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Mitigation, Monitoring, and Geomorphology Related to Gully Erosion of Archaeological sites in Grand Canyon

Paul A. Petersen
Utah State University

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MITIGATION, MONITORING, AND GEOMORPHOLOGY
RELATED TO GULLY EROSION OF
ARCHAEOLOGICAL SITES IN
GRAND CANYON

by

Paul A. Petersen

A thesis submitted in partial fulfillment
of the requirements for the degree
of
MASTER OF SCIENCE
in
Geology

Approved:

UTAH STATE UNIVERSITY
Logan, Utah
2003
ABSTRACT

Mitigation, Monitoring, and Geomorphology Related to Gully Erosion of Archaeological sites in Grand Canyon

by

Paul A. Petersen, Master of Science Utah State University, 2003

Major Professor: Dr. Joel L. Pederson
Department: Geology

Gully erosion has been damaging archaeological sites in Grand Canyon during the last several decades, and there is a need to protect these features through mitigation, monitoring, and better geomorphic understanding. The purpose of this study was to assess the effectiveness of erosion-control structures, determine the accuracy and utility of aerial photogrammetry for monitoring gullies, and understand the geomorphology of the erosion. We performed total-station surveys and other data collection during February and October, 2002, at nine study sites in eastern and western Grand Canyon.

Erosion-control structures are more prone to be damaged by flow when they are placed in reaches of very high local gradient. Treatments are generally successful in slowing erosion or causing deposition of sediment, but damaged erosion-control structures were shown to be less effective than intact structures, and actually increase local erosion in cases.
Aerial photogrammetry was performed on four eroding archaeological sites in western Grand Canyon in March and October 2002 in order to assess the accuracy and change-detection utility of this tool. Accuracy was assessed on several different levels by comparing photogrammetry data to ground-survey data, and mean absolute vertical error ranged from 6-10 cm.

Error of manual photogrammetry digital terrain models (DTMs) increased with topographic ruggedness and decreased with greater photogrammetric point density. Mean error reached a minimum of 5 cm for March and 6.5 cm for October when the ratio of point density to topographic ruggedness was ~40. Ground surveys and repeat photography indicated that two study gullies eroded or aggraded during the study period by 10-20 cm, but these changes were mostly undetected in the photogrammetry DTMs.

Repeat ground surveys showed that gullies erode most at knickpoints and in steep reaches, and that new knickpoints tend to form in relatively steep reaches of a given channel. An area-slope erosion threshold was identified for the study sites and applied in a GIS-based model at four sites to show areas that exceed the threshold and are sensitive to gully erosion. Overall results show an upcatchment control of gully erosion and suggest that baselevel changes due to Glen Canyon Dam operation are subordinate controls.
ACKNOWLEDGMENTS

I would like to thank the Grand Canyon Monitoring and Research Center, the Geological Society of America, and the Colorado Scientific Society for funding of this research. I would especially like to thank my graduate advisor, Dr. Joel Pederson, and my committee members, Dr. John Schmidt and Dr. David Chandler, for their assistance and thoughtfulness during the research and writing process. I have greatly appreciated the insight and proofreading of Wally MacFarlane, who has served as an informal "advisor" and mentor on the subject of photogrammetry. I owe much of the success of this project to the diligent field, lab, and thought assistance of Jen Dierker, Jay Norton, Stacy Petersen, Sammie MacFarlane, Isaac Larsen, Jesse Allen, Lynn, Thomas, Scott Cragun, Rob Mackley, and Tom Monaco. Additionally, the GCMRC survey team and the National Park Service archaeologists were invaluable in their support of field assistance and providing supplementary data. Finally, I thank my family and friends for their moral support and encouragement, especially my wife, Stacy Petersen.

Paul A. Petersen
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- Setting
- Study Sites

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- Photogrammetry

**RESULTS**

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- Point-to-Model
- Model-to-Model
- Minimum Erosion Detectable between March and October

**DISCUSSION**

- Semi-Automated vs. Automated Collection of Photogrammetry Data
- Manual Error—Sources and Accuracy
- Photogrammetric Change Detection

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### 4. Geomorphic Controls of Gully Incision Along the Colorado River Corridor in Grand Canyon

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- Setting
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CHAPTER 1

INTRODUCTION

Grand Canyon is well-known as an erosional landscape and is the subject of a wide variety of research at many scales. Gullies are eroding a series of mid-to-late Holocene alluvial terraces along the main river corridor, which garners attention because archaeological sites are being destroyed in the process. Long-term monitoring of archaeological sites indicates that the erosion has increased over the last two decades, and Glen Canyon Dam has been cited as a possible contributor to this phenomenon. Methods of monitoring and mitigating gully erosion while protecting archaeological sites are unrefined, and the ultimate causality and geomorphology of the erosion is not understood. The goal of this research is to assess the effectiveness of erosion-control structures, test aerial photogrammetry as a viable monitoring tool, and understand the geomorphic conditions of the gully erosion. The overall theme of the three facets of this research is protection of archaeological sites in Grand Canyon. This thesis research will be reported to the Grand Canyon Monitoring and Research Center.

Chapter 2 focuses on stone and brush erosion-control structures that have been placed in gully channels over the last several years. The purpose of these structures is to reduce flow velocity and stabilize the channel, but their effectiveness in these tasks has never been formally examined. Total-station surveys quantifying trends in erosion between February and October 2002, as well as topographic conditions of structure success or failure, yield an ample dataset to perform an analysis of erosion treatments.

Chapter 3 is an account of research testing the utility of aerial photogrammetry as a method to resolve decimeter-scale gully features and to detect change of these features
over time. Conventional ground surveys are accurate, but trample the desert landscape and may put archaeological sites at further risk of being damaged. Aerial photogrammetry is a promising technology that has the potential to measure detailed topography of an area with minimal intrusion.

Chapter 4 explores the geomorphic setting and processes of gully erosion. It addresses the “baselevel hypothesis,” which lays partial blame of the gully erosion on Glen Canyon Dam, and provides a comprehensive study of knickpoints and geomorphic thresholds in the context of Colorado River management and previous topical baselevel research. High-resolution photogrammetric terrain models produced from work related to Chapter 3 also makes GIS prediction of gully-prone areas possible, a product that can benefit Grand Canyon managers in efficiently protecting and monitoring archaeological sites.
CHAPTER 2

ASSESSMENT OF GULLY EROSION-CONTROL STRUCTURES IN GRAND CANYON NATIONAL PARK

ABSTRACT

Erosion-control structures have been used in Grand Canyon during the last decade to protect archaeological features from gully incision. Ground-survey data were used to determine local gradients and contributing drainage areas associated with destruction of these structures, and longitudinal-profile comparisons of data from successive surveys were used to test effectiveness of structures in preventing erosion.

Structures are more prone to be damaged when they are placed in reaches of high local gradient. Shear stress and stream power are greater in these areas and thus there is a greater capacity for flanking or breaching the structures. Treatments are generally successful in slowing erosion or causing deposition of sediment, but damaged erosion-control structures were shown to be much less effective than intact structures, and to actually increase erosion in cases. Gullies with no erosion treatments exhibited greater erosion during the study period than those with rock linings or brush checkdams. Based on our relatively small dataset, brush checkdams were effective in locally raising the channel bed, and also stayed intact better than rock linings. There appears to be no link between structure damage and effective baselevel, and the idea of describing erosion potential in terms of a particular landform on which the gully terminates is misleading.

We recommend that the placement, monitoring, and maintenance of erosion-control structures continue in Grand Canyon, and that brush checkdams be used more frequently.
INTRODUCTION

Gully erosion is an acute problem in many regions, 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). In semi-arid landscapes, gullies are particularly prevalent and typically have flat bottoms, vertical walls, and low width-to-depth ratios (Higgins, 1990; Bull, 1997). Erosion control is often needed, since gully erosion increases sediment yield, removes fertile agricultural soil, destabilizes river banks, and can lower the water table of alluvial aquifers (e.g. Patton and Schumm, 1975; Gellis, 1996; Bull, 1997; Elliot et al., 1999; Norton et al., 2002). Checkdams are often used to control erosion, but have limited durability and effectiveness in trapping sediment or slowing erosion.

Many archaeological sites that lie upon and within Holocene stream terraces along the Colorado River corridor of Grand Canyon National Park are being affected by the advance and incision of gullies (Hereford et al., 1993; Fairley et al., 1994). Erosion-control structures have been installed by members of the Zuni tribe at many sites to reduce or prevent further erosion, but their performance is uncertain, and the National Park Service (NPS) and Grand Canyon Monitoring and Research Center (GCMRC) are in the midst of assessing the effectiveness of this management strategy. Our goal has been to provide the first formal evaluation of gully erosion-control structure effectiveness in Grand Canyon. More specifically, it is our objective to: 1) evaluate the conditions under which erosion-control structures tend to fail (be breached or flanked), and 2) evaluate the effectiveness of channel treatments in slowing or stopping erosion. Assessing the success of mitigation efforts, combined with pinpointing the geomorphic and topographic
controls on gully erosion in the study area, should help improve management of these
sensitive sites.

BACKGROUND

General Gully Erosion-Control Methods

Many attempts have been made to control gully erosion by building dams of
concrete, stone, or wood (Heede, 1976). The purpose of checkdams from an engineering
perspective is to dissipate energy locally and provide a channel gradient that is smaller
than that of the valley or hillslope in the areas upslope from dams (Jaeggi and Zarn,
1999). Since erosion occurs when the driving forces in the flow exceed the resisting
forces of the channel boundary, reducing the hydraulic forces should reduce erosion.
Basal shear stress of a fluid, defined as the force per unit area in the flow direction, is a
measure of the fluid force on the channel:

\[ \tau_o = \gamma D s \]  

(1)

where \( \tau_o \) is average boundary shear stress, \( \gamma \) is the specific weight of the fluid, \( D \) is the
flow depth, and \( s \) is the channel gradient. Thus, reducing channel gradient or flow depth
will proportionally reduce boundary shear stress. Critical shear stress \( (\tau_{cr}) \) is defined by
equating the applied forces to the resisting forces as the threshold of loose grain
entrainment. Shields' (1936) laboratory experiments helped relate the threshold stress
required for entrainment to particle size:

\[ \tau_{cr} = kg(\rho_s - \rho)d \]  

(2)

where \( k \) is a constant (usually 0.045), \( g \) is the gravitational constant (9.8 m/s\(^2\)), \( \rho \) is fluid
density, \( \rho_s \) is sediment density, and \( d \) is the grain diameter (m).
The correct spacing of checkdams needed for full coverage of channel length in an engineered situation depends on the gradient of the deposits expected to accumulate upslope of the dams and the heights of the dams. A simple, efficient and economical spacing approach is to place a checkdam at the upstream toe of the distal deposits of the next dam downstream (Heede, 1966). Woolhiser and Lenz (1965) showed that original channel slope, width of the channel at the structure, and height of the structure spillway inlet above the original thalweg are the most significant variables affecting the gradient of new deposits. Heede (1976) used a formula to calculate the spacing of checkdams:

\[ S = \frac{H}{K \tan \alpha \cos \alpha} \]  

where \( S \) is the spacing (meters), \( H \) is the dam height (meters), \( \tan \alpha \) is the channel gradient, \( \cos \alpha \) is the cosine of the channel angle, and \( K \) is a constant (0.3 for channel gradients less than or equal to 0.2, and 0.5 for gradients greater than 0.2). The gradient of deposits upstream from checkdams will vary in regards to sediment size. Hack (1957) found a significant relationship between slope gradient and median bed material size \((D_{50})\) in sites of equivalent drainage area (approximately equal discharge):

\[ s = 0.006 \left( \frac{D_{50}}{A_d} \right)^{0.6} \]  

where \( A_d \) is drainage area. This elemental relation has been documented in the context of “post-dam” channel gradients. The gradient upslope of the dam is always lower than the original gradient, and Kaetz and Rich (1939) measured steeper deposition slopes in gravel-dominated channels, in contrast to lower slopes associated with finer loads. The ratio of the “post-dam” deposited channel gradient to the original gradient has been estimated to be 0.7 (Heede, 1976), but field investigations show that there is a wide variation in slope ratios (Woolhiser and Lentz, 1965).
Engineers have debated the effect of raising baselevel to control erosion through the construction of small barriers or checkdams in ephemeral arroyos, gullies, and washes. Some researchers suggested that the wedge of sediment behind the dam would build upstream and eventually fill the gully all the way to its head, whereas others maintained that the sediment wedge would extend upstream only a limited distance (e.g. Leopold and Bull, 1979). Kaetz and Rich (1939) tested these ideas by conducting a field survey of the gradient of deposition behind barriers in small to moderate-sized channels. They found that the checkdams exerted an influence on sedimentation only a limited distance upstream. Resurveys several decades later showed that the depositional wedge extended upstream over time only slightly and only in a few cases, and that several of the dams had failed (Leopold and Bull, 1979). This highlights that checkdams are often bypassed or undermined and do not remedy the basic cause of gully erosion.

Typical erosion-control methods rely on rigid concrete, stone, or log checkdams. Brush structures are also used in some places, for example by the Zuni Indians in the southwestern United States. These brush structures reduce erosive power of flows because the high permeability and roughness of woody debris results in less erosive flows and greater time for infiltration (Norton et al., 2002). Brush dams are also cost-effective and take little time to construct. In a single assessment on the Zuni Reservation of New Mexico, Gellis et al. (1995) noted superior integrity of brush checkdams compared to stone checkdams, with only five of the 23 brush structures (22%) in need of repair, in contrast to 28 of the 47 earth and stone structures (60%). Gellis et al. suggested the success of the wood structures was a result of proper spacing of the structures, causing aggradation and decrease of channel slope. Norton et al. (2002) also found that
traditional Zuni brush structures were effective, specifically in retarding erosion, reducing scour, and causing low-energy overbank sheet flow that deposited sediment.

Several of the erosion-control structures in Grand Canyon are wood or stone checkdams, but the great majority of structures studied here are low-profile rock linings. Many of these rock linings were originally constructed as larger rock and rock-and-brush checkdams, but were reduced by maintenance to the small linings in order to prevent future breaching (Dierker et al., 2002). These rock linings essentially serve as "stone armor," which resists hydraulic forces by increasing roughness and adding interlocking support to prevent loss of channel and bank material (Fischenich, 2001). Fischenich (2001) also noted that armoring can cause local scour, especially where there are local constrictions and increases of flow velocity, and that the effects of armoring seldom influence the area beyond the structure itself. Additionally, armor that protects banks that are a significant sediment source for the channel could reduce sediment load relative to flow capacity and result in increased or accelerated bed or bank erosion downstream. Unfortunately, little evaluation of rock linings in gullies has been performed, since brush and stone checkdams are more popular, especially in larger gullies and arroyos.

**Gully Erosion in Grand Canyon**

The gullies of interest in Grand Canyon form on a suite of Holocene stream terraces underlain by sandy alluvium, as well as on eolian dunes and toes of hillslopes. Hereford et al. (1996) studied the Holocene alluvial stratigraphy of the river corridor, and found that most cultural sites are located in deposits he called the "alluvium of Pueblo II age" and the "striped alluvium." These middle-late Holocene deposits generally have not been inundated by historic pre-dam flows of the Colorado River (Fig. 2.1). The striped
alluvium dates from 2500 BC to 300 AD, consists of interbedded slopewash deposits and fluvial sand, and is found mostly in eastern Grand Canyon. The alluvium of Pueblo II age has been dated from 700 – 1200 AD and consists of fine-grained fluvial sand locally interbedded with eolian sand and gravelly slopewash deposits. The “upper mesquite” and “lower mesquite” terraces are composed of silty mainstem sand and are distinguished by the presence of large, mature mesquite trees on the upper terrace and smaller mesquite on the lower terrace (Fig. 2.1). Deposition of upper mesquite sediment may have begun as late as 1400 AD through a series of floods, whereas the lower mesquite deposit was not formed until a late 19th century flood event (Fairley and Hereford, in press).

Figure 2.1. Holocene alluvial stratigraphy along the mainstem Colorado River corridor (from Fairley and Hereford, in press). Most cultural sites subject to gully erosion are associated with the striped alluvium (sa) and alluvium of Pueblo II age (ap) units.

The study gullies are relatively small, ranging from ~20-200 m in thalweg length, and from ~0.2-2.5 m in channel width. Field evidence supports the view that erosion is driven primarily by infiltration-excess overland flow but is also influenced by piping in some settings. These two processes are common in semi-arid to arid landscapes such as
Grand Canyon that feature infrequent, high-intensity precipitation events, low vegetation density, and bedrock predominance. Studied channels degrade through both knickpoint retreat and channel widening from bank undercutting and failure.

The gullies in Grand Canyon drain to some "effective baselevel," which we define as the level where a gully terminates and therefore sets the level to which it can incise. Effective baselevel differs from "ultimate baselevel," which is sea level, and "local baselevel," which can be any point along a drainage (Leopold and Bull, 1979). Hereford et al. (1993) classified erosion potential of Grand Canyon gullies by the landform to which they drain. Gullies sometimes cut from prehistoric deposits all the way to the mainstem Colorado River ("river-based"), but more often drain into tributary washes or debris fans ("side canyon-based"), or terminate within a terrace ("terrace-based"). We disagree with this terminology, because simply describing the landform on which the gully ends does not characterize the causal factors in erosion potential: total relief and gradient between the gully head and effective baselevel.

It is important to note that gullies that reach pre-dam alluvium (pda) or flood sand of 1983 (fs) terraces (Fig. 2.1) are within the stages influenced by Colorado River floods and deposition in the respective pre-dam and post-dam eras, and are typically 3 – 5 m above the dam-regulated river stage. Risers or scarps separating these different terrace levels provide natural initiation points for headward incision (Thompson and Potochnik, 2000).

Hereford et al. (1993) and Thompson and Potochnik (2000) used repeat air photos of sites in both eastern and western Grand Canyon to indicate gully incision has increased since at least 1973, and increased most dramatically between 1973 and 1984. Hereford
and Webb (1992) noted that most years between the mid-1930s and late 1970s were very dry, but were followed by several unusually wet years of higher storm frequency. Hereford et al. (1993) studied changes in daily precipitation and proposed that a period of more intense precipitation from the late 1970s through the 1990s has helped accelerate erosion. These studies make a case for increased gully erosion, yet the existence or true extent of the change in gully activity is uncertain. The causes, processes, and involvement of Glen Canyon Dam in potentially increasing erosion are debated, and is a topic of Chapter 4.

**Erosion Control in Grand Canyon**

Professional archaeologists began studying cultural features in Grand Canyon National Park in the early 1950s. The first documentation of archaeological-site erosion came during increased monitoring immediately after the July 1983 flood from Glen Canyon Dam, when archaeologists began to notice previously buried sites becoming exposed through erosion. A complete archaeological inventory was completed along a 410-km-long segment of the Colorado River corridor from the base of Glen Canyon Dam to Separation Canyon in May 1991. One product of this survey was an evaluation of site conditions and impacts, including gully erosion (Fairley et al., 1994).

Long-term monitoring of cultural sites indicated that some form of mitigation was necessary to impede destruction of archaeological sites (Dierker et al., 2002). The Bureau of Reclamation and the NPS took action in May 1995 by conferring with geologists, geomorphologists, archaeologists, trail crew personnel, and Native American tribal members. They concluded that traditional Zuni-style checkdams of both rock and brush would be constructed at severely eroding sites. The goals were to stabilize existing
channels and prevent further knickpoint retreat by slowing erosion, redirecting runoff, and increasing deposition. Since September 1995, the National Park Service and the Zuni Conservation Program have constructed, monitored, and maintained rock linings, brush linings, rock checkdams, log and rock checkdams, and water-diversion structures at 29 different sites along the Colorado River corridor (Dierker et al., 2002). Although some of these structures have remained intact, many need frequent maintenance or have been destroyed.

METHODS

Archaeological sites in two reaches of the river corridor were selected for study (Fig. 2.2). All sites feature one or more gullies, and a total of 22 gullies were studied. Three sites are in eastern Grand Canyon: 60-mile (four gullies), Palisades (four gullies), and Basalt Cliffs (four gullies). These eastern sites are within 16 river km of each other and are all ~800 m elevation. 60-mile and Palisades have a history of active erosion, whereas the gullies of the Basalt Cliffs site had no knickpoint activity as of the beginning of this study. Four sites are in western Grand Canyon: Indian Canyon (one gully), Arroyo Grande (four gullies), Granite Park (one gully), and Gorilla Camp (four gullies). These western sites are all within 28 river km of each other and are at ~400 m elevation. 60-mile, Palisades, Arroyo Grande, and Gorilla Camp are also “checkdam control sites,” in that they include one eroding gully without any erosion-control features. The seven study sites exhibit a range of geomorphic settings, degrees of erosion, and amount of human disturbance and mitigation (Table 2.1).
Figure 2.2. Locations of erosion-control study sites.

TABLE 2.1. EROSION-CONTROL STUDY SITE DESCRIPTIONS

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Mitigation</th>
<th>Number of Gullies</th>
<th>Geomorphic Setting$^1$</th>
<th>Gradient (m/m)</th>
<th>Drainage Area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60-mile</td>
<td>13 rock linings</td>
<td>4</td>
<td>Bright Angel shale in upper catchment to eolian sand to termination in side canyon</td>
<td>0.22-0.24</td>
<td>0.02-0.05</td>
</tr>
<tr>
<td>Palisades</td>
<td>42 rock linings;</td>
<td>4</td>
<td>low-relief, large distal debris fan/playa catchment to ap$^3$ terrace to termination near Colorado River</td>
<td>0.04-0.05</td>
<td>0.2-2</td>
</tr>
<tr>
<td>Basalt Cliffs</td>
<td>9 rock linings;</td>
<td>4</td>
<td>large alluvial fan catchment; drains across toe of fan to termination on ap terrace</td>
<td>0.07-0.08</td>
<td>0.1-0.25</td>
</tr>
<tr>
<td>Indian Canyon</td>
<td>5 rock linings;</td>
<td>1</td>
<td>talus catchment to eolian, ap, and termination on pda$^3$ sand</td>
<td>0.19</td>
<td>0.05</td>
</tr>
<tr>
<td>Arroyo Grande</td>
<td>9 rock linings</td>
<td>4</td>
<td>basement rock and debris fan catchment to termination on ap/eolian sand</td>
<td>0.12-0.28</td>
<td>0.02-0.18</td>
</tr>
<tr>
<td>Granite Park</td>
<td>15 rock linings;</td>
<td>1</td>
<td>Bright Angel bedrock catchment to eolian, slopewash, and Pleistocene gravel pile to termination on debris fan</td>
<td>0.06</td>
<td>0.16</td>
</tr>
<tr>
<td>Gorilla Camp</td>
<td>15 rock linings</td>
<td>4</td>
<td>talus/debris fan catchment to eolian/ap sand to termination in side canyon or on terrace</td>
<td>0.24-0.4</td>
<td>0.002-0.08</td>
</tr>
</tbody>
</table>

$^1$ Describes catchment characteristics and changes throughout length of gully
$^2$ Alluvium of Pueblo II Age
$^3$ Pre-Dam Alluvium
A total of 116 erosion-control structures were located, identified, and assessed with the help of the NPS. They represent 47% of the structures in Grand Canyon National Park, and over 90% are simple rock linings (Fig. 2.3). Field data collection occurred in February and October 2002, and included a qualitative assessment of damage to the structures from runoff as well as total-station surveys at each site. Surveys were used to measure thalweg profiles, channel gradients, drainage areas entire gullies and individual erosion-control structures, and plan-view areas of treatments. Vegetation transects, soil descriptions, repeat photography, geomorphic descriptions, and sediment strength and permeability tests were performed to gain an understanding of the catchment properties as part of the larger research.

Figure 2.3. Rock lining erosion-control structures typical of gully treatments in Grand Canyon.
The survey data were used to assemble and compare channel longitudinal profiles for all gullies. Each profile was normalized to accommodate comparison between the February and October surveys. Normalization consisted of beginning and ending the profile in the same location for both February and October datasets in order to represent channel length from 0–1. Profiles of each gully between the February and October surveys were compared in order to determine if local treatments trapped sediment or prevented erosion. Relations between local channel gradient (gradient <2 m upstream of each erosion treatment), contributing drainage area, and effective base level to the conditions of erosion-control structures were also investigated.

RESULTS

Summer 2002 Rainfall

Grand Canyon receives ~40-50% of its yearly rainfall in relatively short, intense thunderstorms during the monsoon season, which generally begins in mid-June and lasts until mid-September (Western Regional Climate Center, 2003). The intent of performing the first survey in February and the second in October was to capture the effects of monsoonal runoff on erosion and checkdam integrity. These thunderstorms are localized, so one site may receive one or more large events during a summer, while another may receive little or no rainfall. For example, the largest storm during the study was on September 8, when Lees Ferry received 4.6 cm of rainfall in 35 minutes, but the Phantom Ranch weather station recorded only 0.18 cm of precipitation in 24 hours (Table 2.2). Erosion during the study period was intense at the eastern study sites, but western sites showed little evidence of runoff or erosion over the course of this study (Appendix G).
Since the eastern sites underwent substantial runoff and erosion, they provide the best data to assess the effectiveness of erosion-control treatments in reducing channel incision and widening.

### TABLE 2.2. MAJOR PRECIPITATION EVENTS$^{1,2}$

<table>
<thead>
<tr>
<th>Date</th>
<th>Lee's Ferry$^3$</th>
<th>Phantom Ranch$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/18/2002</td>
<td>2.57</td>
<td>0.00</td>
</tr>
<tr>
<td>7/19/2002</td>
<td>0.00</td>
<td>0.08</td>
</tr>
<tr>
<td>8/4/2002</td>
<td>1.50</td>
<td>0.25</td>
</tr>
<tr>
<td>9/7/2002</td>
<td>0.33</td>
<td>1.32</td>
</tr>
<tr>
<td>9/8/2002</td>
<td>4.57</td>
<td>0.18</td>
</tr>
<tr>
<td>9/9/2002</td>
<td>0.13</td>
<td>0.25</td>
</tr>
<tr>
<td>9/10/2002</td>
<td>0.00</td>
<td>1.27</td>
</tr>
</tbody>
</table>

$^1$ Units are cm

$^2$ No nearby gauges to quantify rainfall in western sites

$^3$ See Fig. 2.2 for station locations

**Integrity of Erosion-Control Structures**

Of the 116 erosion-control structures assessed, 51 (46%) were breached or flanked and in some need of maintenance (Table D.1). Many of these structures were damaged when the study began; others were breached or flanked during the course of the study. A structure was considered flanked if it was eroded at its side (Fig. 2.4), and considered breached if it was damaged in the middle (Fig. 2.5). Both breached and flanked structures are damaged to the point of requiring maintenance, whereas intact structures are defined as needing no maintenance. Of the damaged structures, 47% were flanked, 22% were breached, and 31% were both flanked and breached.

Piping caused significant headcutting and channel widening over the study period at only the Palisades study site, where it undermined structures and caused bank collapse (Fig. 2.6). The relatively large salt pan in the upper catchment of Palisades serves not
only to capture a vast quantity of water during storms, but also encourages piping due to its sodium-rich (dispersive), silty sediment, and desiccation-cracked surface (Appendix B).

Morphometric relationships for each of the 116 erosion-control structures have been assembled (Table H.1). The focus of comparisons was on channel gradient and contributing drainage area. Gradient directly affects erosivity of flow (Equation 1) and drainage area can be a surrogate for discharge, both factors that can influence damage of structures. Mann-Whitney U-tests were used to test for significant difference between these potentially important datasets for intact and damaged structures (Table 2.3).

Figure 2.4. Flanked rock lining at Palisades site.
Figure 2.5. Rock lining being undercut by knickpoint at Basalt Cliffs site, and close to being fully breached. "A" is February photo, "B" is October.
Box-and-whisker plots of gradient and contributing drainage area show that damaged structures exhibit a greater variance than intact structures (Fig. 2.7). The large variance for damaged structures skews the mean for contributing drainage area to notably higher values, whereas medians between intact and damaged structures are relatively similar in value. For this reason, the drainage area dataset fails the U-test, indicating that at the 90% level there is not a significant difference in mean between damaged and intact structures. However, local gradient is significant in the breaching and flanking of erosion-control structures at the 90% level. Boundary shear stress is a function of gradient and flow depth, so structures within steep reaches may be prone to damage. Mean gradients of reaches within 2 m of intact structures are 0.11, in contrast to 0.17 for
damaged structures (Fig. 2.7). A high local channel gradient best predicts structure failure.

