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Predicting ephemeral gully erosion with RUSLER and EphGEE

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Abstract Ephemeral gully erosion is not included in predictions made with the Revised Universal Soil Loss Equation, version 2 (RUSLE2). A new distributed application called RUSLER (RUSLE2-Raster) predicts distributed soil loss and its output can be linked with the new Ephemeral Gully Erosion Estimator (EphGEE). These models were applied to a 6.3 ha research watershed near Treynor, Iowa, USA, where runoff and sediment yield were measured from 1975 to 1991. Using a 3-m raster DEM, results indicate that ephemeral gully erosion contributed about one-third of the amount of sheet and rill erosion, and that considerable deposition of sediment originating from both sources occurred within the grassed waterway. For ambient conditions, predicted annual average watershed sediment yield was 17.5 Mg ha^{-1} year^{-1}, 20% greater than the measured value of 14.6 Mg ha^{-1} year^{-1}.

Key words erosion; ephemeral gully erosion; sediment; sedimentation; waterway

INTRODUCTION

The Revised Universal Soil Loss Equation Version 2 – RUSLE2 (ARS, 2008; Renard *et al*., 2011) is the most recent in the family of Universal Soil Loss Equation (USLE) models that compute sheet and rill erosion and/or deposition in complex, one-dimensional (1-D) hillslopes. RUSLE2 computes erosion along a 1D flow path that extends from the top of the hill, where runoff begins, through eroding and depositional areas to a location where runoff meets a concentrated flow channel. Selection of representative flow paths is the area where the greatest degree of judgement and training is needed to correctly apply RUSLE for conservation planning (Renard *et al*., 2007). New high-resolution topographic data, such as that available through use of Light Detection and Ranging (LiDAR) and similar technologies, may make it possible to overcome this limitation by automatically determining the locations of flow concentration channels that end hillslope profiles and eliminating uncertainties associated with the selection of representative 1-D profiles. Terrain analysis algorithms can define overland flow paths that represent runoff accumulation and convergence created by the field topography.

As described by Vieira *et al*. (2014), to support the application of RUSLE2 in complex 2-D landscapes with flow convergence, the way RUSLE2 estimates slope length was modified and technology to generate a representative series of runoff events was implemented. The new geographical information system based distributed RUSLE2 application, called RUSLER (RUSLE2-Raster), generates spatially distributed estimates of sheet and rill erosion and deposition, as well as water and sediment delivery to in-field concentrated flow channels. Vieira *et al*. (2014) also describe a physically-based ephemeral gully model, EphGEE (Ephemeral Gully Erosion Estimator) that supports complex in-field dendritic channel networks. EphGEE calculates channel erosion and sediment transport, deposition, and delivery to a watershed outlet. The primary objective of this paper is to demonstrate the application of RUSLER and EphGEE to a research watershed located near Treynor, Iowa, USA.

FIELD SITE

RUSLER and EphGEE were applied and predictions were compared with observations on Watershed 11 (Rachman *et al*., 2008) of the USDA-ARS Deep Loess Research Station located near Treynor, Iowa (Karlen *et al*., 2009). The predominant soil was Monona silt loam (fine - silty, mixed, superactive, mesic Typic Hapludolls). This 6.3 ha watershed was selected because of the extensive research archive that exists for it. Specifically, the watershed was used in the original RUSLE1.04 documentation (Renard *et al*., 1997) to illustrate the proper selection of hillslope profiles (our examples are labelled 1 to 4 in Fig. 1), that should extend from ridge tops to areas of concentrated flow.

