GEOMORPHOLOGY AND VEGETATION CHANGE AT COLORADO RIVER CAMPSITES, MARBLE AND GRAND CANYONS, AZ

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ABSTRACT

GEOMORPHOLOGY AND VEGETATION CHANGE AT COLORADO RIVER

CAMPSITES, MARBLE AND GRAND CANYONS, AZ

Daniel R. Hadley

Sandbars along the Colorado River are used as campsites by river runners and hikers and are an important recreation resource within Grand Canyon National Park. Since 1963, Glen Canyon Dam has regulated the flow of the Colorado River through Marble and Grand Canyons, blocking the upstream supply of fine-grained sediment and reducing the magnitude and frequency of flooding events. Sediment reduction has caused widespread erosion at campsites along the Colorado River, and a reduction of flooding events has caused vegetation expansion on open sandbars. Periodic high-flow releases from Glen Canyon Dam have been conducted in an effort to increase the area and volume of sandbars and to improve the quality and size of campsites, but monitoring of campsites since 1998 shows an overall decline.

Campsite monitoring methods employed since 1998 detect changes in campsite area, but the factors that contribute to campsite area gain and loss are not quantified. These factors include, among others, changes in sandbar volume and slope under different dam flow regimes, gullying caused by monsoonal rains, vegetation expansion, and reworking of sediment by aeolian processes. An analysis of topographic and vegetation change was conducted between 2002 and 2009 at selected campsites using 4-band aerial imagery of the river corridor and Digital Elevation Models (DEMs) derived from total station survey data. Over the course of the study period there was a net loss in campsite area of 2431 m^2 at the study sites. Results show that the primary mechanisms of gains and losses in campsite area were due to depositional and erosional processes caused by dam management activities such as high-flow experiments and fluctuating flows used for power generation. However, vegetation encroachment was equally important in terms of long-term net changes in campsite area.

A new campsite survey methodology using a tablet-based GIS approach was tested during two river trips in an effort to accurately map campsite area on digital orthophotographs and to quantify the factors that contribute to campsite area change. The inherent uncertainty in mapping campsite area and the accuracy of the tablet-based method were also evaluated using repeat total station and tablet campsite surveys. Based on these repeated measurements, a previously reported uncertainty of 10 percent when mapping campsite area may have to be revised to around 15 percent. Use of the tablet method adds additional uncertainty, however the benefits of being able to quantify factors that lead to campsite area change may outweigh the additional error. Campsite monitoring may need to consist of a combination of total station and orthophotograph techniques to accurately determine causes of campsite change.

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This project was funded by the Glen Canyon Dam Adaptive Management Program through a cooperative agreement between the U.S. Geological Survey's Grand Canyon Monitoring and Research Center and Northern Arizona University. Support was also received from NAU's Friday Lunch Clubbe. I would like to acknowledge that this project follows in the footsteps of many scientists and boatmen who have chosen to dedicate their time and careers to understanding the magnificent stretch of the Colorado River through Grand Canyon, and who were instrumental in calling attention to the impacts of Glen Canyon Dam.

Many thanks to Matt Kaplinski and Joe Hazel at NAU's Sandbar Monitoring Lab. Without their data collection efforts from the past 24 years and their knowledge of the canyon, this work would not have been possible. All the Nams who have collected this data over the years are also gratefully acknowledged. I would like to thank Tom Gushue and Rob Ross at the USGS Grand Canyon Monitoring and Research Center for being patient with my unending questions regarding all things ArcGIS, as well as Tim Andrews with his help with data processing. Also thanks to Joel Sankey for his help in regards to vegetation datasets and remote sensing.

Thanks to all the participants on the Grand Canyon Youth trip and the amazing boatmen and staff who got us through the canyon (Tom, thanks for keeping me in the boat). Special thanks to Carol Fritz who allowed me to participate in such a great trip, and the National Park Service for letting us carry out our research.

I would also like to thank Abe Springer and Diana Elder for their support as committee members, and who without them some big-picture things would have been missed. Jack Schmidt, your words of wisdom were much appreciated. I could not have asked for better advisors, Paul Grams and Rod Parnell, whose patience, encouragement, and insight got me through this project and ultimately made me a better scientist. It was great to be down on the river with you guys.

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CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 Statement of Purpose and Project Overview

Since 1963, Glen Canyon Dam has regulated the flow of the Colorado River through Grand Canyon National Park (Fig. 1), disrupting the natural flow regime and blocking 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). Sediment reduction, along with a greater frequency of moderate flows from dam operations that export sediment, has caused widespread erosion of sandbars used as campsites along the Colorado River (Kearsley and others, 1994; Kearsley and others, 1999; Kaplinski and others, 2010). The reduced frequency, duration, and magnitude of floods has also limited the potential for sandbar building by decreasing the likelihood that sediment stored in the channel bed is mobilized and deposited at higher elevations. The reduced frequency and magnitude of flooding events has also allowed vegetation to establish and expand at campsites, as vegetation is no longer scoured out and removed during periods of high flow (Kearsley and others, 1994; Webb and others, 1999). The introduction of non-native species such as tamarisk has further exacerbated the problem of vegetation encroachment (Graf, 1978; Turner and Karpiscak, 1980).

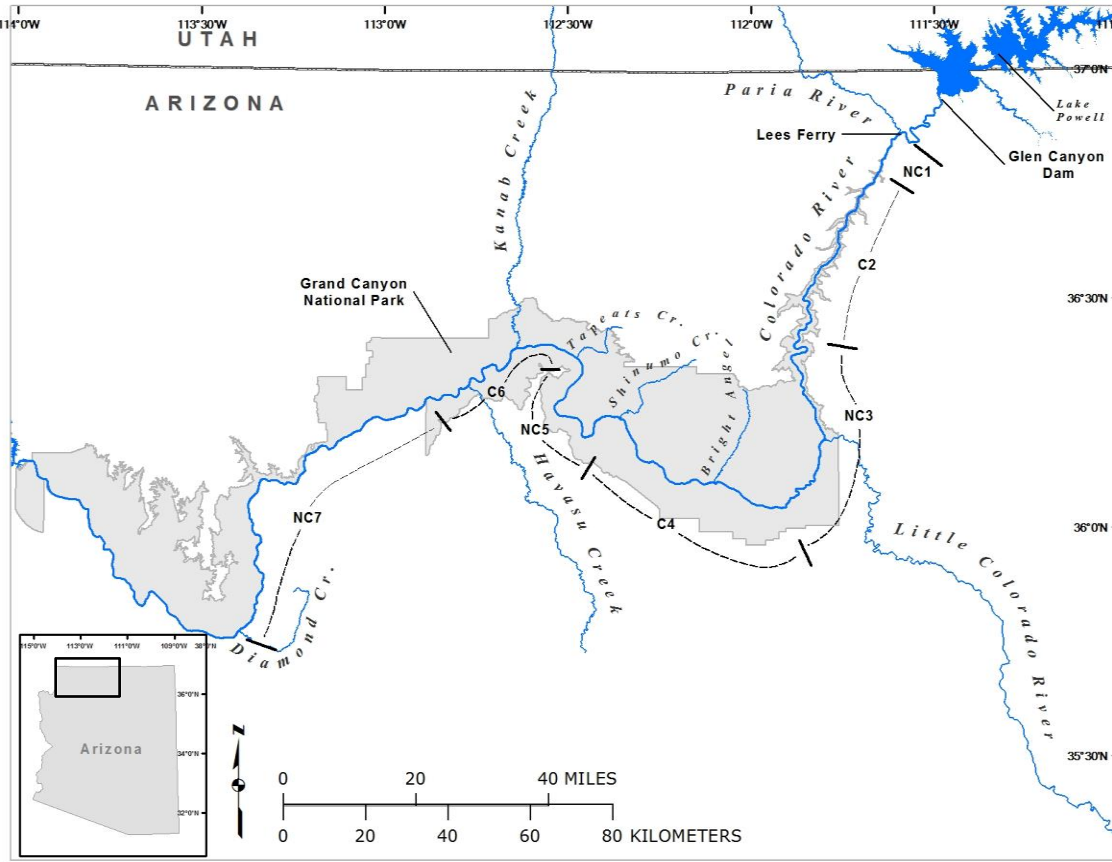


Figure 1. Map of the Colorado River corridor through Grand Canyon National Park showing the location of Lees Ferry, major tributaries, and recreational reach divisions (C, critical; NC, non-critical). Locations of features are conventionally designated by river mile (RM), starting at Lees Ferry (RM 0). Glen Canyon is the stretch of river between Glen Canyon Dam and Lees Ferry (RM 0). Marble Canyon is the stretch 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).

Campsite monitoring conducted since 1998 by Northern Arizona University's (NAU) Sandbar Monitoring Lab detects changes in campsite area, but factors that affect the size and quality of campsites such as sandbar slope, presence of gullying, and the amount of vegetation, are not quantified. Analysis of previous and current campsite monitoring data led to hypotheses that vegetation encroachment, erosion of sandbars due to daily and seasonal dam operations, and gullying caused by monsoonal rains are significant factors in the loss of campsite area, but there has been no systematic effort to quantify the relative magnitude of each of these factors (Kaplinski and others, 2010, 2014).

The goals of this project were to 1) analyze the elevation and slope changes within campsite areas, 2) quantify the amount of vegetation change occurring within campsite areas, 3) determine the primary cause of campsite area change in the context of management activities (high-flow experiments and daily/seasonal dam operations), and 4) develop a more effective campsite monitoring method. Several analyses that span a range of different time periods were conducted to answer these questions (Fig. 2).

Chapter 2 presents an analysis of changes in topography and vegetation between 2002 and 2009 at 35 campsites distributed throughout Marble Canyon and Grand Canyon. This study used digital elevation models (DEMs) derived from total station survey data collected during a longer-term sandbar monitoring study and 4-band aerial imagery of the Colorado River corridor taken in May 2002 and May 2009. DEMs of Difference (DoDs) for elevation and slope were calculated in ArcGIS, as well as areas that had vegetation loss and vegetation gain. The changes in elevation, slope, and vegetation were calculated within areas of campsite change, and were summarized by critical and non-critical recreational reaches designations (as defined by Kearsley and Warren, 1993) and by canyon section (Marble Canyon versus Grand Canyon).

Chapter 3 expands on the vegetation component of the first analysis, and quantifies vegetation change between 2002 and 2009 within 504 current and historic camp boundaries. These camp boundaries are distributed throughout Glen Canyon, Marble Canyon, and Grand Canyon, and are defined by an administrative and historic context which is different than the criteria used to define campsite area (see section 1.3 for a more detailed explanation). Determining the vegetation change within these boundaries allowed broad trends in vegetation tends in vegetation to be seen at campsites throughout the Colorado River corridor. In an effort to better quantify a direct loss of campsite area due to vegetation expansion, vegetation change was also calculated within the total extent of campsite area mapped between 1998 and 2009 at 37 NAU-monitored sites. Vegetation change occurring within camp boundaries and within the total extent of mapped campsite area were also summarized by recreation reach and canyon section.

Chapter 4 discusses an alternative method of campsite monitoring that involves the use of field tablets equipped with GIS capabilities. The goal of this study was to develop a monitoring method that can track geomorphic attributes in addition to changes in campsite area. Tablets equipped with a GIS application allowed for digitizing of campsite areas, gullies, areas of campsite change, boat mooring areas, and

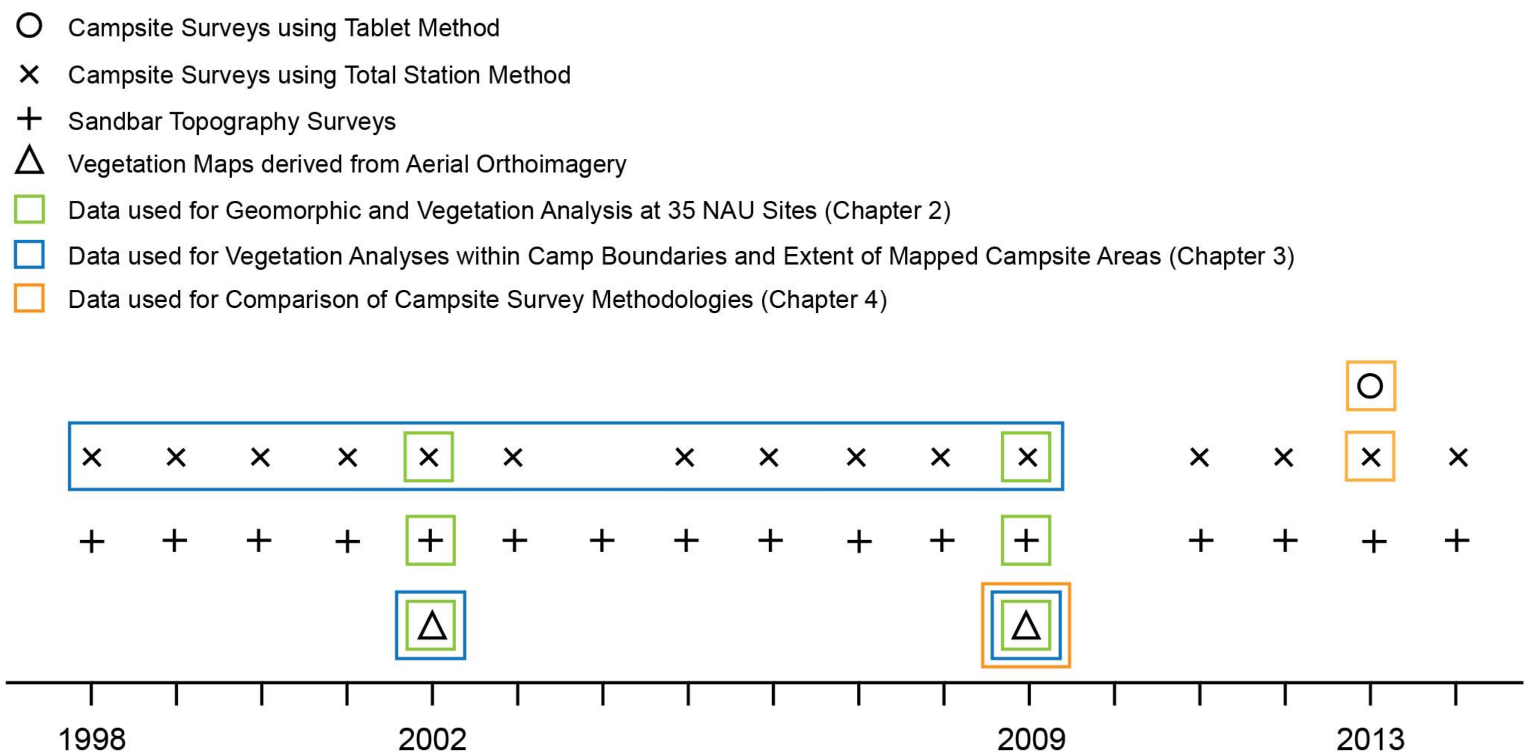


Figure 2. Timeline of data collection and overview of the different analyses conducted for this project. Note that sandbar topography surveys extend back to 1990.

photograph locations directly on to digital orthophotographs. Another goal of this study was to evaluate the uncertainty associated with mapping campsite area regardless of which survey method is used, and to determine if there is additional uncertainty when using the tablet-based GIS approach. Comparisons between repeat total station surveys and between total station surveys and tablet surveys were used to assess the inherent uncertainty of mapping campsite area, similar to a study conducted by Kaplinski and others (2003), and to evaluate the accuracy of the tablet based approach.

1.2 Significance and Regulatory Framework

Sandbars have been historically used as campsites by river runners and hikers, and continue to be 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 (Fig. 1) 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 by river runners, and able to withstand high usage with negligible impact. Rafting trips originating at Lees Ferry are recognized as an internationally significant wilderness experience (Behan, 1999), and these multi-day 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). Campsite carrying capacity is of increasing concern to the National Park Service (U.S. Department of Interior, 1995; Stewart and others, 2000) due to the popularity of commercial and private rafting trips and the steady decline in the number and size of campsites (Beus and others, 1985; Kearsley and Warren, 1993; Kearsley and others, 1994; Kaplinski and others, 2005; Kaplinski and others, 2010). Carrying capacity is defined 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). Carrying capacity is based on the number, size, distribution, and expected lifespan of sandbar campsites, as well as a variety of social factors. Social factors include group sizes, trip lengths, the number of trips on the river at any given time, and the number of people on the river at any given time (National Park Service, 2006). The decline in campsite size and abundance negatively affects social aspects of river trips by increasing competition for sites and the amount of contact time between river groups.

The Grand Canyon Protection Act (GCPA) created in 1992 states that Glen Canyon Dam operate in a manner “as to protect, mitigate adverse impacts to, and improve the values…[of]… natural and cultural resources and visitor use” (U.S. Department of Interior, 1992). Following the Final Environmental Impact Statement for Glen Canyon Dam Operations (U.S. Department of Interior, 1995) and the Record of Decision (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 non-critical reaches in the mainstem…" (Bureau of Reclamation, 2001).

In 1996, 2004, 2008, 2012, and 2013, the Department of Interior conducted high-flow experiments (HFEs), in which large dam releases were used to simulate seasonal floods, with the intent of replenishing sandbars and increasing the size of campsite area. Understanding the casual mechanisms of campsite change is needed to determine whether HFEs are having the desired effect of improving campsites and to enable resource managers to determine if other appropriate actions are needed. Determining the influence of vegetation encroachment on campsite loss could also inform resource managers of campsites with high rates of vegetation encroachment. These sites could be prioritized for possible vegetation removal if resource managers choose to adopt other actions to improve campsites (Ralston and others, 2010).

1.3 Study Area, Units, and Campsite Terminology

Study Area

The study area is the stretch 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 conventionally designated by the river mileage system, with distance measured in miles along the centerline of the channel upstream or downstream of the Lees Ferry gauging station (U.S. Geological Survey 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 gauge and a positive river mile indicates a location downstream of the Lees Ferry gauge. Campsites are identified by river mile, the side of the river that it is on, and place name, after Stevens (1990) and Belknap (2001). The left and right sides of the river are determined from the viewpoint of looking downstream. SI metric units are used for all measurements, with the exception of river mile, as noted above, and discharge, which is reported in cubic feet per second (ft^3/s).

The study area is subdivided into Glen Canyon, Marble Canyon, Grand Canyon, and the reach below Diamond Creek. Glen Canyon is the stretch of river between Glen Canyon Dam (RM -15.8) and the Lees Ferry Gauge (RM 0). Marble Canyon is the stretch 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 stretch of river between the Little Colorado River and Diamond Creek (RM 225) (Fig. 1). The Diamond Creek reach is the stretch of river that extends past Diamond Creek to Quartermaster Canyon (RM 261). The geomorphic analysis discussed in Chapter 2 and the analysis comparing campsite survey methodology discussed in Chapter 4 both took place in Marble and Grand Canyons. The analysis of vegetation change within camp boundaries, discussed in Chapter 3, took place within the entire study area, including Glen, Marble, and Grand Canyons and the Diamond Creek reach.

Campsite Terminology

Sandbars along the Colorado River corridor vary in size, shape, and the amount of vegetation present on them. Not all sandbars can be used for camping purposes, as some lack easy river access (i.e., 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 are large areas of open sand with little or no vegetation, whereas other sites may have patches of vegetation and boulders which offers privacy between sleeping areas and shelter from the elements. For the purpose of this study, campsites are defined as sandbars that are present above normal river fluctuations, are accessible from the river, and not overgrown by vegetation. This is similar to the definition used by Kearsley and others (1999).

The following terms associated with campsite monitoring need to be defined to avoid confusion and to assist the reader (see Figure 3 for an example of each term):

1) The term “camp boundary” refers to regions along the Colorado River corridor, designated by the National Park Service (NPS) and the USGS Grand Canyon Monitoring and Research Center, that have been historically used or are currently being used as campsites (Helen Fairley, personal communication). The 504 camp boundaries located throughout Glen Canyon, Marble Canyon, Grand Canyon, and the Diamond Creek reach were used in the vegetation study

discussed in Chapter 3. Camp boundaries are defined in an administrative and morphologic context. For example, a camp boundary may be a boundary around an open sandbar, the area just on a debris fan, and/or simply an area that the NPS wants to limit users to for management purposes. Camp boundaries are therefore not a current list of campsites, as some are historic sites, nor are they representative of areas that are entirely usable for camping purposes, since the boundaries encompass boulders, vegetation, and morphologic features such as tributaries.

2) The term “campsite polygon” refers to a single area that can be used for camping purposes at a site. Kearsley and Warren (1993) defined these as areas with a smooth substrate (most commonly sand) with little to no vegetation, no more than 8 degrees of slope, and that are suitable for use as a kitchen area or sleeping surface. These criteria have been used in subsequent studies (Kearsley, 1995; Kearsley and others, 1999) including the campsite surveys conducted by NAU’s Sandbar Monitoring Lab. Campsite polygons are therefore smaller areas within an overall camp boundary and do not include features such as boulders, steep areas, or vegetated areas. At a given site, there may be numerous campsite polygons. The term “campsite area” is simply the sum of the campsite polygons. This distinction between campsite area and campsite polygons becomes important in Chapter 4 when comparing uncertainties between survey methodologies.

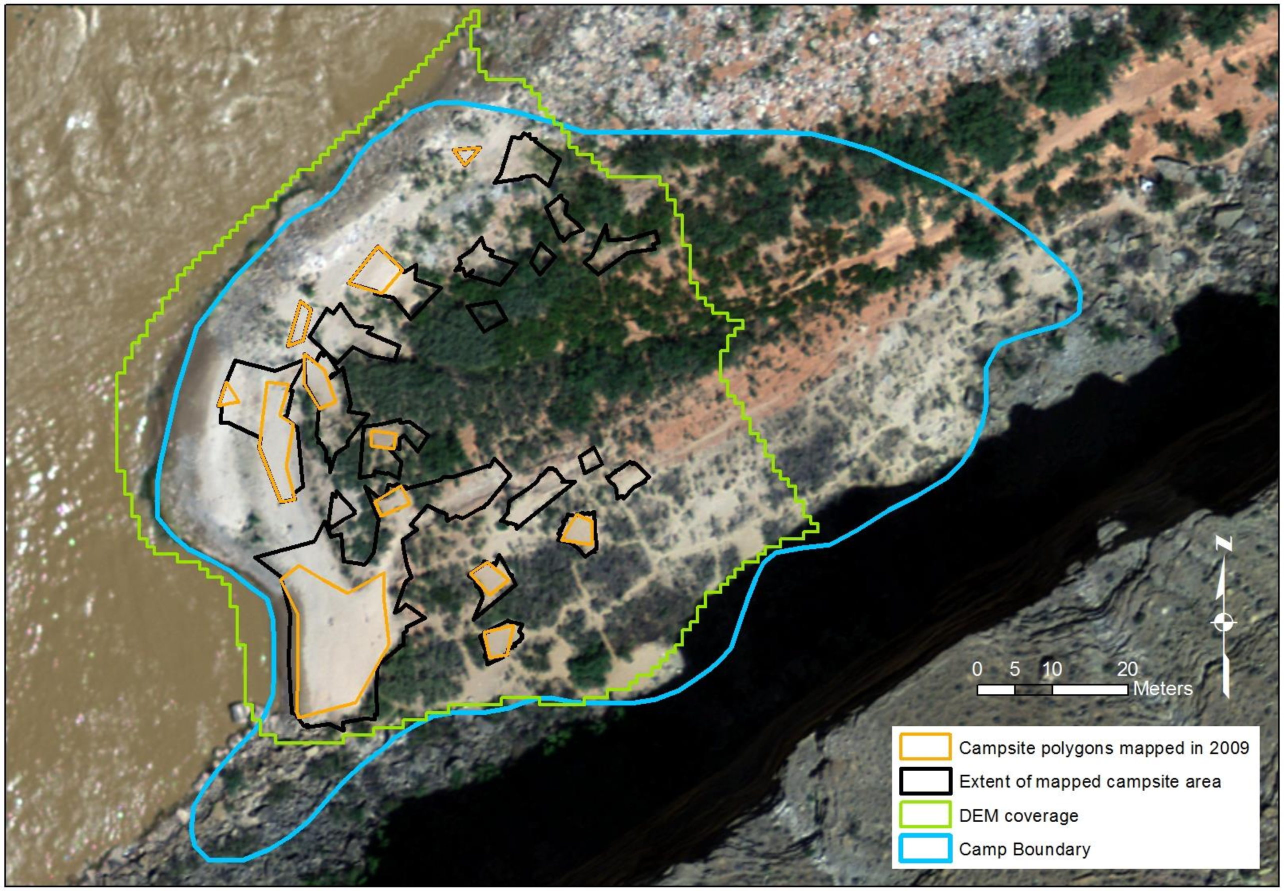


Figure 3. Map of Lower National Camp (RM 167.1L) illustrating the different boundaries and areas associated with campsite monitoring. Aerial photograph was taken in May 2009. The camp boundary for this site is outlined in blue and the extent of all campsite area mapped by NAU at this site is outlined in black. An example of a NAU campsite survey (conducted in October 2009) is shown in orange. Campsite area for October 2009 is the sum of the areas found in each of the orange campsite polygons. The area of the sandbar surveyed for topography in October 2009 (DEM coverage) is outlined in green. Note that campsite area may fall outside of the area surveyed for topography depending on the site.

3) A variety of physical and biological features of sandbars constrain the size of the campsite polygons that make up a campsite area. Features include boulders, bedrock, areas of steep sand, shoreline, patches of vegetation, or deposits of driftwood. The term "campsite-area constraint" refers to these factors that limit the size of a campsite area and is further discussed in Chapter 4 when assessing campsite survey methodologies.
4) The "extent of mapped campsite area" refers to the total extent of campsite area that has been mapped by NAU from 1998 to 2009 at a given site. A component of the vegetation study discussed in Chapter 3 refers to vegetation change within these extents. The creation of these extents were limited to this time period because 1998 was the first year of NAU campsite monitoring and 2009 was the latest imagery available for vegetation change detection.

1.4 Geomorphology of Study Area and Reach Designations

Debris flows from tributaries to the Colorado River deposit coarse sediment such as cobbles and boulders, creating large debris fans (Webb and others, 2005). These debris fans constrict the channel, creating rapids and a downstream eddy. This fan-eddy complex is the defining geomorphologic and hydraulic feature of the Grand Canyon, and is responsible for the formation of various types of sandbars (Howard and Dolan, 1981; Schmidt and Graf, 1990; Schmidt and Rubin, 1995; Schmidt and Grams, 2011a). Between Lees Ferry and Diamond Creek, the Colorado River drops 1,780 feet in elevation

(Schmidt and Graf, 1990). Most of this elevation change occurs at these 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 shallow rapids.

Debris fans affect river hydraulics by creating channel constrictions and expansions. When channel expansion occurs, flow detaches from the channel bank at the separation point, and then meets the bank again further downstream at the reattachment point (Fig. 4). Flow separation creates recirculating eddies, in which water moves back upstream in an eddy return current channel. Eddies are typically areas of lower velocity which leads to deposition of sand from suspension, creating separation bars and reattachment bars. 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.

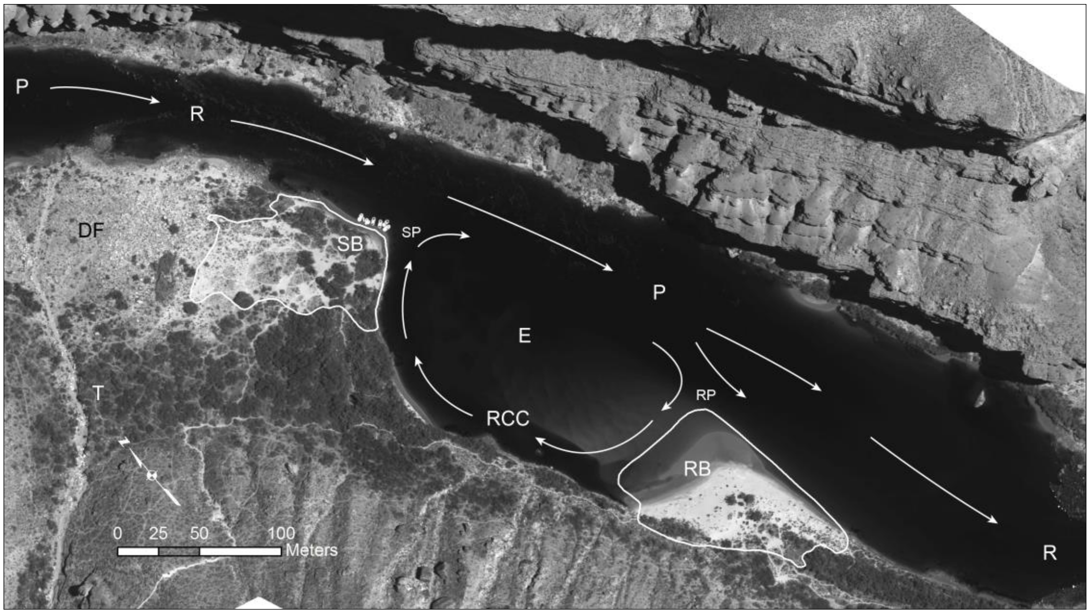


Figure 4. Aerial photograph of Saddle Canyon (RM 47) taken in 2002 showing a typical debris fan-eddy complex. T, tributary; DF, debris fan; P, pool; R, rapid or riffle; E, eddy, RCC, return current channel; SP, separation point; SB, separation bar; RP, reattachment point; RB, reattachment bar. Camp boundaries located on the separation bar and the reattachment bar are outlined in white. Arrows indicate flow direction. Figure modified from Hazel and others, 2010.

The width and depth of the river channel, valley width, and the distribution of debris fans entering the channel is largely controlled by bedrock lithologies and structures (Howard and Dolan, 1981). Bedrock along the river channel that is highly resistant to erosion, such as the Precambrian granites and schist of the Upper Granite Gorge (RM 77-117) create narrow channels. Erodible rocks such as shale produce wider channels, such as 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 non-critical 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. Non-critical reaches are defined by wider sections of the canyon with more numerous and larger fan-eddy complexes and therefore more campsites per mile. In these reaches there is little to no competition for sites. Critical and non-critical reaches are roughly equivalent to the narrow and wide reaches defined by Schmidt and Graf (1990) (Table 1).

Table 1. Geomorphic and recreational reaches along the Colorado River through Grand Canyon National Park. Table modified from Kearsley and others, 1994. Reach locations shown on Figure 1.

<table>
<tr><th colspan="4">Geomorphic Reaches
(Schmidt and Graf, 1990)</th><th colspan="3">Recreational Reaches
(Kearsley and others, 1994)</th></tr>
<tr><th>Reach #</th><th>River Mile</th><th>Name</th><th>Reach Type[1]</th><th>Reach #</th><th>River Mile</th><th>Reach Type[2]</th></tr>
<tr><td>1</td><td>0-11</td><td>Permian Section</td><td>W</td><td>1</td><td>0-11</td><td>NC</td></tr>
<tr><td>2</td><td>11-23</td><td>Supai Gorge</td><td>N</td><td rowspan="2">2</td><td rowspan="2">11-41</td><td rowspan="2">C</td></tr>
<tr><td>3</td><td>23-40</td><td>Redwall Gorge</td><td>N</td></tr>
<tr><td>4</td><td>40-62</td><td>Lower Marble Canyon</td><td>W</td><td rowspan="2">3</td><td rowspan="2">41-77</td><td rowspan="2">NC</td></tr>
<tr><td>5</td><td>62-77</td><td>Furnace Flats</td><td>W</td></tr>
<tr><td>6</td><td>77-118</td><td>Upper Granite Gorge</td><td>N</td><td>4</td><td>77-116</td><td>C</td></tr>
<tr><td>7</td><td>118-126</td><td>Aisles</td><td>N</td><td>5</td><td>116-131</td><td>NC</td></tr>
<tr><td>8</td><td>126-140</td><td>Middle Granite Gorge</td><td>N</td><td rowspan="2">6</td><td rowspan="2">131-164</td><td rowspan="2">C</td></tr>
<tr><td>9</td><td>140-160</td><td>Muav Gorge</td><td>N</td></tr>
<tr><td>10</td><td>160-214</td><td>Lower Canyon</td><td>W</td><td rowspan="2">7</td><td rowspan="2">164-225</td><td rowspan="2">NC</td></tr>
<tr><td>11</td><td>214-225</td><td>Lower Granite Gorge</td><td>N</td></tr>
</table>

[1]Designations “W” and “N” correspond to wide and narrow sections of the canyon

[2]Designations “C” and “NC” correspond to critical and non-critical reaches within the canyon

1.5 Pre-Dam and Post-Dam Flow Regimes

The pre-dam flow regime of the Colorado River was characterized by large springtime floods due to snowmelt from the Rocky Mountains, smaller late summer and fall floods caused by monsoonal rains, and periods of low discharge throughout the winter (Fig. 5). 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 HFEs (Schmidt and Grams, 2011a). Topping and others (2003) estimated that the 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, recorded at Lees Ferry in June 1884, was around 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 a reduction in the magnitude, duration, and frequency of flooding events, and an increase in the magnitude and frequency of low and moderate flows (Fig. 5). The 2-year recurrence peak flow in the post-dam period is now around 31,500 ft^3/s, and the median flow in the post-dam period is now around 12,000 ft^3/s (Schmidt and Grams, 2011a). HFEs conducted in 1996, 2004, 2008, 2012, and 2013, have had flows of 45,900 ft^3/s, 42,500 ft^3/s, 42,800 ft^3/s, 42,300 ft^3/s, and 34,100 ft^3/s, respectively, which are less than the pre-dam mean annual peak flow.

