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Geomorphology and Vegetation Change at Colorado River Campsites, Marble and Grand Canyons, Arizona

Scientific Investigation Report 2017–5096

U.S. Department of the Interior
U.S. Geological Survey

Cover. Photograph looking upstream along the Colorado River at Dinosaur Camp (river mile 50.1 right) in Marble Canyon, Grand Canyon National Park, Arizona (U.S. Geological Survey photograph by Daniel R. Hadley, September, 2013).

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By Daniel R. Hadley, Paul E. Grams, Matthew A. Kaplinski, Joseph E. Hazel, Jr., and Roderic A. Parnell

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Contents

Acknowledgments iii
Abstract 1
Introduction 1
Background 1
Purpose and Scope 3
Description of Study Area 4
Geomorphology and Reach Designations 5
Hydrology and Sediment Supply 6
Vegetation Change at Campsites 8
History of Campsite Monitoring and Campsite Terminology 8
Geomorphic and Vegetation Change at Campsites between 2002 and 2009 13
Introduction 13
Methods 14
Campsite Area Change 14
Elevation and Slope Change/Gully Identification 14
Vegetation Change 14
Intersection of Datasets 19
Statistical Analysis 21
Results 21
The Relative Influence of Erosion, Deposition, and Vegetation Expansion on Campsite Area 21
Comparison by Recreational Reach and Canyon Section 21
Comparison at Individual Sites 28
The Influence of Slope Change on Campsite Area 28
Sandbar-Volume Change and Campsite-Area Change 32
Gullying 35
Vegetation Change within the Extent of Mapped Campsite Area 36
Vegetation Change Within Camp Boundaries 36
Discussion 39
Evaluation of Methods for Measuring Campsite Area 43
Introduction 43
Methods 44
Surveyor Uncertainty 44
Measurement Uncertainty 44
Methods-Based Bias 45
Additional Geomorphic Attributes of Campsites 45
Results 46
Uncertainty Associated With Surveyor Experience 46
Uncertainty Associated with Measurement Error Using the Computer-Tablet Survey Method 46
Total Uncertainty and Methods-Based Bias 46
Physical Constraints on Campsite Area 51
Discussion 51
Conclusions 57
References Cited 58
Appendixes 1–6. Descriptions of Changes at Campsites in Grand Canyon National Park 64

Figures

1. Map of the Colorado River corridor through Grand Canyon National Park, Arizona, showing the location of Lees Ferry, major tributaries, recreational reach divisions, and long-term monitoring sites 2
2. Photographs of upstream view from Cardenas Hilltop near river mile 71.3 in Grand Canyon National Park, Arizona, showing the dramatic increase in vegetation and decrease in sandbar area 3
3. Aerial photograph of Saddle Canyon in Grand Canyon National Park, Arizona, taken in 2002 showing a typical debris fan-eddy complex 5
4. Graphs showing the continuous discharge record for the Colorado River at Lees Ferry, Arizona....7
5. Matched photographs at South Canyon in Grand Canyon National Park, Arizona, showing increases in vegetation cover 9
6. Aerial image of Lower National monitoring site in Grand Canyon National Park, Arizona, illustrating the different boundaries and areas associated with campsite monitoring..10
7. Graphs of mean campsite area from 1998 to 2012 along the Colorado River corridor in Grand Canyon National Park, Arizona....13
8. Example aerial image of a monitoring site, Eminence at river mile 44.5 left, along the Colorado River corridor in Grand Canyon National Park, Arizona, overlaid with digital elevation models....15
9. Example aerial image of a monitoring site, Eminence at river mile 44.5 left, along the Colorado River corridor in Grand Canyon National Park, Arizona, showing categorized rasters of elevation change and slope change derived from 2002–2009 difference rasters....16
10. Bar graphs showing frequency distribution of slope within 2002 and 2009 campsite area along the Colorado River corridor in Grand Canyon National Park, Arizona....17
11. Example photographs of sandbar gullying caused by hillslope runoff leading to recent losses in campsite area along the Colorado River corridor in Grand Canyon National Park, Arizona 18
12. Example aerial photographs overlaid with maps of vegetation change within the extent of mapped campsite areas along the Colorado River corridor in Grand Canyon National Park, Arizona 19
13. Example aerial photograph overlaid with map of vegetation change between 2002 and 2009 within the camp boundary at Hot Na Na along the Colorado River corridor in Grand Canyon National Park, Arizona....20
14. Illustration showing the intersection of datasets for elevation change, slope change, and vegetation change within areas of campsite gain, areas of campsite loss, and stable campsite areas along the Colorado River corridor in Grand Canyon National Park, Arizona....22
15. Pie charts showing cause of gains and losses in campsite area combined for the 35 monitoring sites analyzed in this study along the Colorado River corridor in Grand Canyon National Park, Arizona 23
16. Pie charts showing causes of net loss in campsite area combined for the 35 monitoring sites analyzed in this study and for recreational reach and canyon section along the Colorado River corridor in Grand Canyon National Park, Arizona 23
17. Pie charts showing the cause of gains and losses in campsite area at sites in critical and noncritical reaches along the Colorado River corridor in Grand Canyon National Park, Arizona....26

18. Pie charts showing the cause of gains and losses in campsite area at sites in Marble Canyon and Grand Canyon along the Colorado River corridor in Grand Canyon National Park, Arizona 27
19. Graphs showing the combined effect of erosion, deposition, and slope change on gains in campsite area and losses in campsite area for all sites along the Colorado River corridor in Grand Canyon National Park, Arizona 29
20. Illustration of possible scenarios of campsite area change along the Colorado River corridor in Grand Canyon National Park, Arizona, due to elevation changes that did not cause a change in sandbar slope around the 8-degree threshold used to map campsite areas 31
21. Graphs showing profiles of 22 Mile, along the Colorado River corridor in Grand Canyon National Park, Arizona, before, after, and 6 months after the 2008 controlled-flood release from Glen Canyon Dam 32
22. Bar graphs showing the combined effects of erosion, deposition, and slope change on gains in campsite area and losses in campsite area for critical and noncritical reaches along the Colorado River corridor in Grand Canyon National Park, Arizona 33
23. Bar graphs showing the combined effects of erosion, deposition, and slope change on gains in campsite area and losses in campsite area for Marble Canyon and Grand Canyon along the Colorado River corridor in Grand Canyon National Park, Arizona 34
24. Graphs showing correlation between changes in sandbar volume and changes in campsite area between 2002 and 2009 along the Colorado River corridor in Grand Canyon National Park, Arizona 35
25. Vegetation change between 1998 and 2009 within the extent of mapped campsite area at each of the 37 long-term monitoring sites along the Colorado River corridor in Grand Canyon National Park, Arizona 37
26. Vegetated area within the extent of mapped campsite area along the Colorado River corridor in Grand Canyon National Park, Arizona, occurring above and below the 25,000-cubic feet per second stage elevation for 2002 and 2009 38
27. Images of vegetation cover at Anasazi Bridge along the Colorado River corridor in Grand Canyon National Park, Arizona 41
28. Images of vegetation cover at Nautiloid along the Colorado River corridor in Grand Canyon National Park, Arizona 42
29. Photograph of scientists conducting concurrent computer-tablet and total-station surveys to map campsite area at Eminence along the Colorado River corridor in Grand Canyon National Park, Arizona 45
30. Screenshot of the GIS Pro application showing how data can be attributed to digitized features 47
31. Images showing an example of a complete computer-tablet survey of campsite area at Hot Na Na along the Colorado River corridor in Grand Canyon National Park, Arizona 48
32. Aerial photographs showing examples of repeat total-station surveys of campsite area conducted independently of each other at Eminence and Dinosaur along the Colorado River corridor in Grand Canyon National Park, Arizona 49
33. Graph showing correlation between campsite polygons mapped by experienced total-station survey crews and campsite polygons mapped by inexperienced total-station survey crews for campsites along the Colorado River corridor in Grand Canyon National Park, Arizona 49
34. Aerial photographs showing examples of campsite area mapped using computer-tablet surveys and total-station surveys conducted concurrently at Buck Farm and Lower Saddle along the Colorado River corridor in Grand Canyon National Park, Arizona 50

35. Graphs showing correlation between campsite polygons mapped by computer-tablet surveys and campsite polygons mapped by total-station surveys along the Colorado River corridor in Grand Canyon National Park, Arizona 51
36. Aerial photographs showing examples of repeat surveys of campsite area conducted independently using total-station and computer-tablet methods at Hot Na Na and 22 Mile along the Colorado River corridor in Grand Canyon National Park, Arizona 52
37. Graph showing correlation between campsite area mapped with the computer-tablet method and campsite area mapped with the total-station method, surveyed independently at 22 sites along the Colorado River corridor in Grand Canyon National Park, Arizona 52
38. Bar graph showing campsite-area constraints at 26 long-term monitoring sites along the Colorado River corridor in Grand Canyon National Park, Arizona 54
39. Example images from 51 Mile showing of the limitations of using aerial imagery that predates a field survey by more than 4 years to map campsite area along the Colorado River corridor in Grand Canyon National Park, Arizona 56

Tables

1. Geomorphic and recreational reaches along the Colorado River through Grand Canyon National Park, Arizona 6
2. List of 37 long-term monitoring sites used to monitor changes in campsite area along the Colorado River corridor in Grand Canyon National Park, Arizona, showing which sites were used for each of the analyses conducted 11
3. List of second-order processes associated with changes in campsite area along the Colorado River corridor in Grand Canyon National Park, Arizona 20
4. Cause of gains and losses in campsite area at each of the 35 long-term monitoring sites analyzed in this study along the Colorado River corridor in Grand Canyon National Park, Arizona, summarized by recreational reach and canyon section 24
5 Summary of statistical analysis for elevation and slope changes within areas of campsite gain, areas of campsite loss, and stable campsite areas along the Colorado River corridor in Grand Canyon National Park, Arizona 28
6. Areas of campsite change associated with the combined effects of erosion, deposition, and slope change, summarized by recreational reach and canyon section along the Colorado River corridor in Grand Canyon National Park, Arizona 30
7. Summary of gullies present on 2002 and 2009 sandbar surfaces and the associated change in campsite area due to infilling of gullies or gully formation at sites along the Colorado River corridor in Grand Canyon National Park, Arizona 36
8. Vegetation change within extent of mapped campsite area between 1998 and 2009 summarized by canyon section and recreational reach along the Colorado River corridor in Grand Canyon National Park, Arizona 37
9. Results of Mann-Whitney statistical comparisons of vegetation change between 1998 and 2009 within the extent of mapped campsite area along the Colorado River corridor in Grand Canyon National Park, Arizona, tested at the 95-percent confidence level 37
10. Percentage of vegetation cover within the extent of mapped campsite area along the Colorado River corridor in Grand Canyon National Park, Arizona, above and below the 25,000-cubic feet per second stage elevation 38
11. Vegetation change between 2002 and 2009 within camp boundaries summarized by canyon section and recreational reach 39

12. Results of Mann-Whitney statistical comparisons of vegetation change within camp boundaries along the Colorado River corridor in Grand Canyon National Park, Arizona, tested at the 95-percent confidence level....40
13. Summary of repeat total-station surveys conducted independently at four long-term monitoring sites along the Colorado River corridor in Grand Canyon National Park, Arizona....46
14. Summary of computer-tablet surveys and total-station surveys of campsite area conducted concurrently at three long-term monitoring sites along the Colorado River corridor in Grand Canyon National Park, Arizona....50
15. Summary of computer-tablet and total-station surveys conducted independently at 22 long-term monitoring sites along the Colorado River corridor in Grand Canyon National Park, Arizona....53
16. Summary of campsite-area constraints at 26 long-term monitoring sites along the Colorado River corridor in Grand Canyon National Park, Arizona....55

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
	Mass	
ton, short (2,000 lb)	0.9072	metric ton (t)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre

Datum

Vertical coordinate information is referenced to the Geodetic Reference System 1980 (GRS 80) ellipse defined by the North American Datum of 1983 (NAD 83 (2011). Horizontal coordinate information is referenced to NAD 83 (2011) and projected to State Plane Coordinate System, Arizona Central Zone, in meters. Elevation, as used in this report, refers to distance above the Geodetic Reference System 1980 (GRS 80) ellipse defined by the North American Datum of 1983 (NAD 83) (2011).

Abbreviations and Acronyms

AAB	Adopt-A-Beach program
DEM	digital elevation model
GCDAMP	Glen Canyon Dam Adaptive Management Program
GCMRC	USGS Grand Canyon Monitoring and Research Center
GCPA	Grand Canyon Protection Act
GIS	geographic information system
GLONASS	Global Navigation Satellite System
GPS	Global Positioning System
NPS	National Park Service

Geomorphology and Vegetation Change at Colorado River Campsites, Marble and Grand Canyons, Arizona

By Daniel R. Hadley,[1] Paul E. Grams,[2] Matthew A. Kaplinski,[3] Joseph E. Hazel, Jr.,[3] and Roderic A. Parnell[3]

Abstract

Sandbars along the Colorado River are used as campsites by river runners and hikers and are an important recreational resource within Grand Canyon National Park, Arizona. Regulation of the flow of river water through Glen Canyon Dam has reduced the amount of sediment available to be deposited as sandbars, has reduced the magnitude and frequency of flooding events, and has increased the magnitude of baseflows. This has caused widespread erosion of sandbars and has allowed native and non-native vegetation to expand on open sand. Previous studies show an overall decline in campsite area despite the use of controlled floods to rebuild sandbars. Monitoring of campsites since 1998 has shown changes in campsite area, but the factors that cause gains and losses in campsite area have not been quantified. These factors include, among others, changes in sandbar volume and slope under different dam flow regimes that include controlled floods, gullying caused by monsoonal rains, vegetation expansion, and reworking of sediment by aeolian processes.

Using 4-band aerial imagery and digital elevation models (DEMs) derived from total-station survey data, we analyzed topographic and vegetation change at 35 of 37 long-term monitoring sites (2 sites were excluded because topographic measurements do not overlap with measurements of campsite area) using data collected between 2002 and 2009 to quantify the factors affecting the size of campsite area. Over the course of the study period, there was a net loss in campsite area of 2,431 square meters (m^2). We find that (1) 53 percent of the net loss was caused by topographic change associated with controlled floods and erosion of those flood deposits, (2) 47 percent of the net loss was caused by increases in vegetation cover, the majority of which occurred in high-elevation campsite area, and (3) gullying was significant at certain sites but overall was a minor factor.

Sites in critical reaches—sections of river where campsites are infrequent or where there is high demand by river runners—were subjected to more erosion and changes in sandbar slope than sites in noncritical reaches, suggesting that campsite area is less stable in those reaches. There was also a greater increase in vegetation cover at sites in noncritical reaches than at sites in critical reaches. Our results show a continuation of sandbar erosion and vegetation encroachment that has been occurring at campsites since construction of the dam.

A new campsite survey methodology using a tablet-based geographic information system (GIS) approach was also developed in an effort to map campsite area on digital orthophotographs. Using a series of repeat measurements, we evaluated the inherent uncertainty in mapping campsite area, the accuracy of the new tablet-based method, and if there is any bias between the tablet method and the total-station method that is currently used. We find that uncertainty associated with surveyor judgment while using the total-station method is about 15 percent, which is higher than a previously reported uncertainty of 10 percent. Use of the tablet method adds additional uncertainty; however, the benefits of being able to quantify factors that lead to campsite-area change in the field may outweigh the additional error. Future campsite monitoring may need to consist of a combination of total-station and orthophotograph techniques.

Introduction

Background

Completion of Glen Canyon Dam in 1963 disrupted the natural flow of the Colorado River through Grand Canyon National Park, Arizona, (fig. 1) and eliminated the upstream supply of fine-grained sediment. Sediment supply into the Colorado River in Marble and Grand Canyons is currently limited to sediment inputs from tributaries below Glen Canyon Dam, which has led to less sand available in the channel to be deposited as sandbars (Howard and Dolan, 1981; Schmidt and Graf, 1990; Wright and others, 2005; Hazel and others, 2010). The reduction in sediment supply, coupled with more frequent moderate flows that export sediment, has resulted in widespread erosion of sandbars that are used as campsites (Kearsley and others, 1994; Kearsley and others, 1999; Kaplinski and

[1]Northern Arizona University, Flagstaff, Arizona (now with University of Illinois).

[2]U.S. Geological Survey.

[3]Northern Arizona University, Flagstaff, Arizona.

others, 2010) (fig. 2). The lack of large floods and increase in the baseflow elevation has also allowed native and non-native vegetation to establish and expand at campsites, as vegetation is no longer scoured and removed during floods and is provided with more plant-available water for growth. (Graf, 1978; Turner and Karpiscak, 1980; Kearsley and others, 1994; Webb and others, 1999; Sankey and others, 2015a) (fig. 2). Gullying and hillslope runoff during monsoon events and reworking of sediment by aeolian processes (Melis and others, 1995, Draut and others 2010, Sankey and Draut, 2014; Collins and others, 2016; East and others, 2016) have also contributed to reducing the amount of exposed bare sand along the river corridor, thereby reducing the area available for camping.

Campsite area has been monitored systematically at 32 sites since 1998, with 5 additional sites monitored since 2002 (Kaplinski and others, 2002, 2010, 2014). Although this monitoring shows increases in campsite area associated with controlled floods and declines in campsite area at other times, factors that affect the size and quality of campsites, such as erosion associated with daily and seasonal dam operations, gullying that occurs during monsoon-season thunderstorms, or vegetation encroachment, have not been quantified. Anecdotal evidence suggests that these are significant factors in the loss of campsite area. However, there has been no systematic effort to quantify the relative magnitude of each of these factors (Kaplinski and others, 2010, 2014). In this report, we integrate measurements of campsite area with additional topographic and vegetation datasets to describe the processes that cause changes in campsite area and to quantify their relative magnitude.

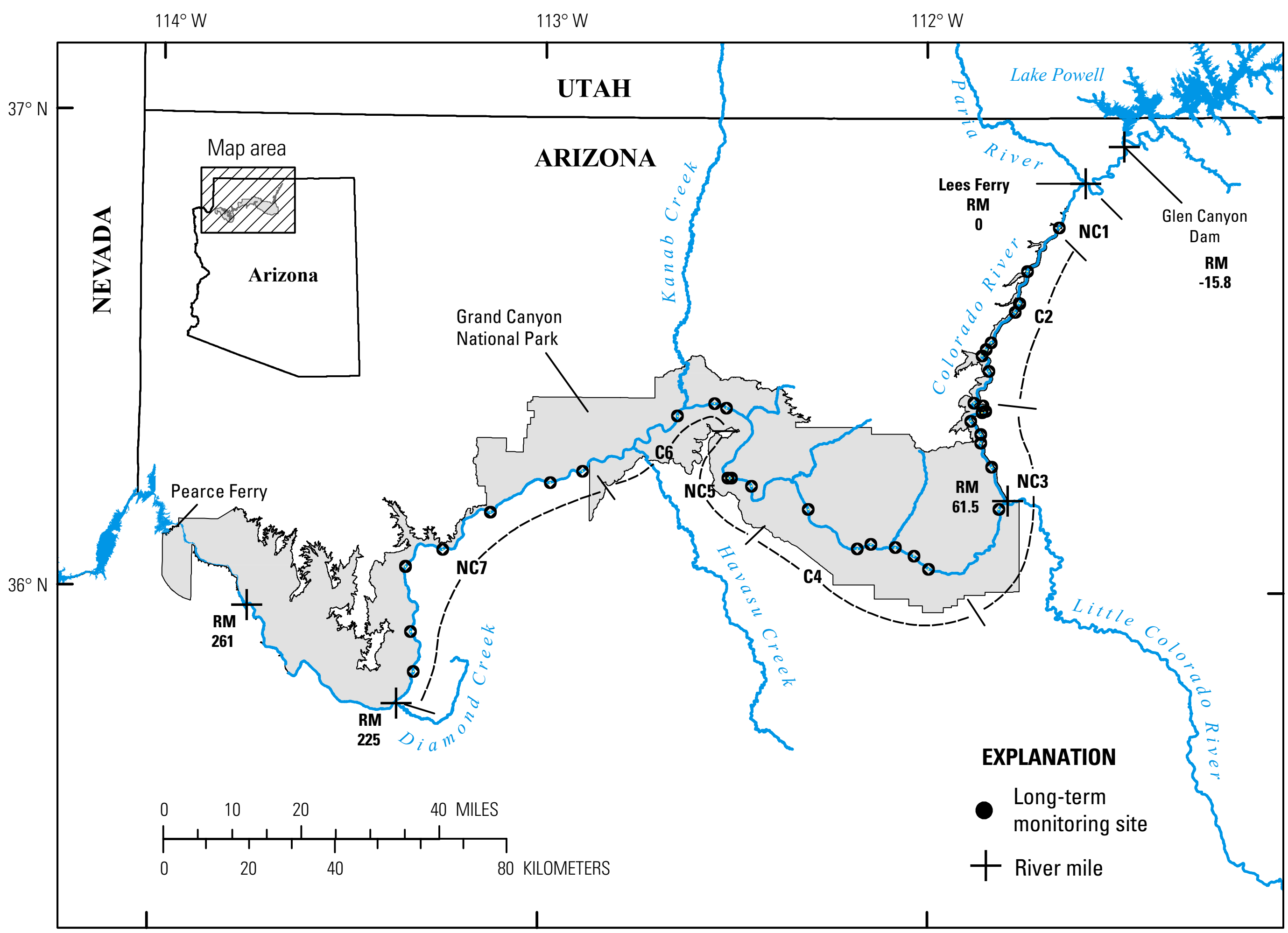


Figure 1. Map of the Colorado River corridor through Grand Canyon National Park, Arizona, showing the location of Lees Ferry, major tributaries, recreational reach divisions (C, critical; NC, noncritical), and long-term monitoring sites. Locations of features are designated by river mile (RM), starting at Lees Ferry (RM 0). Glen Canyon is the section of river between Glen Canyon Dam and Lees Ferry (RM 0). Marble Canyon is the section of river between Lees Ferry and the Little Colorado River confluence (RM 61.5), and Grand Canyon is downstream of the Little Colorado River and extends to Diamond Creek (RM 225). The Diamond Creek reach extends from Diamond Creek to Quartermaster Canyon (RM 261).

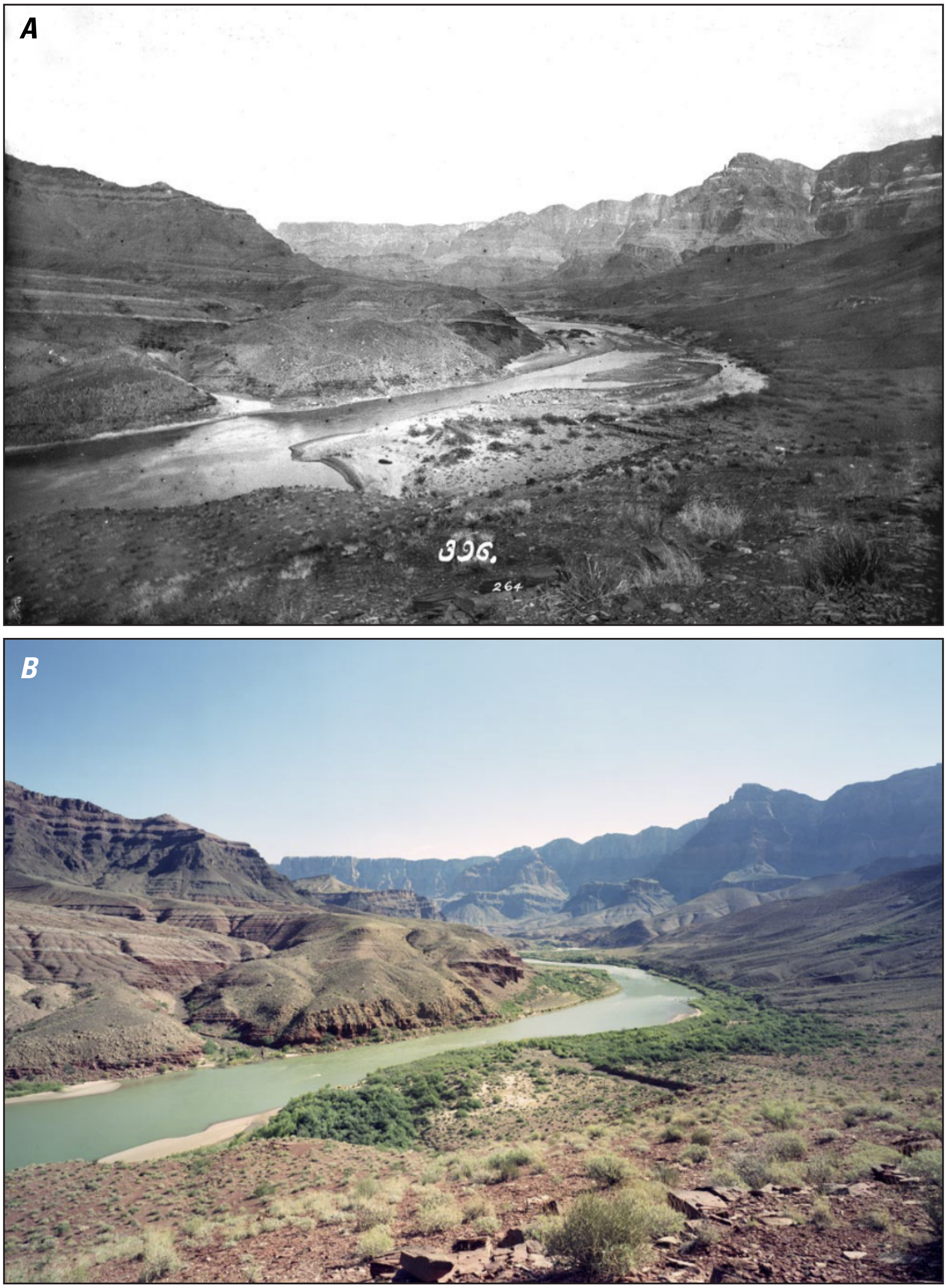


Figure 2. Photographs of upstream view from Cardenas Hilltop near river mile 71.3 in Grand Canyon National Park, Arizona, showing the increase in vegetation and decrease in sandbar area. *A*, Photograph taken by Robert B. Stanton on January 23rd, 1890. *B*, Matched photograph taken on September 20th, 2010 by Bill Lemke. (Photographs from the U.S. Geological Survey, Desert Laboratory Repeat Photography Collection.)

Purpose and Scope

Since John Wesley Powell first descended the Colorado River in 1869, sandbars have been used as campsites by river runners and hikers. To this day, sandbars are an important part of the recreational experience for visitors to Marble and Grand Canyons (Stewart and others, 2003; Kaplinski and others, 2005). The Colorado River corridor through Grand Canyon National Park is dominated by bedrock cliffs and steep vegetated talus slopes. Sandbars are therefore unique areas along the river that are flat, relatively free of vegetation, easily accessible, and able to withstand high usage with negligible long-term impact to the landscape. Rafting trips originating at Lees Ferry are recognized as an internationally significant wilderness experience (Behan, 1999), and these multiday river trips rely on open sandbars distributed throughout the river corridor for campsites (Kearsley and others, 1994).

As many as 25,000 hikers and river runners visit the Colorado River corridor annually (National Park Service, 2006) and campsite availability is of increasing concern to the National Park Service (Bureau of Reclamation, 1995; Stewart and others, 2000) due to the popularity of commercial and private rafting trips and the observed decline in the number and size of campsites (Beus and others, 1985; Kearsley and Warren, 1993; Kearsley and others, 1994; Kaplinski and others, 2005, 2010). Ultimately, resource managers are concerned about campsite carrying capacity, which they define as "the type and level of visitor use that can be accommodated while sustaining acceptable resource and social conditions that complement the park" (National Park Service, 2006). Factors such as the number, size, distribution, and expected lifespan of sandbar campsites, as well as social factors, affect carrying capacity. Social factors include group sizes, trip lengths, the number of trips on the Colorado River at any given time, and the number of people on the river at any given time (National Park Service, 2006). Although quantification of campsite carrying capacity is beyond the scope of this study, campsite area is one aspect of carrying capacity that is related to dam operations and may be objectively quantified. In addition to directly affecting campsite carrying capacity, decline in campsite size and abundance may negatively affect the recreational experience by increasing competition for sites and increasing the amount of contact time among river groups.

The Grand Canyon Protection Act (GCPA) signed into law in 1992 specifies that Glen Canyon Dam shall be operated "to protect, mitigate adverse impacts to, and improve the values . . . [of] . . . natural and cultural resources and visitor use" (Public Law 102-575, 106 Stat. 4600, Title XVIII; see https://www.usbr.gov/uc/legal/gcpa1992.html). Following the release of the Final Environmental Impact Statement (Bureau of Reclamation, 1995) and the Record of Decision for Glen Canyon Dam operations (Bureau of Reclamation, 1996), the Department of Interior created the Grand Canyon Monitoring and Research Center (GCMRC) and the Glen Canyon Dam Adaptive Management Program (GCDAMP), in which adaptive management decisions could be made to maintain and enhance physical, ecological, and recreational resources in accordance with the GCPA. Specifically, the goal of management objective 9.3 within the GCDAMP Strategic Plan is to "increase the size, quality, and distribution of camping beaches in critical and noncritical reaches in the mainstem…" (Bureau of Reclamation, 2001).

Kearsley (1995) documented increases in the size of campsites following the 1993 Little Colorado River flooding events, which supported the use of managed flood releases to rebuild sandbars and improve campsites. Beginning in 1996, the Department of Interior has periodically conducted controlled floods (administratively referred to as high-flow experiments) with the intent of replenishing sandbars and increasing the size of campsite area. Controlled floods are currently the primary management strategy used to improve campsites along the river corridor and have been shown to increase campsite area (Kearsley and Quartaroli, 1997, Kearsley and others, 1999; Kaplinski and others 2010). However, the loss of campsite area in the intervening periods due to sandbar erosion, steepening of sandbar slope, gullying, and expansion of riparian vegetation has outpaced the ephemeral gains in campsite area after a controlled flood (Kaplinski and others, 2010, 2014).

The principal goals of this study were to (1) analyze the changes in sandbar elevation and slope associated with controlled floods, daily/seasonal dam fluctuations, and gullying within campsite areas at long-term monitoring sites, (2) quantify the amount of vegetation change occurring within campsite areas using 4-band aerial imagery of the Colorado River corridor taken in May 2002 and May 2009, and (3) develop a more effective campsite monitoring method using tablets equipped with geographic information system (GIS) capabilities and to evaluate the inherent uncertainty in mapping campsites. Several analyses that span a range of time periods were conducted to address these issues.

Description of Study Area

The study area is the section of Colorado River in northern Arizona that runs through Glen Canyon National Recreation Area below Glen Canyon Dam and through Grand Canyon National Park (fig 1). Locations of campsites and confluences of tributaries are designated by river mile (RM), with distance measured in miles along the centerline of the channel upstream or downstream of the Lees Ferry gaging station (U.S. Geological Survey, USGS, gaging station 09380000). All components of this study adhere to the GCMRC mileage system, with Lees Ferry at river mile 0 (RM 0) (U.S. Geological Survey, 2006). A negative river mile indicates a location upstream from the Lees Ferry gage and a positive river mile indicates a location downstream of the Lees Ferry gage. Campsites are identified by river mile, the side of the river that it is on (left or right, L or R), and place name, after Stevens (1990) and Belknap and Belknap (2001). The left and right sides of the river are determined from the viewpoint of looking downstream. The International System of Units (metric units) is used for all measurements, with the exception of river mile, as noted above, and sand and water discharge, which are reported in tons (short) and cubic feet per second (ft^3/s), respectively.

The study area is subdivided into four canyon sections—Glen Canyon, Marble Canyon, Grand Canyon, and the Diamond Creek reach. Glen Canyon is the section of river between Glen Canyon Dam (RM –15.8) and the Lees Ferry Gage (RM 0). Marble Canyon is the section of river between

Lees Ferry and the Little Colorado River confluence (RM 61.5), and Grand Canyon is downstream of the Little Colorado River (fig. 1). Although Grand Canyon extends to the Grand Wash Cliffs (RM 276), for the purpose of this study the Grand Canyon is referred to here as the section of river between the Little Colorado River and Diamond Creek (RM 225) (fig. 1). The Diamond Creek reach is the section of river between Diamond Creek and Quartermaster Canyon (RM 261).

Geomorphology and Reach Designations

Between Lees Ferry and Diamond Creek, the Colorado River drops 543 meters (m) in elevation (Schmidt and Graf, 1990). Most of this elevation change occurs at steep rapids, which account for only about 9 percent of the total length of the channel (Leopold, 1969). The channel is therefore characterized as having a series of long deep pools broken up by short steep rapids. Nearly all of the rapids are located at channel constrictions caused by debris fans, which are formed by flows from tributary canyons (Howard and Dolan, 1981; Webb and others, 2005). Schmidt and Rubin (1995) described the fan-eddy complex as a suite of geomorphic and hydraulic features, including sandbars that are associated with debris fans (Schmidt and Graf, 1990; Schmidt and Grams, 2011).

Debris fans affect river hydraulics by creating channel constrictions and expansions. At the upstream end of a channel expansion, flow detaches from the bank at the separation point and then rejoins the bank further downstream at the reattachment point (fig. 3). Flow separation creates recirculating eddies, in which water moves back upstream in an eddy return current channel. Eddies are typically areas of lower velocity that lead to deposition of sand from suspension, creating sandbars. Schmidt and Graf (1990) defined separation bars as sand deposits that mantle the debris fan just below the rapid and occur near the separation point and defined reattachment bars as sand deposits at the downstream end of the recirculating eddy near the reattachment point. Reattachment bars project upstream into the eddy and are separated from the river bank by an eddy return current channel (Rubin and others, 1990). Schmidt and Graf (1990) also described other smaller sand deposits such as upper-pool deposits and channel margin deposits. Upper-pool deposits are sand deposits located in the pools upstream of debris fans and are created as sand drops out of suspension from a reduction in velocity as water is pooled behind a rapid. Channel-margin deposits are not associated with fan-eddy complexes and occur in eddies associated with channel-bank irregularities and talus deposits.

