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Investigating Ephemeral Gully Erosion Heads Due To Overland Flow Concentration in Nonpoint Source Pollution Control

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Abstract

Nonpoint source (NPS) pollution is a serious problem causing the degradation of soil and water quality. Concentrated overland flow is the primary transport mechanism for a large amount of NPS pollutants from hillslope areas to downslope areas in a watershed. In this study, a soil erosion model, nLS model, to identify transitional overland flow regions (i.e., ephemeral gully head areas) was developed using the kinematic wave overland flow theory. Spatial data, including digital elevation models (DEMs), soil, and landcover, were used in the GIS-based model algorithm. The model was calibrated and validated using gully head locations in a large agricultural watershed, which were identified using 1-m aerial photography. The model performance was better than two previous approaches; the overall accuracy of the nLS model was 72 % to 87 % in one calibration subwatershed and the mean overall accuracy was 75 to 89 % in four validation subwatersheds, showing that the model well predicted potential transitional erosion areas at different watersheds. However, the user accuracy in calibration and validation was still low. To improve the user accuracy and study the effects of DEM resolution, finer resolution DEMs may be preferred because DEM grid is strongly sensitive to estimating model parameters. Information gained from this study can improve assessing soil erosion process due to concentrated overland flow as well as analyze the effect of microtopographic landscapes, such as riparian buffer areas, in NPS control.

Key words: nonpoint source pollution, overland flow concentration, ephemeral gully erosion, nLS, GIS

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1. Introduction

In soil erosion modeling there are increasing demands for analysis of local overland flow processes that transport sediments as nonpoint source (NPS) pollution. Routines that evaluate the effectiveness of best management practices (BMPs) on NPS pollution reduction require important overland flow characteristics including flowpath delineation and travel time (Jenson and Domingue, 1988). Additionally, understanding the transition between varying overland flow regimes is important because erosion potential significantly increases as flow evolves from overland sheet flow to concentrated flow. As overland flow concentrates, concentrated erosion such as ephemeral gully erosion is established which may develop into permanent gully erosion unless proper management is implemented. Martinez-Casasnovas (2003) indicated that a gully head is the area where concentrated flow begins and an important feature to identify when assessing erosion potential. The author showed the importance of gully heads when documenting the greatest elevation difference in an agricultural watershed between 1952 and 1993 at a gully location that eroded at a rate of 0.8 m in depth per year.

Moore et al. (1988) examined the location of ephemeral gully heads in a 7.5 ha cultivated area with fine sandy loam soil. They evaluated the correlation between two topographic thresholds, $\ln(A_b/S)$ and A_bS, where A_b is the local up slope drainage area(A, m^2) per unit width of contour line(C, m) and S is the slope(m/m). They suggested that ephemeral gullies were formed where $\ln(A_b/S)$ and A_bS is greater than 6.8 and 18, respectively, using 1 meter elevation contour lines. The erosion equation of $\ln(A_b/S)$ is also called wetness index(WTI). Montgomery and Dietrich (1992) reported an AS^2 of $400m^2$ (upper bound) and $500m^2$ (lower bound) as the channelization threshold in grassland vegetation areas.

The two parameters (i.e., slope and contributing area) described above are commonly computed using DEMs that are constructed from field survey data or photogrammetric processes in relatively small drainage areas. DEMs coupled with a geographic information system (GIS) are not only used for estimating topographic properties, but also to calculate important hydrologic variables including traveling time, stream order, and drainage area boundaries which are fundamental inputs for quantitative erosion modeling.

One premise to analyze the correlation between slope and contributing area in gully erosion modeling is to assume homogeneous soil and land cover in a given area. However, this may not be sufficient to evaluate the effect of overland flow concentration or erosion evolution because of spatial-temporal variability in natural environments. Hence, surface cover condition and soil properties should be included to describe the mechanism of overland flow transport, soil detachment, and deposition.

The objectives of this study were to develop and apply a GIS-enabled kinematic wave model (nLS model) to identify where overland flow transitions from sheet to concentrated flow, and to evaluate the performance of this model compared to WTI and AS^2 approached. A third objective was to assess the benefits of incorporating critical shear stress, an additional soil erosion factor, into the basic nLS model.