We also plotted reach gradients against contributing drainage areas for both damaged and intact structures (Fig. 2.8). The trend line representing damaged structures is higher than the trend line representing intact structures, indicating that damaged erosion-control structures have a tendency to have higher gradient-area combinations than those that are intact.

According to the baselevel hypothesis, "river-based" gullies may be incising and widening to a greater magnitude than gullies that terminate at side canyons or terraces (Hereford et al., 1993; Fairley et al., 1994). This would also suggest that erosion-control structures would be more prone to failure in river-based drainages. Contradicting this, a greater proportion of side and terrace-based gullies (52%) currently need maintenance, as opposed to only (39%) of river-based gullies (Table 2.4). Effective baselevel appears to have little influence on erosion-control structure integrity.

<table>
<thead>
<tr>
<th>TABLE 2.3. RESULTS OF MANN-WHITNEY U-TESTS FOR STRUCTURE DAMAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>variable</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>Area</td>
</tr>
<tr>
<td>Gradient</td>
</tr>
</tbody>
</table>
Figure 2.7. Box-and-whisker plots of intact and damaged structures for gradient (A) and drainage area (B). Boxes show 1st (25%), 2nd (median), and 3rd (75%) quartiles, whiskers show outliers at 90%, and dots show outliers at 95%.

Figure 2.8. Local gradient vs. drainage area for intact and damaged structures. 90% confidence intervals shown by dotted lines.

<table>
<thead>
<tr>
<th>Baselevel Landform</th>
<th>Number</th>
<th>Percent Damaged</th>
<th>Mean Gradient (m/m)</th>
<th>Mean Drainage Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side Canyon</td>
<td>24</td>
<td>50</td>
<td>0.27</td>
<td>580</td>
</tr>
<tr>
<td>Terrace</td>
<td>22</td>
<td>55</td>
<td>0.17</td>
<td>1400</td>
</tr>
<tr>
<td>Colorado River</td>
<td>69</td>
<td>39</td>
<td>0.09</td>
<td>11000</td>
</tr>
</tbody>
</table>
Sedimentologic Effectiveness of Erosion-Control Structures

Overall Trends

We tested the ability of structures to control erosion by comparing thalweg longitudinal profiles of the gullies measured in February and October 2002 at sites that underwent measurable erosion during the study period. One “control” gully with similar gradient that featured no form of erosion control was selected at each site. Results are summarized in Table 2.5 and Figure 2.9. Rock linings and brush checkdams appeared to inhibit denudation at the location of the structure and sometimes slightly upstream at ~60% of all structures, and about 50% of those even caused sediment deposition (Table D.2, Table 2.5). All three of the control gullies experienced more denudation than adjacent treated reaches (Table 2.5). Throughout all the sites, damaged structures denuded more than intact structures, whereas intact structures were more prone to cause deposition or impede denudation (Fig. 2.9, Table D.3). Individual erosion-control structures that had been breached or flanked typically have greater local denudation than the average denudation of the entire channel (Table D.2). These data pass a Kolmogorov-Smirnov normality test, and a t-test indicates that denudation at intact vs. damaged structures is significantly different at the 95% level (Table 2.6).
TABLE 2.5. LOCAL EFFECTS OF EROSION-CONTROL STRUCTURES

<table>
<thead>
<tr>
<th>Channel Structure</th>
<th>% Intact</th>
<th>Denudation (m)</th>
<th>Structure Denudation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 (west)</td>
<td>2</td>
<td>50</td>
<td>0.014</td>
</tr>
<tr>
<td>60 (main)</td>
<td>10</td>
<td>40</td>
<td>-0.020</td>
</tr>
<tr>
<td>60 (w trib)²</td>
<td>0</td>
<td>0</td>
<td>0.049</td>
</tr>
<tr>
<td>palisades (s main)</td>
<td>16</td>
<td>44</td>
<td>0.079</td>
</tr>
<tr>
<td>palisades (n main)</td>
<td>7</td>
<td>71</td>
<td>0.048</td>
</tr>
<tr>
<td>palisades (s trib)</td>
<td>8</td>
<td>13</td>
<td>0.045</td>
</tr>
<tr>
<td>palisades (n trib)</td>
<td>10</td>
<td>80</td>
<td>0.030</td>
</tr>
<tr>
<td>palisades (small trib)²</td>
<td>0</td>
<td>0</td>
<td>0.100</td>
</tr>
<tr>
<td>70 (east)</td>
<td>6</td>
<td>17</td>
<td>0.061</td>
</tr>
<tr>
<td>70 (e most)</td>
<td>3</td>
<td>67</td>
<td>0.032</td>
</tr>
<tr>
<td>70 (w most)</td>
<td>1</td>
<td>100</td>
<td>0.018</td>
</tr>
<tr>
<td>70 (west)</td>
<td>4</td>
<td>100</td>
<td>0.034</td>
</tr>
<tr>
<td>70 (untreated reach)²</td>
<td>0</td>
<td>0</td>
<td>0.038</td>
</tr>
</tbody>
</table>

1 Positive numbers represent denudation, negative numbers represent deposition
2 Control gullies
3 Mean erosion of the entire channel
4 Mean erosion within and ~1 m above the erosion control structures

Figure 2.9. Box-and-whisker plot depicting differences in denudation for intact and damaged structures. Dotted lines show mean, dots show outliers at 5 and 95%. In many, but not all, cases, damaged structures can promote increased local denudation.

TABLE 2.6. RESULTS OF T-TEST FOR DENUDATION

<table>
<thead>
<tr>
<th>mean</th>
<th>mean</th>
<th>stdev</th>
<th>stdev</th>
<th>t</th>
<th>t</th>
<th>critical</th>
<th>df</th>
<th>significant?</th>
</tr>
</thead>
<tbody>
<tr>
<td>intact</td>
<td>damaged</td>
<td>intact</td>
<td>damaged</td>
<td>alpha</td>
<td>stat</td>
<td>critical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.01 m²</td>
<td>0.05 m²</td>
<td>0.06 m²</td>
<td>0.07 m²</td>
<td>0.05</td>
<td>3.02</td>
<td>2.00</td>
<td>63</td>
<td>yes</td>
</tr>
</tbody>
</table>
60-mile

At the 60-mile site, a tributary gully with no erosion-control structures incised more than either of the two gullies with treatments (Fig. 2.10, Table 2.4). On average, the main gully aggraded slightly, especially in the lower 2/3 of the channel that features dense treatments in an area of steeper gradient. Most of the denudation of the main channel was located in the upper reach, upstream of any erosion-control treatments. Structures that were breached or flanked still were effective in retarding erosion in general, but field observations and survey data indicate accelerated scour in some cases (Table D.2).

Palisades

The Palisades site is the most complex to assess. Its drainage area and gully dimensions are an order of magnitude larger than any other study site, and its catchment has a very low permeability compared to the other sites (Appendix E). The channels of treated gullies and tributaries at the Palisades site exhibited moderate incision (2–5 cm), except for the south main arroyo. This magnitude is comparable to the other treated gullies at the 60-mile and Basalt Cliffs sites. A small, untreated tributary to the south main Palisades arroyo yielded an average incision of about 10 cm (Fig. 2.11C), 2–8 cm more than the treated reaches (Fig. 2.11, 2.12).

The south main Palisades arroyo denuded an average of 8 cm during the study (Fig. 2.11A). Only three of the nine erosion-control structures upstream of the confluence with a large tributary were in need of repair, whereas six of the seven structures downstream of the confluence were damaged or obliterated. Average incision upstream of the confluence was less than 4 cm; downstream of the confluence, it was
nearly 13 cm. Average gradient upstream of the confluence is 0.015 and downstream of it is 0.04; drainage area increases from 61,000 m² to 85,000 m² at the confluence; slope-area product (proxy for stream power) increases from 920 to 3400.

Most denudation in the south main arroyo took place downstream of the confluence, where flow may have increased over the steep lower reach of profile (Fig. 2.11). This increase of slope-area product index is proportional to the increase of denudation in this lower reach. The confluence contributes greater catchment area to the erosion index, but the nearly three-fold increase in gradient downstream of this point is the dominant effect on the erosion index. The stone erosion-control structures were destroyed where the gradient and discharge product was this large magnitude.

Basalt Cliffs

Brush checkdams at the Basalt Cliffs site were effective in staying intact as well as in trapping sediment and locally aggrading the channel (Figs. 2.13C, D, and see Fig. 2.20). The benefits of these structures are localized, however, since extensive denudation took place between and downstream of the checkdams. All four gullies at the Basalt Cliffs site have similar gradients and drainage areas, but differ in erosion treatment. Rock linings that remained intact were successful to some degree in stabilizing the channel, but did not promote deposition as did the brush checkdams (Fig. 2.13A, B). Both rock and brush structures had new knickpoints immediately downstream of them in some cases, although observations and survey data indicate such knickpoints were more frequent downstream of rock linings (i.e. Fig. 2.5). Like the 60-mile and Palisades sites, the treated parts of the Basalt Cliffs gullies fared better than the untreated segments; a Basalt Cliffs gully with only one checkdam aggraded an average of 3 cm upstream of the
structure, but degraded an average of 4 cm on the untreated reach downstream of the dam (Fig. 2.13D).

Figure 2.10. February and October normalized longitudinal profiles of 60-mile gullies. A and B contain erosion-control structures and aggraded slightly in places between the two surveys, while C has no control and incised between the two surveys. Squares represent failed structures, triangles represent intact structures.
Figure 2.11. February and October normalized longitudinal profiles of south Palisades gullies. Squares represent failed structures, triangles represent intact structures.
Figure 2.12. February and October normalized longitudinal profiles of north Palisades gullies. Squares represent failed structures, triangles represent intact structures. Note erosion spikes at damaged structures in ‘A.’
Figure 2.13. February and October normalized longitudinal profiles of Basalt Cliffs gullies. Squares represent failed structures, triangles represent intact structures. Note higher erosion of untreated reach in 'D.'
DISCUSSION

**Important Controls of Structure Failure in Grand Canyon**

By evaluating over 100 erosion-control structures, several trends become evident when pursuing the question of structure damage. Gradient is more effective in predicting where structures will fail or be successful than is effective baselevel. The gradient of the local channel upstream of the structure and of the structure itself is important in regards to the energy of a given flow of water. A given drainage area (proxy for discharge) will require a critical slope to overcome an erosion threshold and damage the erosion treatments through breaching or flanking. Due to these topographic thresholds, structures in oversteepened gully reaches may repeatedly fail and require constant maintenance. Although treatments are shown to fail at all channel gradients, they seem especially prone to damage at gradients over $\sim 0.2$. Considerable variation may exist in a given structure’s critical slope failure threshold (Fig. 2.8) on account of factors such as construction quality, construction material, maintenance, and stage of gully incision.

The lack of significance of drainage area in itself for controlling structure failure may be due to the fact that gullies with large drainage areas also tend to have higher width-to-depth ratios than smaller, steeper drainages (Fig. 2.14). As a result, flows may not be any deeper or more concentrated than in gully reaches with smaller drainage areas and lower width/depth ratios. This concept can be related back to Equation 1, in which boundary shear stress is function of gradient and flow depth. However, control structures still fail often in these drainages, when there is an extremely large flow event or in locally steep reaches.
Our results have implications to the “baselevel hypothesis” and river management. We feel that describing gullies and their erosional potential in terms of the upcatchment property of gradient is superior to describing them in terms of “effective baselevel.” All gullies, despite baselevel, experienced similar depths of denudation due to runoff from a high-intensity rainfall. Gradient seems to be the control, since “river-based” gullies typically are longer and have a much lower gradient than the shorter, more abrupt “terrace” or “tributary-based” gullies (Table 2.3). “River-based” gullies tend to have much larger catchments and capacity for larger flows, and can have potential for great erosion through oversteepened reaches. However, gradient is shown to be a better predictor for structure failure, and we reiterate our dismissal of baselevel landform terminology.

Effectiveness of Erosion-Control Efforts

Gellis et al. (1995) suggested that structure failure may be influenced by headcutting, piping, local scour, high runoff, poor maintenance, and channel incision and
widening. Several of these factors are present at the Grand Canyon study sites, in particular, channel widening and knickpoint retreat. Erosion-control structures 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. In the case of rock linings, we have evidence that water has the potential to scour around or through the stones (Fig. 2.4, 2.5). Relatively immobile clasts may simply deflect and concentrate the flow into a constriction, increasing flow depth and local gradient and causing local scour. This phenomenon can be accelerated further if the erosion-control structure was built over an existing knickpoint, since water cascading down a knickpoint through the void spaces of cobbles will have a relatively high shear stress. For example, by using Equation 1 we can calculate that a channel with an average gradient of 0.2 may locally experience up to 5 times the mean shear stress when water flows over a knickpoint of 1.0 gradient. It may be impossible to prevent erosion in very steep reaches, if structures in these areas are prone to being damaged and increasing erosion.

Recommendations

Our results show that both rock linings and brush checkdams do in most cases slow erosion or even cause local sediment deposition, and we recommend that the mitigation efforts continue in Grand Canyon National Park. Yearly monitoring and maintenance are inevitably necessary, and will continue to be a key to successful remediation efforts. Structures prone to premature failure either must be consistently maintained in order to prevent positive feedbacks to erosion. If they are not, it would be better if they were completely eliminated, since damaged treatments often promote scour. Monitoring of gullies through repeat surveys of thalwegs and cross sections should also
continue in order to determine the degree of activity. Gullies tend to go through a series of evolutionary stages after initiation that involves incision, widening, and inner floodplain formation (see Elliot, 1979; Gellis et al., 1991; Elliot et al., 1999). Structures would be more prone to breaching or flanking if the channel is still in the stage of active deepening and widening. Such channels tend to have low width-to-depth ratios, high stream power, and high potential to undercut or widen. The lower reach of the Palisades south main arroyo is a current example of such a gully that may be impossible to stabilize.

The contrast between rock linings and brush checkdams yields further insight into the utility of the respective treatment types. Although only five brush structures were available for study, equal structure distribution, similar slopes, and similar drainage areas of the gullies at the Basalt Cliffs site allows some comparison. Despite being in similar gullies that received the same precipitation, the brush dams fared better than the neighboring rock linings in terms of both damage and erosion control. Repeat photography indicated that all of the brush structures not only stayed intact, but also hindered local scour of concentrated flow (Fig. 2.15). Over half of the rock structures in similar gullies at the same site were destroyed by runoff during the study (Table D.1). Due to the higher, more even permeability of their basket-like structure, brush checkdams slow flow and still let water through, causing aggradation of sediment upstream of and within the structure without focusing flow. Unlike a rock lining or dam, brush structures will tend to simply wash downstream through repeated runoff events or during a very high-magnitude runoff event, reducing chances of scour around or within a damaged structure.
Figure 2.15. Repeat photographs of brush checkdams at the Basalt Cliffs site. A) February, 2002; B) October, 2002, filled in with sediment. Notebook for scale.
Several studies suggest that woody debris is effective in causing sedimentation and reducing erosion. The majority of these studies were performed at larger scale and less arid settings than the small gullies studied here, but the general hydraulic qualities of woody debris may be applicable in this study. The ability of woody debris to exert a geomorphic influence is related to relative size of the main woody elements compared to channel size, and also the sensitivity of channel form itself to changes imposed by in-channel obstructions (Montgomery and Piegay, 2003). The fraction of a flow’s energy available to move bed sediment is a function of total channel roughness (Fetherston et al., 1995), which includes in-channel obstructions such as woody debris (Montgomery and Buffington, 1993). Gippel (1995) stated that woody debris hydraulically influences flow by acting as large roughness elements, which create a varied flow environment, reduce average velocity, and locally elevate the water-surface profile. In such a way, the hydraulics of woody debris reduce erosive power and facilitate low-energy overbank flow by damming. Manga and Kirchner (2000) determined that woody debris accounted for nearly 50% of the total flow resistance in a spring-dominated stream in the central Oregon Cascades, despite covering less than 2% of the total streambed. Fetherston et al. (1995) found that woody debris was responsible for up to 87% of sediment storage in a New Hampshire stream, and that 39% of individual debris pieces formed depositional sites in small channels in western Washington.

Our observations that brush structures are superior to stone structures are also supported by several studies in semi-arid to arid climates. In New Mexico, Gellis (1995) observed 23 brush structures, only five of which were damaged, in contrast to 28 of 47 stone structures. Norton et al. (2002) found that the Zuni-made brush piles and
checkdams successfully endured flows up to the magnitude of the 25-year recurrence interval. Larger floods tended to move and redeposit the material in a large debris jam down the channel, which was still beneficial. The intact structures caused large amounts of deposition, and the washed-out structures coalesced to form 10-20 m debris jams, causing upstream deposition of at least 100 m. Norton et al. (2002) also noted the ease of constructing and maintaining the brush structures. Traditional Zuni approaches involve simply placing as much permeable woody material as possible in the channels with little reinforcement, negating the hydraulics and scour sometimes attributed to rigid, relatively impermeable checkdams and rock linings. Extensive lengths of channel could be treated in such a way very rapidly and efficiently.

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Western Regional Climate Center, 2003, Arizona Climate Summaries:

CHAPTER 3

ACCURACY AND UTILITY OF PHOTOGRAMMETRY IN MONITORING GULLY EROSION OF ARCHAEOLOGICAL SITES IN GRAND CANYON

ABSTRACT

We performed aerial photogrammetry on four eroding archaeological sites in western Grand Canyon in March and October 2002 in order to assess the accuracy and utility of this tool. Accuracy was assessed by comparing: a) ground-survey points to photogrammetry points; b) ground-survey points to photogrammetry digital terrain models (DTMs); and c) ground-survey DTMs to photogrammetry DTMs. Accuracy assessments were used to perform change detection between March and October.

The accuracy of the March dataset tended to be similar to, but slightly better than, the October dataset, reflecting the higher quality images collected in March. Absolute value mean error for manual photogrammetry points was 6.6 cm for March and 7.6 cm for October. Both manual and semi-automated Triangular Irregular Networks (TINs) had mean errors of 8-10 cm at both time intervals. Similarly, photogrammetric digital elevation models (DEMs) had mean errors of 10 cm when compared to ground-survey DEMs. Channel longitudinal profiles and cross sections derived from DTMs has a mean vertical error of 6-9 cm. Less than 50% of knickpoints 10-30 cm in relief were resolved by manual photogrammetry, and repeatability for the two time intervals was low.

Error of manual photogrammetry DTMs decreased with photogrammetric point density and increased with topographic ruggedness, which was quantified as the standard deviation of surface elevation (SDSE). A ratio of point density to SDSE therefore can be
used to predict the spatial variation of photogrammetry error, and a theoretical mean vertical error of 5 cm could be obtained with 1:1600-scale photography where this ratio is ~40.

We applied a robust change-detection method to our study sites by applying this same concept that topography and point density causes photogrammetric DTM accuracy to differ across a site. By propagating error between March and October datasets, we determined that topographic change as low as ~20 cm must occur to be confidently detected by photogrammetry at our sites where topography is gentle and point density is high (density/SDSE > 40), whereas several decimeters of topographic change must occur in order to be detected where topography is rugged and point density is low (density/SDSE << 40). Ground surveys and repeat photography indicated that two of the study gullies eroded or aggraded during the study period by <20 cm, but the majority of these changes were undetected in the photogrammetry DTMs. Our conclusion is that aerial photogrammetry is not yet capable of performing rigorous three-dimensional erosion studies of small gully channels at short time intervals, but it may have use in monitoring gullies with very large erosion problems or tracking lateral change of gully banks and heads.

**INTRODUCTION**

Gully erosion along the Colorado River corridor in Grand Canyon National Park has apparently increased in magnitude and frequency in the last few decades, and archaeological sites associated with the eroding deposits are being damaged (Hereford et al., 1993; Fairley et al., 1994; Thompson and Potochnik, 2000). Traditional total-station
surveys, although accurate, can damage the fragile desert landscape and can put cultural resources at further risk through human trampling and disturbance (Fig. 3.1). Thus, there is a need for an efficient and non-destructive monitoring technique to track gully advancement and the condition of erosion-control structures. Aerial photogrammetry is a promising technology that could be used to monitor erosion without ground disturbance through analysis of aerial photographs. This makes it an attractive alternative to conducting intense ground surveys in remote, fragile regions such as Grand Canyon National Park. The purpose of this study is to test the utility of aerial photogrammetry for monitoring gully erosion in western Grand Canyon. This will also determine the accuracy and change-detection limits of aerial photogrammetry as a method at this point in technology.

Figure 3.1. Example of disturbance due to ground survey. Delicate biologic crusts and rainsplash seals that hold soil in place are often destroyed.
BACKGROUND

Previous Work

Photogrammetry is a method of acquiring dependable measurement using images. It was invented in 1851 and is widely used to detect topography. The development of digital photogrammetry has revolutionized the method over the past decade, making it possible to process higher-resolution imagery faster and at a lower cost than the conventional analytical approach (Baldi et al., 2002; Heipke, 1995).

Several recent studies have applied photogrammetry in geomorphic and monitoring studies. It has been used to detect erosion and deposition in mountainous terrain (Oka, 1998; Baldi et al., 2002), shorelines and sandbars (Hapke and Richmond, 2000; O’Brien et al., 2000; Adams and Chandler, 2002), and low-relief fluvial features (Heritage et al., 1998). Aerial photogrammetry has been successful in providing quick, cost-effective assessments of landscape change that correspond with large storm events (Oka, 1998; Hapke and Richmond, 2000). The most recent studies that compare aerial photogrammetry to ground-survey data resulted in mean absolute vertical errors of several decimeters at best (O’Brien et al., 2000; Adams and Chandler, 2002; Baldi et al., 2002), which was sufficient for their respective studies. Adams and Chandler (2002) used their accuracy assessments to statistically determine the amount of topographic change that must be detected by the photogrammetry to be considered genuine geomorphic change rather than measurement uncertainty.

Several variables have been shown to account for error in photogrammetry, most notably topographic slope and irregularity (Heritage et al., 1998; Adams and Chandler, 2002; O’Brien et al., 2000; Baldi et al., 2002). Heritage et al. (1998) also showed that
photogrammetric point density is correlated to accuracy, and suggested that point density should increase with topographic irregularity.

Although terrestrial (ground-based) photogrammetry has achieved high resolution and accuracy in channelized environments (Barker et al., 1997; Heritage et al., 1998), apparently no research has attempted photogrammetry using aerial photography on decimeter-scale, low width-to-depth features such as the gullies we study here.

O’Brien et al. (2000) is the only other study to test the application of photogrammetry in Grand Canyon. They used pre-existing aerial photographs to reconstruct topography of Colorado River sandbars at different time periods using digital photogrammetry. Comparison of these models to ground survey measurements showed that photogrammetry was not as accurate as ground-based topographic surveys, but the level of accuracy was sufficient for measuring larger changes over entire reaches.

O’Brien et al. recommended methods to obtain higher photogrammetric accuracy, which we have followed. These recommendations include use of ground-control panels distributed throughout the study sites, smaller-scale, higher-resolution photographs (1:1600) taken expressly for photogrammetric study, improved methods of image correlation, and more than one study period and reach.

Setting

Grand Canyon is a very steep, erosional landscape located on the Colorado Plateau in northern Arizona. Climate is semi-arid to arid and vegetation is xeric or riparian, and both vary strongly with elevation. Mean annual temperature and precipitation at the canyon bottom are 20.4°C and 213 mm, respectively. The monsoon season, June 15 – October 15, produces 40–50% of Grand Canyon’s yearly rainfall
(Western Regional Climate Center, 2003). The majority of the Colorado Plateau’s local flood and runoff events are initiated during this time through intense, isolated thunderstorms related to the Southwestern monsoon (Hereford and Webb, 1992).

We studied gully erosion at sites along the Colorado River corridor associated with a suite of Holocene sandy stream deposits and terraces. Hereford et al. (1996) studied this Holocene stratigraphy (Fig. 2.1), noting that most cultural sites are found in what they called “alluvium of Pueblo II age” and “striped alluvium,” which have not been inundated by historic pre-dam flow stages of the Colorado River. The striped alluvium dates from 2500 BC to 300 AD and the alluvium of Pueblo II age dates from 700 – 1200 AD. Coarser-grained side canyon stream and debris-flow deposits are interbedded with, overlie, or are overlapped by the mainstem alluvium (Hereford et al., 1996). Gullies can incise all the way to the mainstem Colorado River, but more often drain into a tributary or terminate before reaching the river. Scarps (or risers) separating different terraces may provide initiation places for knickpoints (Thompson and Potochnik, 2000).

These gullies are relatively small, ranging from ~20-200 m in length and 0.2-2.5 m in channel width. Centimeter to meter-high knickpoints, places along drainage profiles where gradient is abruptly greater, exist in many of the channels. Knickpoints locally increase flow depth and velocity, resulting in greater basal shear stress. Thus, erosion rates at knickpoints are higher, driving knickpoint migration up-drainage and resulting substantial erosion, especially if the steep form of the knickpoint remains intact (Brush and Wolman, 1960; Holland and Pickup, 1976; Leopold and Bull, 1979; Gardner, 1983). Gullies on Grand Canyon terraces often feature near-vertical knickpoints with plunge.
pools (Fig. 3.2). These knickpoints can retreat over a meter during an intense rainstorm, but it is unknown to what extent individual knickpoints in Grand Canyon retain their near-vertical form during headward migration. Most of the study knickpoints are \( \sim 10-30 \) cm in height, so it is imperative to test the capability of photogrammetry in achieving decimeter-scale vertical accuracy.

![Knickpoint with plungepool typical of Grand Canyon study sites. This particular feature is \( \sim 30 \) cm high.](image)

**Figure 3.2.** Knickpoint with plungepool typical of Grand Canyon study sites. This particular feature is \( \sim 30 \) cm high.

**Study sites**

Four sites in western Grand Canyon were selected for photogrammetric monitoring: Indian Canyon, Arroyo Grande, Granite Park, and Gorilla Camp (Fig 2.3). These gullies and associated catchments exhibit a range of geomorphic settings, which are summarized in Table 3.1.
**Figure 3.3.** Photogrammetry study sites in western Grand Canyon.

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Number of Gullies</th>
<th>Geomorphic Setting(^1)</th>
<th>Gully Relief (m)</th>
<th>Gully Length (m)</th>
<th>Gradient (m/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indian Canyon</td>
<td>1</td>
<td>talus catchment to eolian, ap(^2), and termination on pda(^3) sand</td>
<td>27</td>
<td>140</td>
<td>0.19</td>
</tr>
<tr>
<td>Arroyo Grande</td>
<td>4</td>
<td>basement rock and debris fan catchment to termination on ap/eolian sand</td>
<td>5-25</td>
<td>20-200</td>
<td>0.12-0.28</td>
</tr>
<tr>
<td>Granite Park</td>
<td>1</td>
<td>Bright Angel bedrock catchment to eolian, slopewash, and Pleistocene gravel pile to termination on debris fan</td>
<td>11</td>
<td>190</td>
<td>0.06</td>
</tr>
<tr>
<td>Gorilla Camp</td>
<td>4</td>
<td>talus/debris fan catchment to eolian/ap sand to termination in side canyon or on terrace</td>
<td>6-12</td>
<td>15-45</td>
<td>0.24-0.4</td>
</tr>
</tbody>
</table>

\(^1\) Describes catchment characteristics and changes throughout length of gully

\(^2\) Alluvium of Pueblo II Age

\(^3\) Pre-Dam Alluvium
METHODS

Aerial Photography

Aerial photography for this research took place on March 1, 2002, and October 15, 2002, by Bechtel Nevada Corporation. Black and white, 1:1,600 photographs were taken using a Wild RC30 photogrammetric camera with a focal length of 152 mm from a Bell 412 helicopter flying at an average height of 240 m. Many photos were taken at each site, and two photos with 60-80% overlap were selected for each of the four study sites resulting in one stereopair per site. Film negatives were scanned on a VEXCEL VX-4000 photogrammetric scanner, which is a device capable of high image quality and excellent positional accuracy, at 12.5 microns (2032 dpi) resulting in an image resolution of 2-2.5 cm per pixel.