The width and depth of the river channel, valley width, and the distribution of debris fans entering the channel is largely controlled by bedrock lithology and structure (Howard and Dolan, 1981). Bedrock along the river channel that is highly resistant to erosion, such as the Precambrian granites

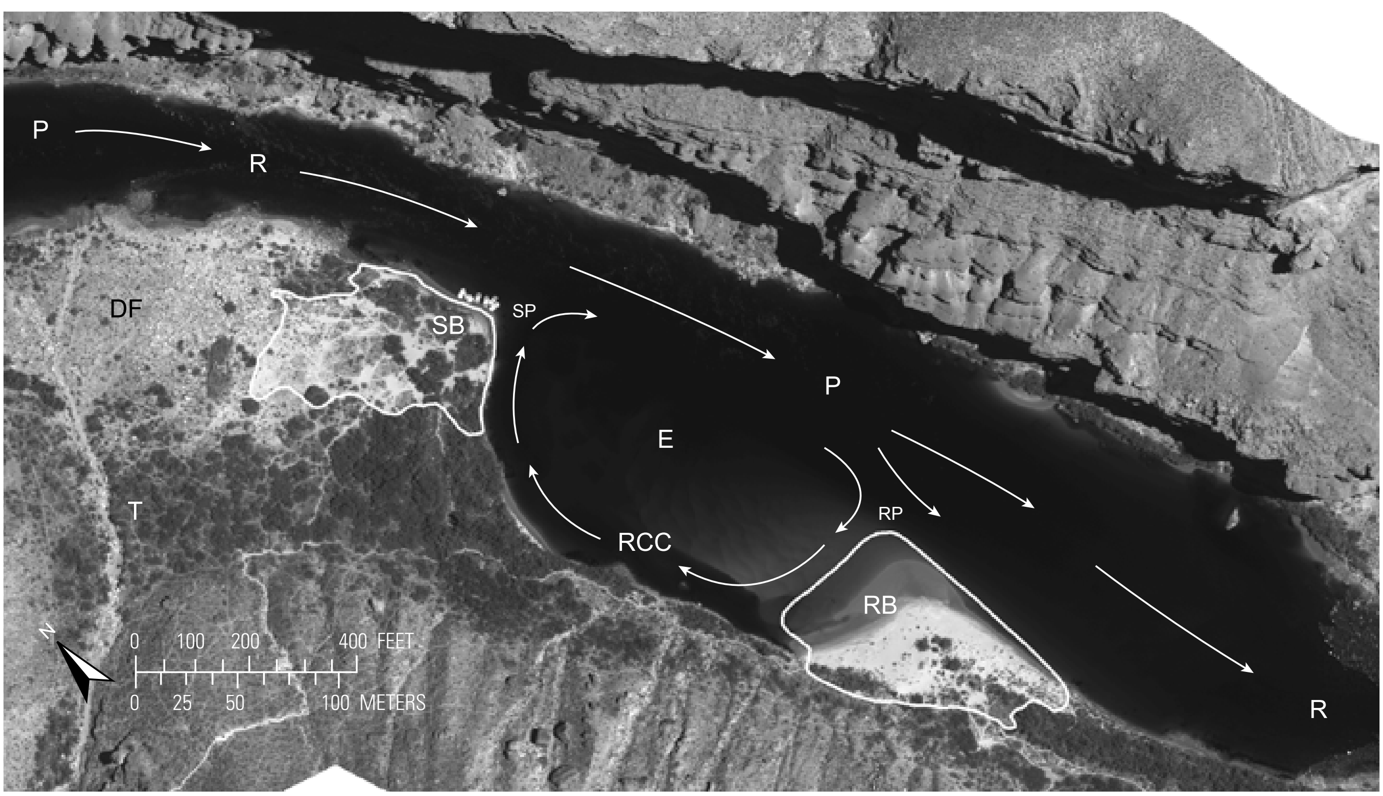


Figure 3. Aerial photograph of Saddle Canyon (river mile 47 right) in Grand Canyon National Park, Arizona, taken in 2002 showing a typical debris fan-eddy complex. T, tributary; DF, debris fan; P, pool; R, rapid or riffle; E, eddy, RCC, return current channel; SP, separation point; SB, separation bar; RP, reattachment point; RB, reattachment bar. Camp boundaries located on the separation bar and the reattachment bar are outlined in white. Arrows indicate flow direction. (Modified from Hazel and others, 2010.)

and schist of the Upper Granite Gorge (RM 77–117) create narrow channels. Erodible rocks such as shale produce wider channels, such as occurs in Lower Marble Canyon (RM 40–61.5), and are associated with larger and more numerous debris fans. Schmidt and Graf (1990) divided Marble Canyon and Grand Canyon into 11 reaches based on bedrock type at river level, average channel width-to-depth ratio, and reach slope, and classified these reaches as "narrow" or "wide" (table 1).

Kearsley and Warren (1993) independently divided the Colorado River corridor into critical reaches and noncritical reaches based on recreational considerations (fig. 1). Critical reaches are defined by narrow sections of the canyon with a limited number of large fan-eddy complexes and therefore a limited number of separation bars and reattachment bars that provide campsites, or simply where competition for campsites is high. These reaches are where campsite carrying capacity is limited. Noncritical reaches are defined by wider sections of the canyon with more numerous and larger fan-eddy complexes and therefore more frequent campsites per river mile. In these reaches, there is little to no competition for sites. Critical and noncritical reaches approximately correspond to the narrow and wide reaches defined by Schmidt and Graf (1990) (table 1).

Hydrology and Sediment Supply

The pre-Glen Canyon Dam flow regime of the Colorado River was characterized by large springtime floods caused by snowmelt from the Rocky Mountains, smaller late summer and fall floods caused by monsoonal rains, and periods of low discharge throughout the winter (fig. 4*A*). Peak flows of about 50,000 ft^3/s were equaled or exceeded every year, which is slightly larger than the magnitude of the post-dam controlled floods (Schmidt and Grams, 2011). Topping and others (2003) estimated that the average flood (a 2-year recurrence peak flow) had a magnitude of about 85,000 ft^3/s and that flows of about 120,000 ft^3/s occurred about every 6 years. The largest recorded flood in the Grand Canyon, which was measured at Lees Ferry in June 1884, was about 210,000 ft^3/s (Topping and others, 2003). In contrast to the large magnitude floods, median flow for the entire pre-dam period was 7,980 ft^3/s, with the month of January having the lowest median flows of 5,140 ft^3/s.

The post-dam flow regime is characterized by large daily fluctuations in discharge, a reduction in the magnitude, duration, and frequency of flooding events, and an increase in the magnitude and frequency of low and moderate flows (Topping and others, 2003) (fig. 4). The 2-year recurrence peak flow in the post-dam period is now about 31,500 ft^3/s, and the median flow in the post-dam period is now about 12,000 ft^3/s (Schmidt and Grams, 2011). Controlled floods conducted in 1996, 2004, 2008, 2012, 2013, and 2014 have had flows of 45,900 ft^3/s, 42,500 ft^3/s, 42,800 ft^3/s, 42,300 ft^3/s, 34,100 ft^3/s, and 37,500 ft^3/s respectively, which are less than the pre-dam mean annual peak flow (fig. 4*B*).

There has also been a substantial decrease in the amount of fine-grained sediment (sand, silt, and clay) carried though Marble and Grand Canyons since the completion of Glen Canyon Dam (Wright and others 2005, 2008; Schmidt and

Table 1. Geomorphic and recreational reaches along the Colorado River through Grand Canyon National Park, Arizona.

[Modified from Kearsley and others, 1994. Reach locations shown on figure 1]

Geomorphic reaches (Schmidt and Graf, 1990)				Recreational reaches (Kearsley and others, 1994)		
Reach no.	**River mile**	**Name**	**Reach type[1]**	**Reach no.**	**River mile**	**Reach type[2]**
1	0–11	Permian Section	W	1	0–11	NC
2	11–23	Supai Gorge	N	2	11–41	C
3	23–40	Redwall Gorge	N			
4	40–62	Lower Marble Canyon	W	3	41–77	NC
5	62–77	Furnace Flats	W			
6	77–118	Upper Granite Gorge	N	4	77–116	C
7	118–126	Aisles	N	5	116–131	NC
8	126–140	Middle Granite Gorge	N	6	131–164	C
9	140–160	Muav Gorge	N			
10	160–214	Lower Canyon	W	7	164–225	NC
11	214–225	Lower Granite Gorge	N			

[1]Designations "W" and "N" correspond to wide and narrow sections.

[2]Designations "C" and "NC" correspond to critical and noncritical reaches.

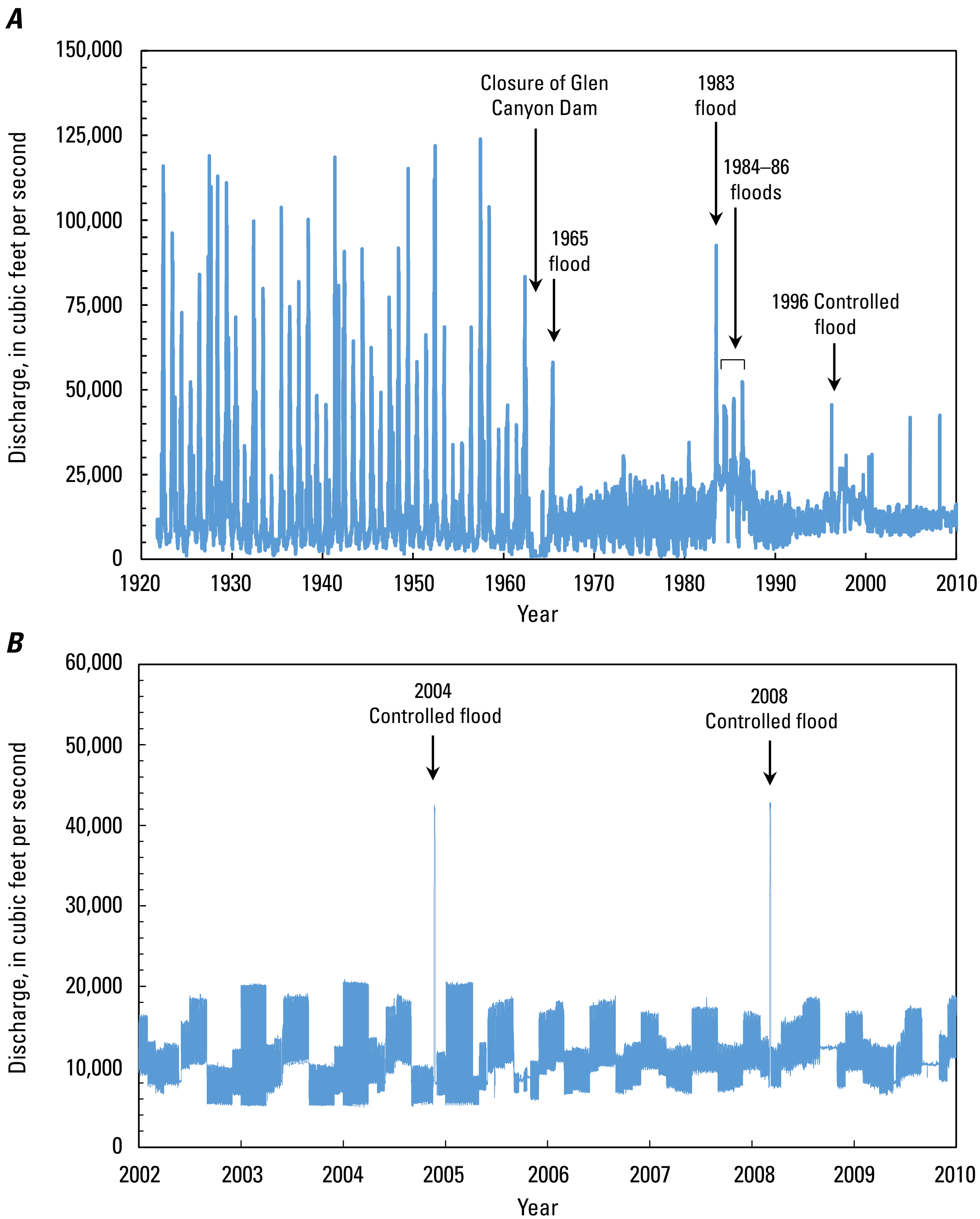


Figure 4. Graphs showing the continuous discharge record for the Colorado River at Lees Ferry, Arizona, (U.S. Geological Survey gaging station 09280000). *A*, Continuous discharge record between 1921 and 2010. *B*, Continuous discharge record between 2002 and 2010.The closure (beginning of operations) of Glen Canyon Dam in 1963 and major flooding events are indicated. Note the substantial decrease in spring floods following closure of the dam and an increase in the low and median flows used for hydroelectric power generation. Figure modified from Schmidt and Grams, 2011. Note the 2004 and 2008 controlled floods which had discharges of 42,500 cubic feet per second (ft^3/s) and 42,800 ft^3/s, respectively, and the daily and seasonal fluctuations in flow.

Grams, 2011). The majority of sandbars are composed of sand, which is defined as particles finer than 2 millimeters (mm) and coarser than 0.062 mm (Schmidt and Grams, 2011). Before dam construction, about 25 million tons of sand passed the Lees Ferry gauge on an annual basis, with an additional 1.7 million tons of sand added from the Paria River and 1.9 million tons of sand added from the Little Colorado River (Topping and others, 2000; Wright and others, 2005). The annual pre-dam sand supply to the Grand Canyon, including inputs from minor tributaries was thus about 29 million tons. In contrast, contributions from the Paria River, the Little Colorado River, and other tributaries below Glen Canyon Dam are currently the only sources of sediment, providing Marble Canyon with sand that is approximately 6 percent of the pre-dam sand supply and Grand Canyon with sand that is approximately 16 percent of the pre-dam sand supply (Wright and others, 2005).

Vegetation Change at Campsites

Expansion of riparian vegetation is common among many regulated rivers in the southwestern United States (Webb and Leake, 2006; Mortenson and Weisberg, 2010) due to alterations of sediment transport and flood frequencies associated with flow regulation (Schmidt and Wilcock, 2008). Since the completion of Glen Canyon Dam, riparian vegetation has expanded along the Colorado River corridor in response to alterations in the flow regime (Turner and Karpiscak, 1980; Waring, 1995; Webb and others, 2002; Ralston, 2005, 2010; Ralston and others, 2008; Sankey and others, 2015a) (fig. 5).

Before the construction of Glen Canyon Dam, riparian vegetation was sparse along the river corridor. Following the closure of the dam, vegetation expanded downslope of the pre-dam high-water zone due to the decrease in flood frequency and magnitude (Turner and Karpiscak, 1980; Waring, 1995). Riparian vegetation that has expanded along the river corridor and onto open sandbar areas includes native species such as catclaw acacia (*Acacia greggii*), coyote willow (*Salix exigua*), and arrowweed (*Pluchea sericea*), as well as non-native species such as tamarisk (*Tamarix ramosissima*) and camelthorn (*Alhagi maurorum*) (Ralston, 2005; Kaplinski and others, 2005, Sankey and others, 2016). Reduced flood frequency has also encouraged the growth of marsh species and marsh habitat development along the river corridor, which was previously a rare occurrence (Stevens and Ayers, 1995; Stevens and others, 1995).

Vegetation expanded along the river corridor until the occurrence of large flooding events from 1983 to 1986. The 1983–1986 floods were caused by unusually large runoff which could not be stored in the Lake Powell reservoir, resulting in large flood releases from the dam. The largest release occurred in June 1983 at a peak discharge of 97,300 ft^3/s (Schmidt and Grams, 2011). These large floods scoured most of the vegetation that had colonized sandbars in the preceding decades (Stevens and Waring, 1986; Stevens and others, 1995). Vegetation recolonized sandbars along the corridor following the 1983–1986 floods and during the period of interim flow in the early 1990s (Stevens and Ayers, 1995). This led to a reduction in the number of campsites from the mid-1980s to the mid-1990s, particularly in noncritical reaches (Kearsley and Warren, 1993; Kearsley and others, 1994). During the 2000s, vegetation expansion continued to occur at elevations as low as below the 25,000-ft^3/s stage largely due to elevated baseflows and infrequent controlled floods that make water available for plant growth (Sankey and others, 2015a). Decreases in tamarisk vegetation specifically have been noted since 2009 due to tamarisk beetle herbivory (Sankey and others, 2016), which may have future effects on campsite area. Nonetheless, findings from more recent campsite monitoring are consistent with the findings of Kearsley and Warren (1993) and indicate that vegetation expansion continues to be an important factor in campsite loss (Kaplinski and others, 2005, 2010).

History of Campsite Monitoring and Campsite Terminology

Sandbars along the Colorado River corridor vary in size, shape, and the extent of vegetation cover. Not all sandbars can be used for camping purposes, as some lack easy river access (that is, steep cutbanks are present or the shoreline is too rocky to easily dock boats), are too densely vegetated, or are too small to accommodate kitchen and sleeping areas. Campsites can have a range of characteristics that make certain sites mores desirable than others. For example, some sites have large areas of open sand with little or no vegetation, whereas other sites may have patches of vegetation and boulders which offer privacy between sleeping areas and shelter from the elements. For the purpose of this study, campsites are defined as sandbars that are present above the zone regularly inundated by normal Glen Canyon Dam operations, are accessible from the river, and not overgrown by vegetation. This is similar to the definition used by Kearsley and others (1999).

Field-based measurements of sandbars have evolved since the early 1970s from simple repeated measurements of topographic profiles using tapes and transits (Howard, 1975; Beus and others, 1985; Schmidt and Graf, 1990) to comprehensive topographic surveys using total-station surveys coupled with channel bathymetry (Hazel and others, 1999, 2008). Campsite inventories and studies concurrent with sandbar monitoring have also been conducted since the mid 1970s—Weeden and others (1975), Brian and Thomas (1984), Kearsley and Warren (1993), Kearsley and others (1994, 1999), Kearsley (1995), Kearsley and Quartaroli (1997), and Kaplinski and others (2005, 2006, 2010, 2014).

Campsite inventories in 1973 (Weeden and others, 1975) and 1983 (Brian and Thomas, 1984), mapped the distribution of campsites along the river corridor and estimated carrying capacity above the 24,000 to 28,000 ft^3/s stage elevation. Kearsley and Warren (1993) conducted a third inventory in 1991 and found a 32-percent reduction in the number of campsites between 1973 and 1991, and a 48-percent reduction

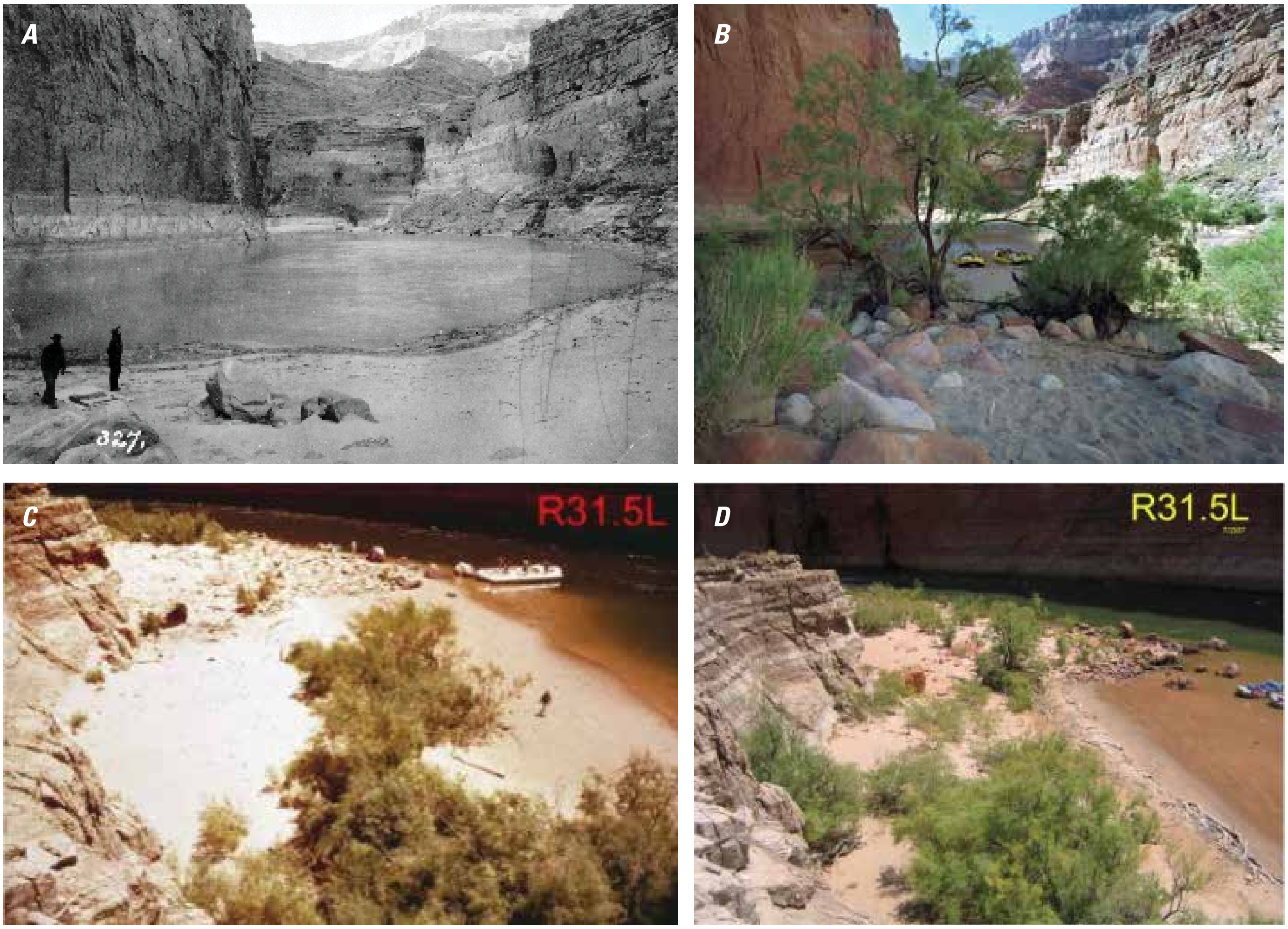


Figure 5. Matched photographs at South Canyon (river mile 31.9 right) in Grand Canyon National Park, Arizona, showing increases in vegetation cover. *A*, Photograph taken by Franklin A. Nims in 1889 during the Stanton expedition, looking downstream and, *B*, matched photograph taken in 2010 by John Mortimer. *C*, Photograph looking upstream and down upon the camp taken by Harmer Weeden in 1973 and, *D*, matched in 2007 by Weeden. (Photographs *A* and *B* from the U.S. Geological Survey, Desert Laboratory Repeat Photography Collection; photographs *C* and *D* from U.S. Geological Survey, Grand Canyon Monitoring and Research Center)

in the number of campsites between 1983 and 1991. Kearsley and others (1994) expanded on Kearsley and Warren's 1993 study, incorporating a comparison of aerial photograph sets from 1965, 1973, 1984, and 1990 to better understand the processes responsible for the loss in the number of campsites. Kearsley and others (1994) concluded that erosion was the primary cause of campsite loss in critical reaches, whereas vegetation encroachment was the primary cause of campsite loss in noncritical reaches.

Subsequent work by Kearsley (1995), Kearsley and Quartaroli (1997), and Kearsley and others (1999) documented changes in campsites caused by the 1993 floods from the Little Colorado River and the first controlled flood conducted in March 1996. Both the natural flood event and the managed flood event increased the number of campsites due to replenishment of sandbars, but bars were eroded within 6 months to a year following the floods. These studies illustrated the potential of using high flows to improve campsites and also documented that gains in campsite area or the number of campsites were ephemeral because of subsequent erosion. The studies conducted by Kearsley and Quartaroli (1997) and Kearsley and others (1999) also improved on campsite monitoring methods by incorporating GIS software to digitize and calculate campsite area.

These early studies evolved into a long-term monitoring program that measures both campsite area and sandbar topography at sites in Marble and Grand Canyons. Thirty-two campsites were selected in 1998, and five additional campsites were added in 2002 (table 2). Topography is measured using standard total-station techniques (Hazel and others, 1999, 2008). Campsite area is measured by surveying the perimeter of areas within the campsite that are actually usable for camping purposes. The specific criteria used to define campsite area and associated terminology are discussed below.

We use "campsite" as a general term to describe a region that may be used by a river party for camping (fig. 6). Within a campsite, some areas are usable for camping purposes, such as sleeping or for meal preparation, whereas other areas may not be usable because the ground is too uneven or covered in dense vegetation. A "camp boundary" is the perimeter of a campsite. Camp boundaries have been mapped by the National Park Service (NPS) and the USGS GCMRC at 504 campsites located throughout Glen Canyon, Marble Canyon, Grand Canyon, and the Diamond Creek reach. This database of mapped camp boundaries includes both current campsites and sites used in the past that may no longer be suitable for camping. Camp Boundary data are available in GIS format in Hadley and others (2018).

We define "campsite area" as the sum of all areas within a campsite that are usable for camping (that is, suitable for use as a kitchen area or sleeping surface). Following the criteria established by Kearsley and Warren (1993), these are areas with smooth substrate (most commonly sand), mostly free of vegetation, and with less than 8 degrees of slope. These areas are typically noncontiguous, and the campsite area within a single campsite is composed of many individual "campsite polygons" (fig. 6). Campsite polygons are typically constrained in size by features such as boulders, bedrock, areas of steep sand, shoreline, patches of vegetation, or deposits of driftwood. We refer to these features collectively as "campsite-area constraints." To measure campsite area, technicians walk sandbars and select areas that fit the established campsite criteria. Points that define the perimeters of campsite polygons are measured with a total station (laser theodolite). Perimeter points are then used to construct each of the campsite polygons. The campsite area is then the sum of the area of all the individual campsite polygons. Campsite area is always, therefore, smaller that the area defined by a camp boundary. An additional term, the "extent of mapped campsite area," refers to the total extent of campsite area that has ever been mapped at a given long-term monitoring site from 1998 to 2009. These extents were used for a component of the vegetation analysis and are further described in the methods section.

The annual campsite monitoring includes 16 sites in critical reaches and 21 sites in noncritical reaches (table 2), and results have been reported by Kaplinski and others (2002, 2005, 2006, 2010, 2014). These studies integrate measurements of campsite area with topographic measurements to report on trends in "high-elevation" and "low-elevation" campsite area. Campsite area above the elevation that would be inundated at a discharge of 25,000 ft^3/s is "high elevation." Campsite area that would be inundated at discharges between 15,000 ft^3/s and 25,000 ft^3/s is "low-elevation." Stage-discharge relations established by Hazel and others (2006) for each site are used to define the high and low elevation zones. The 25,000-ft^3/s stage elevation is significant because daily and seasonal dam releases rarely exceed this discharge, and

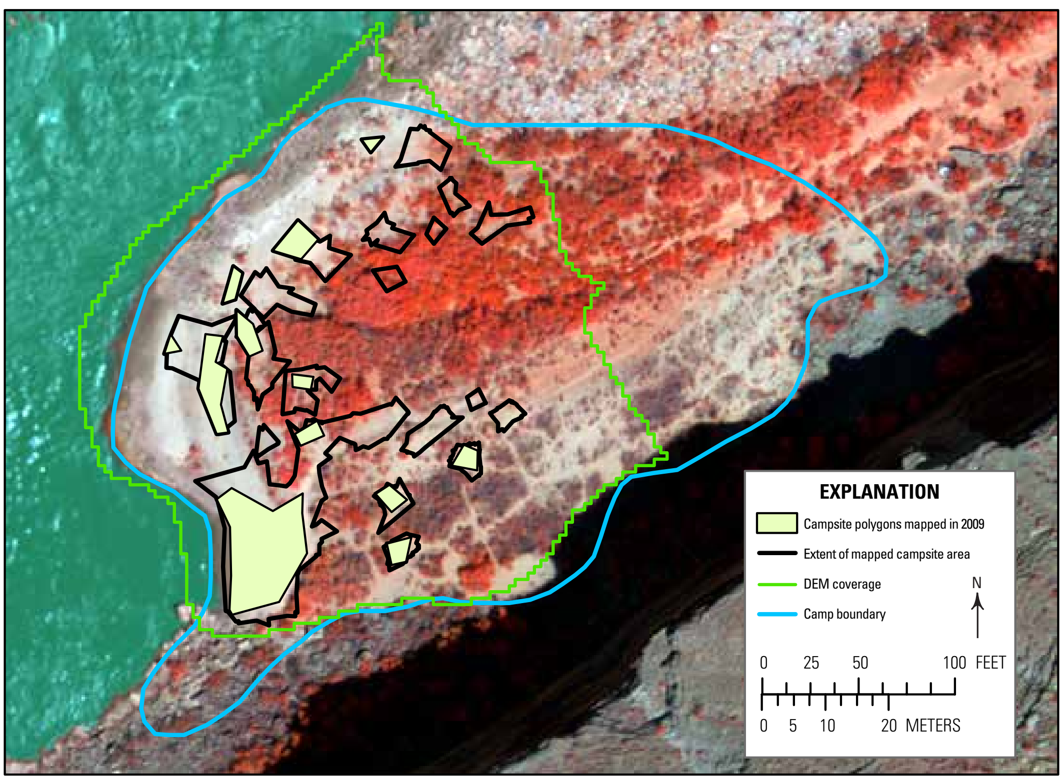


Figure 6. Aerial image of Lower National (river mile 167.1 left) monitoring site in Grand Canyon National Park, Arizona, illustrating the different boundaries and areas associated with campsite monitoring. The camp boundary for this site is outlined in blue and the extent of mapped campsite area is outlined in black. An example of a campsite survey (conducted in October 2009) is shown as green polygons. Campsite area for October 2009 is the sum of the areas found in each of the green campsite polygons. The area of the sandbar surveyed for topography in October 2009 (digital elevation model, DEM, coverage) is outlined in dark green. Note that campsite area may fall outside of the area surveyed for topography depending on the site. U.S. Geological Survey aerial image from May 2009 displayed as false color composite, with green photosynthetically active vegetation displayed as red.

Table 2. List of 37 long-term monitoring sites used to monitor changes in campsite area along the Colorado River corridor in Grand Canyon National Park, Arizona, showing which sites were used for each of the analyses conducted.

[*, campsites added to long-term monitoring in 2002; x, indicates analysis conducted]

Site name[1]	River mile[2]	Side[3]	Recreation reach[4]	Deposit type[5]	Geomorphic analysis	Vegetation analysis		Methodology comparison		
						Camp boundary	Camp boundary	Repeat total-station surveys	Computer-tablet survey versus total-station survey (mapped at same time)	Computer-tablet survey versus total-station survey (mapped independently)
Jackass	8.1	l	NC	S	x	x	x			x
Hot Na Na	16.6	l	C	U	x	x	x			x
22 Mile	22.1	r	C	R	x	x	x			x
Lone Cedar*	23.5	l	C	U	x	x	x			x
Silver Grotto*	29.5	l	C	U	x	x	x			x
Sand Pile	30.8	r	C	R	x	x	x			x
South Canyon	31.9	r	C	U		x	x			
Nautiloid	35.1	l	C	S	x	x	x	x		x
Buck Farm*	41.2	r	NC	S	x	x	x		x	
Anasazi Bridge	43.5	l	NC	R	x	x	x			x
Eminence	44.5	l	NC	S	x	x	x	x	x	
Willie Taylor*	45.0	l	NC	R	x	x	x			x
Lower Saddle	47.7	r	NC	R	x	x	x		x	
Dinosaur	50.1	r	NC	S	x	x	x	x		x
51 Mile	51.5	l	NC	R	x	x	x			x
Kwagunt Marsh	55.9	r	NC	R	x	x	x			
Crash Canyon	63.0	r	NC	R	x	x	x	x		x
Grapevine	81.7	l	C	U	x	x	x			x
Clear Creek	84.6	r	C	R	x	x	x			
Cremation	87.7	l	C	U	x	x	x			
91 Mile	91.7	r	C	S	x	x	x			x
Granite	93.8	l	C	U	x	x	x			x
Emerald	104.4	r	C	R	x	x	x			
119 Mile	119.4	r	NC	R	x	x	x			x
122 Mile	122.8	r	NC	R	x	x	x			x
Upper Forster	123.3	l	NC	R	x	x	x			x
Football Field	137.7	l	C	R	x	x	x			
Fishtail	139.6	r	C	U	x	x	x			
Above Olo	145.9	l	C	R	x	x	x			x

Table 2. List of 37 long-term monitoring sites used to monitor changes in campsite area along the Colorado River corridor in Grand Canyon National Park, Arizona, showing which sites were used for each of the analyses conducted.—Continued.

Site name[1]	River mile[2]	Side[3]	Recreation reach[4]	Deposit type[5]	Geomorphic analysis	Vegetation analysis	Methodology comparison			
						Camp boundary	Camp boundary	Repeat total-station surveys	Computer-tablet survey versus total-station survey (mapped at same time)	Computer-tablet survey versus total-station survey (mapped independently)
Lower National*	167.1	l	NC	S	x	x	x			x
172 Mile	172.6	l	NC	R	x	x	x			
183 Mile Right	183.3	r	NC	R	x	x	x			x
183 Mile Left	183.3	l	NC	R		x	x			x
Hualapai Acres	194.6	l	NC	R	x	x	x			
202 Mile	202.3	r	NC	S	x	x	x			
Pumpkin Springs	213.3	l	NC	U	x	x	x			
Middle 220 Mile	220.1	r	NC	U	x	x	x			

[1]Site names are from Stevens (1990) and Belknap and Belknap (2001) and are informally used.

[2]Location is based on the river mile centerline downstream from Lees Ferry (river mile 0) (U.S. Geological Survey, 2006).

[3]The descriptors "l" and "r" indicate the right or left side of the river viewed in the downstream direction.

[4]NC indicates a noncritical recreation reach, C indicates a critical recreation reach.

[5]Deposit type: R, reattachment bar; S, separation bar; U indicates an undifferentiated deposit, where the distinction between a separation bar and reattachment bar becomes difficult to determine. Undifferentiated deposits also include channel margin deposits and deposits located at the higher elevations of debris fans that are not regularly inundated.

sandbars are inundated above the 25,000-ft^3/s stage elevation only during controlled floods.

Kaplinski and others (2014) reported a 36-percent decrease in the mean total campsite area between 1998 and 2012, an average decrease in high-elevation campsite area of 61 percent, and no significant trend in low-elevation campsite area (fig. 7). They conclude that campsite area had significantly declined during the study period and that the management objectives set forth by the GCDAMP for increasing campsite size had not yet been met.

