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Headcut retreat in a semiarid watershed in the southwestern United States since 1935

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ABSTRACT

Headcuts are prominent features in the southwestern United States. Within the Walnut Gulch Experimental Watershed (WGEW) survey data was available to quantify the retreat of the three most prominent headcuts in sub-watershed 63.011 from 1935 to 2006. The headcuts serve as major sediment sources and were investigated to identify and understand factors controlling retreat rate in this watershed. The data was incorporated and analyzed in a geographical information system (GIS). The headcuts have retreated persistently since 1935. A power relationship was fitted by regression ($R^2 = 0.89$) correlating the retreat rate with the product of contributing drainage area and areal precipitation for precipitation exceeding a threshold intensity ($I30 \geq 25$ mm hr^{-1}). This site specific relationship may not apply universally in other regions. Headcut retreat was not induced by external forcing. The autocyclic behavior of headcut retreat was found typical for the southwestern United States. The data did not allow timing or identification of initial causes for headcut retreat. Data suggests that all three headcuts will continue to retreat in the future, even though the retreat rate of one headcut was severely inhibited by exhumation a layer of cemented material, acting as local base level control. Most of the sediment eroded at the active headcut scarp was not transported very far, indicating that headcutting in this area results in local reworking rather than removal of material from the watershed.

1. Introduction

Gully erosion and associated headcut retreat contribute to both soil loss and sediment production in a variety of environments, contributing to as much as 94% of water driven sediment yield (Poesen et al., 2003). Laboratory and theoretical studies indicate that headcuts start out as little scarps in flow paths where plunge pool erosion initiates a gully (Bennett, 1999; De Ploey, 1989). Concentrated flow forms a channel, and the initial scarp evolves into a headcut (Flores-Cervantes et al., 2006) that defines the local upper limit of channel, or gully, incision. Gully erosion and headcut retreat will continue until the balance between forcing and resistance is re-established, which may take several years, decades, or even centuries, as in the case of arroyo development in the southwestern United States (Bull, 1997). The rate of retreat is thought to show negative-exponential trends (Graf, 1977). This is explained by the declining runoff-contributing area of the gully-head as it moves further away from its point of origin (Begin et al., 1980a, 1980b).

Throughout the southwestern United States, alternating sequences of channel incision leading to headcuts below unincised swales are common geomorphic features of the landscape (Bull, 1997). Their morphology and presence across a range of scales, from large arroyos in valley floors to small incised concentrated flow paths across alluvial fans, indicate disequilibrium conditions that dynamically adjust through cycles of erosion and aggradation (Bull, 1997). Discontinuous ephemeral streams in the semi-arid regions of the southwestern United States are sensitive to short-term as well as long-term environmental conditions (Bull, 1997). Short-term weather patterns and individual storm characteristics can cause significant channel and headcut erosion, while long-term changes in landscape morphology, caused for instance by active tectonics, can result in extended periods of aggradation or degradation.

The upper San Pedro River in southeastern Arizona exemplifies the episodic pattern of channel entrenchment and subsequent filling that is found in the geologic record of many channels in the southwestern United States. The most recent regional episode of accelerated gullying began in the 1880's (Hasting and Turner, 1965). Hereford (1993) investigated the entrenchment and widening of the upper San Pedro River and pointed out several possible causes for entrenchment during the turn of the 19th century and into the 20th century. Southeastern Arizona was disturbed by a high-intensity earthquake in 1887 that affected the existing channel system and might have preconditioned the channel network through disruption of the groundwater zone (Hereford, 1993). During the time of

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entrenchment, the climate of the Southwest was conducive to large floods. While no climate records are available for the Upper San Pedro River for that time span, work by Betancourt and Turner (1993) indicates that rainfall for Tucson (located approximately 90 miles NW of the Walnut Gulch Experimental Watershed) during the late 1800's was unusually high. Over-stocking and other human activity related to rapid settlement at the same time were coincident with entrenchment of the San Pedro River. These interacting factors resulted in entrenchment and widening of the upper San Pedro River, which has created a lower local base level for tributaries (Hereford, 1993). Valentin et al. (2005) expect that land use changes in general have greater impact than climate change on gully formation but in the case of the Upper San Pedro River the main gully erosion periods correspond not only to rapid land use changes, but also to higher frequency of high-intensity rainfall.

Walnut Gulch is an ephemeral tributary to the San Pedro River, and drains the Walnut Gulch Experimental Watershed (WGEW). Osborn and Simanton (1986) investigated gully headcut migration and associated sediment contributions at three headcut sites within watershed 63.011 (824 ha) on the WGEW. Topographic surveys conducted in 1966, 1973, 1976, 1981, and 1982 in combination with hydrologic simulation modeling were interpreted to estimate that as much as 25% of the suspended sediment load was contributed through headcut erosion. In addition, Osborn and Simanton (1986) concluded that gullied watersheds could produce up to three times the total sediment loads as similar sized non-gullied watersheds on the WGEW. The same headcuts on the WGEW have been remeasured and previous surveys have been digitized and combined with current data as well as information derived from aerial photographs taken in 1935. Only few studies have addressed the long-term (several decades) evolution of these erosional systems before. At the same time there is a need to identify appropriate measuring techniques for monitoring gully erosion over long periods of time at various temporal and spatial scales as well as to showcase the interaction of gully erosion processes with hydrological processes (Poesen et al., 2003; Valentin et al., 2005). The objectives of this study are to (i) quantify the temporal rate of the retreat of three headcuts over a 72 year period from 1935 through 2006, (ii) relate headcut retreat to hydrologic data and (iii) interpret headcut retreat with respect to local and regional geomorphic evolution.

Poesen et al. (2003) defined research needs regarding gully erosion research. This contribution will provide information to some of these research questions as it makes available long term data for headcut retreat in the particular setting and bases the analysis on a combination of aerial and terrestrial survey data with quite different spatial and temporal resolution.