Ground-Control Survey

Conventional topographic and ground control-point surveys were performed in late February and mid-October 2002, days before the respective photogrammetry flights on March 1 and October 15 to ensure no change in elevation between the ground survey and photogrammetry datasets. The purpose of these surveys was to georeference the photogrammetry and to create detailed digital terrain models (DTMs) of the gullies at two time increments in the form of a Triangulated Irregular Network (TIN), a set of triangular polygons of irregular dimensions with vertices composed of the survey points. The resulting TINs depict the reference topography. These TINs and their associated points were used to assess the vertical accuracy of the corresponding photogrammetric TINs by comparing elevations for specific points of interest, as well as the general elevation agreement for the entire model.
The February survey provided an antecedent terrain model, with the October survey recording the effects of the monsoon-season runoff relative to the February control data. Total-station ground surveys followed methods employed in previous Grand Canyon Monitoring and Research Center (GCMRC) research for capturing detailed terrain features by high density data collection and defining slope-break lines, channel cross-sections, and thalweg longitudinal profiles to characterize gullies (e.g. Yeatts, 1996; Hazel et al., 2000). Surveys included catchment topography, but focused primarily on recording in detail the gullies themselves. The surveys were tied into the GCMRC control system to ensure accurate coordinates and good repeatability. Ground surveys in Grand Canyon are quite accurate and repeatable, although variability in rod positioning can lead to horizontal and vertical error up to several centimeters.

A related ground-control point survey was conducted at the same time as the overall topographic survey. Ground panels were used to precisely locate the ground control points (GCPs) on the photos during the laboratory triangulation process. Ten to thirteen black and white, 30 x 30 cm, hourglass-shaped panels were positioned at each site and then surveyed (Fig. 3.4). These panels were evenly distributed over as much of the anticipated photo exposure area as possible. GCPs were later collected in the laboratory from these known locations.
Figure 3.4. Control panel on ground with survey prism placed above it.

Photogrammetry

Aerial Triangulation

Aerial triangulation in photogrammetry is the process of establishing the spatial linkage from the aerial photography, through the camera, to the ground surface. The data generated from this process are required as input for the creation of digital stereopairs, DTM's, and orthophotography. The development of a solid aerial triangulation solution is the key to successful DTM's and orthophotography. We used ERDAS™ IMAGINE OrthoBASE Pro Version 8.5 digital photogrammetry software for all these processes.
The first step in the aerial triangulation process is to perform interior orientation. This involves manually defining the location of fiducial ticks on the raw photography based on the calibrated fiducial locations indicated by the camera calibration report. This process is somewhat analogous to registering a map on a digitizing tablet. The root mean square (RMS) error was kept to within 0.3 pixels, lower than ERDAS recommendations of 0.5 pixels, to ensure an accurate solution.

The next step in the aerial triangulation process is exterior orientation, which defines the position and angular orientation of the camera as it existed when the photos were taken. This step involves relating GCPs from ground surveys to their locations on the unreferenced raw photography to estimate the position and orientation of the camera. Tie points common to both photos in a stereopair were used in this process to improve image correlation. We used 8-12 GCPs and 150-300 tie points widely distributed across each image.

A triangulation solution is developed by the software when GCPs and tie points are established on the raw imagery. This solution is based on an algorithm and uses the “least-squares bundle block adjustment,” the most rigorous form of aerial triangulation (ERDAS, 2001). This process minimizes and distributes the errors associated with the imagery, image measurements, GCPs, and tie points. Before the triangulation solution was accepted, the standard deviation of unit weight (a global indicator of the quality of the triangulation) was less than the pixel size of the original photography. Control points not used in the triangulation process were used as checkpoints for additional quality control, and the triangulated coordinates of these points were computed and compared against their surveyed coordinates.
DTM Collection

After the aerial triangulation process was complete, the photography was used to develop topographic models. The photogrammetric TINs were produced using a semi-automated and a manual approach. In the semi-automated process, the software uses a DTM-extraction algorithm that maximized the number of ground-surface points collected while keeping collection on vegetated surfaces to a minimum. It was necessary to manually edit the grid to remove anomalies caused by surface influences such as vegetation. Elevations were collected on a 20-25 cm grid, which is ten times the pixel resolution of the photographs.

In the manual process, a technician uses stereo goggles to view stereo pairs on-screen, and "floats" a cursor to estimate elevation of ground surfaces based on where it appears to "set" on a surface. Manual 3D stereo collection was conducted using ERDAS™ IMAGINE Stereo Analyst, and is performed much like a ground survey. Elevations were collected for gully channels and surrounding topography with a point density similar to that of ground surveys, typically 1000 to 1500 points per site. The manual approach ensures collection of topographic breaklines and other channel features, such as knickpoints and channel banks.

Orthorectification

Orthorectification is the process of removing the geometric errors in the photography. The main variables contributing to geometric errors are camera orientation and topographic relief displacement. The effects of camera orientation are reduced
during the aerial triangulation process. The effects of topographic relief displacement were removed by using a DTM. Orthophotos were derived using the aerial triangulation solution and the newly derived DTMs.

**Accuracy Assessment**

Lateral accuracy is high due to the small pixel size and optimal ground control, and the method’s utility is limited by vertical accuracy, which is the entire focus of this work. Three levels of investigation were used to assess vertical accuracy: point-to-point, point-to-model, and model-to-model comparisons (Table 3.2). Point-to-point comparisons were used at each site to compare elevations for the two dates and methods. The common points for both survey and photogrammetry sets were taken from gullies that showed no field evidence of change. Points between two datasets that lay within 0.025 m of each other (a standard error for rod placement) were located in ArcGIS and directly compared to each other without interpolation. Channel knickpoints were also identified from both photogrammetry and survey profiles as decimeter-scale segments of the channel with gradients over 100% in order to determine the effectiveness of photogrammetry in resolving these features. Planview position of tops of all knickpoints were identified and recorded through both ground and photogrammetric surveys.

<table>
<thead>
<tr>
<th>Level</th>
<th>Data Compared</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point-to-Point</td>
<td>Survey points</td>
<td>1) Accuracy without interpolation</td>
</tr>
<tr>
<td></td>
<td>Manual photogrammetry points</td>
<td>2) Knickpoint resolution and repeatability</td>
</tr>
<tr>
<td>Point-to-Model</td>
<td>Survey points</td>
<td>1) Accuracy of channel models</td>
</tr>
<tr>
<td></td>
<td>Semi-automated and manual photogrammetry TINs</td>
<td>2) Accuracy of long profiles</td>
</tr>
<tr>
<td>Model-to-Model</td>
<td>Survey TINs and DEMs</td>
<td>1) Spatial analysis of error</td>
</tr>
<tr>
<td></td>
<td>Manual photogrammetry TINs and DEMs</td>
<td>2) Accuracy of cross sections</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3) Change detection</td>
</tr>
</tbody>
</table>
Point-to-model comparisons were also conducted at each site for both the semi-automated and manual methods. These comparisons allowed a more robust accuracy analysis compared to the point-to-point method, but required interpolation. We imported ground-survey points into the Accuracy Assessment Module of ERDAS™ IMAGINE OrthoBASE Pro in order to generate residuals between the semi-automated photogrammetry DTM and survey points, which were used to calculate vertical accuracy.

Accuracies of manual photogrammetric TINs were calculated by importing the ground survey points as an Arc/Info point coverage, and then interpolating the photogrammetry elevations for those points from the manual photogrammetric TINs using the Arc/Info tinspot command. This allowed point-specific elevation comparison between the ground surveys and photogrammetry DTMs for both entire channels and longitudinal profiles.

Model-to-model comparisons were performed by rasterizing photogrammetric and ground survey TINs into 0.2 m grids (based on gully scale, point density, and automatic collection). In ArcGIS, the grids were clipped to show only the channels in order to perform raster assessments of accuracy, change detection, and error analyses of surface irregularity and point density. We determined model-to-model accuracy by subtracting photogrammetric digital elevation models (DEM) from ground survey surface DEMs at each site. Focalstd and pointdensity commands were used in Arc/Grid to respectively measure terrain surface irregularity and density of photogrammetry points, and results were related to magnitude of vertical error. Comparing two models requires the most interpolation, but 3-dimensional representation is advantageous for viewing spatial trends and performing change detection.
Two-dimensional model-to-model analyses were also performed through interpolated cross sections. At least one cross section was chosen at each gully in locations that featured both high survey and photogrammetry point density. These high-density areas tended to be in the vicinity of checkdams and knickpoints, features that require dense surveying for the purpose of change detection and monitoring. Points were created in *Terramodel* and elevations were extracted for each dataset in Arc/Info using *tinspot*.

**RESULTS**

**Point-to-Point**

Data were analyzed in terms of both raw difference and absolute value. Means and medians of raw differences are helpful in showing the full range of data and any preference in the positive or negative direction, whereas absolute values indicate magnitude of difference and are valuable for representing probable error of a single point. Point-to-point elevation comparisons of February and October ground survey datasets yield a normal distribution with a mean and median of zero and an absolute-value median of less than 2 cm (Table 3.3, Fig. 3.5A). Comparison of common March and October manual photogrammetry points show a similar distribution, but deviate more from each other than the overlapping ground-survey points. The photogrammetry point distribution is skewed by the Granite Park site, since the October points are consistently higher than any of the other photogrammetry datasets. With Granite Park eliminated, the March-October photogrammetry comparison also has a mean and median near zero. These
distributions validate the qualitative field observation of no elevation change in these areas between time intervals.

March and October manual photogrammetry points were compared to common ground survey points from their respective date to determine elevation error of the photogrammetry. Means and medians of these comparisons are also near zero, indicating lack of systematic error overestimating or underestimating elevation during manual collection. Absolute mean error for March is 6.6 cm, and for October is 7.6 cm. This error is approximately the same spatial scale as the centimeter-to-decimeter dimension gully features of interest.

Profile knickpoint detection varied from site-to-site, but overall the photogrammetric surveying was able to resolve 29 and 25% of knickpoints identified during respective February and October ground surveys (Table 3.4). Only 4 individual knickpoints were resolved at both time intervals, indicating that although photogrammetry has potential to identify small features, the repeatability of the tool at this scale is poor.

Knickpoints were also located in stereo planview. The lateral position of knickpoint tops were recorded and then compared to knickpoint locations from the ground survey. Photogrammetry was more effective in resolving knickpoints in planview than in profile view (Table 3.5), but the method was still only able to locate ~50% of surveyed features on average. 26 of 33 (78%) of individual knickpoints resolved in March were resolved again in October. Simply identifying knickpoints and their position (x, y coordinates) is somewhat more effective and repeatable than modeling full knickpoints (x, y, z coordinates) with photogrammetry. Detection percentages at each
site for both profile and planview identification is consistent between successive surveys, and knickpoint height seems to have no influence. These facts indicate that utility of photogrammetry is site-variable.

**TABLE 3.3. ABSOLUTE VALUE ELEVATION DIFFERENCES OF COMMON POINTS**

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>mean</th>
<th>stdev</th>
<th>min (q0)</th>
<th>q1</th>
<th>median (q2)</th>
<th>q3</th>
<th>max (q4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb/Oct Survey Sets</td>
<td>199</td>
<td>0.030</td>
<td>0.036</td>
<td>0.000</td>
<td>0.008</td>
<td>0.018</td>
<td>0.039</td>
<td>0.233</td>
</tr>
<tr>
<td>Feb/Oct Photo Sets</td>
<td>36</td>
<td>0.092</td>
<td>0.104</td>
<td>0.001</td>
<td>0.028</td>
<td>0.073</td>
<td>0.107</td>
<td>0.529</td>
</tr>
<tr>
<td>Feb Photo Error</td>
<td>84</td>
<td>0.066</td>
<td>0.069</td>
<td>0.003</td>
<td>0.029</td>
<td>0.044</td>
<td>0.079</td>
<td>0.481</td>
</tr>
<tr>
<td>Oct Photo Error</td>
<td>77</td>
<td>0.076</td>
<td>0.078</td>
<td>0.000</td>
<td>0.020</td>
<td>0.053</td>
<td>0.105</td>
<td>0.451</td>
</tr>
</tbody>
</table>

Figure 3.5. Histograms showing point-to-point differences. A) February-October ground surveys; B) March-October photogrammetric surveys; C) March photogrammetry compared to February ground surveys; D) October photogrammetry compared to October ground surveys.
TABLE 3.4. SUMMARY PROFILE KNICKPOINT DETECTION

<table>
<thead>
<tr>
<th>Site</th>
<th>February Survey (#)</th>
<th>March Photogrammetry (#)</th>
<th>Percent Detected</th>
<th>October Survey (#)</th>
<th>October Photogrammetry (#)</th>
<th>Percent Detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indian Canyon</td>
<td>13</td>
<td>5</td>
<td>38</td>
<td>16</td>
<td>6</td>
<td>38</td>
</tr>
<tr>
<td>Arroyo Grande</td>
<td>24</td>
<td>2</td>
<td>8</td>
<td>24</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Granite Park</td>
<td>15</td>
<td>7</td>
<td>47</td>
<td>15</td>
<td>4</td>
<td>27</td>
</tr>
<tr>
<td>Gorilla Camp</td>
<td>16</td>
<td>6</td>
<td>38</td>
<td>13</td>
<td>5</td>
<td>38</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>68</td>
<td>20</td>
<td>29</td>
<td>68</td>
<td>19</td>
<td>27</td>
</tr>
</tbody>
</table>

TABLE 3.5. SUMMARY PLANVIEW KNICKPOINT DETECTION

<table>
<thead>
<tr>
<th>Site</th>
<th>February Survey (#)</th>
<th>March Photogrammetry (#)</th>
<th>Percent Detected</th>
<th>October Survey (#)</th>
<th>October Photogrammetry (#)</th>
<th>Percent Detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indian Canyon</td>
<td>13</td>
<td>8</td>
<td>62</td>
<td>16</td>
<td>9</td>
<td>56</td>
</tr>
<tr>
<td>Arroyo Grande</td>
<td>24</td>
<td>10</td>
<td>42</td>
<td>24</td>
<td>9</td>
<td>38</td>
</tr>
<tr>
<td>Granite Park</td>
<td>15</td>
<td>9</td>
<td>60</td>
<td>15</td>
<td>7</td>
<td>47</td>
</tr>
<tr>
<td>Gorilla Camp</td>
<td>16</td>
<td>6</td>
<td>38</td>
<td>13</td>
<td>5</td>
<td>38</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>68</td>
<td>33</td>
<td>49</td>
<td>68</td>
<td>30</td>
<td>44</td>
</tr>
</tbody>
</table>

**Point-to-model**

**Semi-automated**

The semi-automated photogrammetry collects vast amounts of elevation points in a short of time, but does not offer the control and discretion of a manual photogrammetric or ground survey. Residual statistics from the comparison of ground survey points to semi-automated terrain models show that the March DTMs tended to be more accurate than the equivalent October DTMs, with an absolute mean error for the respective datasets of 8 and 10 cm (Tables 3.6 and 3.7). Semi-automated error distributions are shifted slightly in the positive direction, suggesting that the photogrammetry tends to overestimate elevation (Fig. 3.6).
Figure 3.6. Error distributions for semi-automated DTMs. Both have means and medians that are positive, the October dataset (B) more than the March dataset (A).

**TABLE 3.6. MARCH SEMI-AUTOMATED PHOTOGRAMMETRY ABSOLUTE VALUE ERROR (M)**

<table>
<thead>
<tr>
<th>Site</th>
<th>n</th>
<th>mean</th>
<th>stdev</th>
<th>min (q₀)</th>
<th>q₁</th>
<th>median (q₂)</th>
<th>q₃</th>
<th>max (q₄)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indian Camp</td>
<td>1138</td>
<td>0.09</td>
<td>0.09</td>
<td>0.00</td>
<td>0.03</td>
<td>0.06</td>
<td>0.11</td>
<td>0.83</td>
</tr>
<tr>
<td>Arroyo Grande Overall</td>
<td>1464</td>
<td>0.07</td>
<td>0.09</td>
<td>0.00</td>
<td>0.02</td>
<td>0.04</td>
<td>0.08</td>
<td>0.67</td>
</tr>
<tr>
<td>Arroyo Grande West</td>
<td>273</td>
<td>0.04</td>
<td>0.03</td>
<td>0.00</td>
<td>0.01</td>
<td>0.03</td>
<td>0.05</td>
<td>0.18</td>
</tr>
<tr>
<td>Arroyo Grande Central</td>
<td>431</td>
<td>0.08</td>
<td>0.09</td>
<td>0.00</td>
<td>0.02</td>
<td>0.05</td>
<td>0.10</td>
<td>0.49</td>
</tr>
<tr>
<td>Arroyo Grande Tributary</td>
<td>243</td>
<td>0.05</td>
<td>0.04</td>
<td>0.00</td>
<td>0.02</td>
<td>0.04</td>
<td>0.06</td>
<td>0.28</td>
</tr>
<tr>
<td>Arroyo Grande Main</td>
<td>517</td>
<td>0.09</td>
<td>0.10</td>
<td>0.00</td>
<td>0.03</td>
<td>0.05</td>
<td>0.11</td>
<td>0.67</td>
</tr>
<tr>
<td>Granite Park</td>
<td>1073</td>
<td>0.04</td>
<td>0.05</td>
<td>0.00</td>
<td>0.01</td>
<td>0.03</td>
<td>0.06</td>
<td>0.54</td>
</tr>
<tr>
<td>Gorilla Camp Overall</td>
<td>1261</td>
<td>0.13</td>
<td>0.16</td>
<td>0.00</td>
<td>0.03</td>
<td>0.07</td>
<td>0.16</td>
<td>1.22</td>
</tr>
<tr>
<td>Gorilla Camp West</td>
<td>232</td>
<td>0.14</td>
<td>0.14</td>
<td>0.00</td>
<td>0.04</td>
<td>0.11</td>
<td>0.19</td>
<td>0.72</td>
</tr>
<tr>
<td>Gorilla Camp Central</td>
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<td>0.09</td>
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</tr>
<tr>
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<td>0.05</td>
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<td>0.07</td>
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<td>0.11</td>
<td>0.00</td>
<td>0.02</td>
<td>0.05</td>
<td>0.10</td>
<td>1.22</td>
</tr>
</tbody>
</table>

1See Appendix B for site maps

**TABLE 3.7. OCTOBER SEMI-AUTOMATED PHOTOGRAMMETRY ABSOLUTE VALUE ERROR (M)**

<table>
<thead>
<tr>
<th>Site</th>
<th>n</th>
<th>mean</th>
<th>stdev</th>
<th>min (q₀)</th>
<th>q₁</th>
<th>median (q₂)</th>
<th>q₃</th>
<th>max (q₄)</th>
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<tbody>
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<td>0.71</td>
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<tr>
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<td>0.08</td>
<td>0.13</td>
<td>0.62</td>
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<td>0.00</td>
<td>0.06</td>
<td>0.11</td>
<td>0.21</td>
<td>0.71</td>
</tr>
<tr>
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<td>0.08</td>
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<td>0.06</td>
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<tr>
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<td>0.02</td>
<td>0.03</td>
<td>0.07</td>
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<tr>
<td>Gorilla Camp East-most</td>
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<td>0.03</td>
<td>0.09</td>
<td>0.17</td>
<td>0.74</td>
</tr>
<tr>
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<td>0.00</td>
<td>0.03</td>
<td>0.08</td>
<td>0.13</td>
<td>1.33</td>
</tr>
</tbody>
</table>

1See Appendix B for site maps

**Manual**

Point-to-model comparisons utilized the Arc/Info *tinspot* command to compare elevations of survey points to corresponding points extracted off the manual.
photogrammetry DTMs. We compared channel long profiles as well as entire channel
DTMs. Long-profile comparisons measured the difference between ground-surveyed
thalweg point elevations and the interpolated manually-collected photogrammetry
elevations from the same locations. Again, the March photogrammetry dataset was more
accurate than the October dataset (Tables 3.8 and 3.9), with absolute value mean errors of
6 and 9 cm, respectively, for long-profile datasets. Most interpolated profiles represent
the form of the true survey profile well (Fig. 3.7A), although clusters of anomalous points
that result in higher error exist in reaches that are steep or have overhanging vegetation
that inhibit photogrammetric point collection (Fig. 3.7B).

### TABLE 3.8. MARCH MANUAL PHOTOGRAMMETRY PROFILE

<table>
<thead>
<tr>
<th>Site</th>
<th>n</th>
<th>mean</th>
<th>stdev</th>
<th>min (q₀)</th>
<th>q₁</th>
<th>median (q₂)</th>
<th>q₃</th>
<th>max (q₄)</th>
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<td>0.06</td>
<td>0.00</td>
<td>0.03</td>
<td>0.06</td>
<td>0.10</td>
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</tr>
<tr>
<td>Arroyo Grande Overall</td>
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<td>0.06</td>
<td>0.00</td>
<td>0.02</td>
<td>0.04</td>
<td>0.09</td>
<td>0.39</td>
</tr>
<tr>
<td>Arroyo Grande West</td>
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<td>0.03</td>
<td>0.03</td>
<td>0.00</td>
<td>0.01</td>
<td>0.02</td>
<td>0.05</td>
<td>0.13</td>
</tr>
<tr>
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<td>0.05</td>
<td>0.00</td>
<td>0.02</td>
<td>0.04</td>
<td>0.09</td>
<td>0.25</td>
</tr>
<tr>
<td>Arroyo Grande Tributary</td>
<td>34</td>
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<td>0.04</td>
<td>0.00</td>
<td>0.01</td>
<td>0.03</td>
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<td>0.06</td>
<td>0.11</td>
<td>0.39</td>
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<td>0.01</td>
<td>0.03</td>
<td>0.06</td>
<td>0.20</td>
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<td>0.02</td>
<td>0.05</td>
<td>0.09</td>
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<tr>
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<td>0.09</td>
<td>0.00</td>
<td>0.02</td>
<td>0.04</td>
<td>0.11</td>
<td>0.45</td>
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<td>0.05</td>
<td>0.00</td>
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<td>0.06</td>
<td>0.09</td>
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<tr>
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<td>0.02</td>
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<td>0.03</td>
<td>0.06</td>
<td>0.10</td>
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<tr>
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<td>0.00</td>
<td>0.02</td>
<td>0.04</td>
<td>0.09</td>
<td>0.45</td>
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</table>

### TABLE 3.9. OCTOBER MANUAL PHOTOGRAMMETRY PROFILE

<table>
<thead>
<tr>
<th>Site</th>
<th>n</th>
<th>mean</th>
<th>stdev</th>
<th>min (q₀)</th>
<th>q₁</th>
<th>median (q₂)</th>
<th>q₃</th>
<th>max (q₄)</th>
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<td>0.06</td>
<td>0.00</td>
<td>0.03</td>
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<td>0.08</td>
<td>0.13</td>
<td>0.43</td>
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<tr>
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<td>0.04</td>
<td>0.09</td>
<td>0.14</td>
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<td>0.04</td>
<td>0.05</td>
<td>0.10</td>
<td>0.25</td>
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<tr>
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<td>0.43</td>
</tr>
<tr>
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<td>0.09</td>
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<td>0.00</td>
<td>0.03</td>
<td>0.06</td>
<td>0.14</td>
<td>0.59</td>
</tr>
<tr>
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<td>0.12</td>
<td>0.00</td>
<td>0.05</td>
<td>0.11</td>
<td>0.20</td>
<td>0.59</td>
</tr>
<tr>
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<td>0.04</td>
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<td>0.02</td>
<td>0.04</td>
<td>0.06</td>
<td>0.20</td>
</tr>
<tr>
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<td>0.06</td>
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<tr>
<td>Gorilla Camp East-most</td>
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<td>0.03</td>
<td>0.06</td>
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<td>0.31</td>
</tr>
<tr>
<td>Overall Sites</td>
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<td>0.07</td>
<td>0.00</td>
<td>0.04</td>
<td>0.07</td>
<td>0.12</td>
<td>0.59</td>
</tr>
</tbody>
</table>
Figure 3.7. Longitudinal profiles of gully thalwegs. “A” is an example of a gully with a very accurate manual photogrammetry profile; “B” is an example of a gully with less consistent accuracy.
Accuracies of entire-channel terrain models were determined by comparing model spot elevations to the elevations of all corresponding survey points collected in gullies. March and October accuracy both are ~10 cm for absolute mean and standard deviation (Tables 3.10 and 3.11, Appendix I, Figs. 3.8, 3.9). Histograms of complete point-to-model datasets show that the error is normally distributed around zero for the March manual DTMs. The mean October error is 2 cm (overestimation), but when the Granite Park site is removed the October error curve is a normal distribution with a mean of zero. Other than the October Granite Park site, which is consistently high in elevation, the manual collection appears to be free of systematic error.

<table>
<thead>
<tr>
<th>Site</th>
<th>n</th>
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<th>stdev</th>
<th>min (q1)</th>
<th>q0</th>
<th>median (q2)</th>
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<td>0.97</td>
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<tr>
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<td>0.01</td>
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<td>0.04</td>
<td>0.08</td>
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</tr>
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</tbody>
</table>

<table>
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<tr>
<th>Site</th>
<th>n</th>
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<th>stdev</th>
<th>min (q1)</th>
<th>q0</th>
<th>median (q2)</th>
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<th>max (q4)</th>
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<td>0.02</td>
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<td>0.08</td>
<td>0.15</td>
<td>0.75</td>
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<td>0.03</td>
<td>0.06</td>
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<td>0.59</td>
</tr>
<tr>
<td>Gorilla Camp West</td>
<td>175</td>
<td>0.12</td>
<td>0.12</td>
<td>0.00</td>
<td>0.04</td>
<td>0.08</td>
<td>0.16</td>
<td>0.59</td>
</tr>
<tr>
<td>Gorilla Camp Central</td>
<td>85</td>
<td>0.07</td>
<td>0.07</td>
<td>0.00</td>
<td>0.02</td>
<td>0.05</td>
<td>0.09</td>
<td>0.43</td>
</tr>
<tr>
<td>Gorilla Camp East</td>
<td>267</td>
<td>0.06</td>
<td>0.06</td>
<td>0.00</td>
<td>0.02</td>
<td>0.04</td>
<td>0.08</td>
<td>0.45</td>
</tr>
<tr>
<td>Gorilla Camp East-most</td>
<td>328</td>
<td>0.10</td>
<td>0.10</td>
<td>0.00</td>
<td>0.03</td>
<td>0.07</td>
<td>0.13</td>
<td>0.54</td>
</tr>
<tr>
<td>All Sites</td>
<td>3741</td>
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<td>0.00</td>
<td>0.03</td>
<td>0.07</td>
<td>0.12</td>
<td>0.77</td>
</tr>
</tbody>
</table>
Figure 3.8. Error distributions for March (A) and October (B, C) manual photogrammetric DTMs.
Figure 3.9. Example point-to-model comparison showing photogrammetry DTM vertical error for A) Granite Park and B) Gorilla Camp. Legend shows error in terms of quartiles.
We evaluated the effects of surface ruggedness and point density on DTM data quality using similar methods to Heritage et al. (1998). Standard deviation of surface elevations (SDSE) based on ground surveys was the measure used to quantify local surface variability. Grids with 0.2 m cell size were created in ArcGIS directly from the TINs rather than interpolated from points, and the ARC/INFO Grid module function *focalstd* was used to calculate the SDSE for 1 x 1 m rectangles across each site (Fig. 3.10). Density of the manual photogrammetric sampling was also quantified in Grid using the *pointdensity* function, which employs a kernel function to give a smoothed grid representing the number of elevation points within a 1 m radius of each grid cell (Fig. 3.11). Output SDSE and density values were extracted from these grids at each survey point using *latticespot* to compare to point-to-model error. Dividing density values by SDSE values for each point can put error in terms of the ratio between photogrammetric sampling density and topographic ruggedness (Fig. 3.12).

![Figure 3.10. Example of a SDSE grid. High SDSE (dark shades) values often coincide with high error (black dots)](image-url)
Figure 3.11. Example of a point density grid. Low density (dark shades) values often coincide with high errors (black dots).

Figure 3.12. Example of a density/SDSE grid. This was created by dividing the density grid in Figure 3.11 by the SDSE grid in Figure 3.10. Low density/SDSE values (dark shades) often coincide with high errors (black dots).
The data indicate a positive relation between the SDSE and associated error and a negative relation between photogrammetric sample density and associated error (Fig. 3.13, 3.14). Tremendous scatter exists in these relations, but the general trend can be identified by using a log-bin average, which groups data into logarithmic (increasing by factors of 10) intervals and averages them in order to smooth the scatter. By comparing the ratio of point density and SDSE to error for each point, we can estimate the photogrammetry sampling density needed to adequately represent various types of topography (e.g. Heritage et al., 1998). Both March and October datasets show that absolute error steadily decreases with increasing density/SDSE values, but the trend of decreasing error diminishes when the ratio exceeds ~40 (Fig. 3.15).

