Gullying and erosion control at archaeological sites in Grand Canyon, Arizona

Joel L. Pederson1*, Paul A. Petersen1,2 and Jennifer L. Dierker3
1 Department of Geology, Utah State University, Logan, UT 84322, USA
2 Present address: GeoGraphics, Inc., Logan, UT 84321, USA
3 Grand Canyon National Park, Flagstaff, AZ 86001, USA

Abstract
Gully erosion of cultural sites in Grand Canyon National Park is an urgent management problem that has intensified in recent decades, potentially related to the effects of Glen Canyon Dam. We studied 25 gullies at nine sites in Grand Canyon over the 2002 monsoon–erosion season to better understand the geomorphology of the gully erosion and the effectiveness of erosion-control structures (ECS) installed by the park under the direction of the Zuni Conservation Program. Field results indicate that Hortonian overland flow leads to concentrated flow in gullies and erosion focused at knickpoints along channels as well as at gully heads. Though groundcover type, soil shear strength and permeability vary systematically across catchments, gradient and, to a lesser degree, contributing drainage area seem to be the first-order controls on gully extent, location of new knickpoints, and ECS damage. The installed ECS do reduce erosion relative to reaches without them and initial data suggest woody checkdams are preferable to rock linings, but maintenance is essential because damaged structures can exacerbate erosion.

Topographic data from intensive field surveys and detailed photogrammetry provide slope–contributing area data for gully heads that have a trend consistent with previous empirical and theoretical formulations from a variety of landscapes. The same scaling holds below gully heads for knickpoint and ECS topographic data, with threshold coefficients the lowest for gully heads, slightly higher for knickpoints, and notably higher for damaged ECS. These topographic thresholds were used with 10-cm digital elevation models to create simple predictive models for gully extent and structure damage. The model predictions accounted for the observed gullies but there are also many false-positives. Purely topographical models are probably inadequate at this scale and application, but models that also parameterize the variable soil properties across sites would be useful for predicting erosion problems and ECS failure.

Copyright © 2006 John Wiley & Sons, Ltd.

Keywords: gully; checkdam; slope–area threshold; Grand Canyon

Introduction

Gullies are watercourses marked by steep channel walls, a stepped longitudinal profile, and commonly an abrupt channel head. Though they exist in many settings, they are prevalent in drylands and are often considered a signal of disturbance and accelerated erosion brought about by climate or land-use change. Erosion by gullies can be an acute problem causing high sediment yield, removal of fertile soil, destabilization of hillslopes, and the lowering of water tables in alluvial aquifers (e.g. Patton and Schumm, 1975; Karlstrom, 1988; Bull, 1997; Elliott et al., 1999). Though extensively studied in agricultural settings, there are few quantitative data for gullies in natural landscapes and modelling of the numerous gullying processes is a recent endeavour (e.g. Montgomery and Dietrich 1994; Bennett et al., 2000; Casali et al., 2003; Istanbulluoglu et al., 2003; Kirkby et al., 2003). The need to understand how to monitor and prevent gullying is particularly acute (Poesen et al., 2003), and the search for inexpensive, durable, low maintenance techniques to control gully erosion has proven elusive (Heede, 1966; Gellis et al., 1995; Norton et al., 2002).

Copyright © 2006 John Wiley & Sons, Ltd.
Many cultural sites that lie along the Colorado River corridor of Grand Canyon National Park are being eroded by gullies (Hereford et al., 1993; Fairley et al., 1994), and erosion-control structures (ECS) have been installed to reduce or slow erosion and protect National Register-eligible properties. Understanding this erosion and the success of erosion-control efforts is important both for protecting cultural resources and for identifying the causes of increased gullying, which potentially include the operations of Glen Canyon Dam (Hereford et al., 1993; Fairley et al., 1994; Thompson and Potochnik, 2000). In this study, we used intensive ground-based surveys and field geomorphic data to identify gullying processes and erosion trends at nine sites during 2002. In addition, we used very detailed terrain models from aerial photogrammetry to perform an erosion-threshold analysis. Our objectives are to better understand and quantify gully erosion in Grand Canyon and provide the first evaluation of the effectiveness of installed ECS at slowing erosion and staying intact.

Background

Setting

The gullies of interest in Grand Canyon form along the Colorado River corridor on a suite of Holocene stream terraces underlain by sandy alluvium, aeolian sand, or gravelly colluvium at the toes of hillslopes. Hereford et al. (1993, 1996) studied the Holocene alluvial stratigraphy of the river corridor and found that most cultural sites are located in middle–late Holocene deposits they called the ‘alluvium of Pueblo II age’ and the ‘striped alluvium’ (Figure 1). These deposits generally have not been inundated by historic unregulated (pre-dam) flows of the Colorado River, but have been modified by aeolian processes. Gullies commonly extend below the older prehistoric terraces associated with cultural sites to younger prehistoric and historic sandy flood deposits, and may terminate on any of the terraces, in side-canyon washes, or the Colorado River itself.

Climate and the precipitation that drives erosion vary strongly with elevation in this setting. Mean annual precipitation (MAP) is 647 mm and mean annual temperature (MAT) is 6·3 °C at the north rim of the canyon, whereas MAP is 213 mm and MAT 20·4 °C at Phantom Ranch at the bottom of the canyon, which is more representative of the study sites. The southwestern monsoon, typically between 15 June and 15 October, provides about half of Grand Canyon’s yearly rainfall (Western Regional Climate Center data). Most overland flow and flood events in the region are initiated during this time through intense, isolated thunderstorms (Hereford and Webb, 1992), but some of the largest runoff events have occurred during long-duration, lower-intensity, late autumn or winter storms (Griffiths et al., 1996).