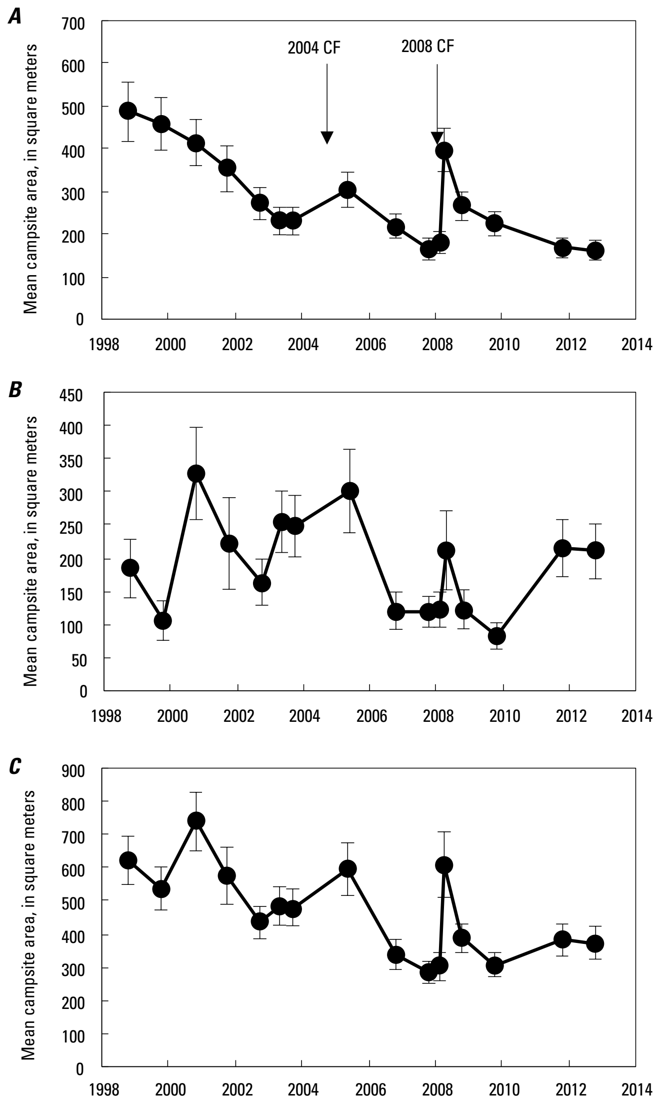


Figure 7. Graphs of mean campsite area from 1998 to 2012 (from 1998–2001 at 32 sites; from 2002–2012 at 37 sites) along the Colorado River corridor in Grand Canyon National Park, Arizona. Error bars show standard error of the mean. *A*, Mean high-elevation campsite area (above the 25,000 cubic feet per second, ft^3/s, stage elevation). *B*, Mean low-elevation campsite area (between the 15,000- and 25,000-ft^3/s stage elevations). *C*, Mean total campsite area (above the 15,000-ft^3/s stage elevation). CF, controlled flood. (Modified from Kaplinski and others, 2014.)

Changes at campsites have also been monitored by repeat photographs. Although the repeat photographs do not provide quantitative measures of campsite area, they do provide a basis for qualitative description of campsite change and illustrations of mechanisms of campsite change. Repeat photographs have been collected at all of the long-term monitoring sites and at additional sites as part of the "citizen science" Adopt-A-Beach (AAB) program. The AAB program was established by the Grand Canyon River Guides (a professional organization of commercial river guides) in 1996 to document changes to campsites through each river running season and to assess the longevity of flood deposits following high-flow releases.

The early campsite inventories (Weeden and others, 1975; Brian and Thomas, 1984; Kearsley and Warren, 1993), annual campsite-area monitoring at the 37 long-term monitoring sites (Kaplinski and others, 2002, 2005, 2006, 2010, 2014), and the results of the AAB program (Hamilton, 2014) link several factors to campsite loss, including sandbar erosion, changes in sandbar slope, vegetation encroachment, hillslope runoff, and aeolian erosion. To date, there has been no systematic effort to quantitatively determine the influence that each of these factors have on campsite loss, which is the purpose of this study. Determining which factors have led to the greatest amount of campsite loss, and to determine if the influence of these factors vary by site, recreation reach, or canyon section, could have important implications for management objectives set forth in the GCDAMP.

Geomorphic and Vegetation Change at Campsites between 2002 and 2009

Introduction

We examined geomorphic and vegetation change at campsites along the Colorado River corridor between 2002 and 2009 to help quantify the effects of Glen Canyon Dam operations and natural processes on campsite size. The purpose of this aspect of the project was to evaluate the relative importance of the different mechanisms that contributed to changes in campsite area using topographic data and 4-band digital orthoimagery. The specific objectives were to (1) quantify the amount of erosion and deposition that occurred within campsite areas and to distinguish between erosion caused by surface runoff generated upslope from sandbars and erosion caused by fluctuating flow releases, (2) quantify changes in slope within campsite areas, (3) quantify change in the proportion of campsite area covered by vegetation, and (4) quantify vegetation change within the extent of mapped campsite areas and camp boundaries.

We used campsite monitoring data collected in 2002 and 2009 at the 37 long-term monitoring sites (fig. 1, table 2). These measurements of campsite area are mostly coincident with measurements of sandbar topography, which are necessary for the analysis. However, two long-term monitoring sites, South Canyon (RM 31.9R) and 183 Mile Left (RM 183.3L), were not included in the topographic analysis because topographic measurements do not overlap with measurements of campsite area at those sites (table 2). The campsite monitoring and topographic data used in this study are available in GIS format in Hadley and others (2018). The 2002 to 2009 period was selected because those are the years for which maps of vegetation were available.

Methods

Campsite Area Change

Changes in campsite area were determined by direct comparison between the campsite polygons mapped in October 2002 and the campsite polygons mapped in October 2009. This comparison was performed with the "union" command in ArcGIS 10.2 (Esri, 2013) (fig. 8). Campsite areas mapped in 2009 but not in 2002 were labeled as campsite gain. Conversely, campsite areas mapped in 2002 but not in 2009 were labeled campsite loss. Campsite areas mapped in 2002 and 2009 were labeled stable campsite area. When mapping in the field, surveyors only map campsite polygons that are near or above the maximum range of daily discharge fluctuations. Our analysis includes all campsite polygons above the 10,000-ft^3/s stage elevation, because maximum daily discharge was 10,000 ft^3/s during the 2002 survey and 10,700 ft^3/s during the 2009 survey. This is different than previous campsite-monitoring reports, which discuss changes in campsite area occurring above the 25,000-ft^3/s stage elevation (Kaplinski and others, 2010), or above the 15,000-ft^3/s stage elevation (Kaplinski and others, 2014). Areas of campsite change by site varied in size from less than 10 m^2 to more than 1,000 m^2.

Elevation and Slope Change/Gully Identification

Areas of erosion and deposition were determined by subtracting the 1-m resolution DEM derived from the 2002 survey from the 1-m DEM derived from the 2009 survey to produce a DEM of difference. Rasters representing the slope of the sandbar in degrees were also derived from the 2002 and 2009 DEM surfaces using the Spatial Analyst Slope tool in ArcGIS (Esri, Inc., 2013). A slope-difference raster was created by subtracting the 2002 slope surface from the 2009 slope surface (fig. 8).

The DEMs of difference were categorized into areas of deposition (areas with >0.04 m of change), erosion (areas with less than –0.04 m of change), and no significant elevation change (areas that were within ±0.04 m) (fig. 9). A four centimeter threshold was used based on uncertainty estimates reported by Hazel and others (2008) and Kaplinski and others (2017). The slope-difference rasters were categorized based on the 8-degree slope threshold used to define campsite area (Kearsley and Warren, 1993), where flat areas were considered to have slopes of less than 8 degrees and steep areas were considered to have slopes greater than 8 degrees. These slope categories are (1) slope change from flat to steep, (2) slope change from steep to flat, (3) flat areas of no change, and (4) steep areas of no change (fig. 9). About 90 percent of campsite area mapped in 2002 and 2009 had a slope of 8-degrees or less (fig. 10), thus the 8-degree slope threshold was appropriate for distinguishing between areas that are considered usable for camping and areas that are too steep to be used for camping.

To distinguish erosion caused by hillslope runoff from erosion caused by fluvial process, gullies were identified from the 2002 and 2009 sandbar surfaces based on the topographic data. Gullies are drainage features that incise into the sandbar surface and are caused by hillslope runoff generated from storm events. Gullies can be small surface features less than 1 m in width or depth (often referred to as rills) or can be large features that are several meters in width or depth (fig. 11). Flow-direction and flow-accumulation rasters were derived from the sandbar-slope rasters in ArcGIS. Raster cells of flow accumulation allowed identification of potential gullies and were further discerned using 0.25-m contour lines generated from the DEMs. Total-station derived surfaces at the long-term monitoring sites support a 0.25-m contour interval at the 95-percent confidence level based on analysis of interpolation uncertainty between total-station survey points (Hazel and others, 2008; Kaplinski and others, 2017)). A series of remote cameras located throughout the river corridor take photographs of sandbars on a daily basis, and these photographs were used to verify the presence of gullies.

Gullies present in 2009 were intersected with areas of campsite loss to determine the amount of loss occurring as a result of hillslope runoff. Gullies present in 2002 were intersected with areas of campsite gain to determine the amount of gain caused by gully infilling. Gullies can infill by fluvial deposition from the mainstem river, alluvial deposition from hillslope transport or backwasting, or aeolian deposition of windblown sand (Sankey and Draut, 2014; Collins and others, 2016; East and others, 2016). The type of infilling was verified with the remote-camera photographs when possible.

Vegetation Change

Four-band aerial imagery (blue, green, red, and near-infrared [NIR]) of the Colorado River corridor below GCD were acquired in May 2002 and May 2009 (Davis and others, 2002; Ralston and others, 2008; Davis, 2012). Image resolution was 0.22 m, and collection occurred in May when most vegetation is at full foliage. Discharge from GCD was held at a constant 8,000 ft^3/s during the time of data acquisition. Maps of total vegetation coverage along the river corridor were created using image classification and interpretation methods to exhaustively identify vegetation (for detailed descriptions of

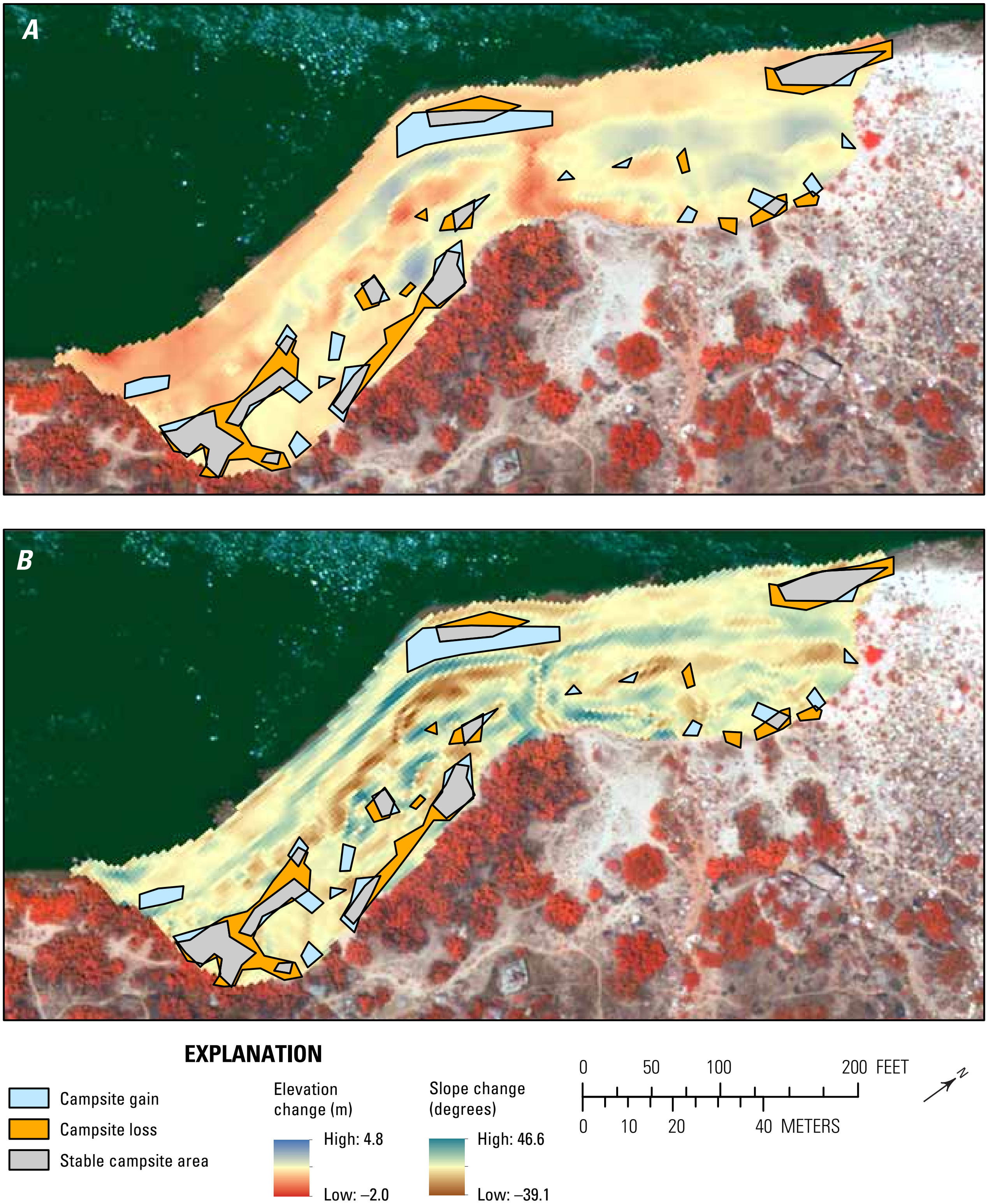


Figure 8. Example aerial image of a monitoring site, Eminence at river mile 44.5 left, along the Colorado River corridor in Grand Canyon National Park, Arizona, overlaid with digital elevation models (DEMs). DEMs of sandbars were used to monitor campsite change along the river. DEMs were generated from total-station survey data to create (*A*) elevation- and (*B*) slope-difference rasters. Difference rasters represent the change in elevation and slope of the sandbar between 2002 and 2009. m, meters. U.S. Geological Survey aerial image from May 2009 displayed as false-color composite, with green photosynthetically active vegetation displayed as red.

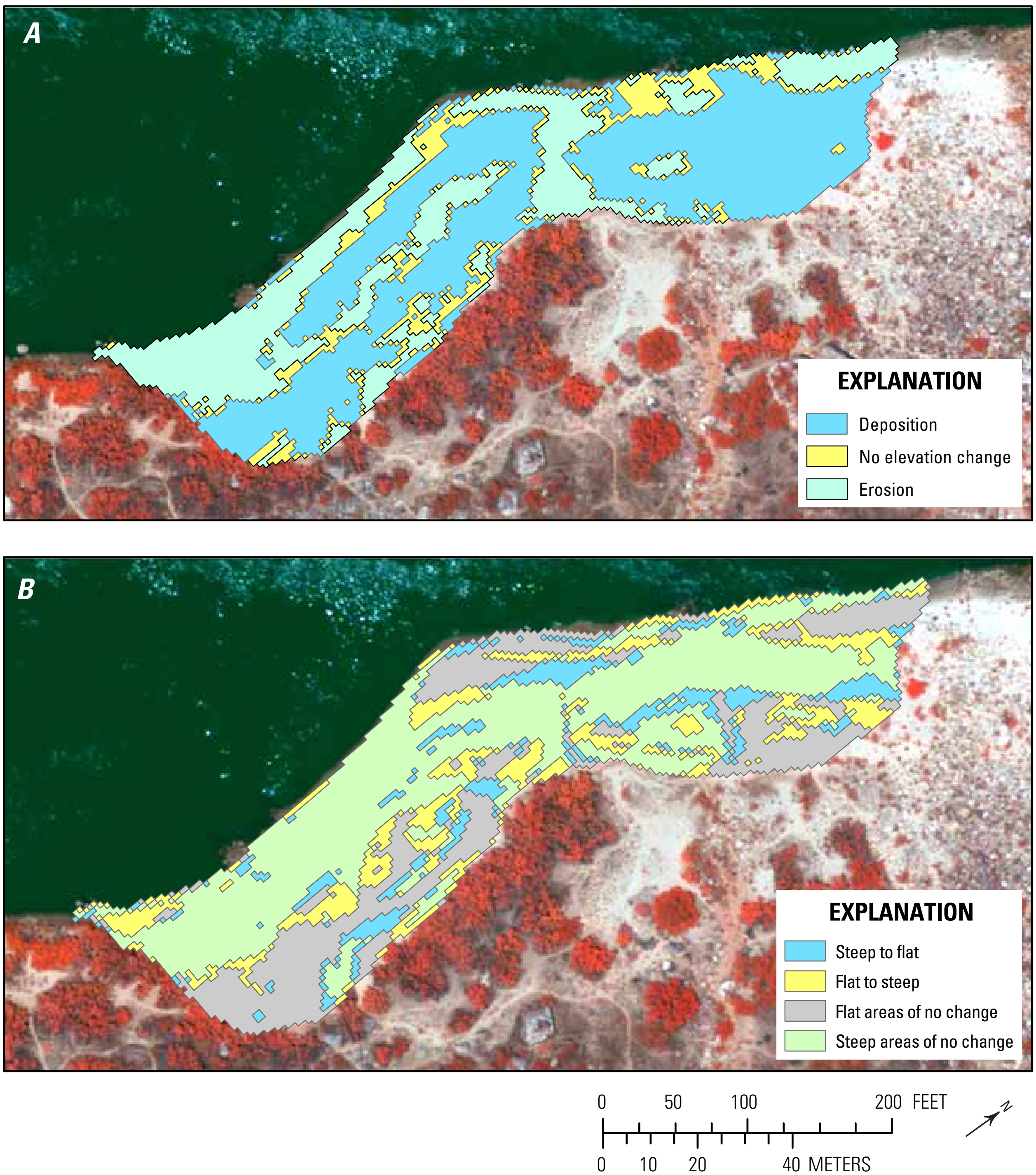


Figure 9. Example aerial image of a monitoring site, Eminence at river mile 44.5 left, along the Colorado River corridor in Grand Canyon National Park, Arizona, showing categorized rasters of (*A*) elevation change and (*B*) slope change derived from 2002–2009 difference rasters (see fig. 8). Elevation change was based around a threshold of ±0.04 meters. Slope change was based on the 8-degree threshold used for campsite monitoring. U.S. Geological Survey aerial image from May 2009 displayed as false-color composite, with green photosynthetically active vegetation displayed as red.

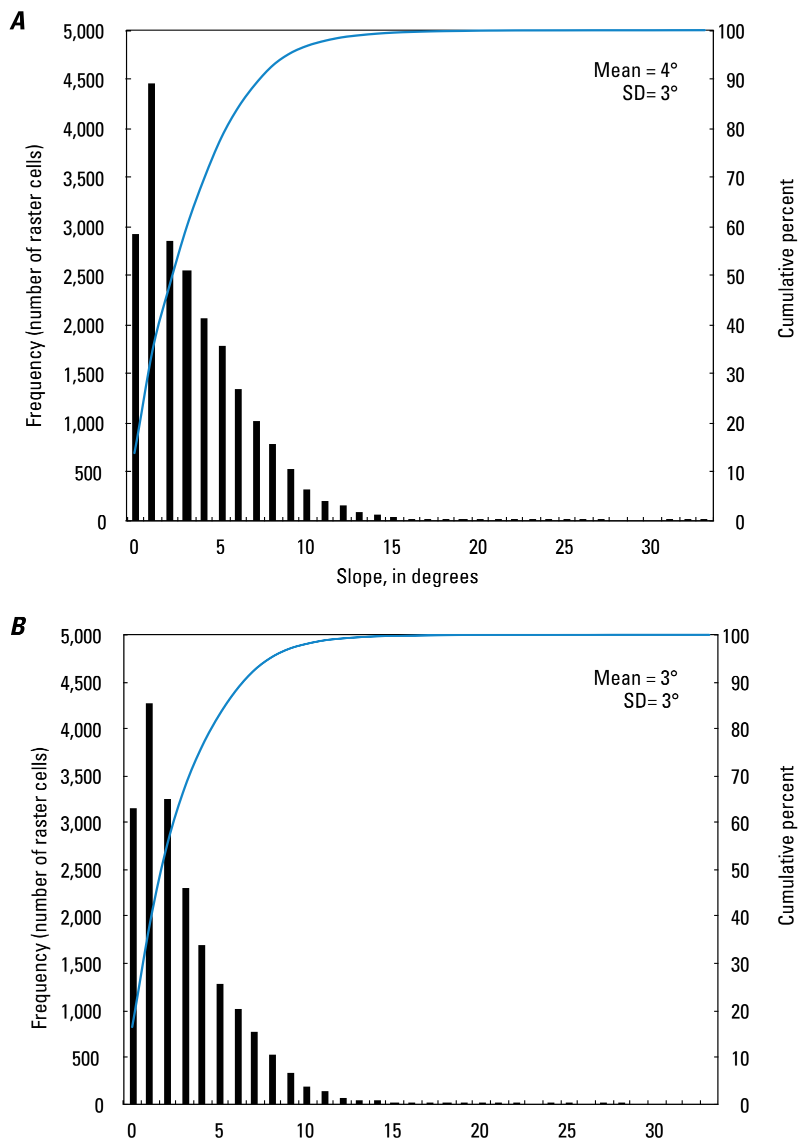


Figure 10. Bar graphs showing frequency distribution of slope within (*A*) 2002 and (*B*) 2009 campsite area along the Colorado River corridor in Grand Canyon National Park, Arizona. Cumulative percentage (blue lines) on the right axis shows that 90 percent of campsite area for both years falls under a slope of 8 degrees. SD, standard deviation.

image acquisition, processing, and vegetation classification, see Davis and others, 2002; Ralston and others, 2008; Davis, 2012; Sankey and others, 2015a; and Sankey and others, 2016; the data at 1-m resolution are available in Sankey and others, 2015b, https://dx.doi.org/10.5066/F7J67F0P). Precise coregistration of the 2002 and 2009 image mosaics (Davis, 2012) allowed for seamless change detection among years. Accuracy of the total vegetation classification for both sets of imagery likely exceeds 95 percent (Ralston and others, 2008; Sankey and others, 2015a).

Areas of vegetation change were created in ArcGIS using the 2002 and 2009 maps of total vegetation coverage. Areas where vegetation was mapped in 2009 but not in 2002 were labeled as areas of vegetation gain. Conversely, areas mapped as covered by vegetation in 2002 but not in 2009 were labeled as areas of vegetation loss. Areas where vegetation was mapped in 2002 and 2009 were labeled as areas of stable vegetation. Only total vegetation coverage was used to calculate vegetation change. Subdividing the total vegetation coverage into vegetation classes or species was beyond the scope of this study.

The maps of vegetation change between 2002 and 2009 were used to analyze the effect of vegetation expansion on campsite area in three different contexts (table 2). First, vegetation changes were analyzed within the campsite areas mapped in 2002 and 2009 at 35 of the 37 long-term monitoring sites. The purpose of this analysis was to evaluate the relative role of vegetation change and other geomorphic processes on changes in campsite area. The analysis was therefore limited to the region of each site where topographic data are available.

Secondly, changes in vegetation were analyzed within the total extent of mapped campsite area at all of the 37 long-term monitoring sites (fig. 12). The total extent of mapped campsite area was defined as any area within a long-term monitoring site ever mapped as a campsite polygon between 1998 and 2009. This analysis was not limited to areas with topographic data coverage and, therefore, includes all campsite polygons at

Figure 11. Example photographs of sandbar gullying caused by hillslope runoff leading to recent losses in campsite area along the Colorado River corridor in Grand Canyon National Park, Arizona. *A*, Gullying at Nautiloid (river mile 35.1 left). *B*, Gullying at Crash Canyon (river mile 63.0 right). Nautiloid photograph (*A*) was taken on September 24, 2013, and is looking down on the tributary channel that cuts through the site. Crash Canyon photograph (*B*) was taken on September 27, 2013, looking upstream. (U.S. Geological Survey photographs.)

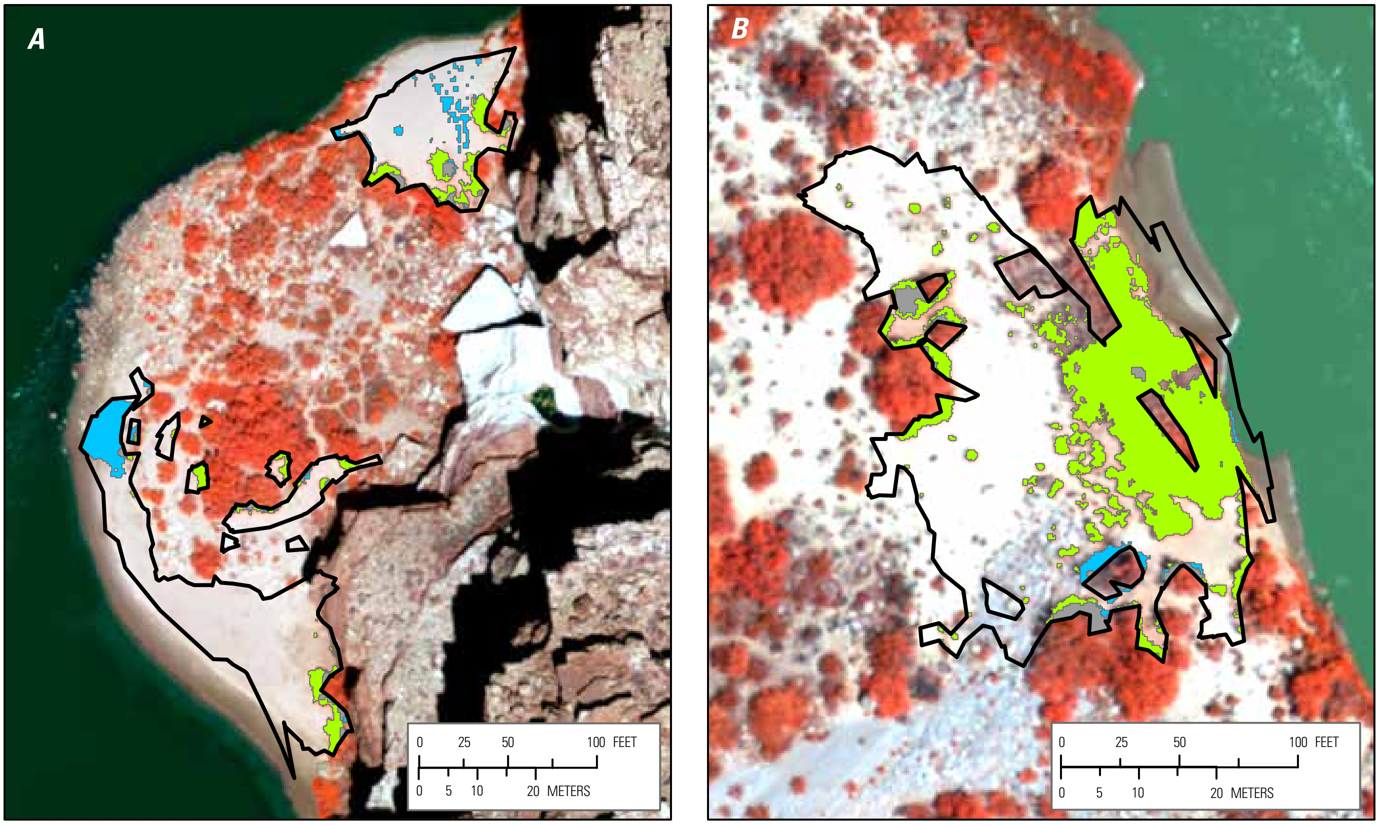


Figure 12. Example aerial photographs overlaid with maps of vegetation change within the extent of mapped campsite areas along the Colorado River corridor in Grand Canyon National Park, Arizona. *A*, Vegetation change at Hot Na Na (river mile 16.6 left). *B*, Vegetation change at Middle 220 Mile (river mile 220.1 right). U.S. Geological Survey aerial imagery from May 2009 displayed as false-color composite, with green photosynthetically active vegetation displayed as red.

those long-term monitoring sites. Because vegetated areas are not surveyed as campsite areas, the extent of mapped campsite area represents areas that were free of vegetation in 1998. This makes it possible to quantify vegetation encroachment between 1998 and 2002 without an explicit map of vegetation coverage for 1998. The absence of vegetation in 1998 was verified by inspecting aerial imagery from May 2000.

Finally, the maps of vegetation change were analyzed within the mapped camp boundaries at each of the 504 sites in the campsite database to determine broader trends in vegetation change throughout the river corridor (fig. 13).

Intersection of Datasets

Changes in vegetation cover, changes in sandbar elevation, and changes in sandbar slope were analyzed within campsite areas along the Colorado River corridor in Grand Canyon to determine the mechanisms that contributed to campsite area change. This was accomplished by intersecting areas of campsite gain, areas of campsite loss, and stable campsite areas with datasets of elevation, slope, and vegetation change (fig. 14). Areas of campsite change that had a gain or loss in vegetation were separated out from areas that never became vegetated or didn't have a change in vegetation cover. This was to ensure that elevation and slope change was exclusive of vegetation change. In other words, changes in slope or elevation were outside of the influence of vegetation change.

The intersection of the datasets produced "first-order" and "second-order" processes associated with changes in campsite area. First-order processes are simply the mechanisms of elevation change (that is, deposition, erosion, or no elevation change) and vegetation change. Changes in the slope of a sandbar were not considered in first-order processes. Second-order processes take into account changes in sandbar slope in addition to the changes in elevation and vegetation and link deposition or erosion with a change in sandbar slope at about the 8-degree threshold used to map campsite area (table 3). Analysis of first-order and second-order processes that led to gains and losses in campsite area were summarized by critical and noncritical recreational reach and by canyon section.

Intersected areas varied in size from less than 1 m^2 to more than 950 m^2. However, it was determined that all the intersected areas under 1 m^2 accounted for less than 1 percent of all the area analyzed for this study and, therefore, were not removed from analysis.

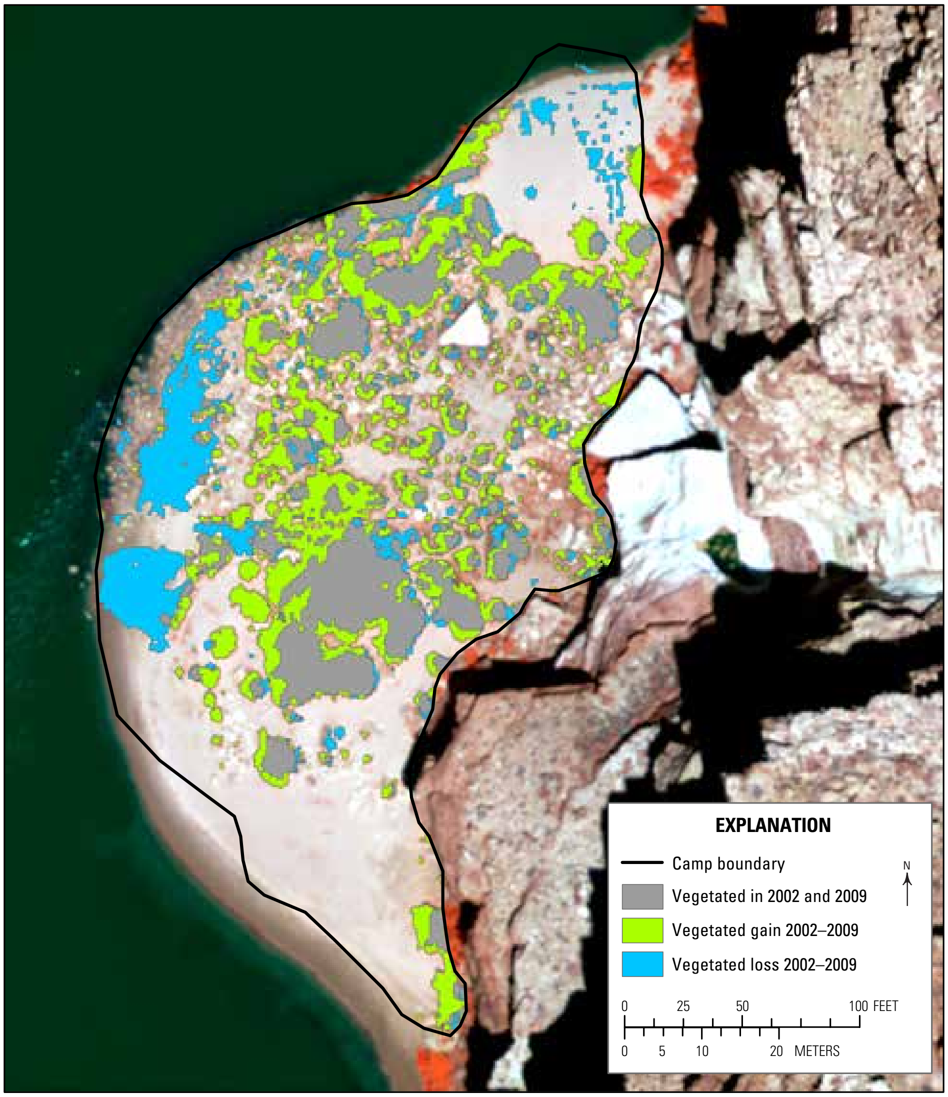


Figure 13. Example aerial photograph overlaid with map of vegetation change between 2002 and 2009 within the camp boundary at Hot Na Na (river mile 16.6 left) along the Colorado River corridor in Grand Canyon National Park, Arizona. U.S. Geological Survey aerial imagery from May 2009 displayed as false-color composite, with green photosynthetically active vegetation displayed as red.

Table 3. List of second-order processes associated with changes in campsite area along the Colorado River corridor in Grand Canyon National Park, Arizona.

[Second-order processes take into account changes in sandbar slope in addition to the changes in elevation and vegetation and link deposition or erosion with a change in sandbar slope at about the 8-degree threshold used to map campsite area. Gains and losses in vegetation took precedence over any change in elevation or slope of the sandbar; therefore, processes 1 and 2 did not have a specific type of elevation or slope change assigned to them. Processes 3 through 11 occurred outside of the influence of any gain or loss in vegetation. Because processes 9 and 10 were very small, they were combined in subsequent results. NA, not applicable]

Process no.	Second-order processes description		
	Type of vegetation change	Type of elevation change	Type of slope change
1	Gain	NA	NA
2	Loss	NA	NA
3	No change	Deposition	Increase
4	No change	Deposition	Decrease
5	No change	Deposition	No change
6	No change	Erosion	Increase
7	No change	Erosion	Decrease
8	No change	Erosion	No change
9	No change	No change	Increase
10	No change	No change	Decrease
11	No change	No change	No change

Statistical Analysis

The Mann-Whitney *U* test was used to see whether differences in net vegetation gain between critical and noncritical recreational reaches and among canyon sections were significant. The Mann-Whitney *U* test is a nonparametric two sample *t*-test (Helsel and Hirsch, 2002) and was chosen because samples sizes varied among reach or section and the data were determined to not be normally distributed with a Shapiro-Wilk test. All statistical tests were conducted using R statistical software (The R Foundation for Statistical Computing, 2013) and were tested at the 95-percent confidence level (α=0.05).

