

Modeling Agricultural Sheet, Rill and Ephemeral Gully Erosion

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ABSTRACT: Conservation planning tools that consider ephemeral gully erosion include RUSLER, the distributed version of the Revised Universal Soil Loss Equation, version 2 (RUSLE2), coupled with the new Ephemeral Gully Erosion Estimator, EphGEE; and AnnAGNPS, the Annualized Agricultural Non-Point Source pollutant loading model. These models were applied to a 6.3 ha conventionally tilled corn field near Treynor, IA, that contained a grassed waterway in the footslope. Using a 3m by 3 m digital elevation model (DEM), AnnAGNPS divided the watershed into 5 channel segments, 13 polygons, and identified 86 headcut initiation locations; RUSLER calculated soil erosion/deposition on 7000 discrete 9 m² cells after defining hillslope ending channels based on contributing area exceeding 600 m². As rainfall input, AnnAGNPS used measured daily values from 1975 to 1991 while RUSLER used only 30-year monthly averages. Both models estimated significant ephemeral gully erosion and sediment deposition in the grassed waterway. Simulated sediment yields of 17.2 Mg ha⁻¹ yr⁻¹ (AnnAGNPS) and 17.5 Mg ha⁻¹ yr⁻¹ (EphGEE) were 18% and 20% greater than the measured average of 14.6 Mg ha⁻¹ yr⁻¹. AnnAGNPS estimated annual runoff of 53 mm yr⁻¹ was closer to the observed 50 mm yr⁻¹ than the RUSLER estimate of 67 mm yr⁻¹.

Keywords: Runoff, Erosion, Sediment Yield, RUSLE2, RUSLER, EphGEE, PEG, AnnAGNPS

1 INTRODUCTION

Ephemeral gully erosion can be a serious contributor to soil degradation in agricultural fields, but this form of erosion is not routinely included in many conservation planning tools. To address this deficiency, the Revised Universal Soil Loss Equation, version 2 (RUSLE2) was modified to generate a gully-forming runoff event sequence suitable for linkage with a new process-based channel model, the Ephemeral Gully Erosion Estimator (EphGEE). At the watershed scale, the Annualized Agricultural Non-Point Source pollutant loading computer model (AnnAGNPS) that uses RUSLE technology to estimate sheet and rill erosion was enhanced to estimate tillage-induced ephemeral gully erosion. These models will be accessed through GIS tools that are under development. At the field scale, a Geographical Information System (GIS) based tool, RUSLE2-Raster (RUSLER), determines the locations of concentrated flow areas that end RUSLE2 hillslopes, organizes and controls the execution of the RUSLE2 computational engine using standard RUSLE2 databases, and links hillslope runoff and sediment yield to EphGEE. At the watershed scale, a web based tool, the Agricultural Integrated Modeling System (AIMS), is under development to facilitate the preparation of AnnAGNPS input files for 12-digit HUCs. The tool will contain topographic, soil, climate, and management databases; define watershed streams and sub-area polygons; execute AnnAGNPS; and link AnnAGNPS outputs to the CCHE-1D channel network model. The purpose of the current study was to apply RUSLER/EphGEE and AnnAGNPS to a small gauged agricultural watershed and to compare simulations with a summary of 17 years of recorded rainfall, runoff and sediment yield.

2 MODELING METHODS

2.1 *RUSLER and EphGEE*

From its climate, soil, and management databases, RUSLE2 estimates long term average monthly runoff, the annual average number of runoff events, and gamma distribution parameters describing the population of runoff event volumes. RUSLE2 uses these results to develop a representative runoff event series that is intended for linkage with a process-based ephemeral gully model (Dabney et al., 2011). When this runoff event series is used, as in this study, runoff is not calculated from a rainfall event series. Because RUSLE2 calculates sheet and rill erosion from rainfall, and hillslope sediment transport based on a scaled 10-year, 24-h precipitation event (USDA-ARS, 2013), cases can arise where RUSLE2 estimates sediment delivery to channels even when little or no runoff is estimated.

