The Impact of GIS-derived Topographic Attributes on the Simulation of Erosion Using AGNPS

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ABSTRACT. *Topographic attributes such as slope steepness and slope length are important factors in predicting soil loss and chemical movement using hydrologic simulation models. The objective of this study was to examine the effects of various slope prediction methods in providing input to the nonpoint source (NPS) simulation model AGNPS. Four algorithms/techniques (neighborhood, quadratic, best fit plane, and maximum slope method) were used to estimate slope from elevation data sets. The effect of each of these methods on slope percentages, slope lengths, and erosion estimates using the grid-based GRASS (Geographical Resources Analysis Support System) GIS and a distributed parameter NPS pollution model AGNPS were demonstrated. The four slope prediction methods were applied to a 124-ha (310-acre) watershed located in Waco County, Texas, using the AGNPS model. Among the four slope prediction methods, notable differences were found in their prediction of topographic attributes and the use of these attributes to predict erosion at the outlet of the watershed and within the watershed (spatial distribution). Observed watershed data best matched simulated watershed response using topographic inputs obtained from the neighborhood method.* **Keywords.** *GIS, Simulation, Nonpoint source pollution.*

Distributed parameter watershed models use a variety of techniques for subdividing the watershed. The grid-cell concept, one of the more common techniques, partitions a catchment into a series of square cells with soil, morphologic (i.e., slope, slope length, aspect) vegetation, and land use properties assigned to each cell. A raster-based Geographic Information System (GIS) similarly divides areas into square grids for data storage, analysis, and manipulation. Models that use this grid format include the Areal Nonpoint Source Watershed Environment Response Simulation model – ANSWERS (Beasley and Huggins, 1982), the AGricultural Non-Point Source pollution model – AGNPS (Young et al., 1985), the Systeme Hydrologique European model – SHE (Abbott et al., 1986) and the grid Water Erosion Prediction Project model (WEPP) (Foster and Lane, 1987).

The topographic input data for these hydrologic models are usually extracted either manually or by using existing GIS techniques from topographic or digital elevation maps. In either case, techniques used to estimate the topographic attributes (slope steepness and slope length) vary significantly. Generally, hydrologic models such as ANSWERS, AGNPS, and WEPP are used to study the effects on watershed response of changes in land use, management practice, or nutrient input levels on nonpoint source pollution. It is usually assumed that the topographic attributes derived are the "true values", even though hydrologic models are sensitive to topographic parameters (Young et al., 1985). Thus, it is essential to take special care while obtaining the topographic parameters for a watershed.

A GIS, defined as a tool to collect, manage, store, and display spatially varying data, can be used effectively to provide the input data sets required by hydrologic and water quality models. Jett et al. (1979) were among the first to describe the role that GIS could play in the hydrologic modeling of agricultural watersheds. They presented examples of ADAPT (Area Design And Planning Tool) applications that included the areas of hydrology, water resources, and wastewater management. Wolfe (1992) described their efforts to use a GIS to reduce the data preparation time for a distributed parameter runoff model. Data preparation time is a severe limitation in the use of a distributed parameter watershed model (Huggins and Monke, 1966). Hession et al. (1989) extracted data from a GIS to operate the AGNPS model and used the model to evaluate best management practice (BMP) scenarios for several watershed areas in Virginia. Ventura et al. (1988) developed a GIS for locating areas in which excessive erosion was occurring by implementing the USLE (Universal Soil Loss Equation) (Wischmeier and Smith, 1978) through GIS data layers. Zhang et al. (1990) linked a root zone solute transport model with a GIS to assess the potential groundwater impacts of common agricultural chemicals for an Oklahoma watershed. Smith et al. (1990) estimated runoff and flood levels for a small watershed and

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displayed the flood levels using a GIS. Halliday and Wolfe (1990) implemented a GIS-based decision support system that used DRASTIC (Aller et al., 1987) and other models to assess the groundwater pollution potential from fertilizers in Texas. Evans and Myers (1990) also implemented DRASTIC in a GIS to evaluate regional groundwater pollution potential. Growing numbers of researchers are exploring the role of GIS in hydrologic and water quality modeling (Tim et al., 1991; de Roo et al., 1989; DeCoursey, 1988; Sifer et al., 1987; Muzik, 1988).