Results

Campsite area declined between 2002 and 2009 at the 35 long-term monitoring sites we analyzed. Given an uncertainty of 15 percent (see Evaluation of Methods for Measuring Campsite Area for further discussion on uncertainty), there were 22,163±3,324 m^2 of campsite area above the 10,000-ft^3/s stage elevation in 2002 and 19,732±2,960 m^2 of campsite area above the 10,000-ft^3/s stage elevation in 2009. Thus, the net loss in campsite area of 2,431 m^2 (an 11-percent decline) is less than the uncertainty in the measurements. However, this evaluation of net change in campsite area obscures the fact that there were significant changes in where campsite areas were located. Only 9,797±1,469 m^2 of the total campsite area did not change locations between years, whereas 12,366±1,855 m^2 of campsite area were lost and 9,936±1,490 m^2 of campsite area were gained.

Due to the incomplete overlap of campsite surveys and topographic surveys, only 92 percent of the gains and losses in campsite area could be analyzed in terms of elevation and slope change. Subsequent results are therefore reported as areas that coincided with topographic coverage or percentages within areas of campsite gain or loss that coincided with topographic coverage (table 4).

The Relative Influence of Erosion, Deposition, and Vegetation Expansion on Campsite Area

Most changes in campsite area were associated with changes in sandbar elevation. Deposition occurred over 59 percent of the area of campsite gain and 41 percent of the area of campsite loss (fig. 15). Erosion occurred over 30 percent of the area of campsite gain and over 39 percent of the area of campsite loss. No change in elevation occurred over 9 percent of the areas of campsite gain and loss. Large percentages of stable campsite area also experienced erosion and deposition (fig. 15). Thus, processes of sandbar erosion and deposition were widespread across the areas mapped as campsites in 2002 and 2009, and both processes were associated with gains and losses in campsite area. Some of the results, such as a gain in campsite area caused by erosion, are counter-intuitive and are discussed further in the following sections. Vegetation expansion occurred over 10 percent of the area of campsite loss, whereas vegetation loss occurred at less than 1 percent of the area of campsite gain.

Most of the losses in campsite area associated with topographic change were compensated by gains in campsite area also associated with topographic change. Therefore, we define net change in campsite area as the difference between campsite area gain and campsite area loss. Overall, and for most sites individually, the net change in campsite area is much smaller than the losses or gains individually (table 4, appendix 1). However, vegetation encroachment is largely one directional. Once vegetation is established on a sandbar, there is essentially a permanent reduction in campsite area unless vegetation is physically removed by high flows, which has not been observed after controlled floods (Ralston, 2010; Sankey and others, 2015a), or removed by campers; although currently ongoing defoliation and mortality of tamarisk vegetation by the tamarisk beetle (*Diorhabda carinulata*) (Sankey and others, 2016) could potentially affect campsite size in the future. In other words, losses in campsite area caused by vegetation expansion are not as likely to be compensated by gains in campsite area caused by loss of vegetation. Thus, net loss of campsite area associated with vegetation encroachment was of comparable magnitude to net loss of campsite area associated with topographic change for all sites (fig. 16).

Comparison by Recreational Reach and Canyon Section

There was a net loss in campsite area in both critical and noncritical reaches and in both Marble and Grand Canyons (fig. 16). However, the influence of erosion, deposition, and vegetation change on the gains and losses that made up those net changes in campsite area varied by recreational reach and canyon section. In critical reaches, a greater proportion of both gains and losses of campsite area were caused by erosion compared to sites in noncritical reaches (fig. 17). In addition, erosion was a larger proportion of the net change in campsite area in critical reaches than in noncritical reaches (fig. 16). This may be due to the fact that sandbars in critical reaches tend to be lower in elevation, have a larger part of sandbar volume below the 25,000-ft^3/s stage elevation, and thus are subjected to more erosion from daily dam fluctuations. In noncritical reaches, deposition played a larger role in both the gains and losses of campsite area in comparison to critical reaches (fig. 17). The net loss of campsite area associated with topographic change was similar to net loss of campsite area associated with vegetation change for both reach types, matching the overall pattern (fig. 16).

In Marble Canyon, there was a greater proportion of both gains and losses of campsite area associated with deposition compared to sites in Grand Canyon (fig. 18). Thus, erosion was a smaller proportion of the net change in campsite area in Marble Canyon than in Grand Canyon (fig. 16). In Grand Canyon, deposition did not play as large of a role in the gains and losses of campsite area and there was a greater loss of campsite area associated with vegetation encroachment (fig. 18). However,

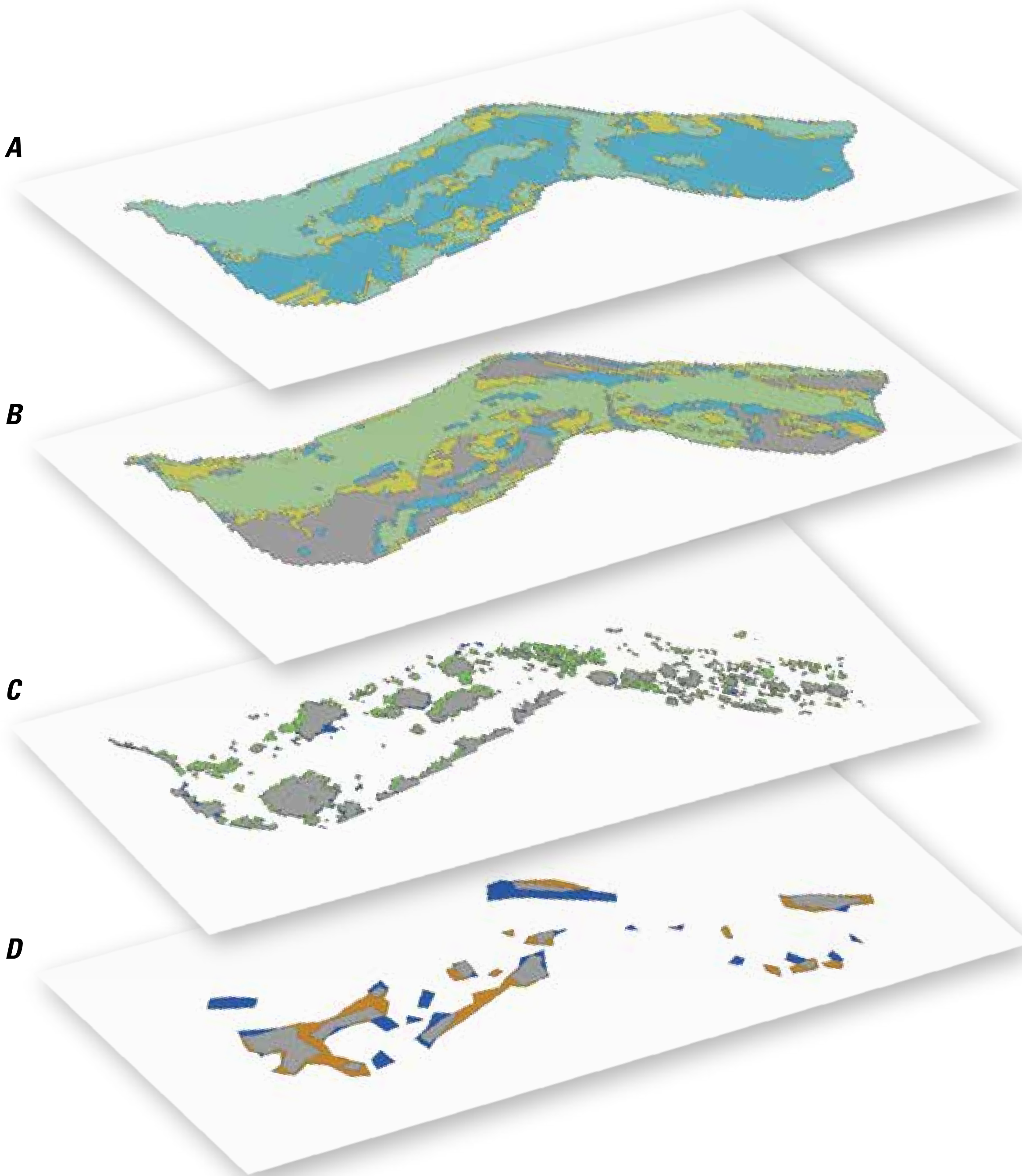


Figure 14. Illustration showing the intersection of datasets for (*A*) elevation change, (*B*) slope change, and (*C*) vegetation change within (*D*) areas of campsite gain, areas of campsite loss, and stable campsite areas along the Colorado River corridor in Grand Canyon National Park, Arizona. Intersection of datasets allowed the mechanisms that contributed to campsite-area change to be determined. Example shown is the long-term monitoring site of Eminence at river mile 44.5 left.

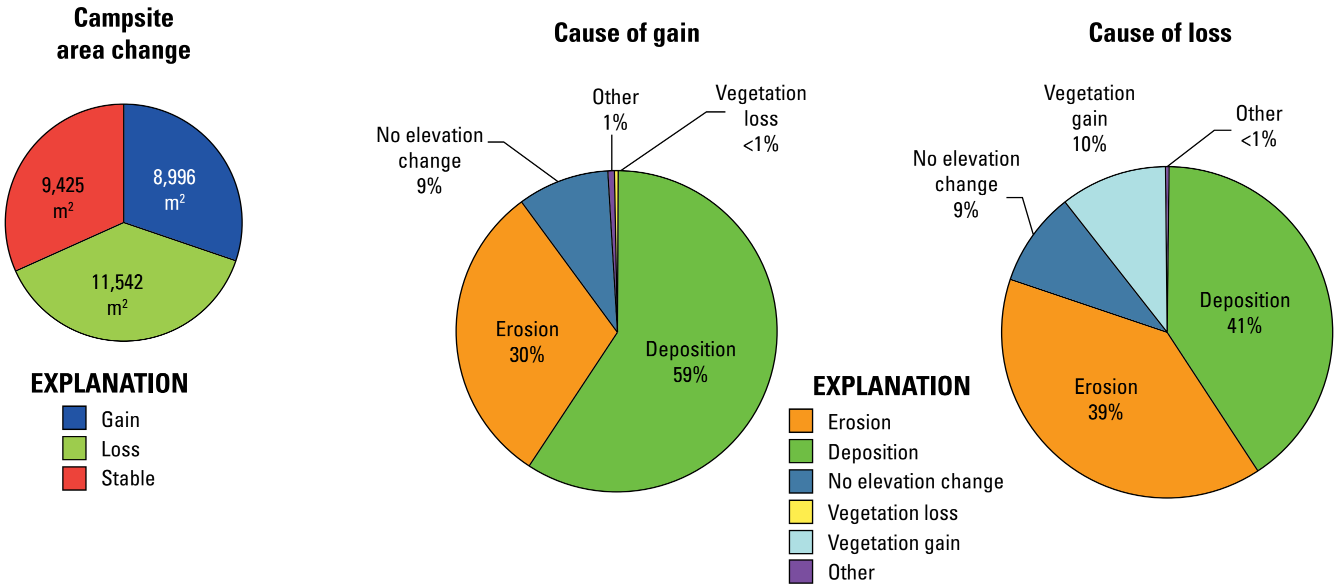


Figure 15. Pie charts showing cause of gains and losses in campsite area combined for the 35 monitoring sites analyzed in this study along the Colorado River corridor in Grand Canyon National Park, Arizona. Areas shown are gains, losses, and stable campsite area coincident with topographic coverage. Results may not sum to 100 percent due to rounding. m², square meters; % percent; <, less than.

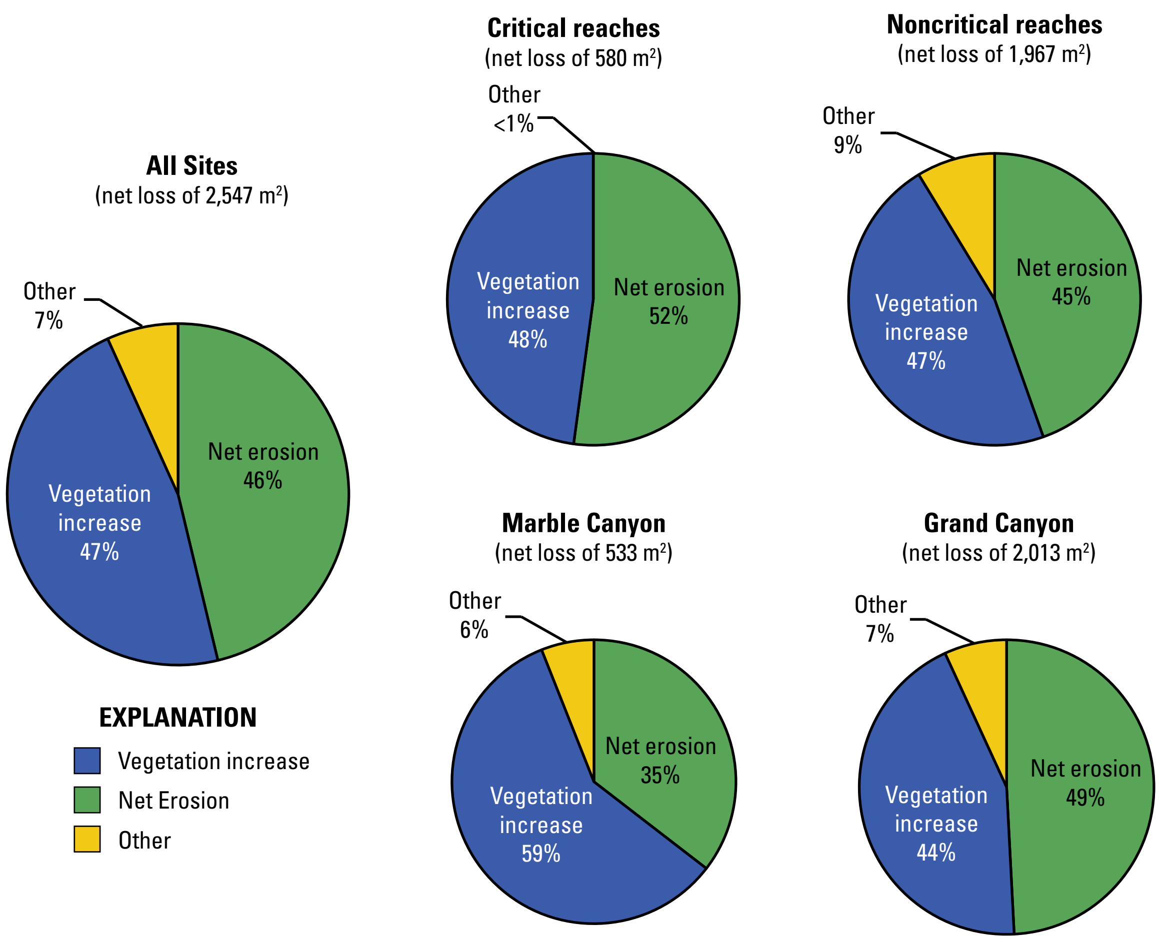


Figure 16. Pie charts showing causes of net loss in campsite area combined for the 35 monitoring sites analyzed in this study and for recreational reach and canyon section along the Colorado River corridor in Grand Canyon National Park, Arizona. Results may not sum to 100 percent due to rounding. m², square meters; % percent; <, less than.

Table 4. Cause of gains and losses in campsite area at each of the 35 long-term monitoring sites analyzed in this study along the Colorado River corridor in Grand Canyon National Park, Arizona, summarized by recreational reach and canyon section.

[Two long-term monitoring sites, South Canyon and 183 Mile Left (table 2), were excluded in the topographic analysis because topographic measurements do not overlap with measurements of campsite area at those sites. m², square meter; %, percent; --, no data]

Site/reach	Campsite area in 2002 (m²)[1]	Campsite area in 2009 (m²)[1]	Gain in campsite area (m²)	Loss in campsite area (m²)	Cause of gain in campsite area (%)[2]					Cause of loss in campsite area (%)[2]					Net change in campsite area (m²)
					Deposition	Erosion	No elevation change	Loss in vegetation	Other	Deposition	Erosion	No elevation change	Gain in vegetation	Other	
Monitoring site															
Jackass	584	662	386	308	31%	54%	15%	0%	0%	17%	55%	18%	10%	0%	78
Hot Na Na	100	243	205	63	97%	0%	3%	0%	0%	71%	0%	22%	6%	0%	142
22 Mile	454	656	315	113	81%	12%	7%	0%	0%	100%	0%	0%	0%	0%	202
Lone Cedar	612	658	377	332	29%	64%	6%	0%	0%	10%	57%	8%	25%	0%	45
Silver Grotto	608	672	341	277	84%	9%	7%	0%	1%	72%	15%	8%	5%	0%	64
Sand Pile	1,012	512	163	663	46%	53%	1%	0%	0%	22%	77%	1%	1%	0%	−500
Nautiloid	468	510	155	113	64%	26%	7%	0%	2%	7%	55%	16%	21%	1%	43
Buck Farm	654	392	117	379	48%	42%	9%	1%	0%	40%	32%	18%	9%	0%	−262
Anasazi Bridge	505	340	137	303	51%	45%	4%	0%	0%	45%	44%	10%	1%	0%	−165
Eminence	750	775	335	310	52%	26%	19%	1%	2%	39%	32%	24%	5%	0%	25
Willie Taylor	818	667	351	502	90%	7%	3%	0%	0%	66%	26%	4%	4%	0%	−151
Lower Saddle	1,304	1,171	665	798	88%	8%	4%	0%	0%	58%	37%	3%	2%	0%	−133
Dinosaur	769	571	184	383	91%	1%	8%	0%	0%	67%	14%	13%	6%	0%	−199
51 Mile	616	292	255	579	15%	80%	5%	0%	0%	42%	41%	15%	2%	0%	−324
Kwagunt Marsh	126	727	724	123	63%	14%	23%	0%	0%	64%	0%	8%	27%	1%	601
Crash Canyon	47	96	70	21	68%	23%	8%	1%	1%	13%	86%	0%	0%	0%	49
Grapevine	871	709	143	305	7%	89%	2%	0%	2%	24%	63%	13%	1%	0%	−162
Clear Creek	315	285	123	154	71%	18%	11%	0%	0%	16%	51%	9%	24%	0%	−31
Cremation	277	129	17	165	74%	5%	8%	8%	5%	45%	23%	8%	20%	4%	−148
91 Mile	208	336	176	48	49%	37%	10%	0%	3%	0%	98%	1%	1%	0%	128
Granite	387	283	123	227	74%	12%	2%	7%	5%	67%	16%	2%	14%	0%	−104
Emerald	207	80	7	135	24%	61%	12%	0%	2%	50%	24%	7%	19%	0%	−128

Table 4. Cause of gains and losses in campsite area at each of the 35 long-term monitoring sites analyzed in this study along the Colorado River corridor in Grand Canyon National Park, Arizona, summarized by recreational reach and canyon section.—Continued.

Site/reach	Campsite area in 2002 (m²)[1]	Campsite area in 2009 (m²)[1]	Gain in campsite area (m²)	Loss in campsite area (m²)	Cause of gain in campsite area (%)[2]					Cause of loss in campsite area (%)[2]					Net change in campsite area (m²)
					Deposition	Erosion	No elevation change	Loss in vegetation	Other	Deposition	Erosion	No elevation change	Gain in vegetation	Other	
119 Mile	812	591	178	399	85%	3%	12%	0%	0%	38%	21%	18%	23%	0%	−221
122 Mile	1,699	1,802	830	727	68%	25%	7%	0%	1%	75%	8%	6%	11%	0%	103
Upper Forster	391	330	259	320	59%	27%	14%	0%	0%	48%	36%	12%	4%	0%	−60
Football Field	1,761	1,587	552	725	11%	86%	3%	0%	0%	8%	87%	3%	2%	0%	−173
Fishtail	33	79	52	7	36%	54%	9%	0%	1%	16%	62%	16%	6%	0%	46
Above Olo	336	331	126	131	54%	37%	9%	0%	0%	76%	21%	1%	2%	0%	−5
Lower National	510	340	108	278	45%	39%	16%	0%	1%	35%	31%	13%	21%	0%	−171
172 Mile	0	535	535	0	53%	41%	6%	0%	0%	--	--	--	--	--	535
183 Mile Right	414	270	65	209	39%	27%	34%	0%	0%	16%	59%	20%	4%	0%	−144
Hualapai Acres	705	507	271	469	72%	6%	17%	1%	5%	34%	20%	32%	13%	1%	−198
202 Mile	1,390	444	89	1,035	91%	1%	3%	0%	6%	38%	38%	3%	20%	0%	−945
Pumpkin Springs	631	520	395	506	66%	26%	6%	0%	1%	42%	35%	2%	21%	0%	−111
Middle 220 Mile	593	320	165	438	57%	18%	22%	2%	1%	10%	58%	9%	22%	1%	−273
Reaches/canyon sections															
Critical reaches	7,648	7,068	2,877	3,457	51%	42%	6%	0%	1%	32%	55%	5%	8%	0%	−580
Non-critical Reaches	13,319	11,352	6,119	8,085	63%	25%	11%	0%	1%	45%	33%	11%	11%	0%	−1,966
Marble Canyon	9,380	8,847	4,711	5,244	64%	26%	10%	0%	0%	45%	39%	10%	6%	0%	−533
Grand Canyon	11,587	9,574	4,285	6,298	55%	35%	9%	0%	1%	37%	40%	9%	14%	0%	−2,013
All Sites	20,967	18,420	8,996	11,542	59%	30%	9%	0%	1%	41%	39%	9%	10%	0%	−2,547

[1]Campsite areas listed are only those that coincided with topographic coverage. The actual amount of campsite area present in 2002 and 2009 may be greater at certain sites.

[2]Results may not sum to 100 percent due to rounding.

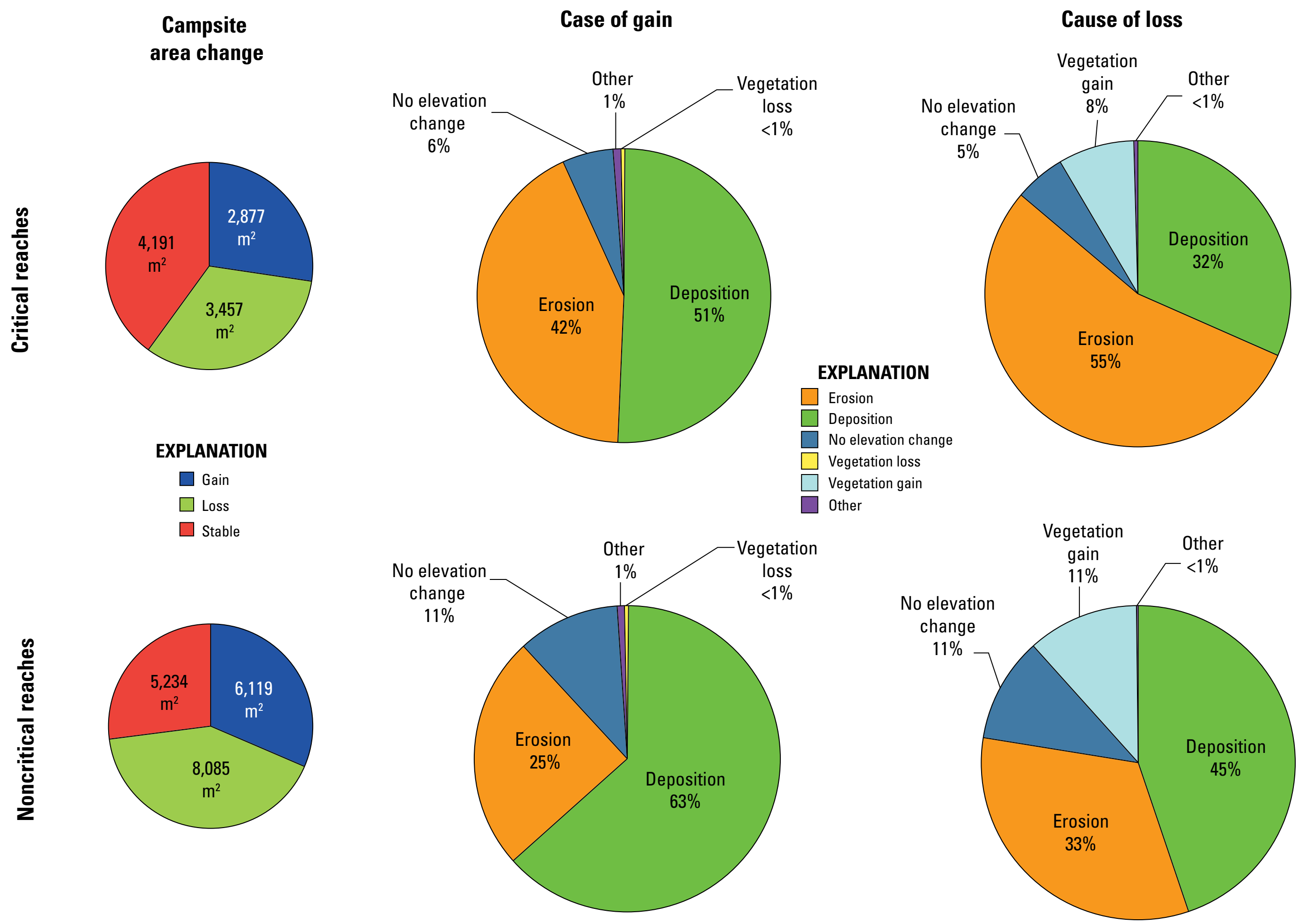


Figure 17. Pie charts showing the cause of gains and losses in campsite area at sites in critical and noncritical reaches along the Colorado River corridor in Grand Canyon National Park, Arizona. Areas shown are gains, losses, and stable campsite area coincident with topographic coverage. Results may not sum to 100 percent due to rounding. m^2, square meters; % percent; <, less than.

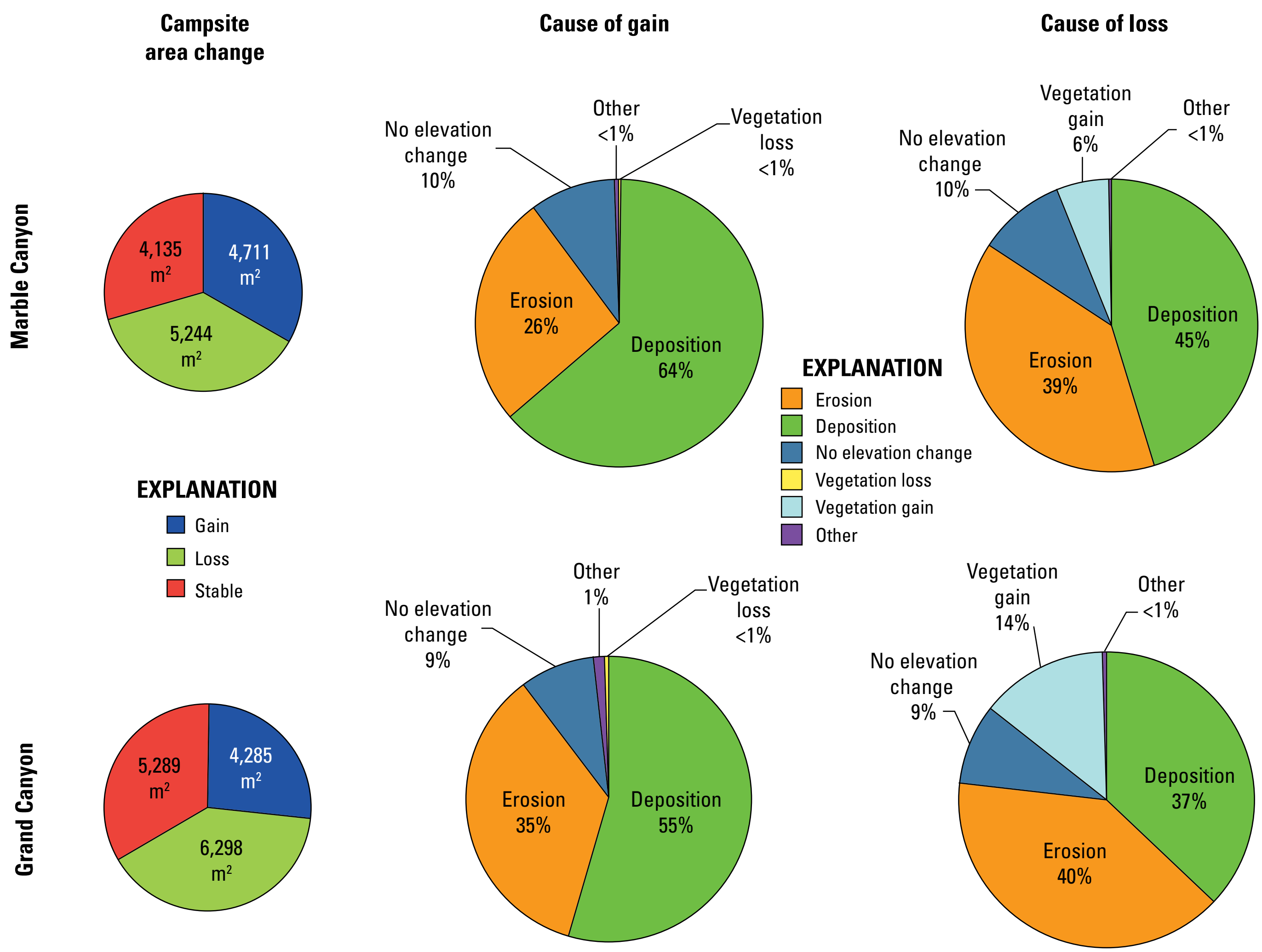


Figure 18. Pie charts showing the cause of gains and losses in campsite area at sites in Marble Canyon and Grand Canyon along the Colorado River corridor in Grand Canyon National Park, Arizona. Areas shown are gains, losses, and stable campsite area coincident with topographic coverage. Results may not sum to 100 percent due to rounding. m², square meters; % percent; <, less than.

in terms of net change, vegetation encroachment was greater in Marble Canyon than in Grand Canyon (fig. 16). This is due to the fact that there was little net loss of campsite area due to topographic change in Marble Canyon, because much of the losses in campsite area associated with topographic change were compensated by gains in campsite area associated with topographic change.

Comparison at Individual Sites

The relative influence of erosion and deposition on gains in campsite area varied considerably by site. At some sites, deposition was by far the predominant process in creating new campsite area. This occurred at sites such as Willie Taylor (RM 45.0L), Lower Saddle (RM 47.7R), and 202 Mile (RM 202.3R), where more than 85 percent of campsite gains were associated with deposition (table 4, appendix 1). In contrast, erosion was by far the predominant process in creating new campsite area at certain sites, such as Grapevine (RM 81.7L) and Football Field (RM 137.7L). At these sites more than 85 percent of campsite gains were associated with erosion (table 4, appendix 1).

In terms of campsite loss, the influence of erosion and deposition also varied considerably by site. Deposition was the predominate process in terms of lost campsite area at sites such as 22 Mile (RM 22.1L) and Above Olo (RM 145.9L), where more than 75 percent of campsite losses were associated with deposition. Conversely, more than 75 percent of campsite losses were associated with erosion at sites such as Sand Pile (RM 30.8R) and Football Field (RM 137.7L) (table 4, appendix 1). The influence of vegetation expansion on campsite loss also varied by site. At many sites, only a few percent of campsite losses were associated with gains in vegetation. However, at sites such as Kwagunt Marsh (RM 55.9R), Clear Creek (RM 84.6R), 119 Mile (RM 119.4R), and Middle 220 Mile (RM 220.1R), more than 20 percent of campsite losses were associated with gains in vegetation (table 4, appendix 1).

Statistical summaries for the elevation change at each site were calculated using ArcGIS zonal statistical tools and show the amount of elevation changes within areas of campsite gain, areas of campsite loss, and stable campsite areas (table 5). Elevation increased on average by 0.19 m over all areas of campsite gain and increased on average by 0.17 m over all areas of campsite loss. However, the amount of elevation changes within campsite areas varied considerably by site. At sites such as 22 Mile (RM 21.1R) and Pumpkin Springs (RM 213.3L), there was more than 0.70 m of deposition on average within areas of campsite gain and areas of campsite loss (appendix 2). Conversely, at Football Field (RM 137.7R), there was more than 0.48 m of erosion on average within areas of campsite gain and areas of campsite loss (appendix 2).

The Influence of Slope Change on Campsite Area

Observations of erosion causing a gain in campsite area and deposition causing a loss in campsite area are counterintuitive but can be explained by a variety of mechanisms. Some of these mechanisms are associated with an elevation change that did not cause a change in sandbar slope (that is, bars built higher in response to controlled floods but retained the same slope following deposition), whereas other mechanisms are associated with an elevation change that led to a change in sandbar slope at about the 8-degree threshold for mapping campsites (table 3, appendix 3). Slope decreased on average by 4 degrees within all areas of campsite gain and increased on average by 5 degrees within all areas of campsite loss (table 5, appendix 2). However, many of those slope increases or decreases observed at individual sites did not result in the slope crossing the 8-degree threshold for qualification as a campsite area.

Most gains in campsite area were the result of deposition that wasn't associated with a significant slope change (fig. 19, table 6). An example of this occurred at Hualapai Acres (RM 194.6L), where there was on average 0.57 m of deposition

Table. 5 Summary of statistical analysis for (*A*) elevation and (*B*) slope changes within areas of campsite gain, areas of campsite loss, and stable campsite areas along the Colorado River corridor in Grand Canyon National Park, Arizona.

[SD, standard deviation; SE, standard error; *n*, number; m, meter]

A.

Elevation change	Largest decrease (m)	Largest increase (m)	Mean (m)	SD (m)	SE (m)	*n*
Areas of campsite gain	–1.33	2.93	0.19	0.58	0.10	35
Areas of campsite loss	–1.69	3.20	0.17	0.74	0.13	34
Stable campsite area	–1.31	3.08	–0.06	0.50	0.09	34

B.