Figure 3.13. Raw and log-bin average plots showing the relation between standard deviation of surface elevation (terrain irregularity) and absolute error for March (A) and October (B).
Figure 3.14. Raw and log-bin average plots showing the relation between photogrammetry sample density and absolute error for March (A) and October (B).

This density/SDSE threshold is approximately 40 for both datasets, although the error inflection point is lower for the March data (0.05 m) than for October (0.065 m). Maximum photogrammetric accuracy should theoretically be achieved under an optimal density/SDSE ratio, a tool that may aid in identifying the desired point density needed for any given terrain in order to maximize DTM accuracy. Simple algebra performed in a GIS can show spatial density requirements for maximum accuracy at each site. Multiplying the standard deviation grid by 40 will result in a required density grid map (Fig. 3.16, Appendix M).
Figure 3.15. Raw and log-bin average plots showing the relation between density/SDSE ratio and absolute error for March (A) and October (B). Note that average error values steadily decrease until a ratio of 40, then appears to level out (shown by dotted line). Obtaining a ratio of higher than 40 would not necessarily result in higher quality data.
Figure 3.16. Calculated density (pts/m²) required to achieve optimal vertical accuracy (density/SDSE = 40) for the topography at (A) Indian Canyon and (B) Granite Park. Granite Park has less relief and topographic ruggedness than Indian Canyon, so it requires a smaller density to obtain high accuracy. Maps such as these could be used during manual photogrammetric collection to ensure proper sampling.
Model-to-Model

Channel DTMs and channel cross-sections were directly compared to each other in the final phase of comparison. Ground survey grids of 0.2 m cell size were subtracted from corresponding manual photogrammetry grids for each site and time interval to identify deviation between the two DTMs. Statistics and spatial trends of grid comparison are shown in Table 3.12 and 3.13, Appendix I, and Figure 3.17. Model-to-model comparisons yielded overall mean and standard deviation error of 10 cm, approximately the same accuracy as point-to-model comparisons. The maximum DTM errors of model-to-model comparison (2.49 m) did tend to be higher than maximum errors resulting from point-to-model (0.97 m), but these deviant points are not present in every gully. This similarity is to be expected, since the DTMs were interpolated directly from the ground survey and manual photogrammetry TINs.

**Table 3.12. March Manual Photogrammetry DEM Absolute Value Error (m)**

<table>
<thead>
<tr>
<th>Site</th>
<th>n</th>
<th>mean</th>
<th>stdev</th>
<th>min (q0)</th>
<th>median (q2)</th>
<th>max (q4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indian Camp</td>
<td>5493</td>
<td>0.12</td>
<td>0.11</td>
<td>0.00</td>
<td>0.04</td>
<td>0.09</td>
</tr>
<tr>
<td>Arroyo Grande Overall</td>
<td>3777</td>
<td>0.13</td>
<td>0.15</td>
<td>0.00</td>
<td>0.03</td>
<td>0.07</td>
</tr>
<tr>
<td>Arroyo Grande West</td>
<td>369</td>
<td>0.04</td>
<td>0.04</td>
<td>0.00</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>Arroyo Grande Central</td>
<td>554</td>
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<td>0.17</td>
<td>0.00</td>
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<td>0.07</td>
</tr>
<tr>
<td>Arroyo Grande Tributary</td>
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<td>0.00</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>Arroyo Grande Main</td>
<td>2330</td>
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<td>0.17</td>
<td>0.00</td>
<td>0.04</td>
<td>0.09</td>
</tr>
<tr>
<td>Granite Park</td>
<td>7343</td>
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<td>0.06</td>
<td>0.00</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>Gorilla Camp Overall</td>
<td>3617</td>
<td>0.11</td>
<td>0.12</td>
<td>0.00</td>
<td>0.03</td>
<td>0.07</td>
</tr>
<tr>
<td>Gorilla Camp West</td>
<td>990</td>
<td>0.12</td>
<td>0.11</td>
<td>0.00</td>
<td>0.04</td>
<td>0.09</td>
</tr>
<tr>
<td>Gorilla Camp Central</td>
<td>462</td>
<td>0.11</td>
<td>0.08</td>
<td>0.00</td>
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<td>0.10</td>
</tr>
<tr>
<td>Gorilla Camp East</td>
<td>696</td>
<td>0.08</td>
<td>0.07</td>
<td>0.00</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>Gorilla Camp East-most</td>
<td>1275</td>
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<td>0.15</td>
<td>0.00</td>
<td>0.03</td>
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</tr>
<tr>
<td>All Sites</td>
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<td>0.10</td>
<td>0.00</td>
<td>0.03</td>
<td>0.07</td>
</tr>
</tbody>
</table>

n represents number of grid cells used in comparison

**Table 3.13. October Manual Photogrammetry DEM Absolute Value Error (m)**

<table>
<thead>
<tr>
<th>Site</th>
<th>n</th>
<th>mean</th>
<th>stdev</th>
<th>min (q0)</th>
<th>median (q2)</th>
<th>max (q4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indian Camp</td>
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<td>0.15</td>
<td>0.00</td>
<td>0.03</td>
<td>0.07</td>
</tr>
<tr>
<td>Arroyo Grande Overall</td>
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</tr>
<tr>
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<td>0.00</td>
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</tr>
<tr>
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<td>0.00</td>
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<td>0.08</td>
</tr>
<tr>
<td>Arroyo Grande Tributary</td>
<td>583</td>
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<td>0.00</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>Arroyo Grande Main</td>
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<td>0.13</td>
<td>0.00</td>
<td>0.04</td>
<td>0.08</td>
</tr>
<tr>
<td>Granite Park</td>
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<td>0.07</td>
<td>0.00</td>
<td>0.04</td>
<td>0.08</td>
</tr>
<tr>
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<td>0.10</td>
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<td>0.06</td>
</tr>
<tr>
<td>Gorilla Camp West</td>
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<td>0.09</td>
<td>0.00</td>
<td>0.03</td>
<td>0.07</td>
</tr>
<tr>
<td>Gorilla Camp Central</td>
<td>462</td>
<td>0.09</td>
<td>0.07</td>
<td>0.00</td>
<td>0.03</td>
<td>0.07</td>
</tr>
<tr>
<td>Gorilla Camp East</td>
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<td>0.00</td>
<td>0.03</td>
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</tr>
<tr>
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<td>0.05</td>
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<td>0.00</td>
<td>0.03</td>
<td>0.07</td>
</tr>
</tbody>
</table>

n represents number of grid cells used in comparison
Figure 3.17. Example model-to-model comparison showing photogrammetry DTM vertical error for A) Granite Park and B) Indian Canyon in March. Legend shows error in terms of quartiles.
At least one cross-section was extracted from photogrammetry and ground survey TINs of each gully channel at each time interval (Appendix L). These cross-section locations were placed in areas of interest with high ground-survey and photogrammetry point density, such as above erosion-control structures or knickpoints. Accuracy of photogrammetric channel cross-sections was slightly better than the accuracy of the DTM-to-DTM surface difference comparison. Mean absolute-value error for both March and October datasets was 9 cm, and the maximum and standard deviation of error was under 0.45 m and 0.09 m, respectively, for each time interval (Table 3.14 and 3.15). Since the cross-sections were placed in high-density regions, fairly accurate representations of the channel could be extracted (Fig. 3.18A). As expected, cross sections extracted from highly irregular channels or areas of low point density are less reliable (Fig. 3.18B).

**TABLE 3.14. MARCH MANUAL PHOTOGRAMMETRY CHANNEL CROSS SECTION ABSOLUTE VALUE ERROR (M)**

<table>
<thead>
<tr>
<th>Site</th>
<th>n</th>
<th>mean</th>
<th>stdev</th>
<th>min (q0)</th>
<th>Q1</th>
<th>median (q2)</th>
<th>Q3</th>
<th>max (q4)</th>
</tr>
</thead>
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<tr>
<td>Indian Camp</td>
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<td>0.06</td>
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<td>0.04</td>
<td>0.04</td>
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<td>0.20</td>
</tr>
<tr>
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<td>0.04</td>
<td>0.00</td>
<td>0.03</td>
<td>0.06</td>
<td>0.08</td>
<td>0.17</td>
</tr>
<tr>
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<td>18</td>
<td>0.05</td>
<td>0.03</td>
<td>0.01</td>
<td>0.02</td>
<td>0.05</td>
<td>0.08</td>
<td>0.10</td>
</tr>
<tr>
<td>Arroyo Grande Central</td>
<td>15</td>
<td>0.07</td>
<td>0.06</td>
<td>0.01</td>
<td>0.02</td>
<td>0.05</td>
<td>0.13</td>
<td>0.17</td>
</tr>
<tr>
<td>Arroyo Grande Tributary</td>
<td>17</td>
<td>0.06</td>
<td>0.04</td>
<td>0.00</td>
<td>0.02</td>
<td>0.07</td>
<td>0.08</td>
<td>0.13</td>
</tr>
<tr>
<td>Arroyo Grande Main</td>
<td>26</td>
<td>0.06</td>
<td>0.02</td>
<td>0.00</td>
<td>0.04</td>
<td>0.07</td>
<td>0.08</td>
<td>0.10</td>
</tr>
<tr>
<td>Granite Park</td>
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<td>0.06</td>
<td>0.05</td>
<td>0.00</td>
<td>0.03</td>
<td>0.05</td>
<td>0.11</td>
<td>0.14</td>
</tr>
<tr>
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<td>0.11</td>
<td>0.00</td>
<td>0.05</td>
<td>0.09</td>
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<td>0.44</td>
</tr>
<tr>
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<td>0.12</td>
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<td>0.13</td>
<td>0.18</td>
<td>0.28</td>
<td>0.44</td>
</tr>
<tr>
<td>Gorilla Camp Central</td>
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<td>0.11</td>
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<td>0.06</td>
<td>0.12</td>
<td>0.20</td>
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</tr>
<tr>
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<td>0.02</td>
<td>0.05</td>
<td>0.07</td>
<td>0.09</td>
<td>0.15</td>
</tr>
<tr>
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<td>0.00</td>
<td>0.07</td>
<td>0.08</td>
<td>0.23</td>
<td>0.39</td>
</tr>
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<td>0.09</td>
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<td>0.01</td>
<td>0.05</td>
<td>0.18</td>
<td>0.27</td>
</tr>
<tr>
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<td>0.00</td>
<td>0.04</td>
<td>0.07</td>
<td>0.13</td>
<td>0.44</td>
</tr>
</tbody>
</table>

1 Each site entry represents one gully cross section
2 n represents number of points in each cross section
### TABLE 3.15. OCTOBER MANUAL PHOTOGRAMMETRY CROSS SECTION ABSOLUTE VALUE ERROR (M)

<table>
<thead>
<tr>
<th>Site</th>
<th>n²</th>
<th>mean</th>
<th>stdev</th>
<th>min ($q_0$)</th>
<th>$q_1$</th>
<th>median ($q_2$)</th>
<th>$q_3$</th>
<th>max ($q_4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indian Camp</td>
<td>17</td>
<td>0.05</td>
<td>0.04</td>
<td>0.01</td>
<td>0.03</td>
<td>0.04</td>
<td>0.07</td>
<td>0.17</td>
</tr>
<tr>
<td>Arroyo Grande Overall</td>
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<td>0.08</td>
<td>0.06</td>
<td>0.00</td>
<td>0.03</td>
<td>0.05</td>
<td>0.14</td>
<td>0.21</td>
</tr>
<tr>
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<td>0.17</td>
<td>0.02</td>
<td>0.13</td>
<td>0.16</td>
<td>0.17</td>
<td>0.19</td>
<td>0.21</td>
</tr>
<tr>
<td>Arroyo Grande Central</td>
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<td>0.06</td>
<td>0.04</td>
<td>0.00</td>
<td>0.02</td>
<td>0.06</td>
<td>0.08</td>
<td>0.14</td>
</tr>
<tr>
<td>Arroyo Grande Tributary</td>
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<td>0.02</td>
<td>0.00</td>
<td>0.01</td>
<td>0.02</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>Arroyo Grande Main</td>
<td>26</td>
<td>0.06</td>
<td>0.05</td>
<td>0.00</td>
<td>0.03</td>
<td>0.05</td>
<td>0.07</td>
<td>0.19</td>
</tr>
<tr>
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<td>0.05</td>
<td>0.01</td>
<td>0.04</td>
<td>0.06</td>
<td>0.09</td>
<td>0.18</td>
</tr>
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<td>0.07</td>
<td>0.14</td>
<td>0.35</td>
</tr>
<tr>
<td>Gorilla Camp West</td>
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<td>0.21</td>
<td>0.08</td>
<td>0.02</td>
<td>0.19</td>
<td>0.25</td>
<td>0.25</td>
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</tr>
<tr>
<td>Gorilla Camp Central</td>
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<td>0.06</td>
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<td>0.03</td>
<td>0.06</td>
<td>0.14</td>
<td>0.22</td>
</tr>
<tr>
<td>Gorilla Camp East</td>
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<td>0.10</td>
<td>0.00</td>
<td>0.01</td>
<td>0.06</td>
<td>0.10</td>
<td>0.35</td>
</tr>
<tr>
<td>Gorilla Camp East-most 1</td>
<td>21</td>
<td>0.06</td>
<td>0.04</td>
<td>0.00</td>
<td>0.04</td>
<td>0.06</td>
<td>0.09</td>
<td>0.14</td>
</tr>
<tr>
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<td>0.05</td>
<td>0.10</td>
<td>0.19</td>
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<td>All Sites</td>
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<td>0.07</td>
<td>0.00</td>
<td>0.03</td>
<td>0.06</td>
<td>0.14</td>
<td>0.35</td>
</tr>
</tbody>
</table>

1 Each site entry represents one gully cross section
2 n represents number of points in each cross section

Figure 3.18. Examples of channel cross-sections extracted from DTMs. A) one of the most accurate photogrammetry-derived; B) one of the least accurate.

**Minimum Erosion Detectable between March and October**

Field evidence and repeat photography during the October survey indicated at least one large runoff and erosion event occurred during the study period in eastern Grand Canyon. However, little to no runoff and erosion occurred in our four study sites in western Grand Canyon, where only two of the 10 gullies exhibited change: Indian Canyon and Gorilla Camp. Repeat photography and survey-profile comparison show that the upper reach of the Indian Canyon gully incised and widened by several centimeters,
the lower reach of the Indian Canyon gully aggraded slightly, and the upper reach of
the eastern-most Gorilla Camp gully was the site of <20 cm of eolian sand deposition
(Figs. 3.19, 3.20). These two gully reaches will be the primary focus of our change
detection, and the relatively subtle changes at these sites are well-suited for realistically
testing the utility of photogrammetry for monitoring.

Figure 3.19. Channel incision and widening in the Indian Canyon gully between
February (A) and October (B).

Figure 3.20. Eolian infilling in the east-most Gorilla Camp gully between February (A)
and October (B). Note that rocks and vegetation in middle of February photo are covered
in eolian sand in October.
It is imperative to determine the amount of topographic change needed to be depicted in a statistically significant way, so it is not confused with measurement uncertainty inherent in field and computational methods. In other words, the topographic change that occurs must be greater than the error of the photogrammetry in order for the tool to be able to detect change with certainty. Recent studies of monitoring methods have used accuracy assessments to calculate a threshold of topographic change needed for true detection (Brasington et al., 2000; Adams and Chandler, 2002). These studies propagate error by applying the following equation (proof in Squires, 1968): 

\[ E = \left( (e_1)^2 + (e_2)^2 \right)^{0.5} \]  

where \( E \) is the combined error, and \( e_1 \) and \( e_2 \) are two standard deviations (2\( \sigma \)) of error distributions in each dataset.

We have shown that photogrammetry DTM error varies spatially with topographic ruggedness and the density of data points collected. Thus it is illogical to assume a single threshold of change detectable across an entire site or even an entire gully. Where the topography is gentle and the DTM dense with points, there will be greater accuracy and certainty than where the gully is deeply incised and DTM points sparse.

Density/SDSE grids for both March and October were created with 0.2 m cell size in ArcGIS and assigned 2\( \sigma \) error values from empirical error regressions for each time interval (Table 3.16, Figure 3.21). Error at 2\( \sigma \) for March is described as:

\[ 0.55(\text{density/SDSE})^{0.33} \]  

and error at 2\( \sigma \) for October is described as:

\[ 0.64(\text{density/SDSE})^{0.31} \]
These power functions, derived from Table 3.16 and Figure 3.21, show that the October data are not as accurate as the March data at a given density/SDSE value.

Error was combined by applying Equation 1 to the October and March density/SDSE grids in the raster calculator to create a "critical error" grid. The thresholds of erosion detection for the two sites are several decimeters when density/SDSE is low and are \(-20\) cm when density/SDSE is 40 or higher. This means that several decimeters of vertical change must occur in rugged topography where there are few photogrammetry points in order to be detected by the tool, whereas the photogrammetry requires as low as 20 cm of topographic change to detect erosion and deposition in gentle terrain with high point density.

"Change" grids, maps showing grid cells of erosion, deposition, and no change, were created by subtracting October photogrammetry elevation grids from March photogrammetry elevation grids at the two sites of interest. A query was then performed in ArcMap to show cells of the "change" grid that exceed the values of the respective cells in "critical error" grid. "Change" cell values that do exceed the "critical error" exhibit significant positive (erosion) or negative (deposition) change, whereas grid cells that do not exceed the critical values are considered to show no change. The critical change threshold and ability of photogrammetry to detect change will vary spatially, depending on the density/SDSE for each grid cell.

We qualitatively compared the photogrammetry change maps to ground survey "change" grids made by subtracting October ground-survey elevation grids from February ground-survey elevation grids and using a fixed value uncertainty buffer of 10
cm (ground-survey deviation at 2\(\sigma\), Table 3.1) to isolate significant ground-survey elevation change and show trends in erosion and deposition.

<table>
<thead>
<tr>
<th>density/SDSE</th>
<th>March Error (2(\sigma)) (m)</th>
<th>October Error (2(\sigma)) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1</td>
<td>0.43</td>
<td>0.17</td>
</tr>
<tr>
<td>1-2</td>
<td>0.37</td>
<td>0.35</td>
</tr>
<tr>
<td>2-3</td>
<td>0.37</td>
<td>0.55</td>
</tr>
<tr>
<td>3-4</td>
<td>0.53</td>
<td>0.50</td>
</tr>
<tr>
<td>4-5</td>
<td>0.39</td>
<td>0.51</td>
</tr>
<tr>
<td>5-6</td>
<td>0.41</td>
<td>0.50</td>
</tr>
<tr>
<td>6-7</td>
<td>0.23</td>
<td>0.46</td>
</tr>
<tr>
<td>7-8</td>
<td>0.30</td>
<td>0.39</td>
</tr>
<tr>
<td>8-9</td>
<td>0.40</td>
<td>0.37</td>
</tr>
<tr>
<td>9-10</td>
<td>0.36</td>
<td>0.31</td>
</tr>
<tr>
<td>10-20</td>
<td>0.33</td>
<td>0.29</td>
</tr>
<tr>
<td>20-30</td>
<td>0.18</td>
<td>0.23</td>
</tr>
<tr>
<td>30-40</td>
<td>0.14</td>
<td>0.21</td>
</tr>
<tr>
<td>40-50</td>
<td>0.13</td>
<td>0.19</td>
</tr>
<tr>
<td>50-60</td>
<td>0.13</td>
<td>0.18</td>
</tr>
<tr>
<td>60-70</td>
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<td>0.18</td>
</tr>
<tr>
<td>70-80</td>
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</tr>
<tr>
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<td>0.20</td>
</tr>
<tr>
<td>90-100</td>
<td>0.14</td>
<td>0.15</td>
</tr>
<tr>
<td>100-200</td>
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<td>0.16</td>
</tr>
<tr>
<td>200-300</td>
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<td>0.12</td>
</tr>
<tr>
<td>&gt;300</td>
<td>0.12</td>
<td>0.09</td>
</tr>
</tbody>
</table>

*1 Taken from bin averages

Figure 3.21. Plot of density/SDSE vs. error at 2\(\sigma\). October data are black squares, March data are gray circles. Power equations of regression lines were used to represent error for any density/SDSE value.
The erosion noted in the upper reach of the Indian Canyon gully (Fig. 3.19) was shown in the ground-survey comparison, but was undetected by repeat photogrammetry (Fig. 3.22). The lower reach of the same channel is lower in gradient and less incised, and a very limited amount of deposition was detected by the photogrammetry, a general trend confirmed by the field survey change grids (Fig. 3.22). Only 12 cells in the eastern-most Gorilla Camp gully had enough change to show significant deposition through photogrammetry (Fig. 3.23). The <20 cm of aggradation observed in the field in the upper reach of this gully is not quite in the range of detectable change for this particular channel.

Comparison of repeat longitudinal profiles illustrates geomorphic change along a gully, and the best (most dense) photogrammetry DTM data are along the thalweg. Each photogrammetry long-profile data point has an associated density/SDSE ratio and error, which can be applied to change detection at each point. The photogrammetry profiles will show significant change where the difference of the March and October elevation at each point exceeds the error associated with the density/SDSE, as outlined above. Profiles from the Indian Canyon gully showed only four points of significant change between the two photogrammetry DTMs, all of which were deposition (Fig. 3.24). The Gorilla Camp eastern-most gully profiles portray overall deposition, but there was not enough deposition to actually be considered significant (Fig. 3.25).
Figure 3.22. Change-detection maps of Indian Canyon. The ground survey change map (A) shows more erosion in the upper reach and more deposition in the lower reach. None of this change is detected by photogrammetry in the upper reach, and very little change is detected in the lower reach (B).
Figure 3.23. Change-detection maps of east-most Gorilla Camp gully. The ground survey change map (A) shows several areas of deposition throughout the gully, especially in the upper reach, whereas the photogrammetry (B) was able to detect very little of this deposition.
Figure 3.24. Indian Canyon photogrammetry profiles (A) and difference plots (B). Ground-survey profiles not shown.
Figure 3.25. Gorilla Camp photogrammetry profiles and difference plots. Although the profile reveals areas of deposition, no elevation change was great enough be considered significant. Positive difference is denudation, negative difference is deposition.
Semi-Automated vs. Manual Collection of Photogrammetry Data

Overall, the accuracies associated with the semi-automated approach are similar to the manual accuracies when both methods are compared to ground surveys (Tables 3.4, 3.6, and 3.7). However, the manual approach is superior to the semi-automated in modeling particular features of interest in the gullies. The semi-automated method was spatially sporadic and did not necessarily collect DTM points in areas of interest such as gully walls, thalwegs, and knickpoints. This phenomenon is due to the fact that many gully features are in "washed-out" sand and therefore have minimal variations of gray level (contrast), making it difficult for the automatic DTM extraction algorithm to collect points on these features. Manual collection was performed specifically to define knickpoints, thalwegs, channel sides, and other breaklines, resulting in a better DTM.

Semi-automated collection is also unappealing because of its tendency to overestimate elevation. O'Brien et al. (2000) found just the opposite in their sandbar monitoring study, that more systematic error was present in the manual collection. The lack of contrast around the channels in the photos often results in relatively low-density data in these places. These semi-automated DTMs have less detail and higher elevation values due to the lack of control in capturing the true shape and vertical form of the gully walls.

Vegetation may also contribute to the overestimation of semi-automated points in areas where ground-survey points were taken under the canopy or near creosote, mesquite, or various cactus species common to the region (Fig. 3.26, Appendix J). Many
of the automatic DTM points are preferentially collected along the periphery and within such shrubs and cacti, due to the gray-level variations (high contrast) they provide. Consequently, points collected on top of the vegetation may show positive error (Fig. 3.27, Appendix K). To remedy this, a particular set of DTM extraction parameters may be selected to limit the collection of points in vegetated areas, but this often results in low point density and the positive error inherent with greater interpolation.

It is possible that the greater positive error exhibited in the October semi-automated DTMs (Fig. 3.6) could be a result of a fuller, leafier plant canopy during October flight than during the March flight, due to time of year (Fig. 3.28). The Arroyo Grande site had the most vegetation obstructing surveyed gullies, driving the high semi-automated and manual error for October (Tables 3.6, 3.7, 3.8, and 3.9).

Figure 3.26. Semi-automated and manual point distribution for central Arroyo Grande gully. Note how automatic points cluster around and within the vegetation, and are unevenly distributed throughout the sandy gully area.
Figure 3.27. Contours derived from manual and semi-automated points shown in Figure 3.26. The contrast provided by vegetation attracts erroneous detail in semi-automated collection that is too high in elevation, which results in overestimation in elevation where vegetation overhangs the gully.

Poor October photo quality is another factor influencing the accuracy. We observed that the October flight photos were "blurry" compared to the March photos. This reduced photo quality was due to a cloudier day and higher helicopter velocity in March (30 knots for March compared to 55 knots for October), which caused the shutter to remain open longer and allowed excessive movement over a pixel during exposure (Philip A. Davis, USGS, personal communication, 2002). This blurriness may have caused greater difficulty in collecting precise point data for the automatic extraction algorithm, and consequently the collected points may not have been as accurate as the March points.
One would expect that the poorer October images would result in higher DTM errors for the manual collection as well. Although point-to-point and profile comparisons show slightly better accuracies for March, DTM comparisons are remarkably similar between the two sets. The poorer image quality for October was compensated for by improved manual extraction equipment. We used the color anaglyph mode for the March photos, but we upgraded to quad buffered stereo mode for October data, which employs better stereo glasses and an emitter, and allows for clearer, more detailed stereo viewing and feature detection.

Manual Error—Sources and Accuracy

Our highest manual errors consistently occurred in highly vegetated or steep, high-relief shadowed areas, and attempts to collect points through the vegetation or
shadow obstruction often resulted in 1-2 m errors (Fig. 3.29). We found that it was actually better to collect as few points as possible in these shadowy or shrubby regions where the ground could not be seen, making confident modeling and knickpoint detection impossible.

Figure 3.29. Examples of high-relief, vertical banks with shadows (A) and complete obstruction of the channel by vegetation (B). The vegetation overhanging ‘B’ obstructs and impedes photogrammetric detection of 8 knickpoints.

Relatively low photogrammetric accuracy in steep or topographically-irregular areas was also observed by Heritage et al. (1998), O’Brien et al. (2000), Baldi et al. (2002), and Adams and Chandler (2002). Heritage et al. (1998) also observed the effect of point density on photogrammetry accuracy and stated that because resolution is a function of survey point density, point collection should be denser where there is greater local variability in the landscape being sampled. Using a modeled surface is advantageous in that elevations can be interpolated at any location, but if the number of data points the model is based on is not enough to represent true landscape ruggedness in a particular area, the model will be increasingly inaccurate.

One can analyze manual photogrammetry error in terms of only DTM point
density and SDSE, and still indirectly factor the external sources of error of vegetation
and shadows. The error driven by vegetation and shadows is inherent in the density and
ruggedness analysis, since steep, high-relief channels that cast shadows have a high
SDSE (Fig. 3.29A), and surfaces that are obstructed by shadows or vegetation (Fig.
2.29B) tend to have low DTM point density.

Absolute value mean and standard deviations of error magnitude for all levels of
manual assessments each ranged between 6-11 cm for combined sites. Profile and cross-
sections were more accurate than full channel DTMs, and consistently exhibited sub-
decimeter error. Lower DTM error tended to be near the middle of the gully channel,
which is usually flat along the bottom (low SDSE), and higher errors tended to be on
channel banks and other high-slope features.

Model-to-model comparisons exhibited very similar error statistics as point-to-
model. The advantages of point-to-model comparison is that it can view accuracy and/or
change in terms of strictly-defined thalweg, channel side, and channel top features, but
model-to-model comparison accommodates very quick, efficient accuracy analysis,
change detection, and spatial analysis, without loss of much quality. DTMs can easily be
used to extract volumes of erosion/deposition, cross-sections, and long profiles, and
provide a very literal interpretation of the landscape if derived from TINs.

Top photogrammetric DTM accuracy is often considered to be twice the pixel
resolution of the original photographs; our pixel resolution is about 2.5 cm, so it is
expected that our best possible accuracy is contained in the neighborhood of 5-6 cm.
Point-to-point comparisons give the best estimate of maximum vertical accuracy for each
dataset, and reveal slightly superior accuracy of the March dataset relative to October,
consistent with the other levels of investigation. Mean point-to-point error for March is 6.6 cm, for October it is 7.6 cm. Similarly, mean accuracy peaks at about 5 cm for March and 6.5 cm for October when the density/SDSE reaches a value of ~40. Under ideal circumstances (good photo quality and optimal DTM quality) an average error magnitude of 5-7 cm may be obtained if a density/SDSE value of 40 is reached throughout a site.