To support RUSLE2 application in complex landscapes with flow convergence, RUSLE2 slope length is calculated by multiplying the cell size by the ratio of runoff generated within a cell or segment to runoff leaving that cell (Dabney et al., 2013). A new GIS-based distributed RUSLE2 application, called RUSLER (RUSLE2-Raster), assigns flow directions to each grid cell in the a digital elevation model (DEM) according to the direction of steepest slope using a deterministic-8 (D8) method (O'Callaghan and Mark, 1984). The flow directions are used to determine drainage paths and flow accumulation. Concentrated flow channels are defined where upslope contributing area exceeds a user-specified threshold. At each channel cell, RUSLER algorithms transfer cell connectivity information for each "channel cell catchment" to the RUSLE2 dynamic-link library (DLL). RUSLE2 calculates runoff, detachment, sediment delivery for each cell. Soil loss in a cell is calculated as sediment delivered from the cell minus sediment delivered into the cell. Thus, RUSLER estimates spatially distributed sheet and rill soil loss, and provides yields of water and sediment to the in-field concentrated-flow channels.

Vieira et al. (2014) describe a physically-based ephemeral gully model, EphGEE (Ephemeral Gully Erosion Estimator) than supports complex in-field dendritic channel networks and is designed to accept output from RUSLER. EphGEE operates on an event basis, calculating channel erosion and sediment transport, deposition, and delivery. For each runoff event, channel cell catchment water yield is converted into steady, spatially varying flow discharges distributed among channel nodes, which are created at a sub-cell scale to increase computational accuracy. Water surface profiles are computed using the Standard-Step Method (Henderson, 1966) using the flow discharge, hydraulic roughness, and channel geometry and steepness at each node. Channel roughness is determined by RUSLE2 as the result of local grain and form roughness and ground cover conditions, and varies seasonally due to mechanical disturbances and the natural roughness decay with time. For each storm, steady water surface profiles are computed along each gully channel, based on channel geometry, hydraulic roughness, and flow discharge; and erosion and deposition rates are based on local available shear stress, sediment transport conditions, and soil erodibility parameters.

In EphGEE, initial channel cross sections are assigned a triangular shape after tillage. Gullies are assumed to evolve with rectangular cross sections, down cutting until a non-erodible layer is reached and then widening. When sediment load exceeds local transport capacity, sediment deposition aggrades channel sections. Deposition is selective, with coarser sediment fractions depositing at faster rates. If sudden decreases in channel slope steepness or backwater regions cause excessive deposition, the model limits the amount of deposition at that location so that the resulting cross sectional depositional area is less than half the flow area for that storm. Flow leaving that location becomes overloaded with sediment, which is distributed and deposited further down the channel, avoiding unrealistic amounts of deposition in transitional regions. This simplified approach is analogous to the assumption of non-equilibrium used in stream sediment transport models (Wu, 2008), where the assumption that sediment transport rate equals transport capacity is relaxed.

2.2 *AnnAGNPS*

Within AnnAGNPS, potential ephemeral gully locations and erosion are calculated based on different procedures than EphGEE. The watershed DEM is discretized into channel reaches and upland polygons using components of the TOPographic PARAMertization model, TOPAZ (Garbrecht and Martz, 1996). The locations of the mouth of the ephemeral gullies throughout the watershed are defined using an automated topographical analysis tool, PEG (Potential Ephemeral Gully). Potential ephemeral gullies mouths (PEG points) are determined based on a modified Compound Topographic Index (CTI) that considers contributing area, local steepness, and planform curvature (Momm et al., 2012). These points

are locations with a high probability of formation of a nick point that can propagate upslope to form ephemeral gullies along trajectories extending along flow paths from a PEG to another PEG point or other boundary. Tillage induced ephemeral gully erosion is calculated by applying a headcut propagation model starting at each PEG point (Gordon et al., 2007). Sediment transport capacity is determined using AnnAGNPS procedures (Bingner and Theurer, 2001).

