REGULATED RIVERS: RESEARCH & MANAGEMENT, VOL. 9, 137–149 (1994)

EFFECTS OF GLEN CANYON DAM ON COLORADO RIVER SAND DEPOSITS USED AS CAMPSITES IN GRAND CANYON NATIONAL PARK, USA

LISA H. KEARSLEY

National Park Service, Division of Resources Management, PO Box 22459, Flagstaff, AZ 86002, USA

JOHN C. SCHMIDT

Watershed Science Unit and Department of Geography and Earth Resources, Utah State University, Logan, UT 84322-5240, USA

and

KATHERINE D. WARREN

National Park Service, Division of Resources Management, PO Box 129, Grand Canyon, AZ 86023, USA

ABSTRACT

Glen Canyon Dam, located on the Colorado River 24 km upstream from Grand Canyon National Park, has affected downstream alluvial sand deposits which are used as campsites by recreational boaters. Inventories of campsite numbers and sizes conducted in 1973, 1983 and 1991, and comparison of aerial photograph series taken in 1965, 1973, 1984 and 1990 show that there has been a system-wide decrease in the number and size of campsites. Campsites are unevenly distributed along the river, and availability is regarded as 'critical' along reaches comprising 45% of the river, based on interviews with river guides. During the first 10 years of Glen Canyon Dam operations, at least 30% of all campsites decreased in size. During the next 18 years, between 1973 and 1991, 32% of all campsites decreased in size, and campsite capacity decreased by 44%. High annual dam releases in excess of power plant capacity in 1983 caused a net system-wide increase in the number of campsites, but decreased campsite capacity in two critical reaches. The 'benefit' of sand aggradation due to the 1983 high flow was short-lived, and by 1991 only a few campsites were larger than they had been in 1973. In contrast, other sites, especially in critical reaches, were eroded by the 1983 high flows and have not recovered in size. Options for future dam management must consider the variable response of campsites to high flows in critical and non-critical reaches and the duration over which 'beneficial' high flow effects persist.

KEY WORDS Sand bars Erosion Colorado River Regulated rivers Campsites

INTRODUCTION

Environmentally sensitive management of regulated rivers requires that downstream flow parameters required for ecosystem maintenance and recreation are reconciled with traditional requirements of water supply, flood control and hydroelectric power production. The development of dam operating criteria must be based on a sound understanding of how the dams affect downstream resources and activities, including recreation.

The Colorado River has the highest proportion of its annual flow stored in reservoirs of any major North American watershed (Hirsch *et al.*, 1990) and the associated environmental changes to the remaining river sections have been dramatic (e.g. Stanford and Ward, 1979; Turner and Karpiscak, 1980; Howard and Dolan, 1981; Andrews, 1986; Stephens and Shoemaker, 1987; Minckley and Deacon, 1991). A primary influence of Glen Canyon Dam on downstream recreation in Grand Canyon National Park has been its effect on sand deposits, many of which are used as campsites. The size and abundance of these sand deposits limit the river's recreational carrying capacity. Campsites are an integral part of all raft trips because the trips are multi-day expeditions. Without open sand deposits, river trips could not be conducted

CCC 0886-9375/94/030137-13

Received 19 November 1993
Accepted 18 April 1994

because the remainder of the shoreline is too rocky or too densely vegetated to be used as campsites except under extreme circumstances.

Campsite carrying capacity is of concern due to Grand Canyon National Park's popularity. The annual number of people travelling downstream on the river through the park increased from 547 in 1965 to 16 428 in 1973 (Shelby, 1981). Presently, the US National Park Service limits use to approximately 22 000 people each year. Even with this limitation, many campsites are used nearly every night during the summer and sometimes, for lack of alternative camps, by two river parties on the same night.

The primary purpose of this paper is to synthesize the available historical data about campsite availability and recreational carrying capacity. Such a synthesis will contribute to the development of future reservoir operating rules. Geomorphological studies of changes in the sand deposits (Beus *et al.*, 1985; Schmidt and Graf, 1990) and the experience of river guides indicate that there are fewer sand deposits available as campsites than there were at the time of dam closure in 1963. The popular belief that the erosion of sand deposits and the related decrease in the size and number of campsites persists (e.g. Udall, 1990) and is one of several factors that initiated the US Bureau of Reclamation's Glen Canyon Environmental Studies program (National Research Council, 1987; 1991), passage of the Grand Canyon Protection Act by US Congress and the development of an environmental impact statement of the effects of current operations on Glen Canyon Dam (US Bureau of Reclamation, 1994). Dam managers and citizens alike require a clear picture of the pattern of historical campsite changes if the imposition of new rules intended to restore campsite size and to benefit other resources is to be justified.

STUDY AREA

The Colorado River flows through the remaining unflooded 24 km of Glen Canyon and the upstream 386 km of the Grand Canyon. An additional 64 km of the Grand Canyon is inundated by the Lake Mead reservoir. Lees Ferry, located at the downstream end of Glen Canyon, is the launch point for boats travelling through Grand Canyon, and the next road access at which boats can be removed from the river is the mouth of Diamond Creek, 362 km downstream (Figure 1).

BACKGROUND

The width of the Colorado River is constrained in its course through the Grand Canyon. Much of the channel is lined by bedrock or large talus and the reach-average channel width is related to the erodibility of bedrock exposed at river level (Howard and Dolan, 1981; Schmidt and Graf, 1990). Debris fans, composed of coarse material supplied from steep ephemeral tributaries, partially block the channel's course at numerous sites (Howard and Dolan, 1981; Webb *et al.*, 1989), often forming rapids (Leopold, 1969; Kieffer, 1985).

