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Monitoring channel head erosion processes in response to an artificially induced abrupt base level change using time-lapse photography

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ABSTRACT

Gullies that terminate at a vertical-wall are ubiquitous throughout arid and semiarid regions. Multi-year assessments of gully evolution and headcut advance are typically accomplished using traditional ground surveys and aerial photographs, with much recent research focused on integrating data collected at very high spatial resolutions using new techniques such as aerial surveys with blimps or kites and ground surveys with LiDar scanners. However, knowledge of specific processes that drive headcut advance is limited due to inadequate observation and documentation of flash floods and subsequent erosion that can occur at temporal resolutions not captured through repeat surveys. This paper presents a method for using very-high temporal resolution ground-based time-lapse photography to capture short-duration flash floods and gully head evolution in response. In 2004, a base level controlling concrete weir was removed from the outlet of a 1.29 ha semiarid headwater drainage on the Walnut Gulch Experimental Watershed in southeastern Arizona, USA. During the ten year period from 2004 to 2014 the headcut migrated upchannel a total of 14.5 m reducing the contributing area at the headwall by 9.5%. Beginning in July 2012, time-lapse photography was employed to observe event scale channel evolution dynamics. The most frequent erosion processes observed during three seasons of time-lapse photography were plunge pool erosion and mass wasting through sidewall or channel headwall slumping that occurred during summer months. Geomorphic change during the ten year period was dominated by a single piping event in August 2014 that advanced the channel head 7.4 m (51% of the overall advance) and removed 11.3 m^3 of sediment. High temporal resolution time-lapse photography was critical for identifying subsurface erosion processes, in the absence of time-lapse images piping would not have been identified as an erosion mechanism responsible for advancing the gully headwall at this site.

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1. Introduction

Incised, or gullied, channels that terminate at a vertical-wall are common features in semiarid watersheds. The geomorphic evolution of gullied channels is often dominated by migration of the headwall, and quantifying multi-year (Montgomery, 1999; DeLong et al., 2014) and multidecadal (Rieke-Zapp and Nichols, 2011; Frankl et al., 2012; Rengers and Tucker, 2014) rates of headcut advance has been the focus of many studies. Knowledge of long-term rates of headcut retreat have been useful for interpreting the effects of land use change (Trimble, 1999; Frankl et al., 2012) and in providing a basis for fundamental comparison among varying landscapes. However, long-term rates provide no information on erosion process dynamics and interactions with hydrologic drivers that are fundamental to furthering our understanding of semiarid geomorphic systems.

Gullies are an important sediment source in drylands, contributing between 50% and 80% of overall sediment production (Poesen et al., 2003). In the southwestern US, headcutting was shown to produce a significant portion of the total sediment load from a 200 ha watershed monitored for 20 years on the USDA-ARS Walnut Gulch Experimental Watershed (WGEW) (Osborn and Simanton, 1986). The sediment contribution from gully banks and headcuts in a discontinuous ephemeral gully system within which a sand bottom channel extends through a broad swale terminating at a near vertical headwall was estimated to be about 25% of the suspended sediment load sampled downstream from the headcut (Osborn and Simanton, 1986). In a more recent study of this gully system, retreat rate was found to be a function of drainage area and 30 min rainfall intensities above 25 mm h^{-1} (Rieke-Zapp and Nichols, 2011). At the spatial scale of approximately 10 ha within the WGEW, small gullied watersheds can produce up to three times the total sediment load as similar-sized nongullied watersheds (Osborn et al., 1976). A sediment budget developed for a 43.7 ha watershed within WGEW revealed that hillslope interfluve areas were the dominant source of sediment (Nichols et al., 2013); however, the authors acknowledged the lack of measurements to explicitly quantify channel process including bank sloughing and erosion. These studies point to the need for additional research to understand the processes involved in sediment production from channels.

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The mechanisms of channel head erosion are many and varied (Dietrich and Dunne, 1993). Plunge pool erosion and impinging jet scour followed by collapse play an important role in headcut migration (Alonso et al., 2002; Flores-Cervantes et al., 2006). Subsurface flow and seepage erosion play an important role in gully development and streambank failure (Dunne, 1990; Bryan and Jones, 1997; Faulkner, 2006), and piping has been identified as a factor in channel head development (Leopold and Miller, 1956; Parker, 1963; Fox and Wilson, 2010; Wilson, 2011). Other mechanisms of erosion include saturation slumping and mass failure of channel banks. When the shear strength of the bank is exceeded, rapid rotational slip (Alonso and Combs, 1990) can contribute large amounts of sediment directly to the channel. All of these erosion mechanisms are affected by topography, parent material, and soil characteristics. Although the regionally important mechanisms of channel erosion listed above have been the subject of a large body of research, these processes have not received much research attention on the WGEW.

Field data and observations describing event scale erosion dynamics in semiarid systems are rare; in large part because collecting data associated with infrequent and unpredictable runoff events is logistically difficult. Recent advances in sensor and datalogging technologies have made it possible to conduct field studies of event scale channel erosion dynamics (DeLong et al., 2014; Rengers and Tucker, 2014). As pointed out by Poesen et al. (2011) the significant interactions between gully erosion and hydrological processes need to be better understood for improving our predictions of hydrological response and land degradation rates under different environmental conditions. Field research is needed to determine modes of gully erosion and quantify relationships among precipitation, runoff, and geomorphic change.