2. *nLS* and *nLSCSS* model

One of the initial purposes behind the development of kinematic theory was to explain the movement of flood waves. A common practical application of kinematic wave theory is calculating the time of concentration within a drainage area as a shock wave runoff hydrograph. The kinematic wave model used to calculate the time of concentration for overland flow is commonly combined with Manning's surface roughness coefficients, expressed as:

$$t_c = \frac{a}{i^{0.4}}\left(\frac{nL}{S^{0.5}}\right)^{0.6} \qquad (1)$$

where t_c, the time of concentration for sheet flow(min); I, the rain fall intensity(mm/hr); n , Manning's coefficient for over land flow; *L*, the length of sheet flow(m); *S*, the slope(m/m); and *a*, a constant (i.e.,7 in metric unit). McCuen and Spiess (1995), however, reported that the value of $nL/S^{0.5}$ (abbreviated hereafter as nLS) should be less than 100 when calculating accurate times of concentration if sheet flow is dominant. In this study, we hypothesized that a range of nLS values slightly greater than 100 can be utilized to determine the overland flow transitional area such as gully head locations.

This study was conducted in the Cheney Reservoir watershed (Figure 1) located in south central Kansas near the city of Wichita. The contributing drainage area of the reservoir is approximately 2,423 km^2 including the tributary streams of the North Fork Ninnescah River.

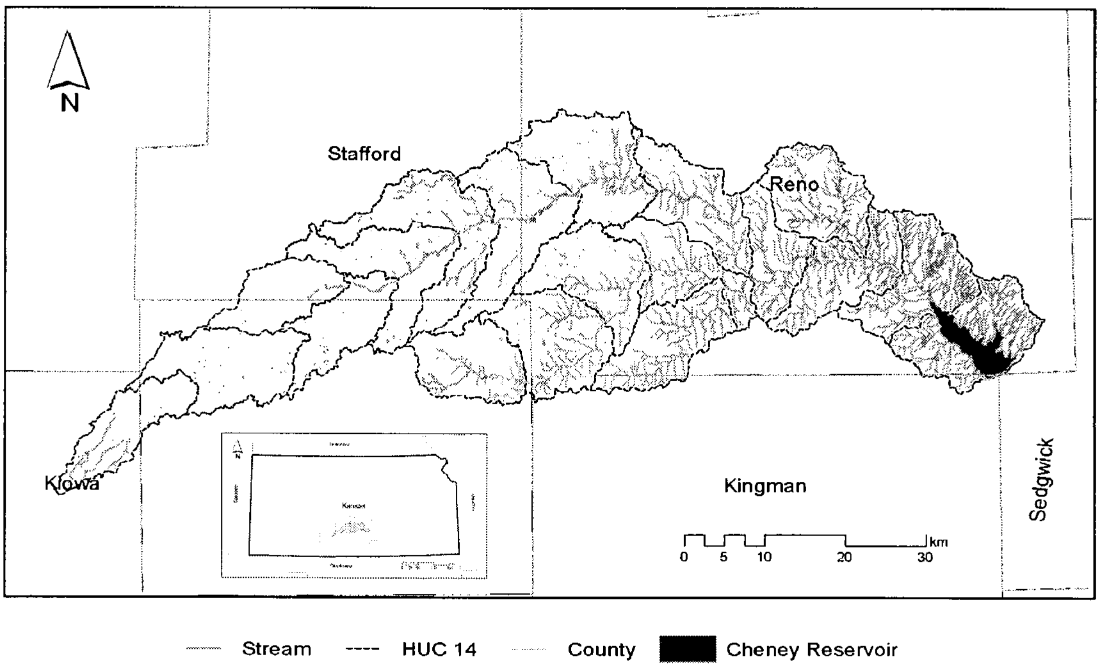

Figure 1. Location of the Study Area, Cheney Watershed and 19 subwatersheds, South Central Kansas

Table 1. Summary of the evaluated erosion models and the source of spatial data in GIS

Model	Equation	Parameters	Data source (SR*)
nLS(1)	$\frac{3.3nL}{\sqrt{S}}$	-Manning's coefficient (n)	Kansas GAP (30 m)
		-The length of overland flow(L, m) -Slope (S, m/m)	USGS National Elevation Data (30 m)
nLSCSS(2)	$\frac{3.3nL}{\sqrt{S}}\frac{1}{CSS}$	-Critical shear stress (CSS, Pa)	SSURGO ver. 2.1 (30 m)
WTI(3)	$\ln\left[\frac{A}{C \times S}\right]$	-Contributing area (A, m^2) -Unit contour line (C, m) -Slope (S, m/m)	USGS National Elevation Data (30 m)
AS2(4)	AS^2	-Contributing area (A, m^2) -Slope (S, m/m)	USGS National Elevation Data (30 m)

Table 1 summaries the equations and spatial data applied to identify the transitional erosion areas in the study.

