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Evaluating ephemeral gullies with a process-based topographic index model

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ABSTRACT

Soil conservation practices have been implemented to control soil degradation from sheet and rill erosion, but excessive sediment in runoff remains among the most prevalent water quality problems in the world. Ephemeral gully (EG) erosion has been recognized as a major source of sediment loss in agricultural watersheds; thus, predicting location and length of EGs is important to assess sediment contribution from EG erosion. Geomorphological models are based on topographic information and ignore other important factors such as precipitation, soil, topography, and land use/land management practices, whereas physically based models are complex, require detailed input information, and are difficult to apply to larger areas. In this study, an approach was developed to incorporate a process-based Overland Flow-Turbulent (OFT) EG model that contained factors accounting for drainage area, surface roughness, slope, soil critical shear stress, and surface runoff in the ArcGIS environment. Two hydrologic models, Soil Water Assessment Tool (SWAT) and ArcCN-Runoff (ACR), were adopted to simulate precipitation excess in Goose Creek watershed in central Kansas, USA. These two realizations of the OFT model were compared with the Slope-Area (SA) topographic index model for accuracy of EG location identification and length calculation. The critical threshold index in the SA model was calibrated in a single field in the watershed prior to EG identification whereas the OFT models were uncalibrated. Results demonstrated overall similar performance between calibrated SA model and uncalibrated OFT-SWAT model, and both outperformed the uncalibrated OFT-ACR model. In simulation of EG location, the OFT-SWAT model resulted in 12% fewer false negatives but 8% more false positives than the SA model, compared with 19% fewer false positives and 6% more false negatives than the OFT-ACR model. Greater errors in runoff estimation by ACR translated directly into errors in EG simulation. All models over-predicted EG lengths compared with observed data, though OFT-SWAT and SA models did so with better-fit exceedance probability curves, about zero Nash–Sutcliffe model efficiency and $\leq$40% bias compared to -3 model efficiency and >100% bias for OFT-ACR. Success of the uncalibrated OFT-SWAT model in producing satisfactory predictions of EG location and EG length shows promise for process-based EG simulation. The OFT-SWAT model used data and parameters also commonly used for SWAT model development, which should simplify its adoption to other watersheds and regions. Further testing is needed to determine the robustness of the OFT-SWAT model to dissimilar field and hydrologic conditions. It is expected that inclusion of more site-specific physical properties in OFT-SWAT would improve model performance in predicting location and length of EGs, which is essential for accurate estimation of EG sediment erosion rates.

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1. Introduction

Over the past few decades, various soil conservation practices have been implemented to control soil erosion originating from agricultural fields. The National Resource Inventory on soil erosion from cropland (NRI, 2007) reported a 43% decrease in soil erosion in the United States between 1982 and 2007; regardless, excessive sediment runoff remains among the most prevalent water quality problems in the U.S.A. (Hargrove et al., 2010). Implemented soil conservation practices substantially reduced sheet and rill erosion, but impact on ephemeral gully (EG) erosion is unclear. Recent studies (Daggupati, 2012; Foster, 1986; Hargrove et al., 2010; Knapen and Poesen, 2010; Nachtergaele and Poesen, 1999; Poesen et al., 1996, 2003, 2011) have shown that EG erosion is a major contributor of sediment in streams and needs serious attention.

EGs are concentrated flow channels of various sizes that form mostly along natural drainage lines in agricultural fields when vegetation cover is minimal and runoff energy of water (precipitation excess) exceeds critical shear stress of soil. EGs erode topsoil, but tillage fills them in, often with less-productive subsoil. If not corrected, EGs may grow into permanent gullies.

