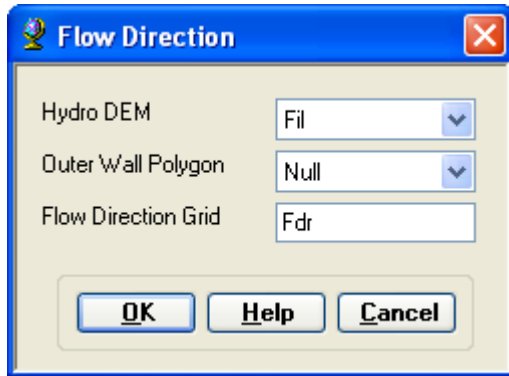
**Press** *OK*. Upon successful completion of the process, the *Fil* layer is added to the map. This process takes a few minutes.

## 3. Flow Direction

This function computes the flow direction for a given grid. The values in the cells of the flow direction grid indicate the direction of the steepest descent from that cell.

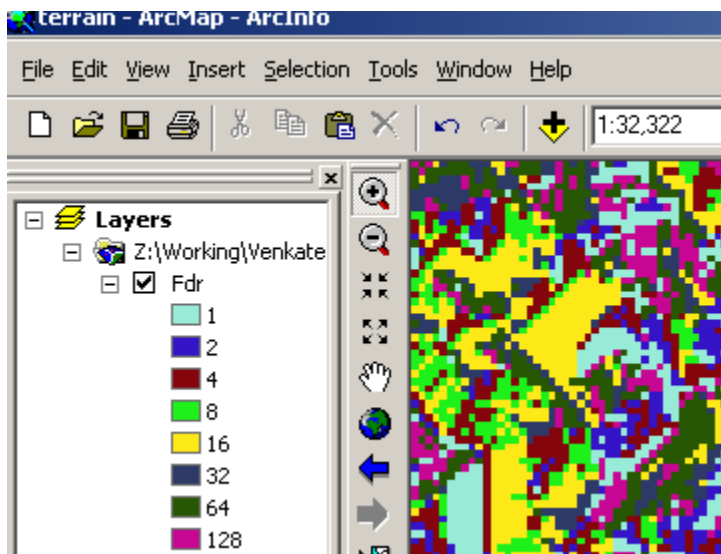
On the ArcHydro toolbar, **select** *Terrain Preprocessing* → *Flow Direction*.

**Confirm** that the input for Hydro DEM is *Fil*. The output is the Flow Direction Grid, named by default *Fdr*. This default name can be overwritten.



**Press OK.** Upon successful completion, the flow direction grid *Fdr* is added to the map.

The **zoomed-in** version of the *Fdr* grid should look similar to the Cedar Creek map below with each color in the cell having one of the eight numbers shown in the legend representing the flow direction according to the eight-point pour flow direction model.

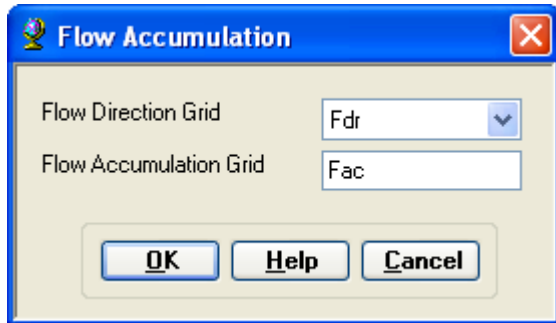


#### 4. Flow Accumulation

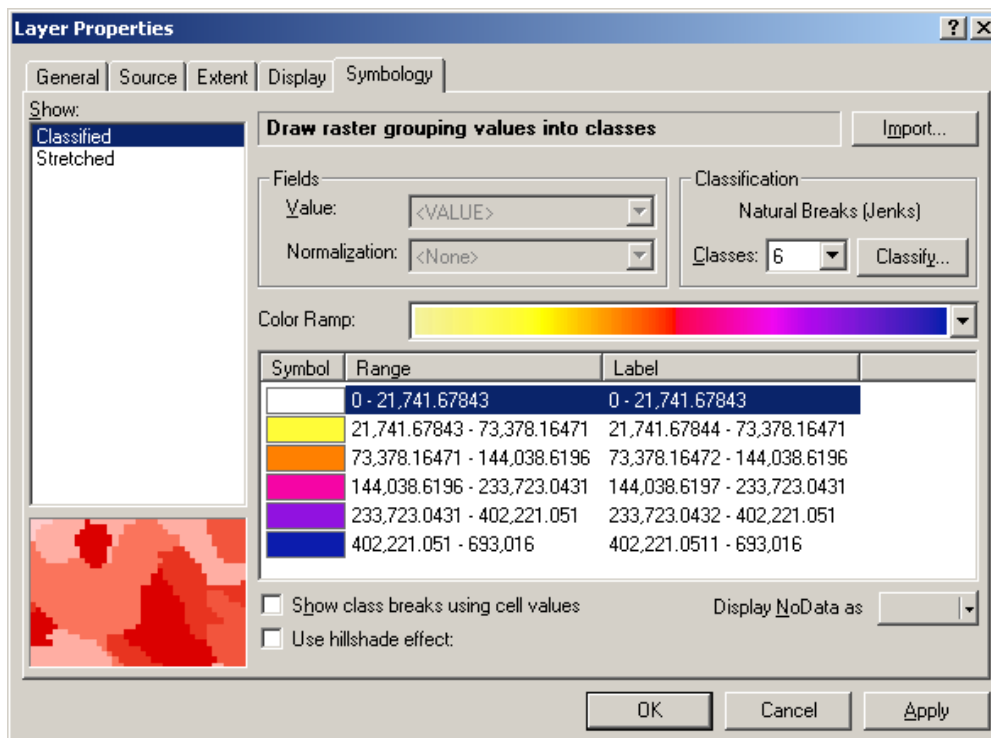
This function computes the flow accumulation grid that contains the accumulated number of cells upstream of a cell, for each cell in the input grid.

On the ArcHydro toolbar, **select** *Terrain Preprocessing* → *Flow Accumulation*.

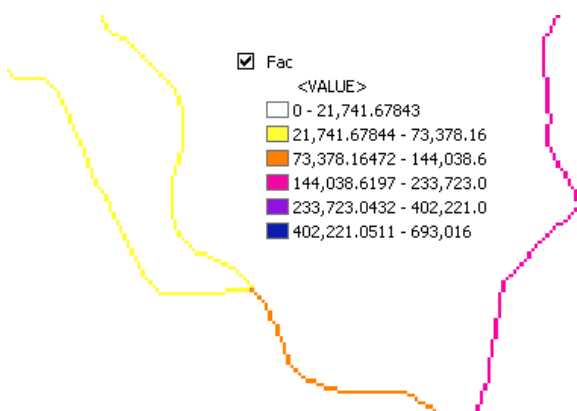
**Confirm** that the input of the Flow Direction Grid is *Fdr*. The output is the Flow Accumulation Grid having a default name of *Fac* that can be overwritten.



**Press OK.** Upon successful completion, the flow accumulation grid *Fac* is added to the map. This process may take several minutes for a large grid! **Adjust** the symbology of the Flow Accumulation layer *Fac* to a multiplicatively increasing scale to illustrate the increase of flow accumulation as one descends into the grid flow network.



**Zoom-in** to a stream network junction to see how the symbology changes from light to dark color as the number of upstream cells draining to a stream increase from upstream to downstream as shown in the Cedar Creek example below.



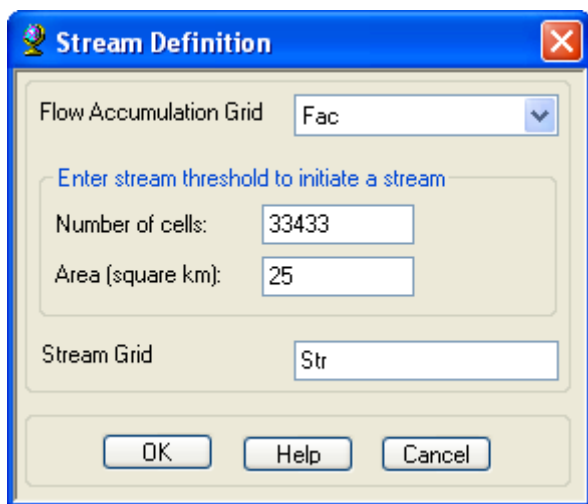
If you **click** at any point along the stream network on *Fac* grid using the identify button you can find the area draining to that point by **multiplying** the Fac number by the area of each cell (cell size x cell size).

Save the map document.

## 5. Stream Definition

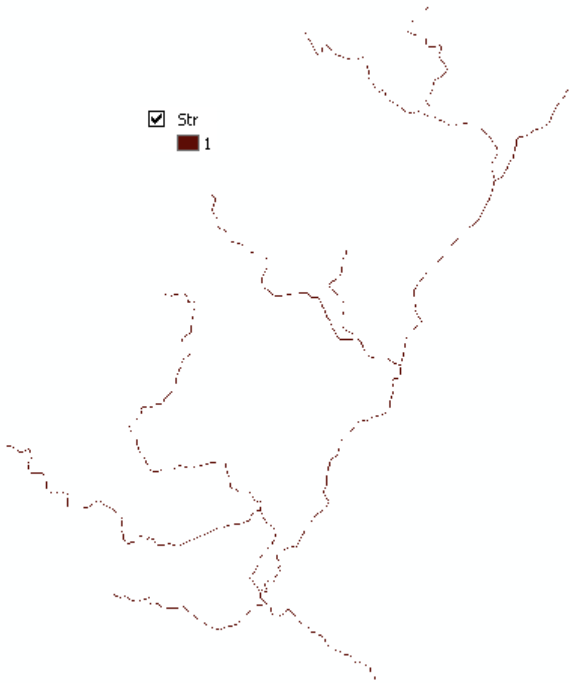
On the ArcHydro toolbar, **select** *Terrain Preprocessing* → *Stream Definition*.

**Confirm** that the input for the Flow Accumulation Grid is *Fac*. The output is the Stream Grid named *Str*, default name that can be overwritten.



A default value is displayed for the river threshold. This value represents 1% of the maximum flow accumulation: a simple rule of thumb for stream determination threshold. However, any other value of threshold can be selected. For example, the USGS Elevation Derivatives for National Applications (EDNA <http://edna.usgs.gov/>) approach uses a threshold of 5000 30 x 30 m cells (an area of 4.5 km<sup>2</sup>) for catchment definition. A smaller threshold will result in a denser stream network and usually in a greater number of delineated catchments. For this exercise, **choose** 0.1 km<sup>2</sup> as the threshold area, and click OK. This may need to be re-evaluated based on the resolution of delineated catchments.

Upon successful completion, the stream grid *Str* is added to the map. This *Str* grid contains a value of "1" for all the cells in the input flow accumulation grid (*Fac*) that have a value greater than the given threshold. All other cells in the Stream Grid contain no data. The cells in *Str* grid with a value of 1 are symbolized with black color to get a stream network as shown in the Cedar Creek example below:



## 6. Stream Segmentation

This function creates a grid of stream segments that have a unique identification. Either a segment may be a head segment, or it may be defined as a segment between two segment junctions. All the cells in a particular segment have the same grid code that is specific to that segment.

On the ArcHydro toolbar, **select** *Terrain Preprocessing* → *Stream Segmentation*.



**Confirm** that *Fdr* and *Str* are the inputs for the Flow Direction Grid and the Stream Grid respectively. Unless you are using your sinks for inclusion in the stream network delineation, the sink watershed grid and sink link grid inputs are Null. The output is the stream link grid, with the default name *StrLnk* that can be overwritten.

**Press OK.** Upon successful completion, the link grid *StrLnk* is added to the map. At this point, notice how each link has a separate value.

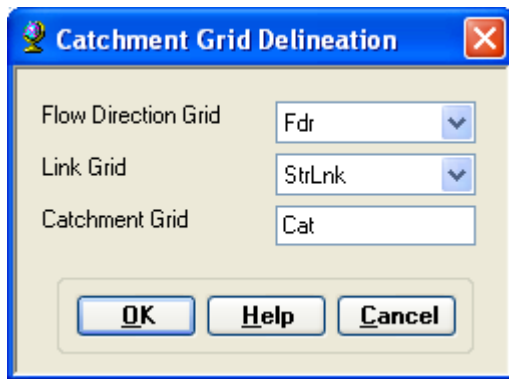
**Save** the map document.

## 7. Catchment Grid Delineation

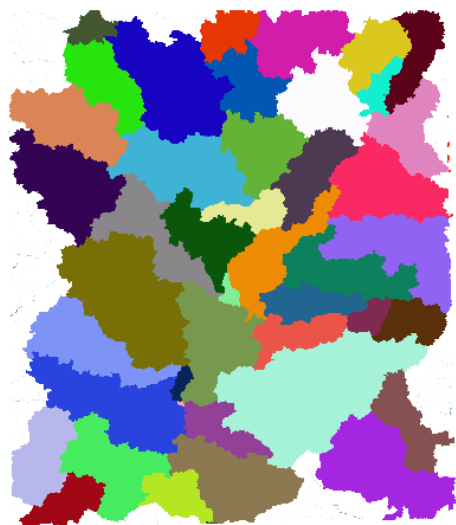
This function creates a grid in which each cell carries a value (grid code) indicating to which catchment the cell belongs. The value corresponds to the value carried by the stream segment that drains that area, defined in the stream segment link grid

On the ArcHydro toolbar, **select** *Terrain Preprocessing* → *Catchment Grid Delineation*.

**Confirm** that the input to the Flow Direction Grid and Link Grid are *Fdr* and *Lnk* respectively. The output is the Catchment Grid layer. *Cat* is its default name that can be overwritten by the user.



**Press OK.** Upon successful completion, the Catchment grid *Cat* is added to the map. If you want, you can recolor the grid with unique values to get a nice display as shown similar to the Cedar Creek example below (**use properties** → *symbolology*).



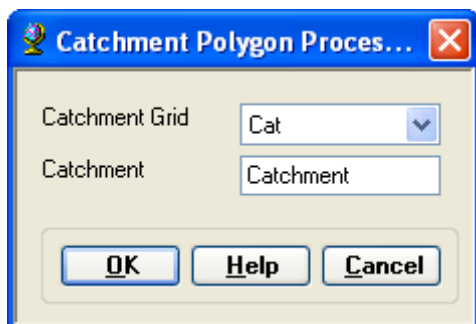
## 8. Catchment Polygon Processing

The three functions Catchment Polygon Processing, Drainage Line Processing and Adjoint Catchment Processing convert the raster data developed so far to vector format. The rasters created up to now have all been stored in a folder named *Layers*. The vector data will be stored in a feature dataset also named *Layers* within the geodatabase associated with the map document. Unless otherwise specified under *APUtilities* → *Set Target Locations* the geodatabase inherits the name of the map document (*ArcHydro.mdb* in this case) and the folder and feature dataset inherit their names from the active data frame which by default is named *Layers*.

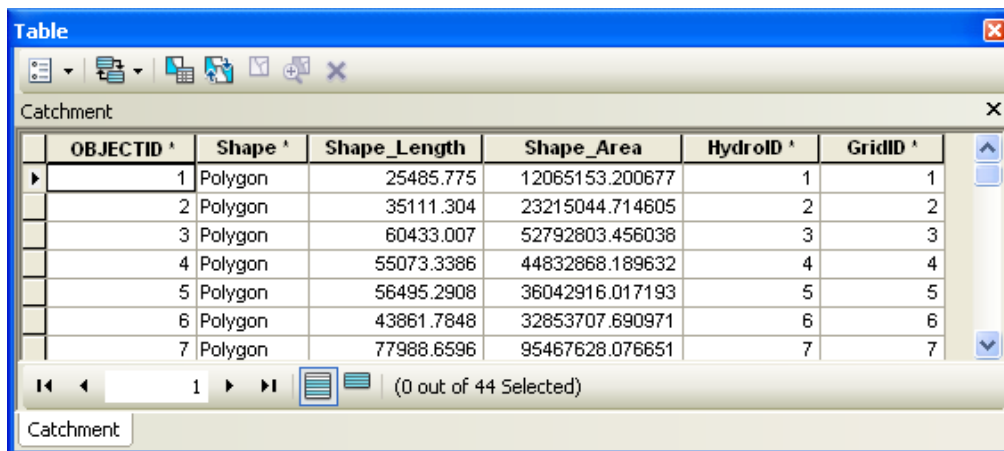
On the ArcHydro toolbar, select *Terrain Preprocessing* → *Catchment Polygon Processing*.

This function converts a catchment grid into a catchment polygon feature.

**Confirm** that the input to the CatchmentGrid is *Cat*. The output is the Catchment polygon feature class, having the default name *Catchment* that can be overwritten.