3 WATERSHED FOR TESTING

A topographic map of Watershed 11 (Rachman et al., 2008) of the USDA-ARS Deep Loess Research Station located near Treynor, Iowa (Karlen et al., 2009) was used as a training diagram in the original RUSLE1.04 documentation (Renard et al., 1997) to illustrate how to select appropriate RUSLE flow paths. Fig. 1a shows four flow paths, labelled 1 to 4, which illustrate that RUSLE hillslopes should extend from ridge tops to areas of concentrated flow that are reflected as upward pointing planform curves in topographic lines. From 1975 to 1991, this 6.3 ha watershed was farmed with contour-planted, conventional-tilled corn (*Zea mays*, L.). Average corn yield for the period 1987 to 1996 was 7.6 Mg ha⁻¹ (Eghball et al., 2000). The predominant soil was Monona silt loam (fine-silty, mixed, superactive, mesic Typic Hapludolls). Rainfall and watershed runoff and sediment yield were recorded on an event basis (Kramer et al. 1999).

Using a 3m resolution DEM and the D8 flow routing algorithm implemented in ArcGIS, Dabney et al. (2013) compared the channels obtained using critical source areas 300 m², 600 m², 900 m², or 4000 m² and concluded that for Watershed 11, a minimum contributing area of 600 m² (Fig. 1a) gave the best match to historical photographs of gullies and the flow paths limits recommended by Renard et al. (1997). This critical source area is not considered optimal or universal, but was used in the RUSLER simulations herein. Using this criterion, RUSLER calculated soil erosion/deposition on 7000 discrete 9 m² cells, and EphGEE evaluated ephemeral gully erosion for 396 discrete channel cells (draining 431 cell catchments) and 1631 channel nodes.

Application of TOPAZ to Watershed 11 with criteria that channels needed to have a minimum 0.5 ha contributing area and a minimum channel length of 30 m divided the watershed into 5 channel segments and 13 polygons. The PEG algorithms identified 86 gully mouth locations. These defined the initiation points of headcuts that could migrate upstream as a result of storm event flow and management impacts. Many gully mouths were located along flow paths with source areas exceeding 600 m² (Fig. 1b), which indicates that the gully erosion could occur as a result of simultaneous migration of multiple gully headcuts along the same flow path. Each AnnAGNPS polygon, channel, and flow path reach was characterized with an average steepness. Although TOPAZ uses a D8 algorithm, the AnnAGNPS implementation truncates elevations to decimeter accuracy, which may account for the slight differences in RUSLER channel and AnnAGNPS flow path locations and watershed boundaries.

RUSLER and AnnAGNPS simulations were based on identical land management descriptions. AnnAGNPS used measured daily rainfall values from 1975 to 1991 while RUSLER used only 30-year monthly rainfall averages.

4 RESULTS AND DISCUSSION

4.1 *Rainfall and Runoff*

Observed average annual rainfall depth during the 1975 to 1991 period was 811 mm, similar to the 30-year county average in the official RUSLE2 database of 801 mm. AnnAGNPS estimated annual runoff of 53 mm yr⁻¹ was closer to the observed 50 mm yr⁻¹ than the RUSLER estimate of 67 mm yr⁻¹. RUSLE2 estimated monthly runoff variation and event depths of varying return periods showed general agreement with observations (Dabney et al., 2012). RUSLE2 characterized ephemeral gully forming runoff as a sequence of 24 runoff events, the largest of which occurred during June and July. The largest runoff event occurred on 23 July and had a depth of 10 mm and an average runoff rate of 26 mm h⁻¹. The AnnAGNPS simulation represents the results of 1168 precipitation events that produced 292 runoff events over 17 years.