There has also been a dramatic decrease in the amount of fine-grained sediment (sand, silt, and clay) carried though Marble and Grand Canyons since the completion of

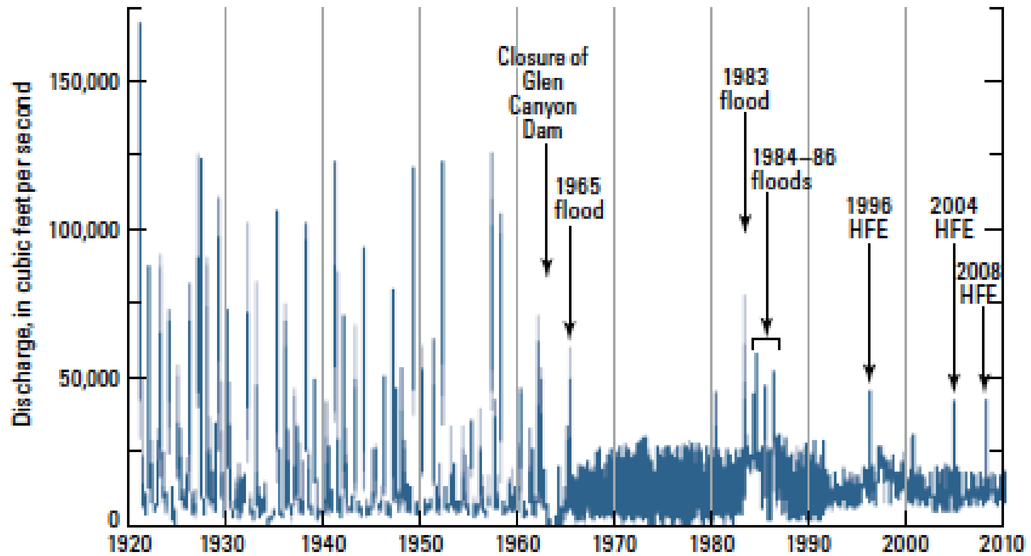


Figure 5. Continuous discharge record for the Colorado River at Lees Ferry (USGS gauging station 09280000) between 1921 and 2010. The closure of Glen Canyon Dam and major flooding events are indicated. Note the dramatic decrease in seasonal flooding events following closure of the dam and an increase in the low and median flows used for hydroelectric power generation. Figure from Schmidt and Grams, 2011a.

Glen Canyon Dam (Wright and others 2005, 2008; Schmidt and Grams, 2011a). The majority of sandbars are composed of sand, which is defined as particles finer than 2 millimeters and coarser than 0.062 millimeters (Schmidt and Grams, 2011a). Before dam construction, around 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 was thus around 29 million tons, excluding inputs from other tributaries. 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).

1.6 Previous and Current Campsite Monitoring

Field-based measurements of sandbars have evolved since the early 1970's 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 stations coupled with channel bathymetry (Hazel and others, 1999, 2008). Campsite inventories and studies concurrent with sandbar monitoring have also been conducted since the mid 1970's, with work by Weeden and others (1975), Brian and Thomas (1984), Kearsley and Warren (1993), Kearsley and others (1994, 1999), Kearsley (1995), Kearsley and Quartoroli (1997), and Kaplinski and others (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 their 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 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 non-critical reaches.

Subsequent work by Kearsley (1995), Kearsley and Quartoroli (1997), and Kearsley and others (1999) documented changes to campsites due to the 1993 floods from the Little Colorado River and the first high-flow experiment 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 away within 6 months to a year following the floods. These studies illustrated the potential of using high flows to improve campsites, but documented that gains in campsite area or the number of campsites were ephemeral due to subsequent erosion. The studies conducted by Kearsley and Quartoroli (1997) and Kearsley and others (1999) also improved upon campsite monitoring methods by incorporating Geographic Information System (GIS) software to digitize and calculate campsite area.

Since 1990, the Northern Arizona University Sandbar Monitoring Lab, in cooperation with the U.S. Geological Survey's GCMRC, has measured topography and sediment storage at selected sandbar study sites using standard total station techniques coupled with multibeam and singlebeam bathymetry (Hazel and others, 1999, 2008, 2014). Beginning in 1998, campsite area has also been measured on a subset of those monitored sandbars using total station survey techniques. Survey crews walk the sandbar and select areas that fit the campsite criteria established by Kearsley and Warren (1993). Points that define the perimeters of campsite polygons are measured with the total station. Perimeter points are then used to construct each of the campsite polygons that make up campsite area. Hazel and others (2008) determined an uncertainty of ±0.05-0.25 m in the horizontal direction and ±0.05-0.09 m in the vertical direction for total station points. Kaplinski and others (2005, 2010, and 2014) report a 10 percent uncertainty associated with mapping campsite area (see Chapter 4 for a more detailed discussion of uncertainty). For a more detailed description of how campsite area is measured in the field using total station survey equipment, the particular reasons for site selection, and methods of data processing, see Kaplinski and others (2014).

Campsite area has been measured at least annually at 37 sites, with 16 of those sites being in critical reaches, and 21 being in non-critical reaches (Table 2). Results from

Table 2. List of NAU-monitored campsites indicating which sites were used for each of the analyses conducted.

						Vegetation Analysis		Methodology Comparison		
Site Name[1]	**River Mile[2]**	**Side[3]**	**Recreation Reach[4]**	**Deposit Type[5]**	**Geomorphic Analysis**	**Extent of Mapped Campsite Area**	**Camp Boundary**	**Repeat Total Station Surveys**	**Tablet vs. Total Station (mapped at same time)**	**Tablet vs Total Station (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
Harry McDonald	23.5	l	C	U	x	x	x			x
Silver Grotto	29.5	l	C	U	x	x	x			x
Sand Pile	30.7	r	C	R	x	x	x			x
South Canyon	31.9	r	C	U		x	x			x
Nautiloid	35.0	l	C	S	x	x	x	x		x
Buck Farm	41.2	r	NC	S	x	x	x		x	
Anasazi Bridge	43.4	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	47.6	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	62.9	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

Table 2 (Continued). List of NAU-monitored campsites indicating which sites were used for each of the analyses conducted.

Site Name[1]	River Mile[2]	Side[3]	Recreation Reach[4]	Deposit Type[5]	Geomorphic Analysis	Vegetation Analysis		Methodology Comparison		
						Extent of Mapped Campsite Area	Camp Boundary	Repeat Total Station Surveys	Tablet vs. Total Station (mapped at same time)	Tablet vs Total Station (mapped independently)
Upper Forster	123.2	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			x
Above Olo	145.9	l	C	R	x	x	x			x
Lower National	167.1	l	NC	S	x	x	x			x
172 Mile	172.2	l	NC	R	x	x	x			
183 Right	183.3	r	NC	R	x	x	x			x
183 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			
220 Mile	220.1	r	NC	U	x	x	x			

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

[2]Location is based on the river mile centerline downstream from Lees Ferry (RM 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 non-critical 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 aren’t regularly inundated.

this ongoing study have been reported in Kaplinski and others (2002, 2005, 2006, 2010, 2014) using area above the 25,000 ft^3/s stage elevation as the primary metric for change in campsite area. The term "high-elevation campsite area" is used to denote campsite area above the 25,000 ft^3/s stage elevation, using the stage-discharge relationships established by Hazel and others (2006), and "low-elevation" campsite areas are those areas between the 15,000 ft^3/s and 25,000 ft^3/s stage elevation. The 25,000 ft^3/s stage elevation is significant because daily and seasonal dam releases rarely exceed this discharge, and sandbars are inundated above the 25,000 ft^3/s stage elevation only during controlled flood events.

Kaplinski and others (2014) reported a 36 percent decrease in the mean total campsite area above between 1998 and 2012, an average decrease in high elevation campsite area of 61 percent, and no significant trend at low elevation campsite area (Fig. 6). They conclude that campsite area had significantly declined during the study period and that the management objectives set forth by the Glen Canyon Adaptive Management Program (GCDAMP) for increasing campsite size has not yet been met. They also conclude that a variety of factors, including changes in sandbar topography and expansion of vegetation have contributed to campsite loss.

In addition to the 37 campsites currently monitored by NAU's Sandbar Monitoring Lab, numerous campsites throughout critical reaches have been monitored by the Adopt-A-Beach program since 1996. The Adopt-A-Beach (AAB) program is on ongoing qualitative effort by Grand Canyon River Guides to assess the quality of sandbar campsites. River guides, private river runners, scientists, and NPS personnel volunteer to

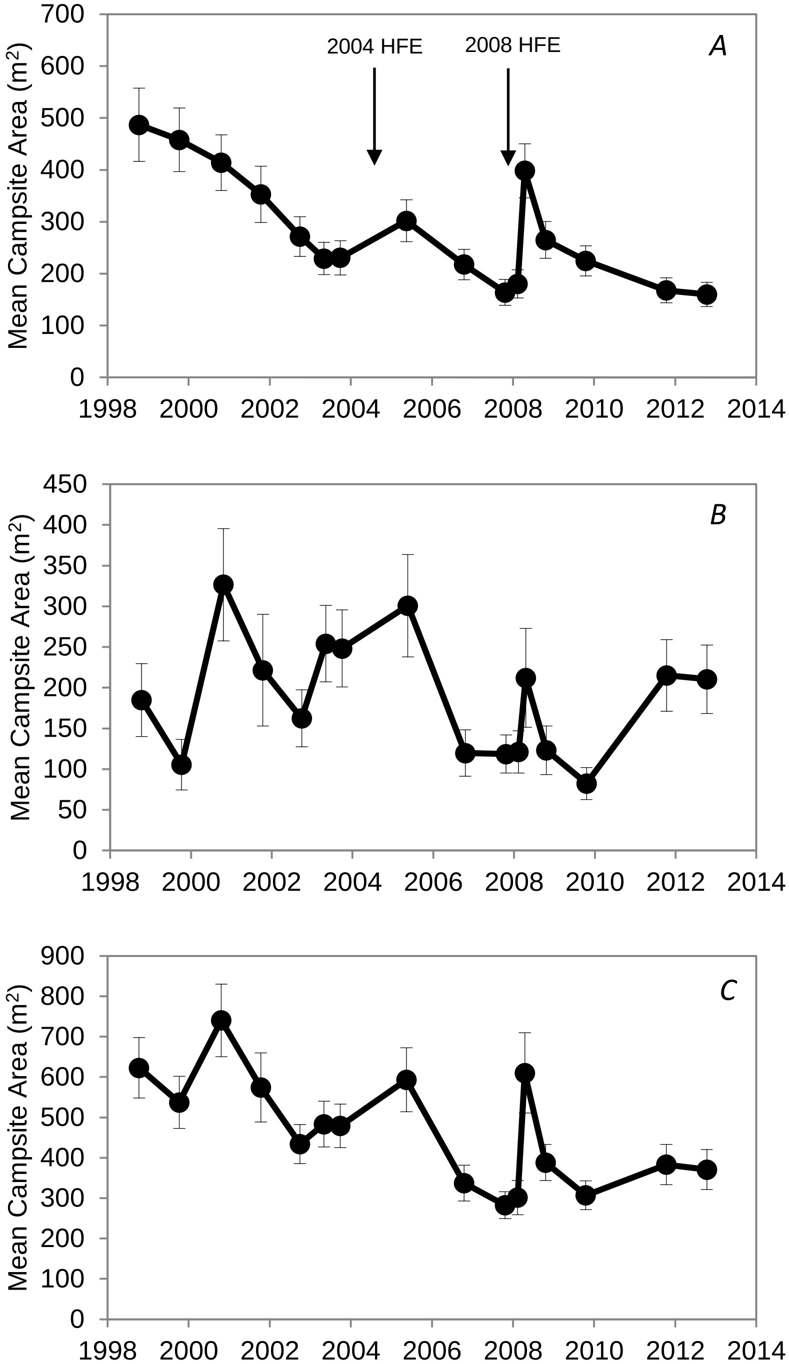


Figure 6. Time series plot of mean campsite area for 37 NAU-monitored sites from 1998 to 2012, with standard error of the mean indicated with error bars. (*A*) Mean high elevation campsite area (above the 25,000 ft^3/s stage elevation). (*B*) Mean low elevation campsite area (between the 15,000 and 25,000 ft^3/s stage elevations). (*C*) Mean total campsite area (above the 15,000 ft^3/s stage elevation). Figure modified from Kaplinski and others, 2014.

“adopt” a beach and monitor it through the spring and fall rafting season. Monitoring includes note taking throughout the season and taking repeat photographs of sites at pre-established locations. The goals of the AAB program are to document changes to campsites through each river running season and to assess the longevity of flood deposits following high-flow releases.

Previous campsite inventory comparisons, monitoring of campsites by the AAB program, and campsite monitoring conducted by NAU’s Sandbar Monitoring Lab link several factors to campsite loss, including sandbar erosion, changes in sandbar slope, vegetation encroachment, hillslope runoff, and aeolian reworking. To date there has been no systematic effort to quantitatively determine the influence that each of these factors have on campsite loss, which is what this study aims to accomplish. Determining which factors have led 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.

CHAPTER 2

GEOMORPHIC AND VEGETATION CHANGE AT CAMPSITES BETWEEN 2002 AND 2009: QUANTIFYING THE EFFECTS OF GLEN CANYON DAM OPERATIONS AND NATURAL PROCESSES ON CAMPSITE SIZE

2.1 Introduction

Sandbars are dynamic landforms along the Colorado River that are deposited in eddies during periods of high flow and high suspended sediment concentration, and are eroded during periods of moderate and low flows when suspended sediment concentration is much lower. Most campsites are located on these dynamic sandbars, therefore the processes that act upon a sandbar invariably cause changes to the size, accessibility, or substrate of a campsite. The closure of Glen Canyon Dam dramatically curtailed the upstream sediment supply into Marble and Grand Canyons, reducing the suspended sediment concentration and amount of available sand to be deposited in eddies (Howard and Dolan, 1981; Schmidt and Graf, 1990; Wright and others, 2005; Hazel and others, 2010) (Fig. 7). Fluctuating flows released by Glen Canyon Dam for hydroelectric power generation carry little suspended sediment and are an erosive force on sandbars (Hazel and others, 1999). Gullying and hillslope runoff during monsoon events (Melis and others, 1995) and aeolian processes such as wind deflation (Draut and others 2010) also contribute to sandbar erosion.

The reduced frequency and magnitude of flooding events has also allowed colonization of open sand by riparian vegetation, as floods no longer scour out or bury vegetation on a regular basis (Turner and Karpiscak, 1980; Waring 1996, Ralston, 2005)

Figure 7. Upstream view from Cardenas Hilltop near river mile 71.3 showing the dramatic 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 courtesy of the U.S. Geological Survey, Desert Laboratory Repeat Photography Collection.

(Fig. 7). Prior to the construction of Glen Canyon Dam, riparian vegetation was sparse along the river corridor due to frequent flooding events. Following the closure of the dam, vegetation expanded along the river corridor until the occurrence of large flooding events from 1983-1986. The 1983-1986 floods were caused by unusually large excess 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, 2011a). These large floods scoured out 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 1990's (Stevens and Ayers, 1995). This led to a reduction in the number of campsites from the mid-1980"s to the mid-1990's due to expansion of riparian vegetation, particularly in critical reaches (Kearsley and Warren, 1993; Kearsley and others, 1994). Vegetation continues to expand along the river corridor due to flow regulation (Sankey and others, *in review*).

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. Periodic high flows have been released from Glen Canyon Dam and have been shown to increase campsite area (Kearsley and Quartoroli, 1997, Kearsley and others, 1999; Kaplinski and others 2010). However, the loss of campsite area in the intervening periods due to sandbar erosion, steeping of sandbar slope, and expansion of riparian vegetation has outpaced the ephemeral gains in campsite area after a controlled flood (Kaplinski and others, 2010, 2014).

2.2 Purpose and Objectives

The purpose of this project was to expand upon previous campsite studies by utilizing topographic data and 4-band digital orthoimagery to determine the primary mechanisms that caused changes in campsite area between 2002 and 2009. Mechanisms include changes in sandbar elevation, sandbar slope, and vegetation cover. Specific objectives were to: 1) quantify the amount of erosion and deposition occurring within campsite areas and to distinguish between erosion caused by surface runoff generated upslope from sandbars and erosion caused by fluctuating flow releases, 2) analyze slope changes within campsite areas caused by depositional and erosional events, 3) calculate the amount of vegetation change occurring at monitored sites, and 4) determine if the factors leading to gains and losses in campsite area varied by recreational reach or canyon section.

This study used data collected between 2002 and 2009 at 35 of the 37 NAU-monitored campsites (Fig. 8, Table 2). Campsite data collected by NAU's Sandbar Monitoring Lab was used for this study because it is the most spatially and temporally consistent dataset of campsites available and is coincident with topographic sandbar measurements. Two sites, South Canyon (RM 31.9R) and 183 Mile Left (RM 183.3L) were not included in this analysis because topographic coverage of the sandbar does not extend throughout these campsite areas (Table 2).

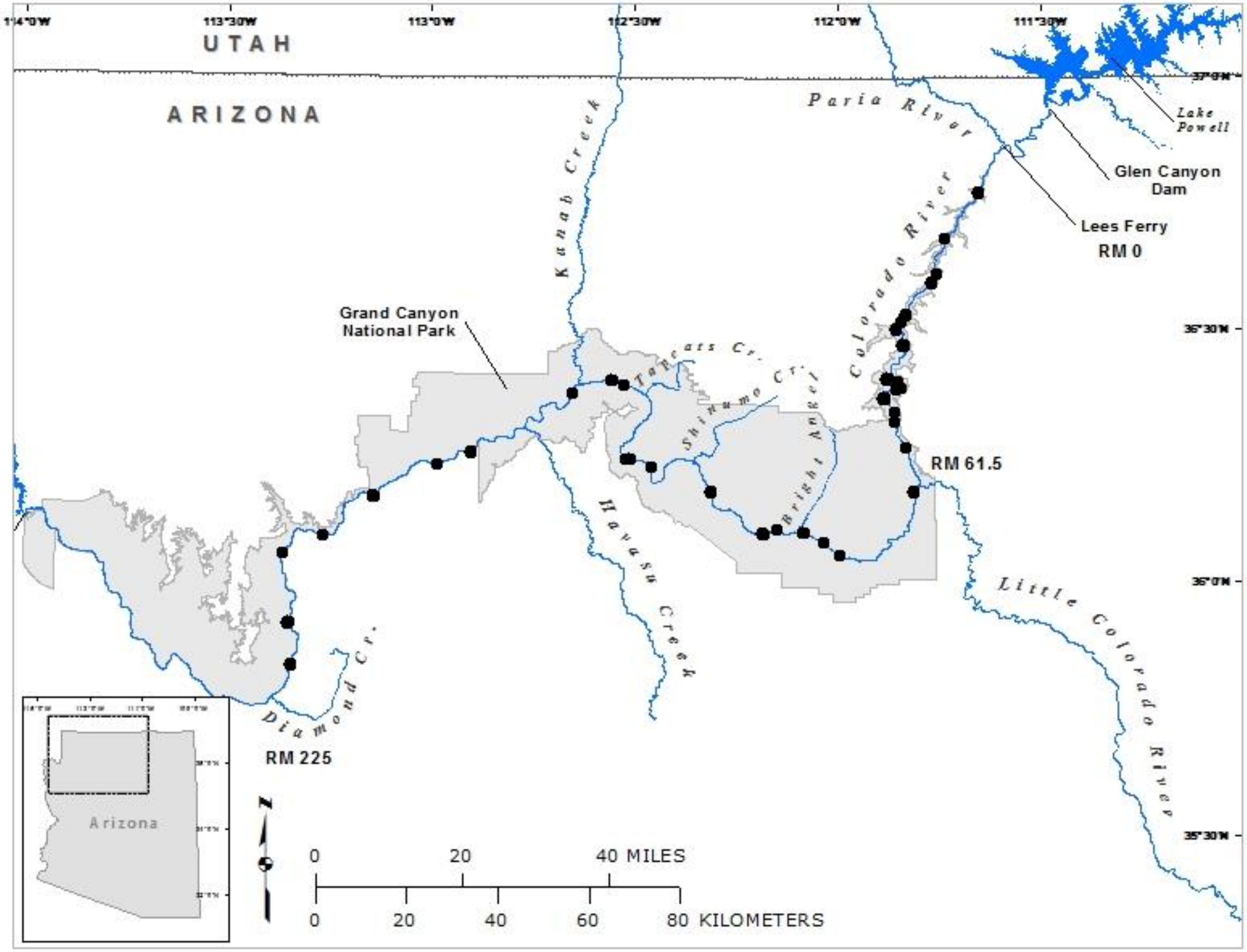


Figure 8. Map of the Colorado River corridor through Grand Canyon National Park showing Lees Ferry, major tributaries, and the locations of NAU-monitored sites used for this study (indicated with black circles).

This study was limited to the period between 2002 and 2009 because maps of vegetative cover along the entire river corridor below GCD are only available for those two years. Two high-flow experiments conducted in November 2004 and March 2008, with discharges of 42,500 ft^3/s and 42,800 ft^3/s, respectively, also make this a significant time period in the context of management activities (Fig. 9).

2.3 Methods

Campsite Area Change

Campsite areas change over time due to dam management activities and natural processes, or can remain relatively constant in size over a long period. Changes in campsite area over the course of the study period were determined in ArcGIS (ESRI, 2013) using NAU campsite surveys from October 2002 and October 2009 (Fig. 10). Because discharge was at or below 10,000 ft^3/s during the time of the 2002 and 2009 surveys, campsite area analyzed for this study includes campsite area mapped from the 10,000 ft^3/s stage elevation and above. This is different than previous NAU campsite monitoring reports, which discusses 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). Gains in campsite area were defined as areas that were mapped in 2009 but not in 2002 and are referred to as "areas of campsite gain." Losses in campsite area were defined as areas that were mapped in 2002 but not in 2009 and are referred to as "areas of campsite loss." Campsite areas that did not change in size over the study period were defined as campsite areas that were mapped in both

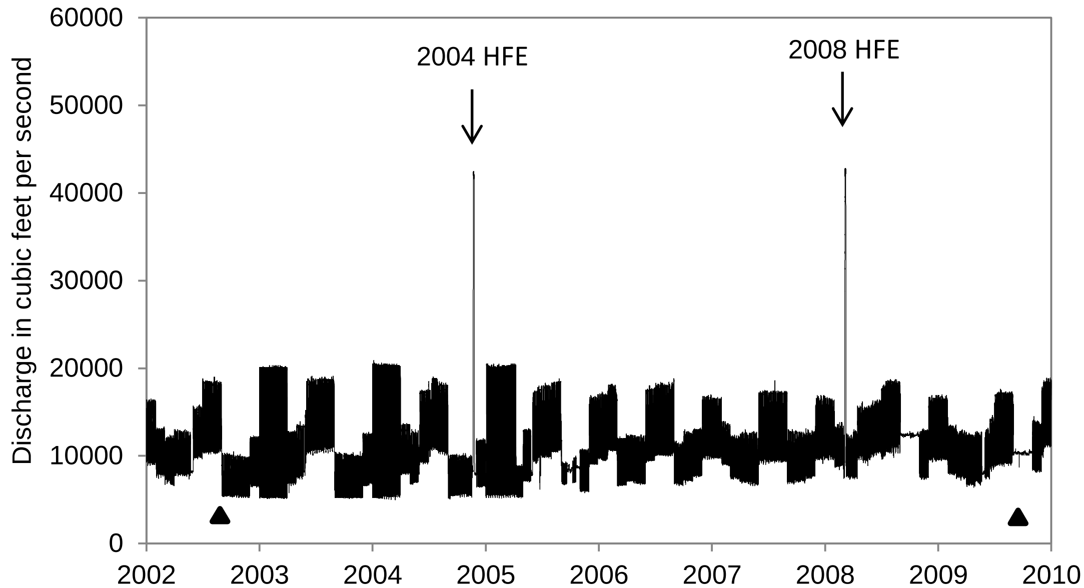


Figure 9. Continuous discharge record for the Colorado River at Lees Ferry (USGS gauging station 09280000) between 2002 and 2010. Black triangles indicate the start and end of the study period. Note the 2004 and 2008 HFEs which had discharges of 42,500 ft^3/s and 42,800 ft^3/s, respectively, and the daily and seasonal fluctuations in flow.

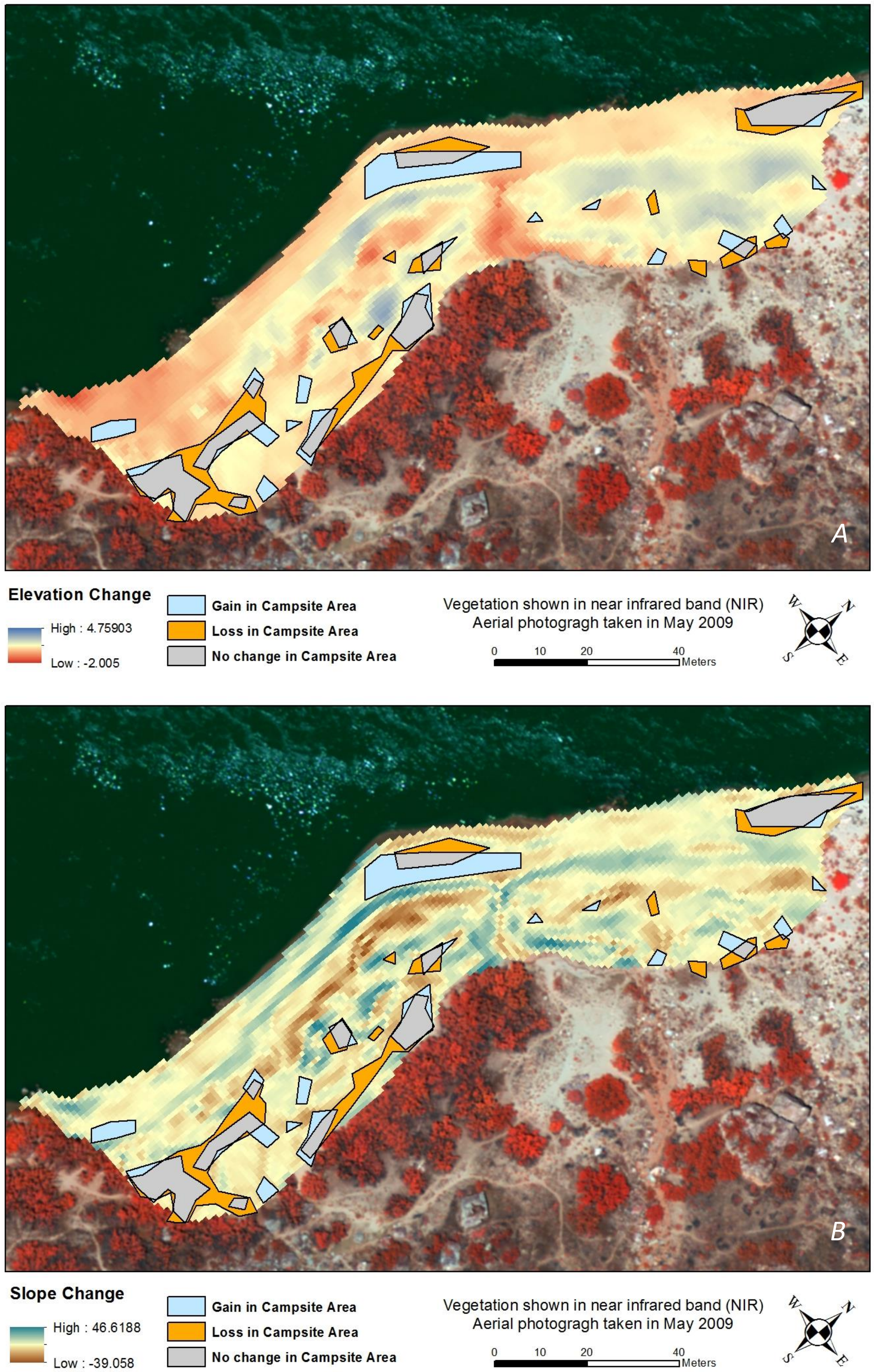


Figure 10. Digital elevation models (DEMs) of sandbars generated from total station survey data were used to create (*A*) elevation and (*B*) slope difference rasters. Difference rasters represent the change in elevation and slope of the sandbar between 2002 and 2009. Example shown is of Eminence Camp at RM 44.5L.

2002 and 2009 and are referred to as “campsite areas of no change.” Areas of campsite change by site varied in size from less than 10 m^2 to over 1000 m^2.

Elevation and Slope Change / Gully Identification

Campsite surveys are conducted concurrently with a long-term sandbar monitoring project that measures area and volume of selected sandbars using total station survey methods (Hazel and others, 1999, 2010; Hazel and others, *in prep*). The majority of campsite surveys therefore overlap with topographic surveys of the sandbar. Surface models of sandbars are created with topographic survey points and surveyed breaklines. Using SDR Mapping and Design software (Datacom Software Research Limited, 1997), Triangulated Irregular Network (TIN) surfaces are made. TINs are then linearly resampled and converted to 1 m^2 grid files, which are then converted to raster digital elevation models (DEMs) in ArcGIS. For a more detailed description of sandbar survey methods, data processing, and calculations of uncertainty associated with surface models, see Hazel and others (*in prep*).

Using the DEMs of sandbars measured concurrently with the October 2002 and October 2009 campsite surveys, a DEM of difference (DoD) was created by subtracting the 2002 elevation surface from the 2009 elevation surface. 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, 2013). A slope difference raster was created by subtracting the 2002 slope surface from the 2009 slope surface. The difference rasters thus represent the change in elevation and slope of the sandbars between 2002 and 2009 (Fig. 10).

Elevation difference rasters were categorized into areas of deposition (areas with > 0.04 m of change), erosion (areas with < -0.04 m of change), and no significant elevation change (areas that were within ± 0.04 m) (Fig. 11). Four centimeters was used as the threshold for significant elevation change since it is the total uncertainty for a total station-derived surface calculated for NAU's topographic surveys (Hazel and others, *in prep*). Slope difference rasters were categorized into areas of change 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: slope change from flat to steep, slope change from steep to flat, flat areas of no change, and steep areas of no change (Fig. 11). About 90 percent of campsite area mapped in 2002 and 2009 falls under a slope of 8 degrees (Fig. 12), 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.

In an effort to distinguish erosion caused by hillslope runoff from erosion caused by fluvial process, gullies were identified from the 2002 and 2009 sandbar surfaces using a combination of elevation and slope 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 0.5 m in width or depth) or can be large features that are several meters in width or depth (Fig. 13). Flow direction and flow

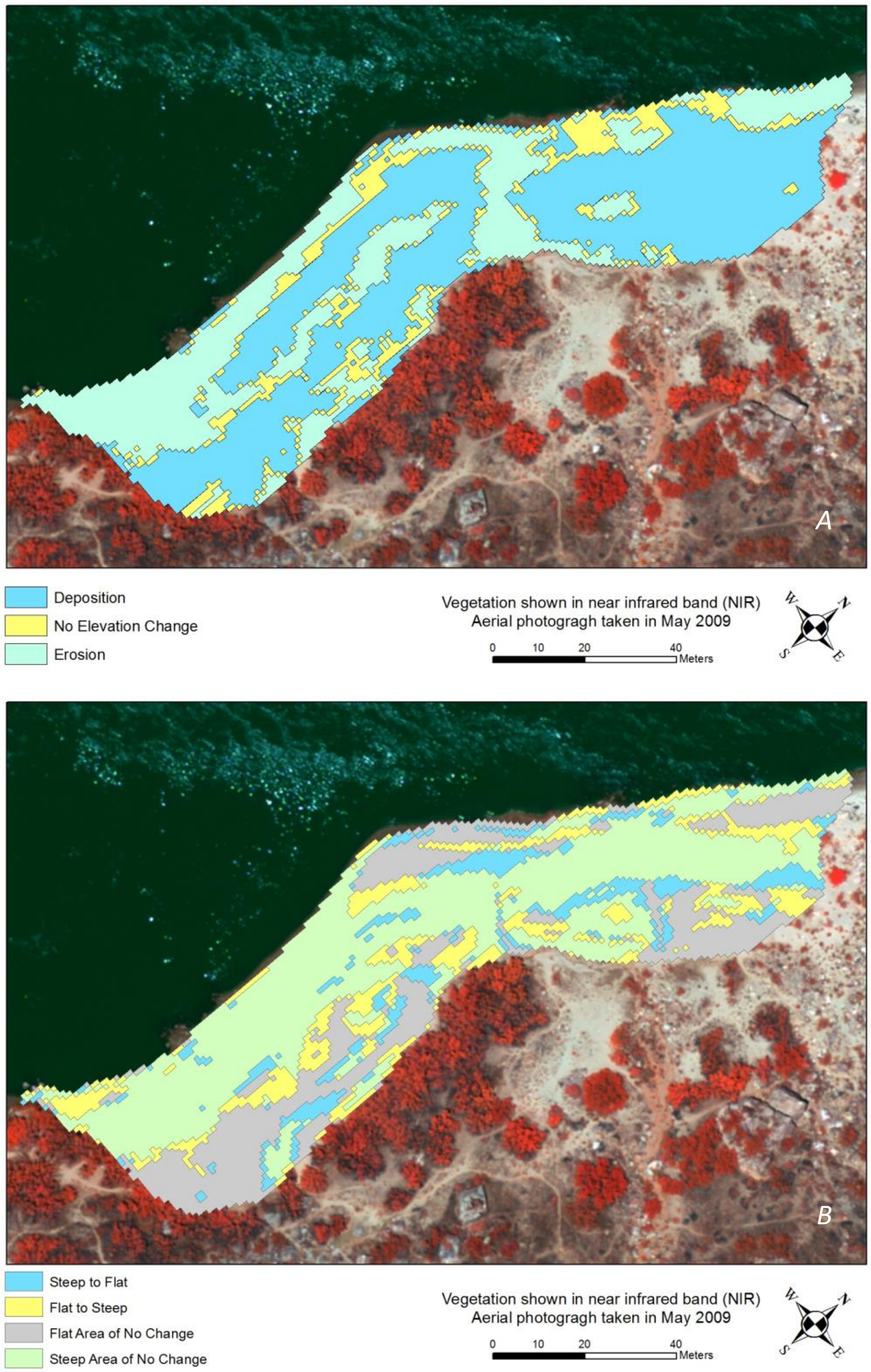


Figure 11. Categorized rasters of (*A*) elevation change and (*B*) slope change derived from the 2002-2009 difference rasters. Elevation change was based around a threshold of ±0.04m. Slope change was based on the 8 degree threshold used for campsite monitoring. Example shown is of Eminence Camp at RM 44.5L.