The study gullies range from c. 20–200 m in thalweg length, and from c. 0·2–2·5 m in channel-top width. The gullies can have either gradual or abrupt channel heads and are discontinuous, typically with several knickpoints and plungepools along the course of the channel. Field observations indicate erosion is primarily the result of infiltration-excess (Hortonian) overland flow becoming focused into gullies and soil detachment by tractive forces, and it is not typically influenced by piping or seepage (Petersen, 2003). Erosion is associated with both knickpoint retreat and channel widening from bank undercutting and failure. These processes are common in actively eroding semi-arid to arid
landscapes such as Grand Canyon that feature infrequent, high-intensity precipitation events, low vegetation density, and bedrock exposure.

**Previous work on Grand Canyon gullies**

Professional archaeologists began formal documentation of cultural sites along the Colorado River corridor in Grand Canyon in the early 1950s, and the first recognition that archaeological sites were undergoing gully erosion came during regular monitoring following an unexpected 1983 flood release from Glen Canyon Dam (Hereford et al., 1991). An archaeological inventory along the Colorado River corridor completed in May 1991 produced an evaluation of site conditions and impacts, including gully erosion (Fairley et al., 1994), and regular monitoring has documented the ongoing erosion of cultural sites along the river corridor (e.g. Leap et al., 1996).

Although erosion is an expected part of larger cycles of aggradation and degradation in the southwestern USA, studies have shown that gully incision in Grand Canyon increased between 1973 and 1984 (Hereford et al., 1993; Thompson and Potochnik, 2000). Hereford et al. (1993) recognized that a period of more intense precipitation from the late 1970s through the 1990s may have driven the accelerated erosion. But these studies also raised the idea that increased erosion is linked to Glen Canyon Dam, which altered base level for some gullies and started controlling the hydrograph of the Colorado River in 1963. Flooding of the Colorado River in the pre-dam era filled in the mouths of gullies near the river, and the lack of flooding in post-dam time has hypothetically allowed some gullies to reach a base level at the river more consistently. Though these studies document increased gully erosion, its causes are still debated and determining the cause is not a goal of this study. Instead our first step is to quantify and understand the erosion itself.

Regardless of cause, it was determined that some form of preservation treatment was required, and a panel of specialists, tribal members, and federal agency representatives decided that checkdams would be constructed under the supervision of the Zuni Conservation Program. Since September 1995, these erosion-control structures have been monitored and maintained at 29 different sites. The current ECS in Grand Canyon range from rock and brush channel linings and water-diversion structures to discreet checkdams of woody debris, but the majority are rock linings. Many of these rock linings were originally constructed as larger rock and rock-and-brush checkdams, but after maintenance were rebuilt into rock linings to armour the channel and hopefully prevent loss of channel and bank material (Dierker et al., 2002). ECS in Grand Canyon have the goal of stabilizing existing drainages, preventing drainage growth, and capturing sediment transported downstream during runoff events (Dierker et al., 2002).

**Erosion-control methods applied elsewhere**

Many attempts have been made globally to control gully erosion by building checkdams of concrete, stone or wood (Heede, 1976). The erosion to be controlled occurs when driving forces of gradient ($S$) and flow depth ($h$) exceed resisting forces of the effective weight and cohesion of sediment:

$$\rho ghS > \theta g (\rho_s - \rho) D$$

(1)

where $\rho$ is fluid density, $\rho_s$ sediment density, $g$ the gravity constant, $D$ the grain diameter, and Shield’s parameter $\theta$ is approximated at 0·045. The general purpose of checkdams is to dissipate flow energy and locally reduce flow depth and channel gradient, thereby decreasing the boundary shear stress at the left of Equation 1. In other words, eroding gullies have a gradient higher than is stable under the current flow regime, and checkdams are an attempt to locally reduce and stabilize channel gradients. The number and height of checkdams needed for engineered erosion control depends on the gradient at which the drainage would be stable (ungullied), as a function of the sediment size, cohesion, channel hydraulic geometry, infiltration, and flow turbulence (e.g. Kaetz and Rich, 1939; Hack, 1957). A couple of studies indicate this lower equilibrium gradient is typically c. 70 per cent that of the gullied channel (Woolhiser and Lenz, 1965; Heede, 1976). The lower equilibrium gradient attained above checkdams causes the influence of the trapped sediment to extend only a limited distance upstream (Kaetz and Rich, 1939; Leopold and Bull, 1979). Given time, checkdams are often bypassed or undercut, and it is important to recognize that they are not intended to remedy the basic cause of gully erosion.

There are few previous studies that evaluate the ECS types emplaced in Grand Canyon, especially rock linings. Fischenich (2001) noted that armouring by rock can cause local scour where flow is constricted and of higher velocity between clasts, and the effects of armouring are not expected to influence the area beyond the structure itself. ECS made of brush are used in some places with success, including on Zuni tribal lands of the southwestern USA Gellis et al. (1995) and Norton et al. (2002) noted that such brush checkdams were relatively effective in trapping sediment
and staying intact, probably because their high permeability and roughness dissipate the power of flows and allow greater time for infiltration (Norton et al., 2002).

