EFFECT OF UPSTREAM SEDIMENT INFLOW ON THE MORPHODYNAMICS OF HEADCUTS

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Abstract  Headcut erosion can severely accelerate soil loss in upland concentrated flows and lead to significant soil degradation in agricultural areas. Previous experimental work has demonstrated that actively migrating headcuts display systematic morphodynamic behavior, and impinging jet theory can provide an excellent theoretical foundation for this erosional phenomenon. This research sought to systematically examine the effect of an upstream sediment inflow on the morphodynamics of actively migrating headcuts in upland concentrated flows. Using a specially-designed experimental facility, actively migrating headcuts were allowed to develop, and then they were subjected to an upstream sediment load composed of sand. As the upstream sediment feed rate increased, the size and migration rate of the headcut decreased markedly, but sediment discharge was less affected. The headcut erosion process was arrested as sediment inflow rate increased above a threshold value. Also, as sediment feed rate increased, the particle size distribution composing the discharged sediment shifted from fine to coarse sediment. This research suggests that headcut erosion can be greatly modulated by an upstream sediment source, emphasizing the need for further enhancements of existing ephemeral-gully models.

INTRODUCTION

Erosion is the principal cause of soil degradation in the U.S., with off-site impacts of sedimentation that severely affect water quality, ecology, and habitat. According to the U.S. EPA (1998, 2000), sedimentation is one of the leading causes of water quality impairment in the nation. Economic costs of soil erosion in the U.S. have been estimated at $30 to $44 billion annually (Pimentel et al., 1995; Uri and Lewis, 1999). While soil erosion has generally been recognized as the primary cause of soil degradation, gully erosion has recently received much greater attention (Poesen et al., 2003; Valentin et al., 2005). Gully erosion represents an important, if not the dominant, sediment source in some watersheds (Watson et al., 1986; Poesen et al., 1996; Bennett et al., 2000; Casalí et al., 2000; Poesen et al., 2003). Gullies are effective links for transferring runoff, sediment, and other potential materials from source to sink, and may serve as critical indices of land mismanagement, desertification, and global climate change (Poesen et al., 2003; Valentin et al., 2005). Ephemeral gullies can grow rapidly in size within individual storm events, and pose a significant challenge in the development of soil erosion prediction technology (Valentin et al., 2005).

In upland concentrated flows such as rills, furrows, and ephemeral gullies, incision into the soil strata and the extension of this channel across landscapes are primarily due to an actively migrating headcut (Smith, 1993; Casalí et al., 1999; Foster, 2005). A headcut is a step-change in bed surface topography where intense, localized erosion takes place (Bennett et al., 2000). The occurrence and migration of headcuts are commonly associated with significant increases in
sediment yield (Mosley, 1974; Meyer et al., 1975; Bryan, 1990; Römkens et al., 1995, 2000, 2001; Helming et al., 1998). Römkens et al. (1996, 1997) observed the failure of surface seals on soils immediately followed by headcut formation, bed incision, and rill development. Prior to headcut development, sediment yield from the soil surface was essentially zero. Slattery and Bryan (1992) and Brunton and Bryan (2000) observed that rill incision and high rates of soil erosion were always the result of headcut development and migration in their laboratory experiments.

An experimental program was initiated to examine actively migrating headcuts in concentrated flows and address this soil erosion phenomenon in mechanistic terms. This research has documented the following observations: (1) steady-state soil erosion can be achieved under specific conditions, wherein a scour hole migrates upstream at a constant rate and dimension, and sediment discharge exiting the flume remains nearly invariant with time; (2) larger scour holes are associated with higher overland flow rates, higher bed slopes, and larger initial step heights; (3) the presence of a non-erodible layer reduces scour depths, nappe entry angles, and sediment discharges; (4) higher tailwater heights downstream of the headcut lead to an immediate cessation of the soil erosion process; and (5) varying subsurface pore-water pressures can either enhance or suppress the headcut erosion process (Bennett, 1999; Bennett et al., 2000; Bennett and Casalí, 2001; Gordon et al., 2007; Wells et al., 2009b).