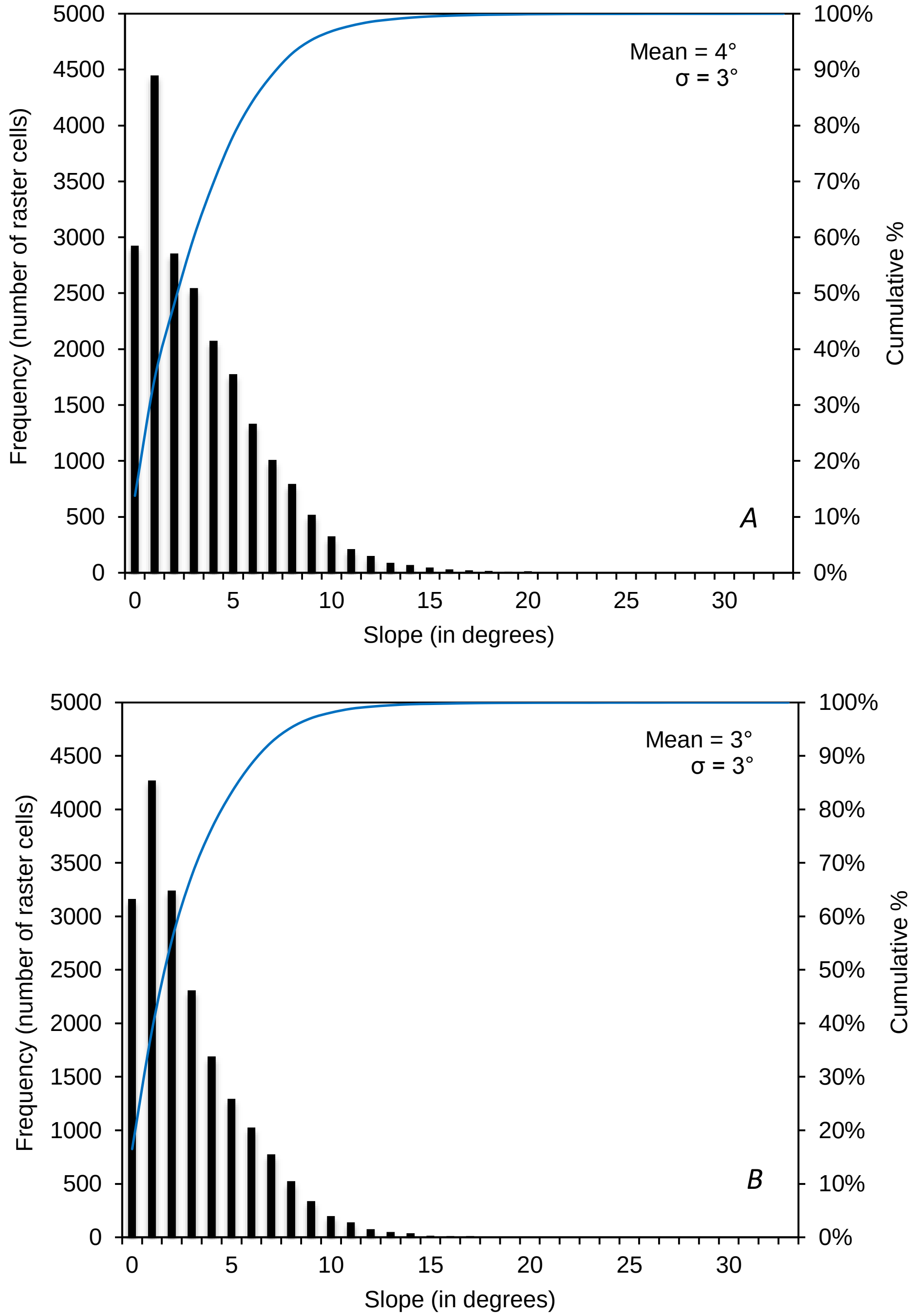


Figure 12. Frequency distribution of slope within (*A*) 2002 and (*B*) 2009 campsite area. Cumulative percentage on the right axis shows that 90 percent of campsite area for both years falls under a slope of 8 degrees.

Figure 13. Examples of gullying caused by hillslope runoff at (*A*) Nautiloid (RM 35.0L) and (*B*) Crash Canyon (RM 62.9R) leading to recent losses in campsite area. Top photograph at Nautiloid was taken on 9/24/2013 and is looking down on the tributary channel that cuts through the site. Bottom photograph at Crash Canyon was taken on 9/27/2013 by Paul Grams looking upstream.

accumulation rasters were derived from the sandbar slope rasters in ArcGIS. Raster cells of high flow accumulation allowed identification of potential gullies and were further discerned using 0.25 m contour lines generated from the elevation surfaces. Total station derived surfaces at NAU-monitored 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, *in prep*). 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 when possible. 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.

Vegetation Change

Four band aerial imagery (blue, green, red and near-infrared [NIR]) of the Colorado River corridor below GCD were acquired in May of 2002 and 2009 at a 0.22 m resolution (Davis, 2002; Ralston and others, 2008; Davis, 2012). Images were collected in May to capture the most vegetation with full foliage. Discharge from GCD was held at a constant 8,000 ft^3/s during the time of data acquisition. Maps of gross vegetation coverage along the river corridor were created by Ralston and others (2008) and Davis (2012) using the NIR band and a Normalized Difference Vegetation Index (NDVI) classification (for detailed descriptions of image acquisition, processing, and vegetation classification, see Davis, 2002; Ralston, 2008; and Davis, 2012). Precise co-registration of the 2002 and 2009 image mosaics (Davis, 2012) allowed for seamless change detection between years. Accuracy of the NDVI classification for both sets of imagery is around 95 percent, based on the accuracy assessment of vegetation classes for the 2002 imagery (Ralston and others, 2008) and the fact that the NDVI classification for both photo sets were rigorously reviewed and edited for the entire length of the Colorado River corridor (Joel Sankey, personal communication).

Areas of vegetation change were created in ArcGIS using the 2002 and 2009 maps of gross vegetation coverage. Three categories were made and are: areas of vegetation gain (defined as areas that were vegetated in 2009 but not in 2002), areas of vegetation loss (defined as areas that were vegetated in 2002 but not 2009), and areas of no vegetation change (defined as areas that were vegetated in both 2002 and 2009). Given the image resolution of 0.22 cm, areas of vegetation change were as small as 0.0484 m^2. Only gross vegetation coverage was used to calculate vegetation change during the study period. Subdividing the gross vegetation coverage into vegetation classes or species was beyond the scope of this study.

Intersection of Datasets

Changes in vegetation cover and the elevation and slope of the sandbars were analyzed within campsite areas mapped in 2002 and 2009 to determine the mechanisms that contributed to campsite area change. This was accomplished by intersecting areas of campsite gain, areas of campsite loss, and campsite areas of no change with the data sets of elevation, slope, and vegetation change created from the difference rasters and

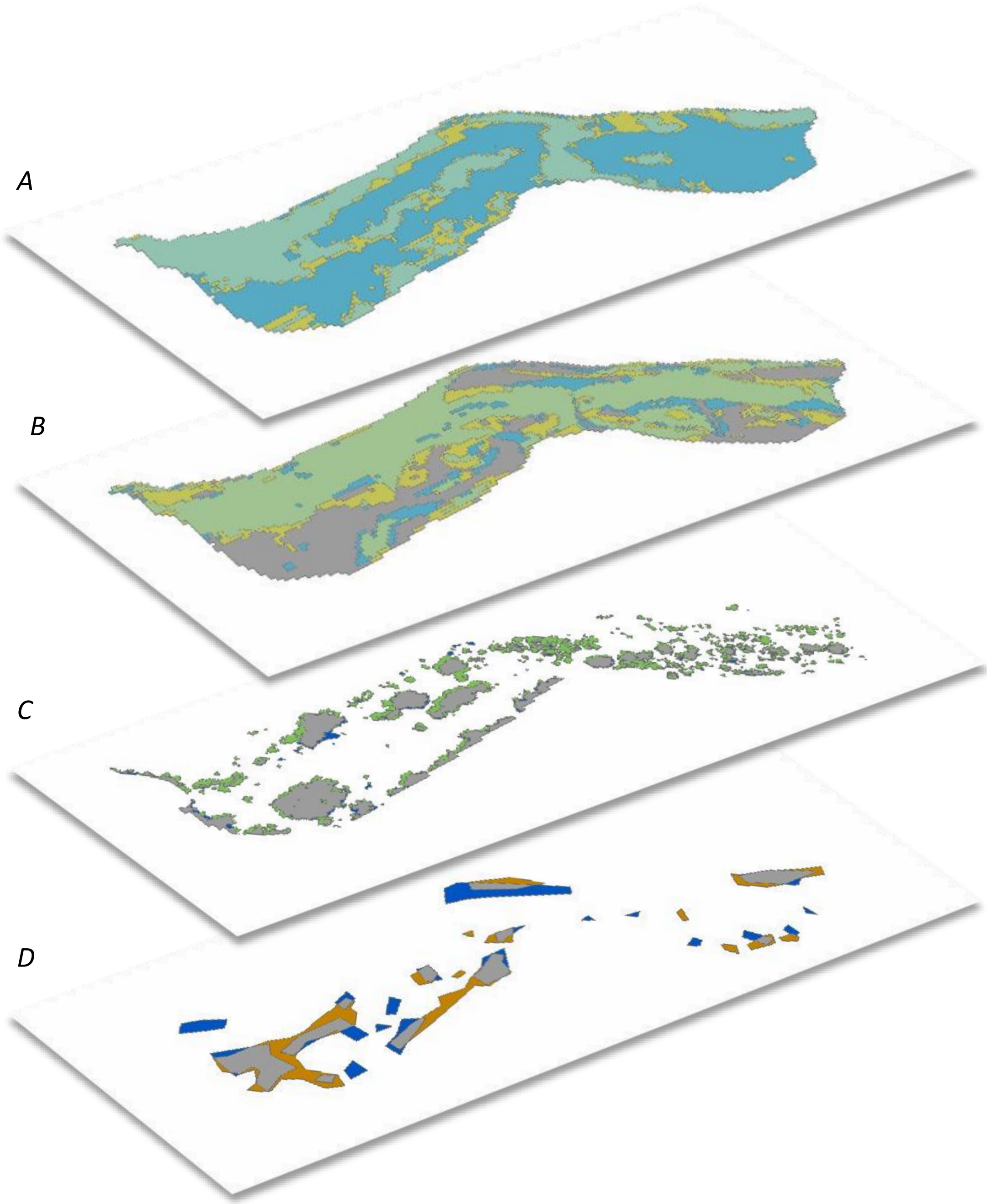


Figure 14. Intersection of datasets for (*A*) elevation change, (*B*) slope change, and (*C*) vegetation change within (*D*) areas of campsite gain, areas of campsite loss, and campsite areas of no change. Intersection of datasets allowed the mechanisms that contributed to campsite area change to be determined. Example shown is of Eminence Camp at RM 44.5L.

vegetation cover maps (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 led to the creation of "first order" and "second order" processes associated with changes in campsite area. First order processes are simply the mechanisms of elevation change (i.e., deposition, erosion, or no elevation change) and vegetation change. Changes in the slope of the 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 links deposition or erosion with a change in sandbar slope around 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 non-critical recreational reach and by canyon section.

Intersected areas varied in size from less than 1 m^2 to over 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.

Table 3. List of second order processes associated with changes in 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.

	Second Order Processes		
	Type of Vegetation Change	**Type of Elevation Change**	**Type of Slope Change**
1	Gain	-	-
2	Loss	-	-
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

2.4 Results

Campsite area declined between 2002 and 2009 at the 35 NAU-monitored campsites used for this study. In 2002 there was 22,162 m^2 of campsite area at the 35 sites, and over the course of the seven year period there was a gain in campsite area of 9,935 m^2, a loss in campsite area of 12,366 m^2, and 9,796 m^2 of area that was mapped as a campsite in both years. This resulted in a net loss in campsite area above the 10,000 ft^3/s stage elevation of 2,431 m^2, which is a decline of 11 percent over the seven year period. Due to the incomplete overlap of campsite surveys and topographic surveys, however, only 92 percent of the gains and losses in campsite area could be analyzed. 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). Because South Canyon (RM 31.9R) and 183 Mile Left (RM 183.3L) had no overlap in campsite area and topographic coverage, they are not reported on in this analysis.

The 11 percent decline in campsite area reported here is different than a 29 percent decline between 2002 and 2009 that can be calculated from NAU's reported values (Kaplinski and others, 2014) (Fig. 6). This is due to the fact that Kaplinski and others (2014) analyzed all 37 sites instead of the 35 used for this study, and are reporting on campsite areas above the 15,000 ft^3/s stage elevation instead of the 10,000 ft^3/s stage elevation used here.

An important distinction needs to be made in regards to changes in campsite area (gains and losses) and a net change in campsite area (the overall gain or loss over a certain time period). Previous campsite reports by NAU's Sandbar Monitoring Lab show the net changes in campsite area over time and qualitatively describe the mechanisms that contribute to that net campsite change. The following first order and second order results describe the processes that contributed to the gains and losses in campsite area, instead of the net change over the study period. The following results are then analyzed in the context of net change and are addressed in the Discussion and Conclusion sections.

First Order Results

Changes in the elevation of the bar accounted for the majority of campsite change, with gains and losses in vegetation being smaller factors. The majority of the gains in campsite area were associated with deposition (59 percent), but erosion was also a large factor (30 percent) (Fig. 15, Table 4). There were also gains in campsite area associated with no change in elevation (9 percent). Vegetation loss was a very minor factor and accounted for less than 1 percent of the gains in campsite area (Fig. 15, Table 4). However, the influence of elevation change and vegetation change on gains in campsite area varied considerably by site. Sites such as Willie Taylor (RM 45.0L), Lower Saddle (RM 47.6R), and 202 Mile (RM 202.3R) had over 85 percent of their campsite gains associated with deposition, whereas sites such as Grapevine (RM 81.7L) and Football Beach (RM 137.7L) had over 85 percent of their campsite gains associated with erosion (Table 4, Appendix A).

Table 4. First order processes associated with areas of campsite gain and areas of campsite loss for each of the 37 NAU-monitored sites, summarized by recreational reach and canyon section.

					Cause of Gain in Campsite Area (%)					Cause of Loss in Campsite Area (%)					
Site/Reach	**Campsite Area in 2002 (m^2)***	**Campsite Area in 2009 (m^2)***	**Gain in Campsite Area (m^2)**	**Loss in Campsite Area (m^2)**	**Deposition**	**Erosion**	**No Elevation Change**	**Gain in Vegetation**	**Loss in Vegetaton**	**Deposition**	**Erosion**	**No Elevation Change**	**Gain in Vegetation**	**Loss in Vegetaton**	**Net Change in Campsite Area (m^2)**
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
Harry McDonald	612	658	377	332	29%	64%	6%	0%	0%	10%	57%	8%	25%	0%	45
Silver Grotto	608	672	341	277	84%	9%	7%	1%	0%	72%	15%	8%	5%	0%	64
Sand Pile	1012	512	163	663	46%	53%	1%	0%	0%	22%	77%	1%	1%	0%	-500
Nautiloid	468	510	155	113	64%	26%	7%	2%	0%	7%	55%	16%	21%	1%	43
Buck Farm	654	392	117	379	48%	42%	9%	0%	1%	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%	2%	1%	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	1304	1171	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%	2%	0%	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%	5%	8%	45%	23%	8%	20%	4%	-148
91 Mile	208	336	176	48	49%	37%	10%	3%	0%	0%	98%	1%	1%	0%	128
Granite	387	283	123	227	74%	12%	2%	5%	7%	67%	16%	2%	14%	0%	-104
Emerald	207	80	7	135	24%	61%	12%	2%	0%	50%	24%	7%	19%	0%	-128
119 Mile	812	591	178	399	85%	3%	12%	0%	0%	38%	21%	18%	23%	0%	-221
122 Mile	1699	1802	830	727	68%	25%	7%	1%	0%	75%	8%	6%	11%	0%	103
Upper Forster	391	330	259	320	59%	27%	14%	0%	0%	48%	36%	12%	4%	0%	-60
Football Beach	1761	1587	552	725	11%	86%	3%	0%	0%	8%	87%	3%	2%	0%	-173
Fishtail	33	79	52	7	36%	54%	9%	1%	0%	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%	1%	0%	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%	5%	1%	34%	20%	32%	13%	1%	-198
202 Mile	1390	444	89	1035	91%	1%	3%	6%	0%	38%	38%	3%	20%	0%	-945
Pumpkin Springs	631	520	395	506	66%	26%	6%	1%	0%	42%	35%	2%	21%	0%	-111
220 Mile	593	320	165	438	57%	18%	22%	1%	2%	10%	58%	9%	22%	1%	-273
Critical Reaches	7648	7068	2877	3457	51%	42%	6%	1%	0%	32%	55%	5%	8%	0%	-580
Non-Critical Reaches	13319	11352	6119	8085	63%	25%	11%	1%	0%	45%	33%	11%	11%	0%	-1966
Marble Canyon	9380	8847	4711	5244	64%	26%	10%	0%	0%	45%	39%	10%	6%	0%	-533
Grand Canyon	11587	9574	4285	6298	55%	35%	9%	1%	0%	37%	40%	9%	14%	0%	-2013
All Sites	20967	18420	8996	11542	59%	30%	9%	1%	0%	41%	39%	9%	10%	0%	-2547

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

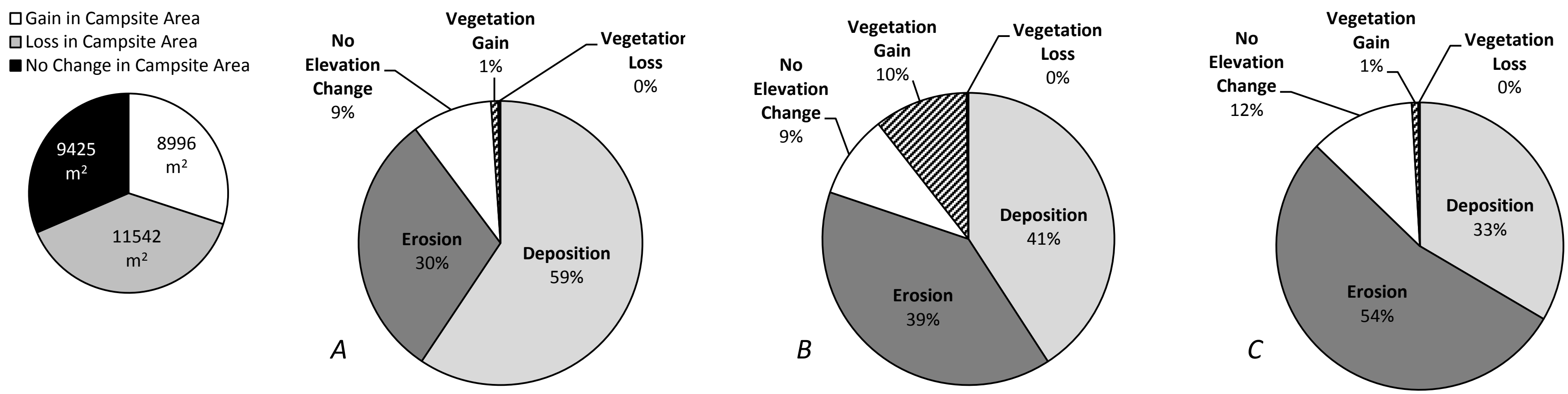


Figure 15. First order processes that were associated with (*A*) areas of campsite gain, (*B*) areas of campsite loss, and (*C*) campsite areas of no change for all analyzed sites. Areas shown are gains, losses, and no changes in campsite area coincident with topographic coverage.

Within areas of campsite loss, deposition and erosion were the two predominant factors that led to a loss in campsite area (41 percent and 39 percent, respectively) (Fig. 15, Table 4). There were also areas of campsite loss that were associated with no change in elevation (9 percent). Vegetation change was more of an influence within areas of campsite loss than in areas of campsite gain, with gains in vegetation accounting for 10 percent of campsite area lost (Fig. 15, Table 4).

The influence of elevation and vegetation change on losses in campsite area also varied considerable by site. Sites such as 22 Mile (RM 22.1L) and Above Olo (RM 145.9L) had over 75 of their campsite losses associated with deposition, whereas sites such as Sand Pile (RM 30.7R) and Football Beach (137.7) had over 75 percent of their campsite losses associated with erosion (Table 4, Appendix A). The influence of vegetation expansion on campsite loss were much larger factors at sites such as Kwagunt Marsh (RM 55.9R), Clear Creek (RM 84.6R), 119 Mile (RM 119.4R), and 220 Mile (RM 220.1R), which all had 20 percent of their campsite losses associated with gains in vegetation (Table 4, Appendix A).

Statistical summaries for the elevation change at each site were also calculated using ArcGIS zonal statistical tools and show the magnitude of elevation changes within areas of campsite gain, areas of campsite loss, and campsite areas of no change (Table 5). Elevation increased on average by 0.19 m within areas of campsite gain and increased on average by 0.17 m within areas of campsite loss (Fig. 16). Elevation changes within campsite areas varied considerably by site, with some sites having over 0.70 m of deposition on average leading to a gain in campsite area (22 Mile [RM 21.1R]

Table 5. Summary of statistical analysis for elevation and slope changes within areas of campsite gain, areas of campsite loss, and campsite areas of no change.

	Largest decrease (in m)	Largest increase (in m)	Mean (in m)	Stdv (in m)
Elevation change within areas of campsite gain	-1.33	2.93	0.19	0.58
Elevation change within areas of campsite loss	-1.69	3.20	0.17	0.74
Elevation change within campsite areas of no change	-1.31	3.08	-0.06	0.50

	Largest decrease (in degrees)	Largest increase (in degrees)	Mean (in degrees)	Stdv (in degrees)
Slope change within areas of campsite gain	-30.19	15.66	-3.50	5.05
Slope change within areas of campsite loss	-28.40	46.62	5.21	7.63
Slope change within campsite areas of no change	-17.53	12.56	-0.21	2.57

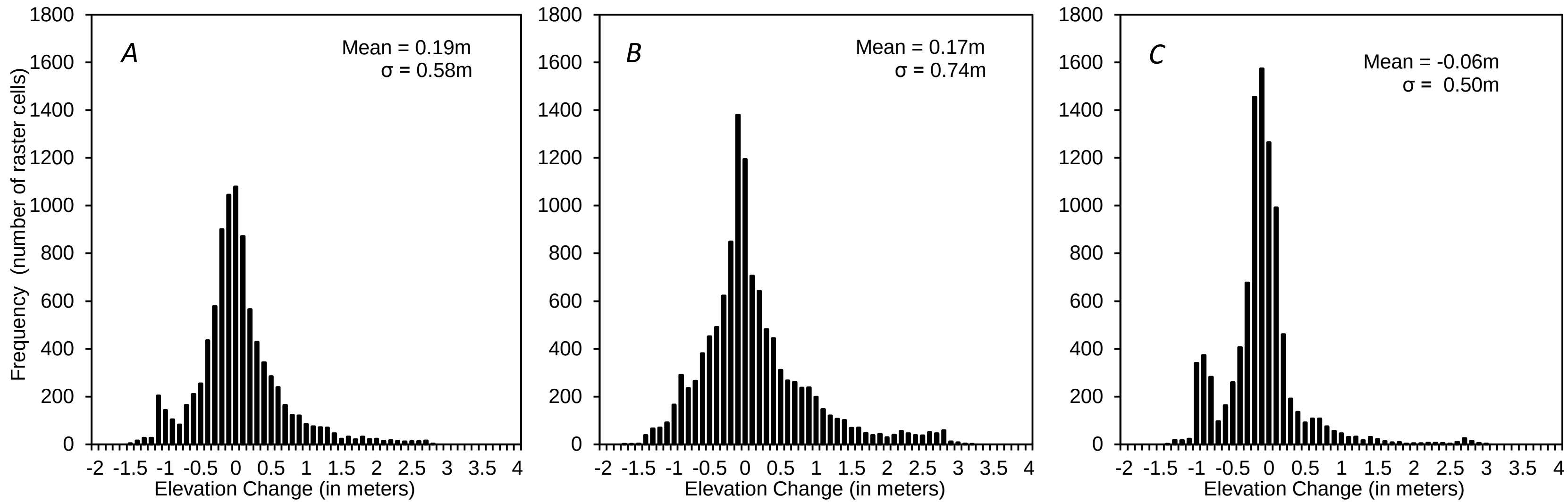


Figure 16. Frequency distributions of elevation change within (*A*) areas of campsite gain, (*B*) areas of campsite loss, and (*C*) campsite areas of no change.

and Pumpkin Springs [RM 213.3L]) and some sites having over 0.45 m of erosion on average leading to a loss in campsite area (91 Mile [RM 91.1R] and Football Beach [RM 137.7R]) (Appendix B).

First Order Results by Reach and Canyon Section

Campsite area within critical reaches made up 35 percent of the total campsite area mapped in 2002 and 2009, with campsite area in non-critical reaches making up the other 65 percent. Gains in campsite area in both critical and non-critical reaches were largely associated with deposition (51 percent and 63 percent, respectively), but erosion was also a large factor (42 percent in critical reaches and 25 percent in non-critical reaches) (Fig. 17. Table 4). Within critical reaches, campsite area loss was largely associated with erosion (55 percent), whereas campsite area loss in non-critical reaches was largely associated with deposition (45 percent) (Fig. 17. Table 4). Overall, there was more erosion leading to gains and losses in campsite area in critical reaches than in non-critical reaches. Vegetation was also a larger factor in campsite loss in non-critical reaches than in critical reaches (11 percent and 8 percent, respectively) (Fig. 17).

Gains in campsite area in both Marble Canyon and Grand Canyon were largely associated with deposition (64 percent and 55 percent, respectively), but erosion was also a large factor (26 percent in critical reaches and 35 percent in non-critical reaches) (Fig. 18. Table 4). Losses in campsite area in both Marble Canyon and Grand Canyon were mostly associated with deposition and erosion, but gains in vegetation led to more

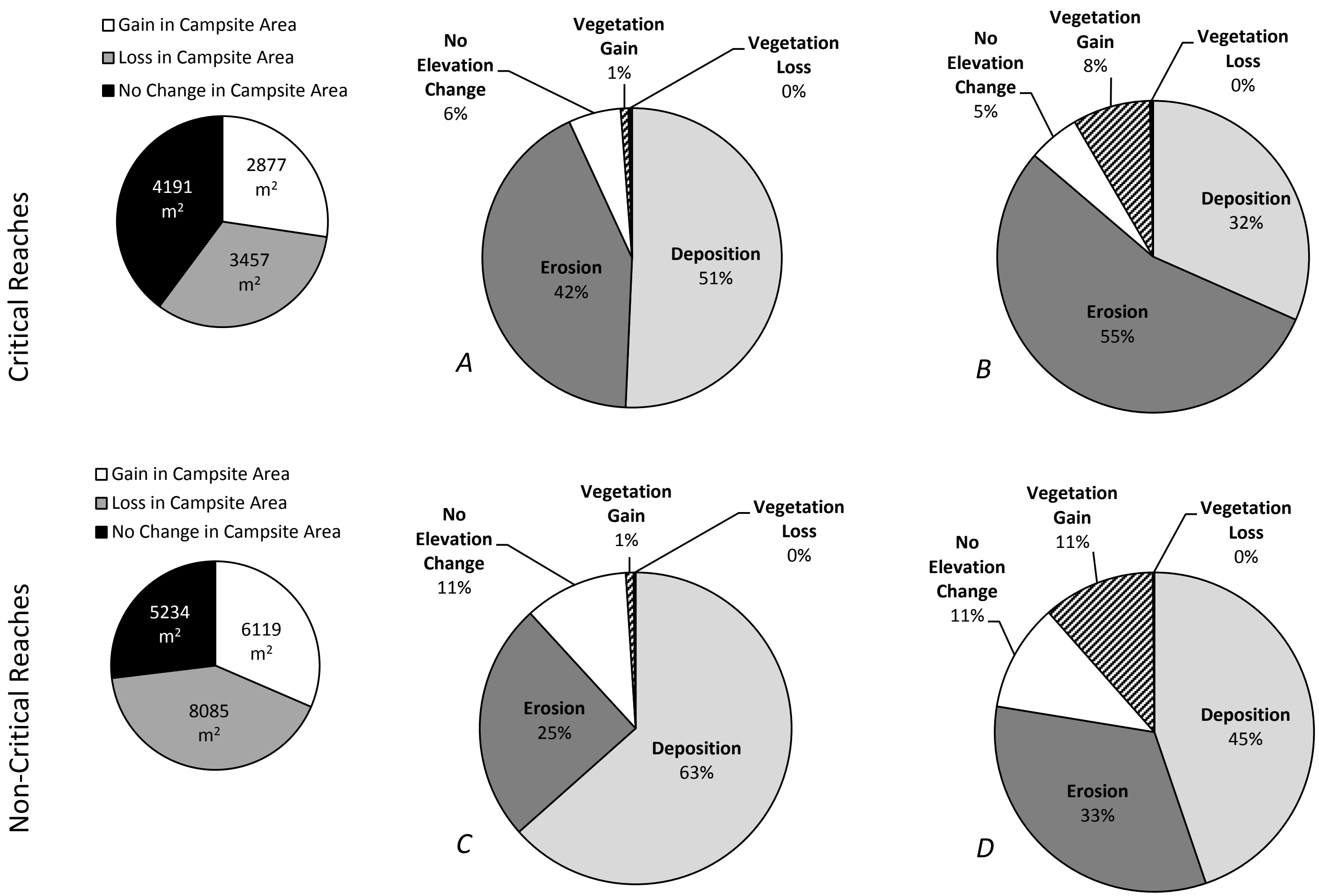


Figure 17. First order processes that were associated with (*A*) areas of campsite gain and (*B*) areas of campsite loss for sites in critical reaches; first order processes that were associated with (*C*) areas of campsite gain and (*D*) areas of campsite loss for sites in non-critical reaches. Areas shown are gains, losses, and no changes in campsite area coincident with topographic coverage.