The Colorado River has a distinctive assemblage of channel elements related to these debris fans (Kieffer *et al.*, 1989; Schmidt, 1990). Upstream from a debris fan, a hydraulic backwater of low-velocity flow may extend several kilometres; downstream from the debris fan channel the cross-sectional area increases greatly and large recirculating eddies occur along the channel banks. Further downstream, a cobble/gravel bar composed of debris reworked from the debris fan accelerates the flow and constrains the downstream length of the recirculating eddies (Schmidt *et al.*, 1993). This assemblage occurs at most tributary mouths and the size of each channel element appears to be related to the size and characteristics of each debris fan, the time sequence of debris flows that replenish the fan and the time sequence of Colorado River discharges (Keiffer, 1985; Melis and Webb, 1993).

Sand deposits used as campsites have characteristic locations in relation to these channel elements. Although changing in size, these deposits typically have not changed location since the closure of Glen Canyon Dam. Campsites remain stationary because most are located on eddy sand bars (Schmidt and Graf, 1990), the flow patterns of which are determined by channel geometry characteristics that are stable over decade to century time-scales (Webb *et al.*, 1991).

The closure of the Glen Canyon Dam decreased the annual sediment load of the Colorado River at Lees Ferry from about $6{\cdot}0 \times 10^{10}$ kg to $8{\cdot}3 \times 10^{7}$ kg (Andrews, 1990). The magnitude and frequency of flooding

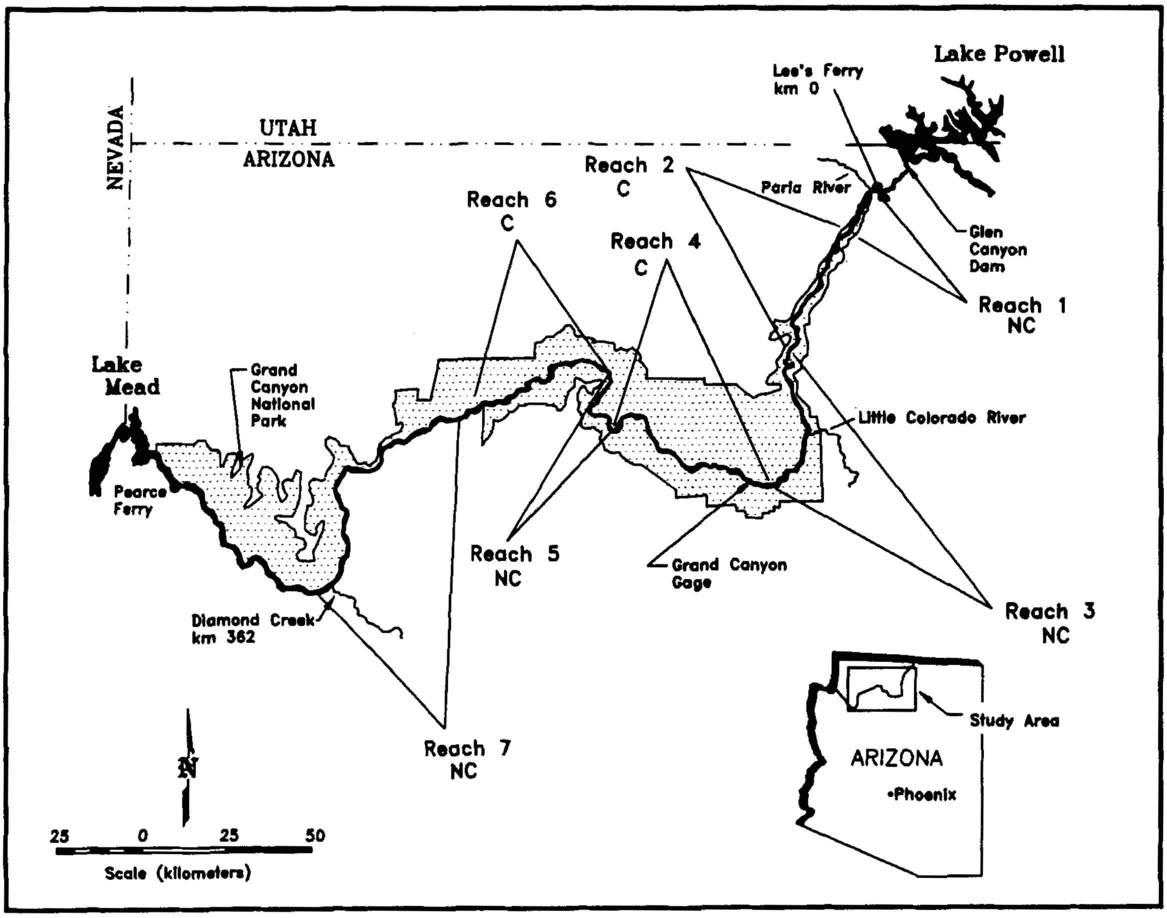

Figure 1. Map of Colorado River and Grand Canyon National Park showing study area. Critical (C) and non-critical (NC) reaches are indicated, based on recreational criteria (see text)

also decreased greatly. During the gauged years between 1921 and 1962, the mean annual flood at Lees Ferry was 2180 m^3/s (Kieffer *et al.*, 1989). Post-dam peak discharge has been restricted by the maximum capacity of the Glen Canyon hydroelectric power plant, which is 940 m^3/s. Only in years when the reservoir is full and inflow is large do dam releases bypass the power plant. During the first 20 years of the dam's existence, between 1963 and 1982, annual instantaneous peak flow at Lees Ferry only exceeded this value in 1965 and 1980. However, a series of high inflow years resulted in a 1983 peak flow at Lees Ferry of 2752 m^3/s and 1984 to 1986 peak flows between 1355 and 1646 m^3/s (Figure 2). No releases have exceeded the power plant capacity since 1986.