This previous work used a clear-water flow as the upstream boundary condition. The presence of sediment in transport within upland concentrated flows is well known to markedly affect flow hydraulics and flow resistance (Li and Abrahams, 1997). Changes to upstream sediment discharge would be communicated to the headcut brinkpoint, markedly affecting the overfall nappe as it enters the scour pool domain and the headcut erosion process. The goal of this research was to systematically examine the effect of an upstream sediment inflow on the morphodynamics of actively migrating headcuts in upland concentrated flows.

**EXPERIMENTAL METHODS AND MATERIALS**

The study consisted of 15 experiments: 2 clear-water (baseline) runs, and 2 runs for each sediment feed rate (except the 20% case where we performed 3 experiments), defined as 20% (0.2Qs), 40% (0.4Qs), 60% (0.6Qs), 80% (0.8Qs), 100% (1.0Qs), and 120% (1.2Qs) of the average asymptotic sediment discharge Qs from the base runs exiting the flume, which was 0.0236 kg s⁻¹. The soil used in the study was an Atwood sandy loam (fine-silty, mixed, thermic Typic Paleudalfs). This well-drained soil formed on a mantle of silty material with underlying deep loamy sediments. The surface is dark brown (7.5 YR 4/4 Munsell notation) with a particle size distribution consisting of 59% sand (18% medium, 39% fine and 2% very fine), 17% silt (10% coarse and 7% fine), and 24% clay. The median grain sizes of the Atwood soil and the sediment used in the present study were 0.250-mm and 0.354-mm, respectively.

All experimental runs were carried out in a 5.5-m long and 0.165-m wide non-recirculating, tilting hydraulic flume (Figure 1). This facility and the procedures employed to apply rainfall and monitor water table heights, runoff, and headcut erosion processes were described in detail by Wells et al. (2009a, b). The procedure for preparing the soil bed is briefly discussed below. Flow discharge was controlled by two adjustable intake valves and monitored by a magnetic flow...
Acoustic transducers monitored upstream and downstream water surface (WS) elevations. The upstream WS elevation was measured 0.44-m upstream of the soil bed and the downstream WS elevation 0.10-m upstream of the flume outlet. A summary of all experimental run parameters is given in Table 1.

Soil samples were air-dried, mechanically crushed to pass a 4-mm sieve, and packed within the soil cavity (2.75-m long, 0.165-m wide, and 0.25-m deep) in increments (0.03-m thick and weighing 15-kg) by vibration transmitted through an aluminum plate. After packing the soil to a depth of 0.22-m, an aluminum headcut-forming plate was installed 2.3-m downstream of the rigid floor, normal to the bed and in contact with the soil. Once the headcut plate was in position, soil was packed upstream of the plate in 7-kg increments and leveled with the upstream rigid floor, thus producing a preformed step 0.03-m high in the bed profile. Simulated rainfall (Meyer and Harmon, 1979) was applied at 21 mm hr$^{-1}$ for 8 hr to the soil bed tilted at a slope of 5%, which ensured that no water would pond on the soil surface.

The bed slope was adjusted to 1% following rainfall, clear water was pumped into an inlet tank, and once filled, the water spilled onto a rigid floor upstream of the soil cavity, then onto the soil bed. Approximately 120-s following the release of overland flow, sediment was released into the flow 0.97-m upstream of the soil cavity at a constant rate using an auger feeder. Water and sediment exiting the soil cavity were captured in 0.5-L glass bottles at 10-s intervals for 3 minutes then 20-s intervals thereafter. Sediment samples were weighed and placed in an oven at 40.5° C for 24 hr, then reweighed. Select sediment samples were sieved to determine the percent mass of size for the following size fractions (all diameters in mm): coarser than 0.5, 0.354, 0.25, 0.178, 0.125, 0.088, 0.063, and less than 0.063 (pan remains). These fractions were combined...
into the following particle size bins: medium sand (coarser than 0.354 mm), fine sand (coarser than 0.178 and finer than 0.354 mm), very fine sand (coarser than 0.063 and finer than 0.178 mm), and silt and clay (finer than 0.063 mm). Bulk density samples of the sediment deposit downstream of the headcut were collected in aluminum rings pressed normal to the surface of the bed. Top and side views of headcut migration and scour hole morphology were recorded to video tape using two cameras attached to a cart mounted on rails atop the flume. Video captured during the experiment was transferred from tape to computer, and morphologic analysis began by capturing video frames recorded at 30-s intervals.