2. Methods

2.1. Study site

The 149 km^2 Walnut Gulch Experimental Watershed (WGEW) in southeastern Arizona (Fig. 1) was established in 1953 to quantify rainfall, runoff, and sediment from semiarid, rangeland watersheds. The semiarid climate of this region is characterized by short duration, localized, convective rainstorms during the "monsoon season" from July through September (Nichols et al., 2002). Approximately two thirds of the annual total precipitation falls during these months. The channels on the WGEW are dry approximately 99% of the time and almost all channel runoff is the result of "monsoon season" precipitation (Stone et al., 2008). In addition to precipitation volume, the aerial coverage of storm precipitation with a 10 minute intensity of greater than 25 mm hr^{-1} has been found to be a reasonable predictor of runoff volume and peak runoff rate (Syed et al., 2002). Watershed size and shape, as well as channel characteristics (wetness, alluvium, etc.) also affect runoff, especially as partial area response associated with individual spatially localized storm cells.

The surface of the WGEW is comprised of fan deposits and Quaternary alluvium (Gilluly, 1956). Subwatershed 63.011 is located in the northeastern part of the WGEW (Fig. 1). Soils in the study site are generally well drained; soil texture ranges from very gravely fine sandy loams to gravely sandy loams (Breckenfield et al., 1995). Soils in depositional swales contain more silts and clays than the channel alluvium and the watershed uplands. In addition, the soil profiles within the swales contain cemented conglomerate layers at approximately 2–3 m deep. This layer is part of the locally named Gleeson Road Conglomerate deposit, which consists of poorly to well cemented alluvium (Osterkamp, 2008). The Gleeson Road Conglomerate ranges in thickness from relatively thick veneers overlying near-surface bedrock to thicknesses of at least 900 m in the north-central part of WGEW (Spangler, 1969). Because it is relatively resistant to erosion, exposed portions of the conglomerate act as local base level controls.

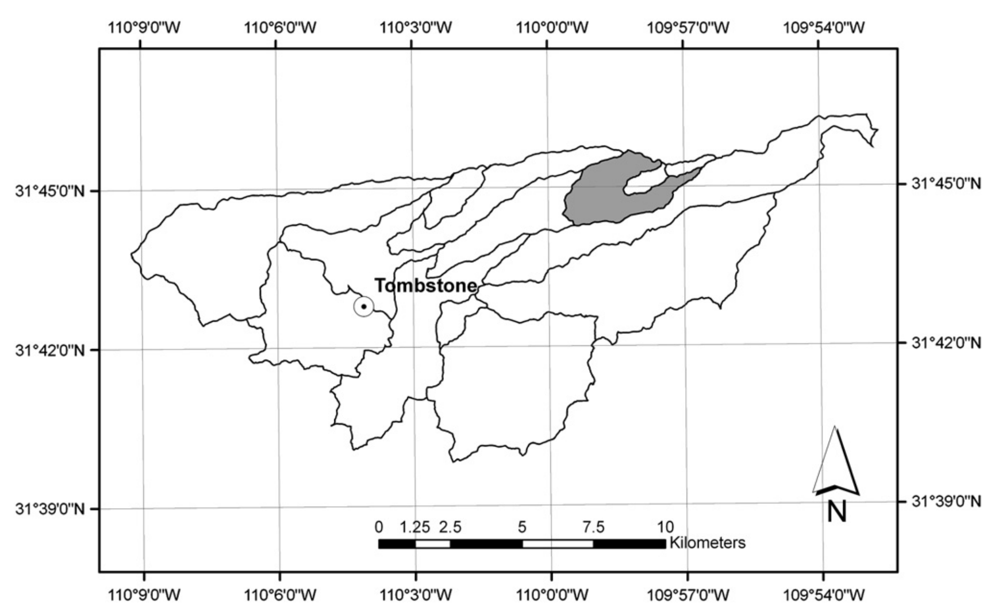

Fig. 1. Walnut Gulch Experimental Watershed with sub-watersheds. Watershed 63.011 marked in gray.

The watershed was used as rangeland since installation of the WGEW in 1953 and aerial photographs from 1935 indicate no significant changes in land use since that time. The most significant changes in this area was the installation of stock ponds 63.216 and 63.218 (Fig. 2) dating back to 1939 and 1940, respectively. The surface area of subwatershed 63.011 is covered by two distinct vegetation communities (King et al., 2008). The majority of the drainage area is dominated by grasses, including black grama (*Bouteloua eriopoda*), three-awn species (*Aristida* species), sideoats grama (*Bouteloua curtipendula*), and Lehmann lovegrass (*Eragrostis lehmanniana*). The remaining approximately 20% of the area is covered by desert shrubs such as whitethorn (*Acacia constricta*), mesquite (*Prosopis velutina*), Mormon tea (*Ephedra trifurca*), and Soaptree yucca (*Yucca eleta*), with relatively little or no grass.

2.2. Measurement methods

Watershed 63.011 has been instrumented since the 1960's to measure rainfall and runoff. Nine raingauges are distributed throughout 63.011 (Fig. 2). Runoff is measured with a concrete supercritical flume at the watershed outlet (Stone et al., 2008), which also acts as a local base level control. Watershed 63.011 can be divided further into three subwatersheds drained by the north, central, and south branches (Fig. 2). Each subwatershed contains one dominant headcut in the major flow path. The contributing drainage area for each headcut is marked in color in Fig. 2. All three headcuts are significant features in the landscape (Fig. 3). Two stock tanks located within the central subwatershed retain surface runoff. Although the exact date of construction is unknown, there is documentation indicating that pond 63.216 existed in 1939 and 63.218 existed in 1940. 18% of the watershed area drains into the stock tank. The trap efficiency of Pond 63.216 is 90% and there were 19 runoff events (out of a total of 199) that overflowed the tank from 1966 to 2003 (Nichols, 2004).

Datasets used to quantify headcut retreat are summarized in Table 1. The data sources exhibit a wide range of scales and were generated using a variety of surveying techniques, and were recorded in various formats (Table 1). The oldest data available to assess the headcuts date from 1935 in the form of aerial photos taken at a scale of approximately 1:30,000. These photographs were scanned and co-registered to recent ortho-imagery based on 16 to 20 homologous points identified in the images. The differences in image scale between old and new imagery as well as the lack of prominent landmark features in the landscape which were persistent over time, made it difficult to align the imagery precisely. Therefore, an individual fine adjustment of the imagery was undertaken for each headcut area. A local best fit solution was performed aligning the local drainage network derived from the 1 m DEM with the drainage network visible on the imagery. This adjustment also reduced scanning errors and image warping of the more than 70 year old paper copies. The alignment of the local drainage networks was within two to five meters. This shift also includes the adjustment of the drainage network within the last decades.