Srinivasan and Engel (1991a) demonstrated the effects of the four slope prediction methods using USLE "LS" factor predictions. They found that the maximum slope method overpredicts erosion loss by 1.6 to 2.0 times as compared to the neighborhood method using the USLE equation for flat (approximately 1% average slope) and steep (approximately 16% average slope) areas, respectively. However, the paper did not address the effects of slope prediction methods on a watershed scale with multiple fields having different landuses, soils, and slopes. Distributed parameter models such as ANSWERS and AGNPS use the USLE to predict erosion at each cell, then route the sediment through the cells to the watershed outlet using the flow direction (aspect), which is a function of the slope prediction methods. The routing equation divides the sediment to erosion and deposition components and involves complex hydrologic processes, and it is a function of slope.

The focus of this article is to describe differences obtained from slope estimation methods commonly used with GIS elevation layers. Four algorithms/techniques that have been widely used to predict slope from elevation data sets (Srinivasan and Engel, 1991a) were applied in estimating topographic attributes (slope percentages and slope lengths) for a 124-ha (310-acre) watershed in Waco County, Texas, called watershed "Y". These attributes were used to build the input data for the AGNPS model using the AGNPS-GIS input interface (Srinivasan and Engel, 1991b). Using the AGNPS-GIS output interface (Visualization Tool) (Srinivasan and Engel, 1991c), the input and model output data were analyzed and differences were found between methods in predicting slope steepness, slope length, and erosion estimates both at the outlet of the watershed and in the spatial distributions within the watershed. The results were compared with observed events.

Slope Length Estimation

The slope length of the USLE (Wischmeier and Smith, 1978), which is one of the AGNPS input data, was estimated for each grid cell using unit stream power theory (Moore and Burch, 1986a, b):

$$LS = \left[\frac{A_s}{22.13}\right]^{0.4}\left[\frac{\sin\beta}{0.0896}\right]^{1.3} \qquad (1)$$

where

LS = USLE LS-factor

A_s = specific catchment area (A/b), defined as the upslope contributing area (A) per unit width (b) normal to the flow direction

β = slope steepness gradient in degrees

The estimated USLE-LS factor was then used to derive the slope length of each cell using the following equation (Wischmeier and Smith, 1978):

$$LS = (\lambda/72.6)^m\,(65.41 \sin^2\theta + 4.56 \sin\theta + 0.065) \qquad (2)$$

where

λ = slope length (ft)

θ = angle of slope

m = 0.5 if the percent of slope is 5 or more

m = 0.4 on slopes of 3.5 to 4.5%

m = 0.3 on slopes of 1 to 3%

m = 0.2 on uniform gradients of less than 1%

The maximum slope length for a cell was restricted to the side length.

Application to Watershed Y

Watershed Y is located in Waco County near Riesel, Texas. All data layers for the Y watershed area have been developed in the GRASS (CERL, 1988) GIS tool using a 30 × 30 m (98 × 98 ft) resolution. The elevation layer was created by digitizing the USGS topographic 3 m (10 ft) interval quad-sheets. Using the GRASS-GIS surface interpolation (using inverse distance) program, a surface was then fit for the study area for the same 30 × 30 m (98 × 98 ft) resolution resulting in a digital elevation map with elevation values for each grid. Using the GRASS-GIS watershed delineation program, a watershed was delineated for an area of 124 ha (310 acre).

Average slopes for the watershed range from 2.1 to 4.3%, depending on the slope estimation algorithm used. The soils in the watershed are primarily the Houston Black soil series which has a high clay content (60%) and a high shrink/swell potential. The soils data layer was developed by digitizing the County SCS soil survey map (1:15840 scale). Table 1 shows the distribution and characteristics ('K' factors, soil textures, and hydrologic soil group classifications) of soils present within watershed Y. The watershed is predominantly pasture (51%) with the remaining area being row-cropped agriculture. The cropland is predominantly in a sorghum, cotton, winter wheat rotation. Other input data required for the AGNPS model were obtained from readily available literature and AGNPS model documentation. Watershed Y was modeled using a 40 × 40 m (131 × 131 ft) resolution 0.16 ha (0.4 acre). This was due to the AGNPS cell size consideration which cannot be more than one decimal. The number of cells in watershed Y at this cell size is 770.