Table 1 Summary of experimental parameters. $M$ (migration rate), $S_D$ (maximum scour depth), $\theta_e$ (nappe entry angle), and $Q_s$ (sediment discharge) were determined prior to sediment addition.

<table>
<thead>
<tr>
<th>Run</th>
<th>Sediment Influx</th>
<th>$\rho_s$</th>
<th>$Q$</th>
<th>$M$</th>
<th>$S_D$</th>
<th>$\theta_e$</th>
<th>$Q_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>0 kg s$^{-1}$</td>
<td>1288 kg m$^{-3}$</td>
<td>0.00114 m$^3$ s$^{-1}$</td>
<td>2.4 mm s$^{-1}$</td>
<td>0.092 m</td>
<td>58 deg</td>
<td>0.0223 kg s$^{-1}$</td>
</tr>
<tr>
<td>Baseline</td>
<td>0 kg s$^{-1}$</td>
<td>1265 kg m$^{-3}$</td>
<td>0.00120 m$^3$ s$^{-1}$</td>
<td>2.3 mm s$^{-1}$</td>
<td>0.089 m</td>
<td>43 deg</td>
<td>0.0144 kg s$^{-1}$</td>
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<tr>
<td>$0.2Q_s$</td>
<td>0.0047 kg s$^{-1}$</td>
<td>1307 kg m$^{-3}$</td>
<td>0.00116 m$^3$ s$^{-1}$</td>
<td>1.9 mm s$^{-1}$</td>
<td>0.096 m</td>
<td>47 deg</td>
<td>0.0254 kg s$^{-1}$</td>
</tr>
<tr>
<td>$0.2Q_s$</td>
<td>0.0047 kg s$^{-1}$</td>
<td>1296 kg m$^{-3}$</td>
<td>0.00119 m$^3$ s$^{-1}$</td>
<td>1.7 mm s$^{-1}$</td>
<td>0.096 m</td>
<td>49 deg</td>
<td>0.0227 kg s$^{-1}$</td>
</tr>
<tr>
<td>$0.4Q_s$</td>
<td>0.0094 kg s$^{-1}$</td>
<td>1331 kg m$^{-3}$</td>
<td>0.00112 m$^3$ s$^{-1}$</td>
<td>1.9 mm s$^{-1}$</td>
<td>0.091 m</td>
<td>47 deg</td>
<td>0.0223 kg s$^{-1}$</td>
</tr>
<tr>
<td>$0.4Q_s$</td>
<td>0.0094 kg s$^{-1}$</td>
<td>1339 kg m$^{-3}$</td>
<td>0.00109 m$^3$ s$^{-1}$</td>
<td>2.8 mm s$^{-1}$</td>
<td>0.087 m</td>
<td>41 deg</td>
<td>0.0278 kg s$^{-1}$</td>
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<tr>
<td>$0.6Q_s$</td>
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<td>1339 kg m$^{-3}$</td>
<td>0.00116 m$^3$ s$^{-1}$</td>
<td>2.7 mm s$^{-1}$</td>
<td>0.076 m</td>
<td>42 deg</td>
<td>0.0234 kg s$^{-1}$</td>
</tr>
<tr>
<td>$0.6Q_s$</td>
<td>0.0142 kg s$^{-1}$</td>
<td>1339 kg m$^{-3}$</td>
<td>0.00116 m$^3$ s$^{-1}$</td>
<td>2.6 mm s$^{-1}$</td>
<td>0.085 m</td>
<td>45 deg</td>
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<td>$0.8Q_s$</td>
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<td>1327 kg m$^{-3}$</td>
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<td>2.8 mm s$^{-1}$</td>
<td>0.084 m</td>
<td>45 deg</td>
<td>0.0316 kg s$^{-1}$</td>
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<td>1270 kg m$^{-3}$</td>
<td>0.00122 m$^3$ s$^{-1}$</td>
<td>2.8 mm s$^{-1}$</td>
<td>0.086 m</td>
<td>42 deg</td>
<td>0.0217 kg s$^{-1}$</td>
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<td>$1.0Q_s$</td>
<td>0.0236 kg s$^{-1}$</td>
<td>1345 kg m$^{-3}$</td>
<td>0.00112 m$^3$ s$^{-1}$</td>
<td>2.9 mm s$^{-1}$</td>
<td>0.079 m</td>
<td>46 deg</td>
<td>0.0345 kg s$^{-1}$</td>
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<td>$1.0Q_s$</td>
<td>0.0236 kg s$^{-1}$</td>
<td>1759 kg m$^{-3}$</td>
<td>0.00114 m$^3$ s$^{-1}$</td>
<td>3.0 mm s$^{-1}$</td>
<td>0.081 m</td>
<td>42 deg</td>
<td>0.0210 kg s$^{-1}$</td>
</tr>
<tr>
<td>$1.2Q_s$</td>
<td>0.0283 kg s$^{-1}$</td>
<td>1325 kg m$^{-3}$</td>
<td>0.00115 m$^3$ s$^{-1}$</td>
<td>2.5 mm s$^{-1}$</td>
<td>0.088 m</td>
<td>40 deg</td>
<td>0.0326 kg s$^{-1}$</td>
</tr>
<tr>
<td>$1.2Q_s$</td>
<td>0.0283 kg s$^{-1}$</td>
<td>1351 kg m$^{-3}$</td>
<td>0.00116 m$^3$ s$^{-1}$</td>
<td>2.8 mm s$^{-1}$</td>
<td>0.092 m</td>
<td>41 deg</td>
<td>0.0235 kg s$^{-1}$</td>
</tr>
</tbody>
</table>