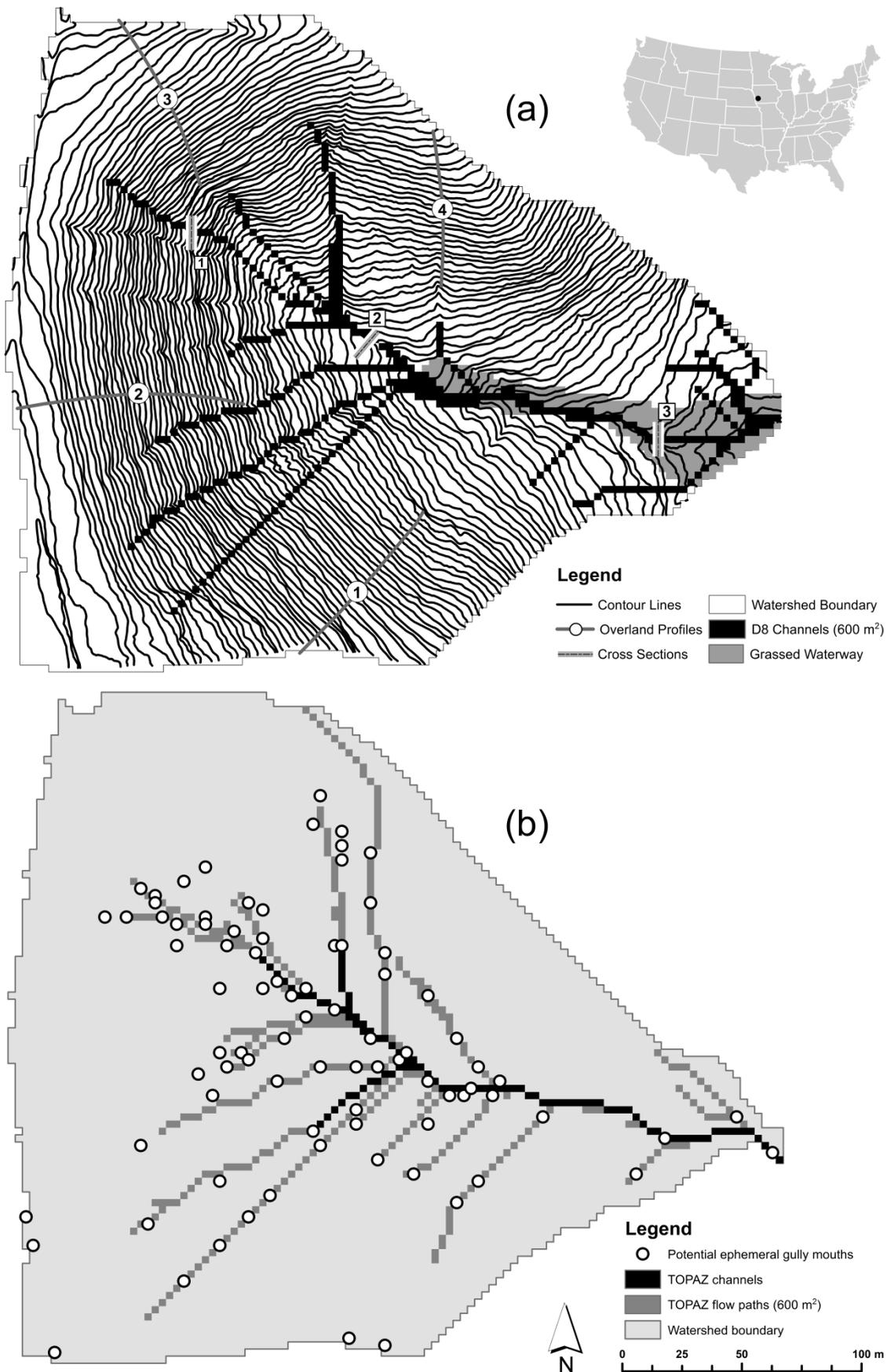


Figure 1. (a) Topographic map (0.31 m contour interval) of Watershed 11 at Treynor, Iowa, illustrating four (circled numbers) appropriate RUSLE hillslope flow profiles (after Renard et al., 1997, fig. 4-5B). The extent of concentrated flow channel cells determined using a D8 method based on a minimum contributing area of 600 m² are indicated by black rasters, and the extent of a grassed waterway is indicated in grey. The locations of three cross sections used to illustrate the behavior of EphGEE are indicated with numbers within square boxes. (b) TOPAZ channels (0.5 ha source area minimum and 30 m minimum channel length) and flow paths, and AnnAGNPS potential ephemeral gully points from which headcuts may propagate upstream.