Table 1. Soil series areas, USLE 'K' factor, soil texture, and hydrologic soil group for watershed Y

Soil Name		Area ha (acre)	USLE 'K' Factor	Soil Texture	Hydrologic Soil Group
Houston Black,	0-1% slope	1.92 (4.8)	0.32	Clay	D
Houston Black,	1-3% slope	60.32 (150.8)	0.32	Clay	D
Heiden Clay,	1-3% slope	19.36 (48.4)	0.32	Clay	D
Heiden Clay,	3-5% slope	23.04 (57.6)	0.32	Clay	D
Lott Silty Clay,	1-3% slope	7.20 (18.0)	0.32	Silt	C
Lott Silty Clay,	3-5% slope	11.04 (27.6)	0.32	Silt	C

AGNPS Model

The AGNPS model was used to explore the effects of the slope estimation techniques on nonpoint source (NPS) pollution estimates. The AGNPS model is used to estimate sediment, nutrients (N, P), and chemical oxygen demand (COD) in runoff waters from agricultural watersheds (Young et al., 1985). It is an event-based model with basic components for hydrology, erosion, nutrients, and COD from animal feedlots, water impoundments, and sediment-associated nutrients. The model uses distributed parameter inputs and operates on a cell basis (uniform square areas subdividing the watershed), thus resembling the raster format in a GIS tool. The distributed parameter approach of the model is most appropriate to preserve the spatial characteristics of the watershed and to obtain more accurate results. Thus, the spatial characteristics of raster GIS data storage, retrieval, manipulation, analysis, and display may be used effectively.

Using the AGNPS-GRASS input interface (Srinivasan and Engel, 1991b), the AGNPS input data for watershed Y were derived for each slope steepness estimation method using a cell size of 40 × 40 m (131 × 131 ft). After running the AGNPS model for each of the input data sets, the erosion and runoff estimates at the watershed outlet and the spatial distribution of topographic attributes and erosion estimates within the watershed were obtained using the AGNPS-GRASS output interface (visualization tool) (Srinivasan and Engel, 1991c).

Results and Discussion

Slope Estimation Methods

From the rainfall records for watershed Y during 1989 through 1991, 10 rainfall events that covered the winter, spring, and summer season events were selected (table 2). Table 2 shows the rainfall dates, rainfall amount, energy intensity values and antecedent moisture condition (AMC) used for the AGNPS model runs.

For the four methods evaluated, the average slope steepness and average slope length for watershed Y varied from 2.1 to 4.3% and from 80 to 104 m (262 × 341 ft) for the neighborhood method and maximum slope method, respectively. In all events studied (table 3), the maximum slope method predicted higher values of slope, slope length, erosion, and deposition for a cell and for the watershed compared to estimates obtained using the neighborhood method. The quadratic surface method and best fit plane method predicted values were between those for the other two methods. Predictions using the quadratic surface method were closer to those for the neighborhood method while the best fit plane method predictions were closer to the maximum slope method predictions.

Table 2. Observed rainfall, date, Antecedent Moisture Condition (AMC), and energy intensity values for the 10 events between 1989-1991 for watershed Y

Event No.	Date	Rainfall mm (in.)	AMC	Energy Intensity (t-m/ha/cm)
1	5/17/89	90.4 (3.6)	I	63.72
2	8/7/89	83.1 (3.3)	I	47.17
3	3/7/90	47.5 (1.9)	I	11.18
4	3/14/90	87.6 (3.5)	I	42.65
5	5/3/90	61.2 (2.4)	I	13.83
6	1/9/91	57.4 (2.3)	II	40.34
7	2/4/91	40.4 (1.6)	I	10.51
8	2/18/91	30.2 (1.2)	I	4.89
9	4/13/91	67.8 (2.7)	I	45.19
10	5/24/91	38.1 (1.5)	I	10.66

Table 3. Average slope, slope length, regression slope, mean and standard deviations of predicted and measured sediment of 10 events and Nash-Sutcliffe coefficients for the four slope prediction methods for watershed Y

Statistics	Neighbor-hood Method	Quadratic Surface Method	Best Fit Plane Method	Maximum Slope Method
Average slope steepness (%)	2 1	2.4	2.7	4 3
Average slope length (m)	87	84	80	104
Mean measured sediment* (tons)	16.76	16.76	16 76	16 76
Mean predicted sediment* (tons)	19.65	22.82	28 77	57.10
Std deviation measured	18 23	18.23	18 23	18.23
Std. deviation predicted	20 97	24.37	30.74	61.21
Regression slope†	0.739	0.636	0.505	0.253
Nash-Sutcliffe coefficient‡	0.60	0.36	–0 46	–11 00

* Measured and simulated sediment delivered to the watershed outlet
† Regression slope of observed sediment yield vs. simulated sediment yield
‡ Nash-Sutcliffe coefficient of observed sediment yield vs simulated sediment yield.