Randle *et al.* (1993) computed the annual sediment budgets each year between 1966 and 1989 for the river between Lees Ferry and the Grand Canyon gauge, located 141 km downstream. Their results, consistent with an earlier analysis by Howard and Dolan (1981), indicated that sediment accumulated in Grand Canyon in years when dam releases were less than the power plant capacity, sediment was removed from the system in years when releases exceeded the power plant capacity, and the sediment budge' was more negative upstream from the Little Colorado River, a major tributary located 98 km downstream from Lees Ferry. High discharges between 1983 and 1986 removed about the same amount of sediment between Lees Ferry and the Grand Canyon gauge as had accumulated between 1963 and 1982, but these flows removed more than the previously accumulated amount upstream from the Little Colorado River. Occasional high tributary flows, such as occurred in January 1993 in the Little Colorado River, can contribute flow and sediment

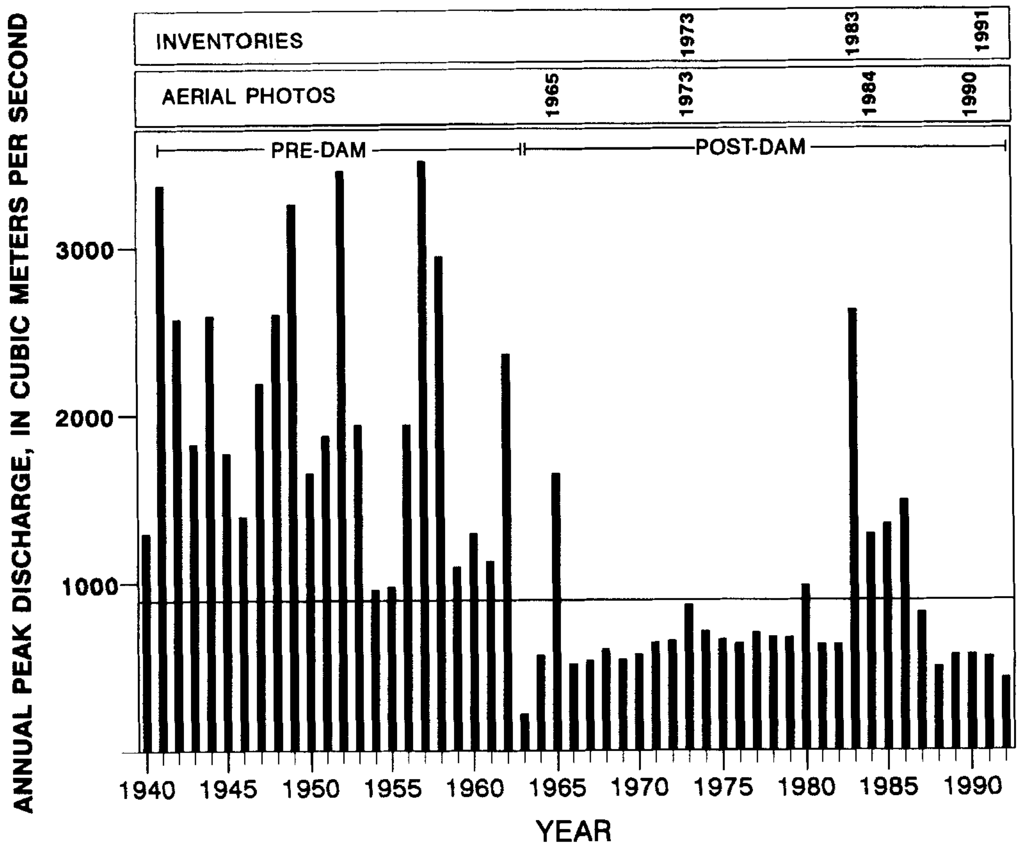

Figure 2. Colorado River peak discharges each year from 1940 to 1992 at Lees Ferry, Arizona (courtesy of the US Geological Survey). Horizontal line at 940 m^3/s indicates maximum power plant capacity. Years when campsite inventories and aerial photographic surveys were conducted are indicated

to the Colorado River capable of entraining mainstem bed sediment and causing significant eddy aggradation over periods of a few days (Beus *et al.*, 1993).

Glen Canyon Dam caused a dramatic increase in vegetation in the Grand Canyon. Early photographs show that riparian vegetation existed only as linear strips near the mean annual flood stage, on higher terraces that exist in some locations and on the high parts of debris fans. Following dam closure, dense riparian vegetation colonized areas near the river not regularly inundated by dam discharge (Turner and Karpiscak, 1980; Johnson, 1991). Between 1965 and 1973, riparian vegetation at selected sites increased at a rate of about 1250 m^2/km/yr; between 1973 and 1980, this rate decreased to about 630 m^2/km/yr (Pucherelli, 1986).

METHODS

Inventory

We prepared a campsite inventory in 1991 by conducting two sets of interviews with professional Grand Canyon river guides during which the group drafted a preliminary list of 1991 campsites between Lees Ferry and Diamond Creek and divided the river into critical and non-critical reaches. Critical reaches are river sections where campsites are infrequent, resulting in severe competition for sites. Non-critical reaches occur where campsites are abundant. In March and May 1991, we conducted river trips with professional river guides to refine this campsite list and evaluate the status of sites identified as campsites in 1983 by Brian and Thomas (1984) but not listed by guides in 1991.