**Topographic erosion thresholds**

Schumm and Hadley (1957) recognized that for a given drainage area there is a critical gradient associated with gully erosion. Relating back to Equation 1, this topographic threshold is presumably where overland flow is of sufficient depth and velocity to exceed a critical shear stress of soil detachment. The inverse relation between this threshold gradient and contributing drainage area below diffusion-dominated upper hillslopes has been used to characterize and model gully initiation by both saturation and infiltration-excess overland flow (e.g. Patton and Schumm, 1975; Thorne et al., 1986; Montgomery and Dietrich, 1989, 1994; Vandaele et al., 1996; Woodward, 1999; Istanbulluoglu et al., 2002; Kirkby et al., 2003). Upslope contributing area is used as a proxy for discharge, assuming that discharge ($Q$) increases downslope proportional to increasing catchment area:

$$Q = (p - I)A$$

(2)

where $p$ is precipitation, $I$ infiltration, and $A$ contributing area for the case of Hortonian overland flow. Using topographic thresholds to predict erosion is attractive for land management due to their simplicity and the increasing availability of digital elevation data. Most studies have focused on soil-mantled landscapes and agricultural fields in relatively moist climates, though they still range across a variety of settings and scales (see Poesen et al. (2003) for an overview).

The topographic thresholds we use here were pioneered by Patton and Schumm (1975) for gully heads in northwest Colorado. A line fitted at the base of their data scatter was used to predict unstable locations above that erosion threshold. Geographic information systems (GIS) and the use of digital elevation models (DEMs) have enhanced this sort of threshold analysis, but they are limited by the quality and density of digital topographic data. For example, Vandaele et al. (1996) and Desmet et al. (1999) obtained topographic data for gully heads in agricultural fields in Belgium and delineated a threshold below which there was no incision, which can be expressed as:

$$S_c A^b = a$$

(3)

where the values of the threshold $a$ and the scaling exponent $b$ are taken from a trendline through their empirical slope–area scatter. Using a GIS, they then subtracted the critical gradient ($S_c$) from the actual local gradient ($S_a$) for each cell within their 5-m DEMs and predicted gullying in cells where $S_a > S_c$. Though comparisons are complicated by different resolutions and methods of obtaining topographic data, similar exercises in many different settings have resulted in a remarkably consistent scaling exponent $b$ for overland flow that matches derivations from sediment transport formulations and experimental data (Montgomery and Dietrich, 1994; Vandaele et al., 1996; Prosser and Abernethy, 1996; Kirkby et al., 2003; Poesen et al., 2003).

Topographic thresholds focus on channel heads, and in certain settings the drainages that extend below them consistently lie above the erosion threshold (e.g. Prosser and Abernethy, 1996). However, Desmet et al. (1999) found that in order to improve the accuracy of their erosion prediction below channel heads, they needed to increase the value of $b$, and thus the relative influence of contributing area in the lower reaches of gullies. The gullies in Grand Canyon are examples where erosion is discontinuously concentrated at a series of knickpoints along the length of the channel. Knickpoint position and migration are therefore important components of gully behaviour, but it is unclear how area–slope relations apply to the initiation of down-channel knickpoints and whether topography alone is adequate to predict such erosion.

**Methods**

Nine cultural sites in an eastern and western reach of the river corridor were selected for study out of the total number monitored (Figure 2). The study sites are representative of a range of geomorphic settings, degrees of erosion, and types of ECS. All feature one or more gullies, and a total of 24 gullies with 116 ECS were studied (Table I), which was 47 per cent of all those in Grand Canyon National Park at the time. The eastern study sites are all within 23 river km of each other and are at c. 800 m elevation, and the western sites are all within 40 river km of each other and are at c. 400 m elevation. Most of the sites have control data, in that they include an unmitigated, eroding gully for comparison to neighbouring gullies that have been treated.
Figure 2. Grand Canyon study site locations and key geographic features.

Field data were collected in February and October 2002 to bracket the erosional changes associated with the summer and early autumn 2002 monsoon season. Several types of data were collected for the overall study to gain an understanding of the catchment properties influencing erosion. These include soil strength measured with a torvane apparatus and saturated permeability tests with tension-disc infiltrometers, as well as vegetation and soil texture data not reported here (Petersen, 2003). Damage to structures from runoff was assessed through observation and repeat photography, as well as total-station topographic surveys of the gully drainages that included detailed thalweg profiles and channel gradient above each gully head, knickpoint, and ECS. In all, 14 000 ground-survey points contributed to this research. These survey data were used to compare normalized channel longitudinal profiles to determine if treatments trapped sediment or prevented erosion compared to control gullies. In addition, they were used to explore relations between topography, erosion, and the condition of ECS.

In addition to using field survey data for topographic analyses, we were able to produce 10-cm cell-size terrain models at sites F, G, H and I by combining high resolution aerial photogrammetry for overall catchments and more accurate ground-survey data along the gullies. Photogrammetry data were derived from photography with <2-cm pixel size and had a mean vertical error of 6.6 cm (Petersen, 2003). Slope and contributing area grids for modelling at these western Grand Canyon sites were derived using the D∞ algorithm to define drainages (Tarboton, 1997). Because our grid size is smaller than the dimension of gullies, we do not correct our data with unit-contour width. The empirically defined thresholds from the field survey data were then applied to the western Grand Canyon terrain models in a GIS in order to predict areas sensitive to gullying and ECS damage.