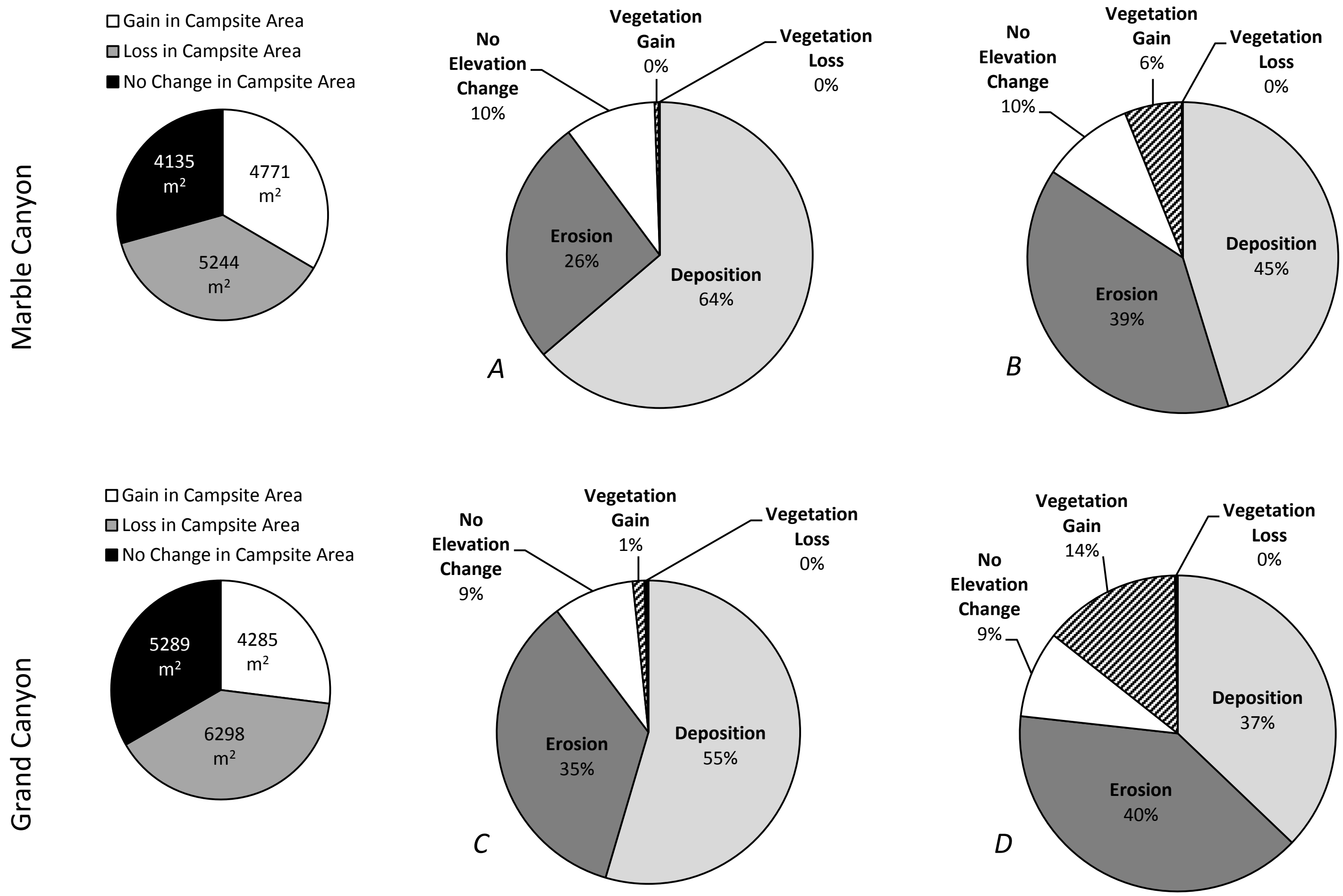


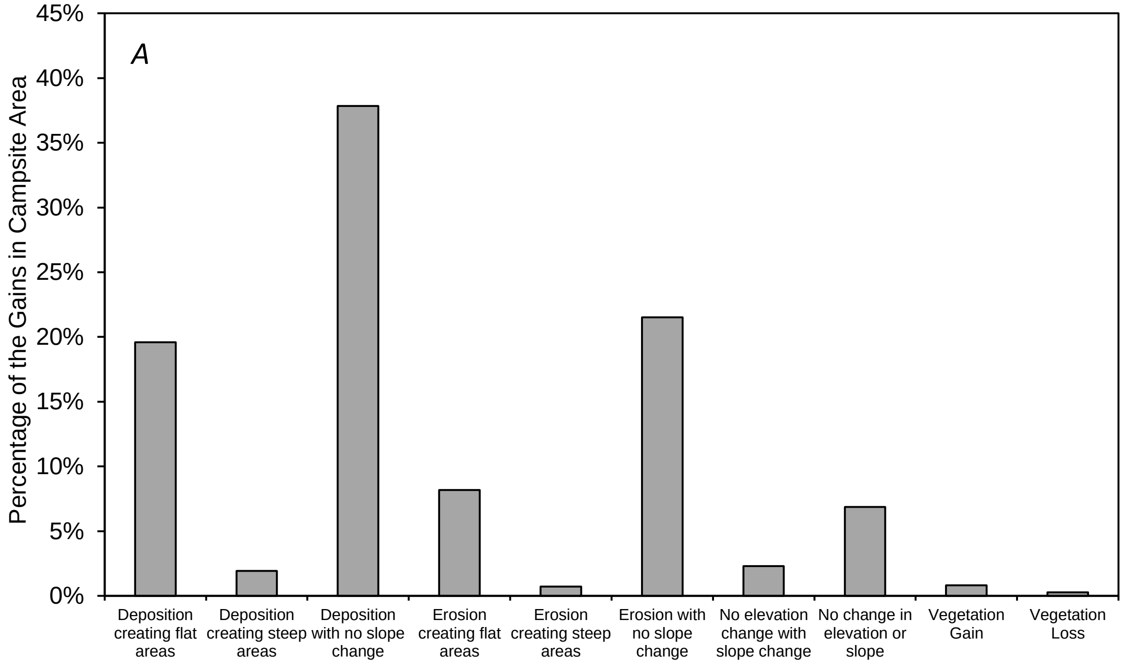
Figure 18. First order processes that were associated with (*A*) areas of campsite gain and (*B*) areas of campsite loss for sites in Marble Canyon; first order processes that were associated with (*C*) areas of campsite gain and (*D*) areas of campsite loss for sites in Grand Canyon. Areas shown are gains, losses, and no changes in campsite area coincident with topographic coverage.

campsite loss at sites within Grand Canyon versus sites within Marble Canyon (Fig. 18. Table 4).

Second Order Results

The intersection of elevation change, slope change, and vegetation change datasets resulted in the classification of 11 second order processes associated with changes in campsite area (Table 3, Appendix C). Second order processes include changes in elevation that led to a change in sandbar slope around the 8 degree campsite threshold, but also include elevation changes that did not cause a change in slope (i.e., bars built higher in response to controlled floods but retained the same slope following deposition). Because processes nine and ten were very small, they were combined in subsequent results. Second order mechanisms also include gains and losses in vegetation cover.

Overall, deposition without causing a significant slope change was the predominant process that contributed to gains in campsite area (38 percent) (Fig. 19, Table 6). Gains in campsite area were also largely caused by erosion without causing a significant slope change (22 percent) followed by deposition which created a flatter sandbar (20 percent) (Fig. 19, Table 6). Erosion without a significant slope change was the primary factor in contributing to a loss in campsite area (25 percent). Losses in campsite area were also largely caused by depositional processes not associated with a change in slope (21 percent) and deposition resulting in steeper sandbars (19 percent) (Fig. 19. Table 6).



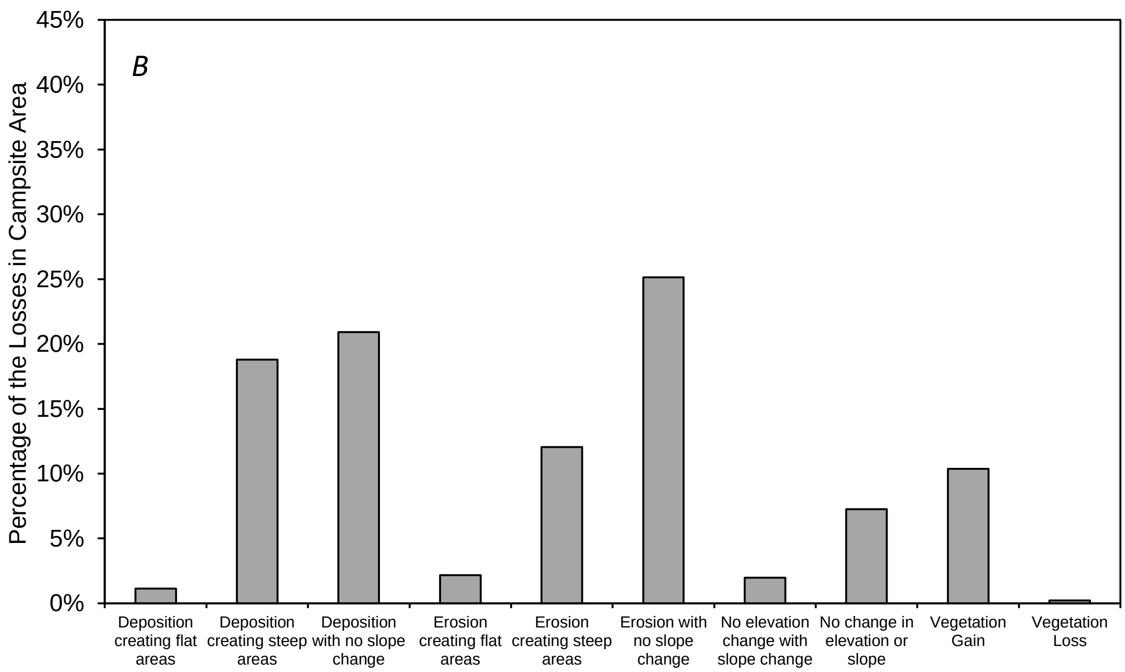


Figure 19. Second order processes associated with (*A*) gains in campsite area and (*B*) losses in campsite area for all sites.

Table 6. Second order processes associated with areas of campsite gain, areas of campsite loss, and campsite areas of no change, summarized by recreational reach and canyon section.

		2nd Order Changes																			
		Area (m²)										Area (%)									
		Depostion 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	Depostion 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 elevation change with slope change	No change in elevation or slope	Gain in Vegetation	Loss in Vegetation
Critical Reaches	Gain in Campsite Area	837	77	544	456	27	738	94	69	24	11	29%	3%	19%	16%	1%	26%	3%	2%	1%	0%
	Loss in Campsite Area	58	587	448	160	705	1023	58	127	278	12	2%	17%	13%	5%	20%	30%	2%	4%	8%	0%
Non-Critical Reaches	Gain in Campsite Area	927	95	2861	279	38	1197	112	548	49	14	15%	2%	47%	5%	1%	20%	2%	9%	1%	0%
	Loss in Campsite Area	73	1581	1965	89	686	1879	170	711	919	13	1%	20%	24%	1%	8%	23%	2%	9%	11%	0%
Marble Canyon	Gain in Campsite Area	1004	118	1881	397	26	806	125	329	19	7	21%	3%	40%	8%	1%	17%	3%	7%	0%	0%
	Loss in Campsite Area	57	847	1470	61	584	1402	82	424	312	6	1%	16%	28%	1%	11%	27%	2%	8%	6%	0%
Grand Canyon	Gain in Campsite Area	760	54	1524	339	38	1129	81	288	53	18	18%	1%	36%	8%	1%	26%	2%	7%	1%	0%
	Loss in Campsite Area	74	1322	944	188	807	1500	146	415	885	19	1%	21%	15%	3%	13%	24%	2%	7%	14%	0%
All Sites	Gain in Campsite Area	1763	172	3405	735	64	1935	206	617	73	25	20%	2%	38%	8%	1%	22%	2%	7%	1%	0%
	Loss in Campsite Area	131	2169	2413	249	1391	2902	228	838	1197	24	1%	19%	21%	2%	12%	25%	2%	7%	10%	0%

Statistical summaries for slope change at each site were calculated using ArcGIS zonal statistical tools and show the magnitude of slope changes within areas of campsite gain, campsite loss, and campsite areas of no change (Table 5, Appendix B). Within areas of campsite gain, slope decreased on average by 4 degrees (Fig. 20). Within areas of campsite loss, slope increased on average by 5 degrees. Changes in slope varied considerably by site, however, with some sites having on average a decrease in slope of 9 degrees or greater leading to a gain in campsite area (22 Mile [RM 21.1R] and Pumpkin Springs [RM 213.3L]) while some sites had an increase in slope of 12 degrees or greater leading to a loss in campsite area (Clear Creek Camp [RM 84.6R] and 119 Mile Camp [RM 119.4R]) (Appendix B). Specific examples of mechanisms linking elevation and slope change with gains and losses in campsite area are presented in the discussion section.

Second Order Results by Reach and Canyon Section

Within critical reaches, deposition leading to a reduction in slope was the predominant process to contribute to gains in campsite area (29 percent) (Fig. 21, Table 6). Erosion and deposition without causing a significant slope change were the next largest factors to contribute to gains in campsite area (26 percent and 19 percent, respectively) (Fig. 21, Table 6). In non-critical reaches deposition without a significant slope change was the primary factor that contributed to gains in campsite area (47 percent), followed by erosion not associated with a slope change (20 percent) and deposition causing a decrease in slope (15 percent).

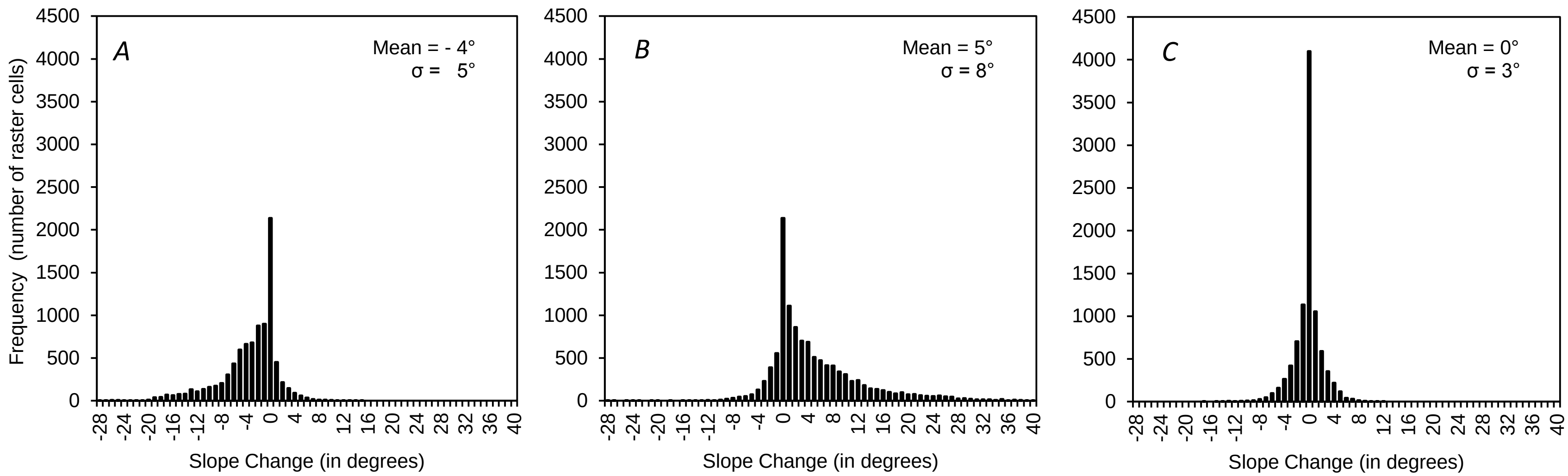


Figure 20. Frequency distributions of slope change within (*A*) areas of campsite gain, (*B*) areas of campsite loss, and (*C*) campsite areas of no change.

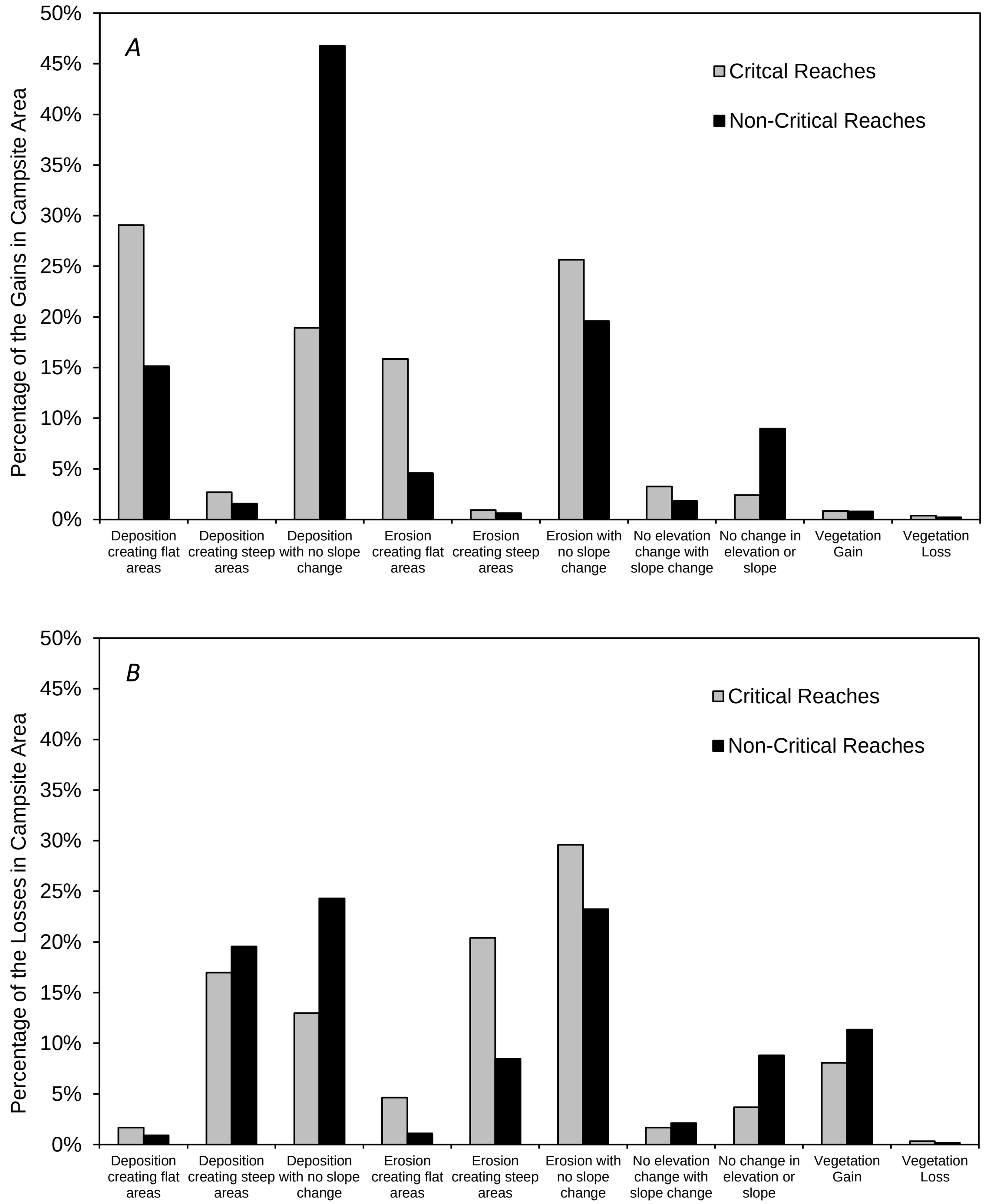
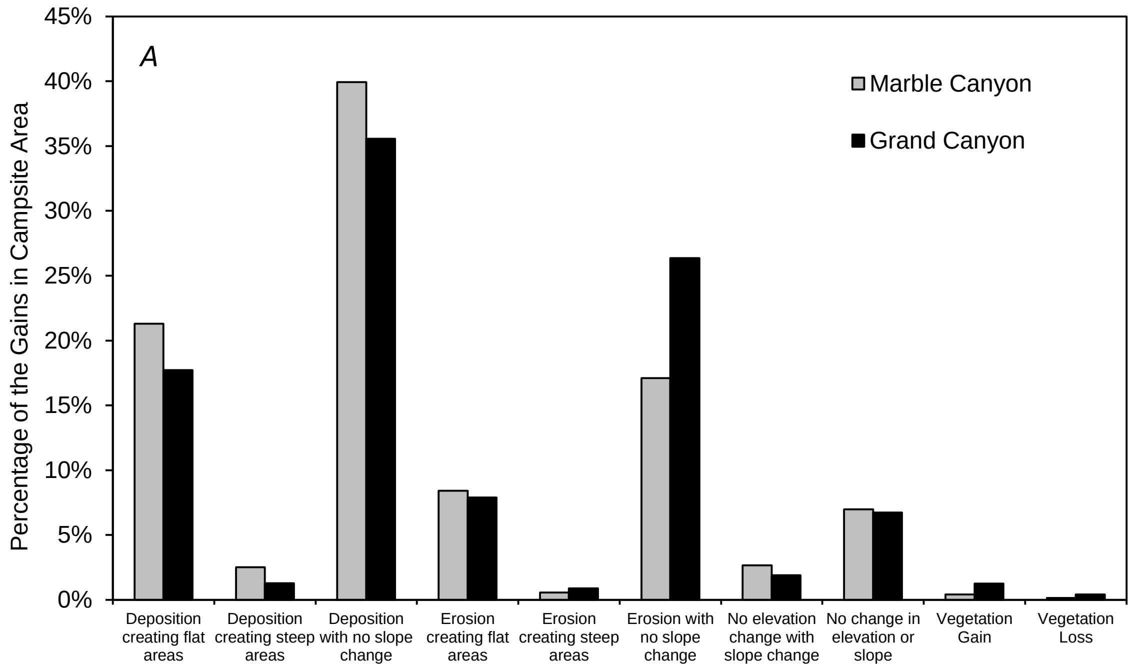


Figure 21. Second order processes associated with (*A*) gains in campsite area and (*B*) losses in campsite area for critical and non-critical reaches.



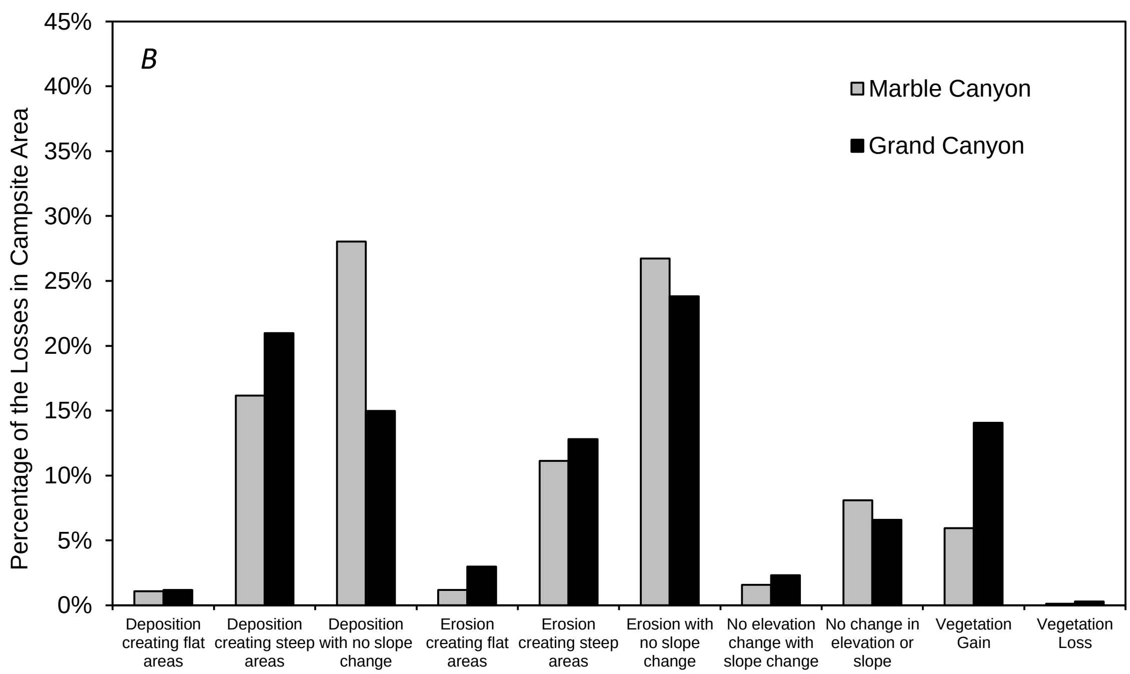


Figure 22. Second order processes associated with (*A*) gains in campsite area and (*B*) losses in campsite area for Marble Canyon and Grand Canyon.

Within critical reaches the largest factor to contribute to a loss in campsite area was erosion without a significant slope change (30 percent), followed by erosion and deposition creating steeper sandbars (20 percent and 17 percent, respectively) (Fig. 21, Table 6). In contrast, deposition without a significant slope change was the primary factor in campsite loss within non-critical reaches (24 percent), and erosion leading to a steeper sandbar was not as significant.

Trends within Marble Canyon and Grand Canyon were similar to one another in regards to the processes that contributed to gains in campsite area. Deposition without a significant slope change was the primary factor in causing gains in campsite area for both Marble Canyon and Grand Canyon (40 percent and 36 percent, respectively) (Fig. 22, Table 6). Within areas of campsite loss, deposition and erosion not associated with a slope change were the two largest factors in Marble Canyon, whereas as erosion without a slope change and deposition creating slope increases were the two largest factors in Grand Canyon (Fig. 22, Table 6).

Gullying

Only two sites, Crash Canyon (RM 62. 9R) and Lower National (RM 167.1L) had a loss of campsite area due to gullying over the course of the study period (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 amount of campsite loss due to gullying was only 117 m^2, which was 1 percent of the overall loss in campsite

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.

Site	River Mile	Side	Gully Area in 2002 (m^2)	Gain in Campsite Area due to Infilling (m^2)	Percentage of Gain due to Infilling
Harry McDonald	23.5	L	241	45	12%
Sandpile	30.7	R	57	0	0%
Eminence	44.5	L	31	10	3%
Crash Canyon	62.9	R	96	21	23%
Grapevine	81.7	L	11	6	3%
Total			436	82	1%

Site	River Mile	Side	Gully Area in 2009 (m^2)	Loss in Campsite Area due to Gullying (m^2)	Percentage of Loss due to Gullying
Crash Canyon	62.9	R	69	15	54%
Lower National	167.1	L	296	102	37%
Total			365	117	1%

area found at the 35 NAU sites. Five sites had gullies present in 2002 and were filled in with flood deposits by 2009, with the exception of Crash Canyon Camp (Table 7). Crash Canyon Camp had a gain in campsite area due to gully infilling but this was mostly negated by another surface runoff event following the 2008 high flow. Harry McDonald Camp was the only site that had a substantial gain in campsite area over the entire course of the study period 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 gain in campsite area 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 NAU sites.

2.5 Discussion

Sandbar Topography Change and Campsite Area Change

Hazel and others (2010) examined the influence of the 2008 HFE and the subsequent erosion of those flood deposits on the changes in campsite area. They showed a strong positive correlation between changes in sandbar volume and changes in campsite area (r^2=0.72, significant at the 95 percent confidence level) 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 burial of vegetation, which would both increase campsite area without causing a change in sandbar area.

Comparisons between changes in sandbar volume and changes in campsite area over the course of the 2002-2009 study period were made for critical and non-critical sites and for low elevation (between the 8,000-25,000 ft^3/s stage elevation for sandbar volume and the 10,000-25,000 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. 23). Changes in sandbar volume and campsite area were calculated as the difference from one survey to the next over the seven year period. In both critical and non-critical 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 non-critical reaches (r^2=0.90 and 0.67, respectively, significant at the 95 percent confidence level) which was similar to the findings of Hazel and others (2008). Changes in campsite area at the low elevation had a very weak correlation with changes in sandbar volume due to the fact that large increases in sand volume at the low elevation, particularly in the 8,000-10,000 ft^3/s range, may not lead to a much of a gain in campsite area because these are areas that are regularly inundated.

The majority of elevation change within areas of campsite gain and loss did not cause a change in sandbar slope (Fig. 24). The most significant process leading to gains in campsite area examined in this study was deposition that wasn’t associated with a significant slope change. This indicates that depositional events are creating new campsite area by smoothing out irregular topography of the sandbar, temporarily

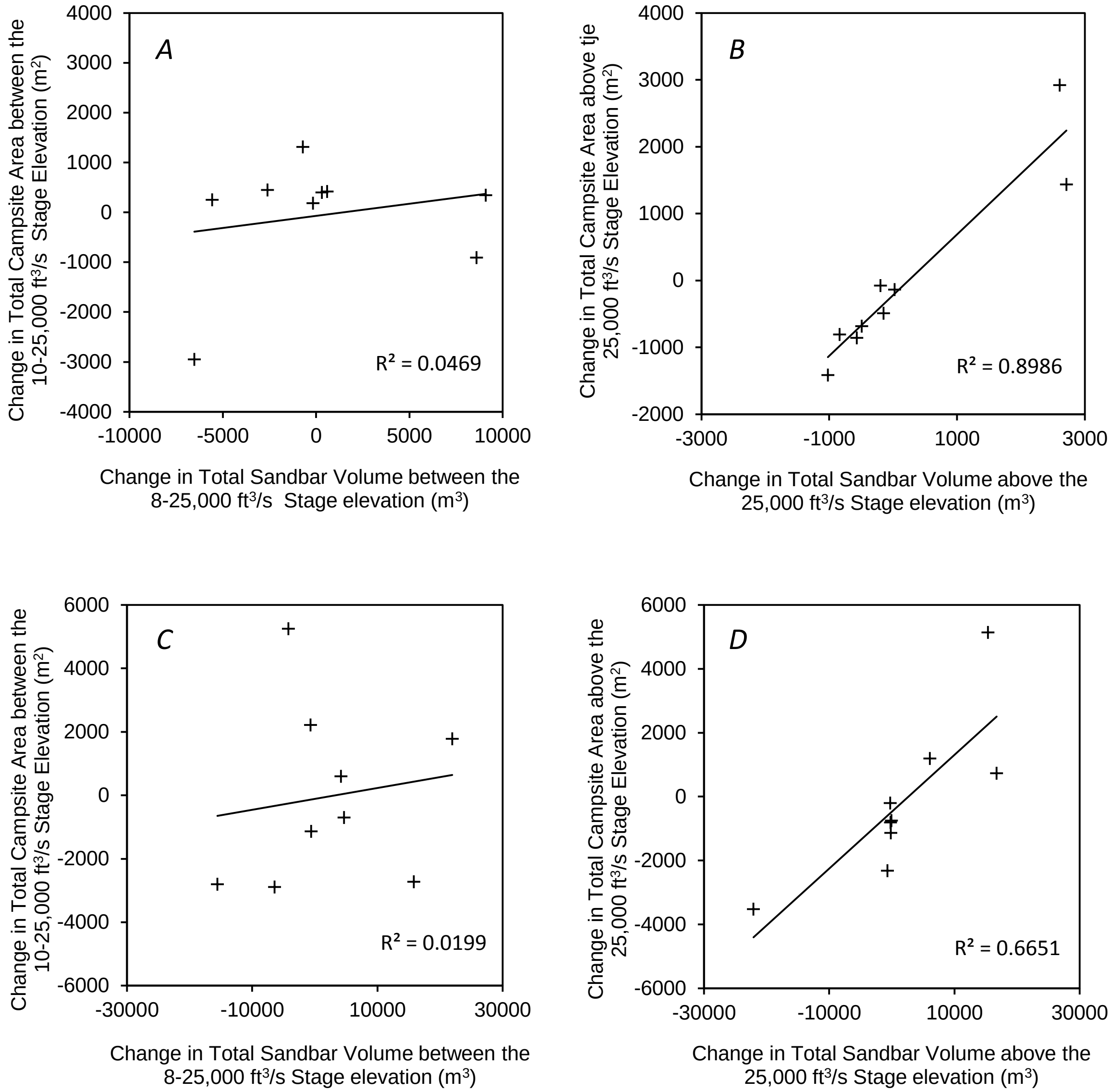


Figure 23. Correlation between changes in sandbar volume and changes in campsite area between 2002 and 2009 at (*A*) low elevations and (*B*) high elevations at sites in critical reaches and (*C*) low elevations and (*D*) high elevations at sites in non-critical reaches.

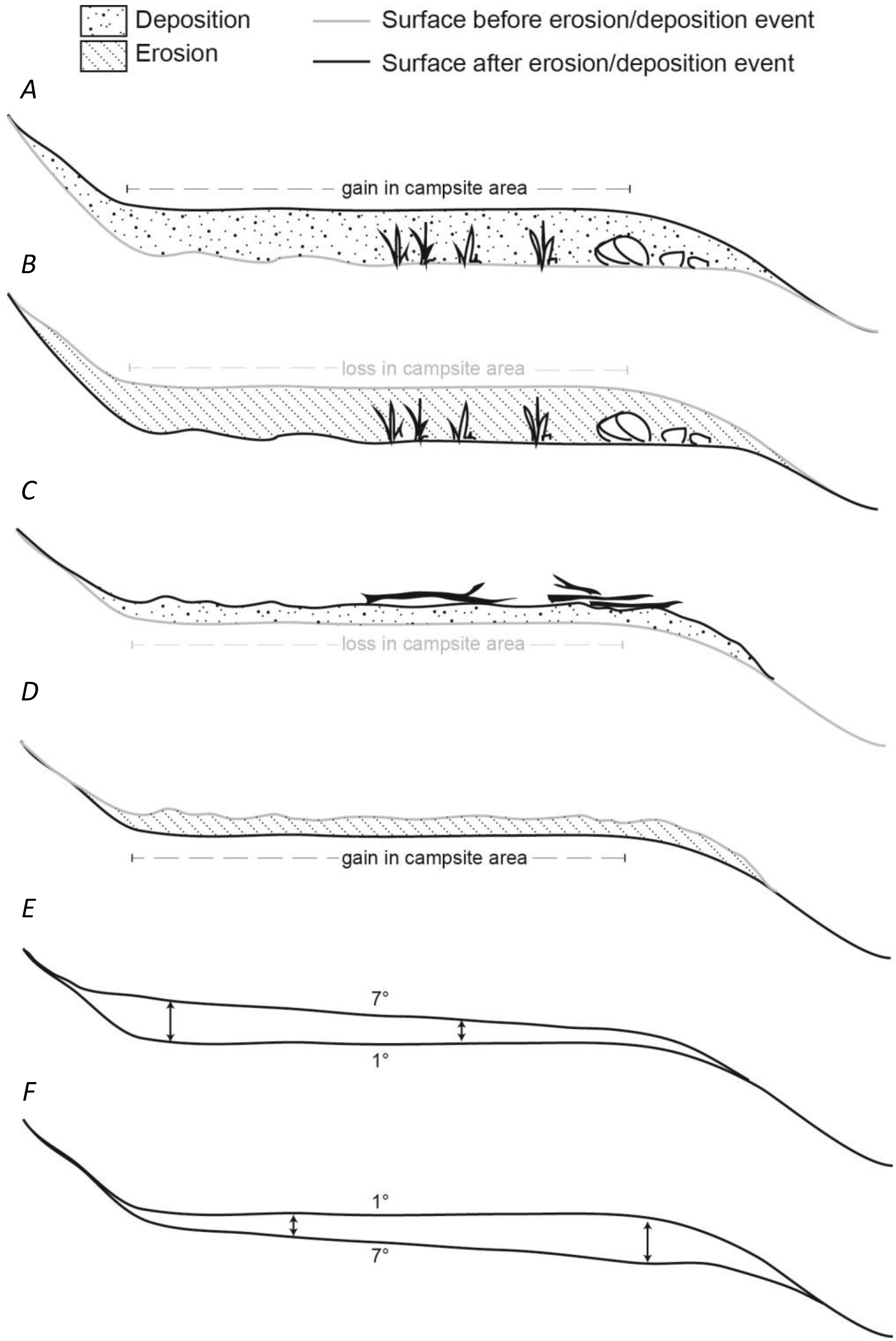


Figure 24. Scenarios of campsite area change due to elevation changes (deposition or erosion) that didn't cause a change in sandbar slope. (*A*) deposition leading to a gain in campsite area due to burial of rough topography, vegetation, or rocks. (*B*) erosion leading to a loss in campsite area due to exposure of rough topography, vegetation, or

rocks. (*C*) deposition leading to a loss in campsite area due to the 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 the 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 it was mapped as a campsite area.

burying rocks along the shoreline, or raising the elevation of the sandbar above zones of regular inundation making them more accessible for camping (Fig. 24). Depositional events could also bury vegetation, which would account for the small losses in vegetation seen at certain sites. This is in agreement with the observations and conclusions of Hazel and others (2010).

