EPHEMERAL GULLY EROSION RESEARCH: PROCESSES AND MODELING

(Keynote)

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1. Introduction

The USDA Natural Resources Conservation Service (NRCS) defines ephemeral gullies as small channels that can be filled in by normal tillage operations only to reform in the same location by subsequent runoff events. Ephemeral gullies contribute significantly to soil erosion in agricultural fields, and NRCS has consistently identified gully erosion as their number one problem to solve. Moreover, headcut development and migration is closely coupled to the initiation of ephemeral gullies and their extension on hillslopes. Research is needed to further understand the physics of these processes, to derive robust predictive algorithms and methodologies, and to develop reliable control methods.

Previous studies, too numerous to be quoted here, have shown that ephemeral gully development is influenced by dynamic hydrologic and landscape attributes that control surface and subsurface erosion processes. The prevalent consensus is that the location and size of ephemeral gullies can be controlled by the generation of concentrated surface flow of sufficient magnitude and duration to initiate and sustain soil erosion. Concentrated flow in cultivated fields can overtop furrows, thereby creating a cascade of water downslope that leads to ephemeral gully development. Field observations support the concept of ephemeral gully as the transition between a hillslope and a drainage channel. Thus, both surface and subsurface flow may converge and interact at locations that become initiating points of the gullies.

Figure 1. Headcut migration and gully widening in a crop furrowed field.

Ephemeral gully erosion usually, but not always, includes one or more headcuts that migrate upslope over time. These are step changes in bed surface elevation where intense, localized erosion takes place, and that are commonly associated with significant increases in sediment load. Reported experimental data shows that actively migrating ephemeral-gully headcuts display a self-similar organization with migration rates dependent on upstream flow depth and discharge, tailwater depth, and soil properties. The depth of ephemeral gullies is often limited by the presence of a non-erodible or impervious soil layer. When erosion reaches such a layer, the ephemeral gully typically widens, creating a wide shallow cross section. The response of the soil to eroding processes is also affected by wetting and drying from rainstorm events, as well as the annual cycle of tillage, crop growth, and freeze-thaw. Once an ephemeral gully is initiated, transport and deposition of the eroded soil and widening of the gully channel further govern its evolution (Figure 1). However, our knowledge of these processes in shallow concentrated flows within agricultural soils is still quite limited and largely scaled down from river hydraulics.

Compared to the roles of surface flow and soil water tension on rill initiation and growth, the contribution of subsurface flow to ephemeral gully erosion is less well known. The two mechanisms of subsurface flow attributed to erosion are seepage and preferential flow. Seepage is common where restriction of downward percolation results in lateral flow that emerges from the soil surface. There is also evidence that positive and negative seepage also influence surface erosion and sediment transport. Water-restrictive layers that focus flow through soil-pipes can also cause ephemeral gully development through soil-pipe collapse or pop-out failures that initiate ephemeral gully development (Figure 3).

The initiation and growth of ephemeral gullies is also greatly affected by land management practices that control evapotranspiration, infiltration, runoff rate, and soil detachment, which alter runoff patterns. These practices include contouring, no-till, cover crops, crop rotation, vegetative barriers, check dams, soil amendments and subsurface drainage. Current approaches to evaluate ephemeral gully initiation and erosion incorporate two basic steps. The first step uses visual observation based on field reconnaissance or from aerial photographs to pinpoint landscape attributes favorable for gully initiation, or critical slope steepness and contributing area relationships for ephemeral gully initiation. The second step is taken once the gully has been identified and involves the application of process-based water erosion models like the Ephemeral Gully Erosion Model (EGEM, Woodward, 1999).

IV International Symposium on Gully Erosion. J. Casalí and R. Giménez (Eds.)
ISBN 978-84–9769-198-7

2. Selected Results from a Team Research Effort

A multidisciplinary team of scientists from the USDA National Sedimentation Laboratory, NRCS, the University at Buffalo, Oklahoma State University, and the University of Nottingham, UK, is collaborating in experimental and modeling research on several aspects of ephemeral gully erosion. Their recent results are detailed in a series of concurrent (oral and poster) papers at this Symposium, and the remainder of the present abstract is devoted to highlight outcomes of this collaborative effort during the intervening period since the 3rd International Symposium on Gully Erosion held in Oxford, Mississippi, in 2004.

2.1. Experimental Studies

Bennett and Alonso (2007) examined the flow characteristics within fixed-bed models of headcut scour holes typical of upland concentrated flows. Velocity data and streamlines show unequivocally that flow within headcut scour holes is analogous to a reattached plane turbulent wall jet. The overfall nappe entering the scour hole domain evolves into a free jet, with flow reattachment occurring just upstream of the maximum scour depth (Figure 2). Recirculation zones bound the free jet region, and the deflected flow downstream of impingement evolves into a classical wall jet. Within headcut scour holes, three hydrodynamic mechanisms are responsible for soil erosion. These are: (1) high shear stresses due to near-bed velocity gradients; (2) high near-bed Reynolds stresses due to turbulent fluctuations in velocity; and (3) large wall pressure gradients near flow reattachment.