Sediment Yield at the Outlet of the Watershed

Detailed statistics were obtained using the AGNPS-GIS output interface (Srinivasan and Engel, 1991c) to find the variability of slope, slope length, overland erosion, and overland deposition within the watershed, in addition to the results obtained at the watershed outlet. Figure 1 shows the simulated sediment yield at the outlet of watershed Y using the AGNPS model along with measured sediment yield for 10 rainfall events (table 2). The results, as seen from figure 1, clearly demonstrate that there are substantial differences in simulated sediment delivered to the watershed outlet for the four slope prediction techniques. The maximum slope method estimates sediment delivered to the outlet to be on average three times greater than estimates obtained using the neighborhood method. Table 3 shows the statistics of the observed and predicted sediment delivered to the outlet of watershed Y for the 10 events.

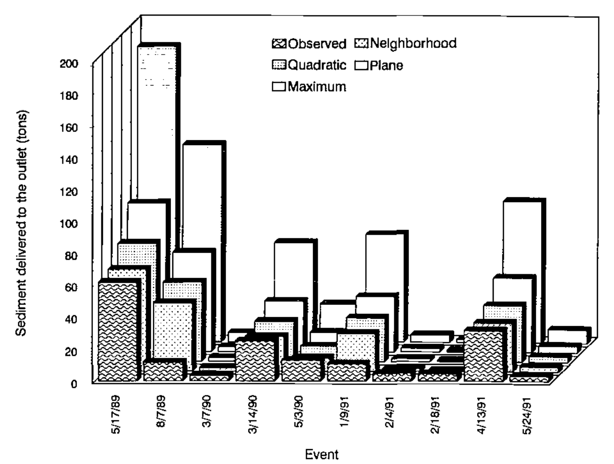

Figure 1–Sediment delivered to the outlet of watershed Y for 10 events: observed data and AGNPS predictions using four slope estimation methods.

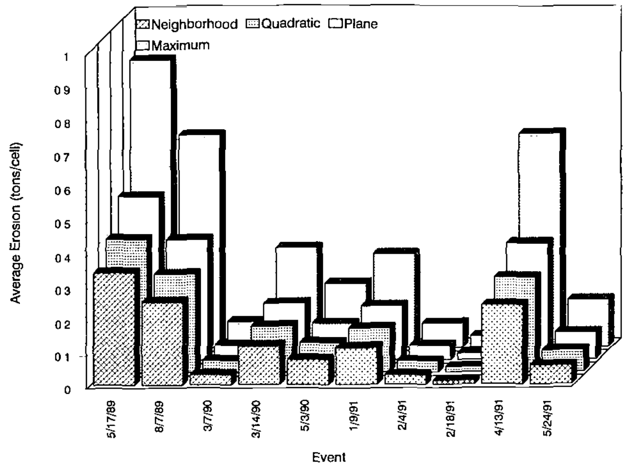

Figure 2–Average overland erosion estimates within watershed Y for 10 events: AGNPS predictions using four slope estimation methods.

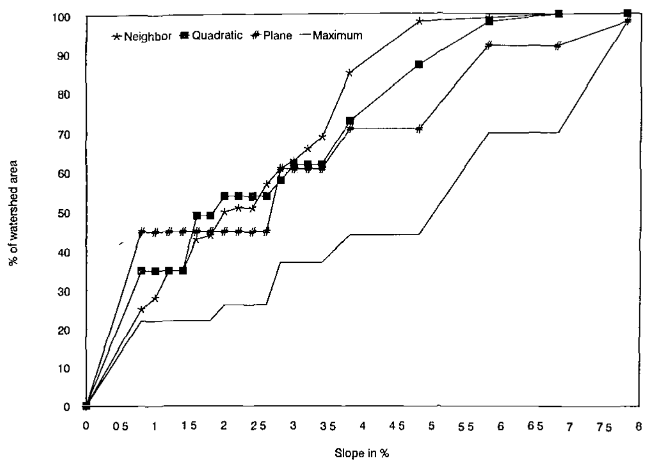

Figure 4–Cumulative percent distribution of slope by the four slope steepness estimation methods for watershed Y elevation layer for event number 1 (table 2).