1 since $Q$ is not available, a value of 0.00116 m$^3$ s$^{-1}$ is adopted here.

RESULTS AND DISCUSSION

All runs with sediment-laden inflows were initiated with clear water flow, and only after the scour holes were observed to reach steady-state (approximately 120-s) was the upstream sediment input initiated. Under the imposed upstream water and sediment inflow conditions, the added sediment created an upstream deposit that was transported downstream as bed load, first as strips then as a uniform layer that covered the entire bed upstream of the headcut brinkpoint. The developmental time, height, and length of this deposit were a function of the imposed sediment feed rate.

Following Wells et al. (2009a), each captured video frame was used to obtain measurements, relative to a preset datum, of maximum scour depth $S_D$, nappe entry angle $\theta_e$, and brinkpoint position $m$. These parameters are plotted as a function of time for all experimental runs (Figures...
2 and 3). The rate of upstream migration $M$ of the headcut brinkpoint was nearly constant for the baseline and $0.2Q_s$ runs, but decreased monotonically for the sediment feed rates of $0.8Q_s$, $1.0Q_s$, and $1.2Q_s$ as the brinkpoint moved closer to the end of the runtime (Figure 2a). Marked changes were observed for the maximum scour depth $S_D$ and the nappe entry angle $\theta_e$. The base and $0.2Q_s$ experiments were essentially the same in terms of time-averaged values of $S_D$ and $\theta_e$, but with each feed rate above $0.2Q_s$, large reductions in $S_D$ and $\theta_e$ occur (Figures 2b and 3a). Sediment discharge exiting the flume, however, is not significantly impacted by the increased inflow of sediment (Figure 3b). In the steady-state baseline tests reported here and elsewhere (Bennett et al., 2000; Gordon et al., 2007; Wells et al., 2009a,b), sediment discharge increases rapidly in response to the initial development of the scour hole and then decreases asymptotically to a quasi-steady level (Figure 3b). For the sediment inflow experiments shown here, the trend in sediment discharge was similar.