The size of inventoried campsites in 1991 was measured by estimating a site's physical carrying capacity. This was done by consensus of interviewed guides and by subsequent on-site evaluations in which the camp area was evaluated and the approximate number of sleeping sites counted. A small site was defined as accommodating 10 to 12 persons; medium size sites accommodate 13 to 24 persons; and large sites accommodate 25 or more persons.

We compared our 1991 campsite inventory with a 1973 inventory (Weeden *et al.*, 1975), conducted 10 years after dam closure, and a 1983 inventory (Brian and Thomas, 1984), conducted approximately two months after recession from the 1983 peak flow. Reach scale campsite capacity in 1973 was determined by adding the number of people accommodated at each site. Reach scale campsite capacity in 1983 and 1991 was determined by multiplying the midpoint range of the number of people accommodated in each size class by the number of size classes.

Aerial photograph evaluation

Aerial photographs of the river corridor taken in 1965 were compared with subsequent air photo series to quantify campsite change throughout post-dam time. Campsites listed in the 1973, 1983 or 1991 inventories were evaluated using aerial photographs taken in 1965, 1973, 1984 and 1990. We compared the estimated area of exposed sand at each inventoried campsite above a reference stage associated with a discharge of $708\,m^3/s$, the average high discharge since dam closure. The October 1983 inventory and the October 1984 photographs are separated by a 76 day period (5 May to 20 July) when the mean daily discharge at Lees Ferry was between 911 and $1282\,m^3/s$, as well as a four day period in August when the annual peak flow of $1646\,m^3/s$ occurred. Thus the 1984 photographs do not describe river conditions solely related to the 1983 peak.

Interpretation of aeriel photographs to determine exposed sand area shown on aerial photographs is subject to error because (1) detailed characteristics such as the density of surface boulders and gravel was estimated and (2) the area of sand above the $708\,m^3/s$ stage had to be estimated on the 1973, 1984 and 1990 air photos. A stereoscope was used to identify the reference stage using criteria proposed by Schmidt and Graf (1990): the highest elevation of clean sand and the lowest elevation of vegetation. The elevation of the $708\,m^3/s$ stage in the 1965 photographs has less error because discharge at the time of these photographs was approximately at this stage.

Because of limitations in interpreting aerial photographs, we did not estimate differences in vegetation density, nor did we categorize the physical carrying capacity of sites; instead, changes in size above the reference stage were recorded as a substantial increase or decrease from the initial 1965 condition. Erosional change was noted when a deposit above the reference stage was completely eroded, was significantly smaller, or when substantially more rocks were visible at the site. We are confident that our estimates of sand bar change based on aerial photograph comparisons underestimate campsite erosion since 1965. We know of many specific sites where there was a loss of sand at elevations above the $708\,m^3/s$ reference stage, but where there was little to no change in area of exposed sand (Figure 3).

We also evaluated the temporal pattern of sand deposit size change by tracking the sequence of change of each campsite between inventories and between photo series. For comparative purposes with the aerial photograph results, we excluded all campsites that were overgrown in 1991. Temporal patterns of size change for all sites in the inventory comparisons and the aerial photograph comparisons are compiled and archived at the Glen Canyon Environmental Studies office, Flagstaff, AZ, USA.

RESULTS AND DISCUSSION

Inventory data

There were 226 campsites between Lees Ferry and Diamond Creek in 1991, the size and abundance of which differed by reach type. Critical reaches had significantly fewer sites (0·5 sites/km) than non-critical reaches (0·7 sites/km) ($n = 3$, Mann–Whitney U test $= 9$; $p = 0{\cdot}05$) and their campsite capacity was only 60% of that in non-critical reaches (Figure 4). The most upstream non-critical reach has an anomalously