Intensively instrumented low-order watersheds within the WGEW offer the opportunity to expand previous studies to quantify channel evolution (Osborn and Simanton, 1986, 1989) and watershed sediment yields (Nichols, 2006; Nearing et al., 2007) to include gully erosion process dynamics. Although understanding semiarid erosion processes has been a primary objective of research on the WGEW since its establishment in 1953, field research has focused on surface rill and interrill erosion process, primarily at the plot scale. Recent research based on tracer studies has expanded the scale of surface erosion to hillslopes and small watersheds (Nearing et al., 2005; Polyakov et al., 2009). Despite the wealth of erosion research on the WGEW, gully erosion processes have received limited attention. The objective of this study is to identify the dominant channel erosion processes and quantify short-term headcut and channel evolution in a low-order watershed within the WGEW.

2. Study site

This study was conducted from 2004 to 2014 in the Lucky Hills subwatersheds within the 150 km^2 WGEW in southeastern Arizona (Fig. 1). From 2004 through 2014, the linear rate of headcut advance was measured, and beginning in 2012, detailed storm event-based observations were made during three runoff seasons.

2.1. Climate, vegetation, and soils

The climate of southeastern Arizona is semiarid and mean annual precipitation measured on the WGEW for the 50 year period from 1956 to 2005 was approximately 312 mm (Goodrich et al., 2008). The precipitation distribution is bimodal with approximately 2/3 generated during the summer monsoon months (July to September) resulting from intense, convective thunderstorms, and the remaining 1/3 originating from less intense frontal storms during winter months. Almost all runoff on the WGEW is generated during summer months with occasional fall and winter runoff, and the main Walnut Gulch channel is dry 99% of the time. Channel runoff occurs in discrete, short duration flash floods lasting from minutes to hours with hydrographs characterized by a rapidly rising limb followed by a tapering recession.

Vegetation at Lucky Hills is dominated by shrubs including whitethorn Acacia [*Acacia constricta* Benth.], Tarbush [*Flourensia cernua* DC], and Creosote [*Larrea divaricata* Cav.] (King et al., 2008). A sparse understory of grasses and forbs is also found (Weltz et al., 1994). Locally, vegetation at the headcut site responds dynamically to monsoon precipitation and grass cover increases through the summer months with an associated reduction in bare soil. During the summer season canopy cover is approximately 25% with only minor amounts of litter on the ground. Although historically grazed, the Lucky Hills complex has been fenced to exclude grazing since 1963.

Soils on the watershed hillslopes are primarily gravelly sandy loams with approximately 39% gravel, 32% sand, 16% silt, and 13% clay and a high fraction (46%) of fragmented rocks (USDA, 2003). The parent material is mixed calcareous fan alluvium and the surface is generally rock covered. Soils are classified as Luckyhills-McNeal (very deep, well drained nearly level to strongly sloping, gravelly moderately coarse and moderately fine textured soils on fan terraces). Classifications for the Lucky Hills soils are coarse-loamy, mixed, thermic Ustic Haplocalcids and the McNeal soils are fine-loamy, mixed, thermic Ustic Calciargids. The gravelly loam layer covers coarse textured calcareous soils that show little soil profile development and an A horizon from 0 to 5 cm deep (USDA, 2003).

2.2. Geomorphic setting

The WGEW is located on an alluvial fan in the basin and range physiographic province in southeastern Arizona surrounding the town of Tombstone. The headwaters are located in the Dragoon Mountains to the east, and the generally westward draining watershed is tributary to the San Pedro River. The San Pedro River entrenched between 1890 and 1908 (Hereford, 1993) and currently, the channel network on the lower end of the WGEW is evolving in response to the resultant energy gradient (Osterkamp, 2008).

A distinct geologic feature of the WGEW is a fault that cuts through the watershed from south to north (Fig. 1). The fault line defines two landscape surfaces characterized by distinct erosional processes that have yielded geomorphic surfaces of varying ages and evolutionary stage (Osterkamp, 2008). The Whetstone Pediment lies to the east of the fault. The upper part of the Whetstone Pediment is characterized by a pattern of swales and headcuts typical of a discontinuous ephemeral stream pattern described by Bull (1997). Headcut migration rates in this area over a 70 year period range from 0.35 to 1.5 m year^{-1} (Rieke-Zapp and Nichols, 2011).

The lower, westerly, part of the Whetstone Pediment, called the Dissected Whetstone Pediment, and the Tombstone surface to the west of the fault on the lower end of the watershed, are characterized by a well-developed, incising channel network. Most of the sediment delivered from the WGEW is generated from the Dissected Whetstone Pediment and the Tombstone Surface (Graf, 1983).

In addition to topographic energy differentials, lithology exerts strong control on erosional processes. Within WGEW, the underlying geology imposes spatial control on channel network evolution. For example, in general, channels on the lower end of the watershed incise until they reach the underlying Emerald Gulch conglomerate which provides a base level that is resistant to erosion. Subsequent channel adjustment occurs as headward migration.

The study site and monitored headcut are located in the intensively monitored Lucky Hills (LH) subwatershed complex (Fig. 2) which is located on the Dissected Whetstone Pediment (Fig. 1). Between the measuring stations at LH101 and LH103, the watershed is drained by a well-defined channel network. The main stem and tributaries are continuous, single thread and incised with near vertical walls in some sections. The main channel bed consists of alluvial sediment ranging in size from sands to cobbles.