![Graphs showing time variation in brinkpoint position and maximum scour depth](image-url)
Figure 3 Time variation in (a) nappe entry angle ($\theta_e$) and (b) sediment discharge ($Q_s$) for the two clear-water (baseline runs; closed symbols) experiments and for each sediment feed experiment (0.2 to $1.2Q_s$; open symbols). Two experiments were conducted for each load, whereas three experiments were conducted for $0.2Q_s$.

Figure 4 illustrates the temporal evolution of the headcut and constructed bed shapes for selected tests and run times (baseline, $0.8Q_s$, $1.2Q_s$; at 360, 600, 690, 750s). Figures 4b and 4c demonstrate that at large sediment-feed rates the slope of the constructed bed increases in relation to the constructed slope attained under clearer flows ($0.01914$-m.m$^{-1}$ for the $1.2Q_s$ case versus $0.00858$-m.m$^{-1}$ for the $0.4Q_s$ case). This slope increase was the result of larger tractive forces needed to transport the coarser sediment mixture downstream. As sediment deposits immediately downstream of the scour pool to accommodate the increase in slope, the tailwater
rises above the pool, thus forcing a decrease in nappe entry angle ($\theta_e$; Figure 3) and maximum scour depth ($S_D$; Figure 2) as shown by Alonso et al. (2002) and further verified below.

![Figure 4 Video frames of headcut development taken during the (a) baseline, (b) $0.8Q_s$, and (c) $1.2Q_s$ experiments. The frame sequence for each selected run corresponds to 360, 600, 690, and 750 s (top to bottom) from run initiation. Flow is left to right, the vertical rulers are separated by 0.15 m, and the sediment fed from upstream is blue in color, which is incorporated into the self-made bed downstream of the headcut.](image)

The rate of sediment production by the actively migrating headcut became suppressed as sediment inflow rate increased, because the rate of headcut erosion decreases with $M$ and $S_D$ (Alonso et al., 2002). Although the total sediment discharge was essentially maintained, it shifted from headcut-controlled flux to sediment-feed controlled flux. Thus the headcut erosion process was arrested as sediment inflow rate increased above some threshold, which appears to be roughly $0.6Q_s$ for these experimental conditions. Total sediment discharge, however, was not as adversely affected as the scour hole dimensions, since upstream sediment feed was continuous in time.

The texture of the sediment efflux within the experiments, however, was affected by the sediment influx. Sediment exiting the flume, downstream of the headcut, was initially dominated by the smaller particle size classes ($< 0.25$ mm) (Figure 5). As sediment feed rate increased, the smaller particle size classes were depleted and the larger size classes were enriched. The shift began with the $0.4Q_s$ and increased with each feed rate above $0.4Q_s$. The texture of the sediment efflux for the baseline experiment was dominated by the sand fraction, particularly the fine sand, as expected since this fraction dominates the composition of the soil material (Table 3), and no discernable time variation in texture was observed in the mass fractions of $Q_s$ for the baseline experiment (Figure 5). Similar textural composition and time variation was observed for the $0.2Q_s$ experiment. Although, as the sediment influx increased above this value, and as the headcut began to respond to this external loading, a marked shift occurred in the texture of the sediment efflux. For the $0.4Q_s$ experiment, these trends were
subtle: by the end of this experiment, the fraction of medium sand had been enriched by about +28% and the finer sand and silt and clay fractions were depleted by about −42% as compared to the baseline experiment (Table 3, Figure 5). For the higher sediment influx experiments, the temporal variations were more striking and the enrichment and depletion values were more pronounced. The increase in the medium sand fraction occurred after about 300 s for the experiments with feed rates of \(0.8Q_s\) and higher (Figure 5), with concomitant decreases in all finer fractions. Medium sand completely dominated the composition of the sediment efflux for the higher influx experiments (more than 90% by mass), achieving enrichment ratios greater than 200%, whereas the finer sand and silt and clay fractions were nearly eliminated in these samples (Table 3, Figure 5).