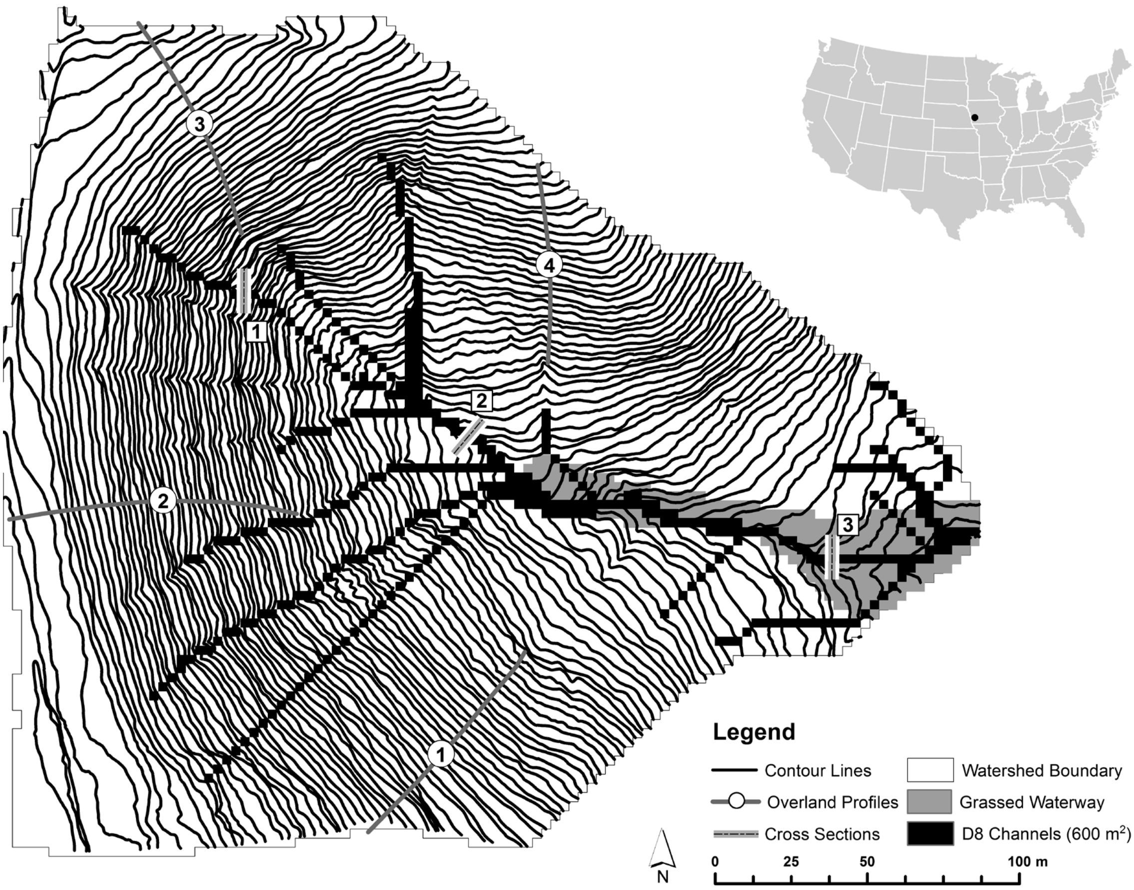

Fig. 1 Topographic map (0.31 m contour interval) of Watershed 11 at Treynor, Iowa, illustrating four (circled numbers) appropriate RUSLE hillslope flow profiles (after Renard *et al*., 1997, Fig. 4-5B). The extent of concentrated flow channel cells determined using a D-8 method based on a minimum contributing area of 600 m^2 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 behaviour of EphGEE in response to runoff events predicted by RUSLE2 are indicated with numbers within square boxes.

Daily runoff and sediment yield were monitored at the watershed outlet from 1975 to 1991. Throughout the period of record, a grassed waterway was located in the lower portion of the watershed (Fig. 1). The field was farmed with contour-planted, conventional-tilled (CT) corn (*Zea mays*, L.). Average corn yield for the period 1987 to 1996 was 7.6 Mg ha^{-1} (Eghball *et al*., 2000).