Headcut retreat was monitored in detail between 1966 and 1981 by Osborn and Simanton (1986) through ground surveys using a theodolite. These surveys were tied to benchmarks that provided horizontal and vertical control and centimeter level precision. Contour maps drafted from these data were digitized.

In 2004 the benchmarks used in previous ground surveys were recovered and the south and central headcuts were surveyed using large scale (1:2000) aerial photographs taken from a helicopter. The instantaneous field of view was approximately 18 mm on the ground per pixel. Ground control points were established using a differential GPS (Global Positioning System) with centimeter point coordinate precision. The same GPS equipment was employed in 2006 for a topographic survey the north headcut.

The resulting 1935–2006 data set was referenced to a common reference frame — North American Datum of 1983 (NAD83). Data were imported and processed with ESRI ArcGIS Version 9.3 to produce models of the 3-dimensional topography with centimeter to decimeter precision, with the exception of the 1935 data which were used to develop 2-dimensional planform descriptions of each headcut area.

Additional data, including a 1 m horizontal resolution Digital Elevation Model (DEM) created in 2003 from Light Detection and Ranging (LIDAR) data, were used to derive geomorphic features of the watersheds. Gaps in the LIDAR DEM covering the northeast corner of watershed 63.011 were filled using a 30 m DEM derived by the United States Geological Survey (USGS). The difference in resolution resulted in a topographic flattening effect for this area relative to the 1 m resolution DEM. This effect may have influenced some of the geomorphic parameters derived for the contributing drainage area of the northern headcut.

2.3. Data analyses

Headcut retreat was analyzed based on measured physical change and through regression analyses to determine the dominant controlling factors.

The planimetric extent of each headcut for different epochs was plotted (Fig. 4). Change in headcut position was measured along the calculated flow path derived from the LIDAR DEM with the Hydrology toolset of ArcGIS's Spatial Analyst extension. Rate of headcut retreat was calculated by dividing the linear change in headcut position by time.

The volume of sediment produced during each period of headcut retreat was calculated by differencing 3-dimensional models of the channel (Fig. 5). The most precise volume calculations were made

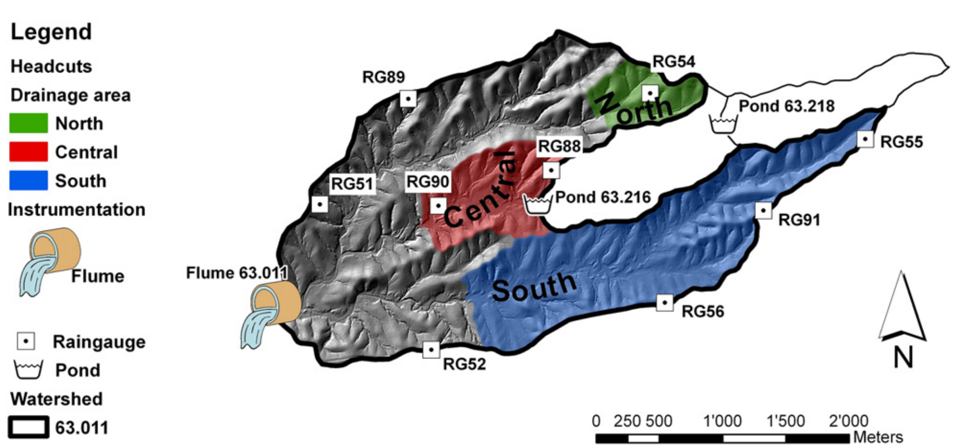

Fig. 2. Instrumentation of subwatershed 63.011.

Fig. 3. The three headcuts are significant features in the landscape.

where sequential surveys overlapped. Several of the surveys covered only the active area of headcut retreat thus limiting the extent of 3-dimensional modeling.

Table 1
Available data.

Year	Headcuts	Data	Record	Coordinates
1935	Central, South	Aerial photographs (1:30,000)	Paper copy	2d
1966	North, Central, South	Theodolite	Paper map	3d
1973	North, Central, South	Theodolite	Paper map	3d
1976	North, South	Theodolite	Paper map	3d
1981	South	Theodolite	Paper map	3d
2003	North, Central, South[a]	LIDAR DEM (1 m resolution)	Digital	3d
2004	Central, South	Aerial photographs (1:2000)	Digital	3d
2006	North	Differential GPS	Digital	3d

[a] The LIDAR DEM covers the whole Walnut Gulch watershed.

The 1 m resolution DEM was used to calculate topographic characteristics including channel profiles, drainage density and slope angles. A simple measure for drainage basin compactness was calculated according to Gravelius (1914). The compactness index is defined as the ratio between the length of the drainage area perimeter and the perimeter of a circle with the same area:

$$C = \frac{P}{2\sqrt{\pi A}} \quad (1)$$

where C is the compactness index, P and A denote perimeter and area of the drainage basin, respectively. The index is greater or equal to 1 and approaches unity when the basin approaches a circular shape.

Analysis of headcut retreat with respect to precipitation and runoff was limited to the time period from 1967 to 2006 when measurements were coincident. Areally distributed daily precipitation volumes and daily maximum 30 min rainfall intensity were determined for each of the three headcut watersheds based on Thiessen polygons (Syed et al., 2002) derived for each of the nine raingauges in watershed 63.011. In addition, these precipitation characteristics were determined for the portion of the internal watersheds above each of the three headcuts. Regression analyses were used to determine significant factors.

3. Results and discussion

3.1. Headcut retreat

All three headcuts have been present in the watershed at least for the period of observation. Although the active scarps each exhibited u-shaped forms, each headcut differed in size, retreat rate and contributing drainage area as well as in the upstream distance from flume 63.011.