Summer 2002 rainfall

There were seven days with measurable rain at stations in the Grand Canyon area during the summer 2002 monsoon study period, all between mid-July and mid-September (Table II). The spatial distribution of July–September 2002 precipitation was highly variable, with 42 per cent average rainfall at Phantom Ranch in central Grand Canyon, and 150 per cent average at Lees Ferry at the northeast head of the canyon (Figure 2). The largest storm was on 8 September, when rangers at Lees Ferry reported 4.6 cm of rainfall in 35 minutes. The Phantom Ranch weather station recorded only 0.18 cm of precipitation on the same day, an example of the isolated nature of these thunderstorms. Though the exact amount and timing of precipitation at individual study sites is unknown, erosion during the study period was relatively intense at the eastern study sites compared to western sites, providing a spectrum of impacts to study.
Table I. Study site information

<table>
<thead>
<tr>
<th>Site name</th>
<th>Geomorphic setting*</th>
<th>Gully</th>
<th>Mean gradient</th>
<th>Drainage area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site A (control)</td>
<td>Talus catchment to termination on aeolian and AP† sand</td>
<td>A1</td>
<td>0.12</td>
<td>0.03</td>
</tr>
<tr>
<td>Site B</td>
<td>Bright Angel shale in upper catchment to aeolian sand to termination in side canyon</td>
<td>B1</td>
<td>0.22</td>
<td>0.05</td>
</tr>
<tr>
<td>Site B</td>
<td>Bright Angel shale in upper catchment to aeolian sand to termination in side canyon</td>
<td>B2</td>
<td>0.22</td>
<td>0.04</td>
</tr>
<tr>
<td>Site B</td>
<td>Bright Angel shale in upper catchment to aeolian sand to termination in side canyon</td>
<td>B3</td>
<td>0.24</td>
<td>0.02</td>
</tr>
<tr>
<td>Site B</td>
<td>Bright Angel shale in upper catchment to aeolian sand to termination in side canyon</td>
<td>B4</td>
<td>0.23</td>
<td>NA</td>
</tr>
<tr>
<td>Site C</td>
<td>Low-relief, large distal debris fan/‘playa’ catchment to AP terrace to termination near Colorado River</td>
<td>C1</td>
<td>0.03</td>
<td>8.28</td>
</tr>
<tr>
<td>Site C</td>
<td>Low-relief, large distal debris fan/‘playa’ catchment to AP terrace to termination near Colorado River</td>
<td>C2</td>
<td>0.03</td>
<td>0.95</td>
</tr>
<tr>
<td>Site C</td>
<td>Low-relief, large distal debris fan/‘playa’ catchment to AP terrace to termination near Colorado River</td>
<td>C3</td>
<td>0.06</td>
<td>0.89</td>
</tr>
<tr>
<td>Site C</td>
<td>Low-relief, large distal debris fan/‘playa’ catchment to AP terrace to termination near Colorado River</td>
<td>C4</td>
<td>0.04</td>
<td>0.35</td>
</tr>
<tr>
<td>Site D</td>
<td>Large alluvial fan catchment; drains across toe of fan to termination on AP terrace</td>
<td>D1</td>
<td>0.09</td>
<td>0.36</td>
</tr>
<tr>
<td>Site D</td>
<td>Large alluvial fan catchment; drains across toe of fan to termination on AP terrace</td>
<td>D2</td>
<td>0.08</td>
<td>0.26</td>
</tr>
<tr>
<td>Site D</td>
<td>Large alluvial fan catchment; drains across toe of fan to termination on AP terrace</td>
<td>D3</td>
<td>0.08</td>
<td>0.37</td>
</tr>
<tr>
<td>Site D</td>
<td>Large alluvial fan catchment; drains across toe of fan to termination on AP terrace</td>
<td>D4</td>
<td>0.08</td>
<td>NA</td>
</tr>
<tr>
<td>Site E (control)</td>
<td>Talus catchment to termination on flat, silty, mainstem AP terrace</td>
<td>E1</td>
<td>0.17</td>
<td>0.08</td>
</tr>
<tr>
<td>Site F</td>
<td>Talus catchment to aeolian, AP and termination on PAD‡ sand</td>
<td>F1</td>
<td>0.19</td>
<td>0.05</td>
</tr>
<tr>
<td>Site G</td>
<td>Bedrock and debris fan catchment to termination on AP/aeolian sand</td>
<td>G1</td>
<td>0.12</td>
<td>0.18</td>
</tr>
<tr>
<td>Site G</td>
<td>Bedrock and debris fan catchment to termination on AP/aeolian sand</td>
<td>G2</td>
<td>0.10</td>
<td>0.04</td>
</tr>
<tr>
<td>Site G</td>
<td>Bedrock and debris fan catchment to termination on AP/aeolian sand</td>
<td>G3</td>
<td>0.20</td>
<td>0.05</td>
</tr>
<tr>
<td>Site G</td>
<td>Bedrock and debris fan catchment to termination on AP/aeolian sand</td>
<td>G4</td>
<td>0.28</td>
<td>0.02</td>
</tr>
<tr>
<td>Site H</td>
<td>Bright Angel bedrock catchment to aeolian, slopewash, and Pleistocene gravel pile to termination on debris fan</td>
<td>H1</td>
<td>0.06</td>
<td>0.16</td>
</tr>
<tr>
<td>Site I</td>
<td>Talus/debris fan catchment to aeolian/AP sand to termination in side canyon or on terrace</td>
<td>I1</td>
<td>0.26</td>
<td>0.08</td>
</tr>
<tr>
<td>Site I</td>
<td>Talus/debris fan catchment to aeolian/AP sand to termination in side canyon or on terrace</td>
<td>I2</td>
<td>0.27</td>
<td>0.06</td>
</tr>
<tr>
<td>Site I</td>
<td>Talus/debris fan catchment to aeolian/AP sand to termination in side canyon or on terrace</td>
<td>I3</td>
<td>0.40</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Site I</td>
<td>Talus/debris fan catchment to aeolian/AP sand to termination in side canyon or on terrace</td>
<td>I4</td>
<td>0.24</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

* Describes upslope to downslope catchment characteristics, see site B photograph in figure 3 for example
† Alluvium of Pueblo II age (Hereford et al., 1996)
‡ Pre-dam alluvium (Hereford et al., 1996)