A DEM was created at 3 m resolution from 0.31 m contour lines (Fig. 1) using the ArcGIS function TopoToGrid, which is based on the package ANUDEM (Hutchinson, 1989). The method used pit filling and enforced flow along the digitized gullies. Four sets of channels were created under assumptions that gullies started where the accumulated drainage area reached four criteria: 300 m^2, 600 m^2, 900 m^2, or 4000 m^2. As discussed by Dabney *et al*. (2013), among these alternatives, the 600 m^2 contributing area resulted in similar flow networks as gullies observed in aerial photos and this criterion was used in analyses herein. Slope steepness was computed using the ArcGIS, which uses a moving 3 × 3 kernel (Horn, 1981).

RUSLER simulations were conducted for the scenario of growing spring-ploughed corn (maize) yielding 7.6 Mg ha^{-1} with no additional conservation practices. Tillage operations that could reset channel dimensions were simulated on 15 April (moldboard plow, 200 mm depth), 1 May (tandem disk, 130 mm depth), 5 May (field cultivator, 100 mm depth), and 10 June (row cultivator, 76 mm depth). Event runoff and sediment delivered to the channels by RUSLER was used as input to EphGEE. The depth of the last tillage operation was taken as the depth of the non-erodible layer for subsequent runoff events. EphGEE simulations were run with and without a grassed waterway in the last 200 m of the watershed's primary channel (Fig. 1). So that sediment delivered to the channel system would be identical for both EphGEE simulations, the RUSLER simulations did not include a change in land management for the area occupied by the grassed waterway. Thus waterway results reported reflect only EphGEE effects.

Standard database climate and soils records for Pottawattamie County, Iowa, were used in all RUSLE2 simulations (USDA-NRCS, 2014). For this management, RUSLE2 predicted total Manning *n* values to vary temporally from a high of 0.073 just after ploughing on 15 April to a low of 0.018 on 14 October, just before corn harvest. The Manning *n* for eroded or depositional surfaces was set at 0.035. When a waterway was simulated, the RUSLE2 simulation was not changed, but a Manning *n* of 0.12 was assigned within EphGEE to waterway reaches. Where erosion or deposition occurred within a channel, an area-weighted average Manning *n* was calculated.

RESULTS

Rainfall and runoff

Observed average annual rainfall depth during the 1975–1991 period was 811 mm, similar to the 30-year county average in the official NRCS database of 801 mm. RUSLE2-predicted average annual runoff was 67 mm, which was higher than the observed runoff of 50 mm, possibly because the RUSLE2 simulation did not include a representation of the grassed waterway that likely slowed down runoff and increased infiltration. Predicted monthly runoff totals and the depths of events with 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 in the predicted event sequence occurred on 23 July and had a depth of 10 mm and an average runoff rate of 26 mm h^{-1}.

Hillslope erosion, runoff, and sediment yield

RUSLER-predicted sediment yield from the hillslopes to the channel system averaged 35 Mg ha^{-1} $year^{-1}$ (Dabney *et al*., 2013), whereas observed sediment yield at the watershed outlet averaged only 14.6 Mg ha^{-1} $year^{-1}$. RUSLER sediment yield does not include any erosion or deposition in the channel system that includes areas of ephemeral gullies and the grassed waterway. The difference between hillslope erosion predictions and observed sediment delivery suggests that at this site and during this period, waterway sediment deposition exceeded ephemeral gully detachment.