**Press OK.** Upon successful completion, the polygon feature class *Catchment* is added to the map. Open the attribute table of *Catchment*. Notice that each catchment has a *HydroID* assigned that is the unique identifier of each catchment within *ArcHydro*. Each catchment also has its Length and Area attributes. These quantities are automatically computed when a feature class becomes part of a geodatabase. Below is the table for the Cedar Creek watershed.



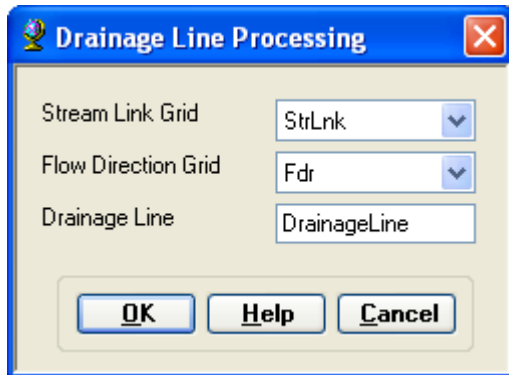
OBJECTID	Shape	Shape_Length	Shape_Area	HydroID	GridID
1	Polygon	25485.775	12065153.200677	1	1
2	Polygon	35111.304	23215044.714605	2	2
3	Polygon	60433.007	52792803.456038	3	3
4	Polygon	55073.3386	44832868.189632	4	4
5	Polygon	56495.2908	36042916.017193	5	5
6	Polygon	43861.7848	32853707.690971	6	6
7	Polygon	77988.6596	95467628.076651	7	7

## 9. Drainage Line Processing

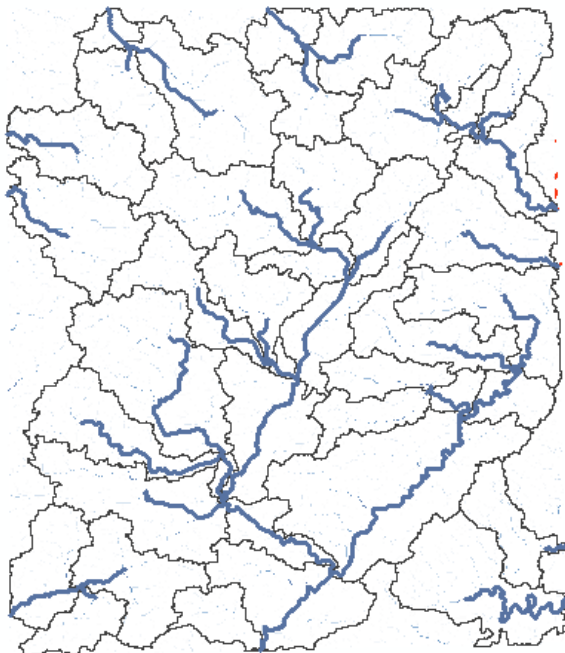
This function converts the input Stream Link grid into a Drainage Line feature class. Each line in the feature class carries the identifier of the catchment in which it resides.

On the ArcHydro toolbar, **select** *Terrain Preprocessing* → *Drainage Line Processing*.

**Confirm** that the input to Link Grid is *Lnk* and to Flow Direction Grid *Fdr*. The output Drainage Line has the default name *DrainageLine* that can be overwritten.



**Press OK.** Upon successful completion, the linear feature class *DrainageLine* is added to the map as shown below.



## 10. Adjoint Catchment Processing

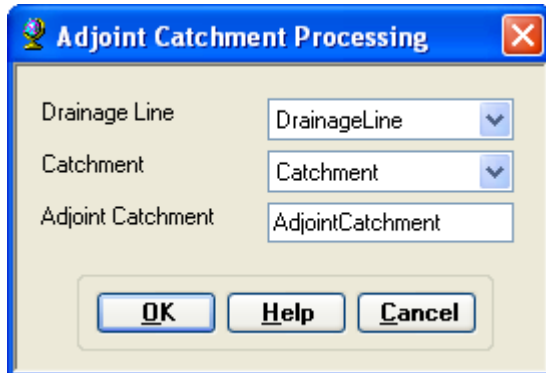
This function generates the aggregated upstream catchments from the *Catchment* feature class.



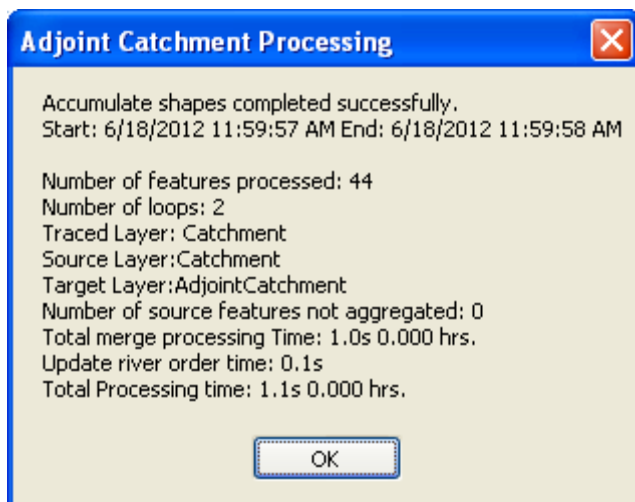
For each catchment that is not a head catchment, a polygon representing the whole upstream area draining to its inlet point is constructed and stored in a feature class that has an *Adjoint Catchment* tag. This feature class is used to speed up the point delineation process.

On the ArcHydro toolbar, **select** *Terrain Preprocessing* → *Adjoint Catchment Processing*.

**Confirm** that the inputs to Drainage Line and Catchment are respectively *DrainageLine* and *Catchment*. The output is Adjoint Catchment, with a default name *AdjointCatchment* that can be overwritten.



**Press OK.** Upon successful completion, you will see a message box similar to the one below that will give you a summary of the number of catchments that were aggregated to create the adjoint catchments. For example:



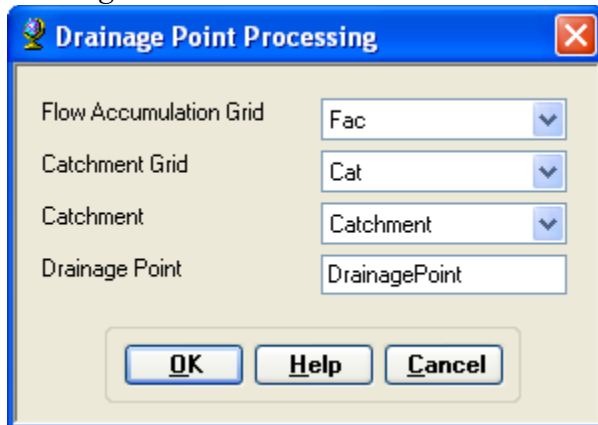
Click OK, and a polygon feature class named *AdjointCatchment* is added to the map.

## 11. Drainage Point Processing

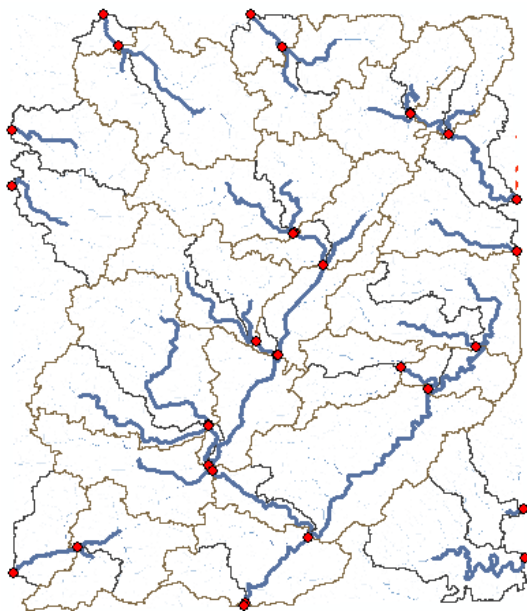
This function allows generating the drainage points associated to the catchments.

On the ArcHydro toolbar, **select** *Terrain Preprocessing* → *Drainage Point Processing*.

**Confirm** that the inputs are as below. The output is Drainage Point with the default name *DrainagePoint* that can be overwritten.

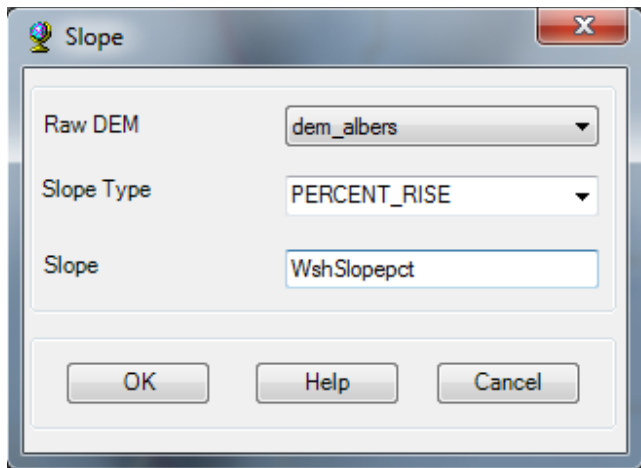


**Press OK.** Upon successful completion of the process, the point feature class “DrainagePoint” is added to the map. For example:



In addition to these datasets, go ahead and also get the slope grid by using the ArcHydro Toolbar. To create a slope grid using ArcHydro tools, **select** *Terrain Preprocessing* → *Slope*.

**Confirm** the input as *dem\_albers*, slope type is *percent\_rise*, and the output will be a slope grid with the default name *WshSlopePct* that can be overwritten.




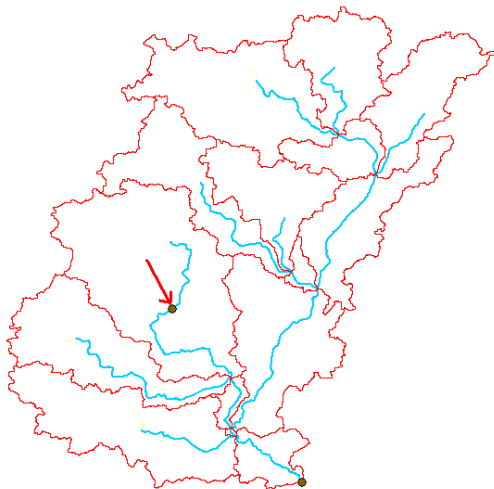
## Watershed Processing

ArcHydro toolbar also provides an extensive set of tools for delineating watersheds and subwatersheds (batch watershed and subwatershed delineation and interactive point delineation). These tools rely on the datasets derived during terrain processing. This part of the exercise will expose you to one of the Watershed Processing functionality in ArcHydro.

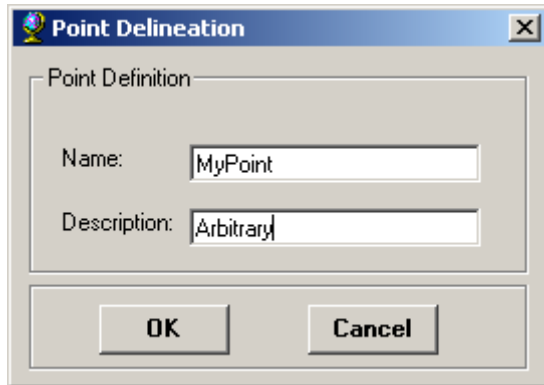
### Interactive Point Delineation

An alternative to delineate watersheds is the Point Delineation tool .

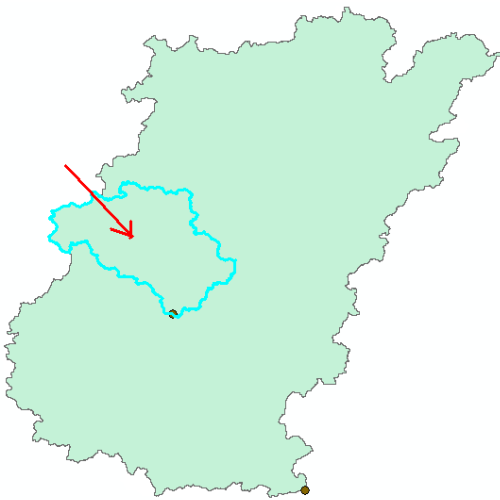
**Click** on the Point Delineation icon  in the ArcHydro toolbar to activate the tool. **Zoom-in** to the network and **click** the mouse (along the drainage line) to create your point of interest. For example:



**Fill-in** the name and comment as shown below in the form below.



The new point will be added to the *WatershedPoint* feature class, and the new Watershed will be added to the *Watershed* feature class.

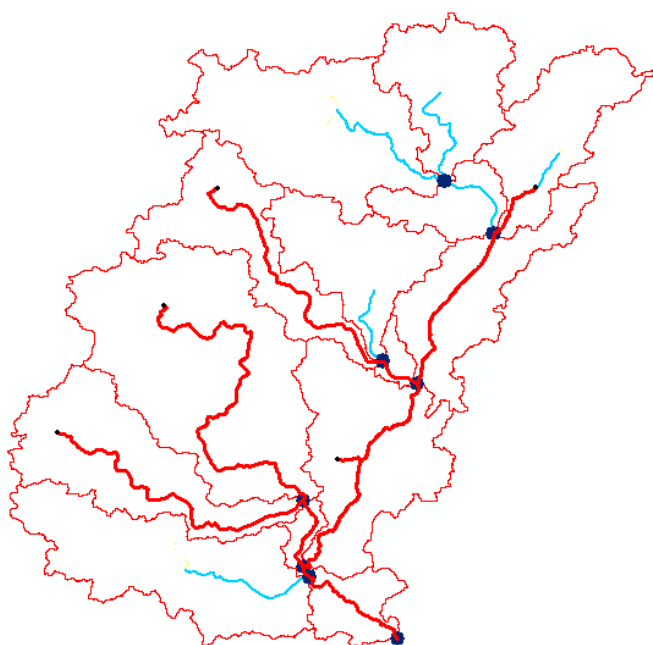


### Flow Path Tracing

The flow path defines the path of flow from the selected point to the outlet of the catchment following the steepest descent. You can use this option to trace the flow path (the path along with water will flow to the outlet) for any point in the watershed. **Click** on *the Flow Path*

*Tracing* icon  in the ArcHydro toolbar to activate the tool.

**Click** your mouse at any point to determine the flow path. If you select a point along the stream network, the flow path will follow the exact path of the stream. See the Cedar Creek example below.



This ends the watershed and stream network delineation.

## **Section 3**

# **Terrain Processing and HMS Model using GeoHMS**

# Terrain Processing and HMS-Model Development using GeoHMS

Prepared by  
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School of Civil Engineering, Purdue University  
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August 2012

Modified by C. Richardson, M. Cal, and J. Ealey for the NMDOT training module

April 2013

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## Introduction

This tutorial is designed to expose you to basic functions in HEC-GeoHMS (ArcGIS 10.1 version) to create input files for hydrologic modeling with HEC-HMS. It is expected that you are familiar with HEC-HMS and ArcGIS.

## Computer Requirements

You must have a computer with windows operating system, and the following programs installed:

1. ArcGIS 10.1 (with spatial analyst extension)
2. ArcHydro tools (version that works with 10.1)
3. HEC-GeoHMS toolbar (version that works with 10.1)

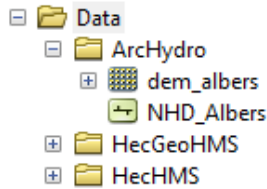
## Data Requirements and Description

The data files used in the exercise consist of a DEM grid for *Otero Mesa* in southern New Mexico and the hydrography data. Although the data are provided with this exercise, and the steps involved in downloading the NED and NHD data from the USGS website are described in the following document.

[http://web.ics.purdue.edu/~vmerwade/education/ned\\_nhd.pdf](http://web.ics.purdue.edu/~vmerwade/education/ned_nhd.pdf)

Note that specific screenshots are provided for key input of data relative to the *Otero Mesa* watershed. Other screenshots from the *Cedar Creek* watershed in Indiana, as developed originally for this tutorial by Dr. Venkatesh Merwade, are retained for illustrative purposes of processed output.