Since 1935, the south, central, and north headcuts have retreated 105, 88, and 25 m, respectively, as measured along the channel flow centerlines. These values correspond to average annual retreat rates of 1.50, 1.26, and 0.35 m a^{-1} (Fig. 6) and are similar to the long term (1953–1993) retreat rates of 0.2 m a^{-1} for gully walls in northeastern Spain derived from aerial imagery by Martinez-Casanovas (2003). The retreat rates in the most active areas of Martinez-Casanovas' (2003) study can be an order of magnitude larger than the average and cover a similar range as the rates shown in Fig. 6. Marzolff and Ries (2007) investigated headcut retreat rates in semi-arid regions in Spain (0.07–0.51 m a^{-1}), Morocco (0–0.31 m a^{-1}) and the west-African Sahel (3.16–9.85 m a^{-1}). The headcuts observed in Spain also retreated in Holocene valley fillings and revealed similar retreat rates as the ones presented in the current study.

With respect to watershed area above each headcut, these retreat rates have resulted in small changes, ranging from <1% to 4%. An exception was the time period from 1973 to 2004 when the contributing area above the central headcut was reduced by 8%.

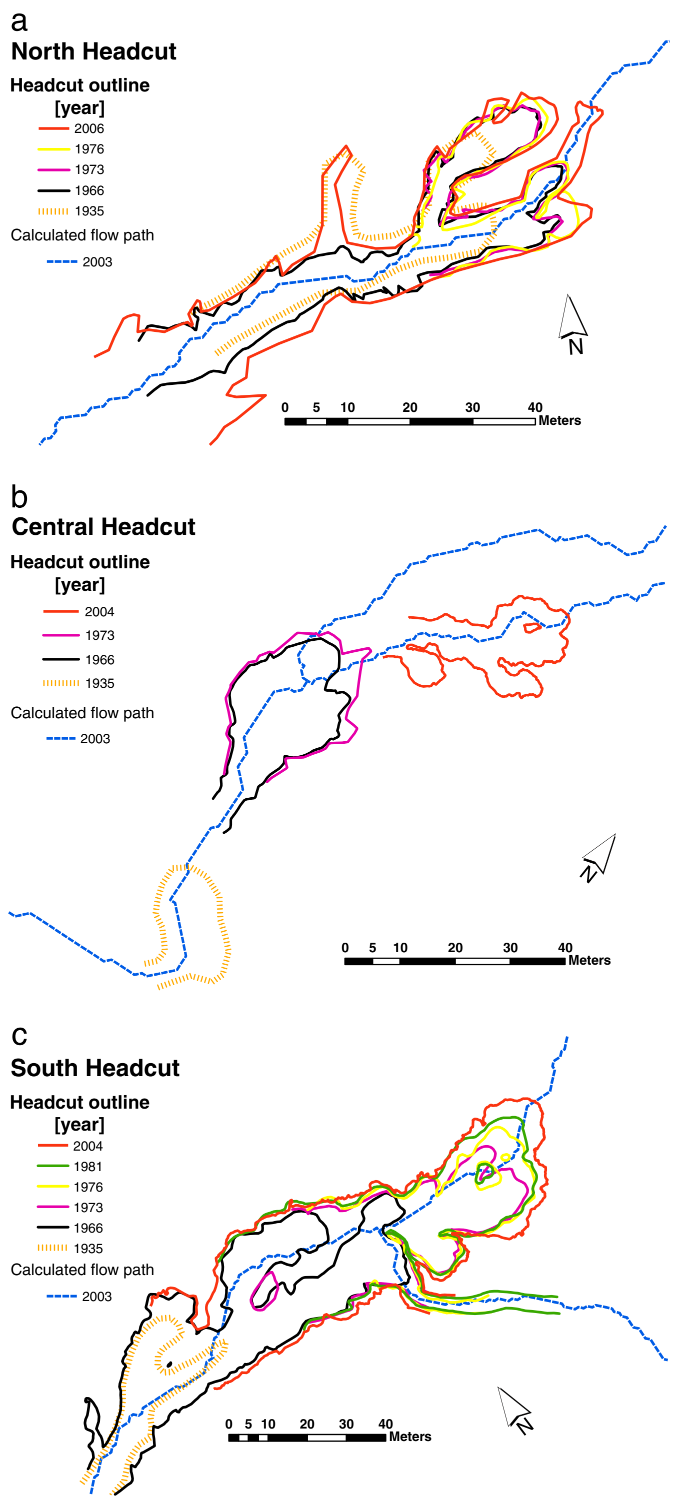

Fig. 4. a. Flow direction is from North East to South West. b. Flow direction is from North to South West. c. Flow direction is from East to West.