Soil loss due to EG erosion can contribute about 10% of the total soil loss in small watersheds (Poesen et al., 1996). In actively eroding areas,

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however, the contribution of EG erosion can range from 30% to as much as 100% of the total soil loss, as reported by Casalí et al. (1999), thus exceeding the contribution of sheet and rill erosion. The contribution of EG erosion varies geographically. In the U.S.A., EG erosion contributed from 17% of total soil loss in New York State to 73% in Washington State (Robinson et al., 2000). In central Belgium, EG erosion accounted for 44% of soil loss (Poesen et al., 1996), whereas in the Mediterranean and southern Portugal regions, EG erosion contributions were as high as 83% (Vandaele et al., 1996b). In the Loess Plateau of China, EG erosion ranged from 41% to 91% of soil loss (Zheng and Gao, 2000).

Four important factors that affect the formation and development of EGs are precipitation, topography, soil, and land use/land management practices. EGs form only after threshold precipitation intensity and duration are attained. Very few studies have investigated threshold precipitation events required for EG formation, and those studies are typically restricted to small areas examined over short time periods (Capra et al., 2009). The threshold precipitation needed for the formation and development of EGs varied geographically depending on soil conditions and initial soil moisture content. Various studies reported the threshold precipitation from 14.5 to 22 mm for cropland. Minimum precipitation depths of 15 mm in winter and 28 mm in summer were needed for the formation of EGs based on a study spanning a 15-year period in central Belgium (Nachtergaele et al., 2001a). Casalí et al. (1999) reported that within the three year period from October 1994 to September 1997, only three rainfall events were able to promote EGs in agricultural fields of Navarra region of Spain: the events with total water depth of 17 mm, 51 mm, and 53 mm and peak precipitation intensity of 54 mm/h, 12 mm/h, and 156 mm/h, respectively. Cerdan et al. (2002) found the precipitation depth of 28.5 mm and maximum 6-minute intensity of 15 mm/h in December and 21.6 mm depth and 98 mm/h 6-minute intensity in summer resulted in the formation of rill EGs in a cropland area. Capra et al. (2009) observed EG formation for an 8-year period and utilized the factors of antecedent precipitation index, maximum value of 3-day precipitation, and a simple surrogate for soil water content to find out that a threshold of 51 mm for the index was needed for EG formation.

Formation of EGs has been described in the literature as a topographic phenomenon (Montgomery and Dietrich, 1994; Patton and Schumm, 1975; Thorne et al., 1986). Topographic attributes such as upstream drainage area (used as surrogate for flow), slope, and plan of curvature are key topographic controls in the formation process. Over the past few decades, these attributes were combined into several indices that have been used to identify locations of EGs (Daggupati et al., 2013; Desmet et al., 1999; Foster, 1986; Knapen and Poesen, 2010; Nachtergaele and Poesen, 1999; Thorne and Zevenbergen, 1984; Vandaele et al., 1996a, 1996b).

Soil (particularly topsoil) resistance to concentrated flow erosion plays an important role in the formation of EGs (Poesen et al., 2003). Knapen et al. (2007) hypothesized that gully initiation at a given location in the landscape is controlled not only hydrologically and topographically but also by erosion resistance of topsoil. Knapen and Poesen (2010) proved their hypothesis using field studies on Belgium loess topsoils. The erosion resistance of topsoil is commonly referred to as soil critical shear stress (τ_{cr}), the threshold at which shearing forces of concentrated water flow initiate soil erosion. Soil critical shear stress is influenced by factors such as soil moisture content, bulk density, particle size distribution, random surface roughness, void space, flow resistance, soil erosivity, surface sealing and crusting, and freezing and thawing (Nearing et al., 1989). Soil critical shear stress values are difficult to define precisely because they vary considerably even for similar soil conditions (Foster, 1986). Few studies reported the values of τ_{cr} that resulted in the formation of EGs: Nachtergaele and Poesen (2002) and Poesen et al. (2003) found that τ_{cr} during peak flow ranged from 3.3 to 32. 2 N/m^2 (mean = 14 N/m^2) for EGs eroded in silt loam (loess-derived) topsoils in Belgium and from 16.8 to 74.4 N/m^2 (mean = 44 N/m^2) for EGs formed in stony sandy loams in Portugal. Poesen et al. (2011) stressed the need to collect and report τ_{cr} values leading to EG formation in a range of environments.