However, this theoretical high accuracy was not reached everywhere in our study sites, due to shadows, vegetation, and variable triangulation accuracies across stereo pairs. If there was a sufficient point density with no other confounding factors, these accuracies may have improved. In areas without shadow or vegetation obstruction, one should improve top accuracy in Grand Canyon gullies when using GIS maps depicting the point density required to achieve a density/SDSE of ~40. This empirical threshold would be expected to change for different landscapes and photogrammetric methods, but the concept should be used anywhere to establish guidelines for proper point sampling for variable topography. Exceeding a density/SDSE threshold of 40 will not result in accuracy under 5-7 cm, and one can save time and money by using GIS maps to predetermine required point density for a desired accuracy. This method will allow a technician to estimate how much time and energy to spend collecting points for any given area, and will prevent over-collection in areas which need little density.

We have used the best methods available to date in order to obtain high accuracy. Unfortunately, direct georeferencing, (the direct measurement of the position and orientation of images as they existed at the time of photographic exposure) was not available. The ideal georeferencing method uses an integrated system consisting of a
Global Positioning System (GPS) and an Inertial Measurement Unit (IMU) to calculate the exterior orientation parameters. The airborne GPS provides position information (i.e., X, Y, and Z) about where the camera is at the time of image capture. The IMU provides orientation information (i.e., Omega, Phi, and Kappa) about where the camera is at the time of image capture. Onboard GPS and IMU may have been a way to improve model quality relative to that of aerial triangulation, which estimates exterior orientation parameters using ground control point data. The greatest benefit to direct georeferencing is the elimination of ground control, which would reduce costs and benefit a remote and fragile environment such as Grand Canyon.

In summary, we have designed this study to test the limits of the accuracy of aerial photogrammetry. The results of ~5-7 cm accuracy obtained in this study give us an idea of the top accuracy of aerial photogrammetry under ideal circumstances. Scale of photography, which is a factor that drives cost, can give us an idea of resultant accuracy, but it is only one of many determining factors. Accuracy is dependent not only on photograph scale, but also pixel size, image quality, use of ground-control panels, accuracy of GCPs, shadows, vegetation, topography, point density, and the ability of the photogrammetrist. Figure 3.30 shows the accuracy of photogrammetric terrain models derived from different scales of aerial photography from various studies. The scatter in Figure 3.30 is due to differences in the aforementioned factors in these respective studies.
Photogrammetric Change Detection

The crux of change detection in this paper is that the amount of change required to be significant will vary spatially in any given gully due to topography and DTM point density. Repeat photogrammetry failed to consistently detect 10-20 cm change. This is due partially to the effects of error propagation (comparing two different datasets with error only results in more error) and partially to the low magnitude of change. Where density/SDSE is high the method can detect change as low as ~20 cm (based on Table 3.16 and Equation 1). Obtaining density/SDSE values near 40 throughout a site should accommodate consistent detection of change over a few decimeters. The aerial photogrammetric method in its present technology, although obtaining very high accuracies relative to previous work, is not sufficient to monitor small-scale gully
channels and knickpoints at the centimeter to decimeter scale. Aerial photogrammetry appears to be just below the threshold of resolution and change detection needed for yearly monitoring and rigorous geomorphic study of small gullies.

Photogrammetry also falls short in change detection due to its inability to consistently resolve knickpoints. Many knickpoints were not identified due to obstruction by shadow or vegetation, or failure to resolve the feature in stereo. For example, the majority of all knickpoints in the Arroyo Grande site were covered by the overhanging vegetation, shown in Figure 3.28. These knickpoints were defined during the ground survey, but hidden in the aerial photos, causing Arroyo Grande’s abysmally low detection percentage of 8% (Table 3.4). Many knickpoints were in “washed-out” channels of low contrast, and their position and relief could not be seen in stereo. The low-gradient, low-relief, relatively non-vegetated gully at the Granite Park site accommodated the best knickpoint detection, but ~50% of the knickpoints still were not identified. The poor repeatability between time intervals is also a concern, since tracking a single knickpoint over time is necessary to determine amounts and rates of erosion.

Aerial photogrammetry may still have value for Grand Canyon gullies if we broaden our goals and scope. An inherent advantage of photogrammetry is that it allows for a technician to “revisit” sites in order to obtain additional data for any study period. Photogrammetry could also be more effective if used at longer time intervals or to detect larger dimensions of channel features and erosion. The study features did not change much over the limited 8-month period, and a longer time increment may allow a greater magnitude of vertical change, which the photogrammetry may detect with confidence. Another facet of scale could be the amount of erosion or deposition that is considered by
managers to be noteworthy. Over the 8-month monitoring period, the photogrammetry essentially detected very little to no change in the two gullies that showed subtle but discernable differences. This failure is negligible if interested parties are only concerned with larger vertical changes, such as those that occur in the south main Palisades arroyo and other large channels. In Grand Canyon National Park, we are interested in preserving archaeological sites from gully erosion, and photogrammetry is presently suitable monitoring erosion at only coarser scales. More subtle feature modeling, change detection, and erosion-control structure evaluation should still be performed with total-station surveys. Managers must determine the level of change detection necessary to best protect archaeological sites, and weigh that against the effects of trampling and human intrusion inherent to ground surveys.

Photogrammetry may also have use in planview monitoring. Changes in channel bank and head position can be easily resolved and monitored through stereo viewing. For example, the subtle incision at Indian Canyon shown in Figure 3.19 was shadowed and presented difficulty in recording elevations, but the change and inset incision itself was qualitatively evident from examining the stereo pairs. In most cases, headcutting and channel widening are the processes that endanger and destroy archaeological features, and these lateral channel changes can be readily measured and tracked in planview using photogrammetry. Since positions of archaeological sites are easily located through photogrammetry, their risk can be evaluated through monitoring gully position in relation to the artifacts.
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CHAPTER 4

GEOMORPHIC CONTROLS OF GULLY INCISION ALONG THE COLORADO RIVER CORRIDOR IN GRAND CANYON

ABSTRACT

Baselevel effects of Glen Canyon Dam and increased precipitation have both been cited as possible contributors to increased gully erosion of archaeological sites along the Colorado River corridor in Grand Canyon National Park. However, any conclusions on the causes of the erosion are premature until the geomorphic conditions surrounding the gullies are understood. This study described basic geomorphology associated with 27 gullies in Grand Canyon, particularly focusing on knickpoints and erosion thresholds. Repeat ground surveys showed that gully profiles erode most at knickpoints and steep reaches, and that new knickpoints tend to form in relatively steep reaches of a given channel. Knickpoint spacing has a strong inverse relation to channel gradient and local gradient above knickpoints has a weak inverse relation to the contributing drainage area. A slope-area erosion index is successful in predicting areas of high erosion and locations of new knickpoints at study sites. A slope-area erosion threshold for the study gullies was determined to be $S_{cr} = 0.017A^{-0.47}$, describing how the critical gradient ($S_{cr}$) needed to cause erosion relates inversely to the size of the contributing drainage area ($A$), which is a proxy for runoff discharge. This threshold was applied in a GIS-based model at four sites to show areas of each site that exceed the threshold and are sensitive to gully erosion, which succeeds in identifying general locations of observed gullies, but includes
several false-positive predictions. It is useful in identifying archaeological sites that are at risk of being gullied.

Overall results show an upcatchment control of gully erosion and suggest that baselevel changes due to Glen Canyon Dam operation are subordinate controls. A baselevel fall that actually does cause an increase in gradient, such as along an abrupt scarp, will increase local erosion in lower reaches of channels, as exhibited in the south main Palisades gully. However, most previous work on the topic indicates that a baselevel fall in a sandy substrate and on a decadal time scale will result in only limited knickpoint propagation and upstream erosion. Future work should determine on a site-by-site basis whether an effective baselevel change has occurred and if this change has caused an increase in gully gradient and erosion potential.

**INTRODUCTION**

Gullies are watercourses marked by steep sides, low width-to-depth ratios, and a stepped profile, often with an abrupt channel head (Higgins, 1990; Knighton, 1998). They tend to be particularly prevalent in drylands and can extend their length rapidly. Gullies are a sign of accelerated erosion and landscape instability often thought of as brought about by a natural or human-induced disturbance, such as climate or land-use change. Gully erosion increases sediment yield, removes fertile agricultural soil, destabilizes hillslopes, and can lower the water table of alluvial aquifers (e.g. Patton and Schumm, 1975; Gellis, 1996; Elliot et al., 1999; Bull, 1997; Norton et al., 2002).

Many archaeological sites that lie upon and within Holocene stream terraces along the Colorado River corridor in Grand Canyon National Park are being damaged by
the advance and incision of gullies (Hereford et al., 1993; Fairley et al., 1994). A variety of monitoring and mitigation methods are currently being explored to protect and preserve these cultural features from gully erosion. It is essential to understand the geomorphic conditions of this erosion for the purpose of protecting such features. This understanding will also contribute to resolving the debate of the roles of Glen Canyon Dam and decadal climate change on erosion of archaeological sites. The purpose of this paper is to determine the geomorphic processes and properties linked to gully erosion in Grand Canyon, and refine resource management.

**BACKGROUND**

**Setting**

Gullies have formed on a suite of sandy Holocene stream terraces along the Colorado River corridor in Grand Canyon, as well as in eolian deposits and the toes of hillslopes. Hereford et al. (1996) studied the Holocene alluvial stratigraphy of the river corridor in eastern Grand Canyon, and found that most cultural sites are located in deposits he called the “alluvium of Pueblo II age (pda)” and the “striped alluvium (sa).” These middle-late Holocene deposits generally have not been inundated by historic pre-dam flows of the Colorado River (Fig. 2.1). The striped alluvium dates from 2500 BC to 300 AD, consists of interbedded slopewash deposits and fluvial sand, and is found mostly in eastern Grand Canyon. The alluvium of Pueblo II age has been dated from 700 – 1200 AD and consists of fine-grained fluvial sand locally interbedded with eolian sand and gravelly slopewash deposits. The “upper mesquite” and “lower mesquite” terraces are
composed of silty mainstem sand and are distinguished by the presence of older mesquite trees on the upper terrace and younger mesquite on the lower (Fig 2.1). Deposition of upper mesquite sediment may have begun as late as 1400 AD through a series of floods, whereas the lower mesquite deposit was not formed until a late 19th century flood event (Fairley and Hereford, in press).

Climate and vegetation vary strongly with elevation. Mean annual precipitation (MAP) is 647 mm and mean annual temperature (MAT) is 6.3°C at the north rim, whereas at the bottom of the canyon MAP is 213 mm and MAT 20.4°C. Desert scrub communities occupy elevations less than 1,500 m and include sagebrush (Artemisia tridentata), Mormon tea (Ephedra nevadensis), catclaw (Acacia greggii), and black-brush (Coleogyne ramosissima) (Cole, 1990a, 1990b). The monsoon season, June 15 – October 15, produces 40–50% of Grand Canyon’s yearly rainfall (Western Regional Climate Center, 2003). The majority of the flood and runoff events of local basins on the Colorado Plateau are initiated during this time through intense, isolated thunderstorms related to the Southwestern monsoon (Hereford and Webb, 1992).

The study gullies in Grand Canyon are relatively small, ranging from ~20-200 m in thalweg length, and from ~0.2-2.5 m in channel top width. The channels typically have near-vertical knickpoints with plungepools, and gradual or abrupt channel heads. Abrupt channel heads may be similar in form to knickpoints, but are differentiated as being the upstream boundary of the channel, whereas knickpoints lie within the channel.

These gullies drain to some “effective baselevel,” which we classify as the point where a gully terminates, defining its erosional potential and setting the elevation to which it can incise. Effective baselevel differs from “ultimate baselevel,” which is sea
level, and "local baselevel," which can be any point along a drainage controlling erosion and deposition immediately upslope (Leopold and Bull, 1979). Ultimate baselevel is pertinent only at large geologic time ($10^6$ yrs) and space scales, whereas local baselevel is relevant on immediate time and individual-grain space scales not applicable here.

Hereford et al. (1993) classified erosion potential of Grand Canyon gullies by the landform to which they drain. In some cases, study gullies cut from prehistoric deposits all the way to the mainstem Colorado River ("river-based"), but they typically drain into tributary washes or debris fans ("side canyon-based"), or terminate within a terrace ("terrace-based"). We believe this previous terminology used in Grand Canyon is faulty because identifying the landform on which the gully ends does not represent to the important factors in erosion potential, which are the total relief and the gradient between the gully head and effective baselevel. It is important to note that gullies that reach the pre-dam alluvium or flood sand of 1983 terraces (Fig. 2.1) are within the stages influenced by Colorado River floods of the pre-dam (1963) and post-dam eras, respectively. These terraces are typically 3–5 m above the dam-regulated river stage.

Previous Work in Grand Canyon

Hereford et al. (1993) and Thompson and Potochnik (2000) used repeat air photos of sites in both eastern and western Grand Canyon to conclude that gully incision increased sometime after 1973, most dramatically between 1973 and 1984. Hereford and Webb (1992) noted that most years between the mid-1930s and late 1970s were very dry,
but were followed by unusually wet years of higher storm frequency. Hereford et al. (1993) proposed that the period of more intense precipitation from the late 1970s through the 1990s has helped accelerate erosion. These studies make a case for increased gully erosion, yet the existence or true extent of the change in gully activity is uncertain.

Hereford et al. (1993) suggested that this unusual run of high rainfall and runoff years drove the erosional process, but lower effective baselevel increased the depth of erosion and amount and rate of knickpoint retreat throughout the catchment. Hereford et al. (1993) were the first researchers to suggest that Glen Canyon Dam operation may be a factor in the increased gully erosion in Grand Canyon. They hypothesized that the effects of flooding at the relatively high stages of the pre-dam terraces slowed or prevented the erosion of “terraced-based” gullies by depositing sand at the mouths of the channels. Conversely, they suggested that lack of flooding and deposition during post-dam time allowed gullies to erode down to the Colorado River channel, reducing effective baselevel by 3-4 m. Hereford et al. (1993) conclude that gully incision may have intensified in ~25% of terrace-based catchments relative to pre-dam conditions as the gullies adjust to their new, lower baselevel.

Thompson and Potochnik (2000) attempted to test Hereford and others’ (1993) baselevel hypothesis. They compared gullied terraces in Grand Canyon to those in Cataract Canyon upstream, which is undammed and still experiences nearly natural peak flows and sediment loads. They suggested that the relative absence and small size of gullies in Cataract Canyon shows that conditions in the two reaches are intrinsically different, despite “geomorphic and climatic similarity,” implying that restorative deposition by mainstem river floods is effective in maintaining a higher effective
baselevel and reducing incision. They proposed the term “restorative baselevel hypothesis” to emphasize the balance between gully erosion and renewed deposition, and suggested that the redistribution of flood sand onto higher terraces by wind may also be a critical component of episodic gully infilling.

**Geomorphic Concepts**

**Baselevel**

Many studies have explored the effects of baselevel change on incision. The time and space scales of a given baselevel change define the extent of its effects, and substrate character defines the longevity and form of knickpoints that are created from a baselevel fall. Studies generally show that baselevel has only a limited effect on upstream erosion and deposition on human time scales in small drainages. Local baselevel change only controls the relative height of the longitudinal profile immediately upstream (Leopold and Bull, 1979; Begin et al., 1980; Schumm, 1993; Schumm and Rea, 1995; Harvey, 1994; Florsheim et al., 2001). In Graf’s (1982) words, the depth of erosion caused by baselevel fall decays with distance upstream until the signal disappears. This influence will be much greater if baselevel is lowered abruptly, such as along a scarp, than if it is lowered gradually, such as along a shallow continental slope or a slope equal to the gradient of the river (Schumm, 1993).

Knickpoints are defined as places along a drainage profile where gradient increases abruptly. They decrease channel width-depth ratio and increase flow velocity, resulting in greater basal shear stress. Thus, erosion rates at knickpoints are higher, driving upslope knickpoint migration depending upon the degree to which the knickpoint
remains intact (Brush and Wolman, 1960; Holland and Pickup, 1976; Leopold and Bull, 1979; Gardener, 1983). Grand Canyon gully knickpoints can retreat several meters during an intense rainstorm, but it is unknown how quickly individual knickpoints in Grand Canyon diffuse or decay from their steep initial form during headward migration.

A baselevel fall may propagate bed incision for greater distances through a positive feedback if the sediment is cohesive or has a resistant layer at its upper lip that is maintained through time (Leopold and Bull, 1979; Gardener, 1983; Schumm, 1993). However, the knickpoint will eventually dissipate and flatten in most cases, and rate of knickpoint migration decreases over time and distance from the outlet (Begin et al., 1980; Graf, 1982; Gardener, 1983; Florsheim et al., 2001). Changes in sinuosity allow channels to quickly adjust to changes of gradient in unconfined or low-cohesion channels, and it often accommodates baselevel falls in alluvial channels rather than complete channel rejuvenation through knickpoint migration (Leopold and Bull, 1979; Schumm, 1993). Baselevel effects will be greatest in bedrock channels at large time scales where change is great, discharge high, and the channel confined, but for most other circumstances upstream knickpoint propagation will be moderate, not influencing the entire drainage system.

The most relevant study to the situation in Grand Canyon is by Harvey (1994), who studied slope-stream coupling on eroding gullies of similar scale in northwest England. He noted that sediment fans at gully mouths were episodically scoured by the river, lowering effective baselevel for gullies, but causing only local incision near the gully mouths. Erosion further upslope was related to catchment hydrologic processes and not to downslope baselevel effects.
Studies such as those performed by Leopold and Bull (1979), Graf (1982), and Harvey (1994) took place over smaller time and space scales on uniform, sandy substrates. If their channels had a clay layer or resistant caprock, or if they had conducted their studies over geologic time, their results may have been different. Similar in scale are the study gullies in Grand Canyon, which have a loose, alluvial substrate. Baselevel does ultimately drive all erosion at geologic time scales, but the effects of baselevel fall and knickpoint propagation should be limited in the sandy substrate and at the short timescale of the study gullies.

Erosion Thresholds

Several empirical studies have related gully erosion to topographic thresholds. Upslope contributing drainage area and local channel gradient have been used in simple models to predict the initiation, location, and soil loss caused by gully erosion (e.g. Patton and Schumm, 1975; Begin and Schumm, 1979; Foster, 1986; Merkel et al., 1988; Thorne et al., 1986; Auzet et al., 1993; Montgomery and Dietrich, 1994). The rationale for this approach is that the location and size of gullies is primarily controlled by the generation of surface runoff of sufficient depth and velocity to exceed a critical shear stress of entrainment. Since runoff discharge data are not available for most studies, upslope contributing area is substituted, assuming that runoff volume increases downslope proportional to increasing catchment area. This should be true where infiltration-excess overland flow dominates (Leopold et al., 1964), but fails to account for significant infiltration into the channel bed. Most runoff in Grand Canyon is from infiltration-excess overland flow, due to high-intensity precipitation events and large proportion of low-infiltration, sparsely-vegetated bedrock and talus in catchments.
Modeling studies of channel initiation have focused on both erosion through saturation overland flow and infiltration-excess overland flow. Montgomery and Dietrich (1994) outlined a model for erosion caused by infiltration-excess overland flow assuming turbulent flow and steady-state rainfall intensity \((R)\) over a loose-sediment substrate with uniform infiltration capacity \((I)\). Discharge per unit contour length \((q)\) may be determined simply by:

\[
q = (R - I)a
\]  

(1)

where \(a\) is the drainage area. A second independent method of estimating unit discharge is through flow depth and the Manning equation, which approximates mean flow velocity:

\[
q = (1/n)h^{5/3}S^{1/2}
\]  

(2)

where \(n\) is the Manning roughness coefficient, \(h\) is flow depth, and \(S\) is water surface slope. A threshold or critical shear stress \((\tau_{cr})\) exists, which a given discharge must overcome to entrain particles:

\[
\tau_{cr} = \rho_w g(hS)_{cr}
\]  

(3)

where \(\rho_w\) is the density of water and \(g\) is gravitational acceleration. Critical discharge \((q_{cr})\) can then be expressed by rearranging (3) in terms of \(h\) and substituting it into (2):

\[
q_{cr} = \tau_{cr}^{5/3} / [(\rho_w g)^{5/3} nS^{7/6}]
\]  

(4)

Equating (4) and (1) and solving for the critical drainage area required for erosion by overland flow yields:

\[
a_{cr} = \tau_{cr}^{5/3} / [(R - I)(\rho_w g)^{5/3} nS^{7/6}]
\]  

(5)

which describes an inverse drainage area-slope relation. Essentially, the contributing drainage area required to cause erosion is nearly proportional to the inverse of local
slope, and the additional factors besides slope needed to actually calculate an area- 
slope threshold are bed roughness, critical shear stress, rainfall intensity, and infiltration 
rate, all which are variable in space and time. A larger drainage area would be required 
for erosion if there was an increase in resisting forces or infiltration capacity of the soil; a 
smaller drainage area is needed with an increase in precipitation intensity or decrease in 
roughness, infiltration, or critical shear stress.

Patton and Schumm (1975) empirically identified an inverse relation between 

drainage basin area and slope above channel heads of entrenched gullies in small, semi­
arid catchments of northwest Colorado, and interpreted that a line fit at the base of their 
data scatter in a slope vs. area plot represents a critical slope-area erosion threshold. 
They suggested that measuring slope and contributing drainage areas of existing gullies 
can aid in identifying potentially unstable locations and allow land managers to predict 
problem areas. This method is advantageous in that it only requires topographic 
measurements of the existing landscape and does not need extensive data on soil 
properties.

The advent of GIS and use of raster datasets of elevation (DEMs) has enhanced 
the threshold analysis suggested by Patton and Schumm (1975), making computation and 
viewing of erosion-sensitivity maps efficient. Vandaele et al. (1996) compiled data sets 
of slope and upstream drainage area measured from field surveys and topographic maps 
just above gully heads in central Belgium. They delineated a threshold line below which 
no incision occurred in their study area, and expressed this as a power function between 
critical slope and area:

\[ S_{cr} = aA^b \] (6)
where $S_{cr}$ is the critical gradient, $A$ is the drainage area (in hectares), and the values of $a$ and $b$ are empirically established from their data sets of gully heads. They subtracted the calculated critical gradient ($S_{cr}$) from the actual local gradient ($S_{ac}$) for each 5x5 m grid cell within the catchment, predicting that if $S_{ac} - S_{cr} > 0$ then gullying is likely to occur in this grid cell, whereas if $S_{cr} \leq 0$ then gullying is not likely to occur in this grid cell. They found good agreement between the predicted and observed locations of ephemeral gullies using this technique. Desmet et al. (1999) quantified the success of the method in predicting gully locations in three catchments in central Belgium using 5 m DEMs. They determined that up to ~80% of the cells with observed gullying were predicted by the model.

In summary, a slope-area analysis can predict places that exceed a topographic threshold for erosion for a particular environment and are therefore at risk of being gullied. Area-slope thresholds provide information as to where either the contributing drainage area or slope is insufficient to sustain runoff and erosion, and thus the theoretical maximum extent of gully head retreat. Modeling the potential maximum extent of current channels and the locations of new channels will aid managers in Grand Canyon National Park to more efficiently identify and protect at-risk artifact scatters. Slope-area thresholds can additionally help us gain a better understanding of the slopes and contributing drainage areas associated with gully head position in Grand Canyon.

**METHODS**

Archaeological sites in two reaches of the river corridor were selected for study (Fig. 4.1). All sites feature one or more gullies, and 27 gullies were studied. Four sites
are in eastern Grand Canyon: Kwagunt (one gully), 60-mile (four gullies), Palisades (four gullies), and Basalt Cliffs (four gullies). These eastern sites are within 23 river km of each other and are all ~800 m elevation. Kwagunt is an “erosion-control” site, in that it features small or no gullies. Five sites are in western Grand Canyon: Parashant (one gully, erosion control site); Indian Canyon (one gully), Arroyo Grande (four gullies), Granite Park (one gully), and Gorilla Camp (four gullies). These western sites are all within 40 river km of each other and are at ~400 m elevation. In addition, data from a concurrent, independent study of gullies at an analogous setting at Paria Eddy were used. The nine study sites exhibit a range of geomorphic settings and degrees of erosion (Table 4.1).

Figure 4.1. Geomorphology study site locations.
TABLE 4.1. GEOMORPHOLOGY STUDY SITE DESCRIPTIONS

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Number of Gullies</th>
<th>Geomorphic Setting</th>
<th>Gradient (m/m)</th>
<th>Drainage Area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kwagunt (control site)</td>
<td>1</td>
<td>talus catchment to termination on eolian and ap(^2) sand</td>
<td>0.12</td>
<td>0.03</td>
</tr>
<tr>
<td>60-mile Palisades</td>
<td>4</td>
<td>Bright Angel shale in upper catchment to eolian sand to termination in side canyon</td>
<td>0.22-0.24</td>
<td>0.02-0.05</td>
</tr>
<tr>
<td>Parashant (control site)</td>
<td>1</td>
<td>talus catchment to termination on flat, silty, mainstem ap terrace</td>
<td>0.17</td>
<td>0.08</td>
</tr>
<tr>
<td>Parashant</td>
<td>1</td>
<td>talus catchment to termination on flat, silty, mainstem ap terrace</td>
<td>0.19</td>
<td>0.05</td>
</tr>
<tr>
<td>Indian Canyon</td>
<td>1</td>
<td>talus catchment to eolian, ap, and termination on pda(^3) sand</td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>Arroyo Grande</td>
<td>4</td>
<td>basement rock and debris fan catchment to termination on ap/eolian sand</td>
<td>0.12-0.28</td>
<td>0.02-0.18</td>
</tr>
<tr>
<td>Granite Park</td>
<td>1</td>
<td>Bright Angel bedrock catchment to eolian, slipewash, and Pleistocene gravel pile to termination on debris fan</td>
<td>0.06</td>
<td>0.16</td>
</tr>
<tr>
<td>Gorilla Camp</td>
<td>4</td>
<td>talus/debris fan catchment to eolian/ap sand to termination in side canyon or on terrace</td>
<td>0.24-0.4</td>
<td>0.002-0.08</td>
</tr>
</tbody>
</table>

1 Describes catchment characteristics and changes throughout length of gully
2 Alluvium of Pueblo II Age
3 Pre-Dam Alluvium

Total-station ground surveys bracketed the summer monsoon season and were performed in February and October 2002 at all the sites in order to collect longitudinal profiles of each gully and measure gradient and contributing drainage area above each gully head. The survey was conducted by Grand Canyon Monitoring and Research Center (GCMRC) technicians in collaboration with researchers involved in this project, with the exception of the Paria Eddy site, which was surveyed independently.

Technicians took care to prevent gully wall failure and disturbance around cultural sites. To gain a better understanding of catchment properties, ground cover was measured with an 8-pin frame (Appendix F), sediment shear strength was measured with a torvane, infiltration tests were performed with a tension-disk infiltrometer on different ground-cover types, and notes on geomorphic setting were recorded. Infiltration tests were converted to saturated hydraulic conductivity to represent minimum infiltration rate.
Field observations showed that several gullies in eastern Grand Canyon experienced erosion during the study period. This denudation was identified by normalizing longitudinal channel profiles from February and October and comparing elevations at each profile point for nine eastern Grand Canyon gullies. Magnitude of denudation along the thalweg was then compared to the slope-area product.

Gully long profiles were also compared and analyzed in terms of their knickpoint characteristics, such as their height and spacing, in order to obtain a better understanding of their characteristics and control. Similarly, the gradient and contributing drainage area above each gully head were plotted in log-log space in order to gain knowledge of topographic threshold conditions associated with gullying in Grand Canyon. This threshold was then applied in a GIS following the methods of Vandaele et al. (1996) in order to identify sensitive areas and archaeological sites that should be actively monitored and protected.

Erosion threshold analyses were performed on four sites in western Grand Canyon (Indian Canyon, Arroyo Grande, Granite Park, and Gorilla Camp) for which high-resolution photogrammetric terrain models were available (see Chapter 3). Dense semi-automated and manual photogrammetry elevation points were merged with ground-survey points to generate DEMs of 10 cm cell-size, using spline-tension interpolation in Arc/Info. Slope and drainage area grids were derived from each DEM using the D∞ algorithm (Tarboton, 1997), which is best for modeling sheetflow on a hillslope because it allows partitioning of flow between multiple neighboring cells. We evaluated and
quantified the accuracy of the vulnerability models by the number of predicted cells that correspond to the location of the gullies observed in the field (after Desmet et al., 1999).