Ephemeral gully erosion

Annual ephemeral gully erosion and channel deposition were calculated on an event basis from EphGEE predicted changes in channel widths and depths and summed over the year. Ephemeral gully channels were filled by tillage operations prior to predicted runoff events on 23 April, 6 May, and 27 June. Changes in channel cross-sections (CS) were studied at the three locations indicated in Fig. 1. CS#3 was located within the area that was managed with a grassed waterway during the experimental period. Annual average sheet and rill erosion and drainage area sediment yield values at each of these three locations are reported in Table 1 for simulations with and without a simulated grassed waterway. These results indicate that for the cropland management simulated, ephemeral gully erosion contributed about 22% of the sediment delivered past CS#1. When no waterway was simulated, the corresponding percentages were 25% at CS#2 and 23% at CS#3. Even without a waterway, topography caused considerable deposition between CS#3 and the watershed outlet. This flat topography may have resulted from prior sediment deposition caused by the flume at the watershed outlet that acted as a grade control structure. When a waterway was simulated, the increased hydraulic roughness caused deposition throughout the extent of the waterway. Overall, sediment yield from the waterway was predicted to be 17.5 Mg ha^{-1} year^{-1}, 20% greater than the measured value of 14.6 Mg ha^{-1} year^{-1}. EphGEE estimated watershed sediment yield of 32.9 Mg ha^{-1} year^{-1} when no grassed waterway was simulated.

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). Units: Mg ha^{-1} year^{-1} unless specified.

Location	Drainage area (ha)	Local channel steepness (%)	RUSLER sheet and rill soil loss[a]	With grassed waterway		No grassed waterway	
				Net channel soil loss	EphGEE watershed sediment yield	Net channel soil loss	EphGEE watershed sediment yield
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

To illustrate the changes in channel dimensions throughout the year, CS#2 was examined for the simulation without a grassed waterway (Fig. 2). Initial channels were assumed to be triangular with 5% side-slope steepness. The first storm after spring tillage was a small runoff event (23 April) and resulted in deposition that transformed the channel cross-section from a triangle to trapezoid. After this event, the channel was reset by tillage operations on 1 and 5 May prior to the second runoff event (8 May) that caused incision of a rectangle that reached the non-erodible layer at a depth of 100 mm. The third and fourth runoff events (23 May and 8 June) widened the channel at this depth before the last tillage event reset the gully on 10 June, that created a new non-erodible layer at 76 mm. Subsequent runoff events were the largest of the year and the gully cut down to the non-erodible layer and widened. Smaller runoff events after 23 August caused no further erosion but rather slight deposition at CS#2.

Changes at CS#1 were similar to those observed at cross section #2. At CS#3, deposition occurred for all runoff events when a waterway was simulated and during some runoff events even when a waterway was not simulated.

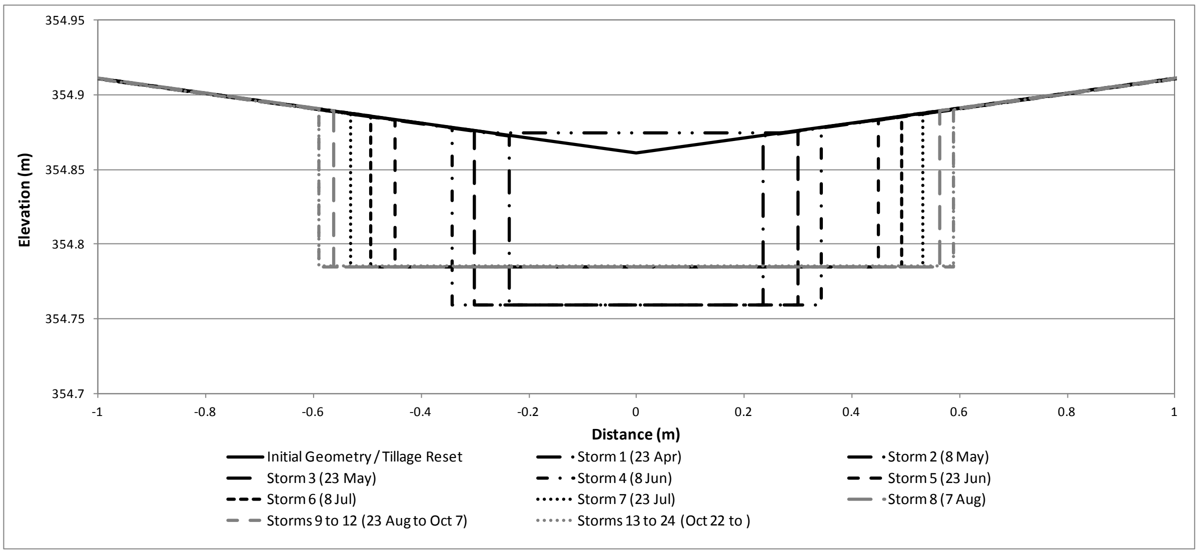

Fig. 2 Cross-sections following selected runoff events for CS#2 (Fig. 1) in simulations without a grassed waterway.