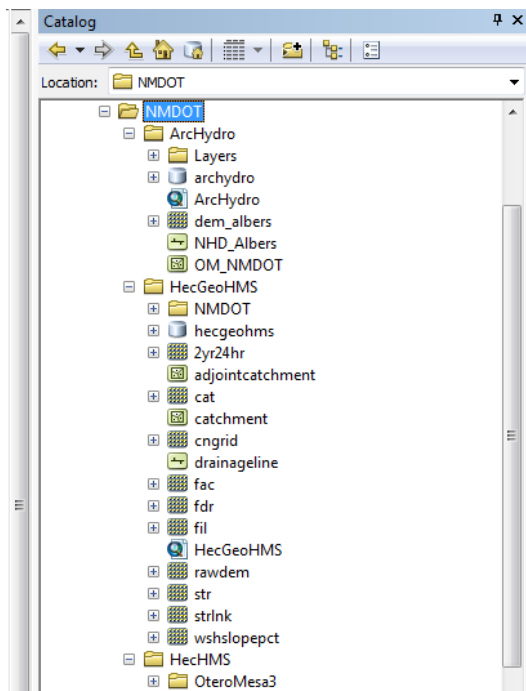
The ArcCatalog-view of the *Otero Mesa* data folder for subsequent processing with HEC-GeoHMS and HEC-HMS is shown below:



*dem\_albers* is the raw 10 m DEM for *Otero Mesa* obtained from USGS and extracted for the study watershed area. The second dataset, *NHD\_Albers*, is a shapefile containing stream network for the study watershed area. *NHD\_Albers* is extracted from the national hydrography dataset (this is done by selecting the stream network for the watershed and exporting it to a shape file). Both rasters are already assigned a projected coordinate system (NAD\_1988\_Albers).

**Note:** It is critical to assign and use consistent coordinate system for all the datasets used in delineating watersheds by using any pre-processing tool.

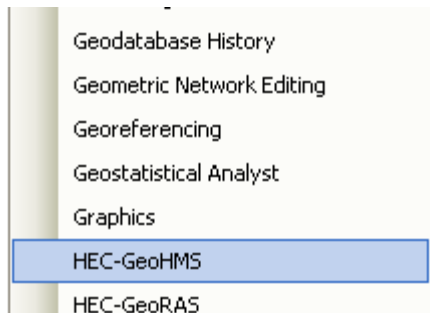
A second folder called *NMDOT* is provided as well for this tutorial as a guide. It contains all ArcHydro, HEC-GeoHMS, and HEC-HMS data generated for the *Otero Mesa* watershed. Below is the screenshot of this folder:



## Getting Started

**Open** ArcMap. Create a new empty map. **Right Click** on the menu bar to pop up the context menu showing available tools as shown below:






**Check** the HEC-GeoHMS menu.

You should now see the HEC-GeoHMS toolbar added to ArcMap as shown below. You can leave it floating or you may dock it in ArcMap.



**Note:** It is not necessary to load the Spatial Analyst by clicking Customize → Extensions..., and checking the box next to Spatial Analyst.

## Load the data to ArcMap

**Click** on the Add icon  to add the raster data. In the dialog box, **navigate** to the location of the data; **select** the raster file *dem\_albers* containing the DEM for *Otero Mesa* and **Click** on the Add button. The added file will then be listed in the Arc Map Table of contents. Similarly **add** *NHD\_albers*, and **Save** the map document as *HecGeoHMS.mxd* under the HecGeoHMS folder.

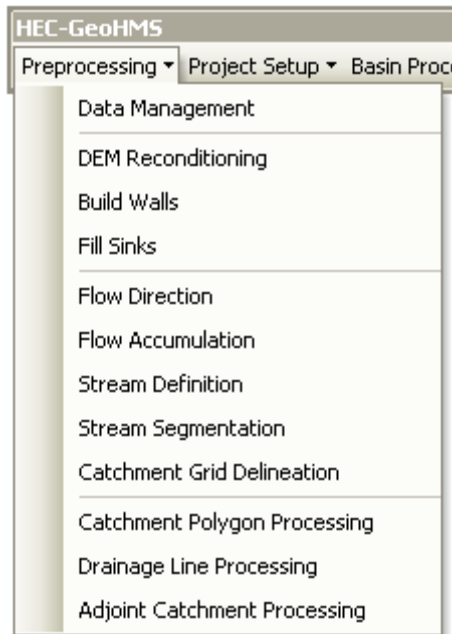
## Dataset Setup

All vector data created with GeoHMS will be stored in a new geodatabase that has the same name as the stored project or ArcMap document (unless pointed to an existing geodatabase) and in the same directory where the project has been saved (your working folder). By default, the new raster data are stored in a subdirectory with the same name as the dataset or Data Frame in the ArcMap document (called Layers by default and under the directory where the project is stored). The specified directory is C: drive and the folder is *Data* for this tutorial for newly generated data. The folder *NMDOT* is a previous processing of the *Otero Mesa* watershed for comparison. The location of the vector, raster, and other data can be explicitly specified using the function *ApUtilities* → *Set Target Locations*.

You can leave the default settings if they are pointing to the same directory where the ArcMap document is saved.

## Terrain Preprocessing

Terrain processing involves using the DEM to create a stream network and catchments. The Processing menu (shown below) in HEC-GeoHMS is used for terrain processing.



All the steps in the Preprocessing menu should be performed in sequential order, from top to bottom. All of the preprocessing must be completed to delineate the watershed for the HEC-HMS model. Towards the end of the ArcHydro Tutorial, you will have the following datasets:

#### Raster Data

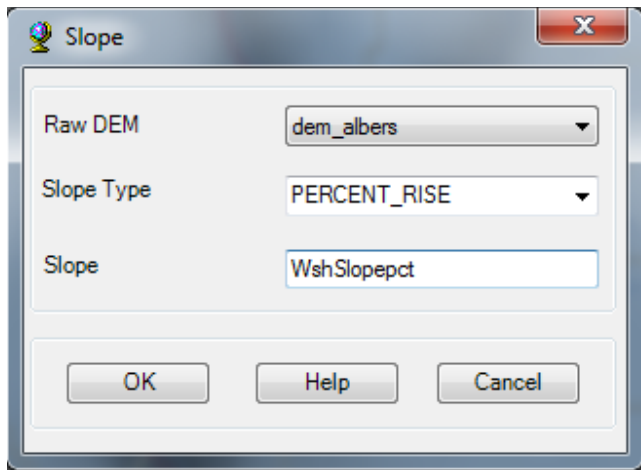
1. Raw DEM
2. HydroDEM (DEM after reconditioning and filling sinks)
3. Flow Direction Grid
4. Flow Accumulation Grid
5. Stream Grid
6. Stream Link Grid
7. Catchment Grid
8. Slope Grid

#### Vector Data

1. Catchment Polygons
2. Drainage Line Polygons
3. Adjoint Catchment Polygons
4. Watershed
5. Watershed Point

In addition to these datasets, if you have not already done so go ahead and get the slope grid by using the Arc Hydro Toolbar. To create a slope grid using Arc Hydro tools, **select** *Terrain Preprocessing* → *Slope*.

**Confirm** that the input as *dem\_albers*, slope type is *percent rise*, and the output will be a slope grid with the default name *WshSlopePct* that can be overwritten.



This concludes the terrain processing part. What you have produced is a hydrologic skeleton that can now be used to delineate watersheds or subwatersheds for any given point on delineated stream network. The next part of this tutorial involves, delineating a watershed to create a HEC-HMS model using HEC-GeoHMS. **Save** your map document.

## HEC-HMS Modeling Development using HEC-GeoHMS

Before you continue, please make sure you have the following datasets in the map document from the previous part. Note that the *dem\_albers* is now called *RawDEM* by the program.

### Specific Rasters

1. *RawDEM* (raw DEM)
2. *Fil* (filled DEM)
3. *Fdr* (flow direction grid)
4. *Fac* (flow accumulation grid)
5. *Str* (stream network grid)
6. *StrLnk* (stream link grid)
7. *Cat* (catchment grid)
8. *WshSlopePct* (slope grid)

### Specific Vectors

1. *Catchment*
2. *DrainageLine*
3. *AdjointCatchment*
4. *Watershed*
5. *WatershedPoint*

**Save** the map document.

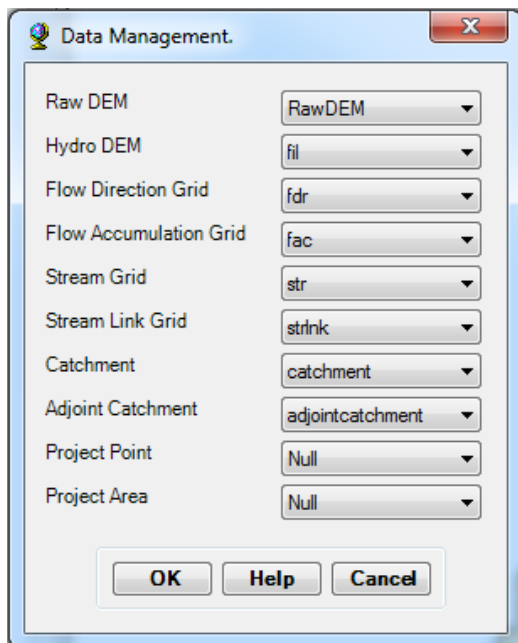
## HEC-GeoHMS Project Setup

*The HEC-GeoHMS project setup menu has tools for defining the outlet for the watershed, and delineating the watershed for the HEC-HMS project. As multiple HMS basin models can be*

developed by using the same spatial data, these models are managed by defining two feature classes: *ProjectPoint* and *ProjectArea*. Management of models through *ProjectPoint* and *ProjectArea* let users to see areas for which HMS basin models are already created, and also allow users to re-create models with different stream network threshold. It is also convenient to delete projects and associated HMS files through *ProjectPoint* and *ProjectArea* option.

## Dataset Setup

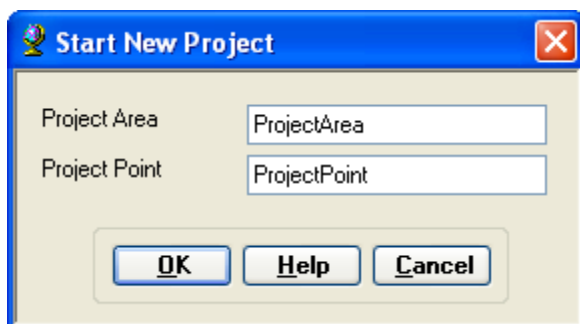
Select *HMS Project Setup*→*Data Management* on the HEC-GeoHMS Main View toolbar. **Confirm/define** the corresponding map layers in the Data Management window as shown below:



Click *OK*.

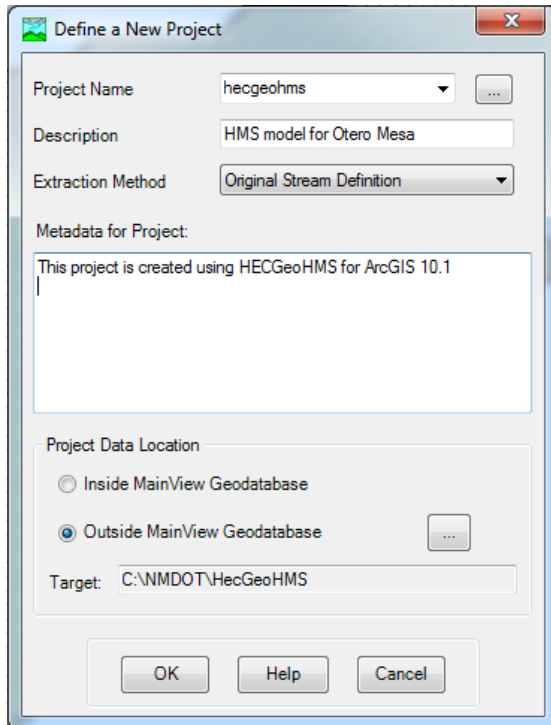
## Creating New HMS Project

Click on *Project Setup*→ *Start New Project*. **Confirm** *ProjectArea* for ProjectArea and *ProjectPoint* for ProjectPoint, and Click *OK*.



(**Note:** For some reason, if you get an error message about accuracy/resolution of the data, this has to do with tolerances for x,y,m,z coordinates in your spatial coordinates which you need to fix in ArcCatalog)

This will create ProjectPoint and ProjectArea feature classes. In the next window, provide the following inputs:



Define a New Project

Project Name: hecgeohms

Description: HMS model for Otero Mesa

Extraction Method: Original Stream Definition

Metadata for Project:

This project is created using HECGeoHMS for ArcGIS 10.1

Project Data Location:

☐ Inside MainView Geodatabase

☒ Outside MainView Geodatabase

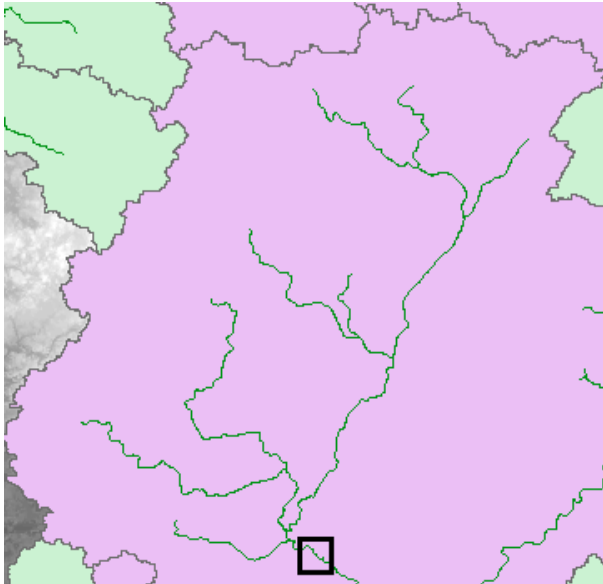
Target: C:\NMDOT\HecGeoHMS


OK Help Cancel

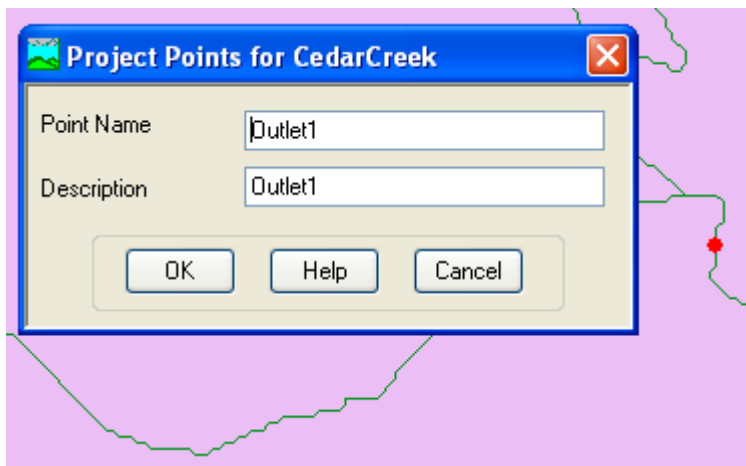
If you click on Extraction Method drop-down menu, you will see another option “A new threshold” which will delineate streams based on this new threshold for the new project. For now **accept** the default original stream definition option. You can write some metadata if you wish, and finally **choose** the outside MainView Geodatabase for Project Data Location, and **browse** to your working directory (HecGeoHMS) where *HecGeoHMS.mxd* is stored. **Click OK**.

**Click OK** on the message regarding successful creation of the project. You will see that new feature classes *ProjectArea* and *ProjectPoint* are added to ArcMap’s table of contents. These feature classes are added to the HecGeoHMS geodatabase (HecGeoHMS.gdb) under your working directory.

Next **Zoom-in** to downstream section of the *Otero Mesa* to define the watershed outlet as shown in the Cedar Creek example below:



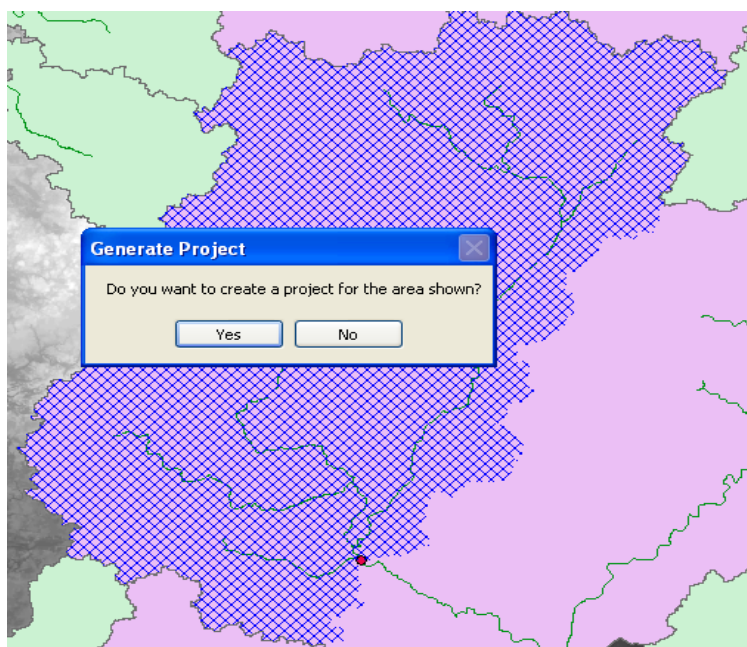
Select the *Add Project Points* tool  on the HEC-GeoHMS toolbar, and **Click** on the downstream outlet area of the *Otero Mesa* to define the outlet point as shown below as red dot:




**Accept** the default Point Name and Description (*Outlet*), and **Click OK**. This will add a point for the watershed outlet in the *ProjectPoint* feature class.