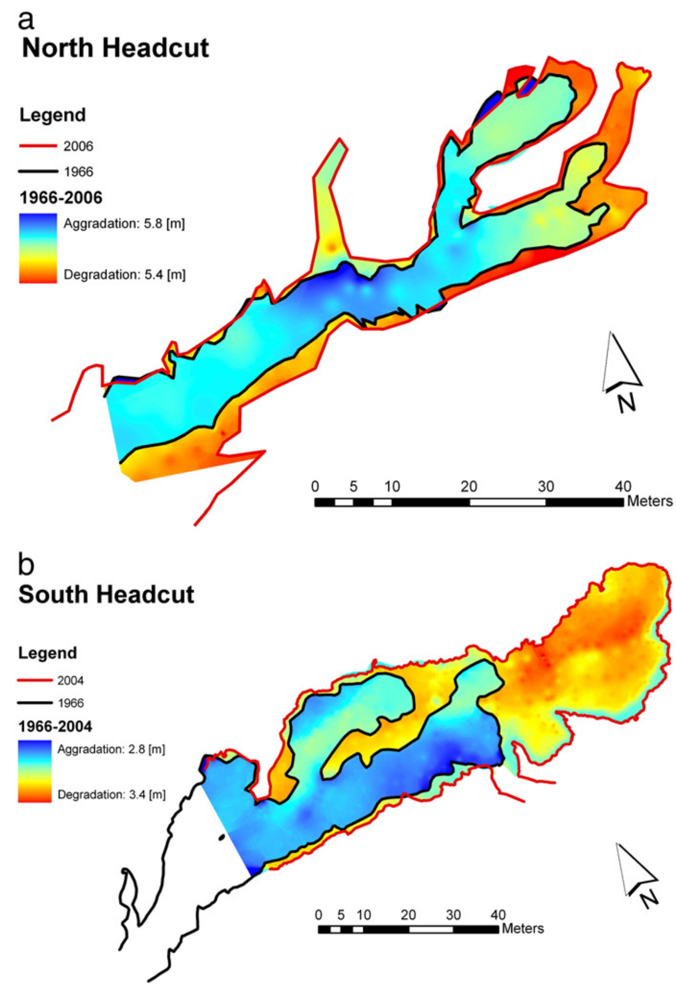

Fig. 5. a. Degradation: 925, Aggradation 498[m^3]. 54% of 925 m^3 was re-deposited in the overlapping area of the two DEMs. b. Aggradation 795 m^3. Degradation 2659 m^3. 30% of 2659 m^3 was re-deposited in the overlapping area of the two DEMs.

During this time period the central headcut retreated along the larger of two flowpaths and the smaller tributary was cut off (Fig. 4).

The central and south headcuts were each located at approximately 5300 and 6200 m upstream from flume 63.011 and are much closer to the flume than the north headcut, which was located approximately 9900 m from Flume 63.011 (Fig. 2, Table 3). The north headcut was located approximately 30 m higher in elevation than the other two headcuts (Fig. 7, Table 3).

Average channel slope from flume 63.011 was flat for all channels leading to the headcuts (Figs. 7 and 8). The central and south headcuts had similar slopes of 0.48% and 0.47%, respectively, the channel to the north headcut had less than 0.70% slope (Table 3, Fig. 7). The slope

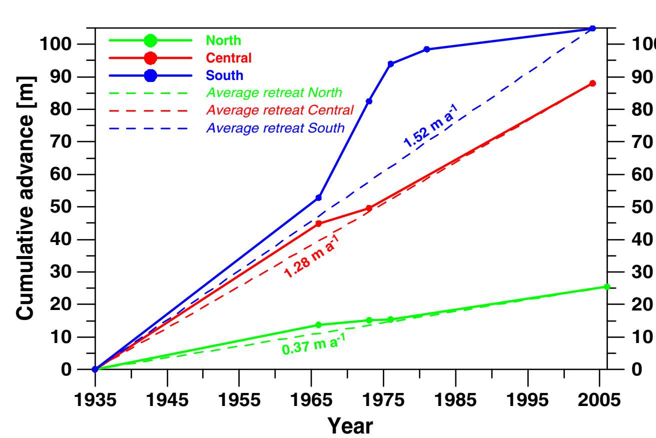

Fig. 6. Cumulative headcut advance and long term average since 1935 for all three headcuts. Based on measurements connecting the inlet of the 2003 drainage path in a straight line for consecutive years.

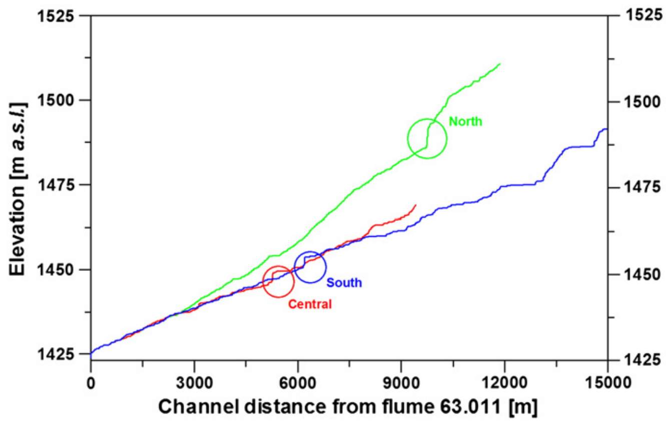

Fig. 7. Slope profile of the main channel from flume 63.011 for all three sub-watersheds. The location of the headcuts is marked with circles. Profiles include the longest 2nd order channel in upslope direction. Please note vertical exaggeration.

angle in the flow path of the areas above and below the headcuts was mostly marginal (Fig. 8) which is common to ephemeral streams developing in alluvial deposits with flat and marginal slopes (Fig. 8). Such conditions are well suited for persistent headcut retreat (Bull, 1997; Flores-Cervantes et al., 2006).

The shape of the south headcut watershed was more elongated with a compactness index of 1.7 as were the central or north (Table 3). Prior to the construction of pond 63.216, the shape and size of the central watershed were similar to the watershed containing the south headcut (Fig. 2).

Since 1935, the south headcut moved the greatest total distance at the fastest rate (105 m, Fig. 4c). Retreat rates increased rapidly between 1966 and 1981, before they decelerated to the present rate, which is much smaller than the long term average (Fig. 6). Although the overall average retreat rate is 1.52 m a^{-1} (Fig. 6), it had retreated from 1966 through 1973 at a rate of 3.7 m a^{-1} and then at a rate of 2.9 m a^{-1} through 1976. Since 1981 the retreat rate slowed to 0.4 m a^{-1} and thus similar to the long term retreat rate of the north headcut with 0.37 m a^{-1}.

The slow retreat rates of the south headcut since 1981 are most likely caused by exhumation of the Gleeson Road Conglomerate. This cemented conglomerate significantly inhibited plunge pool erosion and undercutting of the headcut scarp (Fig. 9). Accelerated retreat rates of up to 3.7 m a^{-1} were observed for the south headcut between 1966 and 1977 when the plunge pool was eroding in softer unconsolidated material. At today's position of the south headcut this soft material is exposed in the top 0.5 m of the headcut scarp (Fig. 9). From 1935 to 1966 south and central headcuts were retreating in softer alluvial material at a retreat rate of approximately 1.3 m a^{-1}. These observations suggest that headcut retreat in this area is to a large extent controlled by the cohesiveness of the underlying sediment layers rather than other factors. Similar observations were made previously in a flume study on concentrated flow erosion (Rieke-Zapp et al., 2007).