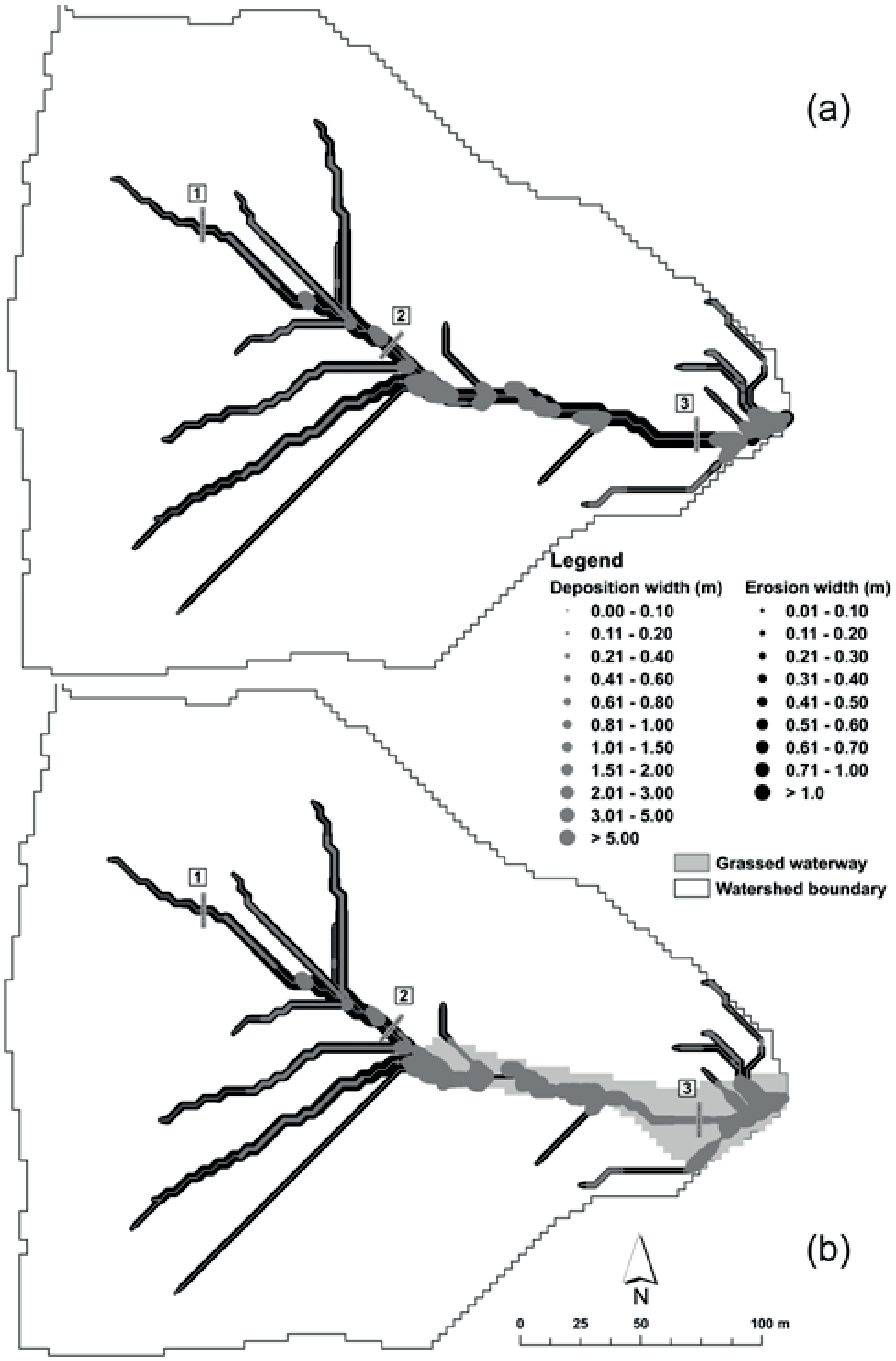

Fig. 3 The maximum widths of EphGEE-predicted eroded channels and sediment deposits within Watershed 11 at Treynor, Iowa, USA, in response to runoff events predicted by RUSLE2 when simulated: (a) without a grassed waterway, and (b) with a grassed waterway.

Spatial patterns of channel erosion and deposition were complex. Even without the waterway established, depositional areas wider than 5 m were predicted at confluences within the lower reaches of the watershed (Fig. 3(a)). Some of the predicted deposition occured in previously