4.2 Erosion and Sediment Yield

4.2.1 RUSLER and EphGEE

Average RUSLE2 estimated sediment yield from the hillslopes to the channel system averaged $36 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ (Dabney et al., 2013), whereas observed sediment yield at the watershed outlet averaged only $14.6 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. The difference between hillslope sediment delivery estimates and observed outlet sediment delivery suggests that waterway sediment deposition exceeded ephemeral gully detachment.

EphGEE simulations were performed with and without the grassed waterway. Figure 2 illustrates the depths of erosion or deposition after the last runoff event before spring plowing. Only the lower part of the watershed including CS#2 and CS#3 is shown so that details are easier to resolve.

Table 1 reports annual average RUSLER sheet and rill erosion and EphGEE sediment yield estimates at each of the three locations illustrated in Fig. 1a. Without local calibration, EphGEE estimated annual sediment yield from the waterway was $17.5 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, 20% larger the measured value of $14.6 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. Ephemeral gully erosion contributed 21 % of the sediment delivered to CS#1 and 25% at CS#2. Without the waterway, the corresponding percentage was 25 % at CS#3, but shallower channel slopes caused considerable deposition between CS#3 and the watershed outlet. When the waterway was simulated, increased hydraulic roughness caused deposition throughout of the waterway (Fig. 2).

Table 1. Average RUSLER sheet and rill erosion and EphGEE watershed sediment yields and net channel erosion/deposition upslope of selected channel cross section locations (Fig. 1).

Location	Drainage area (ha)	Local channel steepness (%)	RUSLE2 sheet and rill soil loss ^a ($\text{Mg ha}^{-1} \text{ yr}^{-1}$)	With grassed waterway		No grassed waterway	
				Net channel soil loss ($\text{Mg ha}^{-1} \text{ yr}^{-1}$)	EphGEE watershed sediment yield ($\text{Mg ha}^{-1} \text{ yr}^{-1}$)	Net channel soil loss ($\text{Mg ha}^{-1} \text{ yr}^{-1}$)	EphGEE watershed sediment yield ($\text{Mg ha}^{-1} \text{ yr}^{-1}$)
CS#1	0.26	15.5	36.3	9.9	46.2	9.9	46.2
CS#2	2.1	5.2	48.5	16.0	64.5	16.0	64.5
CS#3	5.3	5.3	39.7	-18.1	21.6	13.6	53.4
Outlet	6.3	0.2	36.4	-18.9	17.5	-3.5	32.9

^a spatial average to cross section; positive soil loss = erosion, negative soil loss = deposition.

4.2.2 AnnAGNPS

The average annual sediment load simulated at the outlet by AnnAGNPS during the 17-year period was $17.2 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ compared to $17.5 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ by EphGEE and the measured value of $14.6 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. The simulation represents the results during this period of 292 runoff events, 260 sheet and rill erosion events, and 133 ephemeral gully erosion events. The contributions of sheet and rill and gully erosion sources vary by location within the watershed (Table 2) with sediment load decreasing as the sediment moves to the outlet. The grassed waterway has a significant influence on sediment load reaching the outlet by decreasing sediment by over 50% compared to no grassed waterways present. While the soil loss from ephemeral gullies throughout the watershed is over $50 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, most of this sediment is deposited before reaching the outlet resulting in only $3.1 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ at that point.

Table 2. Average annual sheet and rill and gully soil loss and sediment loads upslope of selected cross section locations.