Slope change	Largest decrease (degrees)	Largest increase (degrees)	Mean (degrees)	SD (degrees)	SE (degrees)	*n*
Areas of campsite gain	–30.19	15.66	–3.50	5.05	0.87	35
Areas of campsite loss	–28.40	46.62	5.21	7.63	1.33	34
Stable campsite area	–17.53	12.56	–0.21	2.57	0.45	34

and a slope change of less than 1 degree within the areas of campsite gain (appendix 2). Several mechanisms can account for this, such as temporary burial of vegetation, burial of rocks along the shoreline, smoothing of irregular topography of the sandbar, or raising the elevation of the sandbar above zones of regular inundation, making them more accessible for camping (fig. 20).

A large percentage of the gains in campsite area resulted from erosion not associated with a slope change, which was unexpected (fig. 19, table 6). These observations could be attributed to a variety of factors that are not detectable using the methods of this study. These factors include changes in topography that are finer than the resolution of the 1-m^2 slope rasters, wind erosion (East and others, 2016) that might erode

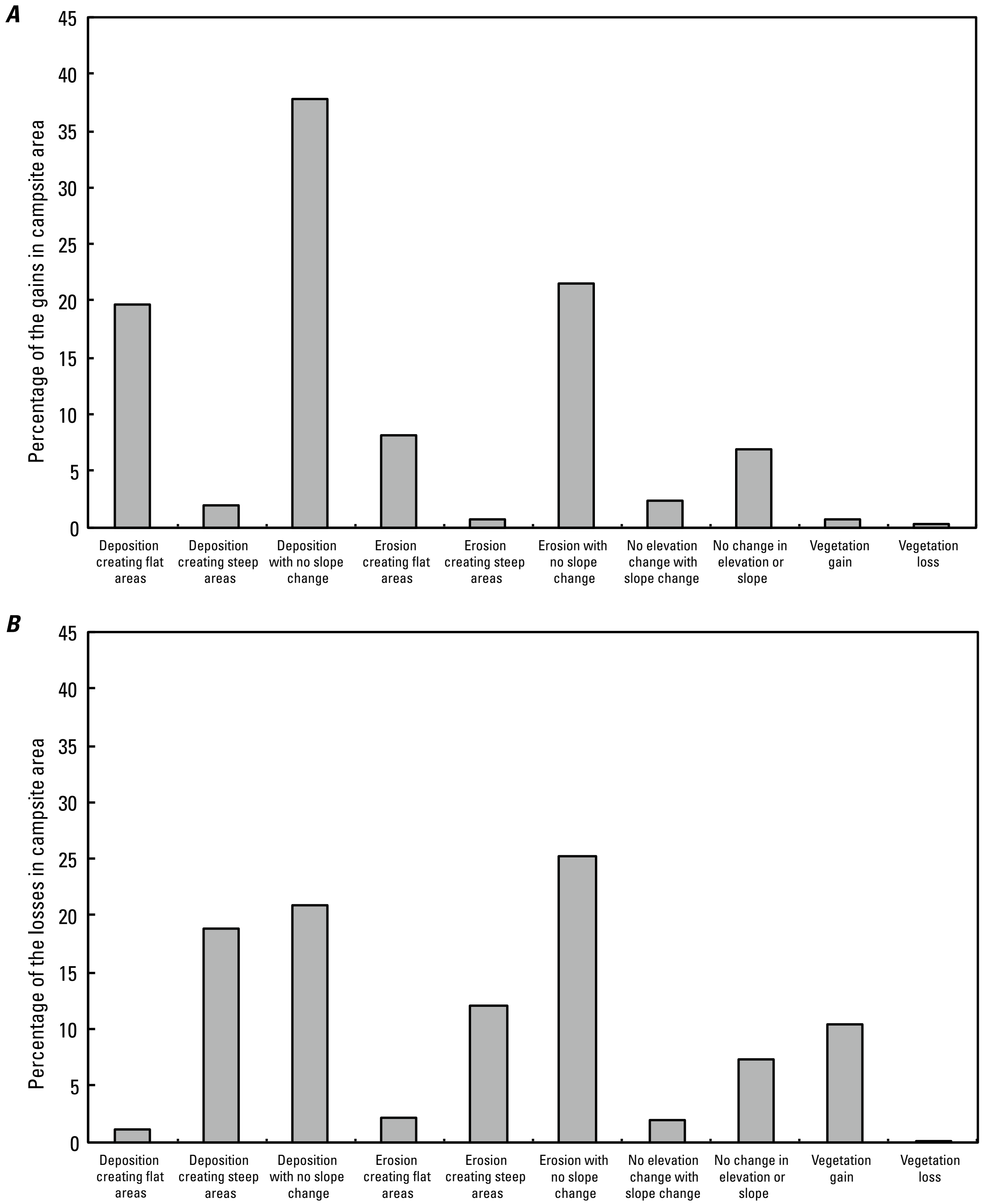


Figure 19. Graphs showing the combined effect of erosion, deposition, and slope change on (*A*) gains in campsite area and (*B*) losses in campsite area for all sites along the Colorado River corridor in Grand Canyon National Park, Arizona.

Table 6. Areas of campsite change associated with the combined effects of erosion, deposition, and slope change, summarized by recreational reach and canyon section along the Colorado River corridor in Grand Canyon National Park, Arizona.

Campsite area	Second-order changes (area, in square meters)									
	Deposition creating flat areas	Deposition creating steep areas	Deposition with no slope change	Erosion creating flat areas	Erosion creating steep areas	Erosion with no slope change	No change in elevation or slope	No elevation change with slope change	Gain in vegetation	Loss in vegetation
Critical reaches										
Gain	837	77	544	456	27	738	94	69	24	11
Loss	58	587	448	160	705	1,023	58	127	278	12
Noncritical reaches										
Gain	927	95	2,861	279	38	1,197	112	548	49	14
Loss	73	1,581	1,965	89	686	1,879	170	711	919	13
Marble Canyon										
Gain	1,004	118	1,881	397	26	806	125	329	19	7
Loss	57	847	1,470	61	584	1,402	82	424	312	6
Grand Canyon										
Gain	760	54	1,524	339	38	1,129	81	288	53	18
Loss	74	1,322	944	188	807	1,500	146	415	885	19
All sites										
Gain	1,763	172	3,405	735	64	1,935	206	617	73	25
Loss	131	2,169	2,413	249	1,391	2,902	228	838	1,197	24

the surface without changing the slope, or a change in slope that still falls under the category of no slope change (fig. 20). For example, the slope of a sandbar could have been 7 degrees but not mapped as a campsite area in 2002, then was eroded to a flat slope and mapped as a campsite area in 2009. This would be a large change in slope but would fall under the category of no slope change because both surfaces were under the 8-degree slope threshold. This example shows the limitations of using one slope-value threshold to classify slope change. Some of these gains in campsite area were also simply due to the uncertainty associated with campsite mapping (further discussed below in Evaluation of Methods for Measuring Campsite Area).

The majority of the losses in campsite area were caused by erosional processes that were not associated with a significant slope change (fig. 19, table 6). An example of this occurred at 51 Mile (RM 51.5L), where there was on average 0.22 m of erosion and a slope change of less than 1 degree within the areas of campsite loss (appendix 2). This result could be attributed to a variety of changes in sandbar surface topography, similar to the mechanisms creating new campsite area. Areas of smooth, flat sand that were mapped as a campsite area in 2002 could have been eroded by fluctuating dam flows or wind, exposing rocks or vegetation that were previously buried or roughening the previously smooth surface (fig. 20). Another mechanism that could explain this would be a change in the slope of a sandbar that still falls under the category of no slope change, as discussed in the previous paragraph. A flat sandbar area could have been mapped as a campsite area in 2002, was eroded to a slope of 7 degrees, and not mapped in 2009 (fig. 20).

A large percentage of the losses in campsite area were also due to depositional processes that were not associated with a significant slope change, which was another unexpected find. Further analysis revealed that much of this loss in campsite area was in fact due to vegetation that was not classified (see Discussion). Changes in the topography of a sandbar that are finer than the resolution of the 1-m^2 slope raster, changes in slope that still fall under a category of no slope change, or deposition of driftwood following a controlled flood were also reasons for this observation. Uncertainty associated with campsite mapping could also have played a role in this.

Although gains and losses in campsite area were caused mostly by elevation changes not associated with a change in sandbar slope, gains and losses were also caused by a combination of elevation and slope change (fig. 19, table 6). However, there is not always a direct relation between erosion and a loss in campsite area or deposition and a gain in campsite area. Erosion caused by fluctuating dam flows can lead to a loss in campsite area by removing flat parts of a sandbar but can also cause a gain in campsite area by removing steep parts of a cutbank. Conversely, deposition following a controlled flood can lead to a gain in campsite area by creating flat areas of sand but can also cause a loss in campsite area if the slope of a sandbar increases too greatly. An example of each of these mechanisms occurred at 22 Mile (RM 22.1R) during and after

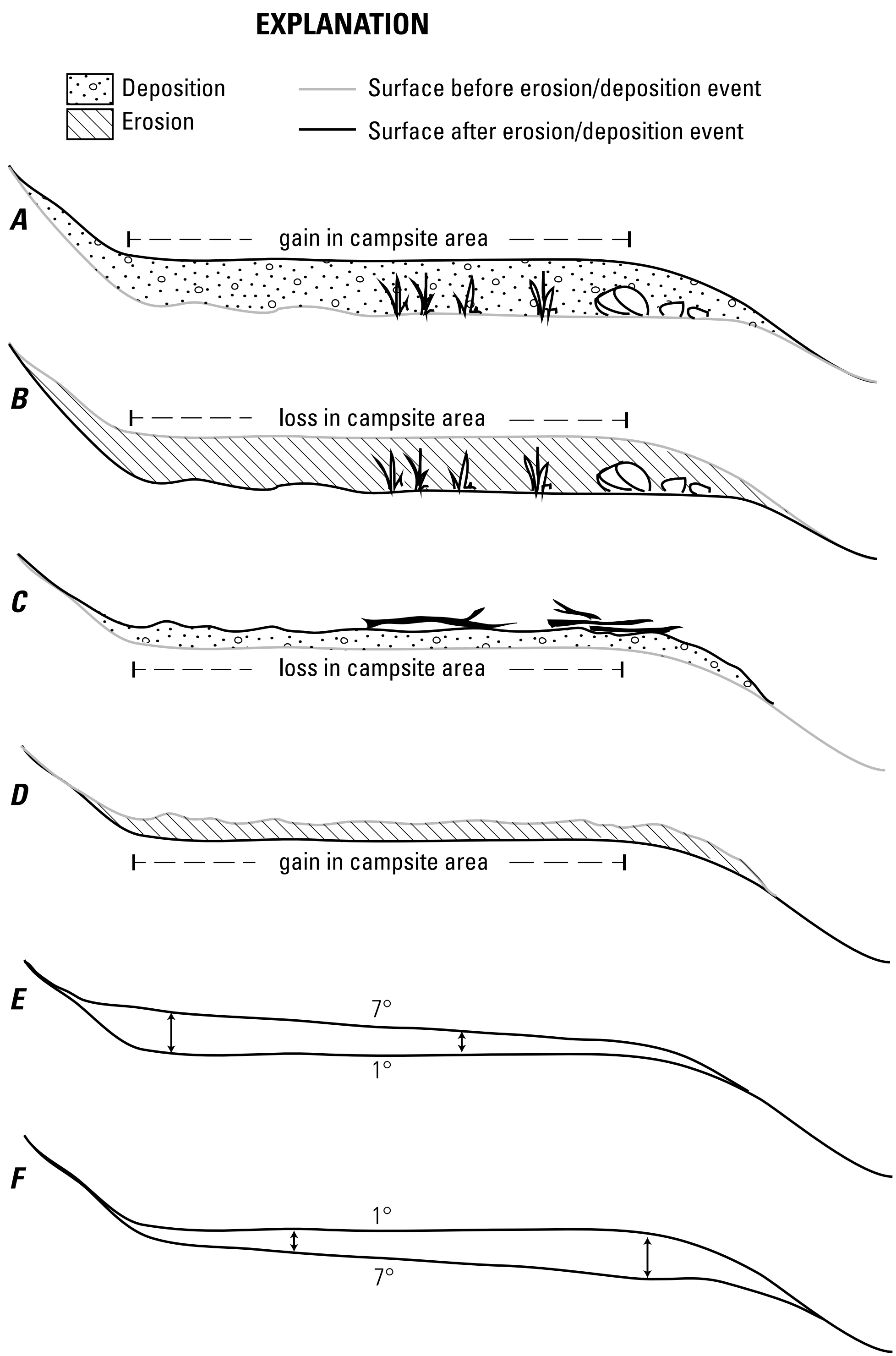


Figure 20. Illustration of possible scenarios of campsite area change along the Colorado River corridor in Grand Canyon National Park, Arizona, due to elevation changes (deposition or erosion) that did not cause a change in sandbar slope around the 8-degree threshold used to map campsite areas. *A*, Deposition leading to a gain in campsite area due to burial of rough topography, vegetation, or rocks. *B*, Erosion leading to a loss in campsite area due to exposure of rough topography, vegetation, or rocks. *C*, Deposition leading to a loss in campsite area due to a deposit's rough surface or presence of driftwood. *D*, Erosion leading to a gain in campsite area due to the removal of rough topography and smoothing of a sandbar. *E* and *F*, Deposition or erosion leading to a loss or gain in campsite area due to a slope change not detectable by the method used to categorize slope change. In both *E* and *F*, slope remained under the 8-degree threshold resulting in a classification of no slope change but could have been significant enough to affect whether or not an area was mapped as a campsite area given the uncertainty of estimating slope in the field during the time of survey.

the 2008 controlled-flood release from Glen Canyon Dam. Before the 2008 controlled flood, both the lower and upper parts of the sandbar had a fairly steep slope. Sand was deposited at both the lower and upper part of the sandbar during the controlled flood, which created new flat areas on the sandbar accessible for camping (fig. 21). However, the previously flat middle part of the sandbar became steeper after deposition, which lead to a loss in available camping area (fig 21). In the 6 months following the controlled flood, lateral cutback retreat during fluctuating flows removed the flat sandbar area at the low elevation, thus removing campsite area, but also removed the steep middle part of the bar, thus creating new campsite area (fig. 21).

The influence of slope change on gains and losses in campsite area varied by reach and canyon section. Changes in slope were a more important factor in the gains and losses in campsite area for sites in critical reaches compared to sites in noncritical reaches (fig. 22, table 6). Within critical reaches, 45 percent of the gains in campsite area were associated with a reduction in sandbar slope (either from deposition or erosion) and 37 percent of the losses in campsite area were associated with an increase in sandbar slope (either from deposition or erosion). In contrast, only 20 percent of the gains in campsite area at sites in noncritical reaches were associated with a reduction in sandbar slope, and 28 percent of the losses in campsite area were associated with an increase in slope. In general, sandbars in noncritical reaches tended to build higher or erode while still maintaining the same slope, whereas the slopes of sandbars in critical reaches changed more in response to deposition or erosion.

For the most part, the influence of slope change on gains and losses in campsite area was the same for both Marble and Grand Canyons (fig. 23, table 6). Within Marble Canyon, 29 percent of the gains in campsite area were associated with a reduction in sandbar slope, and 27 percent of the losses in campsite area were associated with an increase in sandbar slope. At sites in Grand Canyon, 26 percent of the gains in campsite area were associated with a reduction in sandbar slope, and 34 percent of the losses in campsite area were associated with an increase in slope.

Sandbar-Volume Change and Campsite-Area Change

Many of the gains and losses in campsite area were associated with deposition or erosion that did not cause a change in sandbar slope. Essentially, sandbars built higher or were eroded but still maintained the same overall topographic shape. This relation can also be illustrated by comparing campsite area with sandbar volume. Hazel and others (2010) examined the influence of the 2008 controlled flood and the subsequent erosion of those flood deposits on changes in campsite area. They showed a strong positive correlation between changes in sandbar volume and changes in campsite area (R^2=0.72, p-value<0.05) and a correlation between change in sandbar area and change in campsite area that was not as strong (R^2=0.27). They attributed the strong correlation between increases in sandbar volume and gains in campsite area to smoothing of irregular topography and temporary

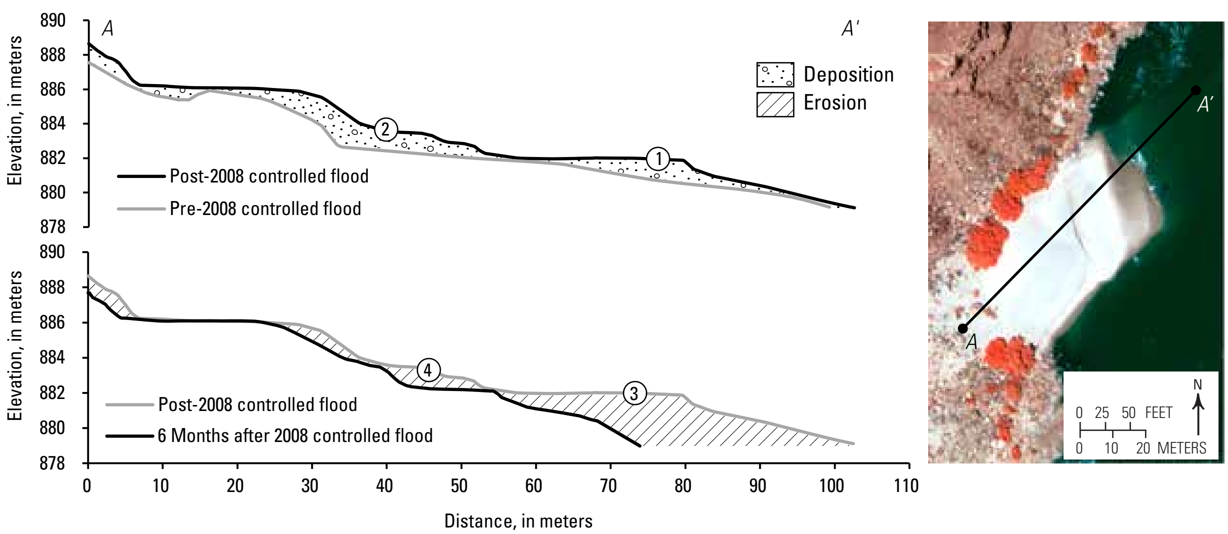
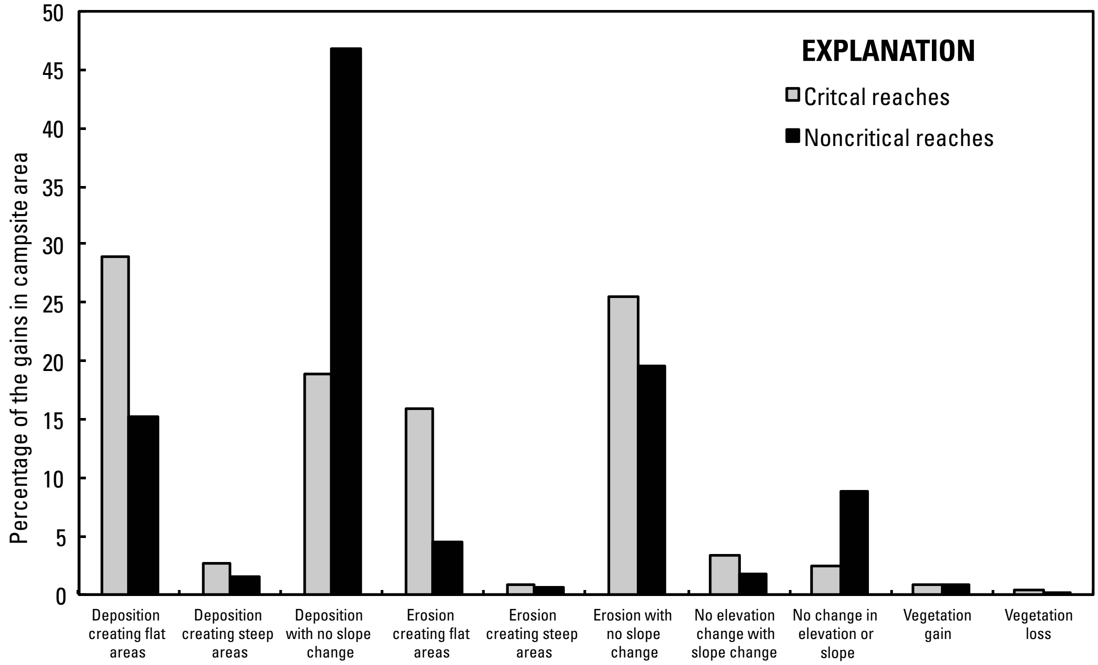


Figure 21. Graphs showing profiles of 22 Mile (river mile 22.1 right), along the Colorado River corridor in Grand Canyon National Park, Arizona, before, after, and 6 months after the 2008 controlled-flood release from Glen Canyon Dam. The profiles show how deposition or erosion can lead to a change in campsite area by changing the slope of a sandbar—(1) deposition causing a gain in campsite area by creating a flatter part of the sandbar, (2) deposition leading to a loss in campsite area by increasing the slope at a part of the sandbar, (3) erosion leading to a loss in campsite area through cutbank retreat, and (4) erosion leading to a gain in campsite area by decreasing the slope at a part of the sandbar. Profiles derived from topographic surfaces. Inset U.S. Geological Survey aerial image showing location of profile *A–A′* is from May 2009 (vegetation displayed in red as false-color composite).

A



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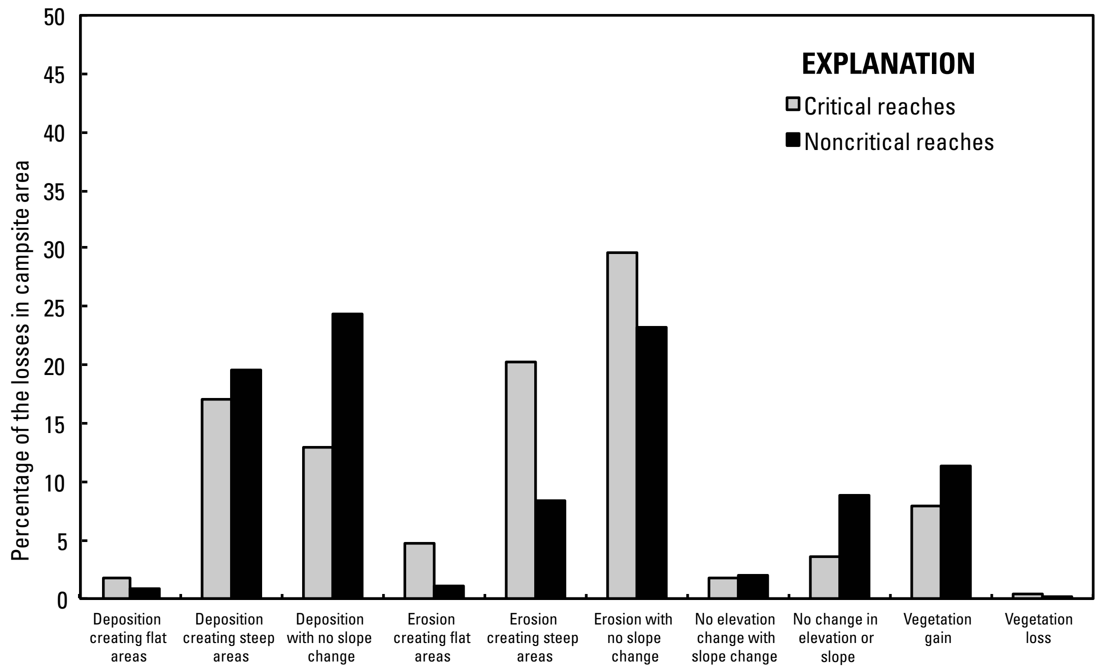


Figure 22. Bar graphs showing the combined effects of erosion, deposition, and slope change on (*A*) gains in campsite area and (*B*) losses in campsite area for critical and noncritical reaches along the Colorado River corridor in Grand Canyon National Park, Arizona.

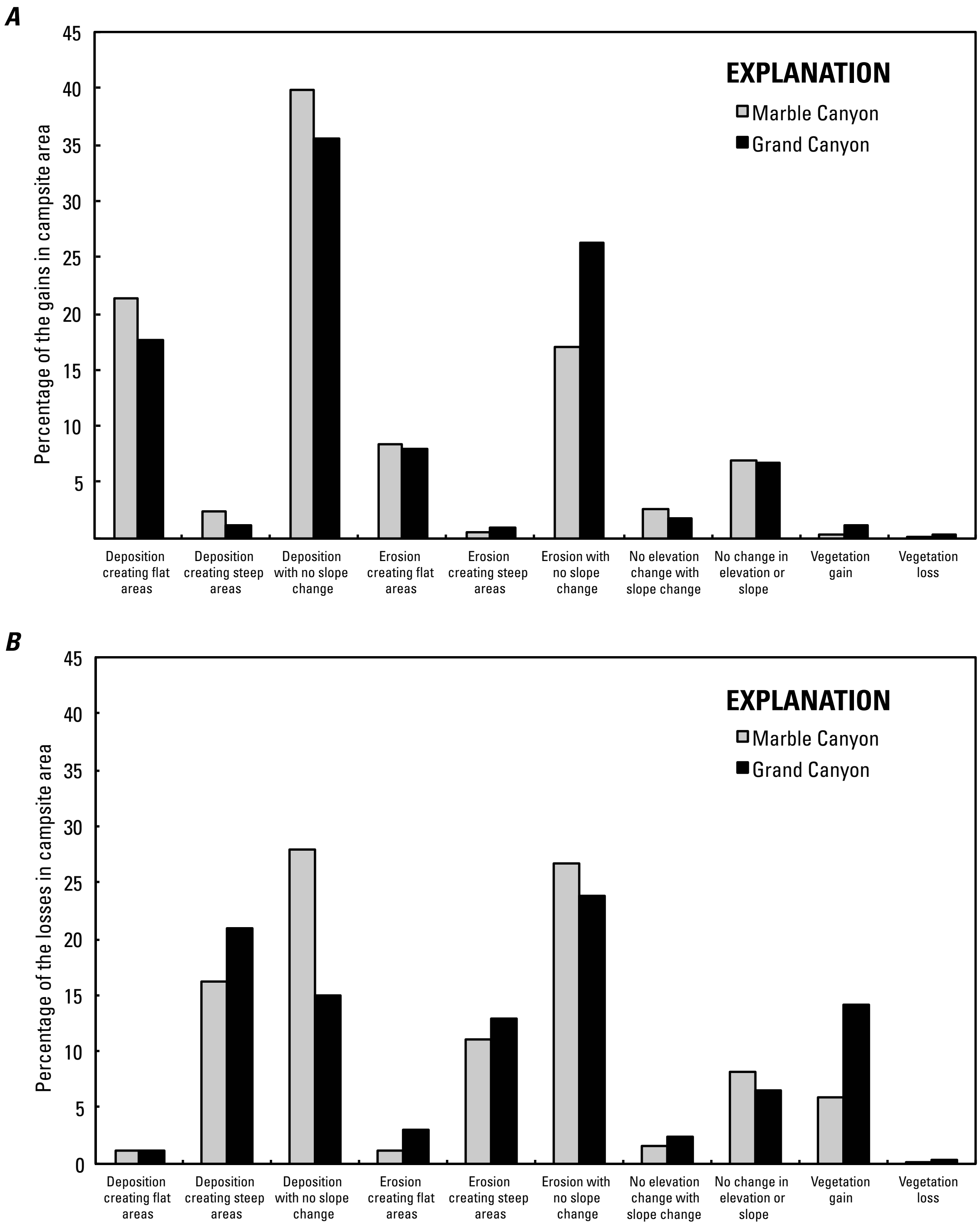


Figure 23. Bar graphs showing the combined effects of erosion, deposition, and slope change on (*A*) gains in campsite area and (*B*) losses in campsite area for Marble Canyon and Grand Canyon along the Colorado River corridor in Grand Canyon National Park, Arizona.

burial of vegetation, both of which would increase campsite area without necessarily causing a change in sandbar area or slope.

Comparisons between changes in sandbar volume and changes in campsite area between 2002 and 2009 were made for critical and noncritical sites at low-elevation zones (between the 8,000 to 25,000-ft^3/s stage elevation for sandbar volume and the 10,000 to 25,000-ft^3/s stage elevation for campsite area) and high-elevation zones (above the 25,000-ft^3/s stage elevation for both sandbar volume and campsite area) (fig. 24). Changes in sandbar volume and campsite area were calculated as the difference from one survey to the next over the 7-year period.

In both critical and noncritical reaches, changes in sandbar volume showed no significant correlation with changes in campsite area at the low-elevation zone (R^2=0.05 and 0.02, respectively). However, there was a strong correlation between changes in sandbar volume and changes in campsite area at the high-elevation zone in both critical and noncritical reaches (R^2=0.90 and 0.67, respectively, p-value<0.05), which was similar to the findings of Hazel and others (2010). Changes in campsite area at low elevation had a very weak correlation with changes in sandbar volume due to the fact that large increases in sand volume at low elevation, particularly between 8,000- to 10,000-ft^3/s stage elevation, may not lead to a much of a gain in campsite area, because these are areas that are regularly inundated and not usable as campsites.

Gullying

Gullying was a significant factor in campsite change at six long-term monitoring sites, but the total area of gullying represented a small fraction of the total loss in campsite

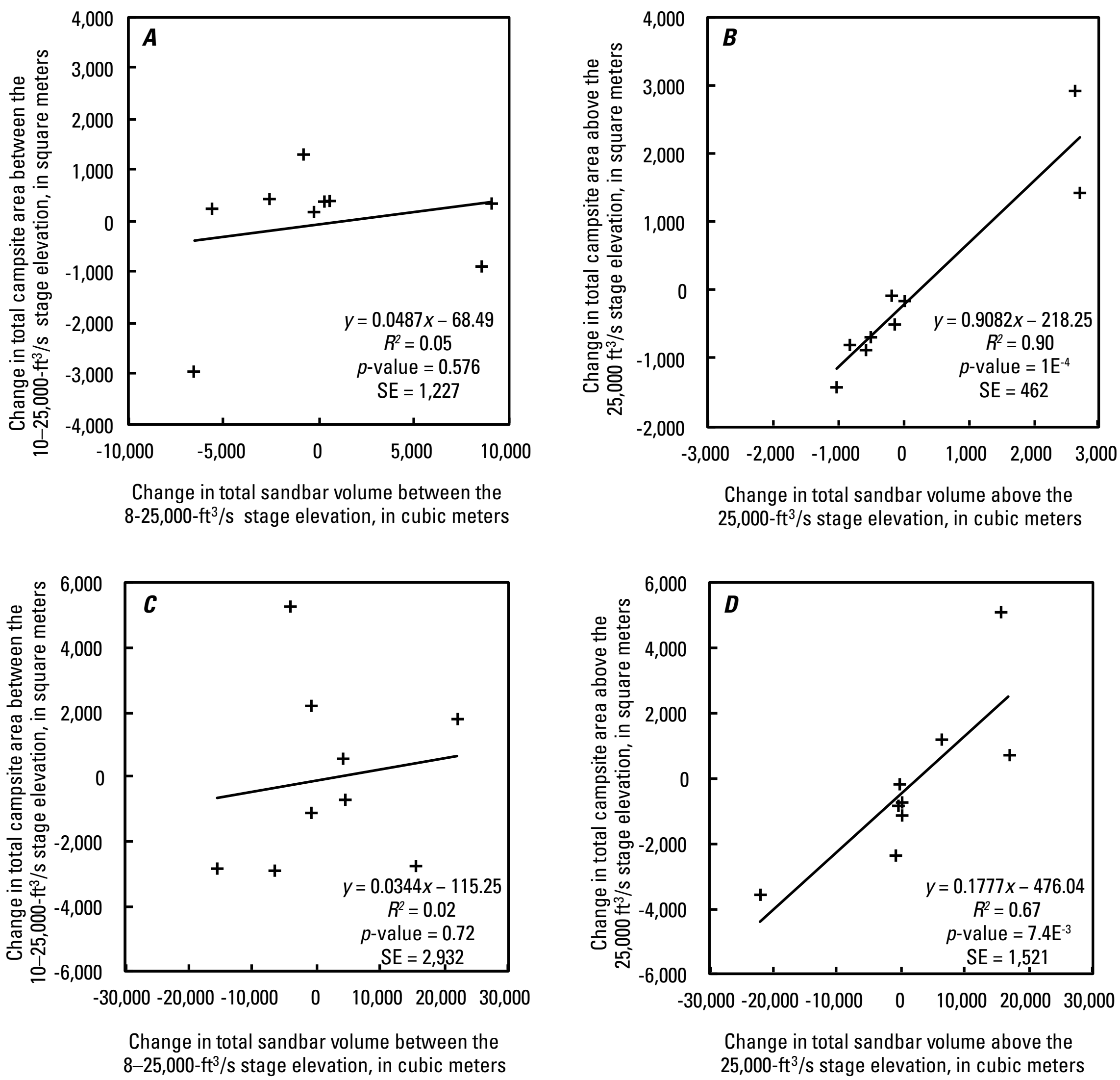


Figure 24. Graphs showing correlation between changes in sandbar volume and changes in campsite area between 2002 and 2009 along the Colorado River corridor in Grand Canyon National Park, Arizona. Sites in critical reaches—*A*, low elevations (8,000 to 25,000-ft^3/s, stage elevation) and, *B*, high elevations (above 25,000-ft^3/s stage elevation). Sites in noncritical reaches—*C*, low elevations (10,000 to 25,000-ft^3/s stage elevation) and, *D*, high elevations (above 25,000-ft^3/s stage elevation). ft^3/s, cubic feet per second; SE, standard error.

area. Only two sites, Crash Canyon (RM 63.0R) and Lower National (RM 167.1L) had a loss of campsite area due to gullying between 2002 and 2009 (table 7). Gullying accounted for 54 percent of the campsite area lost at Crash Canyon and 37 percent of campsite area lost at Lower National. However, the total area of campsite loss due to gullying was 117 m^2, which was only 1 percent of the overall loss in campsite area found at the 35 long-term monitoring sites. Five sites had gullies present in 2002, and these were filled in by 2009, with the exception of Crash Canyon (table 7). Crash Canyon had a gain in campsite area due to gully infilling, but this was mostly negated by another surface runoff event following the 2008 controlled flood. Lone Cedar (RM 23.5L) was the only site that had a substantial gain in campsite area as a direct result of gully infilling, accounting for 12 percent of the gains in campsite area at that site. However, the total amount of campsite area gained due to gully infilling was only 82 m^2, which was less than 1 percent of the overall gain in campsite area found at the 35 long-term monitoring sites. Review of remote camera photographs indicated that the majority of gully infilling was a direct result of fluvial mainstem deposition during the 2004 and 2008 controlled floods.