The north headcut has the smallest drainage area (Table 2) and experienced the smallest retreat rate among the three headcuts (Fig. 4a). The headcut is eroding in fairly cohesive material and exhibited the steepest walls of all three headcuts with a drop height of 3.0 m at present (Table 4, Fig. 3a). Between 1976 and present the north headcut retreated along the major flow line by approximately 9 m. The average annual retreat rate between 1935 and 2006 was relatively constant with a rate of 0.37 m a^{-1} based on five data points (Fig. 6). Drainage density within the north headcut watershed was 0.0063 m m^{-2} and thus smaller than for the other headcut watersheds as well as the entire 63.011 watershed (Table 3). While the north headcut did not retreat as rapidly as the south or central headcuts (Fig. 6.), a considerable amount of material was mobilized by downcutting. The drop height of the north headcut has increased between 1966 and 2006 from 2.35 to 3 m (Table 4). It appeared that removal of material in the plunge pool created below the headwall was the dominant process in the recent evolution of this headcut resulting in an increase in height of 0.65 m over the last 40 years. The cohesiveness of the material resulted in steep and stable walls and allowed only moderate retreat of the headcut in general. The cemented material was mapped by Osterkamp (2008) as part of the Gleeson Road Conglomerate locally covered by Alluvial material from the late Holocene.

The central headcut retreated 3.5 times as far as the north headcut since 1935. The drop height of the central headcut decreased steadily with time (Table 4) and was continuously adjusting with local topography. The current drop height at the active front was 1.1 m (Table 4, Fig. 3b). This was approximately half the drop height of the south and only one third the drop height of the north headcut. Although the pond within the central headcut watershed cuts off runoff from more than half of the overall watershed, this appeared to have had only little influence on headcut dynamics. The central headcut retreated at a fairly constant rate of 1.28 m a^{-1} from 1935 to present. This suggested that although surface runoff was the primary driver of headcut erosion, the retreat rate was also controlled by fairly homogenous soil characteristics and stratigraphy. The shape of the active scarp remained concave between 1935 and 2004 which is typical for headcuts in this region (Fig. 4b).

3.2. Sediment budget

Headcut retreat both reshaped the surface of the drainage basin and contributed to sediment supply (Fig. 5). Although Osborn and Simanton (1986) estimated that approximately 25% of the total

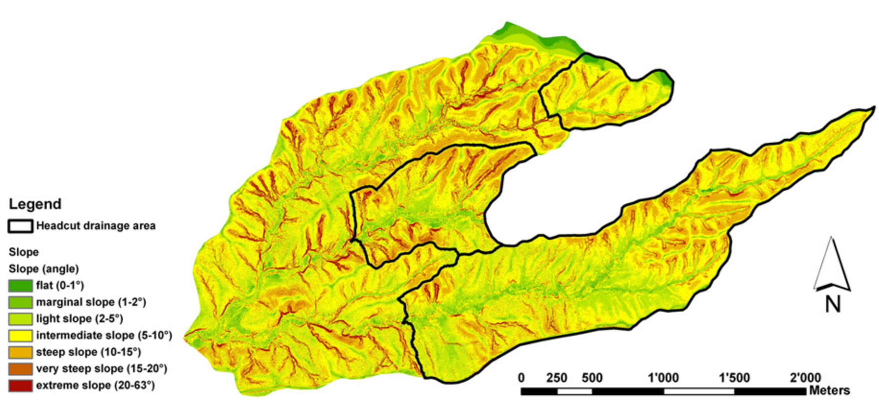

Fig. 8. Slope calculation based on 1 m DEM data. The DEM was filled from the 30 m USGS DEM in the North.

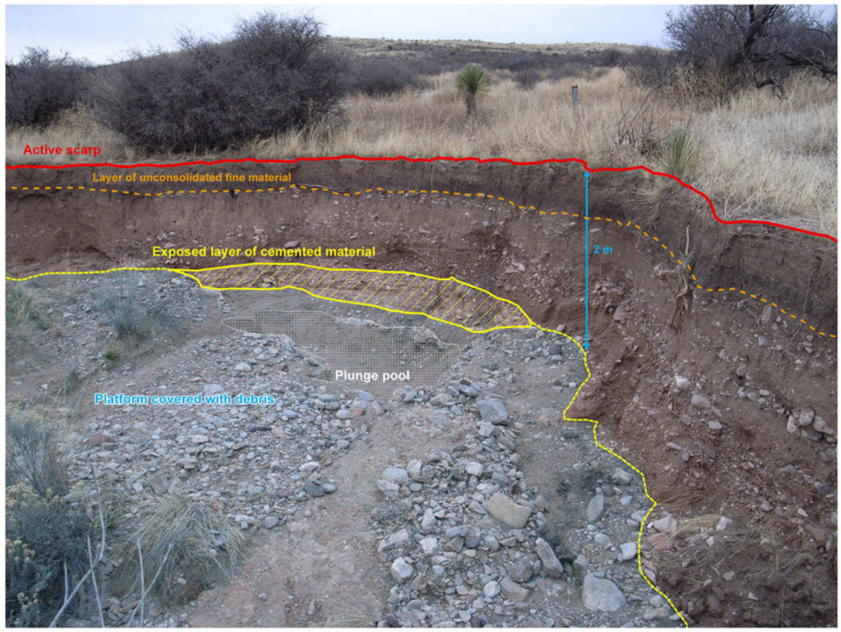

Fig. 9. The plunge pool area of the South headcut exposed cemented conglomerates. This slowed down the advance rate severely since 1981.

sediment load of sub-watershed 63.011 was produced by headcutting, expression of the growth rate in terms of area or volume for the headcuts was difficult even when 3d coordinate data were collected. The surveys often covered only the active area of the headcut at the time of the survey, and did not include areas surrounding the headcut that were formerly active or were to become active area at a later time. This problem was most obvious for the central headcut, where the areas mapped for 1935 and for 2004 did not overlap with the surveys of 1966 or 1973 (Fig. 4b). A partial comparison was possible for the south and the north headcuts, plotting the differences between 1966 and 2004/06 (Fig. 5). Comparing the volumetric changes between 1966 and present for the overlapping area of the surveys of the north and the south headcut (Fig. 5a and b) showed that 54 and 30% of the detached material were aggraded at a distance of approximately 80 and 120 m, respectively, from the presently active front. The re-deposition areas were not limited to the overlapping areas of the surveys. Field observations suggested that not only in case of the north headcut, but also for the south and central headcut, most of the sediment was re-deposited just below the active scarp of the headcut rather than being immediately routed through the channel network. Limited transport capacity therefore resulted in sediment storage within the main channel, thus forming flat to marginally flat slope angles in most parts of the major flow paths (Fig. 8).