One of the original intentions of this study was to employ older surveys from the past five years in order to evaluate longer-term gully change and erosion-control structure impacts. Most of these data came from 1997-1998, and were not included in the present analysis for several reasons. In particular, not all sites were made available, not all sites were in a comparable geographic coordinate system, and those sites that were in the proper coordinate system required major elevation corrections due to an updating of the Grand Canyon coordinate system between the time of these older surveys and the current study. Despite attempting correction factors, uncertainty for these datasets was still too high for accurate erosion monitoring at our scale of interest. For example, the "corrected" 1998 profile of the Palisades south main arroyo showed about 0.3 m of degradation along the entire thalweg over the past four years, which does not agree with photographic evidence and is a result of errors in the datum. Still, the gradient of the 1998 profile should be accurate and is used to show change in the form of the south main Palisades gully.

RESULTS

Basic Geomorphic Data

A key assumption in this work is that erosion is caused by infiltration-excess overland flow, and all field evidence at the sites indicates this is true, as expected for a semi-arid to arid environment. Erosion is also influenced by piping in some locations
These two erosional processes are common in semiarid to arid landscapes such as Grand Canyon that feature low vegetation density and infrequent, high-intensity precipitation events. Observations and survey data indicate the studied channels erode by both knickpoint retreat and channel widening through undercutting and failure of banks (Appendices A and C).

The geomorphic setting of sites tends to be characterized by three zones from top to base of catchments. The upper catchments are typically steep (gradient >0.5) and underlain by bedrock, talus, or debris-flow deposits (Fig. 4.2). Gully heads are usually near the base of the steep, upper catchment. Drainage basins below the upper catchment are relatively narrow and increase in contributing area very little downslope to the gully terminus. The gullies cut through one or more deposits with a sandy-loam texture, although nearby eolian coppice dunes are better-sorted sand (Appendix C).

Sediment shear strength and infiltration rates vary with ground cover type (Appendix D). Median sediment shear strength increases from 0.4 to 0.7 and 1.1 kg/cm² for disturbed sediment (turbated areas, usually channel bottoms), raindrop crusts (usually outside of channel), and cryptobiotic crust, respectively (Fig. 4.3, Appendix D). Median saturated permeability is 0.008 for bare ground to 0.007 cm/s for cryptobiotic crust, then drops significantly to 0.003 and 0.004 cm/s beneath shrubs and grass, respectively (Fig 4.4A, Appendix E). Splitting bare ground into eolian and non-eolian subsets reveals that median infiltration on eolian sediment (0.037 cm/s) is 6 times higher than infiltration on bare alluvium or colluvium (median = 0.006 cm/s) (Fig. 4.4B, Appendix E). Saturated permeability also tends to increase with distance down the catchment, from a median of
Figure 4.3. Box-and-whisker plots showing range of sediment shear strength for three cover types in Grand Canyon. Lower boxes show $q_1$ (25%), middle lines show $q_2$ (median), and upper boxes show $q_3$ (75%); whiskers show outliers up to 90%; dots show outliers at 95%, and dotted lines show means.

Figure 4.4. Box-and-whisker plots showing range of saturated hydraulic conductivity. A) bare ground, biotic crust, grass, and shrub cover types; B) eolian and non-eolian subsets of bareground; C) catchment position.
Profile Analysis

Previous Surveys

Profile comparison between survey data of previous studies and this study is used to show the extent of potential baselevel effects of the Colorado River, and is focused on the south main Palisades gully since it is the only study gully that reaches the river. Datum corrections to the 1998 data would be needed to quantify denudation, and profile analyses from previous surveys were not performed any other gullies. Much of the erosion in the south main Palisades gully has been the result of four 25-80 cm-high knickpoints downslope of the pre-dam alluvium (and thus the natural flood stages) mapped by Hereford (1996) (Fig. 4.5). Gradient of this lower reach has increased from 0.03 in 1998 to 0.04 in 2002, and erosion of the lower reach has been high relative to erosion of the upper reach.

Figure 4.5. 1998 profile (Brode study) and 2002 October profile (this study) normalized for south main Palisades gully. Elevation of pre-dam alluvium is also shown. Offset of profiles is due to systematic data errors (see methods).
February-October 2002 Data

Channel longitudinal profile shapes of Grand Canyon gullies tend to be straight, convex, or concavo-convex (Figs. 4.5, 4.6, 4.7, Appendix N). Typical stream profiles throughout the world are concave in shape, since discharge tends to increase with distance from the channel head, and gradient of the channel will decrease proportionally to equalize energy expenditure along its profile. Many streams in the arid southwest do not gain discharge or even lose discharge to infiltration, and have straight to convex profile shapes. These facts, along with above results pertaining to catchment shapes and infiltration trends of Grand Canyon gullies, suggest that discharge of the studied gullies does not increase significantly between the channel head and outlet. Denudation along channel profiles is discontinuous, with maximum values corresponding to knickpoints and relatively-steep reaches (Fig. 4.6, Appendix N). The peaks and troughs of the slope-area erosion index plot match up relatively well with peaks and troughs in denudation, suggesting that the main control of erosion is the power of runoff from local catchments. Large denudation peaks do not correspond 1 to 1 with large erosion-index peaks, but the simplistic erosion index is a useful means that requires only topographic data to estimate locations of problem reaches and problem knickpoints.

Gullies at the Basalt Cliffs site featured no knickpoints during the February survey, but underwent substantial erosion and knickpoint formation over the study period that was accounted for during the October survey (Fig. 4.7). These knickpoints tended to form in local reaches that were relatively steep, indicating topographic control of knickpoint initiation and position. The slope-area erosion index is useful in identifying these relatively steep locations and predicting where knickpoints will develop.
Figure 4.6. Example of slope-area control of denudation of gully profile. Peaks in denudation correspond well with the relatively-steep lower reach of channel.
Figure 4.7. Profiles and slope-area denudation plots of a Basalt Cliffs gully that did not exhibit any knickpoints at the beginning of the study.
Knickpoint Metrics

Average knickpoint spacing for a given channel is inversely correlated to gradient ($r^2 = 0.92$) (Fig. 4.8):

$$D = 20e^{-9.7s}$$  \hspace{1cm} (7)

where $D$ is average spacing and $s$ is average channel gradient. This trend of closer-spaced knickpoints correlating with steeper gradient is common to gullies of all scales in the study area.

Local gradient (gradient < 1 m above a knickpoint) has no apparent correlation to knickpoint height; that is, knickpoints do not necessarily get bigger when slopes get steeper (Fig. 4.9A). We would anticipate a gully with a large slope-area product may have enough stream power to create larger knickpoints. However, slope-area product has an extremely weak positive correlation to the height of knickpoints ($r^2 = 0.17$) (Fig. 4.9B). There is also a weak negative correlation between local gradient and contributing drainage areas of knickpoints (Fig. 4.10). The channel gradient required to form a knickpoint decreases as drainage area increases.

Figure 4.8. Comparison of average knickpoint spacing to average channel gradient. Squares represent “river-based” gullies, diamonds represent non “river-based” gullies.
Figure 4.9. Comparison of channel gradient (A) and slope-area index (B) to knickpoint height.

Figure 4.10. Plot of local gradient and contributing drainage area above each knickpoint.

Slope-Area Analysis

A topographic erosion threshold was inferred from a plot of contributing drainage area vs. slope above each gully head identified in the field, which mark the upslope initiation point of erosion in a catchment (Fig. 4.11). The position of the threshold line was qualitatively determined by the bottom limit of the main scatter (outliers discussed below) (Vandaele et al., 1996). This line represents an approximation of the theoretical
critical slope-area relation for incision, above which incision occurs. Referring back to Equation 6, we empirically derive $a$ to be 0.017 and $b$ to be -0.47 for the Grand Canyon gully data here. This is a very simplistic tool, but may be useful for identifying areas in a landscape that exceed a topographic threshold and are at risk of gully erosion.

Three outlier points in Figure 4.11 plot below the threshold line. One point is from the head of a very small, inactive gully at the Kwagunt control site. It does not feature a great enough slope for the given watershed size to consistently concentrate erosive flows. The two other points are from active gully heads at the Palisades site. This particular gully system features a very large, impermeable catchment in which virtually all precipitation pools up and runs off (Appendix E). This means that for these two particular gullies, a given drainage area would generate greater runoff than “normal,” and would thus require a smaller slope (lower threshold) to erode sediment and create a gully head.

Figure 4.11. Slope-area threshold for Grand Canyon gullies.
High-resolution photogrammetry DEMs were available for the four western Grand Canyon sites, and grids with values representing critical gradients that must be exceeded in each cell for erosion to occur were created for these sites by multiplying the contributing drainage area grid by 0.017 and taking it to the -0.47 power (Equation 1). Maps predicting areas vulnerable to gully erosion were then constructed by identifying cells in which the actual gradient exceeds the critical gradient of erosion. The model showed good general agreement between predicted and actual locations of gullies (Table 4.2, Fig. 4.12, Appendix O), and the level of this agreement was quantified by comparing total gullied area to overlapping predicted area (Table 4.3), which shows that 20% of all observed gully cells were “predicted” by the model. Although the model is successful in identifying locations of existing gullies, it does not show the full coverage of the observed channels.

<table>
<thead>
<tr>
<th>Site</th>
<th>Number of Gullies Observed</th>
<th>Number of Gullies Represented</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indian Canyon</td>
<td>10</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Arroyo Grande</td>
<td>19</td>
<td>18</td>
<td>95</td>
</tr>
<tr>
<td>Granite Park</td>
<td>19</td>
<td>18</td>
<td>95</td>
</tr>
<tr>
<td>Gorilla Camp</td>
<td>20</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>Total</td>
<td>68</td>
<td>66</td>
<td>97</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Site</th>
<th>Number of Predicted Cells</th>
<th>Percentage of Gully Cells Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indian Canyon</td>
<td>8161</td>
<td>14</td>
</tr>
<tr>
<td>Arroyo Grande</td>
<td>8094</td>
<td>25</td>
</tr>
<tr>
<td>Granite Park</td>
<td>21814</td>
<td>17</td>
</tr>
<tr>
<td>Gorilla Camp</td>
<td>14653</td>
<td>23</td>
</tr>
<tr>
<td>Total</td>
<td>52772</td>
<td>20</td>
</tr>
</tbody>
</table>
Figure 4.12. Example of gully sensitivity map for Gorilla Camp. "Sensitive" cells (black) are those that have an actual slope that exceeds the critical slope for erosion. Archaeological features (stippled polygons) that are at risk of gully erosion can be located where sensitive cells overlap them.

DISCUSSION

Erosion-Threshold Predictive Model

The GIS-based gully prediction model shows basic location of areas that exceed the empirically-derived area-slope erosion threshold. This means that the model should represent existing gullies as well as locations of gullies that could form in a future runoff event. The model does well in outlining observed gully features, even very small,
discontinuous channels. However, the identification is very sporadic, and most often shows a dotted drainage with many gaps and tends not to exhibit the true channel width. This discontinuous, narrow representation drives the poor results of the cell-by-cell comparison shown in Table 4.3. The model cannot then give estimates of channel size, but can predict of locations of most intense erosion and potential erosion. Most erosion in Grand Canyon gullies occurs on knickpoints (Figs. 4.6, 4.7, Appendix N), and 56 of 63 knickpoints (89%) are on cells that exceed the threshold. The model's best application is in resource protection and monitoring, and should aid the National Park Service in efficiently identifying archaeological features that are at risk in Grand Canyon. Once vulnerable sites are identified, resource managers can devote greater time and funds to protecting these sensitive areas in Grand Canyon and avoid expending resources on cultural features that are not gully-prone. This is also another valuable use of aerial photogrammetry DTMs (see Chapter 3), which provide much more robust elevation models than ground surveys.

Cells that exceed the threshold but do not feature observed gullies (false positives) are abundant in this erosion model. This phenomenon can occur for three reasons:

1. Cells that exceed the erosion threshold are merely cells sensitive to gully erosion, not cells certain to exhibit erosion. If a storm initiates a high-magnitude runoff, the "false-positive" cells indicate where the next new gully may erode. Similarly, if the landscape were disturbed through trailing, clearing vegetation, or climate change, new gullies would theoretically incise in these predicted areas.

2. The cells may be areas of deviant substrate or geomorphic setting relative to what typical gullies in Grand Canyon erode through. For example, a dune may have a
sufficient slope and drainage area combination to be sensitive to gully erosion in the model, but in reality infiltration is too high to sustain runoff. Similarly, a talus slope may feature the topography to exceed the empirical erosion threshold, but the bouldery substrate requires too high of a shear stress to be moved by a runoff event that erodes sand-based gullies. The same is true of thickly vegetated areas that would retard flow and hold in soil better.

3. There may be a flaw in the terrain model itself. There are occasionally anomalous elevation points derived from the photogrammetry or ground survey. These can easily be identified by contouring the site, and then edited out during quality control.

The second point has been repeatedly observed in Grand Canyon. slope-area points in Figure 4.10 were primarily taken from gullies in a non-cohesive sandy-loam substrate (Appendix C), so the threshold and any model derived from it will only apply to that particular substrate, climate, and geomorphic setting. In particular, infiltration rates vary immensely with cover type (Fig. 4.3). Sediment under shrubs and grasses/forbs typically had much lower infiltration rates than on bare ground or cryptobiotic crust. Dunes dominate the high end of infiltration values shown in Figure 4.4, and can infiltrate 4-6 times the amount of water during a given time period than “typical” bare ground. Conceptually, a precipitation event would have to be 4-6 times more intense to initiate runoff on a sandy dune than on a sandy-loam alluvial terrace typical to most gullies in Grand Canyon. This spatial variability is also present in the threshold plot itself (Fig. 4.11), shown by the outlier points below the threshold that represent gullies in a different substrate than “normal.”
Montgomery and Dietrich (1994) note that channel heads are dynamic and will migrate up or down slope in response to changes in the erosion threshold. The erosion threshold and location of the channel head are sensitive to changes in climate, vegetation, and soil properties, all which can show variation at both decadal and geologic time scales. An increase of the channel initiation threshold can be caused by changes of physical properties and processes, such as infiltration capacity, and will result in channel contraction. The converse is true if there is a decrease in the channel initiation threshold. For example, if a grassland region undergoes climate change and shifts toward shrub communities, infiltration capacity, through both changes in permeability and roughness, will decrease (e.g. Abrahams et al., 1995). One can use the model of Montgomery and Dietrich (1994) to hypothesize the effects of a climate change or changes in infiltration and ground cover. For instance, in Grand Canyon infiltration rates on eolian sediment are 4-6 times higher than average bare ground (Fig. 4.4). A decrease in eolian influence would then lead to an increase in runoff, a decrease in the drainage area required for erosion, and an expansion of the drainage network. An increase in average rainfall intensity would result in a similar expansion.

If upcatchment processes control position and extent of gullies in Grand Canyon, then changes in these processes should account for increased erosion rates and network rejuvenation throughout time. Climate does change on the Colorado Plateau on a decadal scale and can be the driving force for this particular gullying, and can even be amplified if feedbacks related to ground cover lower the average infiltration. Rogers and Schumm (1991) showed that only small changes in vegetative cover are needed to have an effect
on erosion and sediment yield. Changes in eolian sediment budget and distribution
due to Glen Canyon Dam or natural processes could influence the erosion of
archaeological sites.

**Catchment vs. Baselevel Controls on Grand Canyon Gully Erosion**

The validity of Hereford and others' (1993) baselevel argument and Thompson
and Potochnik's (2000) supportive study are disputable, in that the hypothesis itself is
conceptually flawed, has not been related to the broader geomorphic literature, and has
not been successfully verified or falsified. Thompson and Potochnik's (2000) Cataract
Canyon study sites were below "natural" flood stages, whereas the gullies of interest in
Grand Canyon are on archaeological terraces above pre-dam flood stages. Thus, their
sites were not geomorphically comparable to the archaeologically-related problems in
Grand Canyon. Baselevel merely defines the potential for erosion, but erosion is actually
performed by running water. The actual influence of a baselevel drop on erosion in the
sandy, ephemeral gully system of Grand Canyon is not known. It is also possible that the
effective baselevel of the gullies has not actually dropped, and the actual baselevel needs
to be defined at the scale of this problem. Finally, the role of eolian processes on the
infilling of gullies and hydrology of runoff in Grand Canyon is unknown, as is the effect
of Glen Canyon Dam on these eolian processes. Without knowing the complete
geomorphology of gully erosion in Grand Canyon, these interpretations of cause have
been premature.

Our data illustrate that gradient and contributing drainage area, as well as
catchment properties such as permeability and ground cover are sufficient to describe
trends in knickpoint metrics and extent of gully erosion. This indirectly suggests that baselevel changes at this scale and setting are subordinate controls. The average spacing of knickpoints is very tightly correlated with channel gradient (Fig. 4.8), suggesting that knickpoint generation and spacing is driven by topography rather than a series of baselevel drops that may create knickpoints on an event basis. The identification of an slope-area relation to knickpoint location (Fig. 4.10), a link between magnitude of erosion and a high slope-area product (Fig. 4.6, 4.7), and a slope-area threshold for channel head position (Fig. 4.11) also indicates a dominance of upcatchment processes in controlling erosion. The close spacing of knickpoints on steeper slopes shown in Figure 4.8 may be due to higher-gradient channels exceeding this threshold more often. Knickpoint height between channels of differing gradients is somewhat consistent, indicating steeper channels must have closer-spaced knickpoint steps rather than taller knickpoints over a given channel length for the gully to accommodate a given drop in elevation, similar to the step-pool fluvial systems of Grant et al. (1990).

Having said all this, it is important to note that there are exceptions where baselevel may be important. An abrupt baselevel drop that increases local channel gradient would result in an increase in erosion potential (Schumm, 1993), a phenomenon that may be present in the lower reach of the south main Palisades arroyo. Older survey data were used to determine if the south main Palisades gully has actually increased in gradient over time below the pda surface. Comparing the Brode profile to the current October 2002 profile clearly shows that the lower reach of this gully has increased in gradient, and that relatively more erosion has occurred in this lower reach (Fig. 4.5). Baselevel fall has impacted this particular gully by allowing the slope-area product to
increase in the lower reach, and restorative flood deposition would be beneficial in reducing channel gradient and erosion potential below the pda elevation.

We find it significant that all of the previous literature pertaining to baselevel effects state that the channel rejuvenation caused by a baselevel drop only extends a limited amount upstream, and that its influence decays with distance in sandy channels over decadal time scales (especially Harvey, 1994). Even though knickpoints and baselevel change are limited in upstream influence, a baselevel fall will cause channel rejuvenation and adjustment to some spatial and temporal extent. Most sites, however, even those that have been classified as “river-based,” have very little to no chance of being impacted by river management. Destruction of archaeological sites and erosion treatments occurs due to large magnitudes of runoff flowing down relatively-steep channels, regardless of effective baselevel. It is merely a matter of discerning where gradients can be reduced, major knickpoints infilled, and nearby cultural sites further protected by the effects of a restorative flood. Archaeological terraces of “side canyon-based” and “terrace-based” gullies are eroding as severely and exhibit the same knickpoint characteristics as gullies that have been classified as “river-based.” Furthermore, many of the gullies that have been classified as “river-based” do not actually drain to the Colorado River, but instead terminate on mainstem flood deposits or debris fan deposits 2-5+ m above the river. Future work must re-assess the impact of Glen Canyon Dam on the link between effective baselevel and gradient of gullies. For which gullies has the effective baselevel actually decreased? If the effective baselevel for a particular gully has indeed decreased, does it cause an increase in channel gradient and
increased erosion potential? Answering these questions will help resolve the effects of Glen Canyon Dam on gully erosion and aid in protecting archaeological sites.

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Gully erosion is damaging archaeological sites throughout the Colorado River corridor in Grand Canyon. Methods to remedy and monitor this erosion need testing, and the geomorphic conditions associated with the gullying need to be understood. We assessed erosion-control structures, photogrammetric monitoring techniques, and the geomorphology of gullies in Grand Canyon through two field and lab data collections bracketing the 2002 summer monsoon season. Erosion treatments at seven sites in eastern and western Grand Canyon were studied to discern their effectiveness at staying intact and reducing erosion. Aerial photogrammetry was performed at four sites in western Grand Canyon to test its accuracy and utility for detecting geomorphic change of gully channels. Catchment geomorphology was studied at nine sites in eastern and western Grand Canyon to understand controls on the erosion.

Damaged erosion-control structures tended to be on steeper segments of gully channels. This result alludes to an upcatchment control of structure damage. Both rock and brush structures have been useful in slowing erosion in Grand Canyon gullies, but brush checkdams are recommended because they generally stay intact better, are easier to maintain, cause less scour, and are better at reducing erosion than rock linings. Gullies are unstable and unpredictable by nature, so continued monitoring and maintenance will be needed regardless of treatment type in order to further mitigate the problem and learn more about the gully erosion itself.
Aerial photogrammetry performed on small-scale gully channels was able to achieve absolute mean vertical accuracies of ~10 cm for complete channel DTMs when compared to ground-survey data. Longitudinal profiles and channel cross-sections extracted from photogrammetric TINs had sub-decimeter accuracy. Mean error was shown to vary positively with the topographic ruggedness (SDSE) and inversely with DTM point density, and a density/SDSE quotient >40 yields negligible improvement in accuracy. Change-detection was done taking into account varying topography and DTM point density. Photogrammetry performed on relatively flat areas with a relatively dense topographic dataset (high density/SDSE) can detect significant geomorphic change with an elevation difference of as low as ~20 cm, but relatively sparse data in more rugged landscapes can only detect changes of several decimeters. The vertical accuracy of aerial photogrammetry is lower than the scale of erosion that needs to be measured, and the tool is not yet suitable to quantify erosion or track knickpoints in small channels. On the other hand, photogrammetry may be used for monitoring larger channels with greater erosion problems, or for measuring plan-view changes in gully channels. Use of IMU, on-board GPS, and other advances in technology may further increase accuracy, reduce cost, and make aerial photogrammetry a more viable option in the future.

Studying the geomorphology of eroding archaeological sites revealed that catchment topographic variables can predict the spacing and location of knickpoints, as well as the locations of gully heads and intense erosion. Soil permeability varies with cover type, and a change in climate and/or cover type can affect amounts of runoff and erosion. In particular, infiltration rates on eolian sediment are four-to-six times higher than on alluvium and colluvium, so a decrease in eolian sediment on Grand Canyon
terraces could contribute to increased gully erosion. Considering our findings that the gully erosion of terraces in Grand Canyon can best be predicted by catchment characteristics such as topography and infiltration, potential baselevel changes near the mainstem river are probably a subordinate control. Effective baselevel itself appears to have a very limited influence on erosion-control structure failure, and slope and drainage area are the primary controls on erosion (as modified by critical shear stress, precipitation, infiltration, and surface roughness). Restorative floods could be helpful in cases where gradient is actually lowered and knickpoints infilled in steep gully reaches near the mainstem river, and eolian transport from beaches and lower terraces formed by such flood events is a likely mechanism for sediment infilling of higher gullies.

We recommend that future geomorphic work focus on: 1) continued monitoring of all problem gullies to understand longer-term erosion trends; 2) refined numerical models factoring in more geomorphic variables, such as infiltration, critical shear stress, and roughness, to identify vulnerable cultural sites, as well as predict erosion and simulate hydrologic and erosional effects of climate or ground cover change; 3) understanding the eolian sediment supply, transport, and depositional system along the river corridor; 4) determining on a site-by-site basis if effective baselevel has actually changed, and determining if a given baselevel fall has caused an increase in channel gradient and erosion potential; and 5) if justified by above activities, scaled physical experiments mimicking Grand Canyon gully field conditions and testing knickpoint response to baselevel fall.
APPENDICES
Appendix A. Site Maps
(Naming and showing locations of gullies, erosion-control structures, infiltration stations, vegetation transects, and cross-section lines)
Figure A.1. Kwagunt site map.
Figure A.2. 60-mile site map.
Figure A.3. Palisades site map.
Figure A.4. Basalt Cliffs site map
Figure A.5. Parashant site map.
Figure A.6. Indian Canyon site map.
Figure A.7. Arroyo Grande site map.
Figure A.8. Granite Park site map.
Figure A.9. Gorilla Camp site map.
Appendix B. Site Descriptions
(Overview of catchment geomorphology)
Kwagunt

Kwagunt serves as an erosion-control site; there is no active gully erosion endangering archaeological features. There are two very small gully channels, neither of which features any knickpoints. The catchment is very small (~0.03 ha) and the channel gradients are ~12%. Both channels appear to be old and inactive, and are probably experiencing infilling. The northern channel experienced runoff during the study period, but did not show signs of channel incision or widening. The upper catchment faces the northeast and is set in talus boulders derived from Redwall limestone, Muav limestone, and Bright Angel shale. The small gully features exist at the toe of the talus, where there is still relatively steep gradient, and drains within the ap terrace. A major trail trends parallel to the hillslope near the site. The archaeological site itself lies between the talus toe and a large foredune to the east. All dunes and eolian activity exist to the east of the study site. Vegetation is dominated by cryptobiotic crust, grass and forbs, brittle brush, salt brush, and mesquite. The abundance of grass and forbs and organic detritus relative to other sites is notable.
Figure B.1. Overview of Kwagunt site. Photograph taken on dune, facing southwest. Person standing on boulder for scale.

60-mile

The 60-mile site features one active gully with four notable tributary branches; archaeological sites are endangered and are actively being destroyed. The catchment is small (0.12 ha) and the main gully drops nearly 11 m over the length of 46 m (24% slope). All of the gully channels feature many abrupt, steep knickpoints, and most contain stone erosion-control structures. Channels widened and incised during the summer of 2002, and the east-most tributary is entirely new. The upper catchment is south-facing and is composed of Bright Angel shale bedrock. The gullies begin in the bedrock, and incise through a dune-dominated ap terrace, and drain to a tributary to the Colorado River. The site has experienced trailing on the dune near the gullies, but this path is becoming less visible due to Park Service efforts. Eolian activity is high and the site is very sensitive to impacts due to its dune setting. Vegetation is dominated by cryptobiotic
crust, grass and forbs, mesquite, cholla, prickly pear, saltbrush, and fedra. Raindrop erosion and crusts are readily visible. Infiltration-excess overland flow dominates the runoff regime, creating knickpoints and plunge-pools.

Figure B.2. Overview of 60-mile catchment. Photo taken facing north. Main gully trends through lower middle portion of photo.

**Palisades**

The Palisades site features two very large active gullies, each with a high density of tributaries; archaeological sites are endangered and are actively being destroyed. The catchments are large (~2 ha) and the two gullies drop 5 and 7 m over the length of 185 and 180 m (4 and 5% slope), respectively. All of the gully channels feature many abrupt, steep knickpoints, and most contain stone erosion-control structures. Channels widened and incised during the summer of 2002. The upper catchment faces the west and is
composed of Dox sandstone and Cardenas basalt bedrock and talus. The middle catchment consists of a virtually impermeable, flat, cracked, salt-crusted “playa.” The gullies begin in this playa area, and incise through an expansive mainstem alluvial apron terrace, draining in or near the Colorado River. The site has experienced trailing on both upper and lower sections. Eolian activity is present. Vegetation is dominated by cryptobiotic crust, grass and forbs, mesquite, prickly pear, saltbrush, and arroweed. Salt crusts are prevalent on the upper gully reaches. Piping causes substantial channel initiation, widening, and headward retreat in the upper reaches, and bank caving caused by lateral scour promotes further channel widening. Pipe collapse into small tributary rills is common in the upper reaches. Drainage density decreases in the lower reaches, as the influence of piping diminishes, sediment is more permeable, and vegetation increases. Overall the site can be divided into three gully reaches: 1) upper: unvegetated playa catchment with high drainage density; 2) middle: piping zone with moderate vegetation and hard soil crust; 3) lower: relatively vegetated incised zone with eolian influence.

Figure B.3. Talus upper catchment
Figure B.4. Overview of entire site, looking west from talus slope. Playa in foreground.