Location	Drainage area (ha)	AnnAGNPS sheet and rill soil loss ($\text{Mg ha}^{-1} \text{ yr}^{-1}$)	AnnAGNPS gully soil loss ($\text{Mg ha}^{-1} \text{ yr}^{-1}$)	With grassed waterway		No grassed waterway	
				AnnAGNPS sheet and rill sediment load ($\text{Mg ha}^{-1} \text{ yr}^{-1}$)	AnnAGNPS gully sediment load ($\text{Mg ha}^{-1} \text{ yr}^{-1}$)	AnnAGNPS sheet and rill sediment load ($\text{Mg ha}^{-1} \text{ yr}^{-1}$)	AnnAGNPS gully sediment load ($\text{Mg ha}^{-1} \text{ yr}^{-1}$)
CS#1	0.5	73.7	38.1	58.7	19.1	58.7	19.1
CS#2	2.1	76.0	65.1	54.3	13.3	54.3	13.3
Outlet	6.1	66.3	50.4	14.1	3.1	29.2	6.0

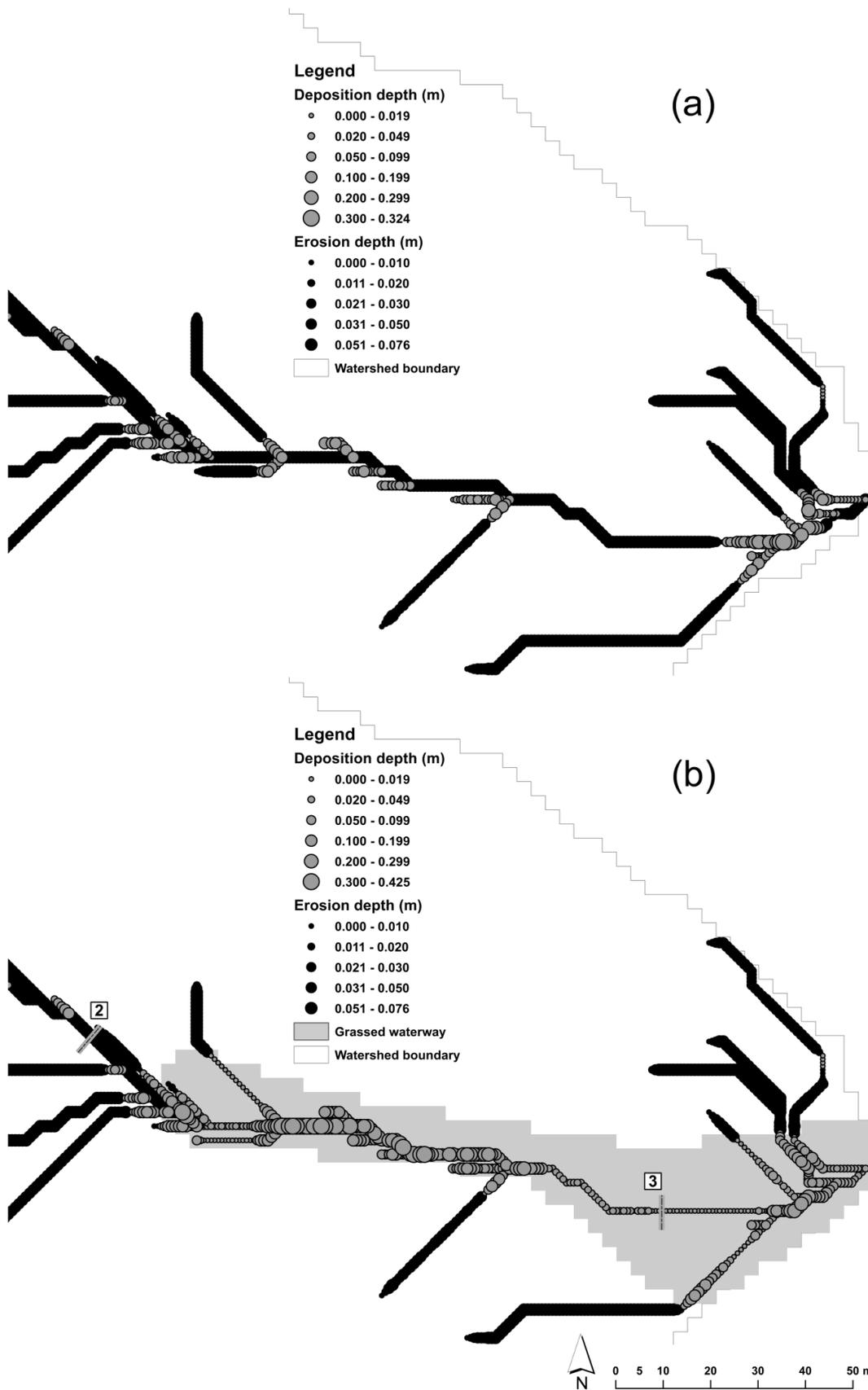


Figure 2. Channel erosion and deposition depths (m) estimated by EphGEE (a) without a grassed waterway, indicating deposition was mainly in backwater areas at tributary confluences and (b) with a grassed waterway showing additional deposition within the grassed waterway.

4.3 Comparing RUSLER/EphGEE and AnnAGNPS

Both models created similar estimates of annual average sediment yield at the field outlet, although their modeling approaches differ considerably. RUSLER/EphGEE simplified the hydrology by considering a

representative runoff event sequence that, for the particular field studied, comprised 24 “channel forming” events that were used to directly estimate long-term average erosion and sediment yield. In contrast, AnnAGNPS considered 1168 observed precipitation events over 17 years, and average annual sediment yield was calculated from the resulting 292 runoff events.

In contrast to the relative simple hydrologic time series used by RUSLER/EphGEE, the spatial representation is more detailed in RUSLER/EphGEE than in AnnAGNPS. The RUSLER/EphGEE detail offers opportunities for exploring the impact of alternative management on portions of individual agricultural fields or farms such as variations in row direction, strip cropping, and alternative buffer alignments. The resulting spatially explicit patterns of erosion and deposition can be used to project decadal landscape evolution or dynamic changes in soil properties (Dabney et al., 2013). In contrast, AnnAGNPS is usually applied at a larger (watershed) scale than the field application illustrated here. In larger-scale