A large percentage of the gains in campsite area were also due to erosion not associated with a slope change, which was a surprising find. These observations are 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, or a change in slope that still falls under the category of no slope change (Fig. 24). For example, the slope of a sandbar could have been 7 degrees and not mapped as a campsite area in 2002, but 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 since 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 (discussed further in Chapter 4). For examples, a flat area of the sandbar may have been missed during the campsite survey in 2002, it become eroded by 2009 but remained flat, and was then mapped.

The majority of the losses in campsite area were caused by erosional processes that were not associated with a significant slope change. This was due to a variety of changes in the surface topography of the sandbar, similar to the processes 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 that were previously buried, or roughening the previously smooth surface (Fig. 24). This result could also be explained by changes in the slope of the sandbar that still fall 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. 24).

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 surprising find. Further analysis revealed that much of this loss in campsite area was in fact due to vegetation encroachment that was simply not classified using NDVI methods (see Chapter 3 for a more detailed discussion). Changes in the topography of the bar 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. However, there is not always a direct relationship 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 portions of the bar but can also cause a gain in campsite area by

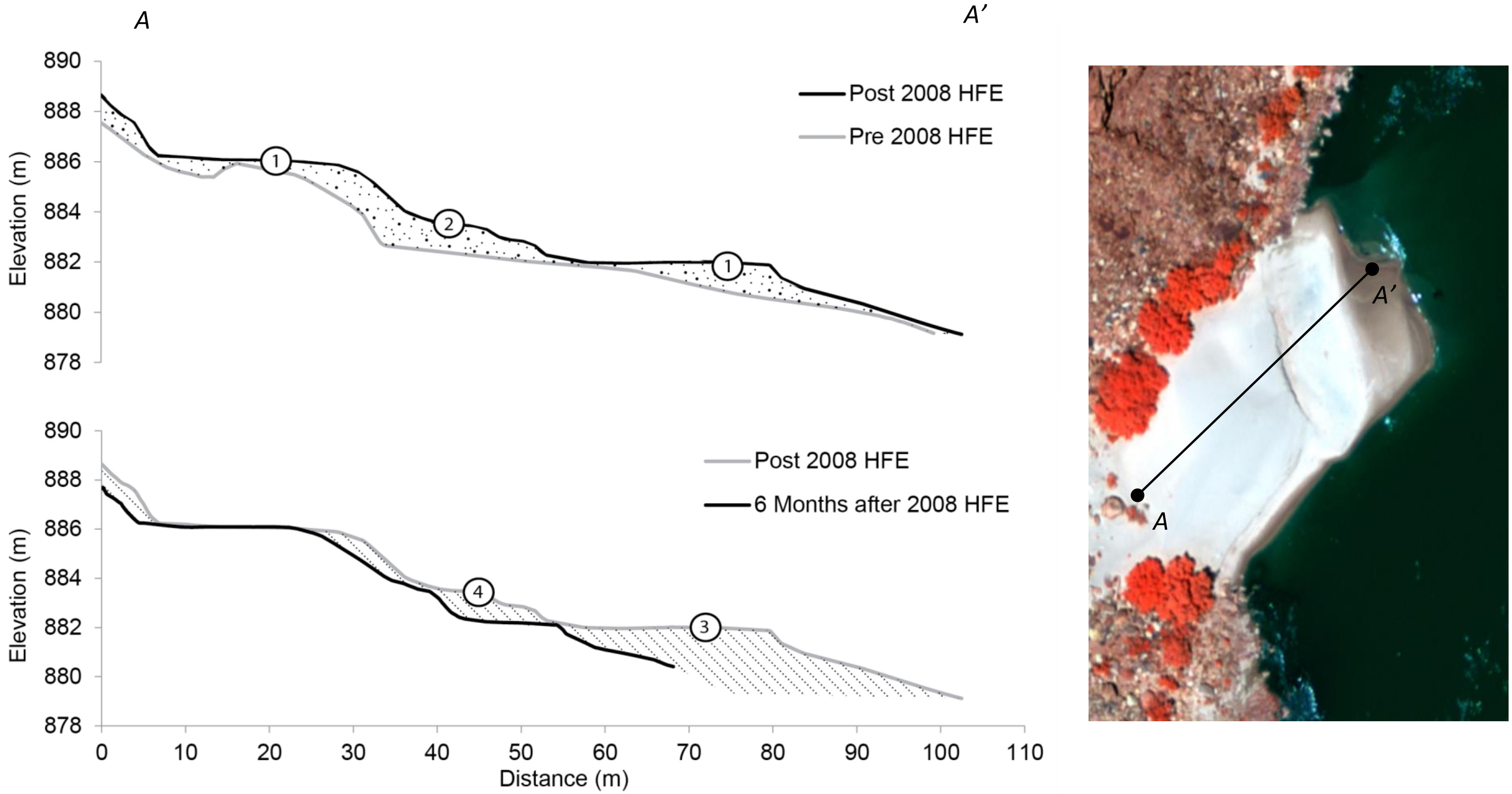


Figure 25. Profiles of 22 Mile (RM 22.0R) before, after, and 6 months after the 2008 high-flow experiment (HFE) showing how deposition or erosion can lead to a change in campsite area by changing the slope of the sandbar. (1) deposition causing a gain in campsite area by creating a flatter portion of the sandbar. (2) deposition leading to a loss in campsite area by increasing the slope at a portion of the sandbar. (3) erosion leading to a loss in campsite area through cutbank retreat. (4) erosion leading to a gain in campsite area by decreasing the slope at a portion of the sandbar. Profiles derived from topographic TIN surfaces. Inset imagery is from May 2009 (vegetation shown in the NIR band).

removing steep portions of a cutbank (Fig. 25). 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 the bar increases too greatly (Fig. 25). This complex relationship is illustrated best within the areas of campsite loss. Even though these areas gained an average of 0.17 m of sand over the course of the study period, they were not mapped as campsite area in 2009 due to much of it becoming too steep (greater than 8 degrees) following deposition.

Mechanisms associated with Net Campsite Area Change

The majority of campsite area change (gains and losses) can be attributed to changes in sandbar topography. However, when it comes to net change, many of the topographic changes can cancel each other out. For example, a very large loss in campsite area due to changes in the elevation and slope of a sandbar could be offset by large gains in campsite area caused by those same processes. This is different than vegetation change, which is largely one directional. Once vegetation is established on a sandbar, there is a more or less permanent reduction in campsite area unless vegetation is physically removed by high flows, which was not observed during the 2008 HFE (Ralston, 2010), or removed by campers. So although gains in vegetation only contributed to 10 percent of the losses in campsite area over the study period, vegetation encroachment is a much larger factor in the context of net campsite area change. Over the course of the study period there was a net loss in campsite area of 2,547 m^2 and there was 1,197 m^2 of area that became covered by vegetation. Thus, vegetation encroachment contributed to 47 percent of the net change in campsite area over the seven year study period with the other 53 percent related to topographic change.

2.6 Conclusions

There was a net loss in campsite area between 2002 and 2009 at the 35 NAU-monitored sites used for this study. Changes in the elevation and slope of sandbars were the dominant mechanisms that contributed to the 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. In terms of net change, the mechanisms of slope and elevation change are still the primary factors, but vegetation change becomes nearly as important. Vegetation encroachment contributed to almost half of the net loss even though it only accounted for 10 percent of campsite area lost over the study period. This is due to the fact that once vegetation is established there is a long-term loss of campsite area unless the vegetation is physically removed.

The majority of the gains and losses that contributed to the net loss in campsite area can be attributed to depositional and erosional processes affecting the slope of the sandbar, and from depositional and erosional processes that did not change the slope of the sandbar around the 8 degree threshold. The primary factors leading to losses in campsite area were erosion caused by fluctuating dam flows and deposition associated with HFEs that increased the slope of the bars too greatly.

Vegetation expansion was greater on average at sites within non-critical reaches than at sites in critical reaches, and was also greater at sites in Grand Canyon in comparison to sites in Marble Canyon. The influence of vegetation expansion on campsite loss may also be greater than what the results indicate due to the error in the NDVI classification within areas of sand that are sparsely vegetated (see the discussion section in Chapter 3 for specific examples). Gullying can be a significant factor in the loss of campsite area at certain sites, such as at Crash Canyon Camp, but overall erosion from surface runoff events was a minor factor.

Hazel and others (2010) attributed gains in campsite area with deposition of sand associated with the 2008 HFE, and attributed losses in campsite area largely with lateral cutbank retreat of the newly deposited sand due to 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 over a longer time period that included two high-flow experiments. The conclusions that depositional and erosional processes due to dam management activities are the primary factors in contributing to campsite area change, and that gullying and encroachment of vegetation are secondary factors, is also consistent with the observations made by AAB participants over the course of the study period (Lauck, 2007, 2009, 2010).

Erosion and changes in sandbar slope occurred more often at sites within critical reaches, suggesting that the dynamic zones of these bars make up a larger percentage of the bar in comparison to sites in non-critical reaches. Therefore, campsite areas in critical reaches may not be as stable as campsite areas in non-critical reaches. Erosion and slope changes were less significant at sites within non-critical 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 Glen Canyon Dam Adaptive Management Program.

CHAPTER 3

ANALYSIS OF VEGETATION CHANGE AT ALL ESTABLISHED CAMPSITES ALONG THE COLORADO RIVER CORRIDOR

3.1 Introduction

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 due to alterations in the flow regime (Turner and Karpiscak, 1980; Waring, 1996; Webb, 2002; Ralston, 2005, 2010; Ralston and others, 2008) (Fig. 26). Flow regulation through Glen Canyon Dam has replaced the natural flow regime, characterized by large seasonal floods and low base flows, with a flow regime that has large daily fluctuations in discharge, median flows that are higher in comparison to pre-dam flow, and a reduction in the frequency and magnitude of flooding events (Topping and others, 2003) (Fig. 5).

Previous studies by Turner and Karpiscak (1980) and Waring (1996) show that riparian vegetation has expanded downslope of the pre-dam high water zone due to the decrease in flood frequency and magnitude. 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). Riparian vegetation that has expanded along the river corridor and

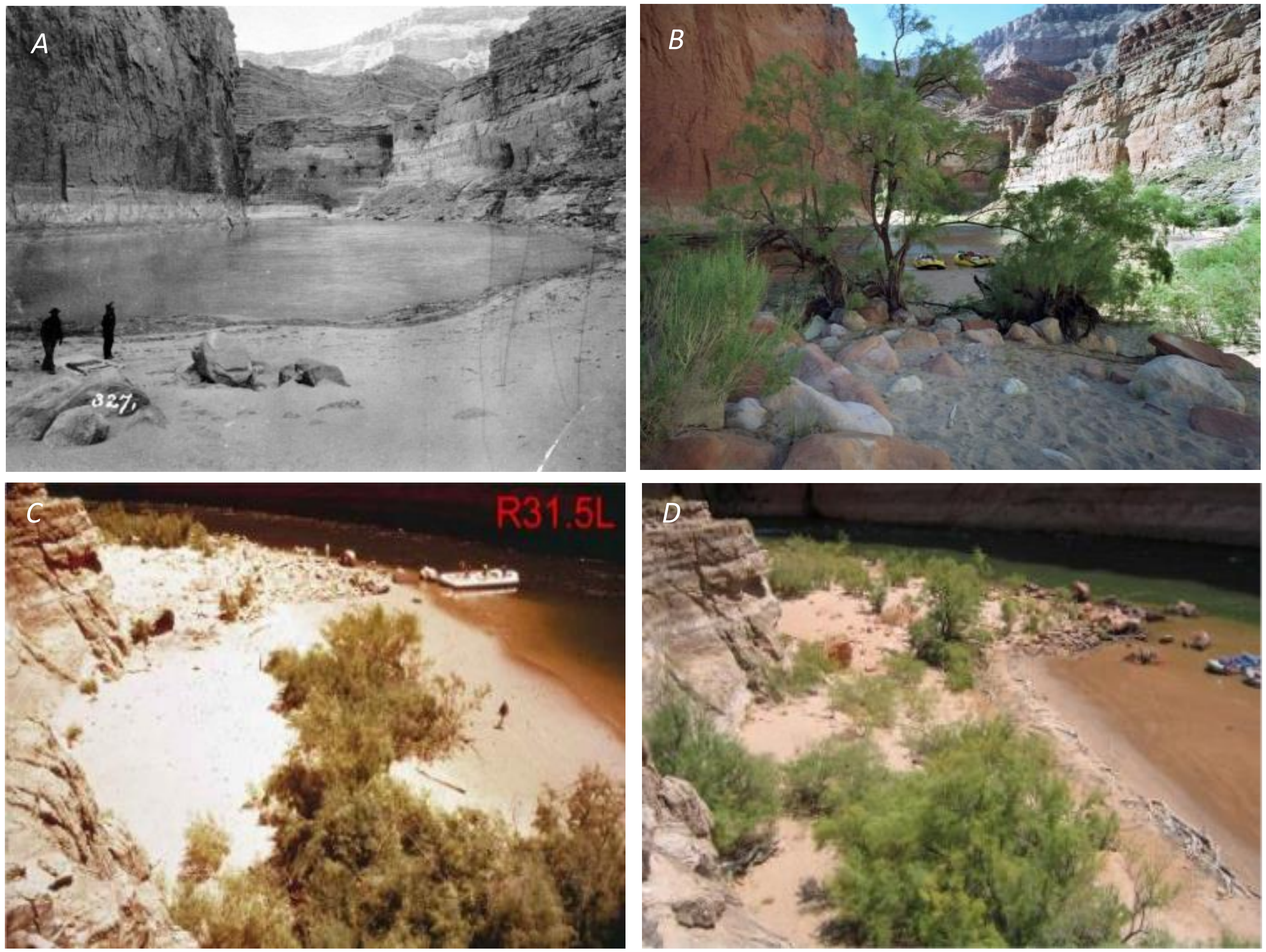


Figure 26. Matched photographs at South Canyon Camp (RM 31.9R) showing the increase in vegetation cover. (*A*) photograph taken by Franklin A. Nims in 1889 during the Stanton expedition, looking downstream, and (*B*), the matched photograph taken in 2010 by John Mortimer. (*C*) photograph looking upstream and down upon the camp taken by Weeden in 1973 and (*D*) matched in 2007 by Weeden.

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).

The 1983-1986 floods scoured out much of the vegetation that colonized open sandbars in the preceding decades (Stevens and Waring, 1986; Stevens and others, 1995), but re-colonization of the bars occurred soon after. Previous campsite studies have indicated that expansion of riparian vegetation on sandbars has been a significant factor in the decline of campsite size and abundance since the 1983-1986 floods. Kearsley and Warren (1993) compared their 1991 campsite inventory with a previous inventory conducted in 1983 by Brian and Thomas (1984), and found that 41 percent of all sites were no longer useable as a camp due to vegetation expansion (see also Kearsley and others, 1994). Vegetation encroachment was found to be higher in non-critical reaches (47 percent) than in critical reaches (15 percent). Further campsite monitoring conducted by Northern Arizona University (NAU) are in agreement with Kearsley and Warren's previous study and conclude that erosion is the primary mechanism of campsite loss in critical reaches, whereas vegetation expansion is the primary mechanism of campsite loss in non-critical reaches (Kaplinski and others, 2005, 2010).

3.2 Purpose and Objectives

The purpose of this particular project was to expand upon the assessment of vegetation change presented in the previous chapter by: 1) quantifying the amount of vegetation change occurring at NAU-monitored sites since the start of monitoring, instead of between 2002 and 2009, 2) quantifying the amount of vegetation change occurring within National Park Service and USGS defined camp boundaries, and 3) comparing the results between critical and non-critical recreational reaches, between canyon sections (i.e. Marble Canyon vs. Grand Canyon), and between different elevation zones.

It is important to reiterate that the 504 camp boundaries located throughout Glen Canyon, Marble Canyon, Grand Canyon, and the Diamond Creek reach are sites that have been historically used or are currently used for camping purposes. The boundaries encompass areas that are used for camping, but also include features such as boulders, areas of steep sand, and morphologic features such as tributaries. NAU's Sandbar Monitoring Lab measures campsite area within 37 of these camp boundaries. Due to logistical reasons not all campsite area within those 37 boundaries are mapped, as some boundaries are very large and complex. Determining the vegetation change within camp boundaries allows broader trends in vegetation to be seen at all campsites throughout the entire Colorado River corridor, instead of just at the 37 NAU-monitored sites. Determining the vegetation change within these boundaries allows inferences to be made about the relationship between vegetation encroachment and campsite loss where monitoring data is absent. Because the boundaries are fixed, they also provide a consistent area in which long term analysis of vegetation change could be conducted with subsequent vegetation datasets. Similar to the methods of vegetation change presented in Chapter 2, only gross vegetation coverage was used to calculate vegetation change within campsite boundaries.

3.3 Methods

Vegetation Change within Camp Boundaries

Maps of vegetation cover along the Colorado River corridor below GCD, created from 4-band aerial imagery acquired in May 2002 and May 2009, were used to calculate vegetation change in each of the 504 camp boundaries over a 7-year period (see methods section in Chapter 2 for detailed description of image acquisition and vegetation classification). Resolution of the imagery for both years is 0.22 m. The precise co-registration of the 2002 and 2009 maps of vegetation cover allowed for simple change detection within the camp boundaries, resulting in areas of vegetation change as small as 0.0484 m^2 (Fig. 27). Areas of vegetation change were created in ArcGIS using the same methods described in Chapter 2 and consist of: 1) areas of vegetation gain (defined as areas that were vegetated in 2009 but not in 2002), 2) areas of vegetation loss (defined as areas that were vegetated in 2002 but not 2009), and 3) areas of no vegetation change (defined as areas that were vegetated in both 2002 and 2009). Areas of vegetation change were as small as 0.048 m^2. Vegetation change within camp boundaries were then summarized by recreational reach and canyon section.

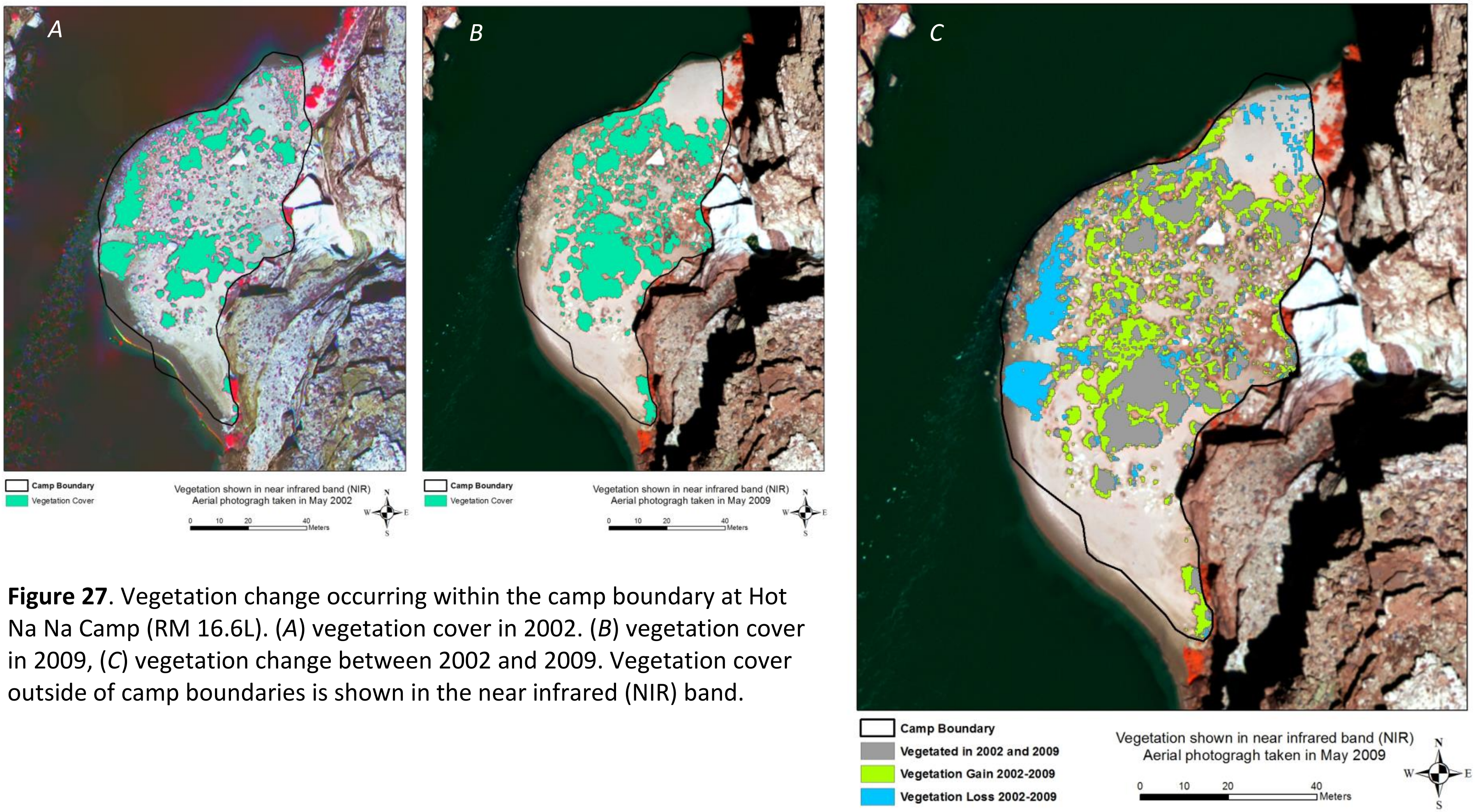


Figure 27. Vegetation change occurring within the camp boundary at Hot Na Na Camp (RM 16.6L). (*A*) vegetation cover in 2002. (*B*) vegetation cover in 2009, (*C*) vegetation change between 2002 and 2009. Vegetation cover outside of camp boundaries is shown in the near infrared (NIR) band.

Vegetation Change within the Extent of Mapped Campsite Area

In an effort to expand upon the previous analysis of vegetation encroachment at NAU-monitored sites, vegetation change was also calculated within the total extent of mapped campsite area (Fig. 28) for each of the 37 NAU-monitored sites. This is different than the previous analysis presented in chapter 2 in that it uses all the campsite surveys conducted at each site instead of just the 2002 and 2009 surveys, and is not limited to just the campsite area with topographic coverage. Extents were created using NAU campsite surveys from 1998-2009 and were limited to this time period because 1998 was the first year of NAU campsite monitoring and 2009 is the latest imagery available for change detection. The extent of mapped campsite area represent areas that were free of vegetation in 1998 because areas that are vegetated are not surveyed as campsite areas. The absence of vegetation in 1998 was verified at each site by viewing aerial imagery from May 2000 and remote camera photographs when available.

Vegetation change within the extent of mapped campsite area was summarized by recreational reach and canyon section. Using stage discharge relationships established by Hazel and others (2006), the amount of vegetation above and below the 25,000 ft^3/s stage elevation was also calculated.

Statistical Analysis

The Mann-Whitney U test was used to see whether differences in net vegetation gain between critical and non-critical reaches and between canyon sections were significant. The Mann-Whitney U test is a non-parametric two sample t-test (Helsel and

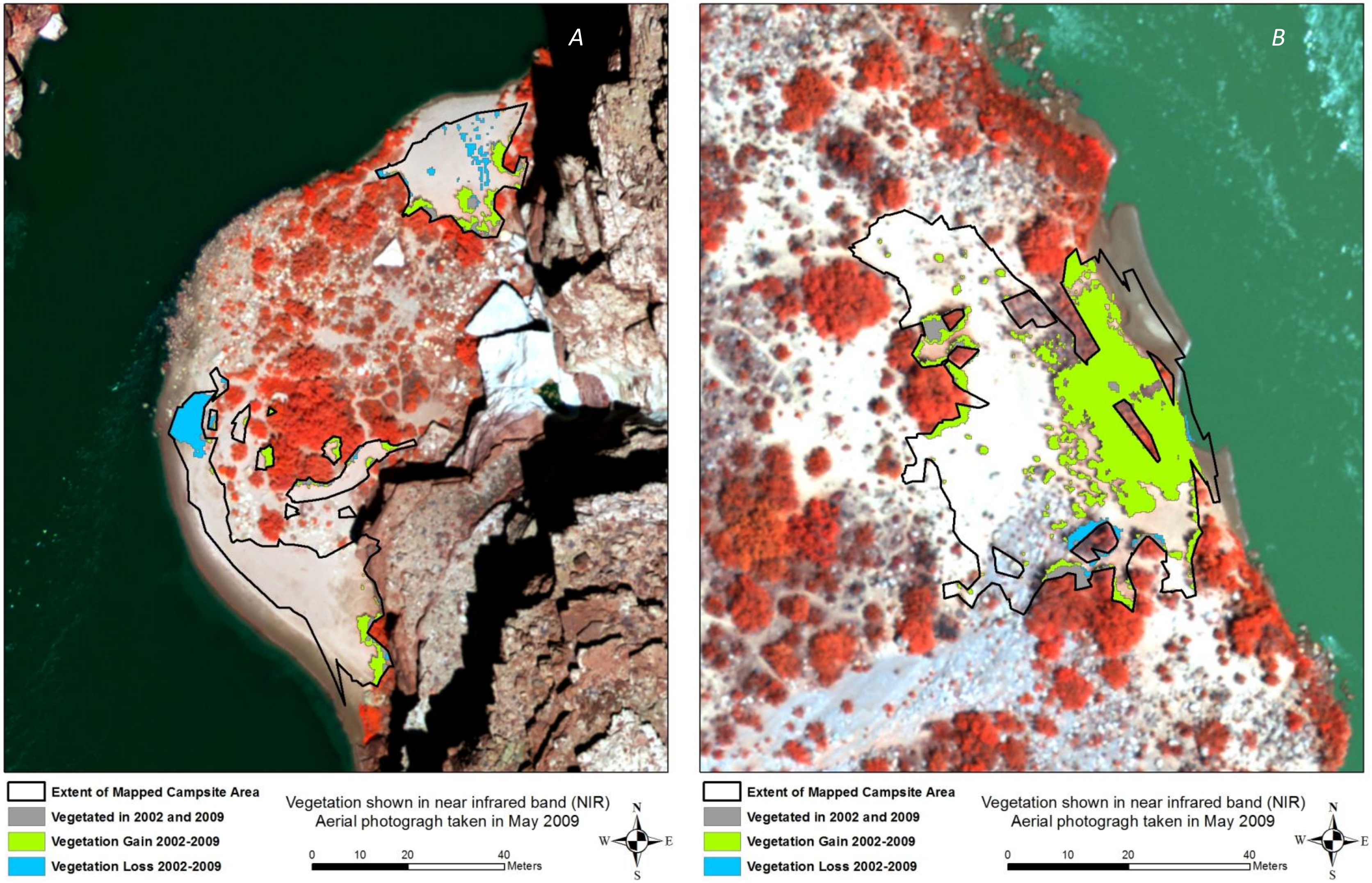


Figure 28. Vegetation change at (*A*) Hot Na Na (RM 16.6L) and (*B*) 220 Mile (RM 220.1R) within the extent of mapped campsite area. Imagery shown is from May 2009 with vegetation cover outside of the extents shown the in the near infrared (NIR) band.

Hirsh, 2002) and was chosen because data was non-normally distributed and samples sizes varied among reach or section. Normality of data was tested using the 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 ($\alpha = 0.05$).

3.4 Results

Vegetation Change within Camp Boundaries

Overall, 13 percent of area within camp boundaries was covered by vegetation in 2002. Between 2002 and 2009 another 13 percent of area within camp boundaries became vegetated and 2 percent of the area lost vegetation, resulting in a net gain of 11 percent during the study period. By 2009, 23 percent of the area within camp boundaries was covered by vegetation (Table 8). Out of 504 sites, only 18 had a net loss in vegetation or had no increase in vegetation, with the remaining 486 sites having a net gain in vegetation. Gains in vegetation varied considerably by sites, with some sites having over 40 percent of their area covered by vegetation during the study period (Lopers Boat Camp [RM 41.4R], Below National Camp [RM 167.5L]) (Appendix D)

Camp boundaries in non-critical reaches had more of their area covered by vegetation in 2002 in comparison to critical reaches (14 percent and 11 percent, respectively) and had slightly more net vegetation gain during the study period in comparison to critical reaches (11 percent and 9 percent, respectively) (Fig. 29). By 2009, 24 percent of the area within camp boundaries in non-critical reaches was

Table 8. Vegetation change between 2002 and 2009 within camp boundaries summarized by canyon section and recreational reach.

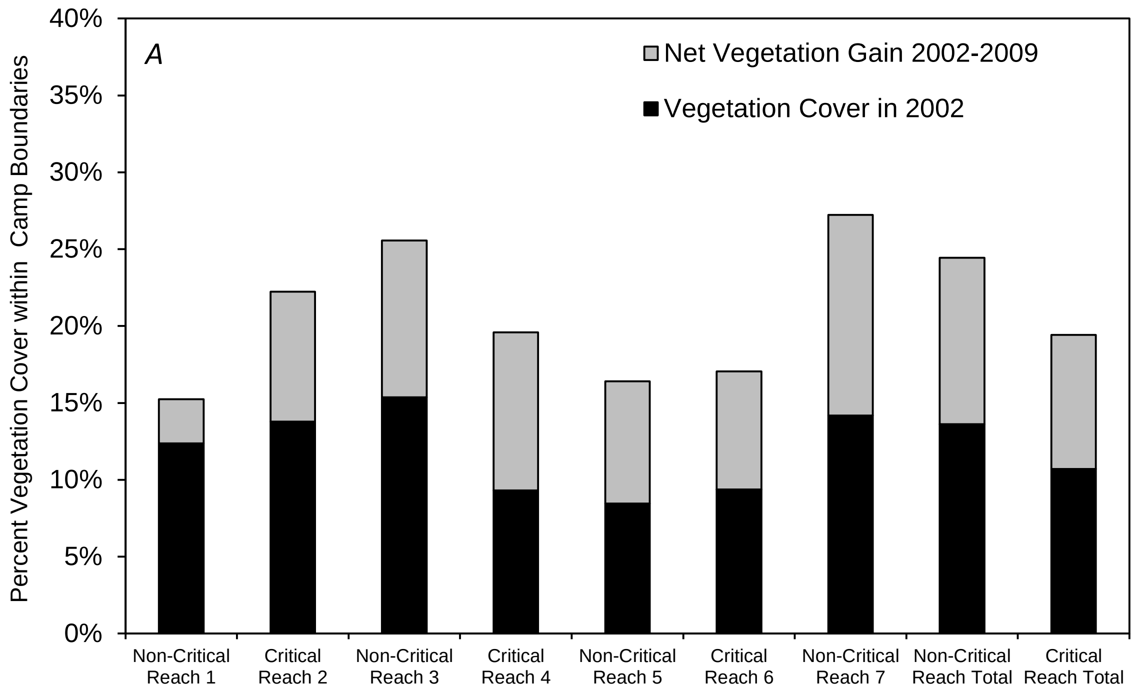
			Percent Vegetation Cover					
Reach	River Mile	Camp Boundary Area (m^2)	Vegetated in 2002	Vegetated in 2009	Vegetated in 2002 and 2009	Vegetation Gain 2002-2009	Vegetation Loss 2002-2009	Net Vegetation Gain 2002-2009
Glen Canyon	-15-0	18849	22%	36%	19%	17%	3%	14%
Marble Canyon	0-62	443333	15%	24%	12%	11%	3%	9%
Grand Canyon	62-225	1256188	12%	23%	10%	13%	2%	11%
Below Diamond	225-267	101333	10%	26%	7%	18%	2%	16%
Non-Critical Reach 1	0-11	66647	12%	15%	9%	6%	3%	3%
Critical Reach 2	11-41	139592	14%	22%	11%	11%	3%	8%
Non-Critical Reach 3	41-77	404958	15%	26%	13%	13%	3%	10%
Critical Reach 4	77-116	144134	9%	20%	8%	11%	1%	10%
Non-Critical Reach 5	116-131	184015	8%	16%	7%	9%	1%	8%
Critical Reach 6	131-164	174155	9%	17%	8%	9%	2%	8%
Non-Critical Reach 7	164-225	586021	14%	27%	12%	15%	2%	13%
Non-Critical Reach Total		1241640	14%	24%	11%	13%	2%	11%
Critical Reach Total		457881	11%	19%	9%	11%	2%	9%
All Sites		1819703	13%	23%	11%	13%	2%	11%

covered by vegetation, with critical reaches having 19 percent of its area covered by vegetation. The net change in vegetation varied by individual recreational reach, with non-critical reach 7 (RM 164-225) having the largest gain (13 percent) and non-critical reach 1 (RM 0-11) having the smallest gain (3 percent). Results of the Mann-Whitney test show that the net vegetation gain in critical reaches was significantly higher than the net vegetation gain in critical reaches (U=20712, p-value < .001, Table 9).