Vegetation Change within the Extent of Mapped Campsite Area

There was a net gain in vegetation between 1998 and 2009 at all 37 long-term monitoring sites (fig. 25). Between 1998 and 2002, 2 percent of the extent of mapped campsite area became covered with vegetation. Between 2002 and 2009 another 8 percent became vegetated. Thus, 10 percent of the area that was free of vegetation in 1998 was covered by vegetation in 2009 (table 8). At some sites, such as Granite (RM 98.3L), 172 Mile (RM 172.6L), and Middle 220 Mile (RM 220.1R), more than 25 percent of the extent of mapped campsite area became vegetated by 2009 (fig. 25, appendix 4).

Overall, there was a greater gain in vegetation at sites in noncritical reaches than at sites in critical reaches (11 percent and 8 percent, respectively), and this gain was shown to be significant at the 90-percent confidence level (U=120, p-value<0.10, table 9). There was considerable variation within individual recreational reaches. In noncritical reach 7 and critical reach 4 (see table 1), vegetation cover expanded by 20 percent and 14 percent, respectively (table 8). Increases in vegetation cover were higher at sites within Grand Canyon (14 percent) than at sites within Marble Canyon (5 percent) (table 8) and were shown to be significant (U=84, p-value<0.01, table 9).

The amount of vegetation cover in high-elevation campsite area and low-elevation campsite area (area above and below the 25,000 ft^3/s stage elevation) was also calculated for each site (appendix 5) and summarized by recreational reach and canyon section (table 10, fig. 26). In all reaches and at most sites, the majority of vegetation cover present in 2002 and 2009 was in the high elevation zone. Overall, 81 percent of the vegetation cover in 2002 was located in the high-elevation zone. By 2009 the amount of vegetation cover in the high elevation zone increased to 86 percent. Thus, a larger proportion of vegetation expansion occurred in the high-elevation zone in comparison to the low-elevation zone. In comparing reaches, there was a greater amount of vegetation in high-elevation campsite area at sites in noncritical reaches than at sites in critical reaches for both 2002 and 2009. In comparing canyon section, there was a greater amount of vegetation cover at high elevation campsite area at sites in Grand Canyon than at sites in Marble Canyon for both 2002 and 2009.

Vegetation Change Within Camp Boundaries

Of the 504 camp boundaries analyzed, only 18 had a net loss or no change in vegetation coverage. At the remaining 486 sites, vegetation expanded, resulting in a net increase of vegetation cover by 11 percent. By 2009, 23 percent of the area within all camp boundaries was covered by vegetation (table 11). Gains in vegetation were greater at certain sites. At sites such as Lopers Boat Camp (RM 41.4R) and Below

Table 7. Summary of gullies present on 2002 and 2009 sandbar surfaces and the associated change in campsite area due to infilling of gullies or gully formation at sites along the Colorado River corridor in Grand Canyon National Park, Arizona.

[Only six long-term monitoring sites had gullying or infilling of gullies during the study period. L, left; R, right; NA, not applicable; --, no data; m^2, square meter; %, percent]

Site	River mile	Side	Gulley area in 2002 (m^2)	Gulley area in 2009 (m^2)	Gain in campsite area due to infilling (m^2)	Loss in campsite area due to gullying (m^2)	Percentage of overall gain due to infilling	Percentage of overall loss due to gullying
Lone Cedar	23.5	L	241	0	45	--	12%	0%
Sandpile	30.8	R	57	0	0	--	0%	0%
Eminence	44.5	L	31	0	10	--	3%	0%
Crash Canyon	63.0	R	96	69	21	15	23%	54%
Grapevine	81.7	L	11	0	6	--	3%	0%
Lower National	167.1	L	0	296	--	102	0%	37%
Total	NA	NA	436	365	82	117	<1%	1%

Table 8. Vegetation change within extent of mapped campsite area between 1998 and 2009 summarized by canyon section and recreational reach along the Colorado River corridor in Grand Canyon National Park, Arizona.

[m², square meter; %, percent; NA, not applicable]

Section/reach	River mile	Extent of mapped campsite area (m²)	Percent vegetation cover		
			Vegetated in 1998	Vegetated in 2002	Vegetated in 2009
Canyon section					
Marble Canyon	0–62	36,528	0%	2%	5%
Grand Canyon	62–225	32,502	0%	2%	14%
Reach					
Noncritical reach 1	0–11	2,391	0%	0%	4%
Critical reach 2	11–41	11,454	0%	2%	5%
Noncritical reach 3	41–77	23,147	0%	2%	6%
Critical reach 4	77–116	6,062	0%	5%	14%
Noncritical reach 5	116–131	6,807	0%	1%	10%
Critical reach 6	131–164	4,601	0%	1%	5%
Noncritical reach 7	164–225	14,568	0%	2%	20%
Reach totals					
Noncritical reach total	NA	46,913	0%	2%	11%
Critical reach total	NA	22,117	0%	3%	8%
All reaches	NA	69,030	0%	2%	10%

Table 9. Results of Mann-Whitney (*U* test) statistical comparisons of vegetation change between 1998 and 2009 within the extent of mapped campsite area along the Colorado River corridor in Grand Canyon National Park, Arizona, tested at the 95-percent confidence level (α=0.05).

[<, less than; >, greater than]

Hypothesis	Result	Test statistic (*U*)	*p*-value
Critical<noncritical	False	120	0.070
Marble Canyon<Grand Canyon	True	84	0.00490
Total>no change	True	703	0.0000000580

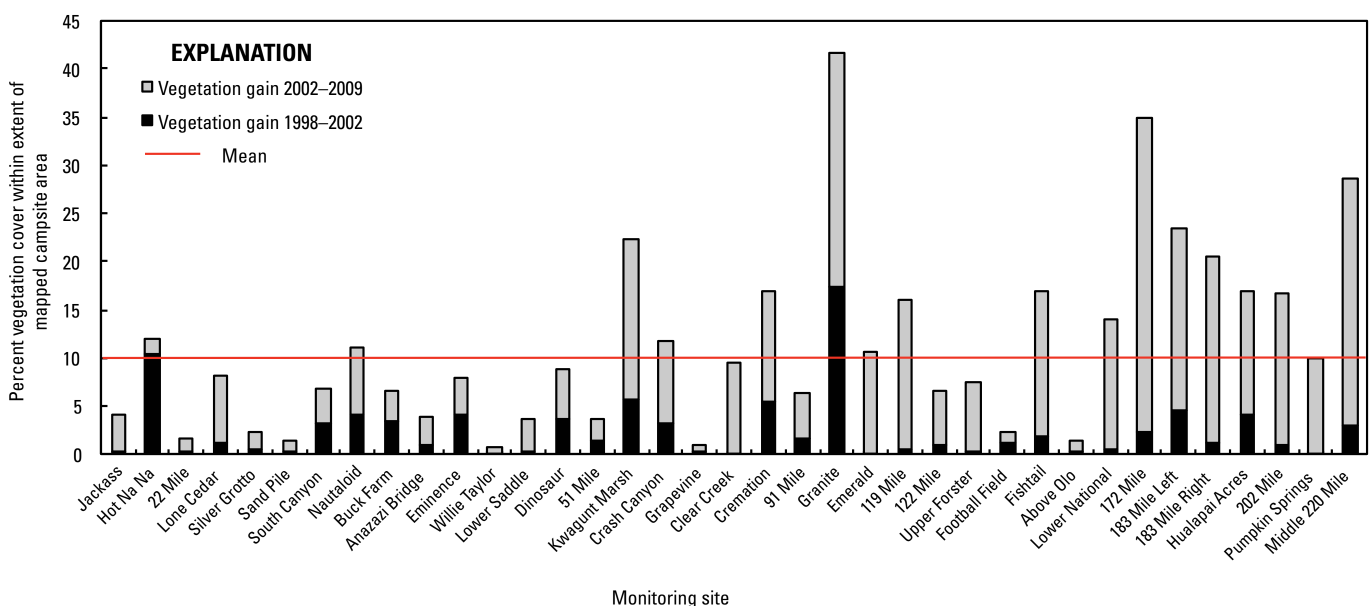


Figure 25. Vegetation change between 1998 and 2009 within the extent of mapped campsite area at each of the 37 long-term monitoring sites along the Colorado River corridor in Grand Canyon National Park, Arizona. The red line represents the mean gain in vegetation between 1998 and 2009.

Table 10. Percentage of vegetation cover within the extent of mapped campsite area along the Colorado River corridor in Grand Canyon National Park, Arizona, above and below the 25,000-cubic feet per second (ft³/s) stage elevation.

[%, percent; NA, not applicable]

Section/reach	River mile	2002		2009	
		Percentage of vegetated area below 25,000 ft³/s	Percentage of vegetated area above 25,000 ft³/s	Percentage of vegetated area below 25,000 ft³/s	Percentage of vegetated area above 25,000 ft³/s
Canyon section					
Marble Canyon	0–62	23%	77%	20%	80%
Grand Canyon	62–225	14%	86%	12%	88%
Reach					
Noncritical reach 1	0–11	26%	74%	22%	78%
Critical reach 2	11–41	41%	59%	35%	65%
Noncritical reach 3	41–77	11%	89%	12%	88%
Critical reach 4	77–116	12%	88%	14%	86%
Noncritical reach 5	116–131	10%	90%	14%	86%
Critical reach 6	131–164	25%	75%	37%	63%
Noncritical reach 7	164–225	14%	86%	9%	91%
Reach totals					
Noncritical reach total	NA	13%	87%	11%	89%
Critical reach total	NA	26%	74%	25%	75%
All reaches	NA	19%	81%	14%	86%

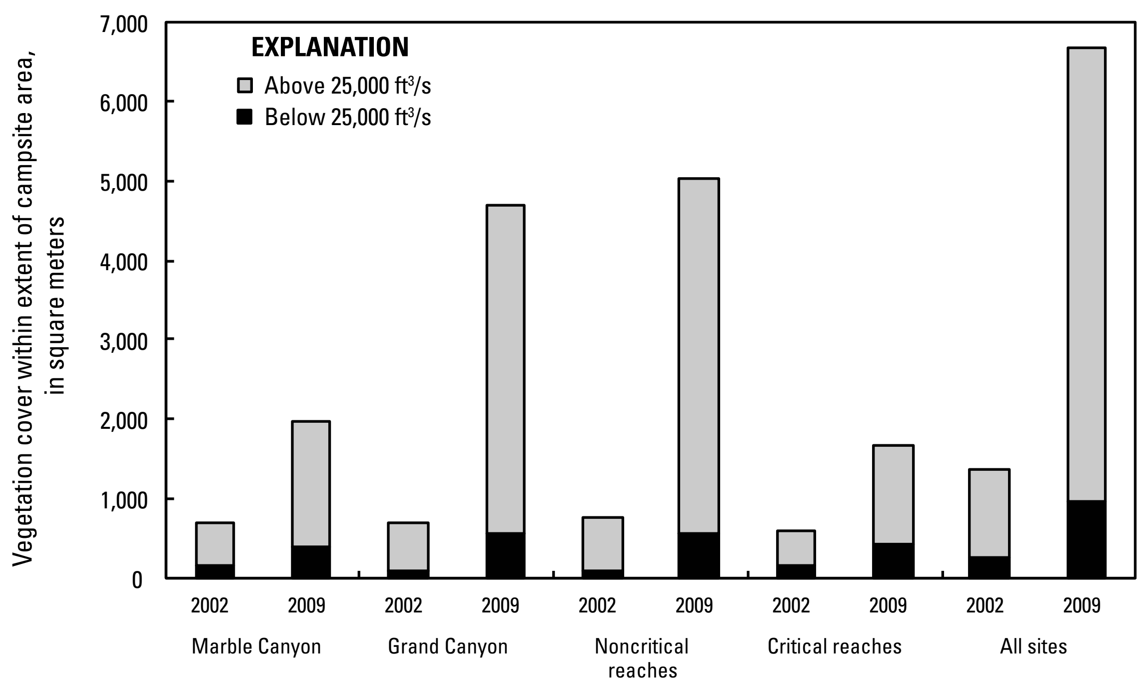


Figure 26. Vegetated area within the extent of mapped campsite area along the Colorado River corridor in Grand Canyon National Park, Arizona, occurring above and below the 25,000-cubic feet per second (ft³/s) stage elevation for 2002 and 2009.

National Camp (RM 167.5L), more than 40 percent of the area became covered by vegetation (appendix 6).

In 2002, there was a greater area covered by vegetation at camp boundaries in noncritical reaches in comparison to critical reaches (14 percent and 11 percent, respectively) and there was slightly more net vegetation gain between 2002 and 2009 at camp boundaries in noncritical reaches in comparison to critical reaches (11 percent and 9 percent, respectively) (table 11). By 2009, 24 percent of the area within camp boundaries in noncritical reaches was covered by vegetation, whereas 19 percent of the area within camp boundaries in critical reaches was covered by vegetation. Results of the Mann-Whitney *U* test show that the net vegetation gain in noncritical reaches was significantly greater than the net vegetation gain in critical reaches (U=20,712, p-value<0.001, table 12).

There was a slightly greater net gain in vegetation cover between 2002 and 2009 at camp boundaries in Grand Canyon in comparison to sites in Marble Canyon (11 percent and 9 percent, respectively) (table 11), and this gain was shown to be significant (U=16,754, p-value<0.001, table 12). Both the Glen Canyon reach and the reach below Diamond Creek had larger net gains in vegetation cover (16 percent and 14 percent, respectively) compared to Marble and Grand Canyons (table 12). By 2009, Glen Canyon had the largest amount of vegetation cover within camp boundaries, which was 36 percent (table 11).

Discussion

There was a net loss in campsite area between 2002 and 2009 at the 35 long-term monitoring sites analyzed in the context of topographic change. Changes in the elevation and slope of sandbars were the dominant mechanisms that contributed to the individual gains and losses that made up that net loss. However, losses in campsite area due to either elevation change or slope change can be offset by gains due to those same processes. This differs from vegetation encroachment, which is largely one directional. As vegetation becomes established at a campsite, the reduction in campsite

Table 11. Vegetation change between 2002 and 2009 within camp boundaries summarized by canyon section and recreational reach.

[m^2, square meter; %, percent; NA, not applicable]

Section/reach	River mile	Camp boundary area (m^2)	Percent vegetation cover					
			Vegetated in 2002	Vegetated in 2009	Vegetated in 2002 and 2009	Vegetation gain 2002–2009	Vegetation loss 2002–2009	Net vegetation change 2002–2009
Canyon section								
Glen Canyon	–15–0	18,849	22%	36%	19%	17%	3%	14%
Marble Canyon	0–62	443,333	15%	24%	12%	11%	3%	9%
Grand Canyon	62–225	1,256,188	12%	23%	10%	13%	2%	11%
Below Diamond	225–267	101,333	10%	26%	7%	18%	2%	16%
Reach								
Noncritical reach 1	0–11	66,647	12%	15%	9%	6%	3%	3%
Critical reach 2	11–41	139,592	14%	22%	11%	11%	3%	8%
Noncritical reach 3	41–77	404,958	15%	26%	13%	13%	3%	10%
Critical reach 4	77–116	144,134	9%	20%	8%	11%	1%	10%
Noncritical reach 5	116–131	184,015	8%	16%	7%	9%	1%	8%
Critical reach 6	131–164	174,155	9%	17%	8%	9%	2%	8%
Noncritical reach 7	164–225	586,021	14%	27%	12%	15%	2%	13%
Reach totals								
Noncritical reach total	NA	1,241,640	14%	24%	11%	13%	2%	11%
Critical reach total	NA	457,881	11%	19%	9%	11%	2%	9%
All sites								
All Sites	NA	1,819,703	13%	23%	11%	13%	2%	11%

Table 12. Results of Mann-Whitney (*U* test) statistical comparisons of vegetation change within camp boundaries along the Colorado River corridor in Grand Canyon National Park, Arizona, tested at the 95-percent confidence level (α=0.05).

[<, less than; >, greater than]

Hypothesis	Result	Test statistic (*U*)	*p*-value
Glen Canyon>Marble Canyon	True	549	0.013
Glen Canyon>Grand Canyon	True	1,478	<0.050
Glen Canyon<Below Diamond	False	73	0.470
Marble Canyon<Grand Canyon	True	16,754	0.00041
Marble Canyon<Below Diamond	True	746	0.000045
Grand Canyon<Below Diamond	True	2,739	0.00072
Critical<Noncritical	True	20,712	0.00024
Total>no change	True	122,079	0.0000000000022

area is essentially permanent because vegetation is no longer removed by natural floods. Thus, in terms of net loss, vegetation encroachment was of comparable magnitude to topographic change.

The influence of vegetation expansion on campsite loss was analyzed in three contexts—(1) within campsite area mapped at the 35 long-term monitoring sites where topographic data were available, (2) within the total extent of mapped campsite area at each of the 37 long-term monitoring sites, and (3) at each of the 504 campsite boundaries. In all three contexts, there was an overall net gain in vegetation, vegetation expansion was greater on average at sites within noncritical reaches than at sites in critical reaches, and vegetation expansion was greater on average at sites in Grand Canyon in comparison to sites in Marble Canyon. Our observations, therefore, show a continuation of the vegetation encroachment that has been documented in the preceding decades by previous campsite inventories, particularly at sites in noncritical reaches (Kearsley and Warren, 1993; Kearsley and others, 1994). Noncritical reaches are typically wider, have a lower gradient, and have relatively small changes in water elevation for a given change in discharge. These characteristics may favor vegetation growth compared to critical reaches. However, tamarisk defoliation and mortality is currently ongoing (Sankey and others, 2016) and could have future implications for campsites. It is unclear whether tamarisk die-offs will increase campsite size in the near term or whether dead stands will persist for years or decades.

Sankey and others (2015a) used the same maps of vegetation to determine the amounts and rates of vegetation encroachment throughout the entire Colorado River corridor for different discharge zones, and show the highest rates of vegetation encroachment between the 25,000 and 45,000-ft^3/s stage elevations. Our observations at the 37 long-term monitoring sites also indicate that a greater proportion of vegetation expansion occurred in campsite areas in the high-elevation zone (above the 25,000-ft^3/s stage elevation) than in the low elevation zone (below the 25,000-ft^3/s stage elevation). Therefore, the increase in vegetation cover at campsites, and the greater proportion of that increase being observed in the high-elevation zone, is consistent with trends of vegetation expansion throughout the entire river corridor over the same time period.

It is worth noting that the influence of vegetation on campsite size can be under or overestimated at certain sites. Two sites, Anasazi Bridge (RM 43.5L) and Kwagunt Marsh (RM 55.9R), illustrate how the influence of vegetation expansion on campsite loss can be underestimated. At Anasazi Bridge, many individual arrowweed plants were not detected in the 2009 vegetation classification due to their small size and very low density. A site visit in 2013 shows that arrowweed has spread across much of the site since 2009, making many areas unusable for camping (fig. 27). At Kwagunt Marsh, stands of tamarisk cover much of the site, and many areas of bare sand that used to be under or adjacent to those canopies are now covered by dead tamarisk branches and needles. Much of this dead vegetation matter was not detected in the 2009 vegetation classification, resulting in only a 22-percent loss of campsite area between 1998 to 2009 due to vegetation expansion. Field observations and remote camera photographs indicate that much more of the observed campsite loss is in fact due to the presence of this dead vegetation matter. Thus, vegetation expansion has had a much greater impact on the loss of campsite area at those two sites than our results show. Conversely, vegetation cover can be overestimated, such as at Nautiloid (RM 35.1L), due to the fact that stands of tamarisk can have canopies that overhang above campsite areas. From an aerial perspective, areas may look vegetated, but underneath the canopy there may be areas of open sand being used for camping (fig. 28). Despite the overestimation or underestimation of vegetation cover at certain sites, it is clear that vegetation is expanding and has had considerable impact on the loss of campsite area.

The majority of the individual gains and losses that contributed to the net loss in campsite area can be attributed to depositional and erosional processes affecting the slope of sandbars and from depositional and erosional processes that did not change the slope of sandbars above or below the 8-degree slope threshold. The primary factors leading to losses in campsite area were erosion caused by fluctuating dam flows

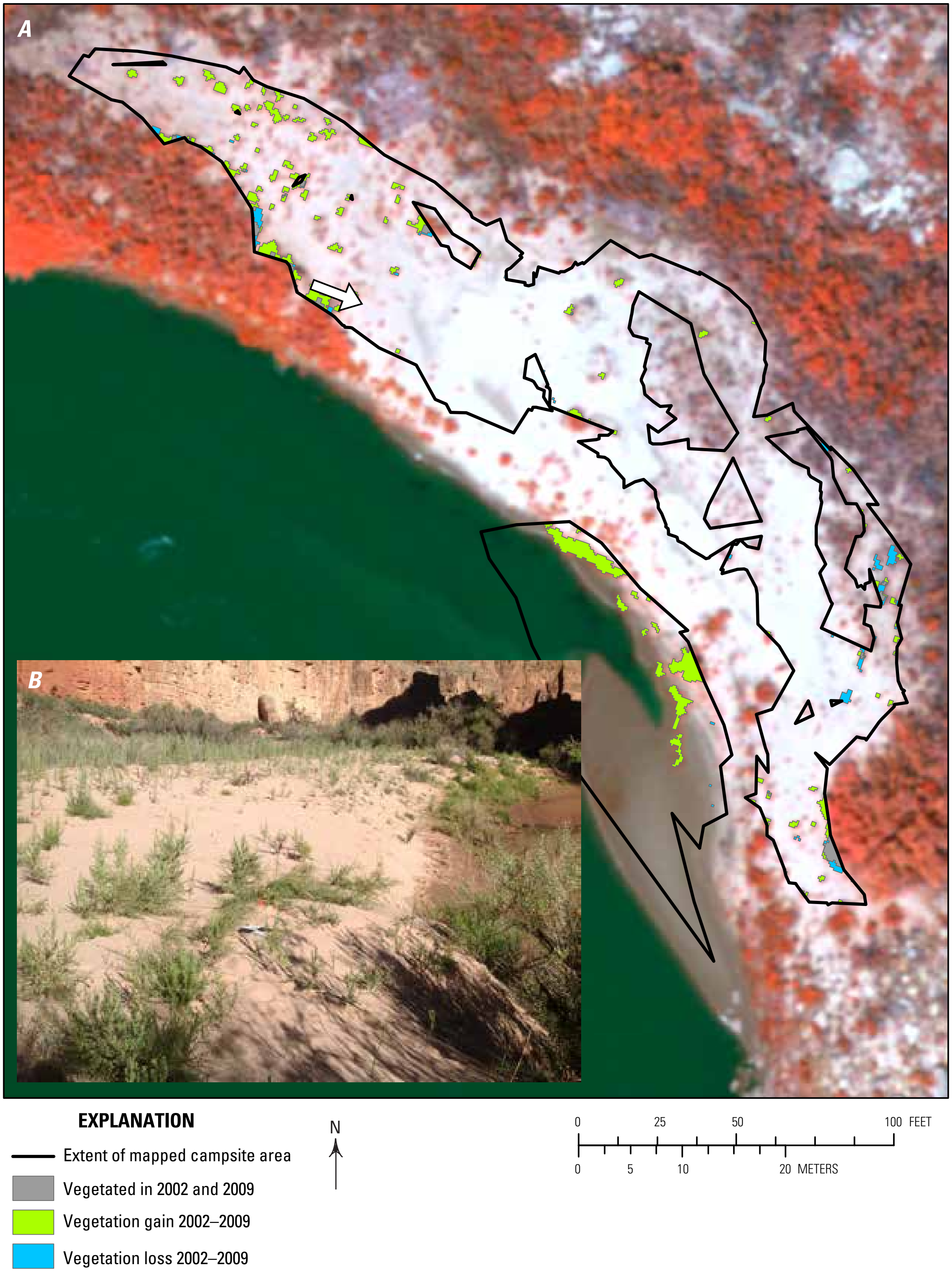


Figure 27. Images of vegetation cover at Anasazi Bridge (river mile 43.5 left) along the Colorado River corridor in Grand Canyon National Park, Arizona. *A*, U.S. Geological Survey (USGS) aerial photograph from May 2009 overlaid with map showing the under representation of vegetation cover. Note that there are small patches of vegetation and individual plants (green photosynthetically active vegetation shown in red as a false-color composite) that have not been detected in 2009 within the extent of mapped campsite area. *B*, USGS photograph taken during a site visit on September 24, 2013 (location and direction shown with arrow on map). The visit found that much of the vegetation present on the site was individual arrowweed (*Pluchea sericea*) plants and that they had expanded since 2009.

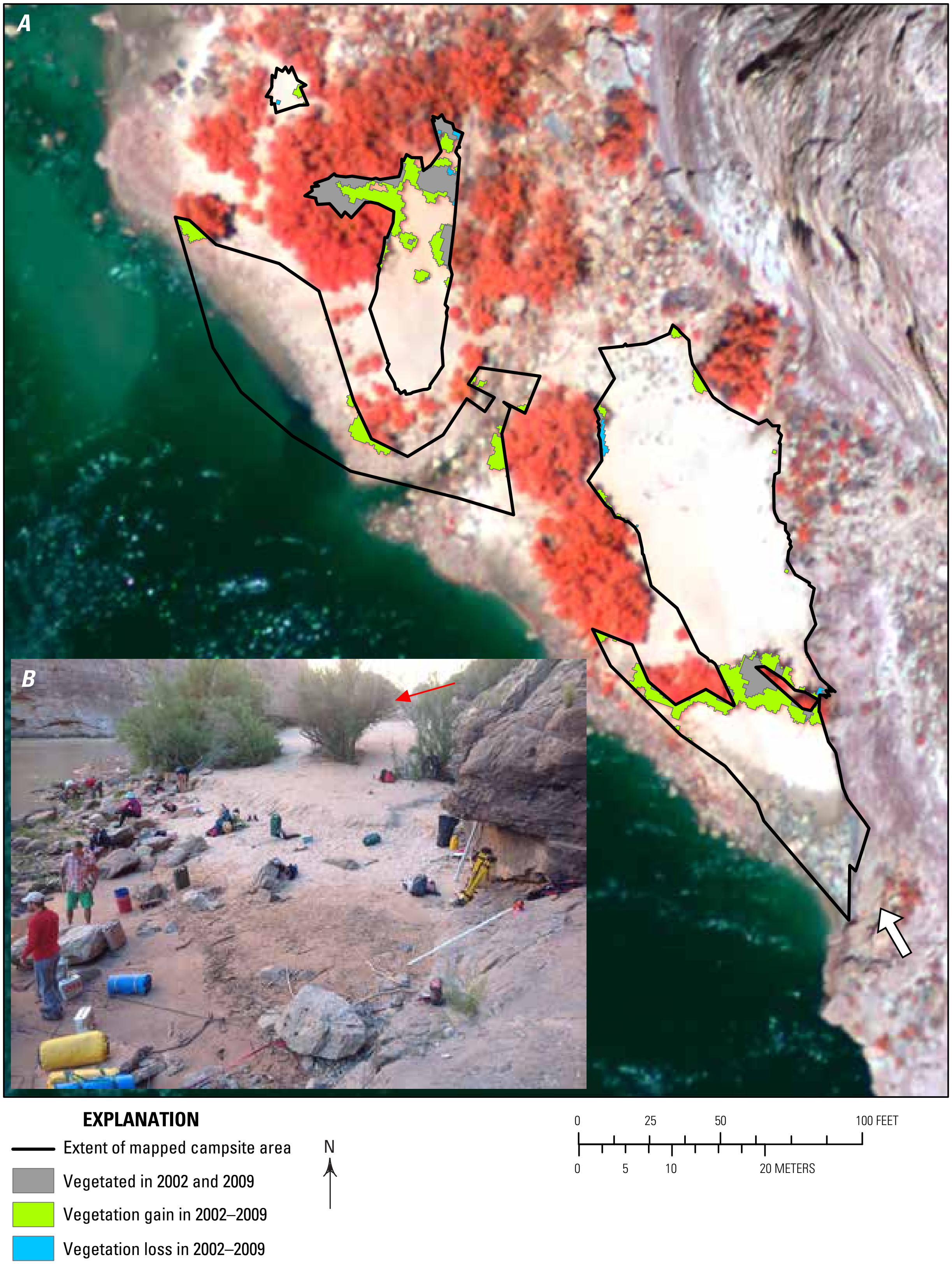


Figure 28. Images of vegetation cover at Nautiloid (river mile 35.1 left) along the Colorado River corridor in Grand Canyon National Park, Arizona. *A*, U.S. Geological Survey (USGS) aerial photograph from May 2009 (green photosynthetically active vegetation shown in red as a false-color composite) overlaid with map showing vegetation and campsite area. *B*, USGS photograph taken during a site visit on September 24, 2013 (location and direction shown with arrow on map). These images illustrate how the amount of campsite loss due to vegetation expansion can be overestimated. Tamarisk (*Tamarix ramosissima*) canopies can overhang campsite areas. From an aerial perspective these campsite areas might look entirely vegetated, but areas underneath the canopies might still be used (red arrow).

and deposition associated with controlled floods that increased the slope of the bars too greatly. Gullying was a significant factor in the loss of campsite area at a few sites, but overall gullying contributed to minor amounts of erosion and campsite loss. This is probably not surprising, as gullying has been shown to be less prevalent in reaches of the river and areas with larger quantities of bare sand (for example, campsites) due to the propensity of backwasting and aeolian deposition to periodically infill gullies with sand (Sankey and Draut, 2014; Collins and others, 2016; East and others, 2016).

Hazel and others (2010) attributed gains in campsite area to deposition of sand during the 2008 controlled flood, and attributed most of the losses in campsite area to lateral cutbank retreat of the newly deposited sand during diurnally fluctuating dam releases. They show that the size of campsite area is largely affected by these dam management activities. The results of this study are in agreement with their observations and conclusions but span a longer time period that included two controlled floods.

Participants of the AAB program also cite cutback retreat caused by fluctuating flows as a primary reason for campsite loss following sand deposition after a controlled flood (Thompson and Pollock, 2006; Lauck 2007, 2008, 2009, 2010). Annual AAB reports indicate that erosion is most pronounced immediately following a controlled flood and then tapers off as beachfronts approach shallower angles and the amount of sediment available to erode is reduced. Thompson and Pollock (2006) and Lauck (2007, 2009, 2010) conclude that erosion from fluctuating flows was the primary factor in the erosion of campsites for the 2002–2005 and 2008–2009 boating seasons, followed by gullying, erosion from the activity of campers, and aeolian erosion. During the 2006 and 2007 boating seasons gullying was the predominant factor in campsite loss, and the effects of fluctuating flows on campsite erosion were less pronounced (Lauck, 2008). Each of the reports also discuss the slow and persistent increase in vegetation cover at campsites. Our conclusions that depositional and erosional processes due to dam management activities are the primary factors in contributing to individual gains and losses in campsite area from year to year, that gullying is a secondary factor, and that encroachment of vegetation is a steady and one-directional process are, therefore, consistent with the observations made by AAB participants over the course of the study period.

Erosion and changes in sandbar slope occurred more often at sites within critical reaches, indicating that campsite areas in critical reaches may not be as stable as campsite areas in noncritical reaches. This may be due to the fact that critical reaches are typically narrower, have a higher gradient, and are thus a higher energy environment compared to noncritical reaches. Erosion and slope changes were less significant at sites within noncritical reaches, indicating that bars and campsite areas are more stable there and that gains in campsite area may last longer there than in critical reaches. Because campsite area within critical reaches is the limiting factor in determining the recreational carrying capacity throughout the river corridor, management strategies that do not lead to a long-term increase in campsite area in critical reaches will not meet the objectives set forth by the GCDAMP (see Bureau of Reclamation, 2001).

Evaluation of Methods for Measuring Campsite Area

Introduction

Campsites along the Colorado River in Grand Canyon have been studied and monitored since the mid-1970s, but monitoring efforts have varied spatially, temporally, and by methodology (Kaplinski and others, 2003). Since the early 1990s, campsite area has been measured by delineation in the field of individual campsite polygons using criteria established by Kearsley and Warren (1993). This approach has continued to be used, because it is a relatively simple and objective way to measure the effects of dam operations on campsite size. Three different methods have been used to delineate campsite polygons in previous studies—(1) hand drawing campsite polygons on aerial photographs in the field (Kearsley and Warren, 1993; Kearsley and Quartaroli, 1997; Kearsley and others, 1999), (2) surveying campsite polygon perimeters in the field with a total station (Kaplinski and others, 2003, 2006, 2010, 2014), and (3) hand-digitizing campsite polygons in the field on tablet computers (Kaplinski and others, 2003).

All of these methods include two independent sources of uncertainty associated with the measurement of campsite area. The first source of uncertainty is the uncertainty associated with the subjective process of choosing the points that delineate the campsite polygons. We term this “surveyor” uncertainty. The second source of uncertainty is “measurement” uncertainty, which is the error that is associated with how accurately the technician is able to place each point that defines a campsite polygon. The purpose of this section is to describe and quantify those sources of uncertainty. Based on repeat campsite surveys conducted in September and October of 2013, we quantify (1) surveyor uncertainty using repeat measurements made by different technicians, (2) measurement uncertainty associated with using the total-station or tablet-computer methods, and (3) any method-based bias between the total-station and tablet methods. Repeat campsite survey data are available in GIS format in Hadley and others (2018). The “air photo” method used in other studies was not evaluated in this study.

An additional objective was to modify the tablet method previously used by Kaplinski and others (2003) to improve on functionality and to collect additional campsite-monitoring data. Using computer tablets equipped with GIS capability, we developed a new tablet method that (1) collects data on the physical causes that contribute to campsite-area change year to year in addition to mapping campsite area, (2) collects data on the physical features that constrain the size of individual campsite polygons, and (3) maps other geomorphic and campsite features such as gullies and boat mooring areas.

Methods

Surveyor Uncertainty

There is a certain degree of subjectivity when mapping campsite area in the field even though survey crews follow established criteria. The established criteria of flat (less than 8-degree slope), open, smooth sand is simple, but is ultimately based on the judgment of technicians. Technicians have to estimate the slope of the sandbar by eye, choose what constitutes a smooth enough surface to camp on, and choose how many points are used to delineate campsite polygons. Campsite area can therefore vary in size depending on which crew conducts the survey. For example, Kaplinski and others (2002) conducted a repeat total-station measurement at Nautiloid (RM 35.1L) and found a 3.7 percent difference in area between the independent surveys. Subsequent studies by Kaplinski and others (2005, 2010, and 2014) have conservatively reported an uncertainty in mapping campsite area of 10 percent using the total-station method.