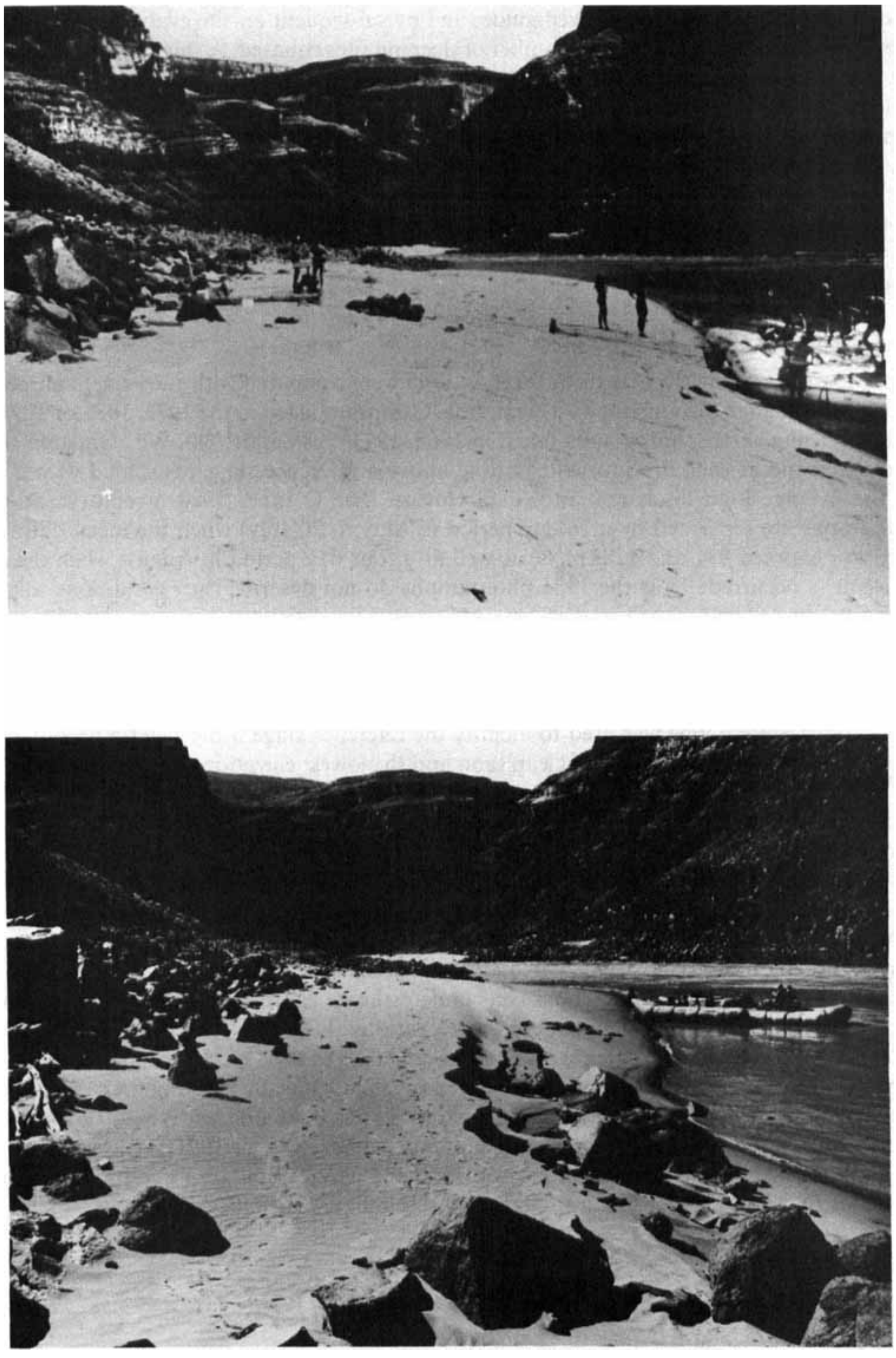

Figure 3. Photographs showing decreased campsite size over time due to erosion, but which are regarded as 'no change' in our inventory comparisons. The top photo was taken in May 1981 and the bottom photo, which shows much less sand and newly exposed rocks near the river, was taken in March 1992

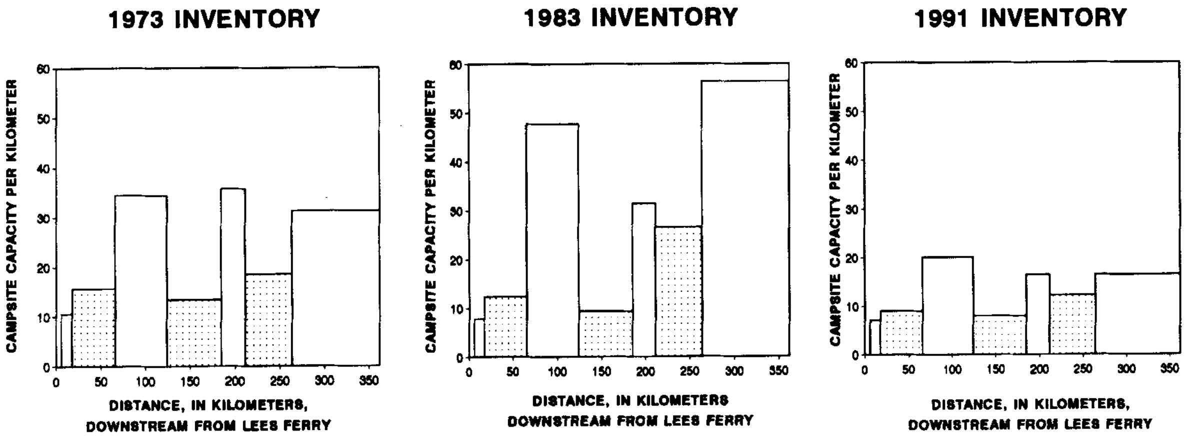

Figure 4. Comparison of campsite capacity per kilometre for the reaches designated in Figure 1 for 1973, 1983 and 1991. Critical reaches are stippled.

low capacity because campsites are more infrequent than in downstream critical reaches. This reach is considered 'non-critical' by guides because demand for campsites is low near Lees Ferry.

Designation of critical and non-critical reaches based on recreational considerations is virtually identical with the geomorphological classification of narrow and wide reaches by Schmidt and Graf (1990), with critical reach designations closely resembling Schmidt and Graf's narrow reach designations. This similarity highlights the fundamental geomorphological controls to the distribution of river-related resources of Grand Canyon.

Comparison of our aggregate 1991 results with previous surveys shows a 34% increase in campsite number between 1973 and 1983, a 48% decrease in number between 1983 and 1991 and an overall decrease of 32% between 1973 and 1991 (Figure 5). The decrease in the number of large campsites between 1973 and 1991 (51%) was greater than that in the other two size categories, resulting in a 44% decrease in campsite capacity between 1973 and 1991. Geomorphological analyses of change between 1973 and 1983 (Beus *et al.*, 1985; Schmidt and Graf, 1990) show that the 1983 high discharge was the only hydrological event after 1965 that created a significant number of high sand bars, and we infer that this high flow created most of the new campsites recorded between 1973 and 1983. Also, the 1983 campsite inventory field notes corroborate numerous first-hand observations of the existence of new sand bars immediately after high flow recession.