**Save** the map document.

Next, **Select** *HMS Project Setup* → *Generate Project*. This will create a mesh (by delineating watershed for the outlet in Project Point), and display a message box asking if you want to create a project for this hatched area as shown below:




(**Note:** This part could be challenging sometimes. If you face problem in creating Project Area, just delineate a watershed using the point delineation tool  in Arc Hydro for the Project Point feature, and load this watershed polygon into ProjectArea feature class. Make sure the HydroID of ProjectArea is same as ProjectID of ProjectPoint. Also you need to make sure the name and description match with each other)

**Click Yes** on the message box. Next, **confirm** the layer names for the new project (leave default names for Subbasin, Project Point, River and BasinHeader), and **Click OK**.

MainViewDEM	MainViewDEM
Raw DEM	RawDEM
Hydro DEM	Fil
Flow Direction Grid	Fdr
Flow Accumulation Grid	Fac
Stream Grid	Str
Stream Link Grid	StrLnk
Catchment Grid	Cat
Subbasin	Subbasin1
Project Point	ProjectPoint1
River	River1

**OK** **Help** **Cancel**

This will create a new folder inside your working folder (HecGeoHMS) with the name of the project and store all the relevant raster, vector and tabular data inside this folder. The raster data are stored in a sub folder with the project name inside this newly created folder. All vector and tabular data are stored in a geodatabase with the project name as a *.mgb* file. You will also notice that a new data frame is added in ArcMap containing data for Otero Mesa. For the generated tutorial data, these are found under the *NMDOT* folder in a geodatabase (*NMDOT*) contained in the working directory (HecGeoHMS).

You can also play with the contributing area tool  to find out contributing area at different points in the basin stream network. With *lnk* grid active, **Select** the contributing area tool, and **Click** at any point along the stream to know the contributing area.

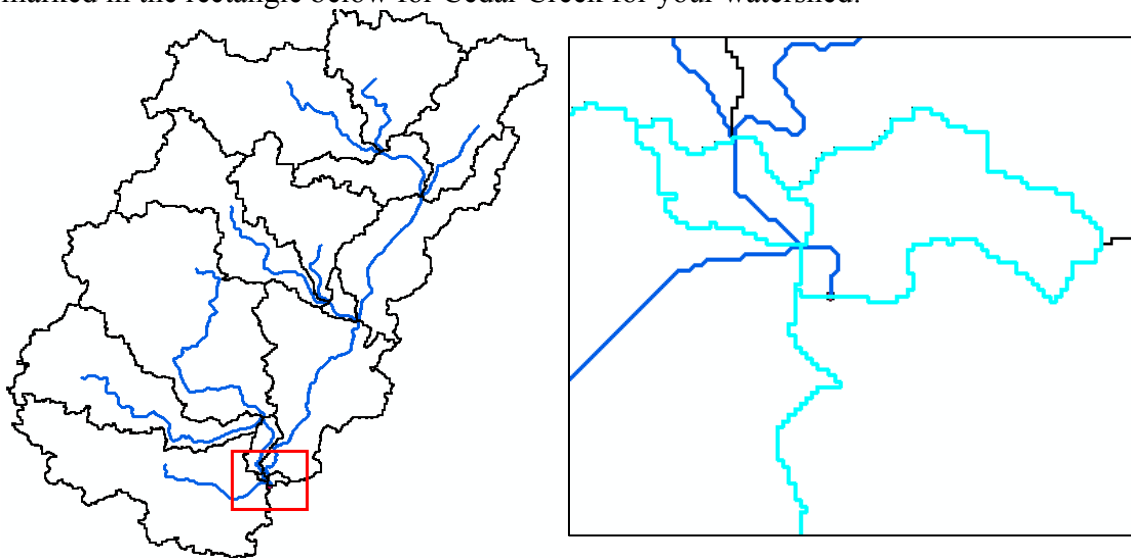
**Save** the map document.


## Basin Processing

The basin processing menu has features such as revising subbasin delineations, dividing basins, and merging streams.

### Merge Basins

This process merges two or more adjacent basins into one. **Zoom-in** to an area similar to that marked in the rectangle below for Cedar Creek for your watershed:



**Select** adjacent basins within your watershed using the standard select tool . **Click** on *Basin Processing* → *Basin Merge*. You will get a message asking to confirm the merging of selected basins (with basins hatched in background), **Click Yes**.

As a result of repeated merging, you now have reduced the number of subbasins and stream segments in the project.

**Save** the map document.

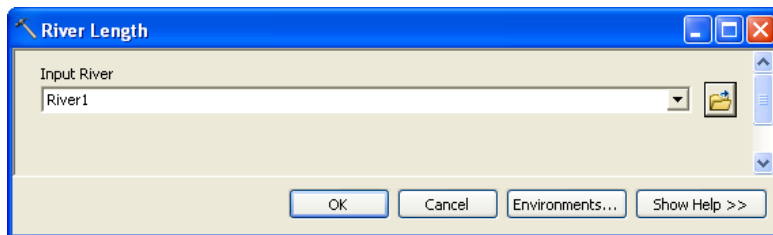


## Extracting Basin Characteristics

The basin characteristics menu in the HEC-GeoHMS Project View provide tools for extracting physical characteristics of streams and subbasins into attribute tables.

### River Length

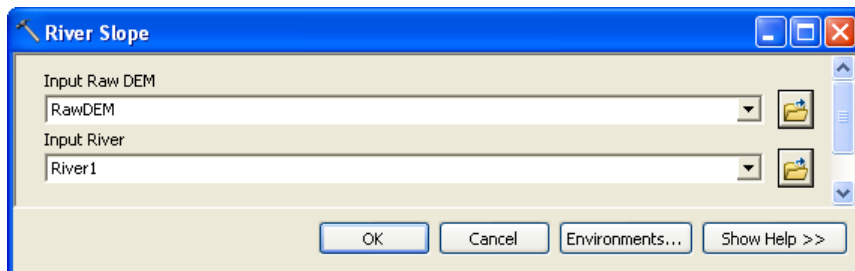
This tool computes the length of river segments and stores them in *RiverLen* field. **Select** *Characteristics* → *River Length*. **Confirm** the input River name, and **Click** *OK*.



You can check the *RiverLen* field in the input *River1* (or whatever name you have for your input river) feature class is populated. **Save** the map document.

### River Slope

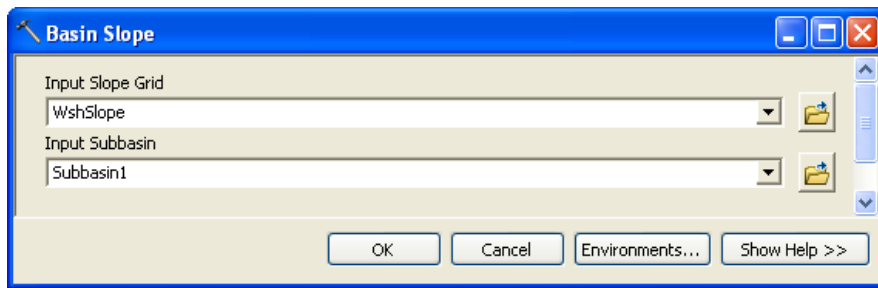
This tool computes the slope of the river segments and stores them in *Slp* field. **Select** *Basin Characteristics* → *River Slope*. **Confirm** inputs for RawDEM and River, and **Click** *OK*.



You can check the *Slp* field in the input *River1* (or whatever name you have for your input river) feature class is populated. Fields *ElevUP* and *ElevDS* are also populated during this process.  $Slp = (ElevUP - ElevDS) / RiverLen$ .

### Basin Slope

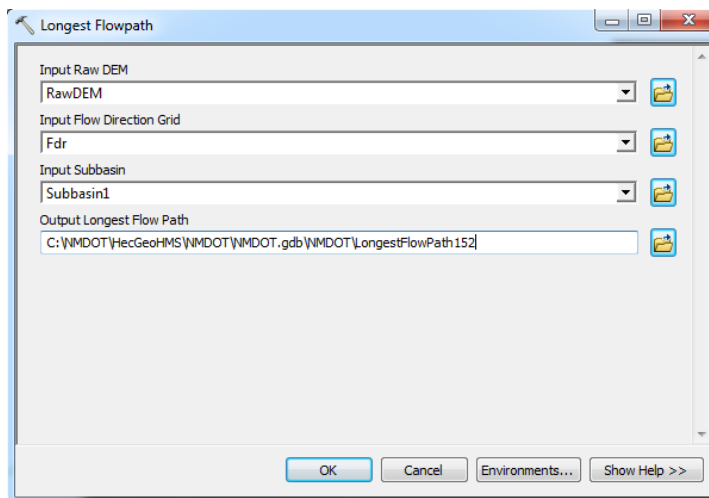
This tool computes average slope for subbasins using the slope grid and subbasin polygons. **Add** *wshslopepct* (percent slope for watershed) grid to the map document. **Select** *Characteristics* → *Basin Slope*. **Confirm** the inputs for Subbasin and Slope Grid, and **Click** *OK*.



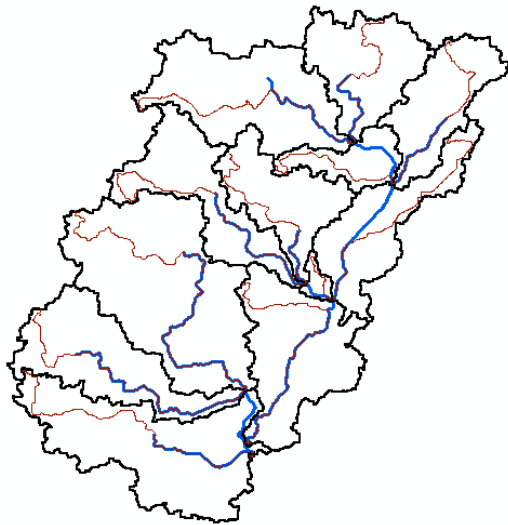
After the computations are complete, the *BasinSlope* field in the input Subbasin feature class is populated.

## Longest Flow Path

This will create a feature class with polyline features that will store the longest flow path for each subbasin. Select *Characteristics* → *Longest Flow Path*. **Confirm** the inputs, and leave the default output name *LongestFlowPath* unchanged. **Click OK**.



A new feature class storing longest flow path for each subbasin in your watershed is created as shown below in the Cedar Creek watershed.

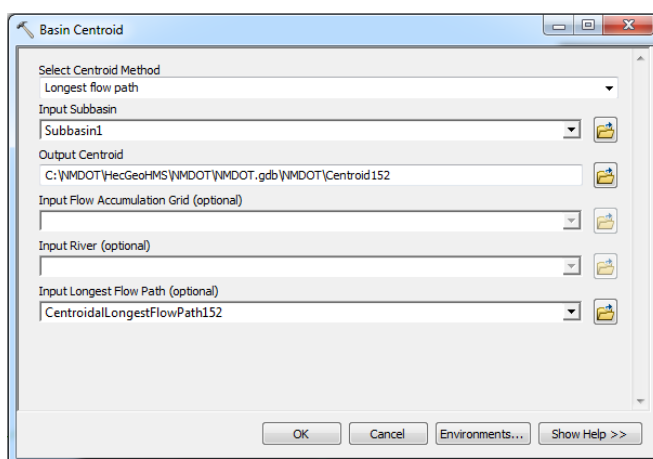


**Open** the attribute table of Longest Flow Path, and examine its attributes. **Close** the attribute table, and **Save** the map document.

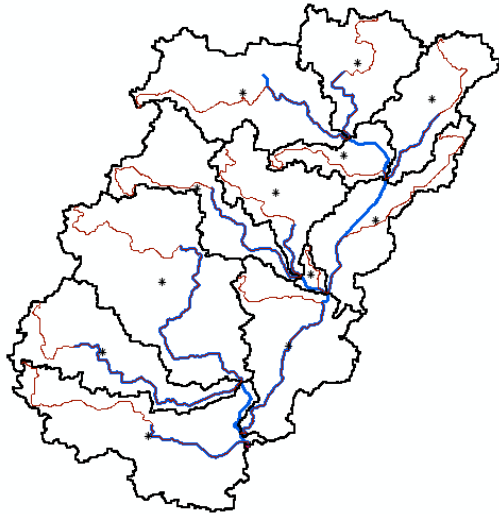
## Basin Centroid

This will create a *Centroid* point feature class to store the centroid of each subbasin. Select *Characteristics* → *Basin Centroid*. **Choose** the Longest Path Method in lieu of the default *Center of Gravity Method*, input Subbasin, and leave the default name for Centroid. **Click** OK.

(Note: *Center of Gravity Method* computes the centroid as the center of gravity of the sub basin if it is located within the sub basin. If the Center of Gravity is outside, it is snapped to the closest boundary. *Longest Flow Path Method* computes the centroid as the center of the longest flow path within the sub basin. The quality of the results by the two methods is a function of the shape of the sub basin and should be evaluated after they are generated.)



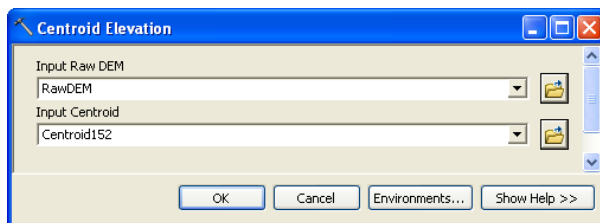
A point feature class showing centroid for each subbasin is added to the map document. See the Cedar Creek example below:



Check to see if the centroid locations look reasonable. If so, proceed. **Save** the map document.

### Basin Centroid Elevation

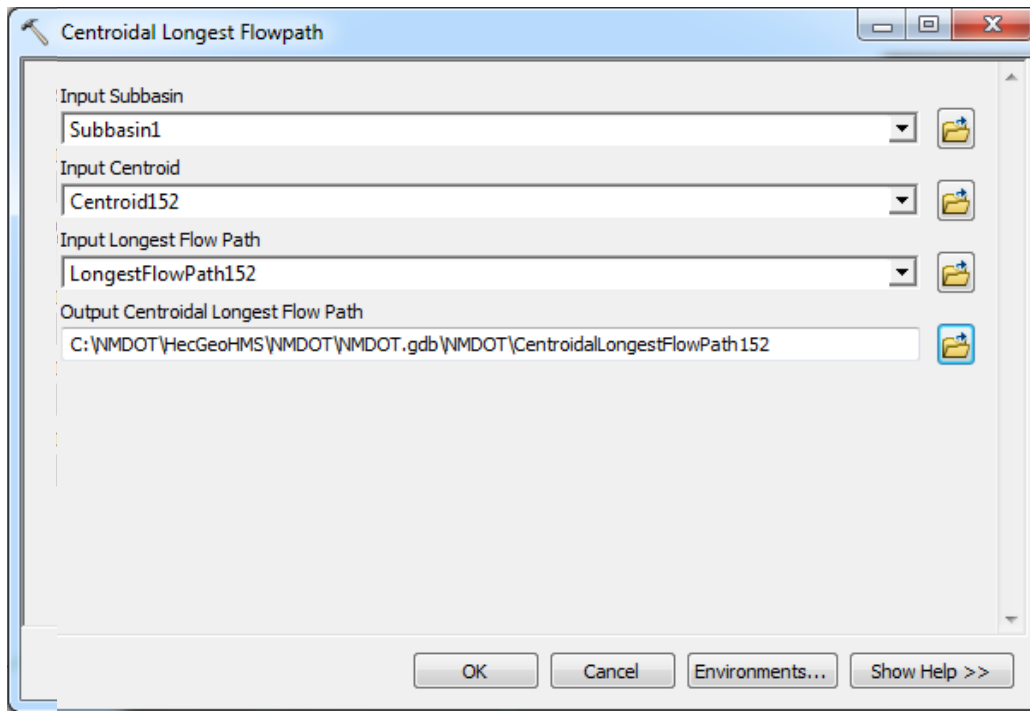
This will compute the elevation for each centroid point using the underlying DEM. **Select Characteristics**→ *Centroid Elevation Update*. **Confirm** the input DEM and centroid feature class, and **Click OK**.



After the computations are complete, **Open** the attribute table of Centroid to examine the Elevation field. The centroid elevation update may be needed when none of the basin centroid methods (center of gravity or longest flow path) provide satisfactory results, and it becomes necessary to edit the Centroid feature class and move the centroids to a more reasonable location manually.

### Centroidal Longest Flow Path

**Select Characteristics**→ *Centroidal Longest Flow Path*. **Confirm** the inputs, and leave the default name for output Centroidal Longest Flow Path, and **Click OK**.