The statistics include regression slope, predicted and measured mean and standard deviations, and Nash-Sutcliffe coefficients. Given the fact that no calibration was performed, AGNPS model results appear quite adequate with measured and predicted means (using neighborhood method) within 5%. The Nash-Sutcliffe coefficient of determination was 0.60 for sediment delivered to the outlet of the watershed using the slope percentages and slope lengths estimated by the neighborhood method. However, for the other methods the results showed differences. The regression slopes of 0.739 and 0.253 show considerable differences between the neighborhood and maximum slope methods.

Figures 2 and 3 show the average overland erosion and deposition within watershed Y for the 10 rainfall (table 2) events. In figures 2 and 3 there are distinct differences between average overland erosion and deposition for a cell for the slope prediction methods. The maximum slope method predicts the average overland erosion per cell for the 10 rainfall events to be 60% greater than the neighborhood method estimate. The maximum slope method predicts the average overland deposition per cell to be 59% greater than neighborhood method predictions for the 10 rainfall events.

The runoff, N, and P movement results were not presented in this study, however, obvious observations are stated for information. The total runoff for the watershed remains constant irrespective of the slope prediction method used. It is clear that runoff estimation is not a function of the slope or slope length within AGNPS since the SCS curve number method is used to estimate runoff, and the curve number method does not consider slope steepness. The peak rate of runoff at the outlet of watershed showed small differences for the four slope prediction algorithms. Similarly, the estimated N delivered to the outlet was nearly constant among the methods since most N is predicted to move with runoff. Simulated P movement showed a similar response to the sediment movement in the watershed for the four methods since most P is predicted to move with sediment.

Spatial Variation within the Watershed

Figures 4, 5, and 6 show the spatial variability of slope, overland erosion, and overland deposition of watershed Y

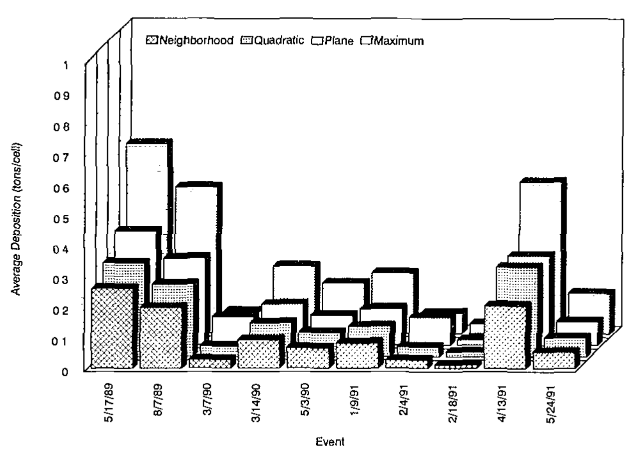

Figure 3–Average overland deposition estimates within the watershed Y for 10 events: AGNPS predictions using four slope estimation methods.

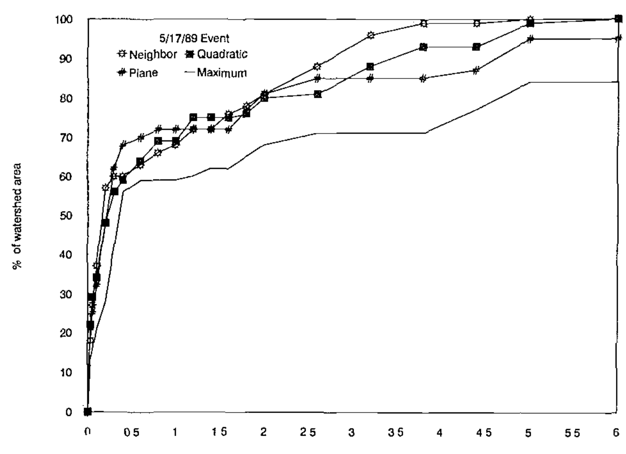

Figure 5–Cumulative spatial distribution of overland erosion estimates for four slope steepness estimation methods for the event on 17 May 1989.