The pattern of these changes is different in critical and non-critical reaches (Figure 4). The pattern in non-critical reaches is similar to the aggregate pattern of change shown in Figure 5: campsite capacity increased between 1973 and 1983, decreased between 1983 and 1991 and decreased overall between 1973 and 1991. In contrast, campsite capacity in the upstream two critical reaches decreased between 1973 and 1983 as well as between 1983 and 1991 (Figure 4).

Two hundred thirty-six of the campsites inventoried in 1983 were so changed by erosion and/or vegetation overgrowth that they were not useable as campsites in 1991. Field inspection showed that 34% of these sites had eroded, 41% were overgrown with vegetation and 20% were eroded and overgrown. The cause of campsite loss differed between critical and non-critical reaches. In critical reaches, erosion was the dominant mechanism of change at 71% of the sites, whereas in non-critical reaches 27% had been eroded, 47% had been overgrown with vegetation and 23% by a combination of these processes ($\chi^2 = 32{\cdot}26$; $p < 0{\cdot}001$) (Figure 6).

The temporal pattern of change of each campsite shows that the sites that were created between 1973 and 1983 were the same sites that decreased in size between 1983 and 1991 (Figure 7). Of the 190 campsites that either increased in size or were added to the campsite inventory between 1973 and 1983, 165 subsequently decreased in size. Most of these 165 sites decreased to their initial 1973 size, whereas 22% decreased but

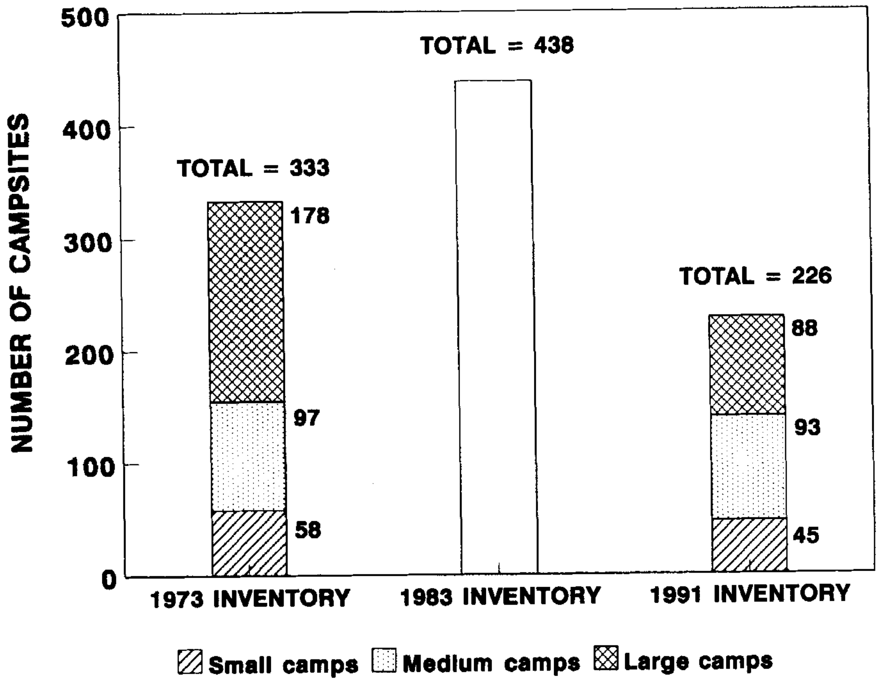

Figure 5. Number of campsites available in 1973, 1983 and 1991. 1973 and 1991 campsites are categorized into small (up to 12 people), medium (13–24 people) and large (25 or more people) size classes. 1983 campsites are not categorized into size classes because 1983 size classes are not compatible

remained larger than their 1973 size, and 13% became smaller than their 1973 size. In contrast, of the 145 sites that decreased in size between 1973 and 1983, 98 became too small for any subsequent use. Thus, despite the large increase in campsite size between 1973 and 1983, the net change in campsites between 1973 and 1991 was that 18% increased in size, 36% were of similar size and 46% decreased in size.

Aerial photograph evaluation

The pattern of sand bar change determined from the aerial photograph evaluation (Figure 8) provides a perspective on the pattern of campsite change over the entire period of dam operations. The pattern is

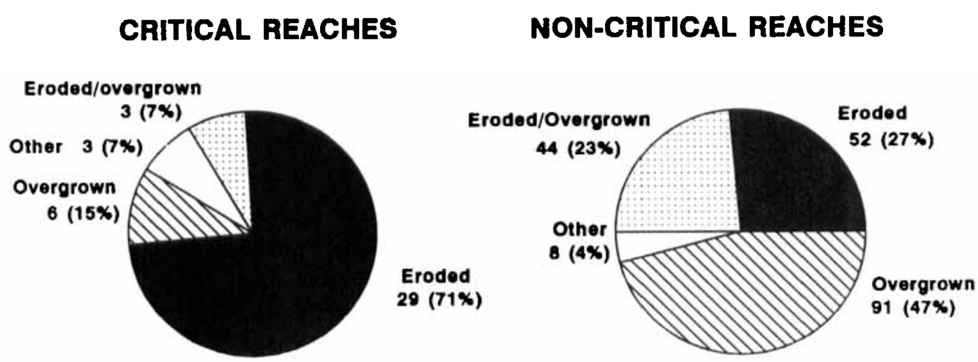

Figure 6. Processes responsible for campsite loss of all inventoried 1983 campsites not considered as campsites in 1991, divided into critical and non-critical reaches