Land use arguably plays the most important role in EG formation. EG forms predominantly in cultivated crop fields where channels can be removed by tillage. Several recent studies have documented that gradual or sudden shifts in land use resulted in triggering of gullying or increased gully erosion rates (Poesen et al., 2011). Field observations in central Belgium showed that an increase in area under maize resulted in increased EG erosion risk (Nachtergaele et al., 2001a, as cited in Poesen et al., 2011). Poesen et al. (2011) stressed the need for more research on the drivers of land use changes causing increased or decreased gully erosion risk. Land cover or vegetative biomass has a direct impact on the formation of EGs. Vandekerckhove et al. (2000) reported that land cover has greater influence than climatic conditions in explaining topographic thresholds for different areas. Land cover affects τ_{cr} directly; i.e., reduction in biomass (either above or below ground) results in lowering the erosion resistance of topsoil, which influences EG formation. Prosser and Slade (1994) demonstrated through flume experiments that increased vegetation cover results in decreased susceptibility of valley floors to gully formation. Plant roots can increase τ_{cr} due to increases in soil cohesion (De Baets et al., 2006, 2007).

Empirical and physically based models have been developed to quantify EG erosion at both field and watershed scales. Woodward (1999) developed a physically based Ephemeral Gully Erosion Model (EGEM) in which locations of EGs and EG length were to be provided by the user. Gordon et al. (2007) addressed limitations of EGEM by revising equations for flow that resulted in a Revised EGEM (REGEM) model and incorporated it as a module within the Annualized Agricultural Non-Point Source Model to add EG erosion prediction to standard sheet and rill erosion. Physically based models require a wide set of input physical parameters and are difficult to apply to larger areas, so simplistic empirical and regression models were developed for EG volume estimates. Nachtergaele et al. (2001a, 2001b) observed a strong relationship between EG volume and EG length in the Mediterranean environment using 112 field-measured EGs. The regression relation between volume (V) and length (L) was represented as $V = 0.048\ L^{1.29}$ with the coefficient of determination (R^2) of 0.91. Capra and Scicolone (2002) and Capra et al. (2005) used data from 92 EGs in Italy to derive a relationship $V = 0.0082\ L^{1.42}$ with R^2 of 0.64. Zhang et al. (2007) reported a similar power-function relationship using 21 EGs in northeastern China to yield $V = 0.015\ L^{1.43}$ with an R^2 of 0.67.

Daggupati et al. (2013) used the GIS environment to automate calculation of potential lengths of EGs using various topographic index models and explored model threshold sensitivity. The studied topographic models were simplistic, purely empirical, and utilized a limited set of physical characteristics (Daggupati et al., 2013); on the other hand, physically based models were complex, required large sets of input parameters, and were difficult and time-consuming to apply to larger areas. Therefore, the objectives of this study were (1) to find a middle ground by developing a physically based model using a GIS framework capable of predicting location and length of EGs and (2) to evaluate performance of the new model on an individual field and in a small watershed.

2. Study area

The Goose Creek watershed (12-digit Hydrologic Unit Code [HUC] 110300140204) is a 13,306 ha subwatershed within North Fork Ninnescah watershed (8-digit HUC 11030014) in Reno and Kingman counties of central Kansas, U.S.A., that drains into the North Fork river (Fig. 1). Primary land use in the watershed was cropland (64%), followed by rangeland (29%), woodland (6%), and 1% other uses (water, urban). Fine loamy-textured soils highly susceptible to EG erosion were predominant in this watershed (KDHE, 2000; Parajuli et al., 2009). Slopes ranged from 0.0 to 46.1% with a median of 0.9%. The major crop in the watershed was winter wheat, which is typically

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