As sediment influx increased within these experiments, there was a significant shift from headcut-controlled flux to sediment-feed controlled flux. The higher sediment influx experiments either caused a significant reduction in or the complete obliteration of the actively
migrating headcut (Figures 2 to 5) with no significant change in sediment efflux (Figure 3b, Table 1). With time, however, the texture of the sediment efflux became heavily enriched in sediment-feed material and depleted in the headcut-derived material. While total sediment discharge within these experiments was not affected by the time-variation or magnitude of the headcut morphodynamics, there was a significant textural shift toward the composition of the sediment influx, which was continuous in rate and texture with time. It is highly likely, given enough time and space, that the texture of the sediment efflux for all experiments with influxes of $0.4Q_s$ and higher would be identical to the sediment influx.

Table 3 Summary of textural variations as mass fractions of the sediment efflux for select experiments. For the Baseline and $0.2Q_s$ experiments, these mass fractions are averaged over time as noted. For all other experiments, these mass fractions are the final samples collected during the run.

<table>
<thead>
<tr>
<th>Run</th>
<th>Time (s)</th>
<th>Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Medium</td>
</tr>
<tr>
<td>Baseline</td>
<td>390-s average</td>
<td>0.07</td>
</tr>
<tr>
<td>$0.2Q_s$</td>
<td>170-s average</td>
<td>0.12</td>
</tr>
<tr>
<td>$0.4Q_s$</td>
<td>680</td>
<td>0.21</td>
</tr>
<tr>
<td>$0.6Q_s$</td>
<td>750</td>
<td>0.50</td>
</tr>
<tr>
<td>$0.8Q_s$</td>
<td>770</td>
<td>0.70</td>
</tr>
<tr>
<td>$1.0Q_s$</td>
<td>720</td>
<td>0.84</td>
</tr>
<tr>
<td>$1.2Q_s$</td>
<td>760</td>
<td>0.88</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

In upland concentrated flows within rills, crop furrows, and ephemeral gullies, the development and migration of headcuts can significantly increase soil losses and sediment yields, and greatly accelerate landscape degradation. Research has focused on quantifying the morphodynamics of soil erosion due to headcut migration on unconstrained hillslopes and agricultural fields. This study sought to examine the effect of upstream sediment inflow on the growth and migration of headcuts in concentrated flows. Clear-water experiments result in steady-state soil erosion wherein a headcut develops and enlarges due to the imposed flow rate, but attains a constant rate of migration, shape, and sediment discharge as a function of time. The size and migration rate of the headcut decreased markedly, as the sediment inflow rate of medium sand increased above a certain threshold, thus arresting local soil erosion. Sediment discharge, in turn, shifted from headcut-controlled flux to sediment-feed flux. The progressive obliteration of the headcut pool demonstrates that headcut migration is greatly modulated by upstream sand inflow, which renders inadequate the use of steady-state, algebraic models. Thus, more comprehensive headcut-erosion predictors are needed that treat this phenomenon as an initial, boundary-value problem solved with fast numerical engines.
ACKNOWLEDGEMENTS

Funding for this research was provided by the USDA-Agricultural Research Service and NSF (EAR0640617). We thank Antonia Smith and Don Seale for providing technical support.

REFERENCES


Römkens, M. J. M., K. Helming and S. N. Prasad (2001), Soil erosion under different rainfall intensities, surface roughness, and soil water regimes, Catena, 46, 103-123.