This creates a new polyline feature class showing the flowpath for each centroid point along longest flow path. **Save** the map document.

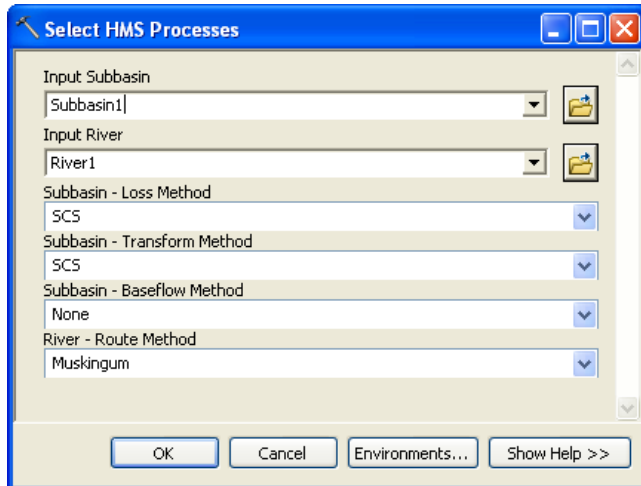
## HMS Inputs/Parameters

The hydrologic parameters menu in HEC-GeoHMS provides tools to estimate and assign a number of watershed and stream parameters for use in HMS. These parameters include SCS curve number, time of concentration, channel routing coefficients, etc.

### Select HMS Processes

You can specify the methods that HMS should use for transform (rainfall to runoff) and routing (channel routing) using this function. Of course, this can be modified and/or assigned inside HMS.

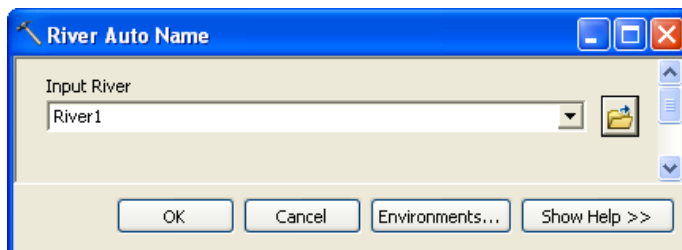
**Select** *Hydrologic Parameters* → *Select HMS Processes*. **Confirm** input feature classes for Subbasin and River, and **Click OK**. Choose *SCS* for Loss Method (getting excess rainfall from total rainfall), *SCS* for Transform Method (for converting excess rainfall to direct runoff), *None* for Baseflow Type, and *Muskingum* for Route Method (channel routing). **Click OK**.



You can **Open** the attribute table of subbasin feature class to see that the subbasin methods are added to *LossMet*, *TransMet*, and *BaseMet* fields, respectively. The Muskingum method is added to *RouteMet* field in the River feature class. You can treat these methods as tentative which can be changed in HMS model. **Save** the map document.

### River Auto Name

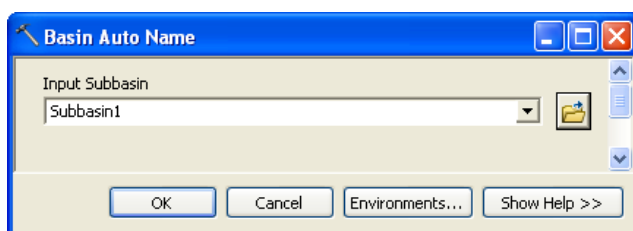
This function assigns names to river segments. **Select Parameters** → *River Auto Name*. **Confirm** the input feature class for River, and **Click OK**.



The *Name* field in the input River feature class is populated with names that have “R###” format, where “R” stands for river/reach “###” is an integer.

### Basin Auto Name

This function assigns names to subbasins. **Select Parameters** → *Basin Auto Name*. **Confirm** the input feature class for subbasin, and **Click OK**.



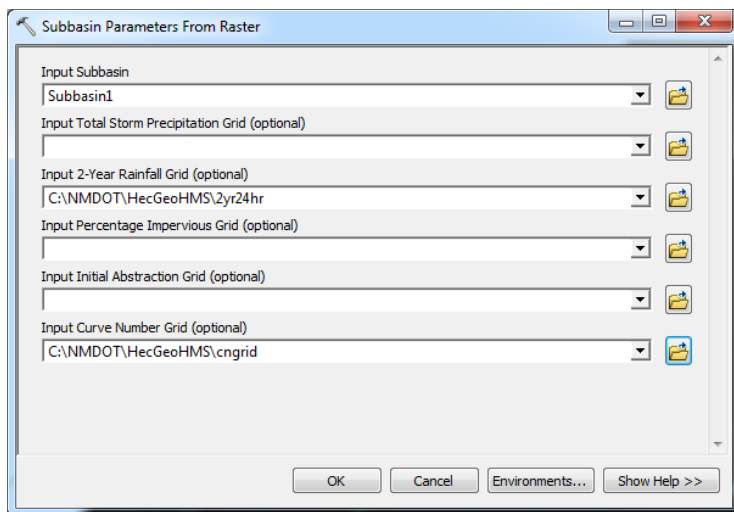
Like river names, the *Name* field in the input Subbasin feature class is populated with names that have “W####” format, where “W” stands for watershed, and “####” is an integer. **Save** the map document.

## Subbasin Parameters

Depending on the method (HMS process) you intend to use for your HMS model, each subbasin must have parameters such as SCS curve number for SCS method and initial loss constant, etc. These parameters are assigned using Subbasin Parameters option. This function overlays subbasins over grids and compute average value for each basin. You will explore only those parameters that do not require additional datasets or information.

**Add** *cngrid* (curve number grid) from HecGeoHMS folder to the map document. **Add** *2yr24hr* (rainfall grid) from HecGeoHMS folder to the map document. *Note that these original raster grids must first be resampled to the grid size of the specific watershed, in this case a 10 x 10 m. The county curve number grids are 30 x 30 m; the rainfall grid is 800 x 800 m.*

**Select** *Hydrologic Parameters* → *Subbasin Parameters*. You will get a menu of parameters that you can assign. **Uncheck** all parameters and **Check** *Curve Number Grid* and *2yr Rainfall Grid* as shown below, and **Click** OK.



**Confirm** the inputs for Subbasin, Curve Number Grid, and 2yr Rainfall Grid, and **Click** OK.

After the computations are complete, you can **Open** the attribute table for subbasin, and see that a field named *BasinCN* is populated with average curve number for each subbasin. **Close** the attribute table, and **Save** the map document.

The SCS Curve Number is extracted using a grid, but parameters can also be extracted by using a feature class and its intersection with subbasins by using the Subbasin Parameters from Features option, but this option is not described in this exercise.

## TR-55 Flow Path Segments

This is used to define different flow regimes along the longest flow path. Under HEC-GeoHMS Project View tool bar **Click** *Hydrologic Parameters* → *TR-55 Flow Path Segments*. **Confirm** the inputs for Subbasin as *Subbasin1*, for River as *River1*, for Longest Flow Path as *LongestFlowPath1*, and Flow Break Points as *FlowBreakPoints1*. **Click** OK. A flow break point layer will be generated with a field named *FlowBreakpoints1*. Verify the field *Name* is populated with data and the ArcMap window is displaying an *AA* and *BB* point on the flow break point layer.

## TR-55 Flow Segment Parameters

This calculates the length and slope for the TR-55 flow path. Under HEC-GeoHMS Project View tool bar **Click** *Hydrologic Parameters* → *TR-55 Flow Segment Parameters*. **Confirm** the input for Longest Flow Path as *LongestFlowPath1*. Leave all other values the same. **Click** OK. The function creates and updates the following fields in the *LongestFlowPath1* shapefile layer.

*ChslopeFpf*: Slope for the TR-55 channel flow segment (ft/ft) between point *BB* and the end of the channel

*ChLengthFt*: Length of the TR-55 channel flow segment (ft) between point *BB* and the outlet of the subbasin

*ShSlopeFpf*: Slope for the TR-55 shallow flow (overland flow) segment (ft/ft) between the remote point and point *AA*

*ConShLengthFt*: Length of the concentrated shallow flow segment (ft) between point *AA* and point *BB*

*ConShSlopeFpf*: Slope for the TR-55 concentrated shallow flow segment (ft/ft) between point *AA* and point *BB*

*ShLengthFt*: Length of the TR-55 shallow flow (overland flow) segment (ft) between the start of the longest flow path and the *AA* point

Verify that the above fields are populated with data in the *Longestflowpath1* shapefile attribute table. *Note that the channel slope (ft/ft) is required for calculating a bulking factor.*

## CN Lag Method

The function computes basin lag in hours (weighted time of concentration or time from the center of mass of excess rainfall hyetograph to the peak of runoff hydrograph) using the NRCS National Engineering Handbook (1972) curve number method. **Select** *Hydrologic Parameters* → *CN Lag Method*. This function populates the *BasinLag* field in the subbasin feature class with numbers that represent basin lag time in hours. **Save** the map document.

Take a look at attribute tables of River and Subbasin feature class to see what fields are populated, and what they mean in hydrologic modeling.

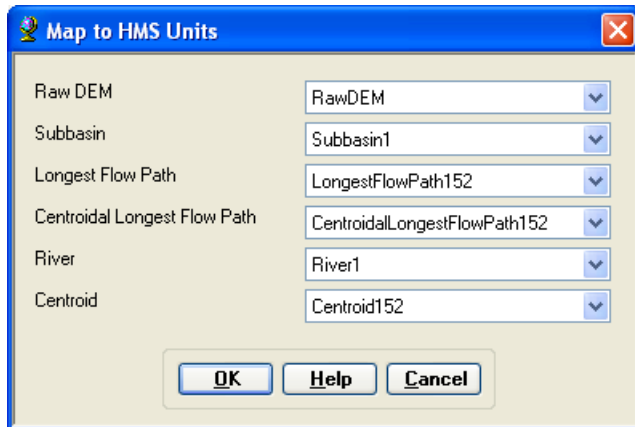
## HMS

The HMS menu has tools for creating input files for HEC-HMS.



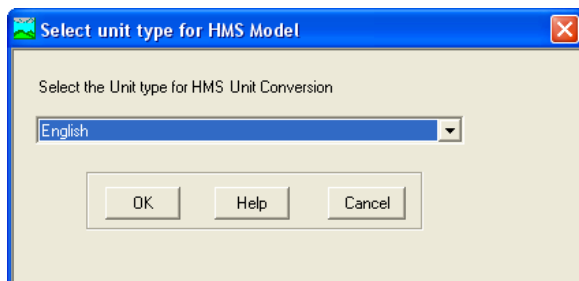
## Map to HMS Units

This tool is used to convert units. **Click** on *HMS*→ *Map to HMS Units*. **Confirm** the input files, and **Click OK**.



(**Note:** Due to some unknown reasons, if you get an error message at this point saying field cannot be added to a layer, **Save** the map document, exit ArcMap and **Open** the document, and try again)

In the next window, **choose** *English* units (default) from the drop-down menu, and **Click OK**.

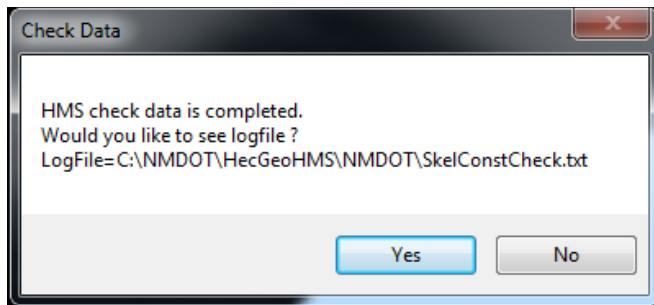


After this process is complete, you will see new fields in both River and Subbasin feature classes that will have fields ending with “\_HMS” to indicate these fields store attributes in the specified HMS units (English in this case). All fields that store lengths and areas will have corresponding “\_HMS” fields as a result of this conversion.

## Check Data

This tool will verify all the input datasets. **Select** *HMS*→ *Check Data*. **Confirm** the input datasets to be checked, and **Click OK**.

You should get a message after the data check saying the check data is completed successfully as shown below:



You can also look at the log file and make sure there are no errors in the data by scrolling to the bottom of the log file as shown below:

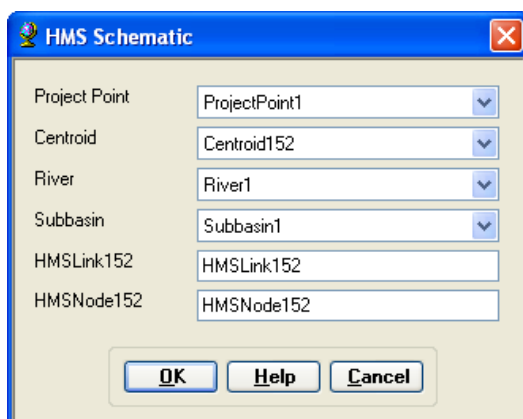
```
CHECKING SUMMARY
*****
```

```
Unique names      - no problems.
River containment - no problems.
Center containment - no problems.
River connectivity - no problems.
VIP relevance     - no problems.
```

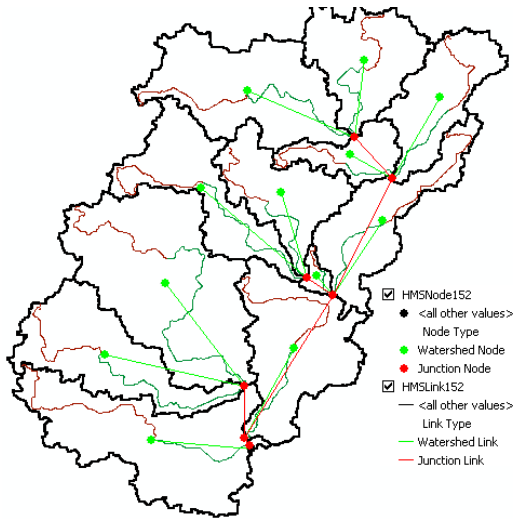
If you get problems in any of the above four categories (names, containment, connectivity and relevance), you can look at the log file to identify the problem, and fix them by yourself. This version of HecGeoHMS apparently gives error with river connectivity even if the rivers are well connected. Therefore, check the data carefully, and if you think everything is OK, ignore the errors (if you get any for connectivity) and proceed.

## HMS Schematic

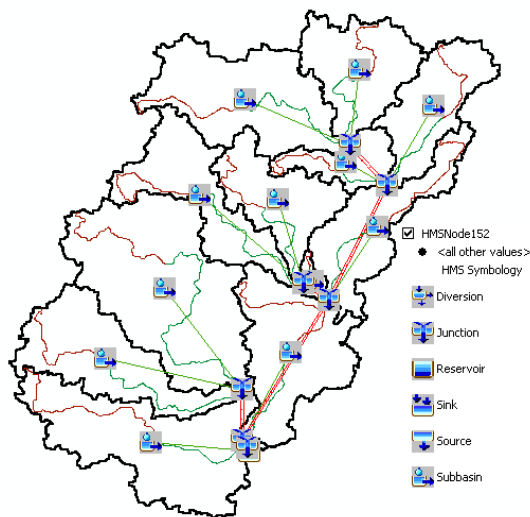
This tool creates a GIS representation of the hydrologic system using a schematic network with basin elements (nodes/links or junctions/edges) and their connectivity. **Select HMS → HMS Schematic. Confirm the inputs, and Click OK.**



Two new feature classes *HMS Link* and *HMSNode* will be added to the map document. See Cedar Creek example below:



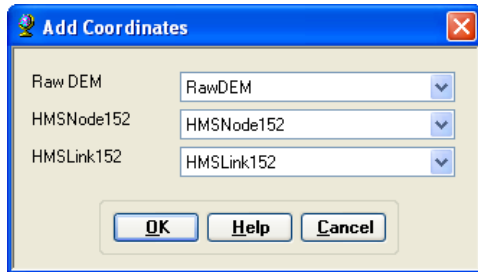
After the schematic is created, you can get a feel of how your model will look like in HEC-HMS by toggling/switching between regular and HMS legend. **Select** *HMS* → *Toggle HMS Legend* → *HMS Legend*. See the Cedar Creek example below:



You can keep whatever legend you like. **Save** the map document.

## Add Coordinates

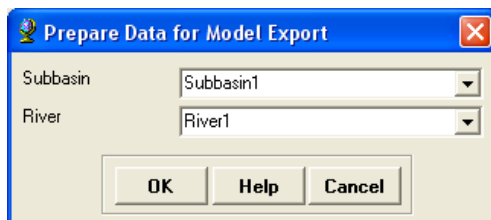
This tool attaches geographic coordinates to features in *HMSLink* and *HMSNode* feature classes. This is useful for exporting the schematic to other models or programs without losing the geospatial information. **Select** *HMS* → *Add Coordinates*. **Confirm** the input files, and **Click OK**.