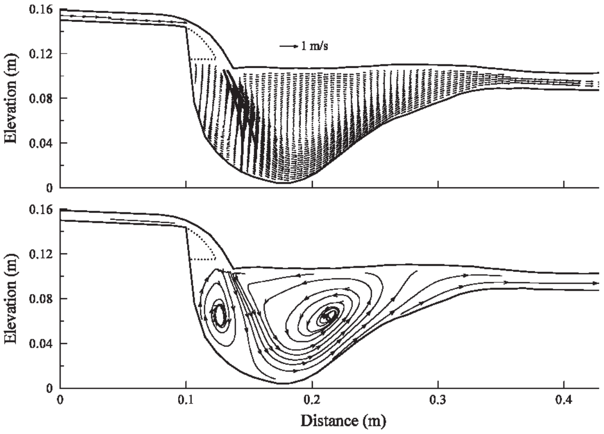

Figure 2. Measured streamline pattern within the scour pool of a fixed-bed headcut model.

Gordon et al. (2007b) investigated the effect of an erosion resistant (ER) soil layer placed at various depths within a fine sandy-loam (Ruston series) on headcut development and migration. When the ER layer was placed at or above the potential scour depth (verified by baseline runs), headcuts were limited in depth to this layer, and while their migration rates remained about the same, total sediment efflux was markedly reduced. These experimental observations were successfully compared to analytic formulations for headcut erosion based on jet impingement theory.

Wells et al. (2007) studied the impact of soil texture, soil pore-water pressure, and tailwater height on scour hole dimensions, migration rate, and sediment yield in headcuts migrating under steady surface runoff conditions. The soils used in this study were the same Ruston soil mentioned above, a silt loam (Atwood series), a silt loam (Dubbs series), and a silty clay loam (Forestdale series). The Ruston and Atwood soils attained steady-state morphology, constant upstream migration, and sediment yield, while the Dubbs and Forestdale soils developed scour geometries characterized by an eroded brinkpoint and tilted back headcut face as the overfall nappe turned into a reattached wall jet. Maximum scour depth increased with decreasing pore-water pressures and an increase in tailwater height dramatically reduced the sediment yield and migration rate.

Figure 3. A soil pipe observed at a gully head immediately above the fragipan layer.

Wilson (2007a) reports results from laboratory lysimeters that examined hydrologic conditions under which soil-pipes initiate or reestablish ephemeral gullies. Tests with continuous soil-pipes did not exhibit sudden development of mature ephemeral gullies by tunnel collapse but experiments on discontinuous soil-pipes did exhibit sudden re-establishment of filled-in gullies. The addition of rainfall resulted in cataclysmic pop-out failures up to 20 times higher than sheet erosion. The result of these pop-out failures is the re-establishment of ephemeral gullies with large initial soil losses. These findings explain the observed reoccurrence of ephemeral gullies at the same locations, and also suggest that conservation practices that focus solely on controlling the surface runoff may be ineffective if subsurface flow controls are not considered (Figure 3).

Parallel field and lysimeter studies reported by Wilson et al. (2007b) use seepage erosion to describe the process of sediment transport out of an edge-of-field gully face by liquefaction of soil particles entrained in the seepage. The undercutting of the gully face by seepage erosion results in mass failure which may be a contributing factor to headcut migration and gully widening. The question remains as to what role this process plays in ephemeral gully erosion in soil profiles containing an erodible surface layer over a water restrictive layer.

2.2. Modeling Studies

The Annualized Agricultural Non-Point Source model (AnnAGNPS; Bingner and Theurer, 2001) is one of the decision tools identified by NRCS for conservation planning on croplands. AnnAGNPS is being developed to provide sediment tracking from all sources within the watershed including ephemeral gullies. Gordon et al. (2007a,c) extended the capabilities of EGEM by adding new algorithms that: (1) create the initial headcut's knickpoint; (2) estimate the headcut migration and erosion rates; and (3) enhance some other existing EGEM components. These enhancements were integrated into the revised Tillage-Induced Ephemeral Gully Erosion Model (TIEGEM). The TIEGEM technology has been incorporated into AnnAGNPS model to provide a watershed-scale assessment of the effect of management practices on the production of sediment from ephemeral gully erosion within croplands (Bingner et al., 2007).

3. Research Needs

The enhancements introduced in the TIEGEM model notwithstanding, some clear limitations remain in this technology. The experimental data reported here and elsewhere by *Bennett* and his coworkers provided the framework for the analytic treatment of headcut migration used in the revision of EGEM. Yet those data were derived in a fixed-width flume where the headcut grew and developed without benefit of adjusting its width. Therefore, the utility of those formulations in field settings and operational models is limited because naturally occurring rills, crop furrows, and ephemeral gullies can, in most cases, freely adjust their widths to the imposed runoff (Figure 1). Similarly, the flume data were collected in flows devoid of upstream sediment load and headcut erosion ensued as the result of a clear-water overfall and scouring jet. This imposed boundary condition is far removed from natural rills, crop furrows, and ephemeral gullies that display the complete spectrum of detachment-limited to transport-limited flows. One can expect that the modulation of jet erosivity due to an upstream sediment load would modify the magnitude of the soil erosion processes within the scour pool. In addition, the complete absence of subsurface flow and erosion treatment imposes further limitations on the application of TIEGEM to natural settings. These limitations, combined with the lack of reliable transport predictors for poorly graded sediments in shallow flows, point to clear directions for future research.

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