Camp boundaries in Grand Canyon had a slightly higher net gain in vegetation cover than at sites in Marble Canyon (11 percent and 9 percent, respectively) (Fig. 29) and was shown to be significant (U=16754, p-value < 0.001, Table 9). 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 9). By 2009 Glen Canyon had the highest amount of vegetation cover within camp boundaries at 36 percent (Fig. 29).

Vegetation Change within the Extent of Mapped Campsite Area

Vegetation change occurring within the extent of mapped campsite area followed similar trends to vegetation change within camp boundaries. Between 1998 and 2002, 2 percent of the extent of mapped campsite area became covered with vegetation. Between 2002 and 2009 another 8 percent of area became vegetated, resulting in 10 percent of the extent of mapped campsite area becoming vegetated by 2009 (Table. 10, Fig. 30). Because mapped campsite areas were free of vegetation in 1998, this indicates a 10 percent loss of campsite area as a result of vegetation



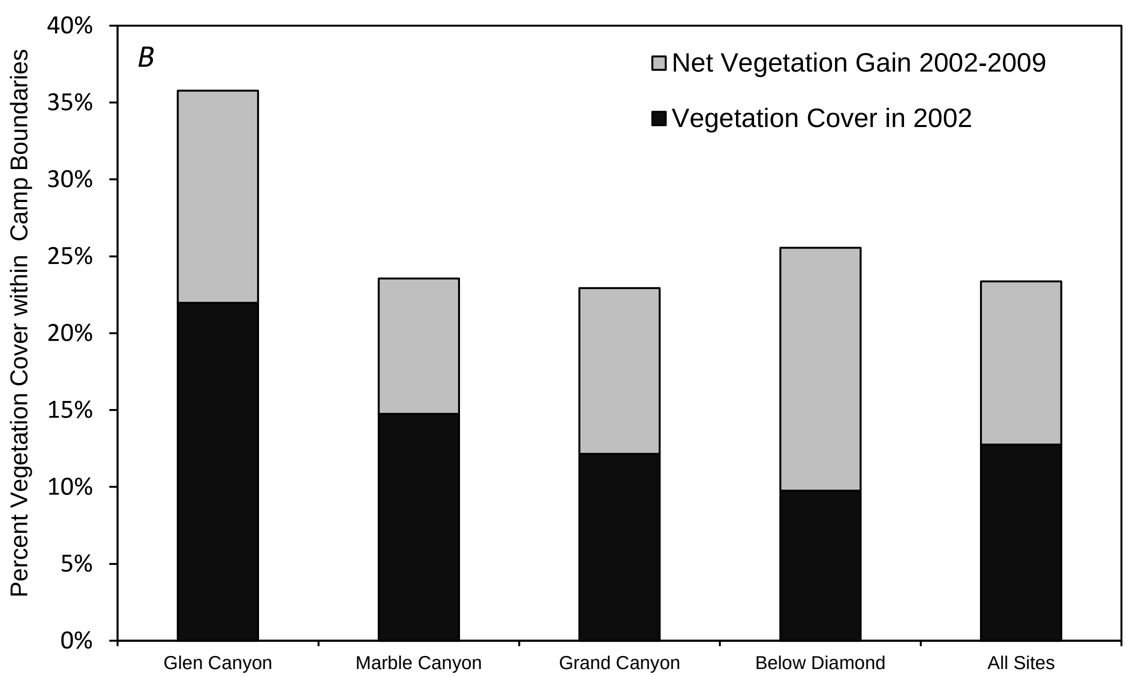


Figure 29. Vegetation change between 2002 and 2009 within camp boundaries summarized by (*A*) recreational reach and (*B*) canyon section.

Table 9. Results of Mann Whitney statistical comparisons of vegetation change within camp boundaries, tested at the 95 percent confidence level (α = 0.05).

Hypothesis	Result	Test Statistic (U)	p-value
Glen Canyon > Marble Canyon	TRUE	549	0.013
Glen Canyon > Grand Canyon	TRUE[1]	1478	0.050
Glen Canyon < Below Diamond	FALSE	73	0.470
Marble Canyon < Grand Canyon	TRUE	16754	4.1E-04
Marble Canyon < Below Diamond	TRUE	746	4.5E-05
Grand Canyon < Below Diamond	TRUE	2739	7.2E-04
Critical < Non-Critical	TRUE	20712	2.4E-04
Total > no change	TRUE	122079	2.2E-12

[1] actual p-value is less than 0.050 but is rounded

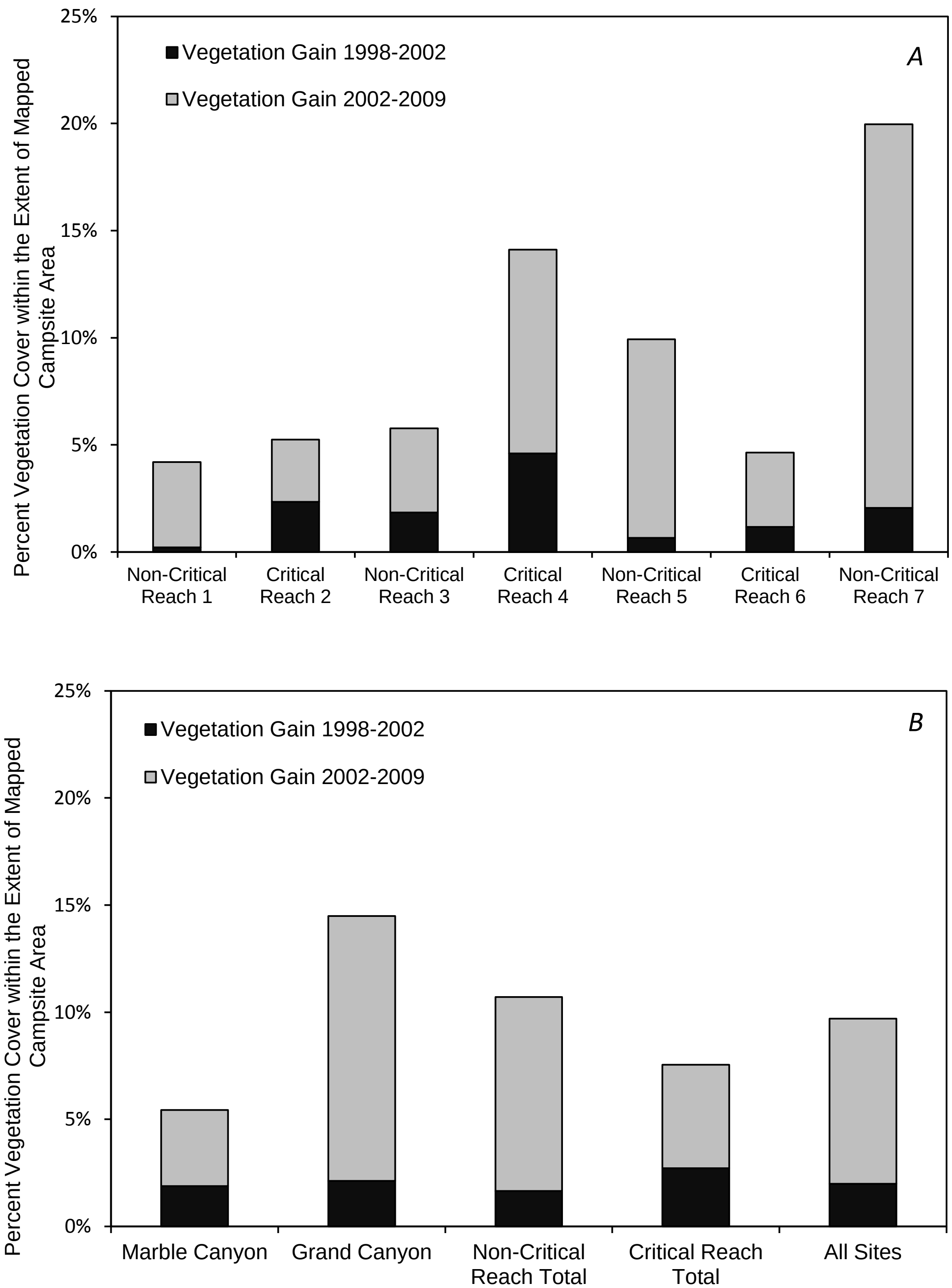


Figure 30. Vegetation change between 1998 and 2009 within the extent of mapped campsite area summarized by (*A*) individual recreational reach and by (*B)* reach totals and canyon section.

Table 10. Vegetation change within extent of mapped campsite area between 1998 and 2009 summarized by canyon section and recreational reach.

			Percent Vegetation Cover						
Reach	River Mile	Extent of Mapped Campite Area (m^2)	Vegetated in 1998	Vegetated in 2002	Vegetated in 2009	Vegetated in 2002 and 2009	Vegetation Gain 2002-2009	Vegetation Loss 2002-2009	Net Vegetation Gain 2002-2009
Marble Canyon	0-62	36528	0%	2%	5%	1%	4%	1%	4%
Grand Canyon	62-225	32502	0%	2%	14%	2%	13%	0%	12%
Non-Critical Reach 1	0-11	2391	0%	0%	4%	0%	4%	0%	4%
Critical Reach 2	11-41	11454	0%	2%	5%	1%	4%	1%	3%
Non-Critical Reach 3	41-77	23147	0%	2%	6%	1%	4%	0%	4%
Critical Reach 4	77-116	6062	0%	5%	14%	4%	10%	1%	10%
Non-Critical Reach 5	116-131	6807	0%	1%	10%	1%	9%	0%	9%
Critical Reach 6	131-164	4601	0%	1%	5%	1%	4%	0%	3%
Non-Critical Reach 7	164-225	14568	0%	2%	20%	2%	18%	0%	18%
Non-Critical Reach Total		46913	0%	2%	11%	1%	9%	0%	9%
Critical Reach Total		22117	0%	3%	8%	2%	6%	1%	5%
All Sites		69030	0%	2%	10%	1%	8%	1%	8%

expansion over the course of the study period. Every one of the 37 sites had a net gain in vegetation. By 2009, some sites had over 25 percent of their area covered with vegetation (Granite Camp [RM 98.3L], 172 Mile Camp [RM 172.2L], and 220 Mile Camp [RM 220.1R], Fig. 31, Appendix E)

Overall, sites in non-critical reaches had a greater gain in vegetation than sites in critical reaches (11 percent and 8 percent, respectively) and was shown to be significant only at the 90 percent confidence level (U=120, p-value < 0.10, Table 11). There was variation within individual recreational reaches, with non-critical reach 7 and critical reach 4 having the largest loss of campsite area due to vegetation encroachment (20 percent and 14 percent, respectively) (Table. 10, Fig. 30). Increases in vegetation cover were higher at sites within Grand Canyon (14 percent) than at sites within Marble Canyon (5 percent) (Fig. 30) and were shown to be significant (U=84, p-value < 0.001, Table 11).

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 calculated using stage discharge relations established by Hazel and others (2006) at each site (Appendix F) and was summarized by recreational reach and canyon section (Table 12, Fig. 32). Overall, 81 percent of the vegetation present in 2002 was in high-elevation campsite area. By 2009 the amount of vegetation present in high elevation campsite area increased to 86 percent. Non-critical reaches had a higher amount or vegetation in high-elevation campsite area in both 2002 and in 2009 in comparison to critical reaches. In comparing canyon section, sites in Grand Canyon had a higher amount or vegetation

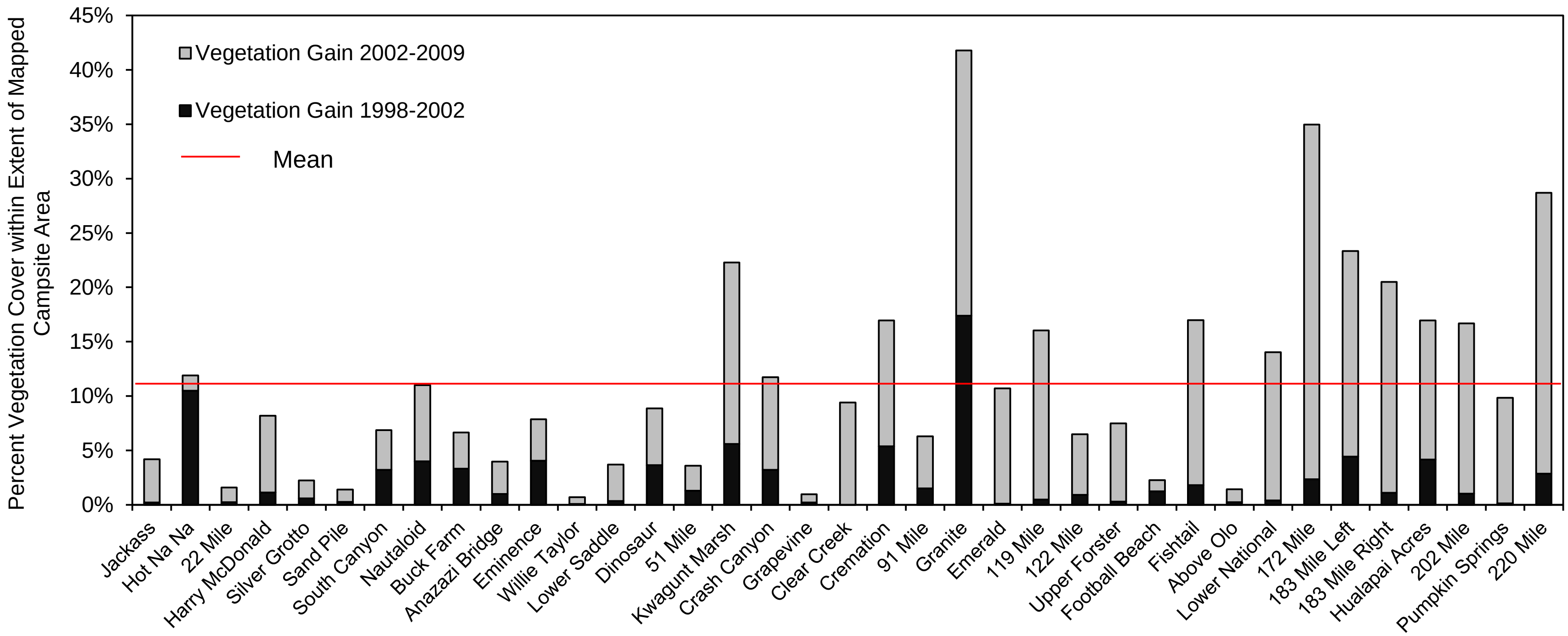


Figure 31. Vegetation change between 1998 and 2009 within the extent of mapped campsite area at each NAU-monitored site.

Table 11. Results of Mann Whitney statistical comparisons of vegetation change between 1998 and 2009 within the extent of mapped campsite area, tested at the 95 percent confidence level ($\alpha = 0.05$).

Hypothesis	Result	Test Statistic (U)	p-value
Critical < Non-critical	FALSE	120	0.070
Marble Canyon < Grand Canyon	TRUE	84	4.90E-03
Total > no change	TRUE	703	5.80E-08

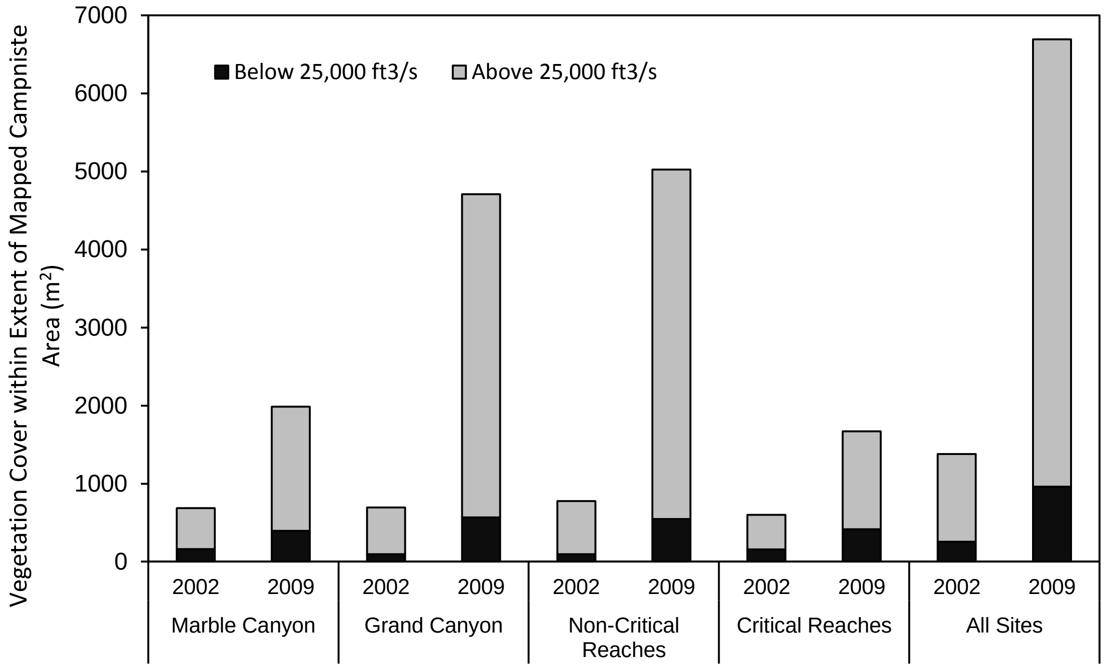


Figure 32. The percentage of vegetated area within the extent of mapped campsite area occurring above and below the 25,000 ft^3/s stage elevation for 2002 and 2009.

Table 12. Percent of vegetation cover within the extent of mapped campsite area above and below the 25,000 ft^3/s stage elevation.

		2002		2009	
Reach	**River Mile**	Percentage of Vegetated Area below 25,000 ft^3/s	Percentage of Vegetated Area above 25,000 ft^3/s	Percentage of Vegetated Area below 25,000 ft^3/s	Percentage of Vegetated Area above 25,000 ft^3/s
Marble Canyon	0-62	23%	77%	20%	80%
Grand Canyon	62-225	14%	86%	12%	88%
Non-Critical Reach 1	0-11	26%	74%	22%	78%
Critical Reach 2	11-41	41%	59%	35%	65%
Non-Critical Reach 3	41-77	11%	89%	12%	88%
Critical Reach 4	77-116	12%	88%	14%	86%
Non-Critical Reach 5	116-131	10%	90%	14%	86%
Critical Reach 6	131-164	25%	75%	37%	63%
Non-Critical Reach 7	164-225	14%	86%	9%	91%
Non-Critical Reach Total		13%	87%	11%	89%
Critical Reach Total		26%	74%	25%	75%
All Sites		19%	81%	14%	86%

in high-elevation campsite area in both 2002 and in 2009 in comparison to sites in Marble Canyon.

3.5 Discussion/Conclusions

Vegetation expanded considerably within camp boundaries during the study period and follows similar trends to vegetation change occurring throughout the entire river corridor (Sankey and others, *in review*). Vegetation expansion was greater within camp boundaries located in non-critical reaches than in critical reaches, which is similar to what has been found for vegetation change within wide geomorphic reaches versus narrow geomorphic reaches (Sankey and others, *in review*). The gain in vegetation between 2002 and 2009 and the total amount of vegetation present by 2009 indicates that vegetation makes up a substantial portion of area within camp boundaries and is likely expanding. However, to attribute vegetation gain within these boundaries to a direct loss of campsite area might be overestimating the impact vegetation expansion has had, since the boundaries may consist of areas that have never been used for camping purposes.

The vegetation cover present by 2009 within the extent of mapped campsite area represents a direct loss of campsite area due to vegetation expansion, as areas that become vegetated can no longer be used for camping purposes. The 10 percent loss of campsite area due to vegetation expansion between 1998 and 2009 (which occurred mostly in high-elevation campsite areas) indicates that vegetation expansion was a primary factor in campsite loss in both non-critical and critical reaches over the course of the 11 year study period in terms of net campsite loss. This is in agreement with the conclusions discussed in Chapter 2 and is consistent with vegetation expansion that has been documented in the preceding decades by river guides and Grand Canyon researchers, historical photographs, and previous campsite inventory studies (Kearsley and Warren, 1993; Kearlsey and others, 1994). Losses in campsite area due to vegetation encroachment varied slightly between this analysis and the analysis discussed in chapter 2 due to differences in the area analyzed. This study analyzed a larger dataset of campsite area (since it included all surveys between 1998 and 2009), whereas the analysis in chapter 2 only calculated vegetation change with campsite areas mapped in 2002 and 2009.

It is worth noting the limitations of using aerial imagery and NDVI classification to map vegetation cover at campsites. Depending on the site, vegetation cover may be underestimated or overestimated. The aerial imagery used for this study does not detect patches of vegetation smaller than the imagery resolution, patches of vegetation that are very sparse, nor are patches of dead vegetation matter detected (such as tamarisk branches) since there is not an infrared signal. Two sites, Anasazi Bridge Camp (RM 43.4L) and Kwagunt Marsh Camp (RM 55.9R), illustrate an underestimation of vegetation cover. At Anasazi Bridge Camp individual arrowweed plants are scattered through the site, making many areas unusable for camping. The density of the arrowweed patches are too low, however, to be detected. The imagery clearly shows that not all the vegetation at that site is being detected within the extent of mapped campsite area (Fig. 33). At Kwagunt Marsh Camp, 22 percent of its campsite area was

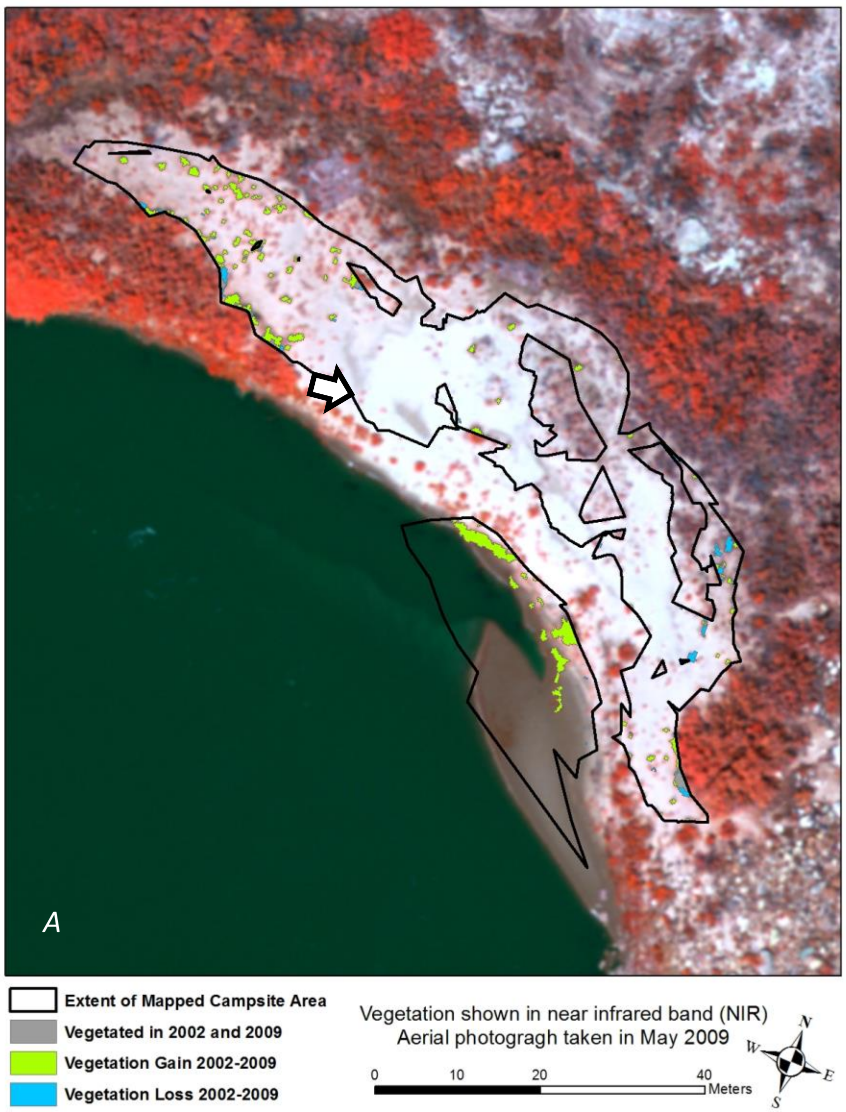


Figure 33. Vegetation cover map (*A*) and photograph (*B*) at Anasazi Bridge (RM 43. 5L) showing the under representation of vegetation cover detected by the NDVI classification. Note the many small patches of vegetation (shown in the NIR band) that have not been detected within the extent of mapped campsite area. Much of the vegetation present is individual arrowweed plants as seen in the photograph taken on 9/24/2013. Location and direction of photograph indicated with arrow.

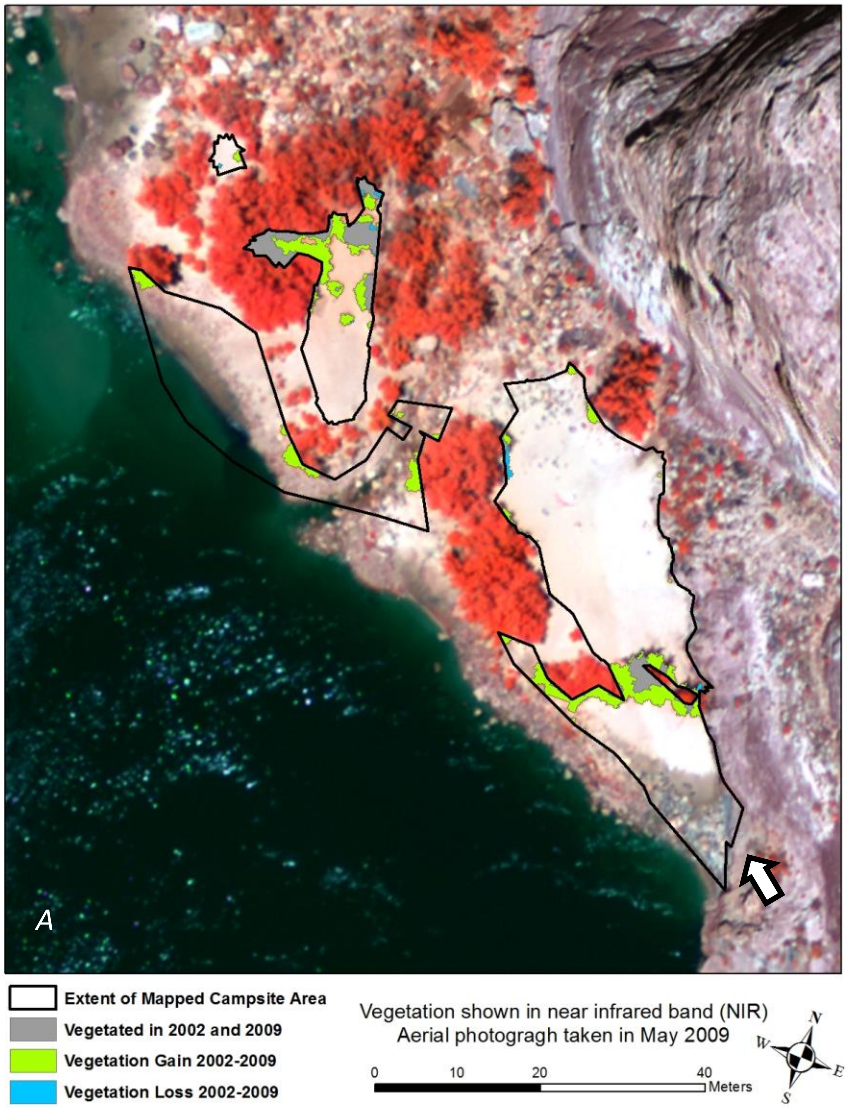


Figure 34. Vegetation cover map (*A*) and photograph (*B*) at Nautiloid Camp (RM 35.1L) illustrating how the amount of campsite loss due to vegetation expansion can be overestimated. Tamarisk canopies can overhang campsite areas. From an aerial perspective these campsite areas might look entirely vegetated, but areas underneath the canopies might still be used (red arrow). Photograph taken on 9/24/2013. Location and direction of photograph indicated with white arrow.

lost due to vegetation expansion, but field observations and the imagery show that dead vegetation matter covers much of the site and that vegetation expansion has had a much greater impact on the loss of campsite area.

On the other hand, vegetation cover can be overestimated at some sites due to the fact that stands of tamarisk can have canopies that overhang above campsite areas. From an aerial perspective it will look vegetated, but underneath the canopy there may be areas of open sand being used for camping (Fig. 34). Despite these exceptions, it is clear that vegetation expansion has had a considerable impact on the loss in campsite area throughout the study period.

CHAPTER 4

EVALUATING THE USE OF GIS-EQUIPPED TABLETS FOR IMPROVING CAMPSITE MONITORING METHODS

4.1 Introduction

A decline in the number, size, and quality of sandbar campsites along the Colorado River corridor since the closure of Glen Canyon Dam has long been recognized by river runners and scientists (Weeden and others, 1975; Brian and Thomas, 1984; Kearsley and Warren, 1993; Kearsley and Quartoroli, 1997; Kaplinski and others, 2005, 2010, 2014). The abundance and size of campsites determines the visitor carrying capacity within Grand Canyon National Park and is the primary metric for evaluating the impact of Glen Canyon Dam operations on recreational resources (Kaplinski and others, 2002). Campsite monitoring is therefore an important component of resource monitoring within the park and is used to inform management decisions regarding recreational resources.

Campsite monitoring has been occurring since the mid 1970's, but it has been recognized that monitoring efforts have varied spatially, temporally, and by methodology (Kalinski and others, 2003). Kaplinski and others (2003) reported on the history of campsite monitoring and the need for a consistent long-term campsite monitoring program that better evaluates campsite change and visitor capacity. They evaluated different campsite survey methodologies which included 1) the use of total stations to measure campsite area (referred to as the total station method), 2) mapping campsite area onto paper copies of aerial photographs (referred to as the aerial photo method), and 3) mapping campsite area directly onto a digital ortho-rectified image using field tablets equipped with ESRI ArcGIS (referred to as the orthophoto method). They concluded that both the orthophoto and total station methods provided sufficient accuracy and precision to map campsite area.

The total station method has been adopted as the preferred choice for campsite surveys for logistical reasons, as it coincides with a longer term sandbar monitoring program. Total station surveys map campsite area from year to year but do not attribute reasons for those changes to campsite area. In other words, the surveys determine how campsite area has changed over time, but the factors that contribute to that change are not quantified.

There is also a certain degree of subjectivity when mapping campsite area in the field even though survey crews follow established criteria. Campsite area can vary in size depending on how survey crews select which areas on a sandbar to be mapped and how they chose to delineate each campsite polygon (it is important to reiterate that campsite area is the sum of campsite polygons mapped at a campsite). Although the horizontal and vertical error associated with individual total station points is very low (±0.05-0.25 m in the horizontal direction and ±0.05-0.09 m in the vertical direction; Hazel and others, 2008), campsite polygons will vary slightly in size between survey crews depending on how many points are used to delineate each campsite polygon. Kaplinski and others (2002) conducted a repeat total station measurement at Nautiloid Camp (RM 35.0L) during a 1998 survey trip a found a 3.7 percent difference in area between the independent surveys completed by two experienced survey crews. Subsequent studies by Kaplinski and others (2005, 2010, and 2014) have conservatively reported an uncertainty in mapping campsite area using the total station method of 10 percent.

4.2 Purpose and Objectives

The primary goal of this project was to develop a robust tablet-based campsite monitoring method that 1) quantifies the factors that contribute to campsite area change in addition to mapping campsite area, 2) maps other geomorphic and campsite features such as gullies and boat mooring areas, 3) can attribute data to digitized features, and 4) is easier and more intuitive than the previous orthophoto method that used ESRI ArcGIS.