Table II. Amount of rainfall (cm) in major precipitation events during 2002

<table>
<thead>
<tr>
<th>Date</th>
<th>Lees Ferry</th>
<th>Phantom Ranch</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 July</td>
<td>2.57</td>
<td>0.00</td>
</tr>
<tr>
<td>19 July</td>
<td>0.00</td>
<td>0.08</td>
</tr>
<tr>
<td>4 August</td>
<td>1.50</td>
<td>0.25</td>
</tr>
<tr>
<td>7 September</td>
<td>0.33</td>
<td>1.32</td>
</tr>
<tr>
<td>8 September</td>
<td>4.57</td>
<td>0.18</td>
</tr>
<tr>
<td>9 September</td>
<td>0.13</td>
<td>0.25</td>
</tr>
<tr>
<td>10 September</td>
<td>0.00</td>
<td>1.27</td>
</tr>
</tbody>
</table>

* Data from Western Regional Climate Center

Results

Geomorphic setting and processes

The geomorphic setting of the study sites can be characterized by three zones from the top to the base of catchments (Figure 3). Upper catchments are typically steep (gradient > 0.5), underlain by bedrock or colluvium, and subsequently tend to have the lowest mean permeability (0.003 cm s⁻¹). The middle zones of catchments, where most gullies begin, are less steep (gradient 0.05–0.25), underlain by sandy alluvium, and have a higher mean permeability.
Gullies terminate or join larger channels in the lowest zone, where gradients decrease to $<0.5$ and mean permeability climbs to $0.09$ cm s$^{-1}$ (Figure 4A). Contributing areas below the upper catchment tend to be narrow and accumulate little runoff downslope to the gully terminus (Figure 3). As mentioned above, gully erosion is dominated by channelized Hortonian overland flow causing knickpoint retreat and channel widening through undercutting and failure of banks (Petersen, 2003). Both median soil-surface shear strength and saturated permeability vary with groundcover type (Figure 4B and C) (Petersen, 2003), indicating that vegetation, soil crusts, and trampling–trailing probably all play roles in the generation of runoff and the cohesion of soil at sites. These surface and soil properties vary systematically across sites and undoubtedly have an influence on the location and extent of gullies. Keeping this in mind for later discussion, we turn to results from the exploration of our topographic data.

**Erosion patterns**

Denudation along channel profiles varies, with maximum values corresponding to knickpoints and relatively steep reaches as illustrated in the two examples of Figure 5. These examples also show the slope–contributing area product calculated along the gully thalwegs based on pre-monsoon profiles, which we use as a simple erosivity index. The sections of the profiles with overall higher slope–area erosion index generally match those reaches with the highest denudation after the monsoon, suggesting that gradient and discharge may be the first-order controls on erosion. Gullies at site D were generally devoid of knickpoints during the pre-monsoon survey but underwent substantial erosion and knickpoint formation over the study period (Figure 5A). These knickpoints formed in places that were relatively steep to begin with, and the highest denudation tended to occur in places with high erosion-index values.

The spacing of down-gully knickpoints has a consistent pattern at study sites. The combined data for all gullies with four or more knickpoints indicate mean spacing is inversely and exponentially correlated to gradient (Figure 6A). This confirms intuition that steeper drainages have a greater number of closely spaced knickpoints. Similarly, we may expect that a steeper gully or one with a larger contributing area would have higher-energy flow and thus taller knickpoints and deeper plunge pools (e.g., Bennett et al., 2000). Yet our data indicate no apparent correlation between knickpoint height and mean gradient of the gullies (Figure 6B), nor have we found a significant correlation of
Figure 4. Box-and-whisker summary plots of data from Petersen (2003). (A) Saturated hydraulic conductivity in the three geomorphic zones of catchments from bedrock and colluvium-dominated upper catchments to middle reaches near gully heads to lower catchments around gully mouths. (B) Saturated hydraulic conductivity of bare ground, biotic crust, grass, and shrub groundcover. (C) Shear-strength values of disturbed (trampled), raindrop crust, and biotic crust ground cover. Dark lines are means, boxes cover 50 per cent of data (second and third quartiles) with lighter line being median, whiskers cover outliers at 90 per cent, and dots at 95 per cent.

knickpoint height to slope–area product (Petersen, 2003). That is, steeper and potentially highly erosive gullies do not necessarily have taller knickpoints (Figure 6B).

The patterns of damage to erosion-control structures echo those of gully erosion in general: 51 of the 116 ECS assessed (45 per cent) were damaged by erosion at the end of the study: 12 of these 51 damaged treatments were demonstrably intact before the 2002 monsoon, with the others presumably damaged over the prior year when maintenance was withheld for the purposes of this study. Regardless, field observations and repeat photography indicate that
Figure 5. Examples of denudation and slope–area index values along profiles of gullies. (A) Gully D1: no knickpoints were present at beginning of study and they formed in the steepest reaches. (B) Gully C3: peaks in denudation correspond to knickpoint retreat in the steep lower reach, consistent with higher erosion index values.
most of those that were already somewhat damaged underwent further erosion during the study (Petersen, 2003). Of the damaged structures, 47 per cent were flanked (eroded at its side), 22 per cent were breached (damaged in the middle), and 31 per cent were both flanked and breached. The mean gradient of reaches with intact structures is 0·11, in contrast to 0·17 for the more variable dataset of damaged structures (Figure 7A), and this difference is significant at 90 per cent using a Mann–Whitney $U$-test (data are not parametric). Mean contributing drainage area of intact structures is 10 600 m$^2$, in contrast to 17 000 m$^2$ for damaged structures (Figure 7B), but this difference is not statistically significant.