3. Identifying the Locations of Gully Head and Drainage Density

Figure 2 presents the methodological diagram used to evaluate the performance of the GIS-enabled kinematic erosion model. Gully head locations were manually input using "heads-up" digitization and saved in a point shape file from high-resolution aerial photography. In this study, the 19 HUC-14 subwatersheds were used as a unit drainage area. The three HUC-11 subwatersheds (i.e., upstream, midstream and downstream) were used to select different geographic subwatershed locations and test an applicability of the nLS model at other watersheds. Selected calibration and validation subwatersheds were determined based on the relationship between drainage density and the number of gully heads.

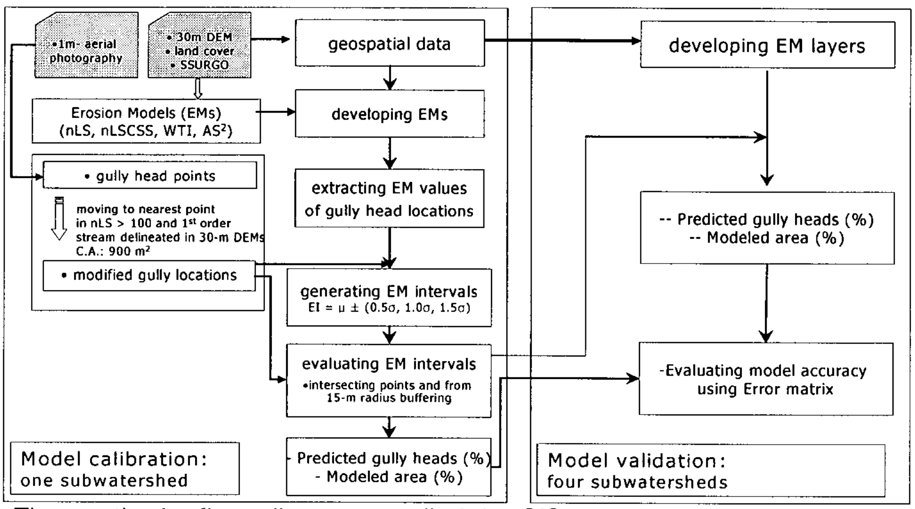

Figure 2. The methods flow diagram applied in GIS to develop, calibrate, and validate erosion models. C.A. indicates contributing area to apply a flow accumulation grid in the first-order stream delineation.

4. Results

About 82 % and 11 % of the identified gully head locations were formed in agricultural land and Conservation Reserve Program, which is former agricultural land and is now typically maintained with grasslands. On the other hand, only 6 % of the gully heads were formed in prairie lands. These results imply that proper soil and water management are required to control accumulated overland flow energy on agricultural lands, including the CRP area. Cropland located toward the downstream region of Cheney Reservoir watershed may cause more serious NPS problems related to soil and water quality. The results from the curvature analysis supported the impact of overland flow concentration, although further analysis is needed to produce more distinct evidence between surface shapes and gully formation.

In comparison to those in the previous studies, the results for WTI and AS^2 showed different thresholds for locating gully heads, possibly caused by differences in soils and vegetation system. In this study, the nLS model had best overall model accuracy (lowest: 74.8% at $\mu \pm 1.0\sigma$, different watershed conditions) for identifying gully head locations and had a wide-applicability for different subwatersheds as resulted in the model validation. However, more information about the impacts of various landcover and soil properties on the nLS operation is still required. The limits of nLS model simulation should be studied to improve the user accuracy and reduce the over-predicted areas. In particular, finer resolution DEMs may provide an improvement on the model performance. Important DEM products (e.g., slope and flow direction) may be affected significantly if finer resolution data is applied.

One of the most important challenges in soil erosion modeling is to analyze the characteristics of local overland flow. Several fully integrated mathematical models are accepted as the standard for assessing this process. However, these models are complex and may be modified because numerous inputs are required. Although a much simpler model such as the nLS model produces only qualitative results, it provides several advantages including less computing time, easy error correction, and cost-effective approach.

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