A secondary goal was to evaluate the uncertainty associated with the proposed tablet-based method of measuring campsite area and to reevalaute the uncertainty of the current total station-based method based on repeated measurements. Because the tablet-method is a new survey method, the uncertainty associated with mapping campsite area using the selected software is unknown.

The total uncertainty (U_{total}) in mapping campsite area using the total station or tablet method can be estimated as:

$$U_{total} = \sqrt{(U_{surveyor})^2 + (U_{method})^2} \quad \text{(1) (Taylor, 1997)}$$

Where $U_{surveyor}$ is the uncertainty associated with how a surveyor selects areas that fit campsite area criteria and how they choose to delineate campsite polygons and U_{method} is the uncertainty associated with measurement error using either total station techniques or tablets (i.e., the ability to accurately map campsite polygons). Because total station measurements are very accurate and the measurement error is very low, the majority of the reported uncertainty when using the total station method is due to a surveyor's selection and delineation of campsite polygons.

4.3 Methods

Initial Assessment of Using iPads as a Campsite Survey Method

iPad tablets equipped with an iPad-based GIS application called GIS Pro (Garafa, LLC, 2013) were used to conduct campsite surveys during two separate river trips. Fourth generation iPads (WiFi + Cellular model) were selected because they have a relatively low cost, they are lightweight, have a long battery life, and are equipped with a 5 megapixel camera and GPS capability. The iPads internal GPS runs on the GPS and GLONASS satellite systems and can be accurate to within a few meters (based on field observations). The GIS Pro program was chosen because of its ability to digitize point, line, or polygon features directly onto imported orthoimagery, it can attribute digitized features, and has customizable field forms and layer symbology (Fig. 35). iPads were also equipped with LifeProof brand waterproof/shockproof cases and anti-glare screen protectors for use in the field.

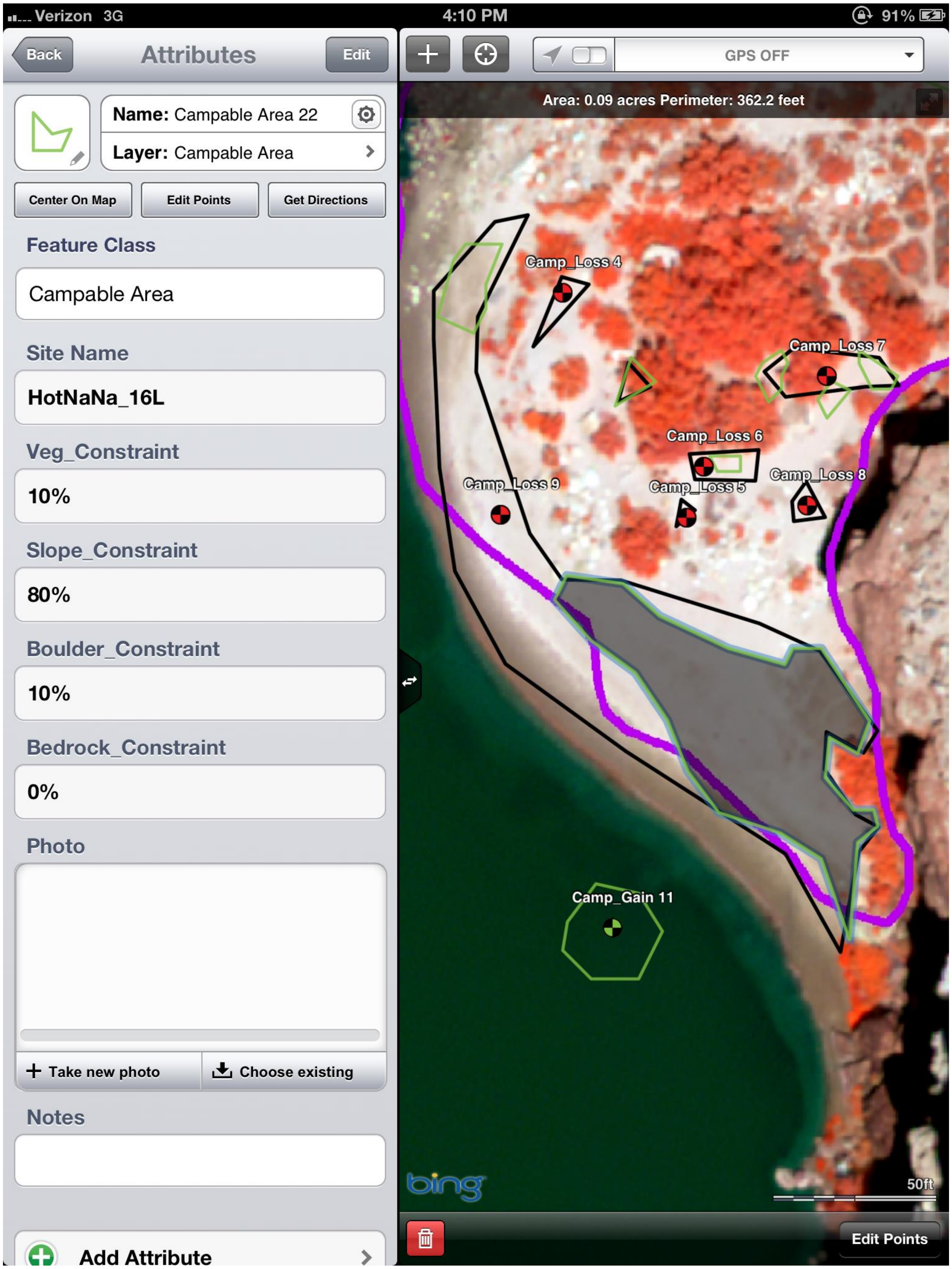


Figure 35. Screenshot of the GIS Pro application illustrating how data can be attributed to digitized features. Example shown is a campsite polygon (shaded grey) at Hot Na Na Camp (RM 16. 6L) being attributed with constraints.

An initial assessment of using iPads in the harsh environment of the Grand Canyon and its potential as an accurate survey method was made during a Grand Canyon Youth (GCY) trip in June 2013. GCY participants worked in groups of 2-3 and conducted campsite surveys at 13 sites throughout Marble and Grand Canyons. Campsite areas, boat mooring areas, gullies, and locations of photographs taken were digitized onto imported orthoimagery and attributed. Four-band aerial imagery of the Colorado River corridor collected during May 2009 was used, as it is the latest orthoimagery available of the canyon (Davis, 2012).

Numerous photographs were taken with the iPad's camera at each site and their locations recorded on the orthoimagery as point features. Notes describing the photographs and orientation of view were attributed to photograph points. Boat mooring areas were digitized as lines and represented the length of shoreline where rafts could pull ashore. Data such as raft capacity, the substrate of the shoreline, and the slope of the approach were attributed to boat mooring areas. Campsite areas were digitized as polygons, following the same criteria established by Kearsley and Warren (1993) and used by NAU's campsite surveys, defined as areas of open sand with a slope of less than 8 degrees that are suitable for camping. Slope was visually estimated in the field. Features such as boulders and patches of vegetation were used as a reference in drawing campsite polygons. Where there were large patches of open sand and little features available to reference ones location the iPads internal GPS was used (estimated to have an accuracy down to a few meters or less based on field observations). Patches of vegetation, boulders, or woody debris that fell within a large campsite area were digitized as exclusion polygons and attributed with a reason for exclusion. Gullies identified at a site were also digitized as polygons and were attributed with an average width and depth.

Factors that constrained the size of campsite areas were also evaluated in the field 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 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. 35). Factors that constrained the perimeters of each campsite polygon were converted to lengths, added together, and then converted back into a percent for the entire site. This resulted in constraints for campsite area at each site and are referred to as campsite-area constraints.

Fall 2013 Tablet Surveys and Improvements to Tablet Method

After the initial GCY trip assessment proved that the tablets could operate in the harsh conditions of the Grand Canyon and that the software was functional, campsite tablet surveys were conducted at 27 sites throughout Marble and Grand Canyons during a fall 2013 sandbar monitoring trip. However, modifications to the tablet survey were made after the initial assessment. The primary modification was that campsite polygons were mapped over the previous year’s campsite survey, allowing areas of campsite gain and areas of campsite loss to be seen. Points were added to areas of campsite gain and loss and attributed with a reason for that change. This allowed areas of campsite change to be identified in the field in addition to mapping campsite area (Fig. 36). Campsite-area constraints were also estimated at 26 out of the 27 sites.

Methods Comparison and Evaluation

In an effort to assess the accuracy of the tablet method in comparison to the total station method, and to reevaluate the uncertainty associated with a surveyor's selection and delineation of campsite polygons, three types of repeated measurements were made during the fall 2013 sandbar monitoring trip: 1) repeat total station surveys conducted independently of one another, 2) total station and tablet surveys conducted concurrently of one another, and 3) total station and tablet surveys conducted independently of one another (Fig. 37, Table 2).

Repeat total station surveys were conducted independently of one another at 4 sites (Nautiloid [RM 35.0L], Eminence [RM 44.5L], Dinosaur [RM 50.1R], and Crash Canyon [RM 62.9R]) in order to reevaluate the uncertainty associated with how a surveyor selects and delineates campsite polygons (for a more detailed description of total station campsite survey methods see Kaplinski and others, 2014). Different survey crews consisting of an instrument operator and one or two rodmen were used to make the repeat measurements. One survey crew 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 campsite

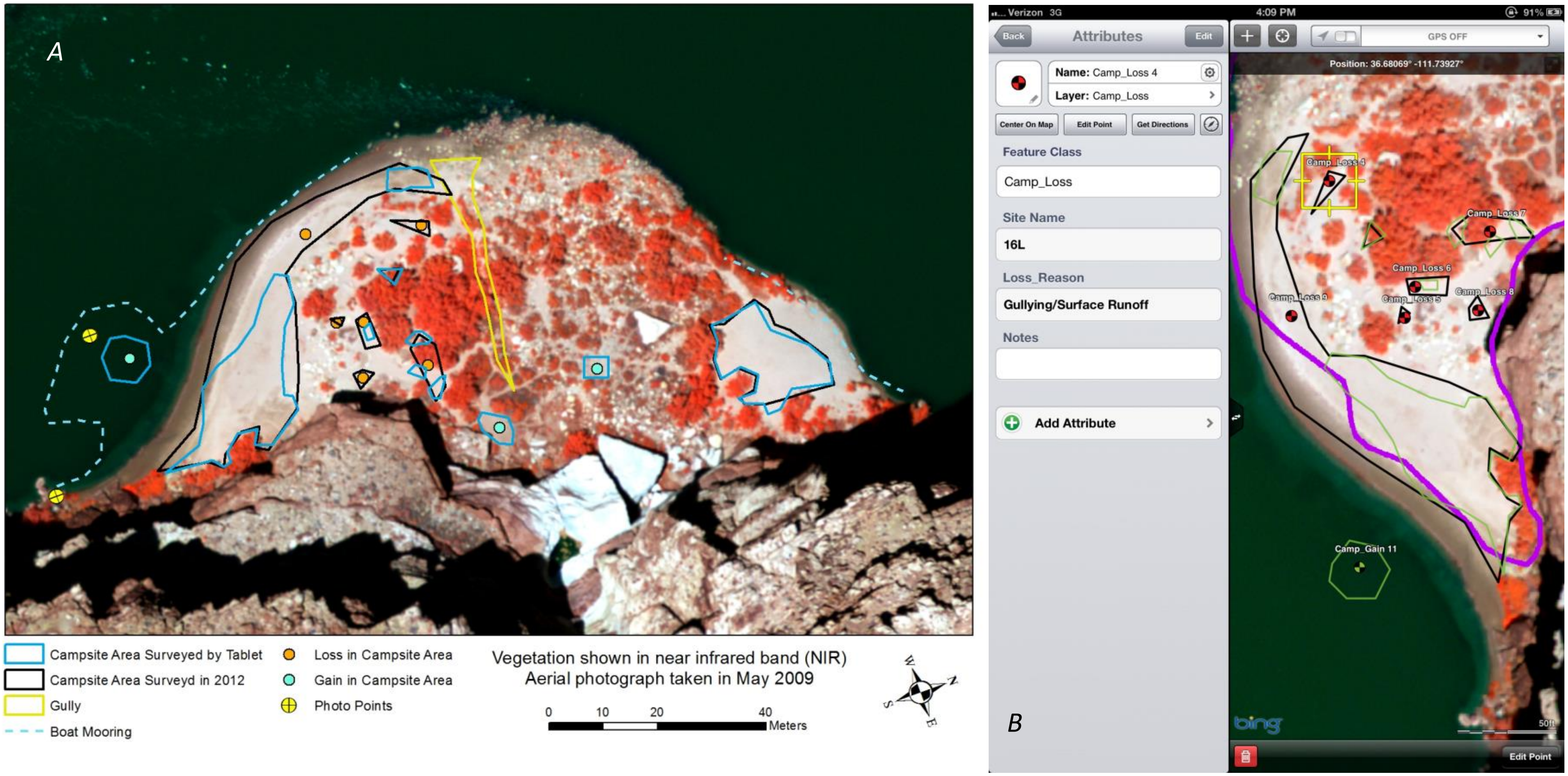


Figure 36. Example of a complete tablet survey (*A*) at Hot Na Na Camp (RM 16.6L) showing digitized campsite polygons, boat mooring areas, and gullies. Digitizing campsite polygons on top of the previous year's campsite survey allowed areas of campsite gain and areas of campsite loss to be seen. Points were added to the areas of campsite gain and areas of campsite loss and were attributed with a gain/loss reason in the attribute form (*B*).

Figure 37. Photographs of repeat campsite surveys. *A*, Repeat total station survey at Dinosaur Camp (RM 50. 1R). *B*, tablet and total station surveys being conducted concurrently at Eminence Camp (RM 44. 4L).

surveys and the second crew either had less than one 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 as to whether or not they were a campsite area. For the purpose of this study, it was assumed that measurement error using total stations was negligible given the error of ±0.05 m in the horizontal and vertical directions, therefore this comparison allowed for the uncertainty associated with how a surveyor maps campsite area to be determined.

Three out of the 27 tablet surveys (Buck Farm [RM 41.2R], Eminence [RM 44.5 R], and Lower Saddle [RM 47.6R]) were conducted at the same time that a total station crew measured campsite area. 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 survey crew as they conducted their campsite survey. Campsite polygons were digitized at the same time that total station points were shot in. Each survey selected the same areas of the sandbar to be mapped as campsite area and campsite polygons were digitized with the tablet using the same number of points that the rodmen used to define each polygon. The uncertainty associated with how a surveyor maps campsite area was therefore eliminated since the tablet surveyor tried to match exactly what the total station crew mapped. This comparison allowed for the error in the tablet method to be calculated and shows the uncertainty associated with digitizing polygons on orthoimagery that is over 4 years old using the selected software.

Twenty-four out of the 27 tablet surveys were conducted independently of total station surveys. 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. Due to logistical reasons, tablet surveyors often had more time to conduct campsite surveys in comparison to the total station crews. 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 shows the difference between using the tablet method versus the total station method, taking into account uncertainty associated with a surveyor, uncertainty associated with method error, and the fact that tablet surveys were conducted under less time constraints.

4.4 Results

Campsite-Area Constraints

Campsite-area constraints varied drastically depending on the site (Fig. 38, Table 13). At a few sites campsite area was constrained almost entirely by steep slopes (22 Mile [RM 22.1R] and Sandpile [RM 30.7R]) whereas some sites had campsite area that was mostly constrained by vegetation (Anasazi Bridge [RM 43.4L] and Fishtail [RM 139.6R]). Sites within critical reaches tended to have most of their campsite area constrained by slope (53 percent) whereas sites in non-critical reaches had most of their campsite area constrained be vegetation (47 percent) (Fig. 39). There was little difference in campsite-area constraints between sites in Marble Canyon versus sites

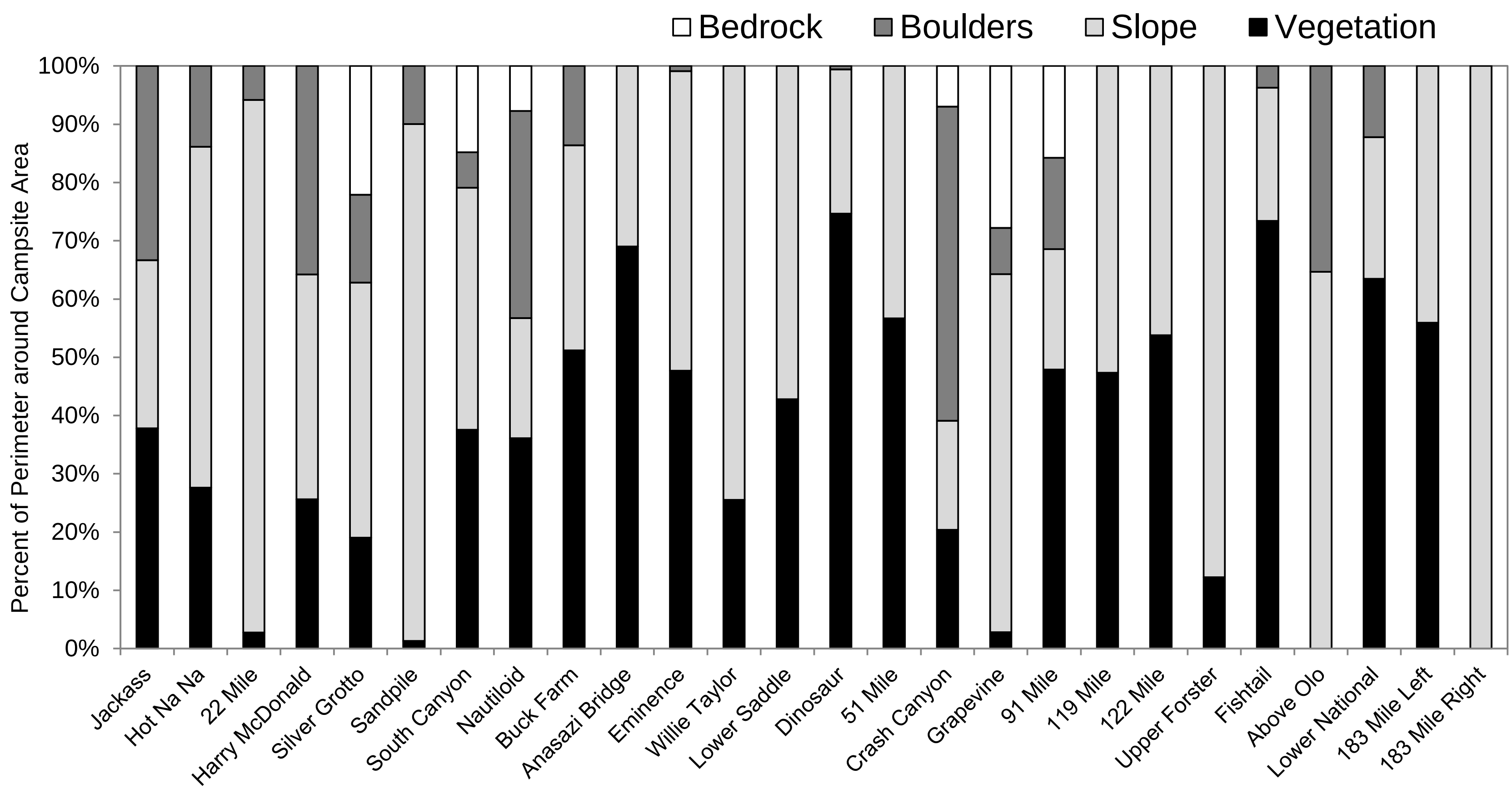


Figure 38. Campsite-area constraints at 26 NAU-monitored campsites. Factors that constrained campsite area were visually estimated in the field as a percentage of the perimeter around mapped campsite area. Note the variability between sites, with some sites have their campsite areas mostly constrained by steep slopes and others having their campsite area constrained mostly by vegetation.

Table 13. Summary of campsite-area constraints at 26 NAU-monitored sites.

				Campsite Area	Campsite-Area Constraint (in m):				Campsite-Area Contraint (%)			
	Site Name	River Mile	Side	(m^2)	Vegetation	Slope	Boulder	Bedrock	Vegetation	Slope	Boulder	Bedrock
	Jackass	8.1	L	392	148	113	131	0	38%	29%	33%	0%
	Hot Na Na	16.6	L	329	91	192	46	0	28%	59%	14%	0%
	22 Mile	22.1	R	276	8	252	16	0	3%	91%	6%	0%
	Harry McDonald	23.5	L	314	80	121	112	0	26%	39%	36%	0%
	Silver Grotto	29.5	L	242	46	106	36	53	19%	44%	15%	22%
	Sandpile	30.7	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	35.0	L	216	78	45	77	17	36%	21%	36%	8%
	Buck Farm	41.2	R	342	175	120	46	0	51%	35%	14%	0%
	Anasazi Bridge	43.4	L	97	67	30	0	0	69%	31%	0%	0%
	Eminence	44.5	L	455	217	234	4	0	48%	51%	1%	0%
	Willie Taylor	45.0	L	286	73	213	0	0	26%	74%	0%	0%
	Lower Saddle	47.6	R	308	132	176	0	0	43%	57%	0%	0%
	Dinosaur	50.1	R	459	343	114	3	0	75%	25%	1%	0%
	51 Mile	51.5	L	159	90	69	0	0	57%	43%	0%	0%
	Crash Canyon	62.9	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	123.2	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%
n	183 Mile Right	183.3	R	97	0	97	0	0	0%	100%	0%	0%
12	Critical Reaches			2812	628	1504	441	239	22%	54%	16%	8%
14	Non-Critical Reaches			3881	1839	1777	259	7	47%	46%	7%	0%
15	Marble Canyon			4619	1699	2262	530	128	37%	49%	11%	3%
11	Grand Canyon			2074	768	1019	170	117	37%	49%	8%	6%
26	All Sites			6693	2467	3281	700	246	37%	49%	10%	4%

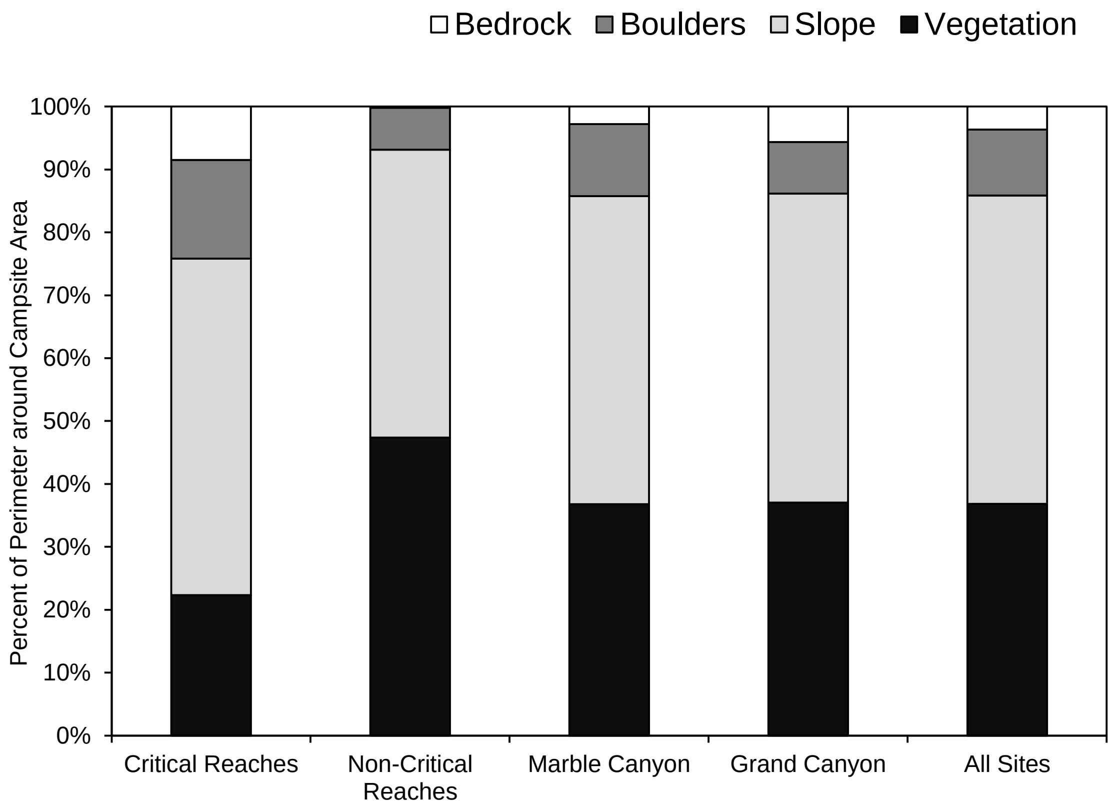


Figure 39. Campsite-area constraints at 26 NAU-monitored campsites summarized by recreation reach and canyon section.

within Grand Canyon. Overall, slope was the largest campsite-area constraint (49 percent) followed by vegetation (37 percent) and boulders (10 percent). Bedrock was the smallest constraint at 4 percent.

Uncertainty Associated with Surveyor

Correlation between campsite polygons mapped by the experienced crew and campsite polygons mapped by the inexperienced crew showed that the inexperienced crew tended to under measure in both area and in the number of campsite polygons (Figs. 40, 41). If a campsite polygon was surveyed by one crew and not the other it was compared to a zero value in the correlation. Campsite area mapped by the inexperienced crew had on average a 13 percent difference from the campsite area mapped by the experienced crew (Table 14). Percent difference in campsite area between survey crews varied by site, with Dinosaur (RM 50.1R) having the largest difference of 22 percent. At Nautiloid (RM 35.0L) the difference was 7 percent, which was higher than the previously reported percent difference determined from the repeat measurements conducted there in 1998 (Kaplinski and others, 2002). Differences in mapped campsite area between survey crews becomes more apparent at large complex sites such as Dinosaur, where campsite area may consist of many campsite polygons. Because measurement error was assumed to negligible when using total stations, the 13 percent difference in campsite area measured by the two survey crews represents the surveyor uncertainty (i.e., the way a survey crew selects and delineates campsite polygons). This surveyor uncertainty is larger than the conservative estimate of

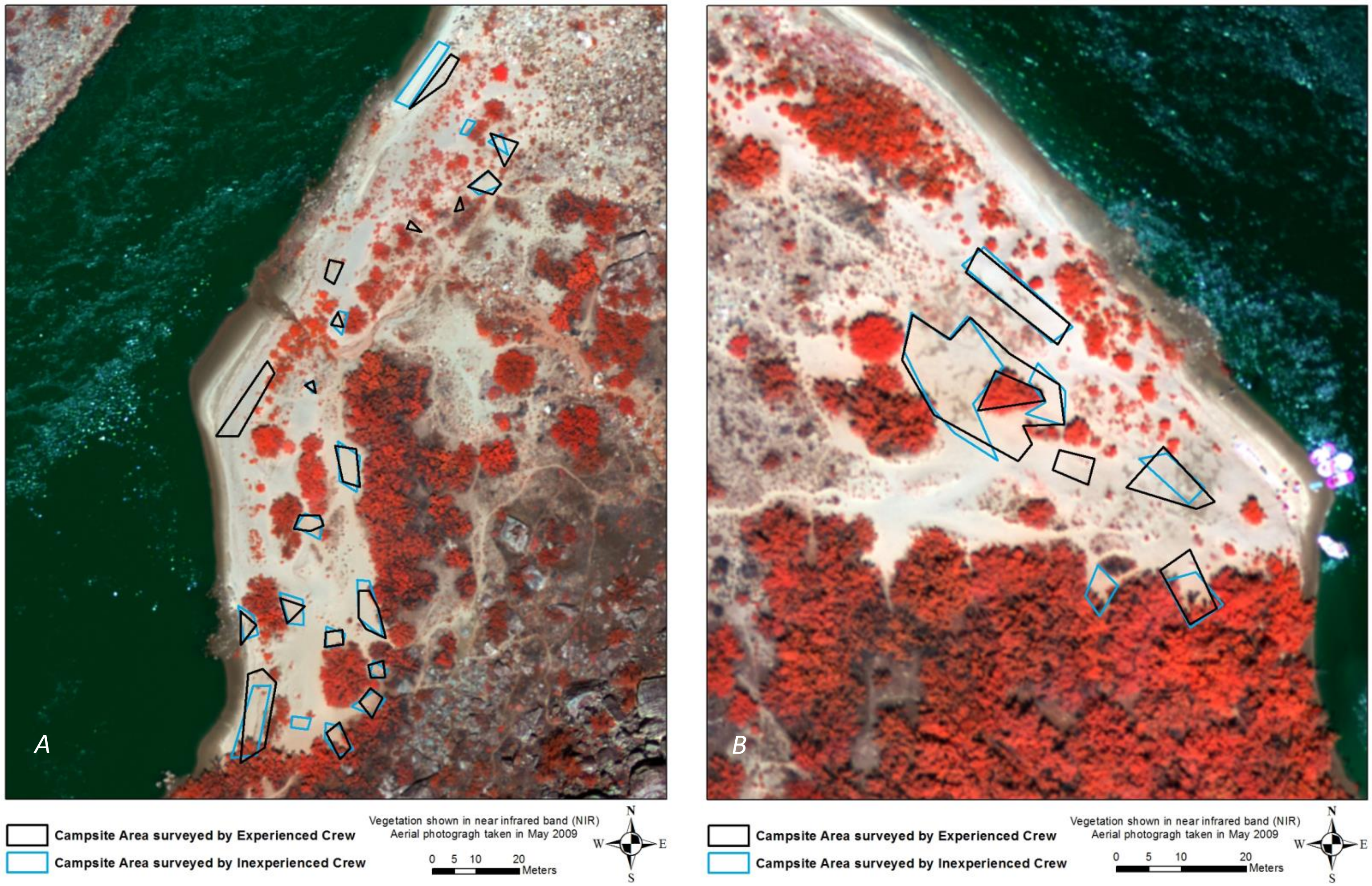


Figure 40. Examples of repeat total station surveys conducted independently of each other at (*A*) Eminence Camp (RM 44.5 L) and (*B*) Dinosaur Camp (RM 50.1R).

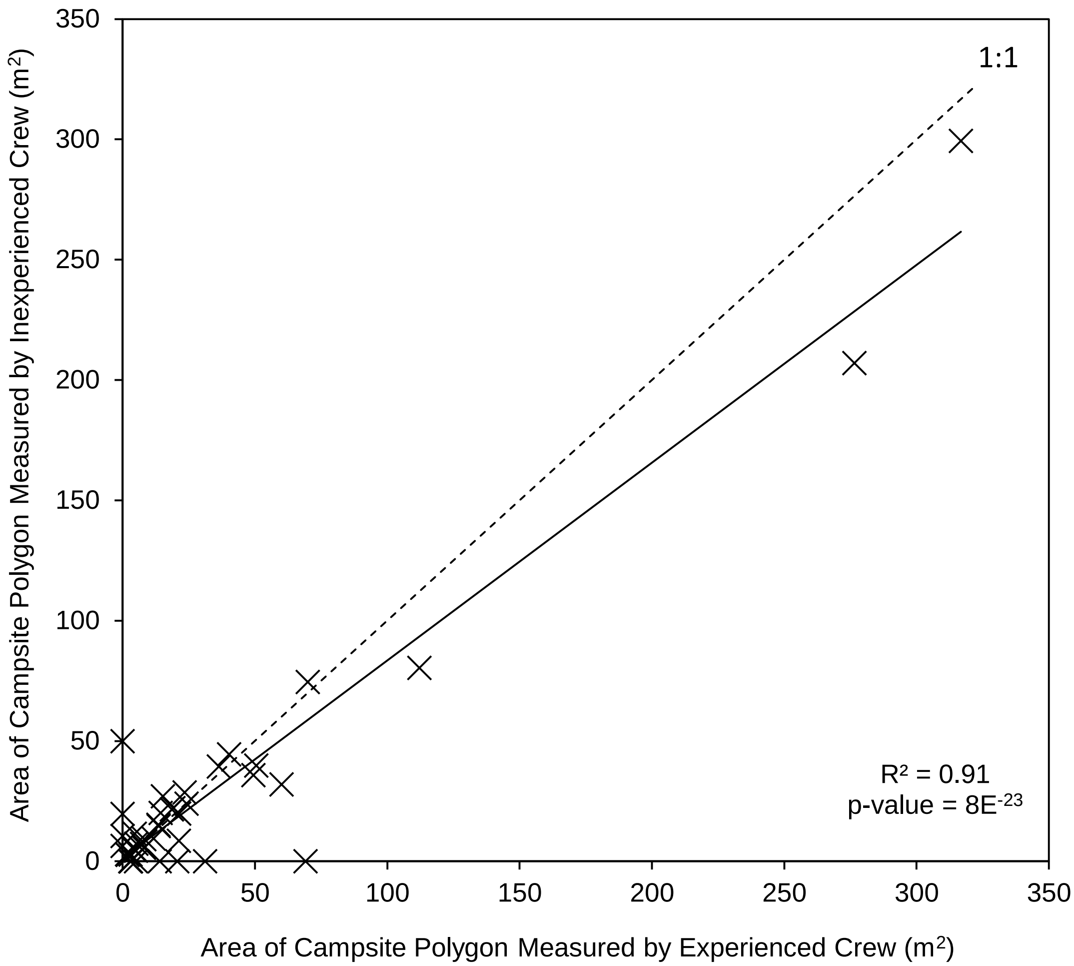


Figure 41. Correlation between campsite polygons mapped by experienced total station surveys crews and campsite polygons mapped by inexperienced total station survey crews. A linear regression fit is shown. Points that fall below the 1:1 line (dashed) are under measurements. Campsite polygons that were surveyed by one crew and not the other were compared to zero values and fall on the x and y axes.