applications, such as the 12-digit HUC scale targeted by the AIMS project, AnnAGNPS channels would not extend into the fields the size of Watershed 11. Rather, the entire field would be characterized as a single polygon with an effective slope length and steepness. Nevertheless, PEG could have identified the same potential ephemeral gully locations and, therefore, the same estimates of ephemeral gully erosion would have been produced. At this larger scale, although no vegetated channel reach would have been modeled, the grassed waterway would be treated as a buffer that would reduce sediment delivery.

Sediment yields estimated by the two models were also quite close at the outlet and at CS#2 for simulations with no grassed waterway. At the outlet, AnnAGNPS estimates of $35.2 \text{ ha}^{-1} \text{ yr}^{-1}$ were 7 % greater than RUSLER/EphGEE estimates of $32.9 \text{ ha}^{-1} \text{ yr}^{-1}$, while at CS#2, AnnAGNPS estimates of $67.6 \text{ ha}^{-1} \text{ yr}^{-1}$ were 5 % greater than RUSLER/EphGEE estimates of $64.5 \text{ ha}^{-1} \text{ yr}^{-1}$. However, at CS#1, the AnnAGNPS simulated sheet and rill erosion of $58.7 \text{ ha}^{-1} \text{ yr}^{-1}$ was 62% larger than the RUSLE2 estimate to the same point, and the AnnAGNPS ephemeral gully sediment yield at that point was $19.1 \text{ ha}^{-1} \text{ yr}^{-1}$, was nearly double the $9.9 \text{ ha}^{-1} \text{ yr}^{-1}$ estimate produced by EphGEE. The CS#1 results suggest that AnnAGNPS may calculate ephemeral gully erosion along flow paths that extend higher in the watershed than does the procedure followed by RUSLER/EphGEE. More detailed field observations would be needed to validate either of the simulations up to CS#1.

5 CONCLUSIONS

The similarity of the sediment yield estimates made with the two models is encouraging considering the diversity of the approaches taken. The complimentary capabilities and varied data requirements offer opportunities for multi-scale analyses if the models can be integrated in a common GIS interface. Our results indicate that comprehensive testing is justified and necessary to determine the practical limitations and uncertainty of these ephemeral gully estimates.

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