**Area–slope analysis**

In addition to the area–slope erosion index, we looked at the distribution of channel head and knickpoint topographic data in area–slope space in order to empirically identify the threshold required to initiate gullying. With knickpoints below channel heads, the channel gradient just above a knickpoint generally decreases as drainage area increases, as expected, but there is a lot of scatter in this relation ($r^2 = 0·33$) (Figure 8A). Knickpoints migrate of course, and so our measurements are not taken at the initiation points. But patterns of measured erosion in our study indicate we have captured many knickpoints near their initiation (e.g. Figure 5A), and so our data may be a proxy that is somewhat informative. A more typical area–slope plot for only channel heads has a nearly identical trend with less scatter ($r^2 = 0·75$) (Figure 8B), and it indicates that gully heads have a slightly lower initiation threshold than our proxy data for downslope knickpoints. A threshold for the gully-head plot was extrapolated by moving a line with the same slope as the linear regression through the data to the base of the main scatter. We exclude three outlier points below our
Gullying and erosion control

Figure 7. Box-and-whisker plots comparing intact and damaged structures in terms of: (A) gradient, which is significantly different; and (B) drainage area, which is not. Dark lines are means, boxes cover 50 per cent of data (second and third quartiles) with lighter line being median, whiskers cover outliers at 90 per cent, and dots at 95 per cent.

threshold line because one is the diffuse head of a small, inactive drainage, and the other two are at an atypical site featuring a virtually impermeable, salt-crusted catchment (Petersen, 2003). Using the equation of this threshold line, we derive $a$ from Equation 3 to be 0.017 and $b$ to be 0.47 for these data. This $b$ value, the inverse slope of the trendline, is consistent with other datasets of overland-flow erosion from various settings and scales (Vandaele et al., 1996; Kirkby et al., 2003; Poesen et al., 2003). Comparison of the erosion threshold $a$ between studies is confounded by its sensitivity to different methods of obtaining topographic data, the spatial scale of the gullying, and other factors (Vandaele et al., 1996; Kirkby et al., 2003). But our generally low threshold values are consistent with the steep, rocky catchments and the sparsely vegetated, fine-grained terrace deposits being gullied in Grand Canyon.

Similarly, a plot of drainage area versus slope above individual ECS has distinct populations of damaged and intact structures (Figure 8C). Predictably, the damaged structures have higher threshold values and the combined data on the plot have the familiar trend of $b$ c. 0.45 associated with the gullies. A threshold line drawn at the bottom of the scatter for damaged structures, representing the conditions above which ECS tend to be damaged, has a relatively high $a$ of 0.069 and a steep $b$ of 0.55.

The erosion threshold in Figure 8B may be useful for identifying areas in a landscape that are susceptible to gullying over short timescales. We test this using the detailed (10 cm) photogrammetry DEMs available for four of the western Grand Canyon sites. A grid of contributing drainage area at each of these sites was multiplied by 0.017 and taken to the $-0.47$ power to produce grids with cell values representing estimated threshold gradients for erosion. Then, at western Grand Canyon sites independent of those gullies used to define the empirical threshold, cells vulnerable to gullying were identified where the gradient in the DEMs exceeds those of the threshold grids. Model results predict erosion in 66 out of 68 gullies observed (Petersen, 2003). Predicted erosion generally coincides well with channel heads and correctly predicts that erosion is discontinuous along the length of most existing gullies (Figure 9A). But results also predict gullies in many areas where none existed (Figure 9A). These false positives could be places that are presently unincised but susceptible to erosion in the near future, or else places where this simple
Figure 8. Slope–area plots for: (A) points in drainages immediately above knickpoints; (B) channel heads; and (C) erosion-control structures. Note that we plot contributing area as the independent variable with slope the dependent variable, in contrast to some previous workers.

topographic model does not capture the influence of varying permeability and soil strength across the sites. In the same way, the steeper threshold relation in Figure 8C was used to predict those channel segments where ECS should fail during runoff (Figure 9B). The results of this exercise at site I serve only as an example for discussion because the prediction has not been verified with ECS independent of those used to define the damage threshold.
Figure 9. Example of area–slope predictive model results for Site I. Black cells have a slope–area product that exceeds the critical value for: (A) channelization according to the threshold defined in Figure 8B, and (B) erosion-control structure damage according the threshold defined in Figure 8C. Note the many false positive results in (A). Erroneous results may be related to the exclusion of varying soil-surface properties in these simple topographic models.
Table III. Local effects of erosion-control structures

<table>
<thead>
<tr>
<th>Gully</th>
<th>Number of structures</th>
<th>(%) Intact</th>
<th>Average denudation (m)*†</th>
<th>Structure denudation (m)†</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>2</td>
<td>50</td>
<td>0.014</td>
<td>-0.008</td>
</tr>
<tr>
<td>B2</td>
<td>10</td>
<td>40</td>
<td>-0.020</td>
<td>-0.038</td>
</tr>
<tr>
<td>B3</td>
<td>0</td>
<td>0</td>
<td>0.049</td>
<td>na</td>
</tr>
<tr>
<td>C1</td>
<td>16</td>
<td>44</td>
<td>0.079</td>
<td>0.030</td>
</tr>
<tr>
<td>C2</td>
<td>7</td>
<td>71</td>
<td>0.048</td>
<td>0.045</td>
</tr>
<tr>
<td>C3</td>
<td>8</td>
<td>13</td>
<td>0.045</td>
<td>0.055</td>
</tr>
<tr>
<td>C4</td>
<td>10</td>
<td>80</td>
<td>0.030</td>
<td>0.034</td>
</tr>
<tr>
<td>C1a‡</td>
<td>0</td>
<td>0</td>
<td>0.100</td>
<td>na</td>
</tr>
<tr>
<td>D1</td>
<td>6</td>
<td>17</td>
<td>0.061</td>
<td>0.034</td>
</tr>
<tr>
<td>D2</td>
<td>3</td>
<td>67</td>
<td>0.032</td>
<td>0.058</td>
</tr>
<tr>
<td>D3</td>
<td>1</td>
<td>100</td>
<td>0.018</td>
<td>-0.044</td>
</tr>
<tr>
<td>D4</td>
<td>4</td>
<td>100</td>
<td>0.034</td>
<td>-0.006</td>
</tr>
<tr>
<td>D3a‡</td>
<td>0</td>
<td>0</td>
<td>0.038</td>
<td>na</td>
</tr>
</tbody>
</table>