Table 14. Summary of repeat total station surveys conducted independently at four sites.

Site	River Mile	Side	# of Campsite Polygons Mapped by Experienced Crew	# 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%
Emminence	44.5	L	19	17	475	418	57	12%
Dinosaur	50.1	R	5	6	478	373	104	22%
Crash Canyon	62.9	R	10	8	65	59	6	9%
Mean			10	9	351	302	49	13%

a 10 percent uncertainty previously reported (Kaplinski and others 2005, 2010, and 2014).

Uncertainty Associated with Measurement Error using the Tablet Method

Fifty four campsite polygons were mapped at the three sites where tablet surveys and total station surveys were conducted concurrently of one another. Campsite area measured with the tablet tended to be larger than the same campsite area measured with the total station (Fig. 42, Table 15). On average, areas measured by the tablet exceeded the total station measurements by 13 percent (Table 15). Percent error of the tablet survey varied by site, with Eminence (RM 44.5L) having a 25 percent error in comparison to the total station survey and Lower Saddle (RM 47.6R) having a 5 percent error. A correlation was made between each of the 54 campsite polygons and was broken up into large campsite polygons (areas over 30 m^2) and small campsite polygons (areas under 30 m^2) (Fig. 43). Tablet surveys tended to over measure for both small and large campsite polygons in comparison to the total station surveys.

Because this comparison controlled for surveyor uncertainty, the 13 percent error between the surveys is the uncertainty associated with measurement error when using the tablet method to map campsite area.

Total Uncertainty using the Tablet Method and Percent Difference between Methods

The total uncertainty when using the tablet method can be calculated from equation 1 using a 13 percent surveyor uncertainty (determined from the repeated total

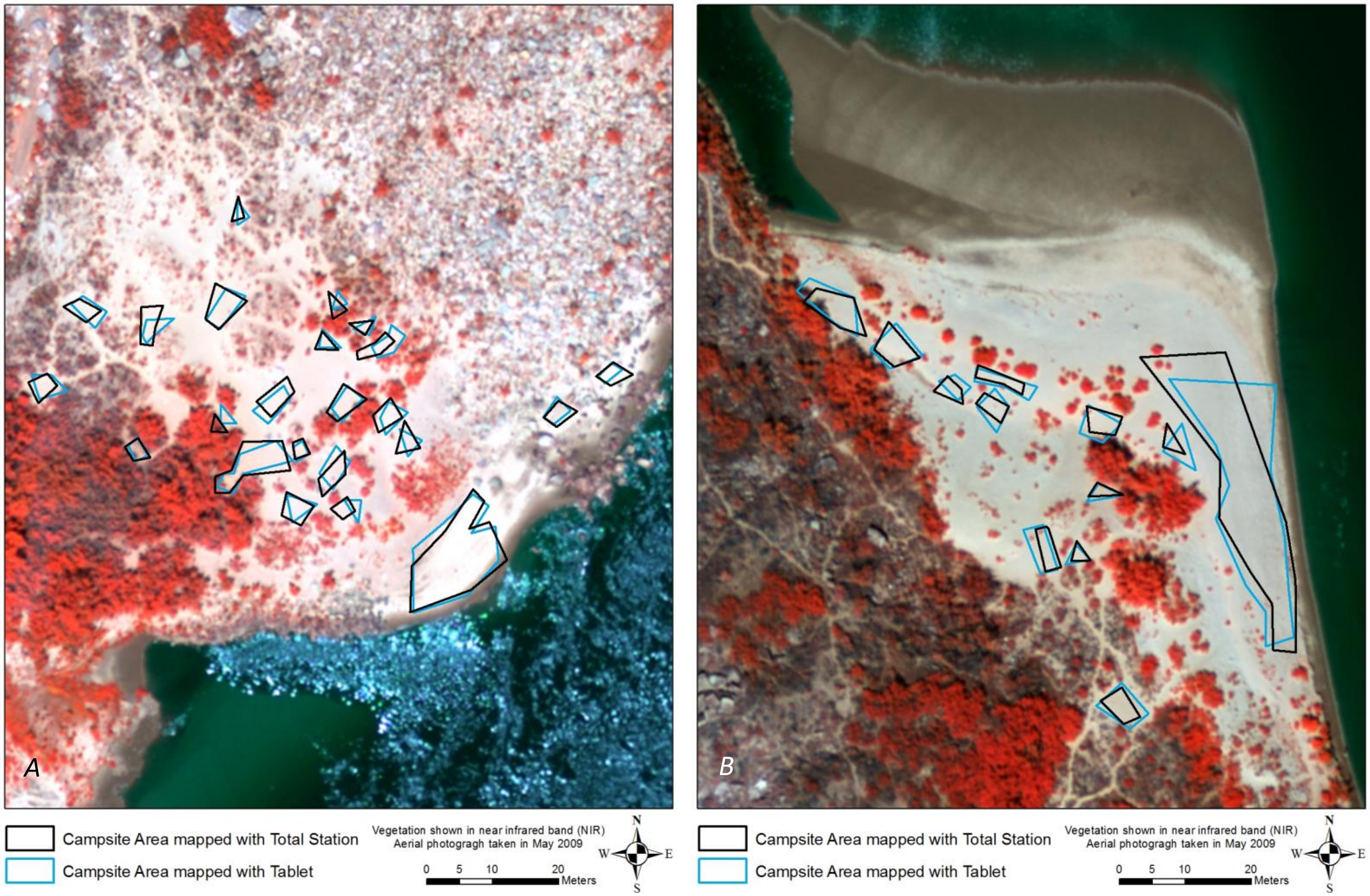


Figure 42. Examples of tablet surveys and total station surveys conducted concurrently at (*A*) Buck Farm Camp (RM 41.2) and (*B*) Lower Saddle Camp (RM 47.6R).

Table 15. Summary of tablet surveys and total station surveys conducted concurrently at three sites.

Site	River Mile	Side	Campsite Area Mapped with Total Station (m^2)	Campsite Area Mapped with Tablet (m^2)	# of Campsite Polygons Mapped	Percent Error from Total Station
Buck Farm	41.2	R	388	350	23	10%
Emminence	44.5	L	475	592	19	25%
Lower Saddle	47.6	R	506	531	12	5%
Mean			456	491	18	13%

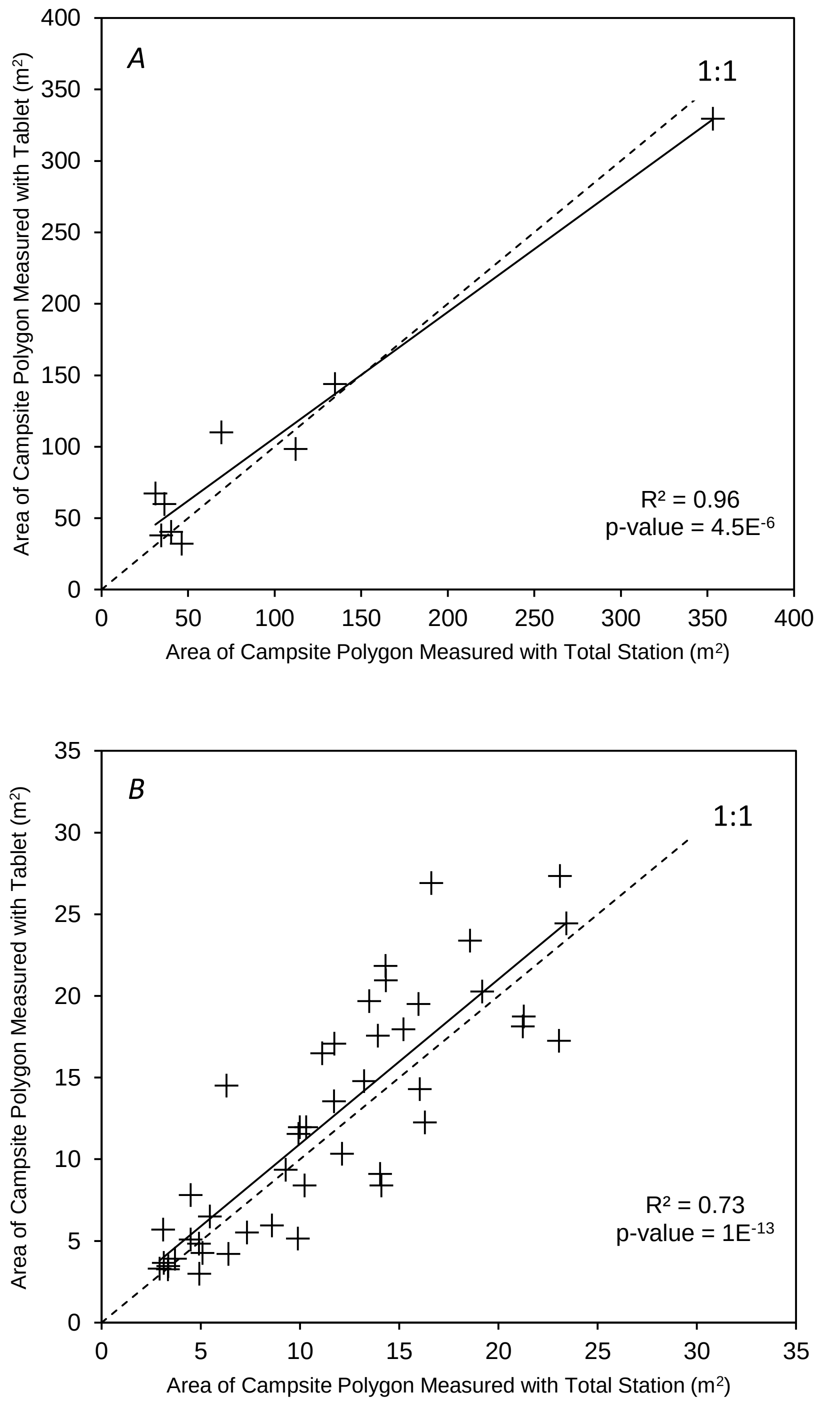


Figure 43. Correlation between campsite polygons mapped with tablets and campsite polygons mapped with total stations. Surveys were conducted concurrently of one another. Campsite polygons were broken up into large campsite polygons (*A*) (areas over 30 m^2) and small campsite polygons (*B*) (areas under 30 m^2). A linear regression fit is shown. Points that fall above the 1:1 lines (dashed) are over measurements.

station measurements) and a 13 percent method uncertainty (determined from the comparisons between tablet surveys and total station surveys conducted concurrently of one another). The calculated total uncertainty using the tablet method was 18 percent. However, comparisons between total station surveys and tablet surveys conducted independently of one another (Fig. 44) shows a much greater percent difference than the expected 18 percent. Campsite area mapped with the tablet method tended to be larger than campsite area mapped with the total station method (Fig. 45, Table 16). On average, campsite area measured by the tablet exceeded the total station measurements by 42 percent (Table 16). This suggests that there may exist a methods based bias that is different between the total station method and tablet method for measuring campsite area.

Percent differences when using the tablet method varied by site, with some sites having differences of over 100 percent when compared to total station surveys (South Canyon [RM 31.9R] and Fishtail [139.6R]) and some sites having differences of only a few percent (Dinosaur [RM 50.1R] and Lower National [RM 167.1L]) (Table 16). Sites that had very large percent differences typically had campsite area that was small in size. This is expected, as small discrepancies in mapped campsite area could have a large percent difference if the mapped areas are very small to begin with. Sites that had campsite area larger in size typically had lower percent differences. When evaluating the percent difference between the 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 16). This was due to large percent differences found at the

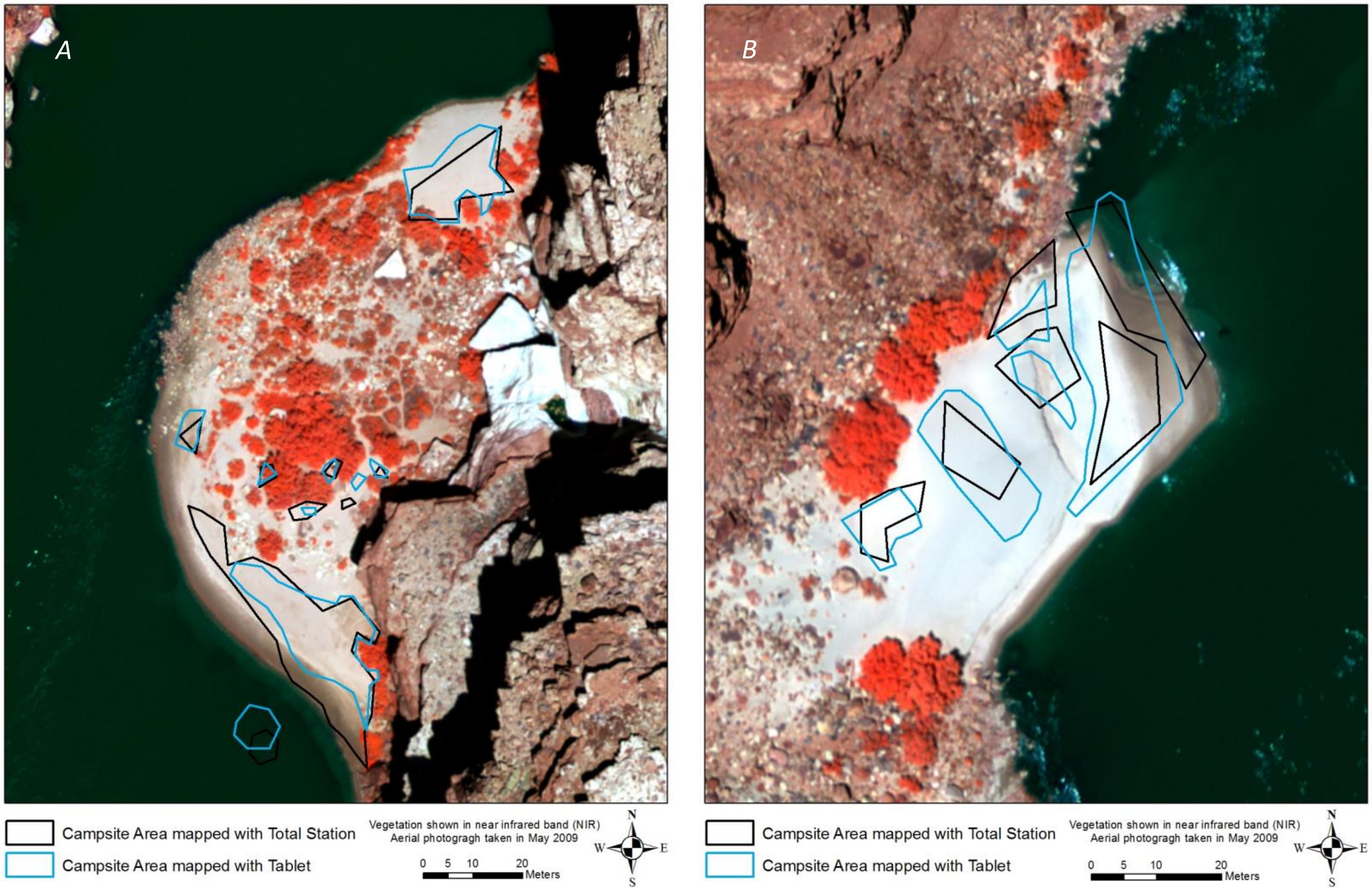


Figure 44. Repeat camp surveys conducted independently using total station and tablet methods at (*A*) Hot Na Na Camp (RM 16.6L) and (*B*) 22 Mile Camp (RM 22.1L). Note the large differences within areas of open sand at 22 Mile Camp

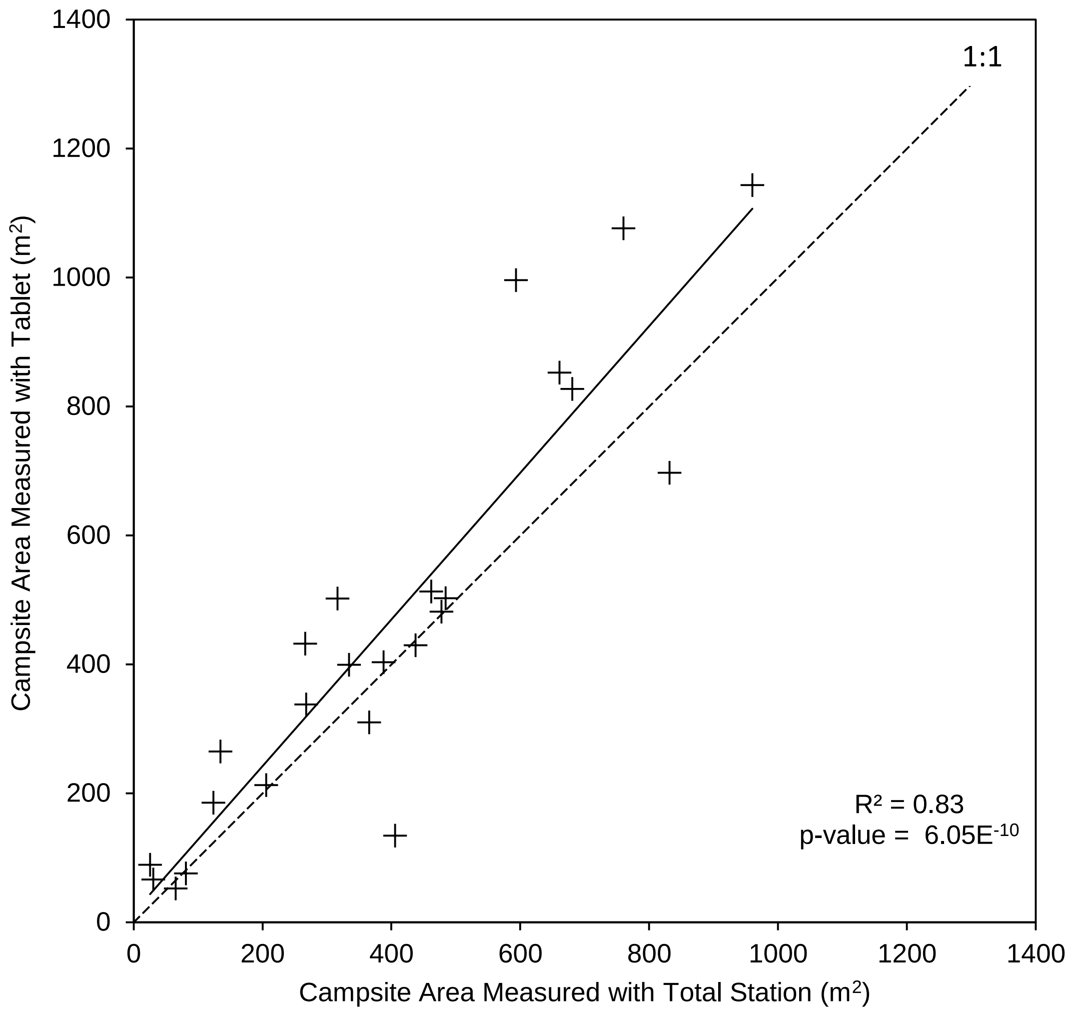


Figure 45. Correlation between campsite area mapped with tablets and campsite area mapped with total stations, surveyed independently at 24 sites. Points that fall above the 1:1 lines (dashed) are over measurements. A linear regression fit is shown indicating that campsite area mapped with tablets tended to be larger than campsite area mapped with total stations.

Table 16. Summary of tablet surveys and total station surveys conducted independently at 24 sites.

Site Name	River Mile	Side	# of Campsite Polygons Mapped by Total Station	# of Campsite Polygons Mapped by Tablet	Campsite Area Mapped with Total Station (m^2)	Campsite Area Mapped with Tablet (m^2)	Difference in Campsite Area (m^2)	Percent Difference from Total Station	Percent Difference from Tablet
Jackass	8.1	L	12	15	334	399	65	20%	16%
Hot Na Na	16.6	L	9	9	832	697	134	16%	19%
22 Mile	22.1	R	6	5	661	852	191	29%	22%
Harry McDonald	23.5	L	10	7	365	310	55	15%	18%
Silver Grotto	29.5	L	3	4	462	513	51	11%	10%
Sandpile	30.7	R	5	6	760	1077	317	42%	29%
South Canyon	31.9	R	3	6	26	89	63	248%	71%
Nautiloid	35.0	L	5	5	388	403	15	4%	4%
Anasazi Bridge	43.4	L	10	8	81	76	5	6%	7%
Willie Taylor	45.0	L	14	10	594	996	403	68%	40%
Dinosaur	50.1	R	5	6	478	482	4	1%	1%
51 Mile	51.5	L	4	6	135	265	130	97%	49%
Crash Canyon	62.9	R	10	10	65	52	13	20%	25%
Grapevine	81.7	L	7	6	681	827	147	22%	18%
91 Mile	91.7	R	7	3	316	502	186	59%	37%
Granite	93.8	L	5	7	406	134	271	67%	202%
119 Mile	119.4	R	9	7	266	432	166	62%	38%
122 Mile	122.8	R	13	9	960	1144	183	19%	16%
Upper Forster	123.2	L	4	6	484	503	18	4%	4%
Fishtail	139.6	R	4	9	30	66	36	118%	54%
Above Olo	145.9	L	3	3	268	338	70	26%	21%
Lower National	167.1	L	12	11	206	213	7	3%	3%
183 Mile Left	183.3	L	2	3	124	185	61	49%	33%
183 Mile Right	183.3	R	1	1	438	430	8	2%	2%
Mean			7	7	390	458	108	42%	31%
Total			163	162	9357	10985	1628	17%	15%

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 (42 percent) but when viewed as a whole survey trip, percent error was much lower (17 percent).

4.5 Discussion

Certain sites were difficult to map using the tablet method due their drastically different appearance in comparison to the 2009 orthoimagery. A good example of this is at 51 Mile (RM 51.5L), which had a low elevation sandbar protruding from the banks at the time of the 2013 survey. In the 2009 imagery this bar is not present, so there was difficulty in deciding where to place that particular campsite polygon on the orthoimagery (Fig. 46). Sites that consisted mostly of open sand had little defining features to reference off of the imagery, making it somewhat difficult to map campsite area (Fig. 44). However, using the internal GPS helped in this regard and was surprisingly accurate. In many cases the GPS was accurate to within a meter or less.

Campsites areas measured when using the tablet method were frequently larger in comparison to areas 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. Total station crews conduct topographic surveys of the 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. For logistical

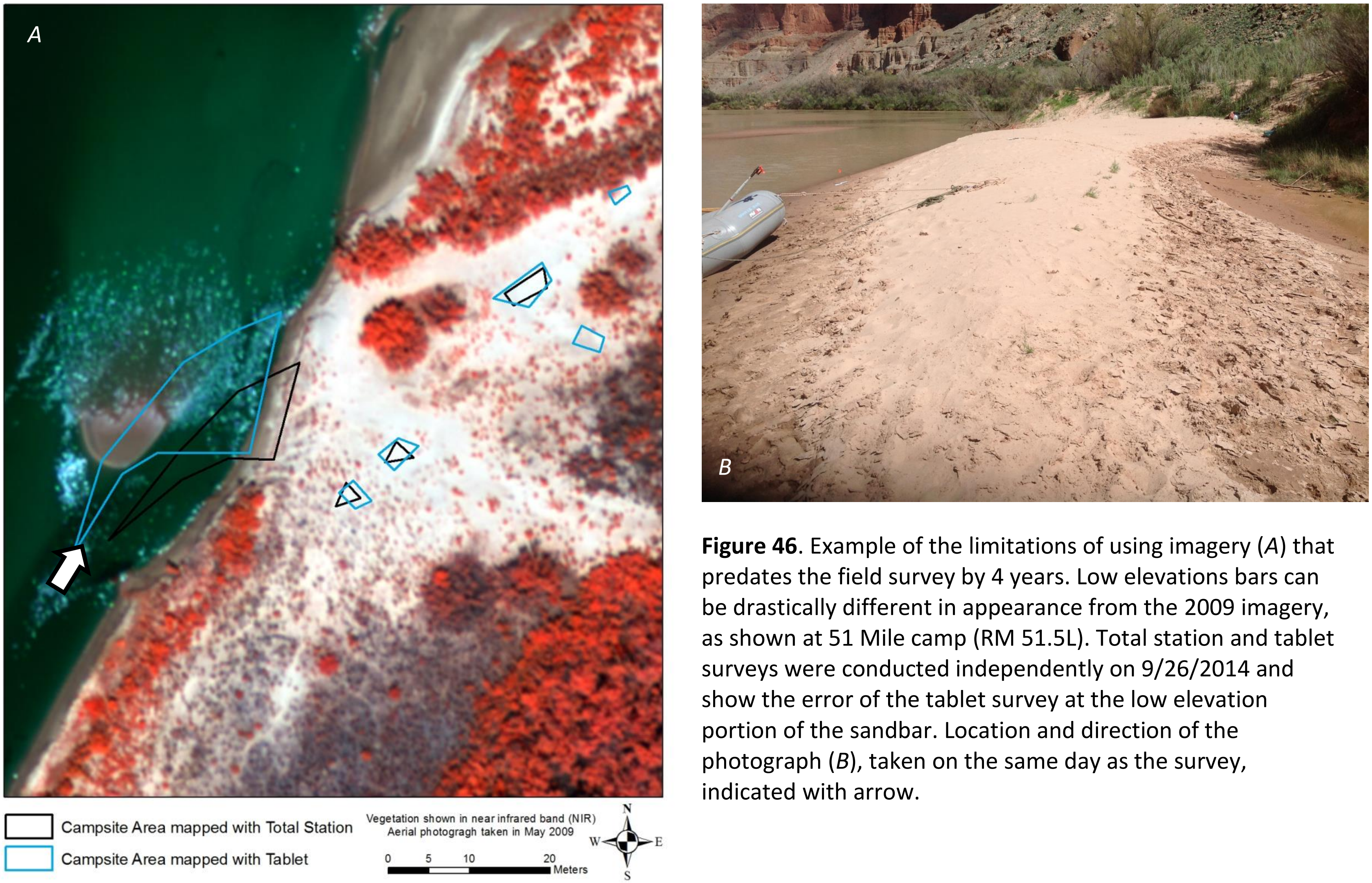


Figure 46. Example of the limitations of using imagery (*A*) that predates the field survey by 4 years. Low elevations bars can be drastically different in appearance from the 2009 imagery, as shown at 51 Mile camp (RM 51.5L). Total station and tablet surveys were conducted independently on 9/26/2014 and show the error of the tablet survey at the low elevation portion of the sandbar. Location and direction of the photograph (*B*), taken on the same day as the survey, indicated with arrow.

reasons surveyors who used the tablet method had more time to walk the sandbars, resulting in digitized campsite polygons that were often more detailed in shape and slightly larger in size.

4.6 Conclusions and Recommendations

Determining campsite-area constraints was a worthwhile measurement to make and shows that the majority of campsite area is bordered by areas of open sand. This has important implications. If a given campsite area is bordered mostly by vegetation and boulders, it may be less likely to increase in size after 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.

Repeat total station measurements show that the uncertainty in mapping campsite area is higher than the 10 percent uncertainty that has been previously reported. Given this additional analysis, and the fact that a variety of surveyors have mapped campsite area since 1998, the uncertainty in mapping campsite area using the total station method may need to be revised to around 15 percent. Using experienced surveyors or even using the same survey crew year after year to map campsite area would decrease surveyor uncertainty.

The tablet method was initially envisioned in the context of a "citizen science" framework with the intent of making it easy enough for non-experienced surveyors to use. This would have allowed campsite surveys to be conducted on a more frequent basis by other stakeholder groups, such as commercial river guides or NPS personnel. But evaluation of the tablet method during the GCY trip and the fall 2013 river trip indicates that surveyors who are experienced with surveying campsites and are familiar with the criteria that define campsite area are needed for an accurate and precise survey.

Use of the tablet method brings an additional uncertainty due to the error associated with mapping on imagery that predates the field surveys. However, the benefits of being able to attribute digitized features and to map areas of campsite change may outweigh the additional error associated with using the tablet method. 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.

CHAPTER 5

CONCLUSIONS

Campsite area continues to decline throughout the Colorado River corridor despite efforts of high-flow experiments to increase the amount of area available on sandbars to be used for camping purposes. Analysis of sandbar geomorphic change and vegetation change indicates that there are two drivers responsible for the net loss in campsite area over the course of the different study periods. There are the gains and losses in campsite area due to depositional and erosional processes associated with high-flow experiments and daily/seasonal dam operations and there are the long-term declines in campsite area due to vegetation encroachment. The gains and losses in campsite area due to depositional and erosional processes can cancel each other out, whereas vegetation change, for the most part, only leads to losses in campsite area. In terms of net change over the course of the 2002 to 2009 study period, vegetation encroachment contributed to about half the net losses (47 percent) with the other half attributed to topographic change (53 percent).

Detailed analysis of sandbar geomorphic change between 2002 and 2009 shows that the majority of the gains and losses in campsite area were not associated with a change in sandbar slope around the critical threshold of 8 degrees. This indicates that deposition or erosion of sandbars while still maintaining the previous topography plays a large role in determining the amount of campsite area available. Specific examples of this include 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 and 4), erosion leading to a gain in campsite area by smoothing the sandbar surface.

Depositional and erosional processes can also change the slope of the sandbar significantly, which also has an effect on campsite area. Elevation and slope changes include 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 removing flat areas of a sandbar, and 4) erosion leading to a gain in campsite area through cutbank retreat removing steep areas of a sandbar. Gullying can be a significant factor in campsite area loss at certain sites, but overall it was a minor factor in comparison to changes in sandbar elevation and slope.

Vegetation encroachment within camp boundaries and within the extents of mapped campsite area was more significant at sites in non-critical reaches than in critical reaches. This is in general agreement with many previous campsite studies that cite vegetation expansion as the primary mechanism for campsite loss in non-critical reaches since the 1983-1986 flooding events. The trends in vegetation encroachment between campsites in non-critical reaches versus critical reaches are also similar to the trends seen in vegetation encroachment within wide and narrow geomorphic reaches.

High-flow experiments lead to increases in campsite area and are currently the only management strategy used to improve campsites along the Colorado River corridor. However, campsite area decreases after high flow experiments largely due to fluctuating dam flows eroding those flood deposits. At the same time, vegetation cover continues to increase, resulting in further loss. The management objectives set forth by the Glen Canyon Dam Adaptive Management Program for increasing the size of campsite area in critical and non-critical reaches has not yet been met. Therefore, high-flow experiments may need to be conducted on a more frequent basis, or daily and seasonal flow patterns altered as to mitigate the effects of post-flood erosion, to increase campsite area throughout the river corridor over a long-term period. Another management strategy would be to target certain sites for vegetation removal. Particular attention should be paid to campsite area in critical reaches. Management strategies that do not increase campsite area over the long term in those reaches will not succeed in increasing the recreational carrying capacity throughout the river corridor. If campsite area continues to decline, the camping behavior of river trips may become altered, such as the use of cots to sleep on areas of steep sand, camping on less desirable sandbars, or having to share campsites with other river parties on a more frequent basis.

Understanding the causal mechanisms of campsite change is necessary for resource managers to make sound decisions in regards to managing campsite along the river corridor. Campsite monitoring conducted by NAU's sandbar monitoring lab represents the most spatially and temporally consistent dataset of campsites available, but is limited by the fact that the total station survey method used does not quantify the factors that lead to campsite area change. Determining the processes responsible for gains and losses in campsite area is difficult to accomplish after the fact, therefore there is a need for a more comprehensive campsite survey that allows 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 allow processes that may not be detectable by remote sensing or analysis of topographic surfaces to be identified. These processes may include aeolian reworking of sand, encroachment of campsites by sparse patches of vegetation, or deposition of driftwood. Use of the tablet method would accomplish this, but it brings an additional uncertainty due to the error associated with mapping on imagery that predates the field surveys.

A possibility for future monitoring could be the combined use of total stations and tablets to monitor changes to campsites. The total station method can continue to be used without modification but could be supplemented by a tablet survey every few years when recent imagery is available. Conducting the tablet surveys only during years when recent imagery is available would reduce the additional error associated with the use of the tablet. However, assigning causes to gains and losses in campsite area in the field over a several year timespan would prove difficult.

Another possibility, which is the recommendation that this author wishes to endorse, would be to modify the total station campsite surveys so that processes that lead to gains and losses in campsite area would be documented in the field on a year by year basis. Instead of just mapping campsite area, survey crews could identify areas of gain and loss by referencing a paper or digital map of last year's survey. Campsite area would still be mapped, but the areas of loss and gain would be identified and assigned with a reason for that change. Processes responsible for a gain or loss in campsite area would be a defined set of reasons that could be recorded by the total station operator or annotated by the crews on a paper or digital map. This method would utilize the accuracy of the total stations, continue to be integrated with the sandbar topography surveys, and would have the benefits of being able to identify causes of campsite area change between surveys.

Regardless of which method is employed, campsite monitoring will always have an inherent subjectivity, therefore there is a need for the same survey crew to map campsite area year after year or at least use surveyors who are very familiar with the sites. 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 make better decisions in regards to improving the size, quantity, and distribution of campsites along the Colorado River corridor in accordance with the GCDAMP. Although these recommendations 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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