Poesen et al. (2003) report on soil loss production by gullies and the importance of permanent gullies in a catchment's sediment budget along with causal off-site effects. The headcuts presented here are also important sources of sediment, but material from the present three headcuts is transported only over short distances and remains within the watershed which is typical for headcuts in semi-arid environments (Bull, 1997). Storage of mobilized sediment within the watershed will allow for a continuous release of sediment within the watershed over decades even if the actual production may diminish over time (Gomez et al., 2003).

3.3. Rainfall and runoff

From 1956 through 2006 there were 320 runoff events recorded at Flume 63.011 with a long term average annual runoff of 8.75 mm and an average annual event maximum of 75.84 mm. Average annual rainfall from 1966 through 2006 was 324, 311, and 318 mm over the north, central, and south headcut watersheds. In the absence of event specific runoff measurements at each headcut, and with the established relation between rainfall and runoff for events with an intensity of 25 mm hr^{-1} (Syed et al., 2002) and between runoff and watershed area on WGEW (Boughton and Stone, 1985; Murphey et al., 1977), event rainfall characteristics were related to headcut retreat to test for significant relationships. A power relationship was fitted by regression correlating areal precipitation and headcut retreat:

$$Y = x^{1.424} \cdot 6.466E{-}009 \qquad (2)$$

$$R^2 = 0.89$$

where Y represents the linear retreat (m) for a given measurement interval and x the product of cumulative areal precipitation and contributing drainage area in the same time interval. Regression analyses revealed a significant relation between these variables, with

Table 2
Contributing drainage area since 1935.

Headcut	Drainage area [ha]				Drainage area change [%]		
	2004/06	1973	1966	1935	1973 to 2004/06	1966 to 1973	1935 to 1966
North	32.96	32.98	32.99	33.84	0%	0%	1%
Central	66.94	71.84	72.25	72.62/222.98[a]	8%	1%	1%/67%[a]
South	207.37	208.27	213.35	214.36	4%	2%	0%

1973 and 1966 Central and South still have a side branch that is disconnected in 2004/06.
[a] A sediment retention pond (63.216 in Fig. 2) reduced the size of the contributing watershed after 1935 cutting off 150.36 ha upstream area.

Table 3
Characteristics of headcut watersheds.

Headcut	Distance from flume 63.011 [m][a]	Drainage density [m m^{-2}]	Average slope [°]	Headcut elevation [m]	Compactness index
North	9852	0.0063	7.2	1493	1.25
Central	5292	0.0080	9.0	1449	1.46
South	6194	0.0073	7.4	1453	1.72

[a] Distance from flume as measured along the channel from the 1 m DEM data.

the exception of one outlier (Fig. 10). This outlier can be explained by the exhumation of the Gleeson Road Conglomerate, which prevented plunge pool erosion and thus mass wasting at the scarp of the headcuts: Between 1981 and 2004 the south headcut retreated therefore only 6.4 m, although there were 57 high intensity rainfall events. Based on the regression relationship, a retreat of 135 m would be expected for the south headcut in this time period (Fig. 10). The regression does not take into account any lithologic differences in the three subwatersheds. Results are site specific and may not represent a universal relationship.

Between 1966 and 2006 a total of 276 rainfall events with $I30 \geq 25$ mm hr^{-1} were recorded. The average number of events for all observation intervals of headcut retreat ranged between 6.8 and 7.6 events per year. The 41 year average was 6.7 events per year. These numbers indicate little variation in intense rainfall events over the last 41 years. There was almost perfect correlation ($R^2 = 0.98$) between the number of rainfall events with $I30 \geq 25$ mm hr^{-1} and total precipitation fitting a linear regression model with no outlier removed. This also implies that the number of high intensity events could be used as proxy for cumulative areal precipitation in this watershed where the precipitation pattern is dominated by high intensity thunderstorms.

Plotting headcut retreat rate versus contributing drainage area or versus areal precipitation alone revealed only much weaker correlation ($R^2 \leq 0.15$). Treating single points as outliers the R^2 value increases up to 0.4.

3.4. Headcut initiation

The specific cause of headcut initiation is unknown, although it is likely that the current erosion and sedimentation dynamics on Walnut Gulch were a response to a complex interaction of several factors. Lowering of the ground water table, increased land use and grazing pressure reduced vegetation at the turn of the century when Tombstone was an active mining town (Bahre, 1991; Dobyns, 1981), and undoubtedly local fluctuations in precipitation and runoff patterns have been important (Hereford, 1993). There are several hypothesized causal factors that have been proposed for the initiation of these headcuts, including response to entrenchment in the San Pedro River during the late 1800's (Hereford, 1993). Although this entrenchment created a lower regional base level, the distance of the headcuts from the San Pedro River (approximately 19 km to the position of the headcuts in 1935) is too far to suggest connectivity between headcuts retreat and San Pedro River entrenchment. Although work by Nachtergaele et al. (2002) suggests that headcuts typically retreat at very large rates after initiation and that rates decline very rapidly over time, attaining soon a more or less constant rate, there is no field evidence that headcuts initiated from a base level change of the San Pedro River.

Table 4
Average dropping height at active front in m.