Figure B.5. Playa. Note mudcracks and sparse vegetation.
The Basalt Cliffs site features four medium-sized gullies and several small tributaries that are separated into eastern and western archaeological sites. Artifacts exist near several of the channels. The catchment is a large north-facing alluvial fan that extends from Dox sandstone in the distance, and the gullies begin in variable locations on the alluvial fan and primarily incise through the steep fan toe. The catchment drains to the dune-dominated apr terrace immediately below, where flow disperses and channelization ceases. The combined catchment for the gully system is large (~0.5 ha) and the two eastern gullies drop 7 m over 84 and 100 m (8 and 7% slope), respectively, in comparison to the two western gullies, which drop 2.3 and 3.2 m over 28 and 42 m (8% slope), respectively. All gullies were inactive and without knickpoints before summer of 2002, but channels widened and incised during the summer of 2002 and now feature many abrupt, steep knickpoints. Stone erosion-control structures are present in the eastern gullies, and brush checkdams are established in the western channels. The site has experienced no trailing. Eolian piles are active throughout the site, near gully heads and below gully mouths. Vegetation is dominated by cryptobiotic crust, annual grasses and forbs, mesquite, prickly pear, and iodine brush. Grasses were particularly abundant during the February visit, as well as organic detritus in the channels. Overland flow dominates the runoff regime and creates prominent plungepools, but piping is not present. The alluvial fan catchment is sandier and much more permeable than the rocky talus catchments of other sites.
Figure B.6. Alluvial fan catchment. Photo taken facing south.

Figure B.7. North-facing view from mid-fan.
Parashant

Parashant is an erosion-control site where no archaeological sites are being destroyed or endangered by active gullies. The catchment is small (0.08 ha) and one very small gully drops 1 meter over 8 m (0.17% slope). The entire gully channel features only one small knickpoint and contains no erosion-control structures. There appeared to be no change between the February and October, 2002 trips. The upper catchment faces the southwest and is composed of talus derived from the Muav limestone. The gully begins at the lower talus slope break, and drains to a flat, silty, mainstem ap terrace, where flow disperses and channelization ceases. The site has experienced extensive trailing below the gully mouth. Eolian activity was not noted. Vegetation is sparse, dominated by
shrubs such as creosote, and mesquite, as well as cryptobiotic crust, and prickly pear. What little runoff occurs is due to overland flow, and piping is not present.

Figure B.9. Talus catchment, Muav source. Photo taken facing northeast.

Figure B.10. Small gully. Knickpoint exists near root across channel.
Indian Canyon

The Indian Canyon site features one large active gully, along with several small, rill-like tributaries and small, discontinuous gullies; archaeological sites are actively being destroyed. The catchment is medium-sized (~0.05 ha) and the main gully drops 26 m over the length of 140 m (19% slope). The gully channel has many abrupt, steep knickpoints, and contains several failed stone erosion-control structures. The channel widened and incised slightly in the upper reach during the summer of 2002. The upper catchment faces the east and consists of talus derived from Bright Angel shale and Muav limestone. The gully begins in the lower talus, incises deeply immediately upon entering the softer, coppice dune-dominated apr terrace, especially through two steep terrace risers, and becomes discontinuous near the bottom before it terminates on 1983 flood sand near the river. The site experiences little visitation, but study impacts and trampling were large due to the sensitive eolian nature of the site. Most dunes are sufficiently vegetated and feature raindrop seals, but several areas exhibit loose sand available for transport. Vegetation is not extremely dense, and is dominated by cryptobiotic crust and creosote, as well as sparse grass, barrel cactus, ocotillo, brittle brush, mormon tea, and blackbrush. Piping contributes to the erosion in places, but overland flow is the dominant runoff process.
Figure B.11. Talus upper catchment. Photo taken facing west.

Figure B.12. View of site from talus slope. Gully is in middle of photo.
Arroyo Grande

The Arroyo Grande site features two small gullies and one large gully with a small tributary, all are active; several archaeological sites are endangered and are being damaged. Two of the gullies feature stone erosion-control structures, while one has no erosion treatments. The catchments range in size with each gully (~0.02-0.18 ha) and the three gullies drop 25, 5, and 5 m over the length of 200, 23, and 18 m (12, 20, 28% slope), respectively. All of the gully channels feature several abrupt, steep knickpoints. Channels changed very little between February and October, 2002, and perhaps infilled with eolian sediment slightly in places. A raindrop seal had formed over the soil between visits; apparently there had not been enough flow to initiate runoff. The upper catchment faces the southwest and is composed of Pleistocene debris-flow material with small outcroppings of Precambrian pegmatite bedrock. The smaller gullies begin on a small ap terrace, incise through the oversteepened terrace riser, and drain to a more expansive Holocene terrace, where flow disperses and channelization ceases. The larger gully begins in the lower talus, incises through the ap terrace, becomes discontinuous, and drains to a Holocene debris flow several tens of meters from the mainstem Colorado River. The site has experienced trailing near the small gully heads, crossing over the largest gully. Eolian activity appears to have a small impact in healing the gullies, and source dunes are present below the ap terrace. Vegetation is dominated by cryptobiotic crust, mesquite, creosote, grasses, ocotillo, prickly pear, and barrel cactus. Piping catalyzes substantial erosion in smaller rills, but the gullies exhibit classic plunge-pools derived from overland flow.
Figure B.13. Quaternary debris flow upper catchment, with ap terrace top in foreground. Photo facing the northeast.

Figure B.14. Modern debris-flow deposit to which large main gully (right foreground) drains.
Granite Park

The Granite Park site features one very long gully and many small, rill-like tributaries; archaeological sites are endangered by several of these small tributaries. The catchment is large (~0.16 ha) and the gully drops 11 m over a length of 190 m (6% slope). The gully channel is not very incised or well-defined, but features a few small knickpoints, and many stone erosion-control structures. Little or no change occurred between the February and October, 2002 surveys, and it is doubtful there was any runoff during the study period. The upper catchment faces the west and is composed of Bright Angel shale and Muav limestone bedrock and talus. The gully head is immediately below the talus slope, at the beginning of an expansive, fine-grained ap terrace with superimposed dunes. The main gully channel trends west, winding through an easily-defined catchment comprised of a convex north-facing and south-facing hillslope set. The north-facing slope is dominated by grass and shrubs and has no erosional features, while the south-facing slope features only cryptobiotic crust, sparse shrubs, and bare ground, and has several small, erosive tributaries draining to the main gully. The gully dissipates at the boundary between the ap terrace and a bouldery modern tributary debris-flow deposit, about 100 m from the mainstem Colorado River. The site has experienced trailing on the far-east side, perpendicular to the gully head, and on the crest of the south-facing hillslope, parallel to the main gully. Dunes are present throughout the ap terrace, and an eolian mantle lies over the most of the terrace. Vegetation is dominated by cryptobiotic crust, grass, creosote, brittle brush, prickly pear, barrel cactus, ocotillo, and some mesquite. Piping plays a small role on the crusted, south-facing hillslope of the catchment, but overland flow dominates as the main process.
Figure B.15. Upper catchment: talus and bedrock. Photo taken facing east.

Figure B.16. View of entire site from talus/bedrock slope. Note vegetated N-facing slope (on left) and bare S-facing slope (right). Trails trend both perpendicular and parallel to gully.
Figure B.17. Thick vegetation where gully terminates. Photo taken from debris-flow deposit, facing east (upcatchment).

**Gorilla Camp**

The Gorilla Camp site features four active study gullies, as well as several other unstudied gullies and smaller tributaries; several archaeological sites are endangered and are actively being destroyed. The study site can be divided into two sub-sites: east and west. The catchments in the west site are very small to medium (~0.002 to 0.06 ha) and the three gullies drop 6, 9, and 9 m over the length of 15, 33 and 37 m (40, 27, and 24% slope), respectively. All of the western gullies feature a few small knickpoints, and channelization is often discontinuous. Two of the three channels exhibit stone erosion-control structures. None of the channels changed or experienced runoff between the February and October surveys. The eastern gully has a medium-sized catchment (~0.075 ha) and drops 12 m over the length of 45 m (26% slope). This gully features a multitude of large, near-vertical knickpoints, and is deeply incised. Erosion-control structures are
present, but are washed out and have not been maintained. Although this gully did not experience runoff or erosion during the monitoring period, significant eolian infilling from a nearby dune occurred, "washing out" several of the upper knickpoints. The upper catchment for all gullies faces the southeast and consists of Pleistocene debris flow deposits, with Tapeats sandstone outcrops above. The western gullies all originate at the top of the ap terrace, and erode through the oversteepened terrace toe, draining to mainstem tributary washes. The eastern gully is longer, beginning on a deflating dune at the terrace top break in slope and becoming discontinuous near the bottom before terminating in thick vegetation some tens of meters from a mainstem cobble beach. The site has experienced little visitation and trailing. Eolian activity differs immensely between the eastern and western sub-sites. The western sub-site general has a more compacted, crusted substrate with little eolian influence, whereas the eastern sub-site is much sandier and dominated by dunes. Vegetation is characterized by cryptobiotic crust, creosote, mesquite, grasses, prickly pear, ocotillo, and barrel cactus. Some piping is present, but overland flow is evident as the dominant runoff type, especially in the eastern gully, which features a multitude of knickpoint-plungepool sets.
Figure B.18. Debris-flow upper catchment for western gullies. Photo taken facing north.

Figure B.19. Debris-flow upper catchment for east-most gully. Photo taken facing north.
Figure B.20. Ephemeral wash to which western gullies drain. Photo taken facing east.

Figure B.21. Mouth of east-most gully (terminates in the vegetation)
Appendix C. Soil Properties
(see Fig. C.1 for sample datasheet; terminology and abbreviations from Jorgenson, 1989)
Figure C.1. Sample soil properties data sheet.
Kwagunt

Talus Mantle (0 - 5 cm)
Texture: 52/42/6 (sandy loam)
Sodium absorption ratio: 1.4
Horizon: Av
Dry Color: 2.5Y 6/3
Structure: 1-f-sbk
Gravel %: 50
Wet consistence: so-ps
Dry consistence: lo
Notes: slightly vesicular, but due to rooting; not pavement; effervesces

Talus Matrix (50 cm)
Texture: 52/42/6 (sandy loam)
Sodium absorption ratio: 1.6
Horizon: C
Dry Color: 10YR 6/3
Structure: 1-f-sbk
Gravel %: >75
Wet consistence: so-ps
Dry consistence: lo
Notes: rooted; structure very weak, not pedogenic; effervesces

Toe (0 - 5 cm)
Texture: 58/36/6 (sandy loam)
Sodium absorption ratio
Horizon: A
Dry Color: 2.5Y 5/3
Structure: 1-f-sbk
Gravel %: 25
Wet consistence: so-ps
Dry consistence: lo
Notes: more sand than talus matrix; structure slightly more; parent material pebbly (angular) sandy silt (slopewash, not talus)

Misc. soil notes: Talus parent deposit is clast-supported, angular, cobble-boulder "breccia," uncemented, probably original open-framework (rockfall), no visible fabric; clasts are limestone, rare sandstone.

60-mile

Bedrock catchment regolith (0 – 4 cm)
Texture: 66/18/16 (sandy loam)
Sodium absorption ratio: 4.6
Horizon: Av/C
Dry Color: 5YR 4/3 (deep red from bedrock)
Structure: 1-m-abk
Gravel %: 25
Wet consistence: s-po
Dry consistence: so
Notes: sweet pavement; 1-2 cm of Av; effervesces

Representative eolian
Texture: 45/50/5 (silt loam/sandy loam)
Sodium absorption ratio: 1.6
Horizon: na
Dry Color: 2.5Y 6/3
Structure: 1-f-sbk
Gravel %: 0
Wet consistence: so-po
Dry consistence: so
Notes: pseudo-structure; effervesces

Misc. soil notes: parent material sediment of eolian: massive rooted vf-f sand; thin Av over bedrock regolith: pebbled-sized sandstone and shale chips, clear slope parallel fabric, in areas seems quite stable, clasts varnished; these pavements protect areas from rainsplash (seen elsewhere); HOF hitting bedrock above has already created gullies at midslope

Palisades

Red muddy local playa
Texture: 37/39/24 (loam)
Sodium absorption ratio: 83
Horizon: na
Dry Color: 7.5YR 5/3
Structure: 2-c-sbk
Gravel %: 0
Wet consistence: s-p
Dry consistence: h
Notes: structure not pedogenic; has “flaky” texture; laminated, small (2 mm) salt modules; red/tan color varies on laminae-scale; vesicular throughout; flakiness may be due to geochem characteristics/ dispersion or smectites

Sandy overbank mainstem playa
Texture: 76/17/7 (sandy loam/loamy sand)
Sodium absorption ratio: 164
Horizon: na
Dry Color: 2.5Y 6/3
Structure: 1-m-sbk
Gravel %: 0
Wet consistence: so-po
Dry consistence: sh
Notes: clean, well-sorted, vfU sand; ripple cross-stratification (subcritical) and
few thin low-angle crossbed strata; paleocurrents variously directed, including
both up and downstream relative to mainstem

Sandy coppice dunes
Texture: sand (field)
Sodium absorption ratio: na
Horizon: na
Dry Color: na
Structure: sg/1-m-sbk
Gravel %: 0
Wet consistence: so-po
Dry consistence: so
Notes: vfU-fU sand, rooted; biotic crust in areas

Misc. soil notes: “eolian” coppice dunes actually largely trapped flood sand (pda and
mesquite terrace), only minor eolian reworking and capture at crest of coppices; as much
or more evidence for deflation as is for deposition

Basalt Cliffs

Early Holocene (?) alluvial fan—mid (0-1 cm)
Texture: 86/7/7 (loamy sand/sand)
Sodium absorption ratio: 1.4
Horizon: Av
Dry Color: na
Structure: sg
Gravel %: 10
Wet consistence: so-po
Dry consistence: lo/so
Notes: not vesicular, but trapped silty vf-f sand

Early Holocene (?) alluvial fan—mid (1-20 cm)
Texture: 76/17/7 (sandy loam/loamy sand)
Sodium absorption ratio: 1.4
Horizon: C
Dry Color: 5YR 4/3
Structure: m/sg
Gravel %: >75
Wet consistence: ss-po
Dry consistence: sh
Notes: fine, flaky, chippy, pebbly gravel; angular fragments ≥ 2 cm; matrix silty
vf-f sand; in channels, pebbles clearly imbricated, in deposit imbricated and slope
parallel; no pedogenics seen, but not a good soil profile, just cutbank exposure

Parashant
na

Indian Canyon

Talus (0 – 15 cm)
  Texture: 70/23/7 (sandy loam)
  Sodium absorption ratio: 2.0
  Horizon: na
  Dry Color: 2.5YR 5/3
  Structure: 1-f-sbk
  Gravel %: 10
  Wet consistence: ss-ps
  Dry consistence: so/sh
  Notes: talus pile with open matrix; describing matrix only; talus is clast-supported
  and has high percentage of gravel; vfssi; effervesces; sparse bio-crust; not much
  varnish

Gullied middle section of site—sandy alluvium (capped by coppice dunes)
  Texture: 88/8/4 (sand)
  Sodium absorption ratio: 2.0
  Horizon: na
  Dry Color: 2.5Y 6/3
  Structure: sg-m-sbk
  Gravel %: 0
  Wet consistence: so-po
  Dry consistence: so
  Notes: vfu-fu sand; ripple cross-stratification to laminated; rooted and heavy
  biocrusts; mainstem sand of ap, mesquite and pda.

Misc. soil notes: in talus there is a slope-parallel pavement of pebbles; below pavement is
Av horizon: good sign of eolian deposition

Arroyo Grande

Ap surface with biotic crust (0 – 25 cm)
  Texture: 76/19/5 (loamy sand)
Sodium absorption ratio: 1.8
Horizon: na
Dry Color: 2.5YR 6/3
Structure: 1-f-sbk
Gravel %: <10
Wet consistence: so-po
Dry consistence: so
Notes: lots of rooting/bioturbation; massive eolian; effervesces wildly; from trib bank of main e-most gully

Pleistocene debris fan (0 – 25 cm)
Texture: 60/34/ (sandy loam/loamy sand)
Sodium absorption ratio: 2.2
Horizon: na
Dry Color: 10YR 6/4
Structure: 1-vf-sbk
Gravel %: 50-75%
Wet consistence: ss-ps
Dry consistence: vh
Notes: poorly-sorted; effervesces wildly; clast-supported, poorly-sorted conglomerate (pebble to boulder size); calcite cemented; no imbrication

Lower eolian with grass and biotic crust
Texture: sand (field)
Sodium absorption ratio: na
Horizon: na
Dry Color: na
Structure: 1-f-sbk
Gravel %: 0
Wet consistence: so-po
Dry consistence: so
Notes: well-sorted, medium sand; rooting; eolian; right next to 207-5 infiltration

Granite Park

Representative of hillslope-proximal material (base of bedrock/talus slope)
Texture: 49/44/7 (loam)
Sodium absorption ratio: 21.9
Horizon: na
Dry Color: 10YR 6/3
Structure: 1-f/m-sbk
Gravel %: 0
Wet consistence: so-ps
Dry consistence: sh
Notes: massive vf sandy silt; unusually boring—very little rooting, vesicularity, etc.

Representative of lower catchment coppice dune sand
Texture: Sand (field)
Sodium absorption ratio: na
Horizon: na
Dry Color: na
Structure: m/sg
Gravel %: 0
Wet consistence: so-po
Dry consistence: lo
Notes: massive? rooted, bioturbated, moderately-sorted, vf-f sand

Miscellaneous notes: northward flank of lower catchment (at toe of bedrock to slope to about 35 m riverward) includes buried Pleistocene pebble-cobble subrounded (clast-supported) gravel peeking out of lower cutbanks

Gorilla Camp

Ap/coppice sand below feature (roasting pit) next to gully with checks
Texture: 65/30/5 (sandy loam)
Sodium absorption ratio: 7.7
Horizon: na
Dry Color: 2.5Y 6/3
Structure: 1-m-sbk
Gravel %: 0
Wet consistence: so-po
Dry consistence: so
Notes: silty and vf sand; some fU sand; bioturbated, rooted, trace ash? from roasting pit (or other organic litter?)

Debris fan sediment exposed in main wash walls
Texture: 66/29/5 (sandy loam)
Sodium absorption ratio: 0.9
Horizon: na
Dry Color: 2.5Y 6/3
Structure: m/1-sbk
Gravel %: >75
Wet consistence: so-ps
Dry consistence: lo
Notes: clast-supported, pebble-boulder gravel; clasts subangular; matrix = (from interflow/wash) vf-m sandy silt; heterogeneous in places—imbricated, slightly
sorted gravel, interbedded by sand layers; in other, open framework cobbles and boulders (rock avalanche)
Appendix D. Soil Shear Strength
(Reports mean soil shear strength; measured with a torvane; units are kg/cm²)
### Torvane (Shear Stress) Data Sheet

#### Study Site

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<th>Date</th>
<th>Site Number</th>
<th>Site Name</th>
<th>River Mile</th>
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#### Measurements

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<th>Torvane Size</th>
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Figure D.1. Soil shear strength data sheet.
Kwagunt

#1: talus
  silty w/ fine organic litter: 0.442
  biotic crust (covers most of talus): 1.009

notes: near perm station; silty ground—largely disturbed areas, in hillslope gully bottoms, or under canopy of bushes and rocks; biotic crust—strength depends upon substrate = on old talus remnant face high-relief crust grows on fine eolian mantle (reading ~3.5-4.0); on younger colluvium, lower-relief crust on more compact fines (reading ~5.0-9.0)

#2: toe of slope, near arch sites
  silt w/ weak biotic crust: 0.491

notes: pretty much same readings as talus slope soils w/ no biotics

60-mile

#1: high in catchment
  more active/in gullies: 0.488
  older, more stable colluvium: 0.802

notes: just of younger/more active colluvium and older varnished/paved colluvium; no bedrock itself; this is, in some cases, the $\tau$ of angle of sliding friction of pavement chips, in strongest $\tau$ cases, it is biotic crust

#2: lower in catchment, near arch sites
  trail: 0.14
  gully channel: 0.261
  interfluve: 0.416
  biotic crust: 0.95

notes: eolian; gully channel stronger b/c of rock fragments; also, gully channel stronger where people hadn’t stepped, often b/w erosion control rocks; forms kind of crust, just like sed off of trail; most likely rainsplash seal

Palisades

#1: upper part of site (playa and salt crust)
  playa: 3.423
  salt: 1.276
notes: note deviation from torvane size, even though they are measuring essentially the same strength soil; thickest salt crusts were selected for measurement

#2: middle of catchment, near coppice dunes
   sand, b/w veg, w/o biotic crust, not disturbed: 0.369
   areas w/ biotic crust: 0.952 (0.2)

notes: two of the smaller veins in 0.2 are broken off, thus values are minimum τ; inevitably “break through” and detach crust in order to get vein penetration, thus these are minimum τ for biotic crust

#3: midsection of main gully
   untrampled channel, often w/ mud drape/crust or smoothed (by flow) sand: 0.688
   loose channel sand and gravel, or channel sand disturbed by trampling: 0.128

notes: all done within 20 m segment of gully channel

#4: upper part of site (playa and salt crust)
   playa: 2.571
   salt: 0.934

**Basalt Cliffs**

#1: alluvial fan
   channel: 0.194
   interfluve: 0.377

notes: na

#2: dune
   channel: 0.439
   interfluve: 0.864

notes: na

#3: alluvial fan
   channel: 0.264
   interfluve: 0.407

notes: na

#4: dune
   channel: 0.595
   interfluve: 0.524

notes: na
Parashant

#1: around gully channel
   channel bottom (undisturbed): 0.32
   non-channel: 0.49

Indian Canyon

#1: upper talus reach
   channel (sand): 0.255
   interfluve (sand w/ biotic crust): 1.474
notes: lot of raindrop sealing in non-channels

Arroyo Grande

#1: gullied area (middle part of site?)
   channel (sand): 0.711
   interfluve (sand w/ crust): 0.792
notes: na

#2: debris fan (upper catchment)
   channel (sand and rock): 0.400
   interfluve (rocky, crust): 1.980
notes: na

#3: lower section of site
   channel (sandy): 0.448
   interfluve (sandy): 0.653
notes: na

#4: middle reach of site
   channel: 0.262
   interfluve: 0.643

Granite Park

#1: gullied area (middle of site?)
   channel (sand): 0.711
   interfluve (sand w/ crust): 0.792
notes: na

#2: debris fan (upper catchment)
channel (sand and rock): 0.400
interfluve: (rocky, crust): 1.980
notes: from debris fan above gullies

#3: lower section of site
channel (sandy): 0.448
interfluve (sandy): 0.653
notes: none

#4: middle reach of site
channel: 0.262
interfluve: 0.643
notes: none

Gorilla Camp

#1: around 3 main gullies
interfluve (biotic crusts): 2.595
channel (sand): 0.451
notes: none

#2: E-most gully
stable interfluve: 0.419
deflated interfluve (dune): 0.148
channel: 0.271
notes: on active sand dune
Appendix E. Soil Permeability

(Equilibrium rate at zero head at which saturated soil can take in water; measured with a tension-disc infiltrometer; units are cm/s)
Guelph Permeameter Data Sheet

**STUDY SITE**

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<th>Date</th>
<th>Site Number</th>
<th>Site Name</th>
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**Measurements (use extra sheets if needed)**

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<th>Reading</th>
<th>Time (min)</th>
<th>Time Interval (min)</th>
<th>Head Level (mm)</th>
<th>Reservoir Level (cm)</th>
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Figure E.1. Infiltrometer data sheet
**Kwagunt**

56-1: 0.006
notes: taken up on talus slope in silty soil; lot of biotic crust in vicinity, as well as mesquite, saltbrush, hedgehog cactus, and grass; taken on a slight slope

56-2: 0.003
notes: at small gully head in lower part of site

56-1a: 0.002
notes: October repeat of 56-1

56-2a: 0.004
notes: October repeat of 56-2

**60-mile**

60-1: 0.026
notes: on sand dune; run out of water, weird scatter in data, value not trustworthy

60-2: 0.002
notes: upper catchment—shale and colluvium

60-1a: 0.024
notes: October repeat of 60-1

60-2a: 0.003, 0.006, 0.002
notes: October repeat of 60-2 (3 repetitions)

60-3: 0.012, 0.005
notes: on cryptobiotic crust at mid-site

**Palisades**

65-1: na (virtually impermeable, infiltration did not change with tension)
notes: playa; flat, salt-crusted soil; little veg nearby; lot of mudcracks

65-2: 0.007
notes: mid-site; fine sand (eolian-derived); surrounded by bio-crusts; flat, right above small gully head

65-3: 0.023
notes: lower part of site, on Arroweed Terrace; low slope; arroweed, mesquite, and biotic crust immediately surrounding; medium-grain sand

65-4: 0.021
notes: lower part of site, on Arroweed Terrace; bank above main arroyo, near the outlet; med grain sand; instrument acting funny at time, but data plot looks good

65-1a: na (virtually impermeable, weird scatter in data)
notes: October repeat of 65-1

65-5: 0.004, 0.002
notes: talus slope, underneath a mesquite (two repetitions)

65-6: 0.000, 0.012, 0.001
notes: salty piping reach, on bare ground (three repetitions)

65-4a: 0.026
notes: October repeat of 65-4

65-7: 0.003
notes: Arroweed Terrace near 65-4, under a shrub

Basalt Cliffs

70-1: 0.023
notes: alluvial fan; pebbly alluvial fan with fine sand matrix; vegetation relatively sparse, mainly scrub brush with some grass and occasional mesquite; no biotic crust; on moderate slope; above all gullies

70-2: 0.014
notes: near (above) gully head on c:046; fine sand; take on bare ground, but area mesquite-dominated, plus grasses

70-3: 0.01, 0.005
notes: stony interspace-mid fan (above channel heads, 2 repetitions)

70-4: 0.001, 0.001
notes: alluvial fan, under bush, near 70-3 (2 repetitions)

70-5: 0.001, 0.014
notes: at gully heads, lower fan: coppice dune sand (2 repetitions)

70-6: 0.006, 0.005
notes: beneath mesquite tree at gully mouth (2 repetitions)
**Parashant**

198-1: 0.001  
notes: talus, above gully heads, bare ground

198-2: 0.006  
notes: footslope, near gully head, under shrub

198-3: 0.002  
notes: lower footslope, near gully mouth, cryptobiotic crust

198-4: 0.001  
notes: lower footslope, near gully mouth, grass/forb

198-5: 0.001  
notes: lower footslope, near gully mouth; trampled bare soil

**Indian Canyon**

206-1: 0.004  
notes: talus slope; fairly steep angle; very rocky, not much soil; ~70% rock cover

206-2: 0.003  
notes: talus slope; same as 206-1

206-3: 0.014  
notes: middle incised reach; adjacent to middle incised channel; have alluvial sand with scattered crypto, also creosote around; pretty level

206-4: 0.051  
notes: lowest reach

206-1A: 0.003  
notes: talus, bare ground

206-1B: 0.003  
notes: talus, under shrub

206-1C: 0.002  
notes: talus; crypto

206-1D: 0.006  
notes: talus; grass
206-2A: 0.007
notes: lower talus, gully head region; bare ground

206-2B: 0.004
notes: lower talus, gully head region; under shrub

206-2C: 0.006
notes: lower talus, gully head region; crypto

206-2D: 0.001
notes: lower talus, gully head region; grass

206-3A: 0.039
notes: incised gully reach; bare ground

206-3B: 0.003
notes: incised gully reach; under shrub

206-3C: 0.007
notes: incised gully reach; crypto

206-3D: 0.015
notes: incised gully reach; on small blue grama plant

206-4A: 0.046
notes: upper unincised reach; dune, bare ground

206-4B: 0.009
notes: upper unincised reach; under prickly compound leaf shrub

206-4C: 0.062
notes: upper unincised reach; crypto

206-4D: 0.014
notes: upper unincised reach; on small forb

206-5A: 0.054
notes: lower unincised reach ('83 sand); bare ground

206-5B: 0.014
notes: lower unincised reach ('83 sand); under shrub

206-5C: 0.015
notes: lower unincised reach ('83 sand); crypto
206-5D: 0.052
notes: lower unincised reach (’83 sand); on large bunchgrass

**Arroyo Grande**

207-1: 0.018
notes: above gully head; little veg or rock cover nearby; on fine sand

207-2: 0.006
notes: debris fan; hillside above gullies; rocky; very little soil; pavement-like

207-3: 0.001
notes: debris fan; odd scatter in data; hard to trust

207-4: 0.011
notes: between two w-most, steep gullies; on biotic crust; crusty substrate beneath that

207-5: 0.037
notes: lower dune near main gully; sand

207-1A: 0.002
notes: debris flow; extremely gravely, bare ground

207-1B: 0.000
notes: debris flow; under acacia bush

207-1C: 0.002
notes: debris flow; on well-developed crust, on benchlet above acacia