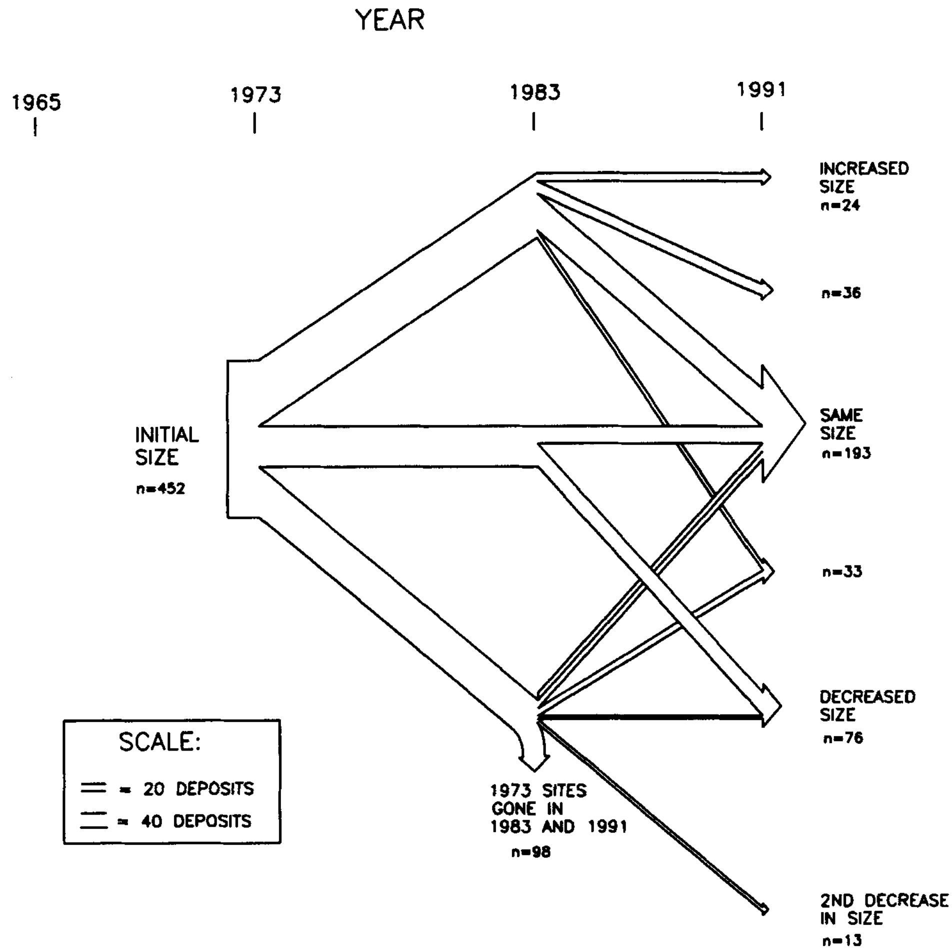

Figure 7. Temporal change in size of individual sand bars used as campsites based on inventory comparisons. Arrow thickness scaled to reflect number of campsites following each pattern between years. Upward pointing arrows represent new campsites and campsites which have increased in size. Downward pointing arrows represent lost campsites and campsites which have decreased in size

generally similar to that of the campsite inventory evaluation (Figure 7), with notable differences. Overall, there has been a significant decrease in campsite size since dam closure.

Fifty-two per cent of all campsites were smaller, 46% were the same size and only 2% were larger in 1990 than in 1965. Most of this decrease occurred between 1965 and 1973, before the first campsite inventory; more than one-third of all sites decreased in size and did not subsequently recover. Fewer campsites decreased in size between 1973 and 1984, and even fewer decreased between 1984 and 1990. Forty-six campsites increased in size, but this increase occurred only between 1973 and 1984, and twice as many campsites decreased in size during the same period. Consistent with the campsite inventory results, some campsites were more stable than others. Forty-four per cent of the campsites did not change in size, whereas others have changed several times since 1965 (Figure 8).

The percentage of campsites which increased in size between 1973 and 1984 in the aerial photograph evaluation (Figure 8) was much smaller than the percentage that increased between 1973 and 1983 based on the inventory comparison (Figure 7). Although methodological differences between the campsite inventory and aerial comparisons account for some of this difference, we believe that the difference primarily results from a significant decrease in campsite size and number between 1983 and 1984. This conclusion is