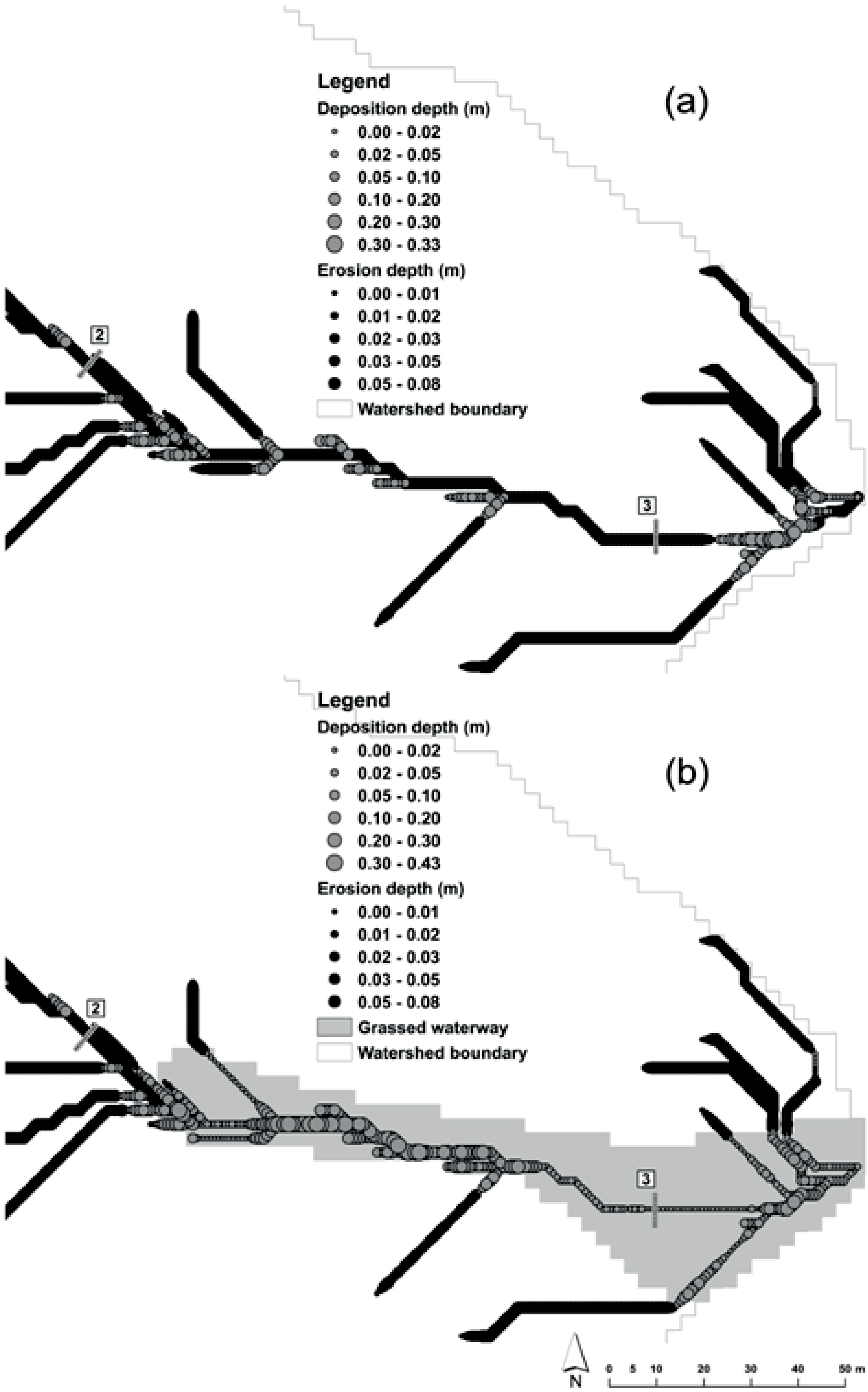

Fig. 4 Channel erosion and deposition depths (m) predicted: (a) without a grassed waterway, indicating deposition was mainly in backwater areas at tributary confluences, and (b) with a grassed waterway showing additional deposition within the grassed waterway.

eroded channels. Figure 4 illustrates the depths of erosion or deposition after the last runoff event before spring ploughing. Note that some of the areas showing deposition in Fig. 3 coincide with areas of net erosion (incision) in Fig. 4 (e.g. CS#2). In the simulation without a waterway, deposition occurred most often at confluences of channels (Vieira *et al*., 2014), and the main thalweg shows incision to the non-erodible layer (Fig. 4(a)) and a width greater than 1 m (Fig. 3(a)) until within 30 m of the watershed outlet where the topography leveled. When the grassed waterway was simulated, the main thalweg had deposition throughout its length (Fig. 4(b)). The simulated depths of deposition in the waterway thalweg are somewhat exagerated since no sediment deposition was simulated in the RUSLER simulation because the waterway raster cells where simulated as cropland. If a grass waterway had been simulated in RUSLER, increased deposition in the waterway field areas would have decreased sediment load to EphGEE and, thus, reduced sediment depth predicted by EphGEE. Deposition depths would also have been lower if the watershed cross-section had started out as a trapezoid rather than a triangle. However, Spomer *et al*. (1985) showed triangular initial grassed waterway cross-sections and reported that waterway sediment deposition more than 0.5 m deep and extending 40 m wide occurred between 1963 and 1980 in an adjacent field.