* Mean denudation within 1 m above erosion-control structures
† Positive numbers represent denudation, negative numbers represent deposition
‡ Control gullies with no structures

Effectiveness of erosion-control structures

We tested the effectiveness of structures in trapping sediment and reducing erosion by comparing thalweg longitudinal profiles measured before and after the 2002 summer monsoon at sites in eastern Grand Canyon that underwent measurable erosion. One control gully or reach with no ECS was included at each site. Relative to gullies overall, seven out of ten reaches at and immediately above treatments were associated with lower denudation or even deposition, and most control gullies denuded more than adjacent treated gullies or reaches (Table III). For example, the channels of treated gullies and tributaries at site C incised a typical amount (2–5 cm), but the comparable untreated gully that neighbours it incised an average of c. 10 cm (Table III). At site D, the only reaches with denudation in gully D4 were between or below the influence of checkdams, but the high denudation of gully D1 was associated with the failure of five of its six stone linings (Figure 10). Similarly, greater denudation occurred at or above damaged structures when comparing them to intact treatments at all sites (Figure 11), and damaged structures were always associated with the greatest local denudation in their particular gullies. Thus, the intact ECS in Grand Canyon do, in fact, tend to reduce erosion and promote deposition, but damaged structures appear to locally enhance erosion. Finally, site D is a useful example because all four gullies have similar gradients and drainage areas, but gullies D1 and D2 have rock linings and gullies D3 and D4 have brush checkdams. This small set of results indicates that brush checkdams were more effective than rock linings at staying intact and trapping sediment (Figures 10 and 12).

Discussion

Controls on gullying and erosion-control failure

Our field data confirm that variations in vegetation, soil crusts, and soil texture across sites influence the fundamental geomorphic properties of infiltration rates and soil shear strength. It follows that the overland flow and soil detachment that create and enlarge the gullies are influenced by these same surface properties. Most of our focus, though, has been on using the very detailed DEMs of the study sites to explore the utility of topography alone in understanding the erosion and the success of installed erosion-control structures for this land-management problem. We have done this in terms of simple correlations between local gradient, contributing area, and the product of the two as an erosivity index along gully profiles, and then by plotting slope–area data for channel heads, knickpoints, and ECS to identify trends and thresholds.

Our basic topographic data indicate that gully initiation, knickpoint formation, channel denudation, and damage to ECS are associated with higher local channel gradient and higher slope–contributing area product. Gradient alone seems to be the single most important variable in these processes, whereas contributing area itself has less significance.
Figure 10. Pre-monsoon and post-monsoon normalized longitudinal profiles of site D gullies. Squares represent up- and downstream boundaries of failed erosion-control structures, triangles represent intact structures. D1 and D2 are gullies with only rock linings, whereas D3 and D4 have only brush checkdams, none of which failed. Note erosion of untreated reach in gully D3.

Figure 11. Box-and-whisker plot depicting differences in denudation for intact and damaged structures during the study period. Difference of means is significant at the 95 per cent level. Dark lines are means, boxes cover 50 per cent of data (second and third quartiles) with lighter line being median, whiskers cover outliers at 90 per cent, and dots at 95 per cent. In many, but not all, cases, damaged structures can promote increased local denudation.
(Figures 5 and 7). Likely reasons for this are that gullies in this setting at locations with larger contributing areas also tend to have higher width-to-depth ratios than those with smaller, steeper upslope catchments (Petersen, 2003), and catchments tend to narrow downslope and have little contributing area in lower reaches (Figure 3). Thus, discharge in these larger gullies may not be any higher in basal shear stress (deeper) than in gullies with smaller drainage areas. Also, despite the common assumption of Equation 2, discharge in ephemeral drainages of dry environments does not necessarily increase with drainage area regularly, or at all, because of infiltration into the channel (Leopold and Bull, 1979). This is also seen in the strong power of $S$ relative to $A$ along the length of gullies in the data of Figure 8. In terms of the coefficients for contributing area ($m$) and slope ($n$) in stream-power formulations, this is consistent with $n/m < 1$ and coefficient $m < 1$ as expected for dry environments (Kirkby et al., 2003).

Our slope–area plots of channel head, knickpoint, and ECS data all show a consistent relation of local gradient and contributing area down the study gullies, as expressed in trendlines with essentially identical slopes ($b = 0.45$). As others have shown, there is a fundamental scaling of driving forces in both Hortonian and saturation overland flow gullying that is independent of setting, supporting numerical derivations of this scaling from process laws for general purposes (Begin and Schumm, 1979; Montgomery and Dietrich, 1994 Prosser and Abernethy, 1996; Istanbulluoglu et al., 2002; Kirkby et al., 2003). Montgomery and Dietrich (1994) derive a steeper $b$ of 0.87 ($n/m = 7/6$) for turbulent flow, and one might expect the trend of gully thalweg topography below channel heads to reflect channelized, turbulent flow. This does not seem to be the case with our knickpoint data, which have a weak trend similar to that for gully heads (Figure 8A). The threshold defined for the damage of ECS does have a steeper trend suggesting that, for some reason, contributing area has a greater relative influence on this (Figure 8C).