Surveyor uncertainty is minimized by giving technicians printed maps of the survey from the previous year to ensure previously excluded areas are not included (Kaplinski and others, 2014), and when possible, having at least one experienced technician on the survey crew who is familiar with the site. Despite these efforts, it is not always possible to survey campsite area at every site with only the most experienced technicians. Previous estimates of this source of uncertainty (Kaplinski and others, 2002) did not explicitly evaluate the uncertainty that may result from use of less experienced survey crews, nor did it evaluate this uncertainty at larger sites with more complex features. We evaluated surveyor uncertainty by conducting repeat total-station surveys of the same site with different survey crews made up of technicians with different levels of experience.

Repeat total-station surveys were conducted at four sites (Nautiloid, RM 35.1L; Eminence, RM 44.5L; Dinosaur, RM 50.1R; and Crash Canyon, RM 63.0R), which vary in size and complexity (that is, Crash Canyon is a small rocky site, whereas Eminence is a large site with numerous patches of vegetation). One survey crew (consisting of an instrument operator and two technicians) would map campsite area and would be followed by a different crew later that day or the next morning. In each case, the first crew to map campsite area had several years of experience in conducting surveys and the second crew either had less than 1 year of experience or had never mapped campsite area before. Both crews stayed within the limits of a defined survey area to ensure that the same areas of a sandbar were evaluated.

We argue measurement uncertainty is negligible when total-station methods are used to survey campsite polygons. The horizontal error associated with individual points surveyed using the total-station method is typically on the order of a few centimeters (Hazel and others, 2008), which is very small relative to the size of the campsite polygons being measured and relative to the uncertainty associated with the selection of the point itself. Therefore, this comparison allowed for surveyor uncertainty to be determined, while controlling for measurement uncertainty.

Measurement Uncertainty

Because we assume that measurement error is negligible when using the total-station method, our evaluation of measurement uncertainty is only focused on the tablet-computer method. Several factors contribute to measurement uncertainty using the tablet method, which include the ability of a surveyor to match their location on the ground to a location on the image, the error associated with digitizing polygons using the selected GIS software, and the error associated with using digital imagery that is older than the actual time of the survey.

Fourth generation iPad tablets (WiFi+Cellular model) equipped with an iPad-based GIS application called GIS Pro (Garafa, LLC, 2013) were used to conduct the tablet surveys. iPads were selected because they have a relatively low cost, have a long battery life, and have Global Positioning System (GPS) capability. The iPad's internal GPS runs on the GPS and Global Navigation Satellite System (GLONASS) systems and can be accurate to within a few meters (based on field observations). iPads were also equipped with LifeProof brand waterproof/shockproof cases and anti-glare screen protectors for use in the field. Campsite polygons were digitized onto the same orthoimagery collected in 2009 that was used to make the maps of vegetation discussed earlier in Geomorphic and Vegetation Change at Campsites Between 2002 and 2009. Thus, the imagery used for the tablet method predated the actual time of surveys by several years; however, it was the latest orthoimagery available at the time.

We evaluated measurement uncertainty for the tablet method by conducting side-by-side surveys with the tablet and total-station methods at three sites (Buck Farm, RM 41.2R; Eminence, RM 44.5 R; and Lower Saddle, RM 47.7R). In each case, the surveyor using the tablet method tried to map the same campsite polygons mapped by the total-station survey crew. This was accomplished by having the tablet surveyor follow the total-station technicians as they conducted their campsite survey (fig. 29). Campsite polygons were digitized on the tablet at the same time that total-station points were surveyed. Each survey selected the same areas of a sandbar to be mapped, and campsite polygons were digitized on the tablet using the same number of points that the technicians used to define each polygon. Thus, surveyor uncertainty was eliminated because the tablet surveyor followed the total-station crew. This comparison, therefore, allowed the measurement uncertainty using the tablet method to be calculated, while controlling for surveyor uncertainty.

Methods-Based Bias

A third set of repeat measurements were made to determine if a methods-based bias exists between the tablet and total-station methods. Campsite areas mapped with one method may be consistently larger or smaller than areas mapped by the other method given that the two methods differ in the way campsite polygons are delineated. Also, due to logistical reasons, tablet surveyors often had more time to conduct campsite surveys than the total-station crews.

We evaluated the potential bias between the tablet and total-station method by conducting repeat surveys at 22 sites (table 2) at different times using different crews. In each case, campsite area was mapped by a total-station crew and then mapped later that day by a different surveyor using the tablet method. Each survey delineated campsite polygons independently of one another but stayed within the same defined survey area. On average tablet surveyors had about 45 minutes to conduct a survey, whereas total-station crews had about 15 minutes. Comparisons between these repeated measurements show the difference between using the tablet method versus the total-station method, taking into account surveyor uncertainty, measurement uncertainty, and the fact that surveys were conducted under different time constraints.

Additional Geomorphic Attributes of Campsites

Another goal of using the tablet method was to collect additional information on geomorphic attributes of campsites in the field. The GIS Pro program (Garafa, LLC, 2013) allows features to be digitized directly onto imported orthoimagery, allows digitized features to be attributed, and has customizable field forms and layer symbology (fig. 30). Once campsite area was surveyed, additional features of the campsite, such as boat mooring areas, gullies, and locations of photographs taken were digitized as point, line, or polygon features (fig. 31). Areas of campsite gain and campsite loss from the previous year's survey were also determined by overlaying the previous year's campsite polygons on the newly digitized campsite polygons. Points were added to areas of campsite gain and loss and attributed with a reason for that change (fig. 31). This allowed areas of campsite change to be identified in the field at the time of survey versus determining reasons for change at a later date using photographs or topographic data.

Physical factors that constrain the size of campsite area were also evaluated in the field at 26 sites and attributed to each digitized campsite polygon. Factors included the presence of boulders, vegetation, bedrock, or a change in the slope of open sand. These were visually estimated in the field as a

Figure 29. Photograph of scientists conducting concurrent computer-tablet and total-station surveys to map campsite area at Eminence (river mile 44.5 left) along the Colorado River corridor in Grand Canyon National Park, Arizona (U.S. Geological Survey photograph).

percentage of the perimeter around a mapped campsite polygon. For example, a mapped campsite polygon may have had 10 percent of its perimeter bordered by vegetation, 10 percent of its perimeter bordered by boulders, and 80 percent of its perimeter bordered by sand that is steeper than 8 degrees (fig. 30). Factors that constrained the perimeters of each campsite polygon were converted to lengths, added together, and then converted back into a percentage for the entire site, and are referred to as "campsite-area constraints."

Results

Uncertainty Associated With Surveyor Experience

The inexperienced crews tended to under measure the number of campsite polygons (table 13) and the area of individual campsite polygons (figs. 32 and 33). The average difference in campsite area mapped by the inexperienced crew compared to the experienced crew was 13 percent (table 13). The largest difference in campsite area measured by the different crews was 22 percent, which occurred at Dinosaur (RM 50.1R). The closest match between the two independent survey crews occurred at Nautiloid (RM 35.1L), where the inexperienced crew mapped 7 percent less campsite area than the experienced crew. Differences in mapped campsite area between survey crews was greater at large complex sites such as Dinosaur, where campsite area may consist of many campsite polygons. Because we assume that measurement error using total-station surveys is negligible, the average difference between survey crews of 13 percent represents the surveyor uncertainty (that is, the way a survey crew selects and delineates campsite polygons).

Uncertainty Associated with Measurement Error Using the Computer-Tablet Survey Method

Fifty-four campsite polygons were mapped at the three sites where computer-tablet surveys and total-station surveys were conducted concurrently (fig. 34). Campsite area measured with the tablet method tended to be larger than the same campsite area measured with the total-station method (fig. 35). On average, areas measured by the tablet exceeded the total-station measurements by 13 percent (table 14). The percent difference in campsite area measured by the tablet method compared to the total-station method varied from 5 percent (Lower Saddle, RM 47.7R) to 25 percent (Eminence, RM 44.5L). Because this comparison controlled for surveyor uncertainty, the 13-percent difference between the surveys is the uncertainty associated with measurement error when using the tablet method.

Total Uncertainty and Methods-Based Bias

Using the equation of Taylor (1997), the total uncertainty (U_{total}) in mapping campsite area using either the total-station or computer-tablet method can be estimated as:

$$U_{total} = \sqrt{\left(U_{surveyor}\right)^2 + \left(U_{method}\right)^2}, \quad (1)$$

where $U_{surveyor}$ is the uncertainty associated with how a surveyor selects areas that fit the campsite area criteria and how they choose to delineate campsite polygons and U_{method} is the uncertainty associated with measurement error (that is, the ability to accurately map campsite polygons using the equipment of a particular method). Because measurement error was assumed to be negligible when using the total-station method, the observed 13 percent surveyor uncertainty also represents the total uncertainty when mapping campsite areas with total-station surveys. This total uncertainty is larger than the 10-percent uncertainty estimate previously reported by Kaplinski and others (2005, 2010, and 2014).

Assuming that surveyor uncertainty is independent of the survey method (that is, there would be a 13-percent difference between survey crews if both used the tablet method) and that there is an observed measurement uncertainty of 13 percent when using the computer-tablet method, the total uncertainty associated with the tablet method can be calculated using

Table 13. Summary of repeat total-station surveys conducted independently at four long-term monitoring sites along the Colorado River corridor in Grand Canyon National Park, Arizona.

[L, left; R, right; m^2, square meter; %, percent; NA, not applicable]

Site	River mile	Side	Number of campsite polygons mapped by experienced crew	Number of campsite polygons mapped by inexperienced crew	Campsite area mapped by experienced crew (m^2)	Campsite area mapped by inexperienced crew (m^2)	Difference in campsite area (m^2)	Percent difference from experienced crew
Nautiloid	35	L	5	4	388	359	29	7%
Eminence	44.5	L	19	17	475	418	57	12%
Dinosaur	50.1	R	5	6	478	373	104	22%
Crash Canyon	63.0	R	10	8	65	59	6	9%
Mean	NA	NA	10	9	351	302	49	13%

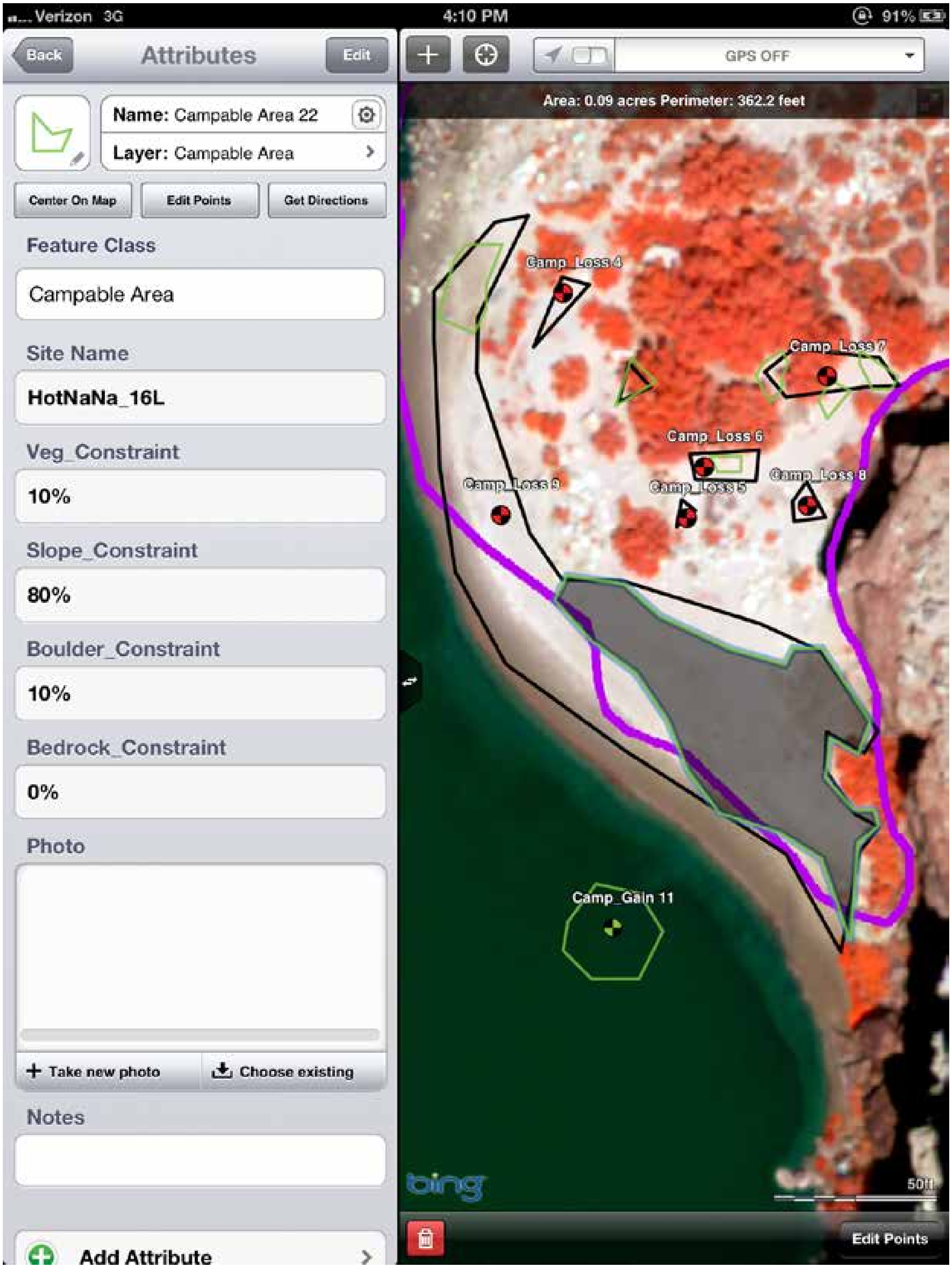
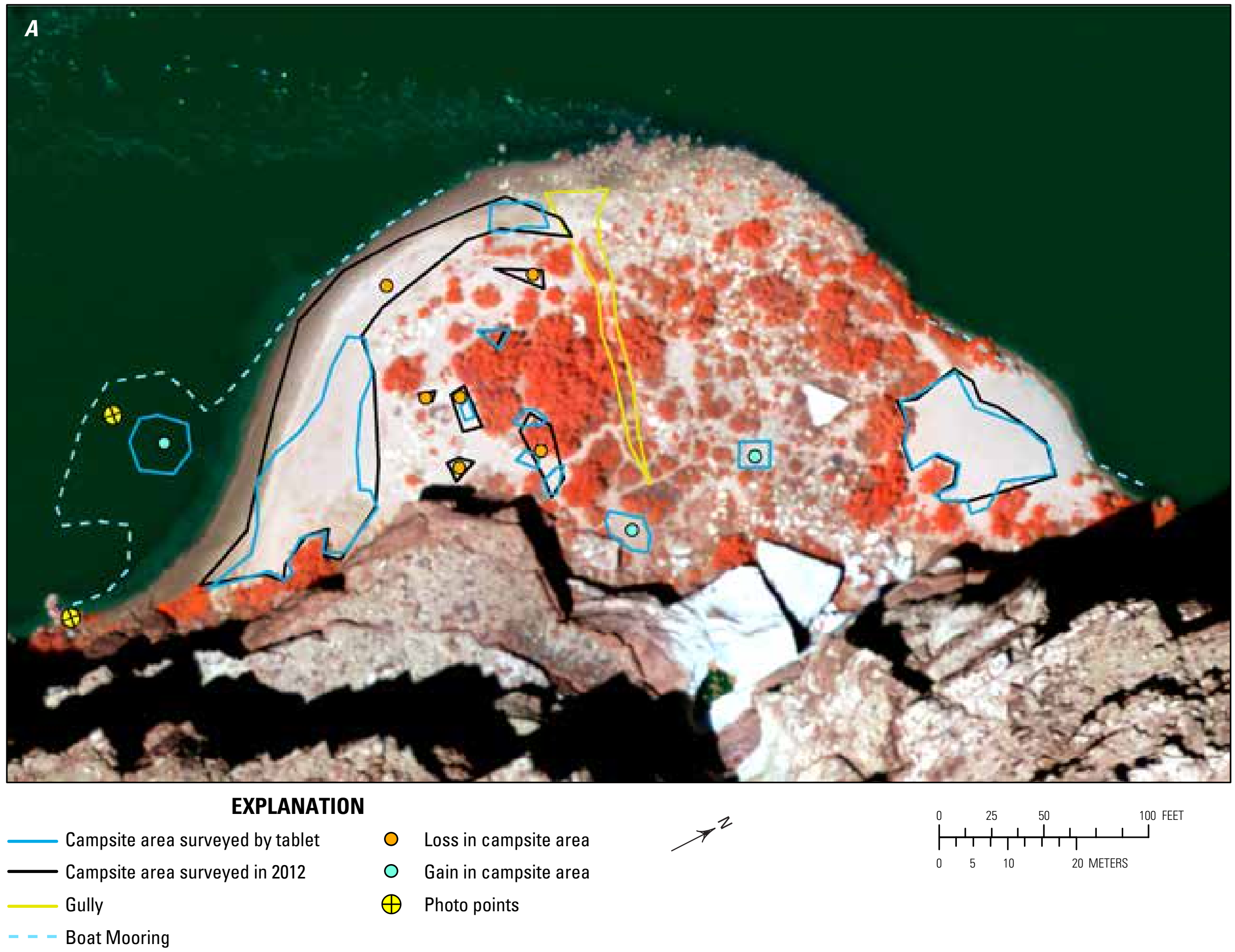


Figure 30. Screenshot of the GIS Pro application (Garafa, LLC, 2013) showing how data can be attributed to digitized features. Example shown is a campsite polygon (shaded grey) being attributed with constraints at Hot Na Na (river mile 16.6 left) along the Colorado River corridor in Grand Canyon National Park, Arizona.



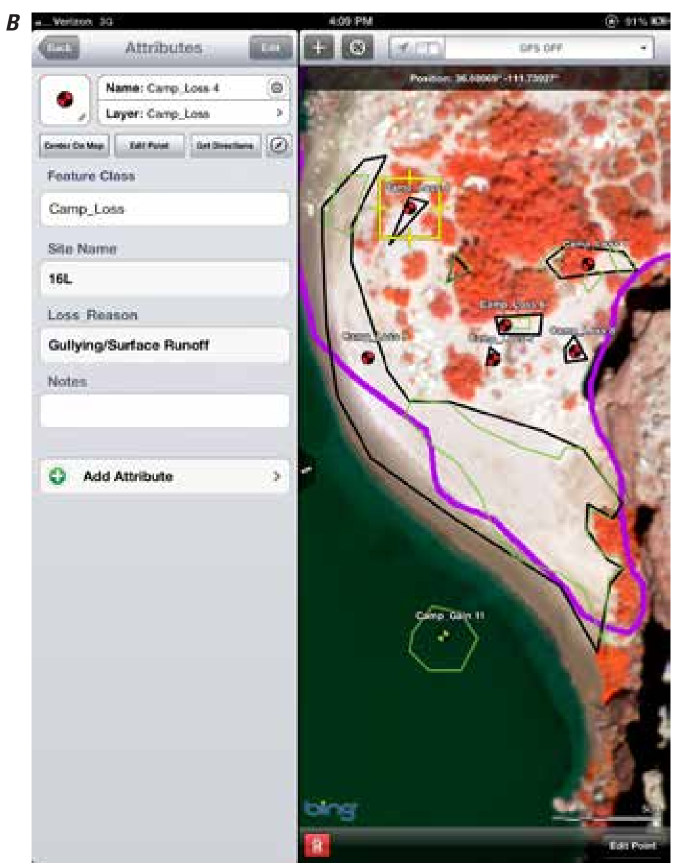


Figure 31. Images showing an example of a complete computer-tablet survey of campsite area at Hot Na Na (river mile 16.6 left) along the Colorado River corridor in Grand Canyon National Park, Arizona. *A*, U.S. Geological Survey (USGS) aerial photograph from May 2009 (green photosynthetically active vegetation shown in red as a false-color composite) overlaid with map showing digitized campsite polygons, boat mooring areas, and gullies. Digitizing campsite polygons on top of the previous year's campsite survey allowed areas of campsite gain and areas of campsite loss to be seen. *B*, Screenshot of the GIS Pro application (Garafa, LLC, 2013) showing points that were added to areas of campsite gain and areas of campsite loss and were attributed with a gain/loss reason in the attribute form.

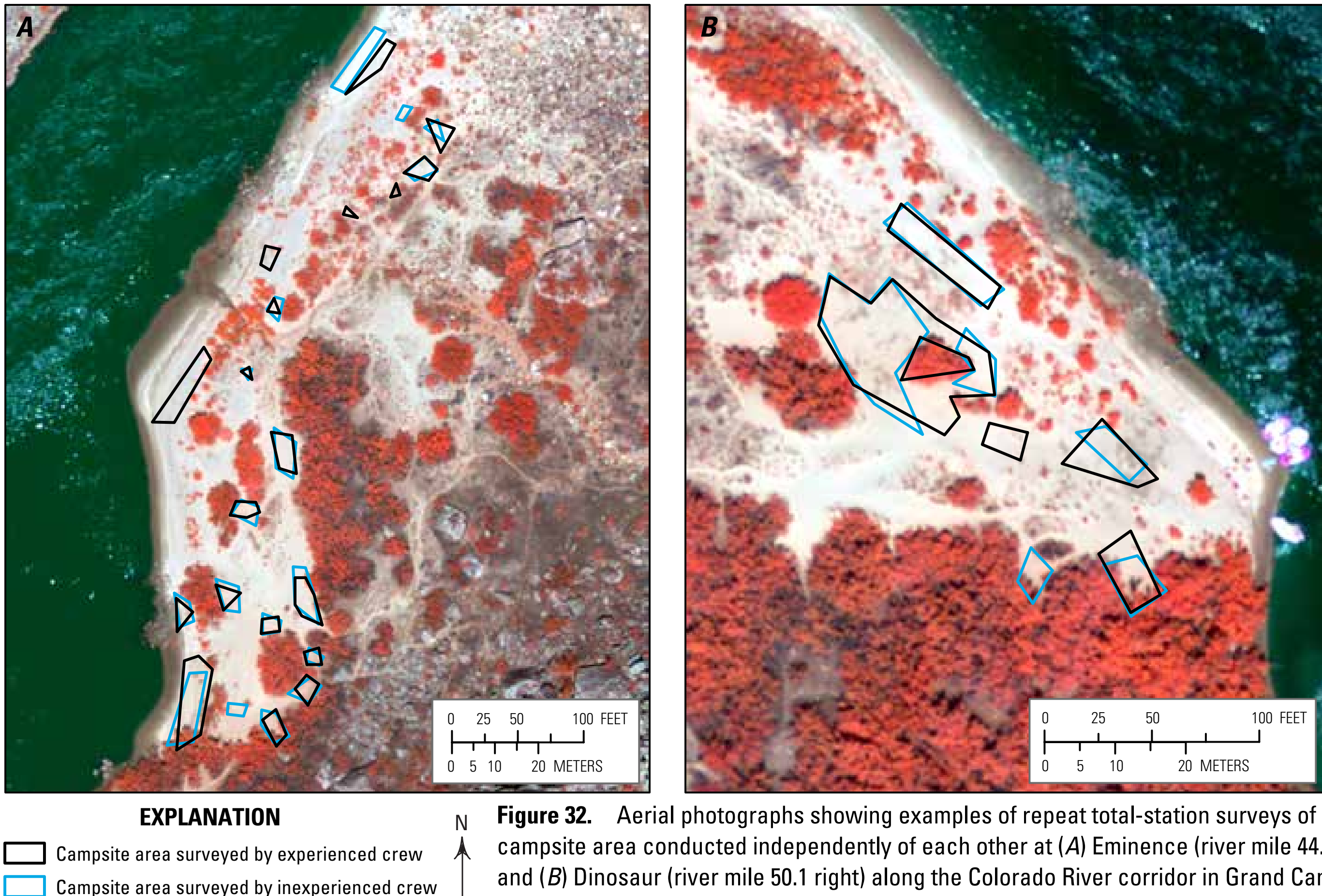


Figure 32. Aerial photographs showing examples of repeat total-station surveys of campsite area conducted independently of each other at (*A*) Eminence (river mile 44.5 left) and (*B*) Dinosaur (river mile 50.1 right) along the Colorado River corridor in Grand Canyon National Park, Arizona. U.S. Geological Survey aerial imagery from May 2009 displayed as false color composite, with green photosynthetically active vegetation displayed as red.

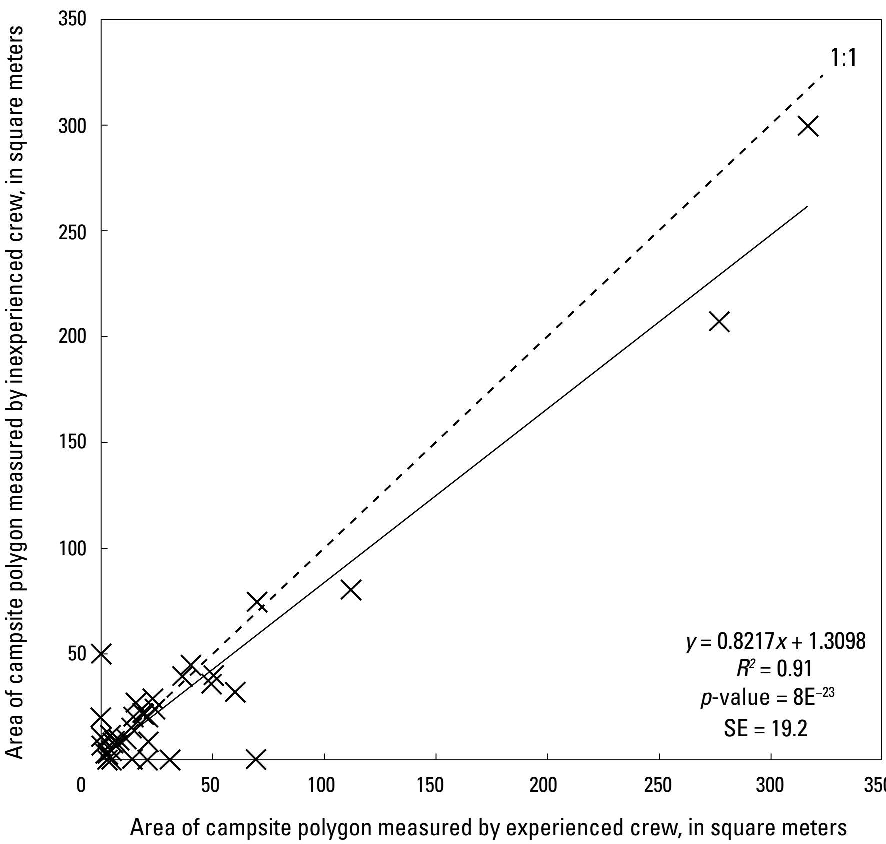


Figure 33. Graph showing correlation between campsite polygons mapped by experienced total-station survey crews and campsite polygons mapped by inexperienced total-station survey crews for campsites along the Colorado River corridor in Grand Canyon National Park, Arizona. A linear regression fit is shown. Points that fall below the 1:1 line (dashed) are under measurements. Campsite polygons that were surveyed by one crew and not by the other were compared to zero values and fall on the x and y axes. SE, standard error.

Table 14. Summary of computer-tablet surveys and total-station surveys of campsite area conducted concurrently at three long-term monitoring sites along the Colorado River corridor in Grand Canyon National Park, Arizona.

[L, left; R, right; m^2, square meter; %, percent; NA, not applicable]

Site	River mile	Side	Campsite area mapped by total-station surveys (m^2)	Campsite area mapped by computer-tablet surveys (m^2)	Number of campsite polygons mapped	Percent difference of computer-tablet surveys from total station surveys
Buck Farm	41.2	R	388	350	23	10%
Eminence	44.5	L	475	592	19	25%
Lower Saddle	47.7	R	506	531	12	5%
Mean	NA	NA	456	491	18	13%

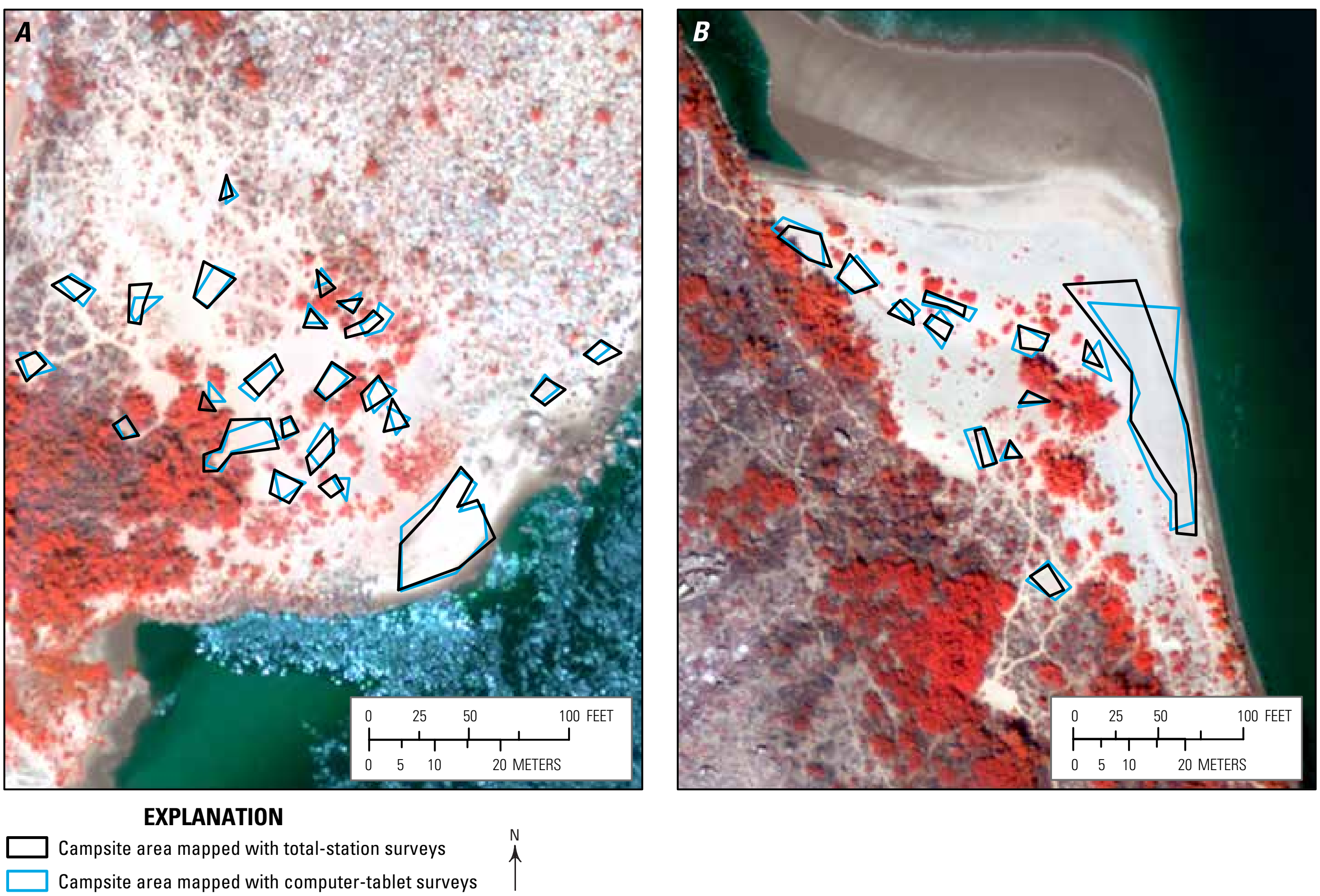
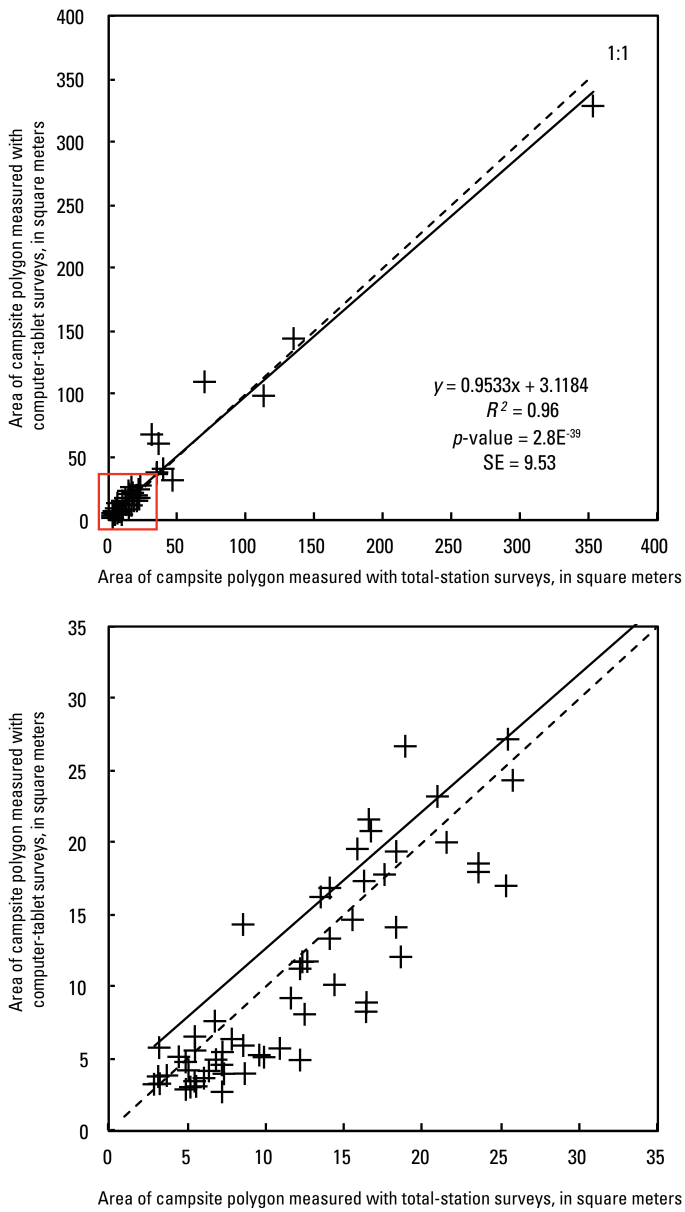


Figure 34. Aerial photographs showing examples of campsite area mapped using computer-tablet surveys and total-station surveys conducted concurrently at (*A*) Buck Farm (river mile 41.2) and (*B*) Lower Saddle (river mile 47.7 right) along the Colorado River corridor in Grand Canyon National Park, Arizona. U.S. Geological Survey aerial imagery from May 2009 displayed as false color composite, with green photosynthetically active vegetation displayed as red.

equation 1. We calculate the total uncertainty associated with using the tablet method as 18 percent, which is higher than the total uncertainty associated with using the total-station method.