The soil at the study site was derived from loess and contained 9% sand, 67% silt and 24% clay. For the simulations conducted, with no waterway the sediment delivered from the watershed was predicted to be 30% clay and 69% silt; with a waterway, the sediment delivered was 66% clay and 34% silt.

Under the simulated conventional tillage management conditions, channel deposition exceeded channel erosion in this field. Under no-till management, channel deposition would be expected to be much lower and ephemeral gully erosion would be expected to contribute a higher percentage of sediment loads since sheet and rill erosion would be reduced by more than runoff (Dabney *et al*., 2012).

CONCLUSIONS

Results of this initial evaluation of an integrated sheet, rill and ephemeral gully erosion prediction technology are promising. The system relies on detailed topographic elevation data; existing RUSLE2 databases published by the USDA-NRCS; RUSLE2 estimates of a hillslope runoff, sediment yield, time-varying Manning roughness coefficients; and independent estimates of channel soil critical shear stress and erodibility parameters. The system estimated that within an agricultural field in western Iowa, establishment of a grassed waterway reduced sediment yield by 42% even though the lower part of the watershed already contained depositional areas when the grassed waterway was absent. The relatively close match between predicted and observed watershed sediment yield is encouraging and suggests that the methods, approximations and simplifications described may allow distributed assessment of soil degradation and water quality impacts from agricultural management. Further testing and development will be needed to clarify the ability of this technology to approximate observations over a wider range of climate, soil and management systems.

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