The geographic coordinates including the “z” coordinate for nodes are stored as attributes (CanvasX, CanvasY, and Elevation) in *HMSLink* and *HMSNode* feature classes.

## Prepare Data for Model Export

**Select HMS**→ *Prepare Data for Model Export*. **Confirm** the input Subbasin and River files, and **Click OK**.



This function allows preparing subbasin and river features for export.

## Background Shape File

**Select HMS**→ *Background Shape File*. This function captures the geographic information (x,y) of the subbasin boundaries and stream alignments in a text file that can be read and displayed within HMS. Two shapefiles: one for river and one for subbasin are created in the project folder. **Click OK** on the process completion message box.

## Basin Model

**Select HMS**→ *Basin Model File*. This function will export the information on hydrologic elements (nodes and links), their connectivity and related geographic information to a text file with .basin extension. The output file for the tutorial example, *OteroMesa.basin* (project name with .basin extension), is created in the project folder (*HECHMS* under the subfolder *OteroMesa3*). **Click OK** on the process completion message box.

You can also **Open** the .basin file using Notepad to examine its contents.

## Meteorologic Model

You do not have any meteorologic data (temperature, rainfall etc) at this point. You will only create an empty file that can be populated inside HMS. **Select HMS**→ *Met Model File*→ *Specified Hyetograph*. The output file for the tutorial, *NMDOT.met* (project name with

.met extension), is created in the project folder. **Click** *OK* on the process completion message box.

You can also **Open** the .met file using Notepad and examine its contents.

This ends the terrain processing and HMS-Model Development using GeoHMS tutorial.

## **Section 4**

# **Hydrologic Modeling HEC-HMS**

# Hydrologic Modeling using HEC-HMS

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April 2012

Modified by C. Richardson, M. Cal, and J. Ealey for the NMDOT training module

April 2013

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## Introduction

The intent of this exercise is to introduce you to the structure and some of the functions of the HEC-Hydrologic Modeling System (HEC-HMS), by simulating the runoff hydrograph resulting from a 100 yr 24 hr design storm on the *Otero Mesa* watershed in Southern New Mexico. This exercise involves estimating peak discharge and runoff volume using SCS rainfall-runoff analysis. The physical parameters describing the watershed were developed previously using GIS pre-processing tool called HEC-GeoHMS.

Note that specific screenshots are provided for key input of data relative to the *Otero Mesa* watershed. Other screenshots from the *Cedar Creek* watershed in Indiana, as developed originally for this tutorial by Dr. Venkatesh Merwade, are retained for illustrative purposes of processed output.

## Computer Requirements

You must have a computer with the latest windows operating system and HEC-HMS 3.5 installed.

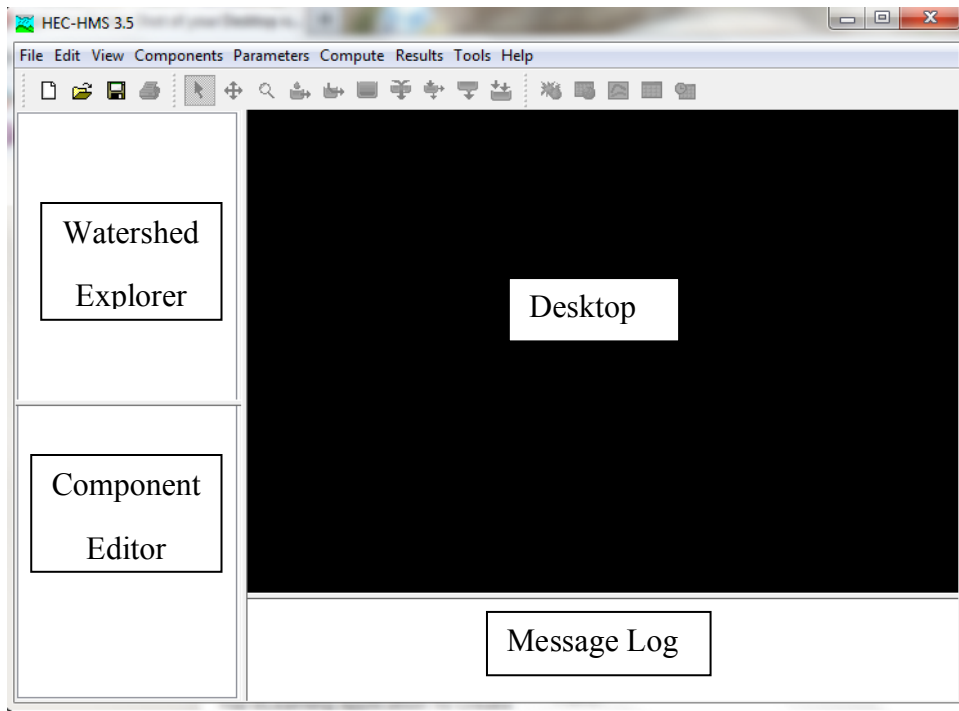
HEC 3.5 for windows is available for free from the Hydrologic Engineering Center's home page at: <http://www.hec.usace.army.mil/software/hec-hms/download.html>. A user's manual is also available at this location.

## Data Requirements

To run HEC-HMS model, a basin file is needed to specify the physical parameters of the watershed, and a map file to give the outline of the drainage areas and streams.

## Getting Started

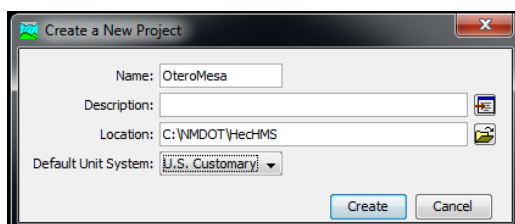
**Start** HEC-HMS by clicking on the HEC-HMS icon by going to *Start* → *Programs* → *HEC-HMS* → *HEC-HMS 3.5*. After a few seconds, the following should appear:



This window is the HMS Interface and consists of a menu bar, tool bar, and four panes as indicated: *Watershed Explorer*, the *Component Editor*, the *Message Log* and the *Desktop*.

## Creating a New Project

Select **File** → **New** to specify the name of the project and its location as shown below:



## Opening a HEC-HMS project

Open the *Otero Mesa* HEC-HMS project by **Selecting File** → **Open** in the menu bar. Browse to *OteroMesa3.hms*. **Open** *OteroMesa3.hms*.

After you open the project, you will see a folder named for the project in the watershed explorer. Under this folder, you will see a folder called Basin Models. Expand the Basin Models folder, and then expand Otero Mesa basin to see the basin in the HEC-HMS desktop window.

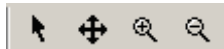
What you just did is opened a Basin Model for your project in HEC-HMS. The Basin Model contains information relevant to the physical attributes of the model, such as basin areas, river







reach connectivity, or reservoir data. In addition to basin model, you will need a meteorologic model to describe the meteorology (e.g., rainfall) of the watershed. A Control Specifications file contains information pertinent to the timing of the model such as when a storm occurred and what type of time interval you want to use in the model, etc. The Basin Model, Meteorologic Model, and Control Specification file are called as Components in HEC-HMS model, and can be created by using the Components Tab in the main menu.

## Navigating the HMS Desktop

You can use the following four tools in the tool bar to navigate through the HMS desktop:



The arrow tool  lets you select any hydrologic element in the basin. You can use the zoom-in tool  to zoom-in to a smaller area in the desktop, and zoom-out tool  to zoom out to see a larger area. The pan tool  can be used to move the display in the desktop.

## Hydrologic Elements

Depending upon the specific basin you have delineated, different hydrologic elements may be possible. The following description gives brief information on each symbol that is used to represent individual hydrologic element.



**Subbasin** – Used for rainfall-runoff computation on a watershed.



**Reach** – Used to convey (route) streamflow downstream in the basin model.



**Reservoir** – Used to model the detention and attenuation of a hydrograph caused by a reservoir or detention pond.



**Junction** – Used to combine flows from upstream reaches and subbasins.



**Diversion** – Used to model abstraction of flow from the main channel.



**Source** – Used to introduce flow into the basin model (from a stream crossing the boundary of the modeled region). Source has no inflow.

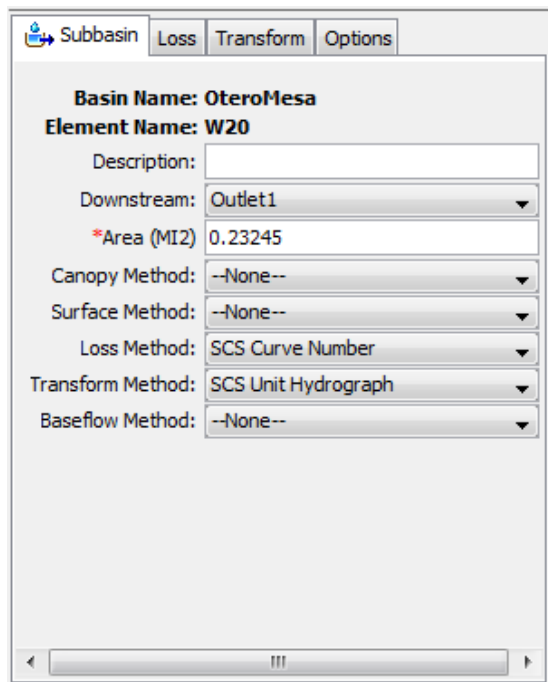


**Sink** – Used to represent the outlet of the physical watershed. Sink has no outflow.

Notice that when a stream flows through a watershed, the additional local runoff from the drainage area around the stream is not accounted for until the downstream end of the reach, where its flow is combined at a junction with the flow coming from the upstream reach.

## Editing a Basin Model

Make sure the project basin is expanded in the watershed explorer to see all the hydrologic elements in the basin. **Select** the *Arrow* tool from the tool bar, and **Click** on one of the subbasin's icon in the watershed explorer. After this subbasin is highlighted, information related to this subbasin will appear in the *Component Editor* window. *Note that for the Otero Mesa watershed, there is only one subbasin, which is the basin itself.*



The screenshot shows the 'Component Editor' window for the 'OteroMesa' subbasin. The window has a tabbed interface with 'Subbasin', 'Loss', 'Transform', and 'Options' tabs. The 'Subbasin' tab is active, displaying the following information:

- Basin Name:** OteroMesa
- Element Name:** W20
- Description:** (empty text field)
- Downstream:** Outlet1 (dropdown menu)
- \*Area (MI<sup>2</sup>):** 0.23245 (text field)
- Canopy Method:** --None-- (dropdown menu)
- Surface Method:** --None-- (dropdown menu)
- Loss Method:** SCS Curve Number (dropdown menu)
- Transform Method:** SCS Unit Hydrograph (dropdown menu)
- Baseflow Method:** --None-- (dropdown menu)

At the bottom of the window is a horizontal scrollbar.

Remember the subbasin element is used to convert rainfall to runoff. So the information on methods used to compute loss rates, hydrograph transformation and baseflow is required for each subbasin element. The loss method allows you to choose the process which calculates the rainfall losses absorbed by the ground. In this case, you are using the SCS Curve number method to compute losses and get excess rainfall from the total rainfall. **Click** (do not select any!) on the drop down menu to see your choices. Some options are *Initial and Constant*, *Soil Moisture Accounting*, and *Green & Ampt*.

The *Transform method* allows you to specify how to convert excess rainfall to direct runoff. Again, **Click** on the drop down menu to view your options. This model employs the *SCS* technique (dimensionless unit hydrograph). The *modClark* model takes gridded rainfall data, subtracts the losses as specified through the *Loss Rates*, and converts the excess rainfall to a runoff hydrograph using a variation of what is known as the Clark unit hydrograph. There is no baseflow method specified for this model, but you can look at the available options. If you specify baseflow, this baseflow will be added to the resulting direct run-off hydrograph to produce total streamflow hydrograph.

Once the loss and transform methods are chosen for the subbasin, the next step is to specify the parameters for these methods. **Select** the *Loss* tab in the *Component Editor* to look at the parameters for the loss method.

The screenshot shows the 'Loss' tab in the Component Editor. The 'Basin Name' is 'OteroMesa' and the 'Element Name' is 'W20'. The 'Initial Abstraction (IN)' field is empty. The '\*Curve Number' is set to 72.640. The '\*Impervious (%)' is set to 0.0.

For SCS Curve Number method, each subbasin requires a value for the *Curve Number* and *percent imperviousness*. The *Curve Number* was added when you used HEC-GeoHMS to create the basin file. If the % impervious value differs from 0, that % of the land area is assumed to have no losses and the loss method is applied only to the remainder of the drainage area

Similarly **Select** the *Transform* tab to look at the parameters for the transform method.

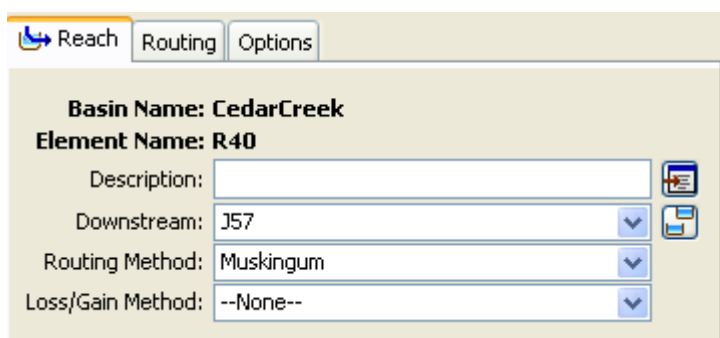
The screenshot shows the 'Transform' tab in the Component Editor. The 'Basin Name' is 'OteroMesa' and the 'Element Name' is 'W20'. The 'Graph Type' is set to 'Standard'. The '\*Lag Time (MIN)' is set to 56.914.

Note that the SCS unit hydrograph method requires only one parameter for each subbasin: lag time between rainfall and runoff in the subbasin. The parameter that is specified here is  $t_p$ , and the program will compute  $T_c$  (time of concentration) and  $Q_p$  (peak flow) to rescale the SCS dimensionless unit hydrograph. This is then used to compute the direct runoff hydrograph for this subbasin.

The *Options* tab is used to enter observed streamflow and stage data, which is not applicable for this *Otero Mesa* model.

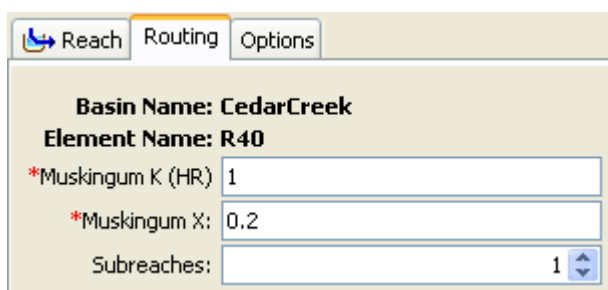
After the subbasin element, one can look at a reach element if your basin contains multiple reaches. *Note that Otero Mesa does not contain any reaches.* If multiple reaches exist for your project watershed, **Click** on any reach (e.g., *R40* in the Cedar Creek watershed as shown below), and **Look** at its parameters in the component editor.

Since the reach element route flows, only one method (routing) is associated with it. **Click** on the drop-down menu to look at choices available for routing flows. The *Muskingum* method is specified here, which is a common routing technique used for the reaches in a basin.



The screenshot shows the 'Reach' component editor with the 'Options' tab selected. The 'Basin Name' is 'CedarCreek' and the 'Element Name' is 'R40'. The 'Description' field is empty. The 'Downstream' dropdown is set to 'J57'. The 'Routing Method' dropdown is set to 'Muskingum'. The 'Loss/Gain Method' dropdown is set to '--None--'. There are icons for help and save on the right side of the form.

This simulation routes the water through the reaches by the Muskingum method in which  $K$  is the travel time of a flood wave passing through the reach,  $X$  is a measure of the degree of storage ( $X = 0$  means a level-pool reservoir or maximum storage,  $X = 0.5$  means a pure transmission reach in which there are no storage effects, and  $X$  ranges between 0 and 0.5). The reach is divided into a number of subreaches if necessary to keep the computations numerically stable. **Click** on the *Routing* tab to see the Muskingum parameters for this reach.

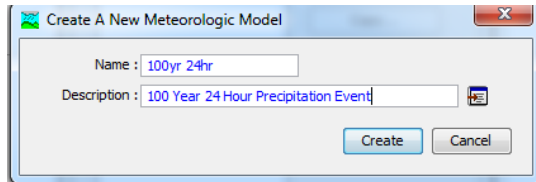


The screenshot shows the 'Reach' component editor with the 'Routing' tab selected. The 'Basin Name' is 'CedarCreek' and the 'Element Name' is 'R40'. The '\*Muskingum K (HR)' field is set to '1'. The '\*Muskingum X' field is set to '0.2'. The 'Subreaches' field is set to '1' with a dropdown arrow.