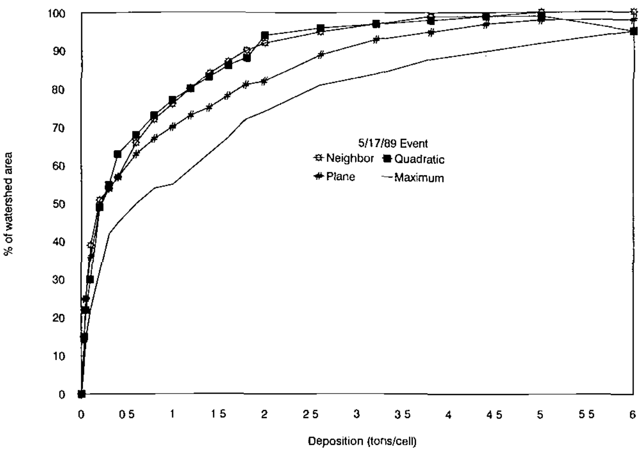

Figure 6–Cumulative spatial distribution of overland deposition estimates for four slope steepness estimation methods for the event on 17 May 1989.

for the four slope prediction methods for rainfall event No. 1 (17 May 1989). Figure 4 shows that considerable differences in slope estimates exist among the four slope prediction methods. The neighborhood method predicts that 98% of the watershed area has slopes under 4.8% whereas the maximum slope method predicts only 44% of the watershed area with slopes under 4.8%. The quadratic surface and best fit plane method estimates fell between these two estimates.

Because slope steepness and slope length are directly proportional in estimating the overland erosion and overland deposition for a cell (Young et. al, 1985), the overland erosion and deposition prediction for each cell were affected by the four methods. Figures 5 and 6 show the spatial variability of overland erosion and deposition for watershed Y, resulting from the variation in the input (slope and slope length) to the AGNPS model. The neighborhood method predicted that 96% of the area had under 3.2 ton/cell of overland erosion whereas the maximum slope method predicted 71% of the area for the same erosion limit. For overland deposition, 97% and 84% of the area were under 3.2 ton/cell for the neighborhood method and maximum slope method, respectively.

Summary and Conclusions

Slope steepness and slope length play a major role in estimating the sediment and phosphorus movement within a watershed and their delivery to the watershed outlet. Increasingly, GIS are used to study the sediment and nutrient movement in a watershed using NPS pollution models. The GIS is used to extract spatially referenced input data for the NPS pollution model and to visualize the NPS model results. This technique has proven to be a most effective and efficient way of studying NPS pollution for a watershed within a short time. The GIS model offers several different slope steepness estimation methods to derive slope steepness from DEMs (Digital Elevation Models). Since slope steepness and other topographic attributes are vital in modeling a watershed using a NPS model, it is important to understand the different slope steepness estimation methods and their effect on estimates of topographic attributes and on NPS pollution model predictions.

This article explored four slope steepness estimation methods (neighborhood method, quadratic surface method, best fit plane method, and maximum slope method) that are commonly used to derive topographic attributes using GIS tools or by manual or other computational means. The effect of the topographic attributes derived from the four slope steepness estimation methods on AGNPS model outputs was analyzed using a 124-ha (310-acre) watershed near Riesel, Texas.

Substantial differences were found among the four slope estimation methods in estimating slope steepness and slope length for a cell and average values for the watershed. The slope length was estimated using unit stream power theory for each cell. Consequently, the topographic attributes and the results from the AGNPS model showed notable variation in both spatial and nonspatial outputs. The spatial outputs are erosion and deposition for a cell, and the nonspatial outputs are sediment delivered to the outlet of the watershed, phosphorus (P) delivered to the outlet, average overland erosion, and average deposition for the watershed. However, they are not linked to topographic attributes in the AGNPS model, the runoff volume, peak rate of runoff, and total N did not show differences. From the analyses for this watershed, the AGNPS simulation results obtained using the neighborhood method best matched the observed data for the watershed. The maximum slope method predicted larger values for all of the topographic inputs and resulting outputs studied than the neighborhood method. The best fit plane method and quadratic surface method estimates were between estimates from the other two methods.

The final conclusion from this study is that care should be taken in the selection of a slope steepness prediction algorithm. It has been clearly demonstrated that using the maximum slope method with AGNPS results in higher erosion predictions and therefore one has to be cautious in using this method. One could be more judgmental if comparisons of simulated scenarios with observed data could be made, thereby the best slope steepness estimation method for the site could be selected.

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