Comparisons between total-station surveys and computer-tablet surveys conducted independently of one another (fig. 36) show a greater percent difference on average than the total uncertainty calculated for either method. Campsite area mapped with the tablet method tended to be larger than campsite area mapped with the total-station method (fig. 37, table 15). On average, campsite area measured by the tablet method exceeded the total-station measurements by 29 percent (table 15), indicating that a method-based bias exists between the two methods. At one site (51 Mile, RM 51.5L), campsite area measured by the tablet exceeded total-station measurements by almost 100 percent, whereas at other sites this difference was only a few percent (Dinosaur, RM 50.1R, and Lower National, RM 167.1L) (table 15).



Large percent differences were typically observed at sites where campsite area was small. This is expected, as small discrepancies in mapped campsite area would have a large percent difference if the mapped areas are very small to begin with. Small percent differences were typically observed at sites where campsite area was much larger. However, when evaluating the percent difference between the computer-tablet surveys and total-station surveys for all the sites combined, percent difference was much lower than the average percent difference on a site-by-site basis (table 15). This was due to large percent differences found at smaller campsite areas being cancelled out by the smaller percent differences found at the larger campsite areas. In other words, on a site-by-site basis, percent difference between methods was high (29 percent) but when viewed as a whole survey trip, percent error was lower (16 percent).

Physical Constraints on Campsite Area

The physical factors that constrain campsite area varied greatly among the monitoring sites (fig. 38, table 16). Although boulders and bedrock are major constraints at a few sites, steep slopes and vegetation were the dominant constraints at most sites. Slope was the most common constraint on campsite area within critical reaches, whereas vegetation was more dominant in noncritical reaches (table 16). There was little difference in campsite-area constraints between sites in Marble Canyon versus sites in Grand Canyon (table 16).

Discussion

Repeat total-station surveys show that the uncertainty in mapping campsite area using this method is higher than the 10 percent uncertainty that has been previously reported by Kaplinski and others (2002, 2005, 2010, and 2014). Given our observed surveyor uncertainty of 13 percent, and the fact that campsite surveys have been conducted by a variety of surveyors with different levels of experience, the uncertainty in mapping campsite area using the total-station method should be revised to about 15 percent. Using experienced technicians or even using the same survey crew year after year to map the same campsites would decrease surveyor uncertainty.

Use of the computer-tablet method brings an additional measurement uncertainty to a campsite survey. Our observed measurement uncertainty of 13 percent is largely due to the error associated with mapping on imagery that predates the

Figure 35. Graphs showing correlation between campsite polygons mapped by computer-tablet surveys and campsite polygons mapped by total-station surveys along the Colorado River corridor in Grand Canyon National Park, Arizona. Surveys were conducted concurrently of one another. Campsite polygons in the red box in *A* are shown at larger scale in *B*. A linear regression fit is shown. Points that fall above the 1:1 lines (dashed) are over measurements. SE, standard error.

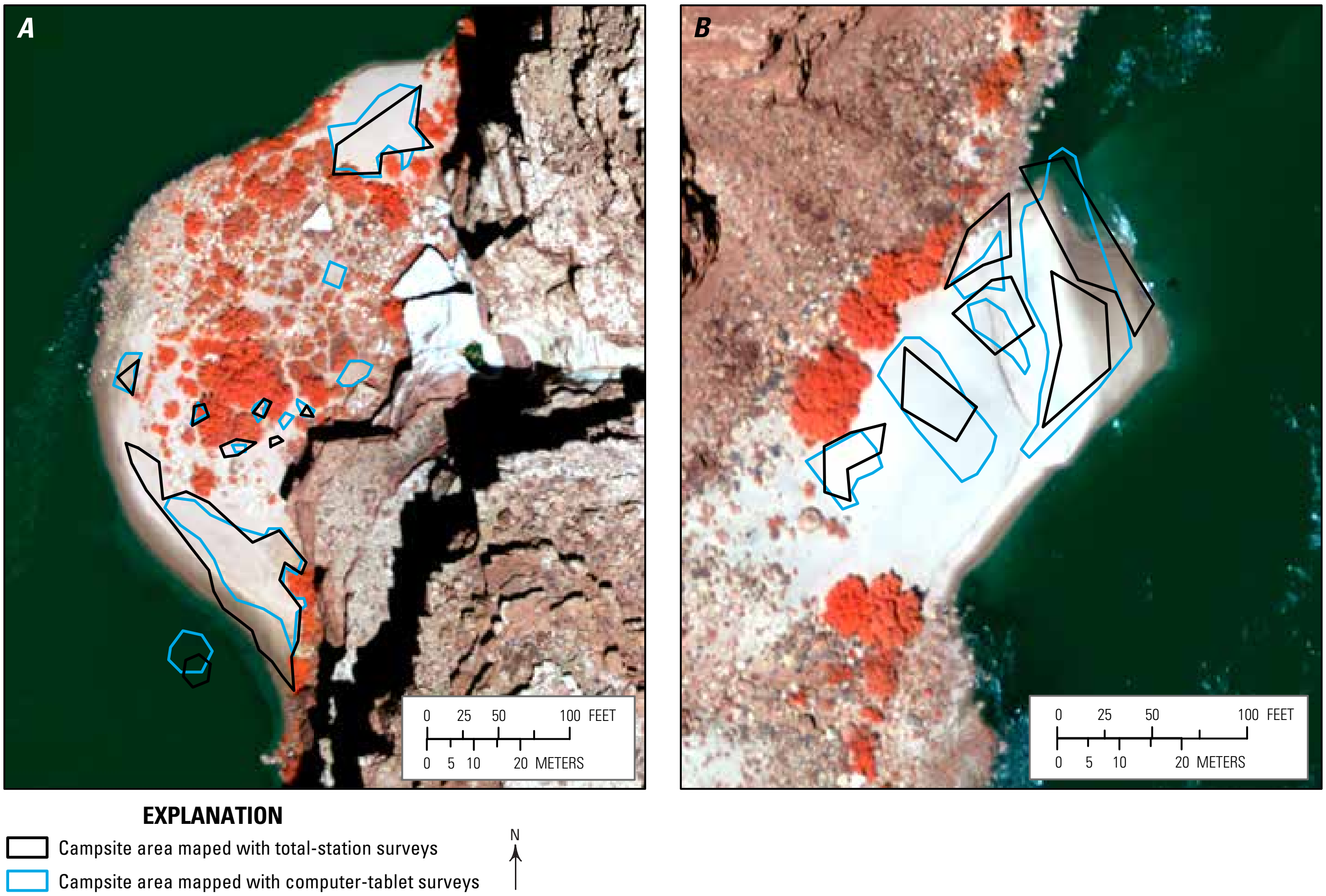


Figure 36. Aerial photographs showing examples of repeat surveys of campsite area conducted independently using total-station and computer-tablet methods at (*A*) Hot Na Na (river mile 16.6 left) and (*B*) 22 Mile (river mile 22.1 left) along the Colorado River corridor in Grand Canyon National Park, Arizona. Note the large differences within areas of open sand at 22 Mile. U.S. Geological Survey aerial imagery from May 2009 displayed as false color composite, with green photosynthetically active vegetation displayed as red.

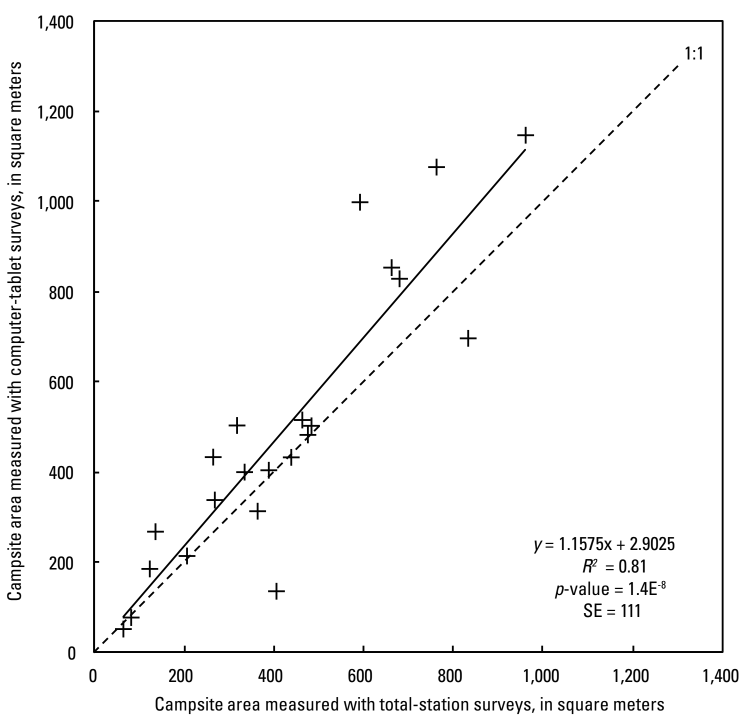


Figure 37. Graph showing correlation between campsite area mapped with the computer-tablet method and campsite area mapped with the total-station method, surveyed independently at 22 sites along the Colorado River corridor in Grand Canyon National Park, Arizona. Points that fall above the 1:1 lines (dashed) are over measurements. A linear regression fit is shown indicating that campsite area mapped with the computer-tablet method tended to be larger than campsite area mapped with the total-station method. SE, standard error.

Table 15. Summary of computer-tablet and total-station surveys conducted independently at 22 long-term monitoring sites along the Colorado River corridor in Grand Canyon National Park, Arizona.

[L, left; R, right; m^2, square meter; %, percent; NA, not applicable]

Site	River mile	Side	Number of campsite polygons mapped by total-station survey	Number of campsite polygons mapped by computer-tablet survey	Campsite area mapped with total-station survey (m^2)	Campsite area mapped with computer-tablet survey (m^2)	Difference in campsite area (m^2)	Percent difference of computer-tablet surveys from total-station surveys
Jackass	8.1	L	12	15	334	399	65	20%
Hot Na Na	16.6	L	9	9	832	697	134	16%
22 Mile	22.1	R	6	5	661	852	191	29%
Lone Cedar	23.5	L	10	7	365	310	55	15%
Silver Grotto	29.5	L	3	4	462	513	51	11%
Sandpile	30.8	R	5	6	760	1,077	317	42%
Nautiloid	35.1	L	5	5	388	403	15	4%
Anasazi Bridge	43.5	L	10	8	81	76	5	6%
Willie Taylor	45.0	L	14	10	594	996	403	68%
Dinosaur	50.1	R	5	6	478	482	4	1%
51 Mile	51.5	L	4	6	135	265	130	97%
Crash Canyon	63.0	R	10	10	65	52	13	20%
Grapevine	81.7	L	7	6	681	827	147	22%
91 Mile	91.7	R	7	3	316	502	186	59%
Granite	93.8	L	5	7	406	134	271	67%
119 Mile	119.4	R	9	7	266	432	166	62%
122 Mile	122.8	R	13	9	960	1,144	183	19%
Upper Forster	123.3	L	4	6	484	503	18	4%
Above Olo	145.9	L	3	3	268	338	70	26%
Lower National	167.1	L	12	11	206	213	7	3%
183 Mile Left	183.3	L	2	3	124	185	61	49%
183 Mile Right	183.3	R	1	1	438	430	8	2%
Mean	NA	NA	7	7	423	492	114	29%
Total	NA	NA	156	147	9,302	10,830	1,529	16%

field surveys. For example, campsite area was difficult to map at 51 Mile (RM 51.5L), where there was a low-elevation sandbar protruding from the banks during the survey. In the 2009 imagery, this sandbar was not present, and there was difficulty in deciding where to place that particular campsite polygon on the orthoimagery (fig. 39). Campsite area can also be somewhat difficult to map at sites that consisted mostly of open sand, as there may be few defining features to reference off of the imagery. However, using computer-tablet's internal GPS helped in this regard, and in many cases the GPS was accurate to within a meter or less.

The total uncertainty associated with mapping campsite area using the computer-tablet method was calculated as 18 percent. If this method is adopted in the future, an estimate of significant change detection would need to be at least 18 percent, or conservatively may need to be about 20 percent. Although use of the tablet method brings an additional uncertainty, the benefits of being able to map areas of campsite change and determine reasons for those changes in the field, may outweigh the additional error. The tablet method would be a good option for surveying campsites if imagery becomes available on a more frequent basis and if there is a desire by resource managers to adopt a more comprehensive survey method.

A methods-based bias exists between the computer-tablet and total-station methods. The total-station method has been used consistently since 1998 and is the baseline for comparison; however, it is not necessarily the most accurate method. Total-station crews conduct topographic surveys of an entire sandbar and then map campsite area afterward. Due to logistical constraints and the large number of sites that are visited during a river trip, campsite polygons need to be measured fairly quickly and are often simplified to squares or triangles. Campsite area measured using the computer-tablet method was frequently larger in comparison to campsite area measured using the total-station method. This was largely due to the fact that there was simply more time available to survey campsite area using the tablet method. For logistical reasons, surveyors who used the tablet method had more time to walk the sandbars and often mapped campsite polygons with more vertices. This resulted in digitized campsite polygons that were often more detailed in shape and slightly larger in size in comparison to campsite polygons mapped by the total-station survey crew. Given that the tablet method often resulted in more detailed mapping of campsite polygons, we argue that campsite area measured using the total-station method is biased low. If a total-station survey crew had more time to delineate campsite polygons, the method-based bias that exists between the computer-tablet and total-station methods would likely be much less.

Determining campsite-area constraints was a worthwhile measurement to make and shows that areas of open sand border a large percentage of campsite area. This has important implications. If a given campsite area is bordered mostly by

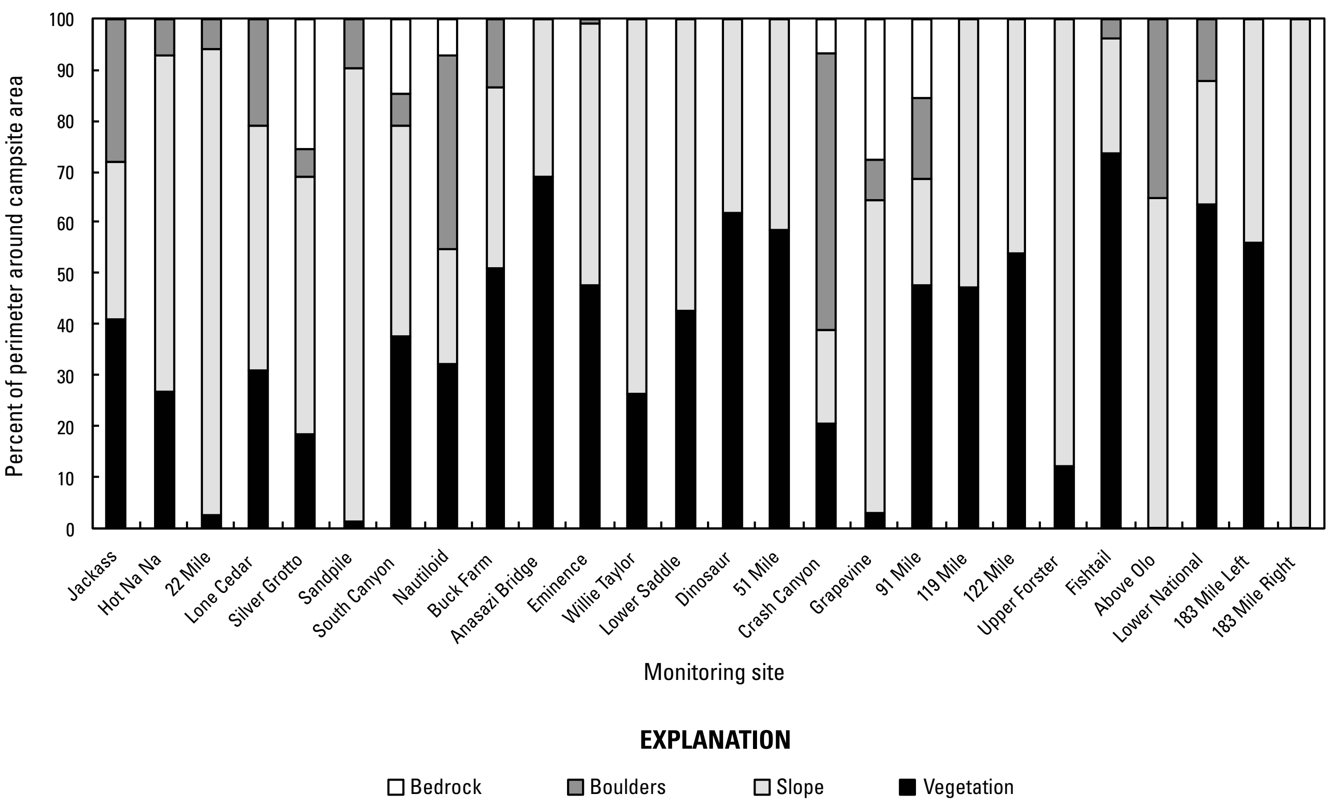


Figure 38. Bar graph showing campsite-area constraints at 26 long-term monitoring sites along the Colorado River corridor in Grand Canyon National Park, Arizona. Factors that constrained campsite area were visually estimated in the field as a percentage of the perimeter around mapped campsite polygons.

Table 16. Summary of campsite-area constraints at 26 long-term monitoring sites along the Colorado River corridor in Grand Canyon National Park, Arizona.

[L, left; R, right; m, meter; %, percent; NA, not applicable; *n*, number of monitoring sites]

Name	River mile	Side	Campsite area perimeter (m)	Campsite-area constraint (m):				Campsite-area constraint (percent)[1]			
				Vegetation	Slope	Boulder	Bedrock	Vegetation	Slope	Boulder	Bedrock
Monitoring site											
Jackass	8.1	L	353	144	109	99	0	41%	31%	28%	0%
Hot Na Na	16.6	L	292	78	192	22	0	27%	66%	7%	0%
22 Mile	22.1	R	276	8	252	16	0	3%	91%	6%	0%
Lone Cedar	23.5	L	236	74	113	49	0	31%	48%	21%	0%
Silver Grotto	29.5	L	210	39	106	12	53	18%	50%	6%	25%
Sandpile	30.8	R	353	5	313	35	0	1%	89%	10%	0%
South Canyon	31.9	R	393	148	163	24	58	38%	42%	6%	15%
Nautiloid	35.1	L	190	61	43	72	14	32%	23%	38%	7%
Buck Farm	41.2	R	342	175	120	46	0	51%	35%	14%	0%
Anasazi Bridge	43.5	L	97	67	30	0	0	69%	31%	0%	0%
Eminence	44.5	L	449	214	232	4	0	48%	52%	1%	0%
Willie Taylor	45.0	L	270	71	198	0	0	26%	74%	0%	0%
Lower Saddle	47.7	R	308	132	176	0	0	43%	57%	0%	0%
Dinosaur	50.1	R	276	171	105	0	0	62%	38%	0%	0%
51 Mile	51.5	L	148	87	61	0	0	59%	41%	0%	0%
Crash Canyon	63.0	R	96	20	18	52	7	20%	19%	54%	7%
Grapevine	81.7	L	292	8	180	23	81	3%	61%	8%	28%
91 Mile	91.7	R	186	89	39	29	29	48%	21%	16%	16%
119 Mile	119.4	R	255	121	134	0	0	47%	53%	0%	0%
122 Mile	122.8	R	421	227	194	0	0	54%	46%	0%	0%
Upper Forster	123.3	L	170	21	149	0	0	12%	88%	0%	0%
Fishtail	139.6	R	102	75	23	4	0	73%	23%	4%	0%
Above Olo	145.9	L	109	0	70	38	0	0%	65%	35%	0%
Lower National	167.1	L	191	121	46	23	0	63%	24%	12%	0%
183 Mile Left	183.3	L	154	86	68	0	0	56%	44%	0%	0%
183 Mile Right	183.3	R	97	0	97	0	0	0%	100%	0%	0%
Reaches/canyon sections											
Critical reaches (*n*=12)	NA	NA	2,640	584	1,495	324	236	22%	57%	12%	9%
Noncritical reaches (*n*=14)	NA	NA	3,627	1,656	1,739	225	7	46%	48%	6%	0%
Marble Canyon (*n*=15)	NA	NA	4,193	1,472	2,215	379	126	35%	53%	9%	3%
Grand Canyon (*n*=11)	NA	NA	2,074	768	1,019	170	117	37%	49%	8%	6%
All Sites (*n*=26)	NA	NA	6,267	2,240	3,235	549	243	36%	52%	9%	4%

[1]Results may not sum to 100 percent due to rounding.

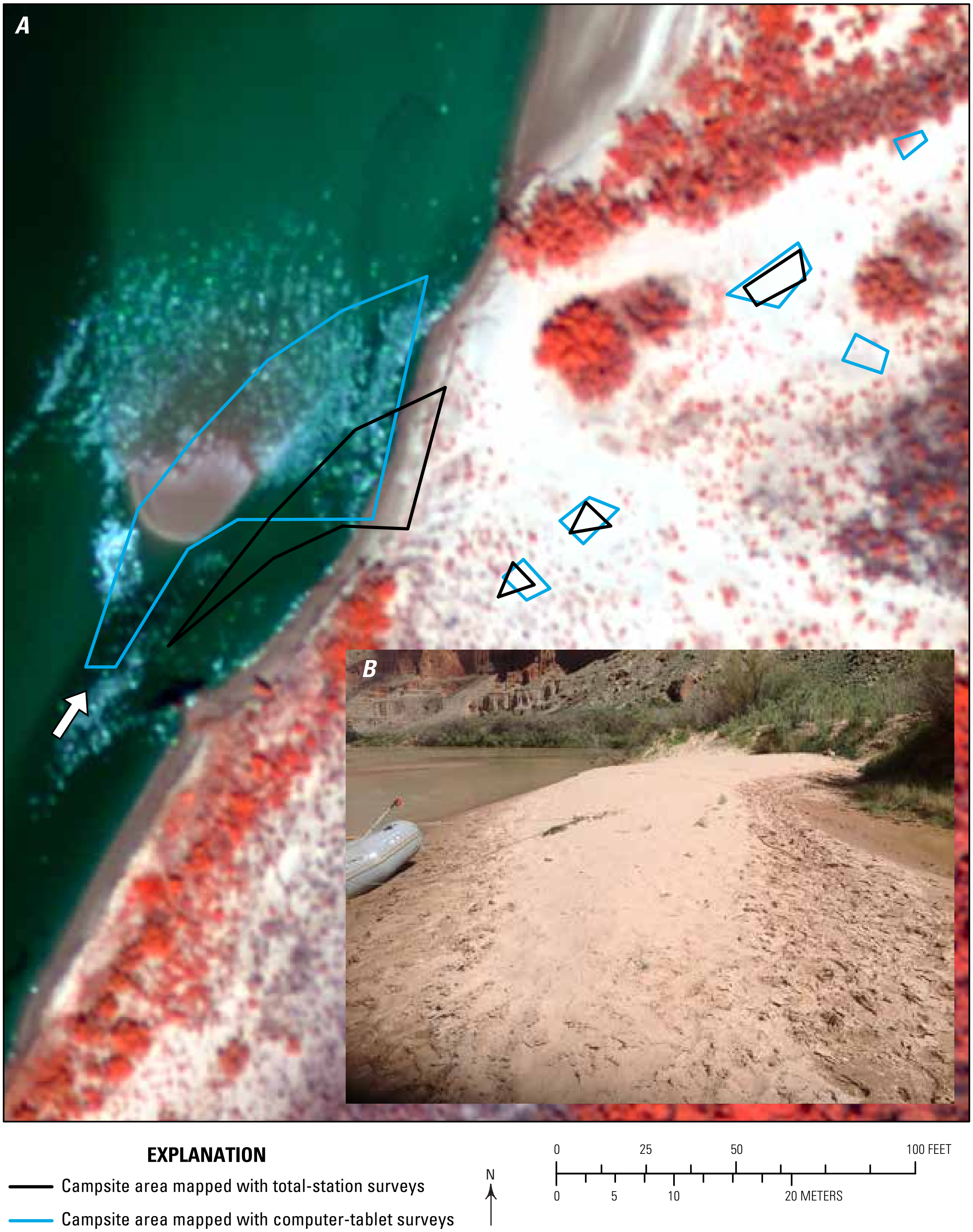


Figure 39. Example images from 51 Mile (river mile 51.5 left) showing of the limitations of using aerial imagery (*A*) that predates a field survey by more than 4 years to map campsite area along the Colorado River corridor in Grand Canyon National Park, Arizona. *A*, U.S. Geological Survey (USGS) aerial photograph from May 2009 (green photosynthetically active vegetation shown in red as a false-color composite) overlaid with map showing areas independently mapped on September 26, 2013, using total-station and computer-tablet methods. As shown here, low-elevation sandbars can be drastically different in appearance in imagery from previous years, and the image shows the error of the computer-tablet survey at the low elevation part of the sandbar. *B*, USGS photograph of the sandbar taken on the same day as the 2013 surveys (arrow on map shows location and direction of the photograph).

vegetation and boulders, it may be less likely to increase in size after sand deposition from a controlled flood. Deposition would have to bury the vegetation or the boulders for the campsite area to increase in size. However, if a given campsite area is bordered by open sand and is only limited in size by a steep slope, it may be more likely to increase in size following a controlled flood. Deposition would only have to flatten out the slope or smooth out the sandbar to increase campsite area instead of having to bury boulders or vegetation that could be substantial in size. Tracking how campsite-area constraints change over time may also be useful in determining the amount of vegetation encroachment during the years when aerial imagery is not available.

Conclusions

Campsite area at long-term monitoring sites along the Colorado River corridor in Grand Canyon National Park declined between 2002 and 2009, despite temporary increases in sandbar area caused by controlled floods. Analysis of sandbar geomorphic change and vegetation change indicates that there were two primary drivers responsible for the net loss in campsite area—(1) increases and decreases in campsite area as a result of deposition and erosion associated with controlled floods and regular dam operations and (2) long-term declines in campsite area due to vegetation encroachment. Gains and losses in campsite area associated with topographic change can cancel each other out, whereas vegetation change, for the most part, only leads to losses in campsite area. In terms of net change, vegetation encroachment contributed to 47 percent of the overall net loss in campsite area, and topographic change contributed to 53 percent of the overall net loss in campsite area.

The majority of the gains and losses in campsite area caused by topographic change were not associated with a change in sandbar slope around the critical threshold of 8 degrees. This indicates that deposition or erosion that still maintains the previous topography of a sandbar plays a large role in determining the amount of campsite area available. Specific mechanisms of this were (1) deposition leading to a gain in campsite area through burial of vegetation, boulders, and rough topography, (2) removal of sand leading to a loss in campsite area by exposing vegetation and boulders, (3) deposition leading to a loss in campsite area by roughening a sandbar surface or depositing driftwood, and (4) erosion leading to a gain in campsite area by smoothing a sandbar surface.

Increases and decreases in campsite area can also be associated with changes in sandbar slope caused by deposition or erosion. Specific mechanisms of this were (1) deposition leading to a gain in campsite area by creating a flatter sandbar, (2) deposition leading to a loss in campsite area by increasing the slope of a sandbar, (3) erosion leading to a loss in campsite area through cutbank retreat by removing flat parts of a sandbar, and (4) erosion leading to a gain in campsite area through cutbank retreat by removing steep parts of a sandbar. Gullying was a significant factor in campsite area change at six sites but overall was a minor factor in comparison to changes in sandbar elevation and slope. Erosion and changes in sandbar slope occurred more often at long-term monitoring sites in critical reaches, suggesting that these sandbars are more dynamic and less stable than sites in noncritical reaches.

Vegetation encroachment within camp boundaries and within the extents of mapped campsite area was greater at sites in noncritical reaches than at sites in critical reaches. Increases in vegetation cover also occurred more often in high-elevation campsite area. Our observations, therefore, show a continuation of the vegetation expansion that has been documented by previous campsite inventories and studies following the 1983–1986 flooding events and is consistent with trends of vegetation expansion occurring throughout the entire river corridor.

Controlled floods can lead to increases in campsite area and are currently the only management strategy used to improve campsites along the Colorado River corridor. However, erosion of flood-deposited sandbars during normal dam operations following controlled floods causes these increases in campsite area to be short lived. At the same time, vegetation cover continues to increase, resulting in the progressive decline of campsite area. One potential strategy to increase campsite area more often is more frequent implementation of controlled floods to build sandbars. This strategy was initiated by the Bureau of Reclamation in 2012 by the adoption of a high-flow experimental protocol. This protocol allows for the implementation of a controlled flood every year, provided there is sufficient sand supplied by the Paria River (Bureau of Reclamation, 2012). Preliminary findings indicate that the protocol is resulting in larger sandbars (Grams and others, 2015). However, there is not always a direct correlation between increases in sandbar size and increases in campsite area. Whether this strategy leads to increases in campsite area that meet the management objectives set forth by the Glen Canyon Dam Adaptive Management Program for increasing the size of campsite area in critical and noncritical reaches remains uncertain.

Removal of vegetation may be another viable strategy for increasing the size of campsite area. Although most vegetation expansion is occurring in noncritical reaches, these sites tend to be larger in size and more numerous along the river corridor. Physically removing vegetation at these sites would likely accomplish little in terms of increasing recreational carrying capacity, because many of these sites can still accommodate large river groups despite having increases in vegetation cover. Instead, targeting smaller sites in critical reaches and focusing on removal of groundcover shrubs such as arrowweed and camelthorn (and (or) removal of tamarisk that is impacted by tamarisk beetle herbivory) would likely be the most practical and successful vegetation removal strategy. Sites such as Clear Creek (RM 84.6R) or Emerald (RM 104.4R) would be good examples of where this strategy may work best, as they are located in critical reaches, are small in size, and are sites that have vegetation communities that are predominately groundcover shrubs (versus thick stands of healthy woody tamarisk).

Our geomorphic and vegetation analyses indicate that a variety of factors affect the size of campsite area and that these factors are highly variable among sites. Determining which of these factors are responsible for gains and losses in campsite area is difficult to accomplish after the fact. Therefore, a more comprehensive campsite survey would allow surveyors to document, in the field, the reasons for gains and losses on a year-by-year basis. Documenting reasons for campsite change in the field would also allow identification of processes that were not explicitly examined in this study. These processes may include aeolian erosion of sand, erosion caused by campers, encroachment of campsites by sparse patches of vegetation, or deposition of driftwood. By understanding the causal mechanisms of campsite change on a site-by-site basis and on a reach scale, resource managers could better determine if current management strategies for increasing the number and size of campsites are effective or if new strategies need to be considered.

The need for more precise information about the causes of campsite-area change may require a change or modification to current monitoring methods. The total-station method currently being used to measure campsite area has the advantage of being integrated into the topographic surveys already being conducted at the long-term monitoring sites and has a negligible measurement error. However, as currently implemented, the total-station method does not include description of the causes for increases and decreases in campsite area (it is simply a measurement of campsite area present at the time of survey) and may underestimate the amount of campsite area at a site given the short timespan in which the surveys are conducted. The computer-tablet method developed in this study would allow for documentation of the causes of campsite change in the field, but it brings an additional uncertainty due to the error associated with mapping on imagery that predates the field surveys.

Continued use of the total-station method may be the best option for campsite surveys unless imagery of the river corridor becomes available on a more frequent basis. However, modification to the total-station method may be very beneficial to understanding changes in campsite area. In addition to mapping campsite area, survey crews could identify areas of gain and loss by referencing a paper or digital map of the previous year's survey. A defined set of processes responsible for a gain or loss in campsite area could be recorded by the total-station operator or annotated by the technicians on a paper or digital map. If feasible, technicians could also spend more time conducting the survey, allowing for more detailed delineation of campsite polygons. These modifications would allow the causes of campsite area change to be documented in the field and would reduce undermeasurement of campsite polygons. If imagery become available on a more frequent basis, adoption of the computer-tablet method would be beneficial, because additional geomorphic attributes of campsites, such as campsite-area constraints and boat mooring areas, could be described and documented.

Regardless of which method is employed, campsite monitoring will always have an inherent subjectivity. Our analysis of repeat total-station campsite surveys indicates that the uncertainty associated with surveyor judgment is about 15 percent when using the total-station method and when following the established criteria used to map campsite area. This uncertainty can be minimized by using experienced technicians as much as possible. By identifying processes responsible for campsite-area change in the field and reducing uncertainty by using experienced surveyors, campsite monitoring will become more robust. This would allow resource managers to better understand if management strategies are improving the size and number of campsites along the Colorado River corridor in accordance with the GCDAMP. Although these observations are specific to campsite monitoring in the Grand Canyon, they may be applied to other rivers that are managed for recreational resources.

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Appendixes 1–6. Descriptions of Changes at Campsites in Grand Canyon National Park

Appendixes 1–6 are available online only as comma separated value (.csv) files and an Excel (.xlsx) file at https://doi.org/10.3133/sir20175096. These appendixes provide descriptions of mapped and measured changes at campsites in Grand Canyon National Park:

Appendix 1. First-order changes within areas of campsite gain, areas of campsite loss, and stable campsite area at 35 long-term monitoring sites, summarized by recreational reach and canyon section along the Colorado River corridor in Grand Canyon National Park, Arizona.

Appendix 2. Summary of statistical analysis for elevation and slope changes within areas of campsite gain, areas of campsite loss, and stable campsite areas at 35 long-term monitoring sites along the Colorado River corridor in Grand Canyon National Park, Arizona.

Appendix 3. Second-order changes within areas of campsite gain, areas of campsite loss, and stable campsite areas at 35 long-term monitoring sites, summarized by recreational reach and canyon section along the Colorado River corridor in Grand Canyon National Park, Arizona.

Appendix 4. Vegetation change within the extent of mapped campsite area between 1998 and 2009 at 37 long-term monitoring sites along the Colorado River corridor in Grand Canyon National Park, Arizona.

Appendix 5. Percent of vegetation cover within the extent of mapped campsite area above and below the 25,000-cubic feet per second (ft^3/s) stage elevation at 37 long-term monitoring sites along the Colorado River corridor in Grand Canyon National Park, Arizona.

Appendix 6. Vegetation change between 2002 and 2009 within 504 camp boundaries between Glen Canyon Dam and Pearce Ferry along the Colorado River corridor in Grand Canyon National Park, Arizona.

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