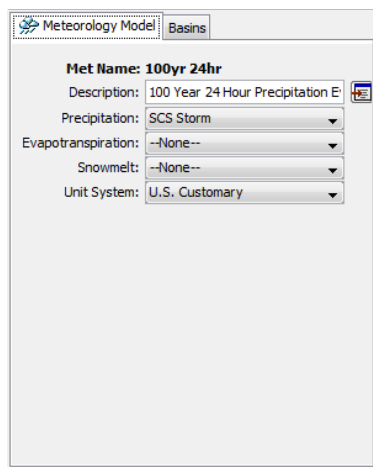
In addition to looking at individual elements and their parameters, you can look at the parameters for all hydrologic elements by selecting Parameters in the menu bar and selecting a method. For example, **Select Parameters** → *Transform* → *SCS Unit Hydrograph* gives a list of lag times for all the subbasins in the model. *Note that for Otero Mesa, there is only one value of lag time.*

## Creating a Meteorologic Model

**Select** *Components* → *Meteorologic Model Manager* → *New* to name and describe the model as shown below. The meteorologic name for this exercise is *100 yr 24hr*. The created model will now be visible in the *Watershed Explorer* pane.



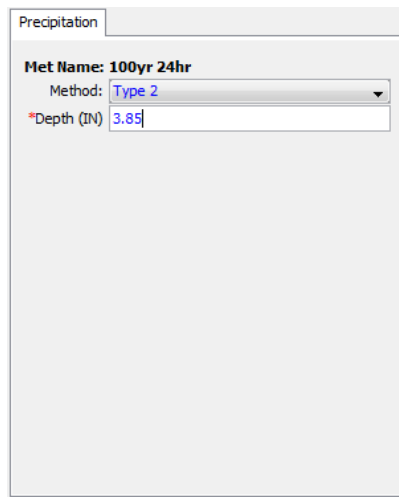
**Select** the *Meteorology Model* tab visible in the *Component Editor* pane. Use the pull-down menu to specify the precipitation as a *SCS Storm*.



Next **Select** the *Basins* tab and specify *Yes* to include subbasins.



**Click** on *SCS Storm* under the subset of the *100 yr 24hr* folder visible in the *Watershed Explorer*. Under the *Precipitation* tab in the *Component Editor*, specify the method as a *Type 2* storm with a *100 yr 24 hr* precipitation depth of 3.85 inches for the *Otero Mesa* watershed. This precipitation depth may be obtained from the National Weather Service NOAA Precipitation Frequency Data Server web site (<http://dipper.nws.noaa.gov/hdsc/pfds/>).

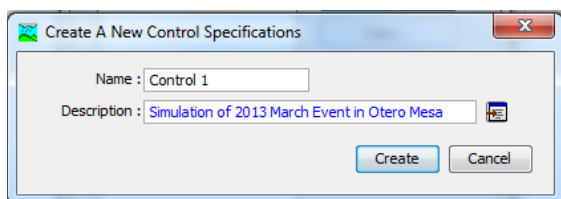


The screenshot shows a window titled 'Precipitation'. Inside, there is a section for 'Met Name: 100yr 24hr'. Below this, there is a 'Method:' dropdown menu set to 'Type 2'. Below that, there is a '\*Depth (IN)' text box containing the value '3.85'.

After the meteorologic data are provided, the model is ready for simulation. One final step before executing the model is to specify the time step information and the duration of the simulation. This is done by using the *Control Specifications Manager*.

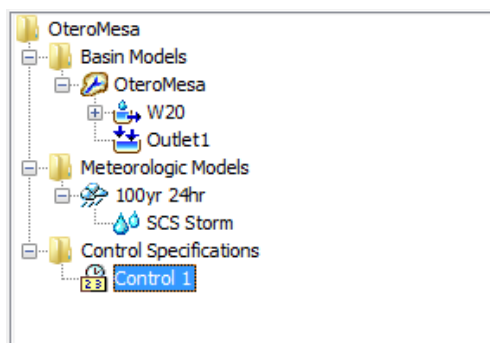
**Defining the Control Specifications** (*this is specific to the type of rainfall information used. The Control Specification file must be changed appropriately for other inputs including Frequency Storm or gauged rainfall*). The tutorial herein uses a rainfall depth resulting from a *100 yr 24 hr* design storm.

The final task in the model setup involves establishing the model's time limits. **Select Components** → *Control Specifications Manager* → **New** and **Type** the following name (*Control 1*) and any user descriptive information:



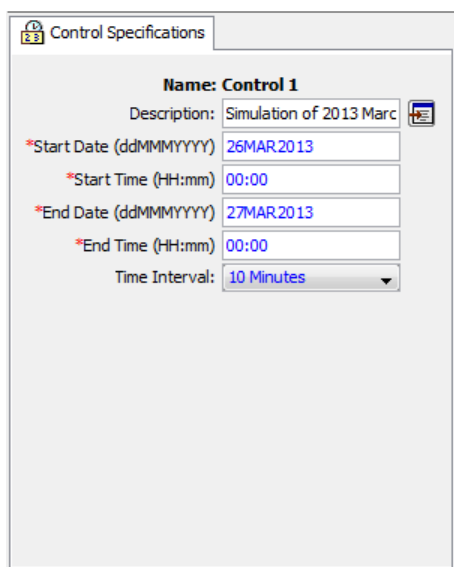
The screenshot shows a dialog box titled 'Create A New Control Specifications'. It has two text input fields: 'Name' with the value 'Control 1' and 'Description' with the value 'Simulation of 2013 March Event in Otero Mesa'. At the bottom right, there are two buttons: 'Create' and 'Cancel'.

**Click Create** and **Close** the Control Specifications Manager. This will add a Control Specifications folder in the *Watershed Explorer* pane.




To see the control specifications file, **Expand** the folder, and **Select** *Control 1*.

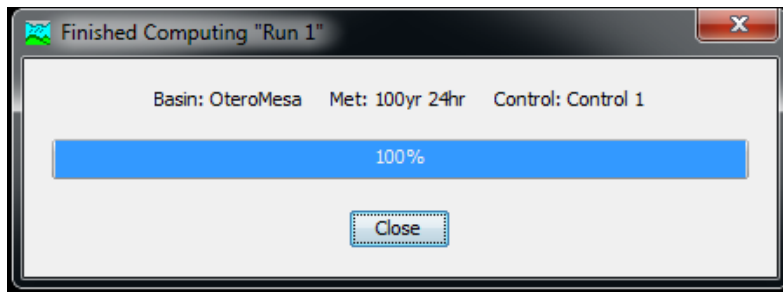
This will prompt the control specifications tab in the *Component Editor* pane. **Specify** the duration of the simulation in date and time, and also the time interval of the calculations as shown below.



In this case, the duration is arbitrary. It must be long enough to depict the runoff from a 24 hr storm. A typical time interval may be 5 to 10 minutes. The resultant peak discharge will vary slightly with its specification; however, the runoff volume will be constant.


## Executing the HMS Model

Finally, you have finished perusing the data involved in creating the model. The last step is to run the model. **Select** *Compute* → *Create Simulation Run*. **Accept** the default name for the run (Run 1), **Click** *Next* to complete all the steps and finally **Click** *Finish* to complete the run. Now to run the model, **Select** *Compute* → *Select Run* → *Run 1*, and then go to *Compute* → *Compute Run [Run 1]* to see the following window (alternatively you can click the compute run tool  in the tool bar):



**Click Close.** You will see a log in the *Message Log* as program executes the model. If there are errors in the model, you will see them in red color. For this model, there are no errors.

## Viewing HMS Results

The HMS allows you to view results in tabular or graphical form. To view a global results table, **select Results** → *Global Summary Table* (alternatively you can click the Global Summary tool  in the tool bar). You will get a window like the one shown below which summarizes the peak discharge, total volume of storm runoff, and the drainage area from which it came.

*Note that the peak discharge and runoff volume are needed to estimate the bulking factor.*

Hydrologic Element	Drainage Area (MI <sup>2</sup> )	Peak Discharge (CFS)	Time of Peak	Volume (AC-FT)
W20	0.23245	77.7	26Mar2013, 12:55	17.3
Outlet1	0.23245	77.7	26Mar2013, 12:55	17.3

This ends the hydrologic modeling exercise using HEC-HMS.

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## **Section 5**

### **2-D LS Factor *ModelBuilder* Procedure**

## Two Dimensional *LS*-Factor Procedure using Modelbuilder

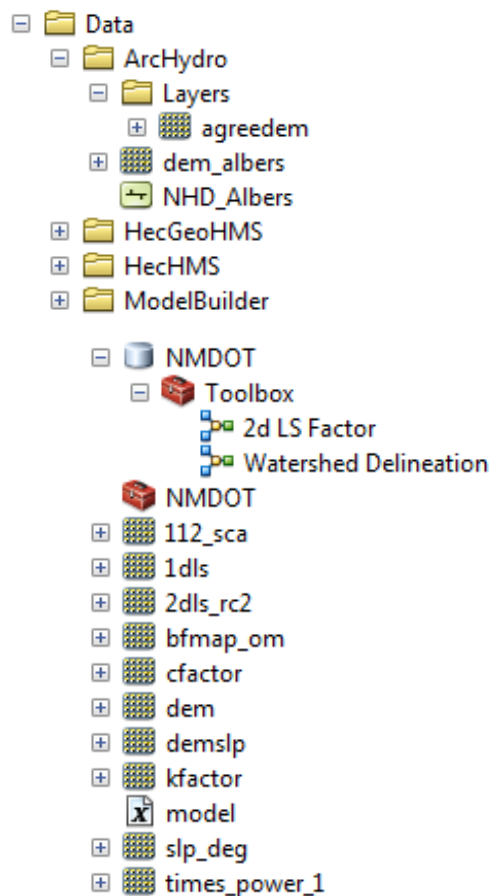
### Software required

ArcGIS 10.1 (ArcInfo License)

Spatial Analyst Extension for ArcGIS 10.1

TauDEM (Version Corresponding to ArcGIS version installed)

The ArcCatalog-view of the *Otero Mesa* data folder for subsequent processing is shown below:



### Data Required

The only data required is the Raw DEM Raster Grid for the corresponding watershed.

### DEM Pre-processing Required

Pre-processing requires that you convert the Raw DEM Raster Grid to Tiff format.

In ArcMAP **Right Click** the DEM Raster Grid layer.

**Click:** Data → Export Data. Under *Format* choose *TIFF*.

**Select** an appropriate name.

Save the file in the proper location under the ModelBuilder folder.

**Click: Save.**

**Click YES** when the window opens and asks “Would you like to add the exported data to the map as Layer”.

The Raw DEM TIFF Raster is now complete.

### **ModelBuilder Method for 2-Dimensional *LS*-Factor**

**Open** the NMDOT ArcToolbox.

**Click:** 2D LS Factor Model.

**Load** .tif RawDEM layer for the “RawDEM Must be a TIFF File”.

**Create** a folder and location for the data to be generated in the “Folder” box.

**Type** a three-letter abbreviation as a name in the “Watershed” box (e.g. 112).

**Click:** OK

A Specific Catchment Area Raster (*112\_sca*) and a 2 Dimensional LS-Factor Raster (*times\_power\_1*) will be added to the ArcMAP and the created folder. The average *LS*-factor for the delineated watershed is then found by right clicking the grid file in the map document: go to→ properties→ symbology→ classified→ classification statistics to view the mean.

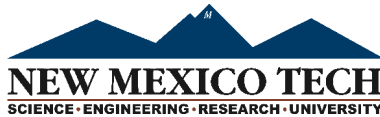
## **Section 6**

# **Bulking Factor ( $BF$ ) Calculator User Manual**

## **User Manual for the Bulking Factor Calculator**

Project No. NM10DSN-01

Prepared by



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in Cooperation with  
The U.S. Department of Transportation (USDOT) Federal Highway Administration (FHWA)

May 9, 2013

# User Manual for the Bulking Factor Calculator

## Overview

The macro-based, color-coded Excel spreadsheet developed to estimate a watershed bulking factor ( $BF$ ) is based on the methodology of Mussetter Engineering, Inc. (MEI ,2008). Appendix F.1 provides the underlying equations and delineates the assumptions used herein. Figure 1 shows a screen shot of the  $BF$  calculator. The spreadsheet contains 3 sheets: Sheet 1 is the calculator, Sheet 2 contains the necessary Woo coefficients (Woo, 1985) used in the method; and Sheet 3 is the user input watershed-specific database.

The calculator automatically generates an estimate of the  $BF$  based on user input, as well as the composite variables  $LSK$ ,  $LSKC$ , and  $I$  (unit shear force) that can be used to develop linear correlations. The calculator provides the user with flexibility to modify the underlying MEI (2008) assumptions and to perform sensitivity analysis. Three pull-down menus are provided to collect the needed information from the database, select the method used to evaluate the length-slope factor ( $LS$ ), and specify a sediment size ( $d_{50}$ ). Color-coded comment cells are provided to assist the user in implementing the calculator and to explain specific entries or assumptions. The calculator is unit dependent as it is formulated in the  $BG$  system of units and not  $SI$  units.

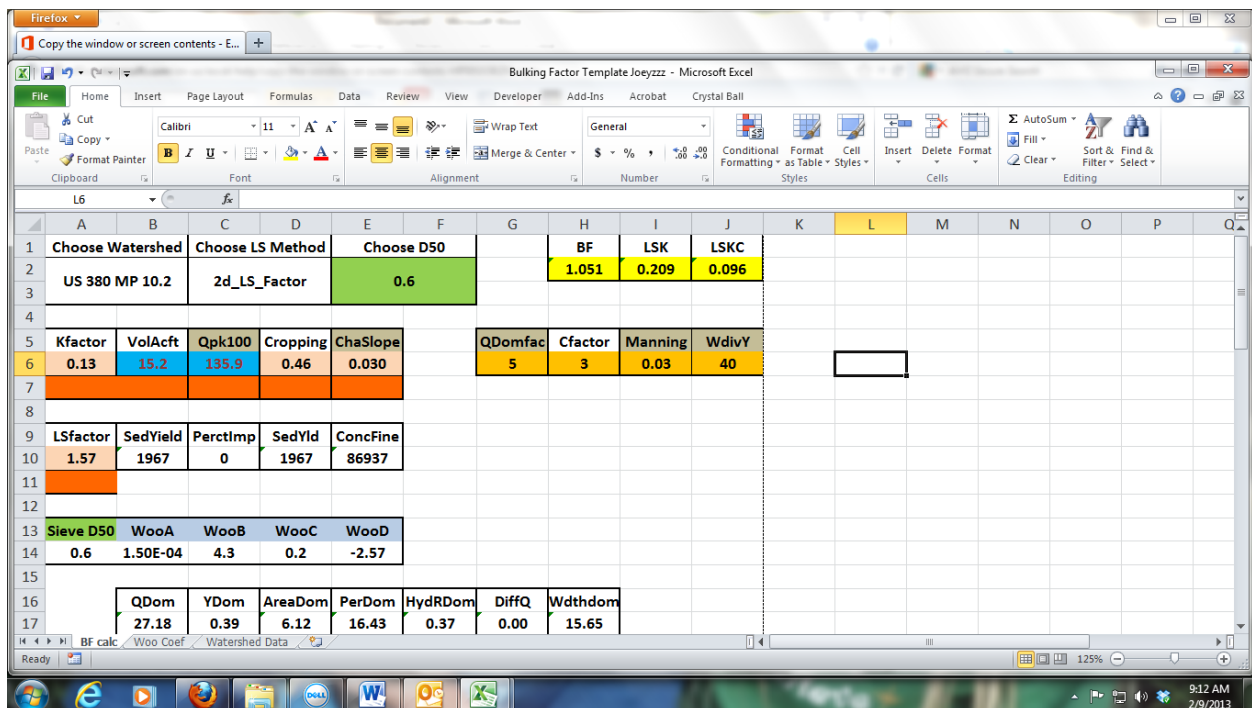


Figure 1: Screen Shot of the Bulking Factor Calculator (Sheet 1).