Application of a topographic-threshold model at sites with detailed DEMs successfully predicts the extent of even small gullies, and correctly indicates that down-gully erosion should be discontinuous. But there are also abundant

Figure 12. Repeat photographs of an example brush checkdam at Site D: (A) before the 2002 monsoon; and (B) after monsoon, with notebook for scale. Initial data suggest that brush checkdams are better than stone structures at trapping sediment and remaining intact.
false-positive results (Figure 9A), though the utility of such a model lies in its ability to identify unincised locations
that are vulnerable to erosion with these false-positives. Topographic predictions are a first step, but alone they appear
inadequate for this particular problem in Grand Canyon. A model that incorporates empirical parameters such as
infiltration capacity and soil shear strength, as well as detailed topography for routing runoff, could be very useful.
Many cells in our model results lie in areas with different soil properties from the mean trend used to construct the
model, partly accounting for the scatter in the empirical plots (Figure 8). These properties vary not only with distance
across a site, but also through time. For example, a decadal climate change to generally more intense precipitation,
and/or less vegetative cover in Grand Canyon would result in lower infiltration, more runoff and channel expansion,
effectively decreasing the threshold for erosion.

Our observations indicate that erosion-control structures in relatively steep gully reaches will eventually fail and
require maintenance. The irony is that ECS have been placed over knickpoints and steep reaches in order to slow
erosion, but these structures are themselves in danger of being breached or flanked due to this high gradient, thereby
exacerbating the erosion problem. Critical-failure thresholds, like that in Figure 8C, may be useful in predicting those
ECS vulnerable to damage, but the scatter in these slope–area data and model results can be attributed not only to
local variation soil properties but also to variable construction and maintenance of ECS. Checkdams in places near the
area–slope threshold will likely be more successful, since deposition behind the dam would reduce upstream channel
gradient below the threshold, whereas ECS in locations that greatly exceed the threshold should be more prone to
damage, and regular maintenance can be anticipated. Thus, refined models could be an important tool for land
managers, producing maps such as those in Figure 9 that can be used as guidelines for mitigation.

Brush checkdams versus rock linings

This first assessment of erosion-control structures in Grand Canyon indicates that they are working to trap sediment
and slow erosion, but that this effectiveness is contingent upon consistent maintenance. In addition, data from site D
suggest that not all ECS are created equal. Though this small dataset needs to be expanded, brush dams fared better
during this study than the neighbouring rock linings in terms of both damage and erosion control. Repeat observations
indicated that all of the brush structures stayed intact and were not associated with local scour, whereas over half of
the rock structures in similar gullies at the same site were destroyed by runoff during the study period (Petersen,
2003). In some cases, the relatively immobile clasts of rock linings simply deflected and concentrated the flow,
increasing flow depth and causing local scour. Logically, the greater, more uniform permeability of brush structures
should serve to slow runoff but still let water through, causing aggradation at and above the structure without
concentrating flow (Figure 12).

These indications that brush structures may be preferable to stone structures are supported by other studies in the
region. On the Zuni Reservation in New Mexico, Gellis et al. (1995) observed that only five of 23 brush structures
were damaged during his study and Norton et al. (2002) found that brush structures successfully endured 25-year
recurrence interval flooding, with larger floods beneficially redepositing the woody material down the channel. Though
at a different scale and setting, some hydraulic qualities of woody debris in larger perennial streams should be
applicable across a wide range of scales and environments (Montgomery and Piegay, 2003). Woody debris reduces
flow velocity and the fraction of a flow’s energy applied to sediment transport (e.g. Fetherston et al., 1995; Gippel,
1995), providing much of the flow resistance in some channels (e.g. Manga and Kirchner, 2000). With further data and
testing, a potential conclusion may be that brush ECS in Grand Canyon utilize these hydraulic properties to provide an
effective method of slowing gully erosion.

Conclusions

The gully erosion of cultural resources in Grand Canyon has apparently increased in rate, and has received significant
attention as a land-management problem. We set out to better understand this erosion and report on the success of the
erosion-control structures (ECS) installed by the National Park Service under the guidance of the Zuni Conservation
Program. Gradient is the single largest factor in controlling the location of channel heads, ECS failure, and perhaps
knickpoint initiation, though contributing area and soil and surface properties certainly have an influence. There
appears to be consistent scaling between contributing area and slope with respect to channel heads and down-gully
points, and useful topographic thresholds can be defined for gully heads and ECS damage. The actual thresholds are
variable through space and time due to variations in geomorphic properties and climate, but indications are that
empirically augmented models run over detailed topography could aid land managers in determining which gully
segments and ECS need the most resources and attention. Controlling or stopping gully erosion through more
involved engineering or alteration of sites is infeasible in this national park setting, and therefore erosion control is the goal. This research shows that rock linings and, perhaps to a greater degree, brush checkdams installed in Grand Canyon are effective in slowing erosion, but all structures need monitoring and maintenance because damaged structures tend to further exacerbate erosion. With effective placement, monitoring and maintenance, erosion-control structures can be a useful but labour-intensive tool for temporarily preserving cultural resources in this highly erosive environment.

Acknowledgements

We would like to thank Grand Canyon National Park, and the archaeology office in particular, for permission to access study sites and for providing guidance and data. The Grand Canyon Monitoring and Research Center (GCMRC), Geological Society of America, and Colorado Scientific Society funded this research. Numerous people provided field assistance, and Mark Gonzales, Keith Kohl and Kristin Brown of the GCMRC provided an enormous amount of survey support. Wally MacFarlane, Jack Schmidt and David Chandler edited an earlier draft, and we thank Allen Gellis and Louise Bracken for reviews.

References