Year	Headcut		
	North	Central	South
1966	2.35	1.52	1.37
1973	2.74	1.46	1.68
1976	–/–	–/–	1.68
1981	–/–	–/–	1.89
2004/06	3.00	1.10	2.00

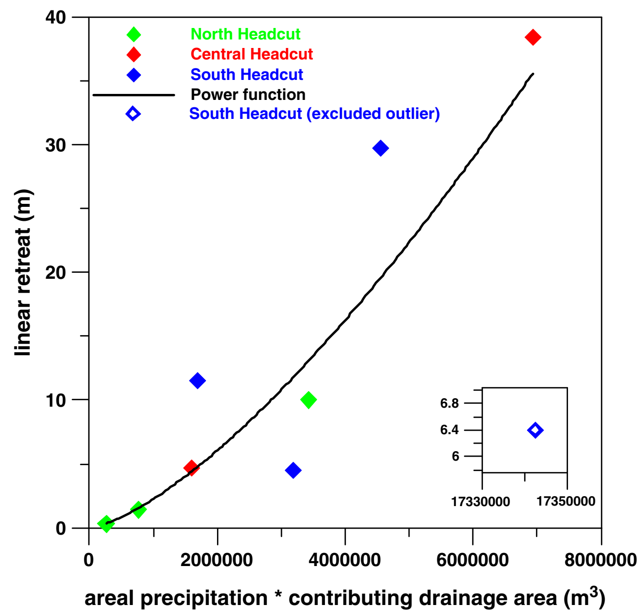

Fig. 10. Regression analysis of headcut retreat plotting the product of contributing drainage area and areal precipitation versus linear retreat rate.

All three headcuts were present on the landscape in 1935, prior to installment of flume 63.011 or ponds 63.216 and 63.218, meaning that the flume did not impose a base level control during the initiation of the headcuts. No signs of tectonic forcing on the drainage network were found in the landscape.

It is more likely that the headcuts were the result of autocyclic processes acting within the watershed. Human activity and overgrazing may have initiated or accelerated headcut development and retreat. Hereford (1993) reports that large floods resulted in a lowering of the base level of the Upper San Pedro River between 1881 and approximately 1900. The three headcuts were in place in 1935 and probably even earlier. So, it is likely that they developed during this period of instability even though it is not clear when the alluvial material started filling the swales and when exactly headcut retreat may have started. Radiocarbon or luminescence dating (Ballarini et al., 2003; von Blanckenburg, 2005) may be applied to date the recent sedimentation history within the watershed for determining times and rates of accelerated erosion.

The three headcuts show the typical characteristics of discontinuous ephemeral channels in semi-arid environments (Bull, 1997). Headcuts probably formed due to the combined effects of intense precipitation events followed by high velocity runoff and physical variations in the substrate under the flow paths. The resulting concentrated flow acting on lithologically weaker soils created knickpoints on the landscape that ultimately evolved to their current state (Bull, 1997). This idea was further supported by the presence of several smaller headcuts leading to incised channels that lose their definition as they approach the swales above the subject headcuts within each of the three watersheds (Fig. 8). The three discussed headcuts were the most prominent and persistent among many headcuts in this watershed.

In general, there was little lateral expansion and development of incised tributaries. Observations by Flores-Cervantes et al. (2006)

would suggest that this lack of lateral expansion is indicative for the continuing persistence of the headcuts. The headcuts retreated in alluvial material with flat to light slopes (Fig. 8). The alluvial material originated from side tributaries. Accumulation of material suggested a transport limited sediment routing systems in the major flow path of the watershed above the headcuts. These conditions are well suited for persistent headcut retreat (Flores-Cervantes et al., 2006). The mobilized sediment from the walls was removed by runoff after intense rainfall events in semi arid region similar to field observation by Bull (1997) or Martinez-Casanovas (2003). In sub-humid regions collapse of gully side walls or anthropogenic interaction can lead to a relatively quick infilling of gullies (Vanwalleghem et al., 2005).

The side tributaries of the Walnut Gulch headcuts reveal steeper slope angles than found in the area downstream of the headcuts. They have developed incised channels that become wider and flatter when reaching the major flow path. Some of the side tributaries were backfilled with sediment indicating that the site tributaries are not at equilibrium with the main channel. The headcut areas are not infilled with sediment by the site tributaries as runoff from intense rainfall events running over the headcut scarp continuously removes sediment in this area. While north and south headcut increased their dropping height since 1966 (Table 4) only the central headcut lost height and may be the first of the three to adjust with local topography. All the observations mentioned above indicate that all three headcuts will remain significant features in the landscape in the near future.

4. Conclusions

Several data sources were combined in a GIS system to quantify the retreat rate of three headcuts in watershed 63.011 over a 72 year period. A power function was fitted by regression analysis correlating retreat rate with the product of contributing drainage area and cumulative areal precipitation ($R^2 = 0.89$) for intense rainfall events (I30 larger than 25 mm hr^{-1}). The number of intense rainfall events could be used as proxy for total precipitation. The regression relationship reflects site specific conditions and may not represent a universal relationship for headcut retreat. Relating the retreat of all three headcuts to contributing drainage area or high intensity precipitation alone resulted in much weaker correlations. All headcuts retreated in alluvial material with flat slope angles. Current observations suggest that the headcuts will continue to retreat in the near future. The rate of retreat will be different for each headcut and is controlled by the local base level, in case of the south headcut namely the Gleeson Road Conglomerate. Most sediment produced by the process of headcut retreat was not immediately carried out of the watershed, but deposited just downstream of the active scarp. This process is typical for discontinuous ephemeral streams in this area and provides for little off-site impact by the mobilized sediment. No external forcing was identified thus indicating autocyclic behavior of the headcuts in the watershed.

While the compilation of several data sources in a GIS based dataset allowed calculation of retreat rate, contributing drainage area and other parameters, more research will be needed to identify the cause for headcut retreat as well as the time frame when headcut retreat started and when the alluvial material was deposited. Application of dating methods on outcrops of alluvial material may help to define when the material was deposited and also provide information when deposition stopped and when headcut development was initiated.

The precipitation regime of this area is shaped by isolated thunderstorms with high intensity rainfall. More frequent surveying of the headcuts, i.e. on seasonal or annual basis, would allow studying the short term effect of changes in precipitation on headcut retreat. In order to include wetter and drier years such a survey would need to include data from five to ten years of observation.

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