## Pull-down Menus

*Choose Watershed:* This menu is keyed to the watershed database (Sheet 3). Figure 2 provides a screen shot of this sheet. It currently contains watershed data for 16 watersheds. The user can replace individual watershed row entries with new data or expand it to include additional row entries using Excel based operations for “*Creating a Drop Down List*”. However, the user must be aware that the five key variables retrieved from the database (specific cells) are specified in terms of a *VLOOKUP* address that must be changed in each affected cell should the database be expanded. The affected cells include *Kfactor* (soil erodibility), *VolAcFt* (runoff volume), *Qpk100* (peak flow), *Cfactor* (cropping factor), *ChaSlope* (channel slope), and *LSfactor* (length-slope factor).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	County	Type	Watershed	K Factor	C Factor	2d LS Factor	LS Factor	Channel Slope	Q Peak	Runoff Volume								
2				Avg	Avg	Avg	Avg	(ft/ft)	(CFS)	(AC-FT)								
3	Socorro	1- 8"CMP	US 380 MP 10.2	0.133	0.46	1.57	1.39	0.030	135.9	15.2								
4	Lincoln	1-CBC 5x8	US 54 MP 103.4	0.186	0.42	0.64	0.37	0.020	100.1	21.8								
5	Otero	2- CBC 3x4	US 54 MP 97.2	0.236	0.45	0.97	0.70	0.018	21.8	4.9								
6	Catron	1-10' CMP	NM 36 MP 12.2	0.281	0.31	4.61	5.60	0.032	262.0	28.2								
7	Rio Arriba	N/A CMP	NM 96 MP 14.0	0.386	0.23	3.07	3.37	0.060	439.6	43.2								
8	Rio Arriba	2-72" CMP	US 285 MP 340.7	0.310	0.42	5.68	9.22	0.040	290.9	50.5								
9	Socorro	CMP	I-25 MP 172.2	0.175	0.49	0.76	0.39	0.018	129.0	21.1								
10	Dona Ana	N/A	Dona Ana Case Study	0.249	0.42	3.10	8.30	0.029	871.8	144.4								
11	Sandoval	N/A	Sandoval CaseStudy	0.233	0.45	1.07	0.70	0.010	5280.1	2075.3								
12	Sandoval	3CBC 10X11	I-25 Site B MP 241.2	0.315	0.15	12.02	27.57	0.100	1845.3	199.2								

Figure 2: Screen Shot of the Watershed Database (Sheet 3).

*Choose LS Method:* The user has two options for the length-slope (*LS*) factor used in the calculation based on a *1-D* or *2-D* perspective. The *1-D LS* factor is the watershed average taken from the respective clipped watershed using the statewide *1-D LS* raster and *ArcGIS*® Spatial Analyst. This factor is based on a 30 m *DEM*. The associated equations used to generate this raster may be found in Gallegos (2012). The *2-D LS* factor is based on the finer resolution 10 m *DEM*. It is calculated from the 10 m *DEM* for the respective clipped watershed using *Modelbuilder*. Currently, a statewide *2-D LS* raster has not been generated due to the computing limitations of the associated algorithm.

*Choose  $d_{50}$ :* The user selects a sediment size based on a sample grain size distribution analysis. This pull-down menu is keyed to Sheet 2 (Woo coefficients) and spans a range from 0.2 mm to 4.0 mm. Figure 3 provides a screen shot of this sheet.

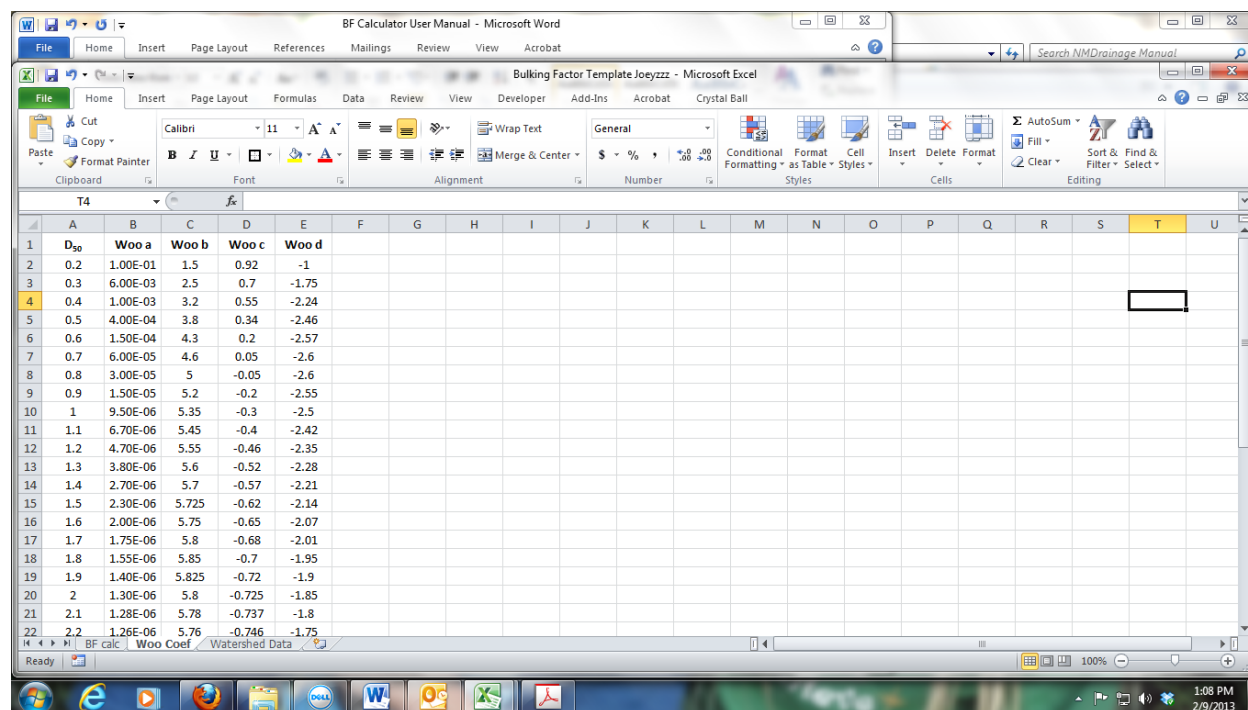


Figure 3: Screen Shot of the Woo Coefficients (Sheet 2).

### Watershed Variables:

The five key variables specific to each watershed are: *Kfactor* (soil erodibility), *VolAcFt* (runoff volume), *Qpk100* (peak flow), *Cfactor* (cropping factor), *ChaSlope* (channel slope), and *LSfactor* (length-slope factor). These are retrieved using the *Choose Watershed* menu. However, the user may choose to evaluate the sensitivity of a particular variable by simply entering an alternate value into the cell directly below the retrieved cell. Doing so, the new value now replaces the retrieved cell contents and a new *BF* is calculated. Deleting the cell contents of the cell directly below the retrieved cell returns the original value taken from the database.

### MEI Assumptions:

Three cells contain assumptions used in the MEI (2008) method: *QDomfac* (ratio of  $24Q_{100}$  to  $24Q_{dom}$  equal to 5:1), *Alpha* (region specific calibration factor equal to 285), and *WdivY* (channel width to depth ratio equal to 40:1 based on a rectangular cross-section). A fourth cell (*Manning*) specifies a channel bed roughness coefficient typical of sand-bed arroyos. The user may change these four cells directly to again evaluate model sensitivity. Note that the original development of Eq. 2 (Appendix F.1) set *Alpha* equal to 95. The MEI (2008) method uses a



multiplier of 3 to adjust the calibration factor to conditions typical of the middle and lower Rio Grande watersheds.

### **Sediment Yield:**

Sediment yield (*SedYield*) is calculated using *Alpha*, *VolAcFt*, *Qpk100*, *LSfactor*, *Kfactor*, and *Cfactor*. The percent of impervious area may be accounted for using *PerctImp*. The corrected sediment yield is *SedYld*. The concentration of fine sediment (*ConcFine*) is then estimated (Appendix F.1, Eq. 4).

### **Manning's Equation:**

Manning's equation is solved twice as a roots problem using Excel *Goal Seek* and a *Visual Basic* code (Appendix F.2). This yields values of velocity and depth at the prescriptive peak discharge ( ${}_{24}Q_{100}$ ). Based on the dominant discharge established by *QDomfac* a flow depth (*YDom*) and channel width (*WdthDom*) are calculated by setting up the first roots cell (*Diff*), where area (*AreaDom*), wetted perimeter (*PerDom*), and hydraulic radius (*HydRDom*) are specified in terms of *YDom*.

A second iteration of Manning's equation using this *WdthDom* and the  ${}_{24}Q_{100}$  yields an average cross-sectional velocity (*Vfps100*) and hydraulic depth (*Y100*) for the design storm.

### **Sediment Flow:**

The wash load flow (*Qwashcfs*) is determined by Eq. 5 (Appendix F.1) based on *Qpk100*, *Concfine*, and specific gravity of the fine sediment (*SpgrSed*). The bed-material load flow (*Qsedcfs*) is estimated using Eqs. 6 and 7 based on channel width (*Width* = *WdthDom*), cross-sectional velocity ( $V100 = Vfps100$ ), fine sediment concentration (*ConcFine*), and the Woo coefficients (*WooA*, *WooB*, *WooC*, and *WooD*). The total sediment flow is the sum of these two sediment flow and is given by *Qtotalcfs*.

### **Bulking Factor Calculation:**

The *BF* is calculated using *Qpk100* and *Qtotalcfs* via Eq. 1 (Appendix F.1). Alternatively, *BF* may be calculated using *Qsedcfs* and *Qtotalcfs* expressed as concentrations or *ConcBed* and *ConcTotal*, respectively. The separate calculations yield the same *BF* value.

### **Hydraulic Factors:**

Various hydraulic parameters are calculated based on the iterated solution at design flow. These include a particle Reynolds Number (*Re\**), Froude Number (*Froude*), flow shear stress (*Tau*), and unit length shear force (*UnitShear*). Appendix F.3 provides an overview of these attributes. The gravitational constant (*Gravity*), unit weight of water (*Gamma*), and viscosity of water (*WaterVis*) are the associated constants used in the hydraulic factors.

## Appendix F.1

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

$$BF = \left( \frac{1}{1 - C_v} \right) = \frac{Q_p + Q_{s\text{total}}}{Q_p} \quad (1)$$

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 is used for a typical rectangular cross section with width-depth ratio of 40 at a dominant discharge, assuming critical flow conditions and a range of median ( $d_{50}$ ) particle sizes (MEI 2008).

The *MUSLE* is used to calculate the fine sediment (wash load) yield ( $Y_s$ ) in tons resulting from a single storm (Eq. 2). *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):

$$Y_s = \alpha (Qq)^\beta K L S C P \quad (2)$$

where:

$Y_s$  = single storm sediment yield (tons)

$\alpha$  = region specific calibration factor

$\beta$  = 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).

Based on watershed analysis of the middle and lower Rio Grande in New Mexico, an  $\alpha$  of 285 is recommended (MEI 2008). A value for  $\beta$  was taken as 0.56 as a standard default. The  $K$ -factor and  $LS$ -factor are taken as a watershed average value, respectively, for each site as determined by raster grid databases and *ArcGIS*<sup>®</sup> Spatial Analyst. The  $LS$  factor is derived from a *DEM* of the watershed and may be based on a 1-D or 2-D perspective.

To account for the cropping factor, a watershed specific cropping factor ( $C$ ) has been derived from Normalized Difference Vegetation Index (*NDVI*) data in raster format using Eq. 3.

$$C = e^{-\alpha \left\{ \frac{NDVI}{\beta - NDVI} \right\}} \quad (3)$$

where

$\alpha$  and  $\beta$  = unitless parameters that determine the shape of the curve.

van der Knijff *et al.* (2002) found that an  $\alpha$  of 2 and  $\beta$  of 1 gave reasonable results when applied to Eq. 3. A *NDVI* raster layer is based on an average of 16 years of maximum seasonal data for New Mexico (Bulut, 2011). An  $\alpha$  of 2 and  $\beta$  of 1 is used herein (van der Knijff *et al.* 2002).

For undeveloped watersheds, the erosion control factor ( $P$ ) is set at 1. The hydraulic inputs of peak flow ( $q$ ) and runoff volume ( $Q$ ) are determined using HEC-HMS coupled with the NRCS TR-55 Curve Number method.

The fine sediment concentration is given by

$$C_f = 10^6 \left( \frac{Y_s}{W_w + Y_s} \right) \quad (4)$$

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 then calculated by

$$Q_f = \left( \frac{Q_p}{s_g} \right) \left( \frac{C_f}{10^6 - C_f} \right) \quad (5)$$

where

$S_g$  = specific gravity of the sediment (unitless).

The MEI (2008) procedure for bulking factor estimation uses the Woo (1985) relationship for computing suspended solids concentration coupled with the MPM bed-load equation to obtain a method for estimating bed-material load in streams carrying high concentrations of suspended sediment, or

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

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 (1985) 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:

$$Q_s = q_s W \quad (7)$$

where

$W$  = average channel width (ft).

Total sediment discharge ( $Q_{total}$ ) as defined in Eq. 1 is, therefore, the sum of the wash load and a computed bed-material load, or.

$$Q_{total} = Q_f + Q_s \quad (8)$$

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 is 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 requires 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 is 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 ( $W$ ) is 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 (Eq. 6).

The last inputs required for the calculating of a bulking factor is the specification of the Woo (1985) coefficients and a specific gravity. A specific gravity of 2.65 is used for sand-bed

arroyos common in New Mexico. Random sediment sampling within the culvert proper (inlet, middle, and outlet) is performed for each watershed site to evaluate a  $d_{50}$  sediment size based on *ASTM C 136-93* standard test method for sieve analysis of fine and coarse aggregates. This size is used to determine the Woo coefficients. The Sediment and Erosion Design Guide (MEI 2008) provides a graph of the coefficients  $a$ ,  $b$ ,  $c$ , and  $d$  as a function of average grain size in mm defined as  $d_{50}$ . Equations or tabular values to determine the respective coefficient for a given grain size are not available. However, a narrow range set of coefficients was estimated based on scaling the appropriate coefficient y-axis at specific values of the grain size x-axis (Sheet 2). Additional details on the application of this methodology and the *GIS*-based requirements to generate and implement input data may be found in Gallegos (2012).

## References

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- 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.
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- 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.

## Appendix F.2

```
Sub Worksheet_Change(ByVal Target As Excel.Range)
On Error GoTo TheEnd
If Target.Address = "$A$2" Then
Application.EnableEvents = False
Range("G17").GoalSeek Goal:=0, ChangingCell:=Range("C17")
Range("G20").GoalSeek Goal:=0, ChangingCell:=Range("C20")
ElseIf Target.Address = "$E$7" Then
Application.EnableEvents = False
Range("G17").GoalSeek Goal:=0, ChangingCell:=Range("C17")
Range("G20").GoalSeek Goal:=0, ChangingCell:=Range("C20")
ElseIf Target.Address = "$C$7" Then
Application.EnableEvents = False
Range("G17").GoalSeek Goal:=0, ChangingCell:=Range("C17")
Range("G20").GoalSeek Goal:=0, ChangingCell:=Range("C20")
ElseIf Target.Address = "$G$6" Then
Application.EnableEvents = False
Range("G17").GoalSeek Goal:=0, ChangingCell:=Range("C17")
Range("G20").GoalSeek Goal:=0, ChangingCell:=Range("C20")
ElseIf Target.Address = "$I$6" Then
Application.EnableEvents = False
Range("G17").GoalSeek Goal:=0, ChangingCell:=Range("C17")
Range("G20").GoalSeek Goal:=0, ChangingCell:=Range("C20")
ElseIf Target.Address = "$J$6" Then
Application.EnableEvents = False
Range("G17").GoalSeek Goal:=0, ChangingCell:=Range("C17")
Range("G20").GoalSeek Goal:=0, ChangingCell:=Range("C20")
ElseIf Target.Address = "$E$6" Then
Application.EnableEvents = False
Range("G17").GoalSeek Goal:=0, ChangingCell:=Range("C17")
Range("G20").GoalSeek Goal:=0, ChangingCell:=Range("C20")
```

```
End If
TheEnd:
Application.EnableEvents = True
End Sub
```



### Appendix F.3

*Particle Reynolds Number ( $Re^*$ )*

$$Re^* = \frac{\sqrt{gRS}d_{50}}{\nu} = \frac{V^*d_{50}}{\nu}$$

where

$g$  = gravity

$R$  = hydraulic radius

$S$  = channel slope

$d_{50}$  = mean sediment size

$\nu$  = kinematic viscosity of water

$V^*$  = shear velocity

*Froude Number ( $Fr$ )*<sup>1</sup>

$$Fr = \frac{V}{\sqrt{gY}}$$

where

$V$  = cross-sectional velocity at design flow ( $_{24}Q_{100}$ )

$Y$  = flow depth at design flow

<sup>1</sup>Assumes a wide rectangular channel

*Flow Shear Stress ( $\tau$ )*

$$\tau = \gamma RS$$

where

$\gamma$  = unit weight of water

*Unit Length Shear Force ( $\Gamma$ )*

$$\Gamma = \tau P = \gamma AS$$

where

$P$  = wetted perimeter at design flow

$A$  = cross-sectional area at design flow