207-1D: 0.001
notes: debris flow; on small blue grama (cut off at ground)

207-2A: 0.008
notes: gully heads; on level sandy bench (bare ground); raindrop crust

207-2B: 0.001
notes: gully heads; 2/3 in from edge of large creosote; hydrophobic

207-2C: 0.002
notes: gully heads; on crypto

207-2D: 0.001
notes: gully heads; on small blue grama
207-3A: 0.022
notes: gully mouths; raindrop crust on arroyo bank (bare ground)

207-3B: 0.001
notes: gully mouths; just in from edge of large prickly comp shrub; hydrophobic

207-3C: 0.022
notes: gully mouths; on well-developed but fragmented crust

207-3D: 0.001
notes: gully mouths; on dead bunchgrass base

207-4A: 0.058
notes: below gully mouths; bare ground

207-4B: 0.143
notes: below gully mouths; under shrub

207-4C: 0.002
notes: below gully mouths; crypto

207-4D: 0.007
notes: below gully mouths; grass

207-5A: 0.001
notes: debris-flow slope gravel surface

207-5B: 0.002
notes: gully mouths; under dead shrub; very slow to start

207-5C: 0.002
notes: gully heads; crypto

207-5D: 0.018
notes: below gully heads; cut off dead bunch grass; very slow to start; on dune

Granite Park

209-1: 0.019
notes: hillslope crest between drainages; sandy, stabilized, vegetated dune; bare ground with biotic crust and grasses nearby

209-2: 0.003
notes: bedrock upper catchment; steep slope above site; very rocky; scatter in data; cannot trust because taken on bedrock
209-3: 0.008
notes: south-facing slope in lower catchment; sparse vegetation; taken on crusted bare ground right next to trib gully

209-4: 0.009
notes: north-facing slope in lower catchment; very grassy; set on grass on flatter part of slope

209-1A: 0.007
notes: talus; bare ground

209-1B: 0.011
notes: talus; under shrub

209-1C: 0.001
notes: talus; crypto

209-1D: 0.004
notes: talus; grass

209-2A: 0.002
notes: near gully head; bare ground on small, sandy blowout

209-2B: 0.001
notes: near gully head; under large shrub canopy; very slow to start

209-2C: 0.000
notes: near gully head; crypto on NE-facing knoll

209-2D: 0.006
notes: near gully head; on small blue grama; surrounded by crust, in channel

209-3A: 0.005
notes: mid-catchment; bare ground with raindrop crust

209-3B: 0.005
notes: mid-catchment; under shrub; had to prime w/ 30 ml water

209-3C: 0.009
notes: mid-catchment; crypto

209-3D: 0.004
notes: mid-catchment; cheat grass
209-4A: 0.006  
notes: near gully mouth; bare ground

209-4B: 0.006  
notes: near gully mouth; under large shrub canopy

209-4C: 0.025  
notes: near gully mouth; crypto

209-4D: 0.012  
notes: near gully mouth; cheat grass

209-5A: 0.023  
notes: non-vegetated south slope; bare ground on outer edge of larria

209-5B: 0.001  
notes: non-vegetated south slope; under larria shrub; very slow to start

209-5C: 0.005  
notes: non-vegetated south slope; crypto

209-5D: 0.001  
notes: non-vegetated south slope; on new weeds

209-6A: 0.003  
notes: grassy north slope; on small bare patch in large crust area

209-6B: 0.002  
notes: grassy north slope; under large larria shrub canopy

209-6C: 0.007  
notes: grassy north slope; on dry moss

209-6D: 0.004  
notes: grassy north slope; cheat grass/litter

**Gorilla Camp**

223-1: 0.004  
notes: debris fan catchment; very rocky; sparse vegetation; bare ground

223-2: 0.009  
notes: near gully heads; bare ground
223-3: 0.004  
notes: up from E-most gully head, near deflated dune; on sand

223-4: 0.005  
notes: debris flow catchment above E-most gully; on slope above 223-3; very rocky; on bare ground

223-5: 0.047  
notes: on deflated dune next to 223-3; had to refill reservoir; bare sand

223-6: 0.005  
notes: debris fan, b/w 2 sub-sites; right by main tributary wash; set right on biotic crust

223-1A: 0.008  
notes: western debris flow catchment; bare ground

223-1B: 0.000  
notes: western debris flow catchment; under shrub

223-1C: 0.011  
notes: western debris flow catchment; crypto

223-1D: 0.017  
notes: western debris flow catchment; grass

223-2A: 0.002, 0.045  
notes: western gully heads; bare ground

223-2B: 0.011, 0.021  
notes: western gully heads; under mostly dead shrub with no litter

223-2C: 0.006, 0.026  
notes: western gully heads; on level cryptobiotic crust

223-2D: 0.000, 0.007  
notes: western gully heads; on cut off dry grass

223-3A: 0.000, 0.026  
notes: western gully mouths; bare ground on very steep slope

223-3B: 0.002, 0.003  
notes: western gully mouths; under dead bush

223-3C: 0.007, 0.033  
notes: western gully mouths; crypto on very steep slope
Appendix F. Vegetation Transects

(Performed with an 8-pin frame along a 50 m transect; readings were taken every 2.5 meters for 20 total stations; nested frequency was determined by dividing the total number of cover type occurrence by 20 for a given transect; ground cover determined by totaling cover type occurrence using 8-pin frame).
<table>
<thead>
<tr>
<th>Date:</th>
<th>notes: quadrat size 1 = 12.5 x 12.5 cm</th>
<th>column a = nested frequency (ground)</th>
</tr>
</thead>
<tbody>
<tr>
<td>location:</td>
<td>quadrat size 2 = 25 x 25 cm</td>
<td>column b = ground cover from 8-pin frame</td>
</tr>
<tr>
<td>Transect</td>
<td>quadrat size 3 = 25 x 50 cm</td>
<td></td>
</tr>
<tr>
<td>Researchers:</td>
<td>quadrat size 4 = 50 x 50 cm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>b</td>
<td>a</td>
<td>b</td>
<td>a</td>
<td>b</td>
<td>a</td>
<td>b</td>
<td>a</td>
<td>b</td>
<td>a</td>
<td>b</td>
<td>a</td>
<td>b</td>
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<td>b</td>
<td>a</td>
<td>b</td>
<td>a</td>
<td>b</td>
<td></td>
</tr>
</tbody>
</table>

Figure F.1. Vegetation transect data sheet.
### TABLE F.1. VEGETATION TRANSECT DATA FOR KWAGUNT

<table>
<thead>
<tr>
<th></th>
<th>#1-a</th>
<th>#1-b</th>
<th>#2-a</th>
<th>#2-b</th>
<th>#3-a</th>
<th>#3-b</th>
</tr>
</thead>
<tbody>
<tr>
<td>grass/forb</td>
<td>26</td>
<td>1</td>
<td>48</td>
<td>1</td>
<td>33</td>
<td>1</td>
</tr>
<tr>
<td>shrub</td>
<td>7</td>
<td>0.45</td>
<td>0</td>
<td>0.15</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>cactus</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>litter</td>
<td>34</td>
<td>1</td>
<td>48</td>
<td>1</td>
<td>84</td>
<td>1</td>
</tr>
<tr>
<td>soil</td>
<td>23</td>
<td>0.95</td>
<td>51</td>
<td>0.95</td>
<td>40</td>
<td>0.95</td>
</tr>
<tr>
<td>rock</td>
<td>32</td>
<td>0.95</td>
<td>6</td>
<td>0.25</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>crypto</td>
<td>42</td>
<td>1</td>
<td>10</td>
<td>0.25</td>
<td>3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

- **a**: nested frequency (ground), 50x50 cm quadrat size
- **b**: ground cover from 8-pin frame
- #1: talus
- #2: near gully heads
- #3: below gully mouths

### TABLE F.2. VEGETATION TRANSECT DATA FOR 60-MILE

<table>
<thead>
<tr>
<th></th>
<th>#1-a</th>
<th>#1-b</th>
<th>#2-a</th>
<th>#2-b</th>
<th>#3-a</th>
<th>#3-b</th>
</tr>
</thead>
<tbody>
<tr>
<td>grass/forb</td>
<td>1</td>
<td>0.8</td>
<td>20</td>
<td>0.95</td>
<td>21</td>
<td>0.9</td>
</tr>
<tr>
<td>shrub</td>
<td>3</td>
<td>0.25</td>
<td>1</td>
<td>0.05</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>cactus</td>
<td>4</td>
<td>0.1</td>
<td>3</td>
<td>0.3</td>
<td>4</td>
<td>0.25</td>
</tr>
<tr>
<td>litter</td>
<td>3</td>
<td>0.85</td>
<td>15</td>
<td>0.9</td>
<td>11</td>
<td>0.85</td>
</tr>
<tr>
<td>soil</td>
<td>14</td>
<td>0.85</td>
<td>59</td>
<td>1</td>
<td>113</td>
<td>0.95</td>
</tr>
<tr>
<td>rock</td>
<td>127</td>
<td>0.95</td>
<td>35</td>
<td>0.65</td>
<td>6</td>
<td>0.4</td>
</tr>
<tr>
<td>crypto</td>
<td>12</td>
<td>0.4</td>
<td>27</td>
<td>0.65</td>
<td>9</td>
<td>0.4</td>
</tr>
</tbody>
</table>

- **a**: nested frequency (ground), 50x50 cm quadrat size
- **b**: ground cover from 8-pin frame
- #1: bedrock above gully heads
- #2: near gully heads
- #3: below headcuts, mid-site

### TABLE F.3. VEGETATION TRANSECT DATA FOR PALISADES

<table>
<thead>
<tr>
<th></th>
<th>#1-a</th>
<th>#1-b</th>
<th>#2-a</th>
<th>#2-b</th>
<th>#3-a</th>
<th>#3-b</th>
<th>#4-a</th>
<th>#4-b</th>
</tr>
</thead>
<tbody>
<tr>
<td>grass/forb</td>
<td>1</td>
<td>0.65</td>
<td>3</td>
<td>0.25</td>
<td>28</td>
<td>0.8</td>
<td>7</td>
<td>0.55</td>
</tr>
<tr>
<td>shrub</td>
<td>1</td>
<td>0.15</td>
<td>1</td>
<td>0.25</td>
<td>1</td>
<td>0.35</td>
<td>7</td>
<td>0.6</td>
</tr>
<tr>
<td>cactus</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0.1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>litter</td>
<td>47</td>
<td>0.9</td>
<td>1</td>
<td>0.45</td>
<td>5</td>
<td>0.95</td>
<td>26</td>
<td>1</td>
</tr>
<tr>
<td>soil</td>
<td>19</td>
<td>0.6</td>
<td>145</td>
<td>1</td>
<td>119</td>
<td>1</td>
<td>118</td>
<td>1</td>
</tr>
<tr>
<td>rock</td>
<td>88</td>
<td>0.95</td>
<td>3</td>
<td>0.5</td>
<td>1</td>
<td>0.15</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>crypto</td>
<td>2</td>
<td>0.35</td>
<td>7</td>
<td>0.15</td>
<td>6</td>
<td>0.3</td>
<td>2</td>
<td>0.15</td>
</tr>
</tbody>
</table>

- **a**: nested frequency (ground), 50x50 cm quadrat size
- **b**: ground cover from 8-pin frame
- #1: talus upper catchment
- #2: playa
- #3: salty piping reach
- #4: Arroweed Terrace
TABLE F.4. VEGETATION TRANSECT DATA FOR BASALT CLIFFS

<table>
<thead>
<tr>
<th></th>
<th>#1-a</th>
<th>#1-b</th>
<th>#2-a</th>
<th>#2-b</th>
<th>#3-a</th>
<th>#3-b</th>
</tr>
</thead>
<tbody>
<tr>
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<td>2</td>
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<tr>
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<td>0.05</td>
<td>0</td>
<td>0.05</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>cactus</td>
<td>4</td>
<td>0.15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>litter</td>
<td>6</td>
<td>0.8</td>
<td>9</td>
<td>1</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>soil</td>
<td>63</td>
<td>1</td>
<td>94</td>
<td>1</td>
<td>80</td>
<td>1</td>
</tr>
<tr>
<td>rock</td>
<td>72</td>
<td>1</td>
<td>55</td>
<td>0.95</td>
<td>5</td>
<td>0.45</td>
</tr>
<tr>
<td>crypto</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
<td>55</td>
<td>0.85</td>
</tr>
</tbody>
</table>

a: nested frequency (ground), 50x50 cm quadrat size
b: ground cover from 8-pin frame
#1: alluvial fan upper catchment
#2: near gully heads
#3: below gully mouths

TABLE F.5. VEGETATION TRANSECT DATA FOR KWAGUNT

<table>
<thead>
<tr>
<th></th>
<th>#1-a</th>
<th>#1-b</th>
<th>#2-a</th>
<th>#2-b</th>
<th>#3-a</th>
<th>#3-b</th>
</tr>
</thead>
<tbody>
<tr>
<td>grass/forb</td>
<td>1</td>
<td>0.2</td>
<td>3</td>
<td>0.25</td>
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<td>shrub</td>
<td>12</td>
<td>0.4</td>
<td>1</td>
<td>0.1</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>cactus</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>litter</td>
<td>55</td>
<td>1</td>
<td>64</td>
<td>1</td>
<td>71</td>
<td>1</td>
</tr>
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<td>soil</td>
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<td>0.55</td>
<td>21</td>
<td>0.7</td>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>rock</td>
<td>71</td>
<td>1</td>
<td>43</td>
<td>0.85</td>
<td>10</td>
<td>0.65</td>
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<tr>
<td>crypto</td>
<td>13</td>
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<td>29</td>
<td>0.95</td>
<td>77</td>
<td>1</td>
</tr>
</tbody>
</table>

a: nested frequency (ground), 50x50 cm quadrat size
b: ground cover from 8-pin frame
#1: talus upper catchment
#2: near gully heads
#3: below gully mouths

TABLE F.6. VEGETATION TRANSECT DATA FOR INDIAN CANYON

<table>
<thead>
<tr>
<th></th>
<th>#1-a</th>
<th>#1-b</th>
<th>#2-a</th>
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<th>#4-b</th>
<th>#5-a</th>
<th>#5-b</th>
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<td>0</td>
<td>0.05</td>
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<td>10</td>
<td>0.7</td>
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<tr>
<td>shrub</td>
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<td>0.05</td>
<td>2</td>
<td>0.15</td>
<td>1</td>
<td>0.05</td>
<td>1</td>
<td>0.05</td>
<td>3</td>
<td>0.6</td>
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<tr>
<td>cactus</td>
<td>0</td>
<td>0.1</td>
<td>1</td>
<td>0.05</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>litter</td>
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<td>1</td>
<td>19</td>
<td>1</td>
<td>8</td>
<td>0.95</td>
<td>34</td>
<td>0.8</td>
</tr>
<tr>
<td>soil</td>
<td>23</td>
<td>1</td>
<td>50</td>
<td>0.95</td>
<td>24</td>
<td>0.8</td>
<td>25</td>
<td>0.9</td>
<td>11</td>
<td>0.6</td>
</tr>
<tr>
<td>rock</td>
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<td>1</td>
<td>9</td>
<td>0.2</td>
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<td>122</td>
<td>0.95</td>
<td>59</td>
<td>0.85</td>
</tr>
</tbody>
</table>

a: nested frequency (ground), 50x50 cm quadrat size
b: ground cover from 8-pin frame
#1: talus upper catchment
#2: gully head
#3: middle incised reach
#4: upper unincised reach
#5: lower unincised reach (1983 sand)
### TABLE F.7. VEGETATION TRANSECT DATA FOR ARROYO GRANDE

<table>
<thead>
<tr>
<th></th>
<th>#1-a</th>
<th>#1-b</th>
<th>#2-a</th>
<th>#2-b</th>
<th>#3-a</th>
<th>#3-b</th>
<th>#4-a</th>
<th>#4-b</th>
</tr>
</thead>
<tbody>
<tr>
<td>grass/forb</td>
<td>6</td>
<td>0.65</td>
<td>7</td>
<td>1</td>
<td>2</td>
<td>0.3</td>
<td>5</td>
<td>0.55</td>
</tr>
<tr>
<td>shrub</td>
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- a: nested frequency (ground), 50x50 cm quadrat size
- b: ground cover from 8-pin frame
- #1: debris flow upper catchment
- #2: gully heads
- #3: gully mouths
- #4: beyond gully mouths

### TABLE F.8. VEGETATION TRANSECT DATA FOR GRANITE PARK

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- a: nested frequency (ground), 50x50 cm quadrat size
- b: ground cover from 8-pin frame
- #1: talus upper catchment
- #2: gully head
- #3: mid-catchment
- #4: gully mouth
- #5: south-facing slope
- #6: north-facing slope

### TABLE F.9. VEGETATION TRANSECT DATA FOR GORILLA CAMP

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</table>

- a: nested frequency (ground), 50x50 cm quadrat size
- b: ground cover from 8-pin frame
- #1: western debris flow upper catchment
- #2: western gully heads
- #3: western gully mouths
- #4: eastern debris flow upper catchment
- #5: eastern gully head
- #6: eastern gully mouth
Appendix G. Erosion-Control Photo Comparison
(Repeat photographs of select erosion-control structures taken in February and October, 2002)
Figure G.1. 60-mile structures #2 (left) and #3 (right), at confluence in main channel. February (A) #3 is intact, but #2 needs repair due to minor flanking, scour, and undercutting; October (B) very little change overall.
Figure G.2. 60-mile structure #6. February (A) right side is intact; left side features minor breaching at knickpoint; October (B) right side still intact, but left side flanked such that structure cobbles removed.
Figure G.3. 60-mile structure #8. February (A) completely intact; October (B) completely intact.
Figure G.4. Palisades structure #42. February (A) flanked; October (B) up to 60 cm of lateral erosion (by arrow).
Figure G.5. Palisades structure #41. February (A) piping in channel bank; October (B) some deepening, widening, and retreat of erosion features in channel bank.
Figure G.6. Palisades structure #41. View downstream. February (A) note fracturing of bank (arrow); October (B) blocks in (A) have collapsed.
Figure G.7. Palisades small, unnamed structures. February (A) in high drainage density region with many rills nearby; October (B) 30-cm tall block of sediment below was undercut and failed (arrow), structures at top were flanked.
Figure G.8. Palisades small, unnamed structure in tributary gully. February (A) completely flanked; October (B) major channel widening and headcut retreat.
Figure G.9. Palisades structure #35N. February (A): completely intact. October (B): still fairly stable. Possible deposition to side of structure (arrow). Channel in foreground is new (arrow).
Figure G.10. Palisades structure #21, F7. February (A) woody debris has been incorporated into this structure through erosion. Flanked and scoured; October (B) left side of channel has been scoured out, nearly doubling channel width.
Figure G.11. Palisades structure #17N (?). February (A) intact, gully healed; October (B) still stable, except for slight scour near pen on left-central side.
Figure G.12. Basalt Cliffs eastern gully with two structures (see arrows, #9 in foreground). February (A) all structures are intact; October gullies flowed, channels widened, knickpoint formed in front of structure #9. Some infilling within structure #9 (arrow).
Figure G.13. Basalt Cliffs structure in western gully. February (A) intact; October (B) knickpoint just below structure, some channel widening, sediment deposition in middle part of structure, some rocks removed.
Figure G.14. Basalt Cliff's wooden checkdam structures #2 (background) and #3 (foreground) in west gully in C:13:348. February (A) intact; October (B) not much change in #2, but #3 has filled in with sediment.
Figure G.15. Basalt Cliffs unnamed, wooden checkdam structure in east gully. February (A) intact; October (B) sediment deposition, still intact.
Figure G.16. Indian Canyon structure #4. February (A) flanked; October (B) widening, incision, and knickpoint retreat at structure, sediment deposition at base of photo (arrow).
Figure G.17. Indian Canyon structure #5. February (A) breached; October (B) incision and widening of smaller, rejuvenated thalweg cut evident.
Figure G.18. Arroyo Grande structure #2. February (A) intact; October (B) no change.
Figure G.19. Arroyo Grande structures in western gully. February (A) most structures are flanked; October (B) partially filled with eolian sediment.
Figure G.20. Arroyo Grande structure #1. February (A) intact; October (B) no change.
Figure G.21. Granite Park structure #3. February (A) intact; October (B) no change.
Figure G.22. Granite Park structure #2. February (A) intact, although minor erosion near pen; October (B) minor erosion near pen filled in through rainsplash creep.
Figure G.23. Granite Park unnamed structures in foreground, structure #2 in background. February (A) intact, minor flanking around foreground boulders; October (B) little change.
Figure G.24. Unnamed structures. February (A): intact. October (B): sediment filling at bottom and top of photograph (arrows).
Figure G.25. Granite Park series of unnamed structures. February intact; October sediment infilling in front checkdam (arrow).
Figure G.26. Granite Park structure #1. February (A) intact; October (B) no change.
Figure G.27. Granite Park structure #4. February (A) intact; October (B) no change.
Figure G.28. Gorilla Camp Structures #8 (top) and #10 (bottom). February (A) #8 is intact, but #10 is flanked; October (B) no change.
Figure G.29. Gorilla Camp structure #10. February (A) some flanking; October (B) no change.
Figure G.30. Gorilla Camp structure #5. February (A) minor breaching, but mostly intact; October (B) no change.
Figure G.31. Gorilla Camp structures #7 (foreground) and #6 (background). February (A) both are intact; October (B) some deposition within structure #7 (arrow).
Figure G.32. Gorilla Camp structure #16. February (A) flanked and breached; October (B) no change.
Figure G.33. Gorilla Camp structure #1 (bottom), unnamed structures (top). February (A) #1 has minor breaching and flanking; unnamed structures intact; October (B) no change.
Figure G.34. Gorilla Camp structure #2. February (A) minor breaching, rock displacement; October (B) little change.
Figure G.35. Gorilla Camp structure #11. February (A) intact; October (B) infilled by eolian sand.
Figure G.36. Gorilla Camp structure #14. February (B) minor breaching and flanking; October (B) no change.
Appendix H. Erosion-Control Structure Data Tables
(Properties and denudation associated with erosion-control structures measured by total-station ground surveys)
240
TABLE H.1. EROSION-CONTROL STRUCTURE ASSESSMENT
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Contributing on
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Downstream February
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¹ Positive numbers represent denudation, negative numbers represent deposition.
Appendix I. Photogrammetry DTM Error
(Spatial error maps resulting from point-to-model and model-to-model comparisons)
Figure 1.1. Point-to-model manual photogrammetry DTM error for Indian Canyon in March (A) and October (B).
Figure I.2. Model-to-model manual photogrammetry DTM error for Indian Canyon in March (A) and October (B).
Figure I.3. Point-to-model manual photogrammetry DTM error for Arroyo Grande in March (A) and October (B).
Figure I.4. Model-to-model manual photogrammetry DTM error for Arroyo Grande in March (A) and October (B).
Figure I.5. Point-to-model manual photogrammetry DTM error for Granite Park in March (A) and October (B).
Figure I.6. Model-to-model manual photogrammetry DTM error for Granite Park in March (A) and October (B).
Figure I.7. Point-to-model manual photogrammetry DTM error for Gorilla Camp in March (A) and October (B).
Figure I.8. Model-to-model manual photogrammetry DTM error for Gorilla Camp in March (A) and October (B).
Appendix J. Photogrammetry Point Distributions
(Elevation point locations for manual and semi-automated collections)
Figure J.1. March manual (A) and automatic (B) point distributions for Indian Canyon.
Figure J.2. October manual (A) and automatic (B) point distributions for Indian Canyon.
Figure J.3. March manual (A) and automatic (B) point distributions for Arroyo Grande.
Figure J.4. October manual (A) and automatic (B) point distributions for Arroyo Grande.
Figure J.5. March manual (A) and automatic (B) point distributions for Granite Park.
Figure J.6. October manual (A) and automatic (B) point distributions for Granite Park.
Figure J.7. March manual (A) and automatic (B) point distributions for Gorilla Camp.
Figure J.8. October manual (A) and automatic (B) point distributions for Gorilla Camp.
Appendix K. Photogrammetry Contours
(Comparison of manual to semi-automated contours and comparison of manual to ground-survey contours)
Figure K.1. Automatic and manual photogrammetry contours for March (A) and October (B) for Indian Canyon.
Figure K.2. March manual (A) and automatic (B) photogrammetry contours compared to respective survey contours for Indian Canyon.
Figure K.3. October manual (A) and automatic (B) photogrammetry contours compared to respective survey contours for Indian Canyon.
Figure K.4. Automatic and manual photogrammetry contours for March (A) and October (B) for Arroyo Grande.
Figure K.5. March manual (A) and automatic (B) photogrammetry contours compared to respective survey contours for Arroyo Grande.
Figure K.8. March manual (A) and automatic (B) photogrammetry contours compared to respective survey contours for Granite Park.
Figure K.9. October manual (A) and automatic (B) photogrammetry contours compared to respective survey contours for Granite Park.
Figure K.10. Automatic and manual photogrammetry contours for March (A) and October (B) for Gorilla Camp.
Figure K.11. March manual (A) and automatic (B) photogrammetry contours compared to respective survey contours for Gorilla Camp.
Figure K.12. October manual (A) and automatic (B) photogrammetry contours compared to respective survey contours for Gorilla Camp.
Appendix L. Photogrammetry Long Profiles and Cross-Sections
(Compares photogrammetry gully long profiles and channel cross-sections to corresponding ground survey long profiles and cross-sections)
Figure L.1. Indian Canyon March (A) and October (B) long profiles.
Figure L.2. Arroyo Grande west gully March (A) and October (B) long profiles.
Figure L.3. Arroyo Grande central gully March (A) and October (B) long profiles.
Figure L.4. Arroyo Grande main gully March (A) and October (B) long profiles.
Figure L.5. Arroyo Grande tributary gully March (A) and October (B) long profiles.
Figure L.6. Granite Park March (A) and October (B) long profiles.
Gorilla Camp: March survey and photogrammetry profiles for central gully

Figure L.7. Gorilla Camp west gully March (A) and October (B) long profiles.
Gorilla Camp: March survey and photogrammetry profiles for central gully

Figure L.8. Gorilla Camp central gully March (A) and October (B) long profiles.
Figure L.9. Gorilla Camp east gully March (A) and October (B) long profiles.
Gorilla Camp: March survey and photogrammetry profile for east-most gully

Figure L.10. Gorilla Camp east-most gully March (A) and October (B) long profiles.
Indian Canyon: Interpolated cross-section #1

Indian Canyon: Interpolated cross-section #2

Figure L.11. Indian Canyon cross sections. #1 (A) is upstream of #2 (B).
Figure L.12. Arroyo Grande cross sections for west (A), central (B), main (C), and tributaries (D) gullies.
Figure L.13. Granite Park cross section.

Figure L.14. Gorilla Camp: West gully cross-section.
Gorilla Camp: Central gully interpolated cross-section

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Gorilla Camp: East gully interpolated cross-section

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Figure L.14. Gorilla Camp cross sections for west (A), central (B), east (C), and east-most (D, E) gullies. For the east-most gully, cross section #1 (D) is upstream of #2 (E).
Appendix M. Optimal Photogrammetry Density Maps
(Estimates point density needed to achieve optimal photogrammetry accuracy)
Figure M.1. Optimal photogrammetric density for Indian Camp.

Figure M.2. Optimal photogrammetric density for Arroyo Grande.
Figure M.3. Optimal photogrammetric density for Granite Park.

Figure M.4. Optimal photogrammetric density for Gorilla Camp.
Appendix N. Eastern Grand Canyon Survey Profile Comparisons and Slope-Area Indices
(Western Grand Canyon omitted due to lack of change)
Figure N.1. February-October survey comparison and slope-area index values for main gully (A) and west gully (B) at 60-mile site.
Figure N.2. February-October survey comparison and slope-area index values for south main gully (A), south tributary gully (B), north main gully (C), and north tributary gully (D) at Palisades site.
Figure N.3. February-October survey comparison and slope-area index values for east gully (A), east-most gully (B), and west gully (C) at Basalt Cliffs site.
Appendix O. Gully Sensitivity Maps
(GIS-based model showing locations that exceed a slope-area erosion threshold)
Figure O.1. Gully sensitivity map for Indian Canyon.
Figure O.2. Gully sensitivity map for Arroyo Grande.
Figure O.3. Gully sensitivity map for Granite Park.
Figure O.4. Gully sensitivity map for Gorilla Camp.