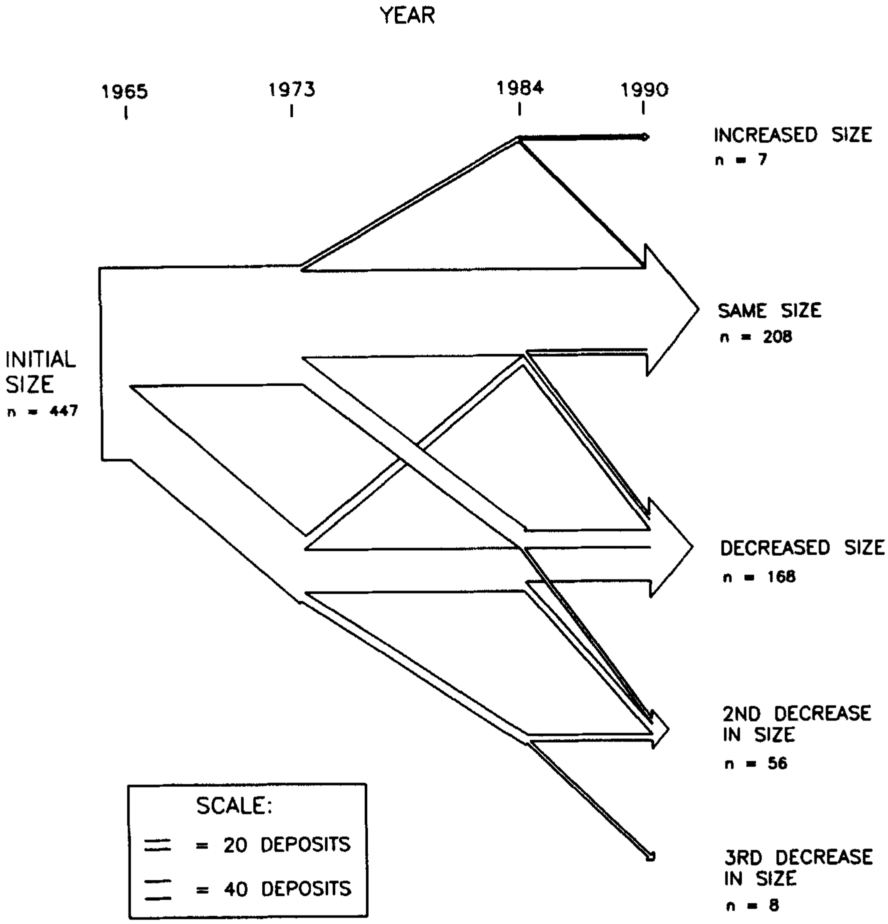

Figure 8. Temporal change in size of individual sand bars used as campsites based on aerial photograph evaluation. Arrow thickness scaled to reflect number of campsites following each pattern between years

consistent with first-hand observations of active erosion along most bar faces immediately following recession from 1983 peak flows (Brian and Thomas, 1984). High erosion rates after recession from depositional flooding events have been noted by others (Beus *et al.*, 1985; Schmidt and Graf, 1990; Hazel *et al.*, 1993). Profile resurveys and stratigraphic analysis of trenches show that peak flows in 1984 caused significant scour and fill at some sites (Beus *et al.*, 1985; Rubin *et al.*, 1990). We cannot resolve whether the decrease in campsite numbers between 1983 and 1984 was caused by post-flood recession between autumn 1983 and spring 1984 or by 1984 peak flows.

An integrated history of campsite changes

We integrated the results from both of our analyses into a temporal sequence of campsite change related to sand bar size (Figure 9). Vegetation invasion effects were not considered. This integration was accomplished by combining the records of change of all sites as determined by the two methods.

This integrated perspective of campsite change shows that the size of campsites has generally declined with time, but at a decreasing rate. The 1983 peak discharge appears to have caused short duration increases in campsite number and size, but the net increase has been minimal. Various investigators have ascribed sand bar erosion, determined by profile resurvey, to either (1) the sequence of high flows under progressively more sediment-starved conditions or (2) rapid adjustment to the resumption of lower steady discharges that

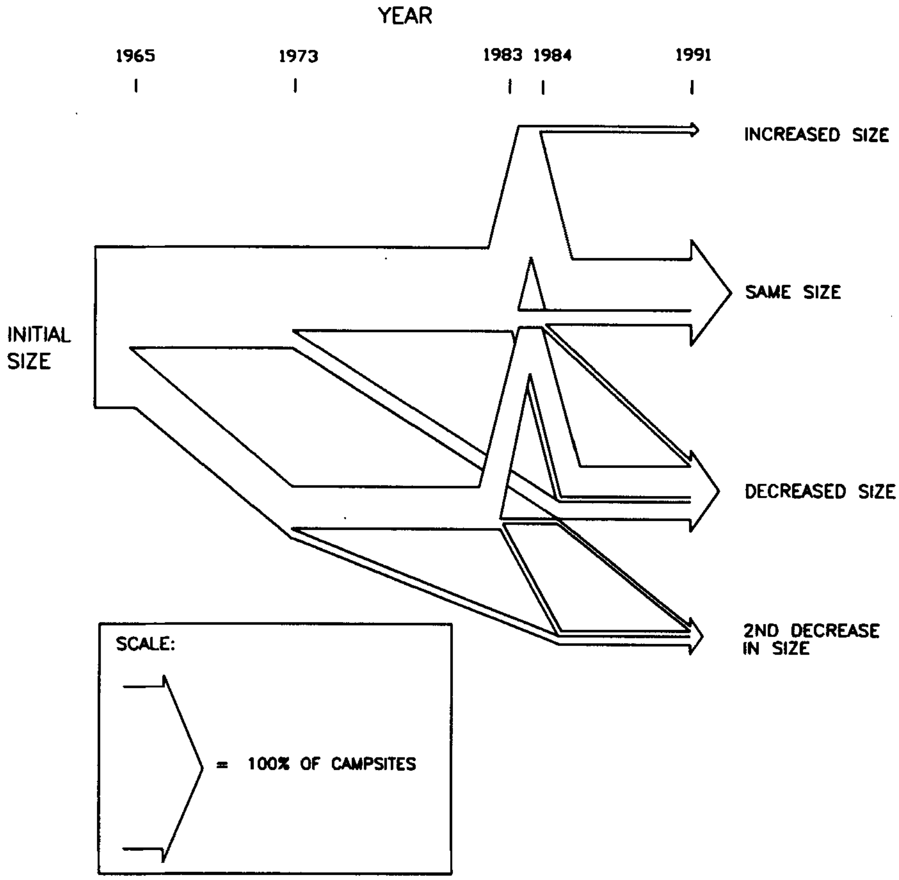

Figure 9. Temporal change in size of individual sandbars used as campsites based on a composite of results from inventory comparisons (Figure 6) and aerial photograph comparisons (Figure 7). Arrow thickness scaled to reflect number of campsites following each pattern between years. Scaled so initial width is 100% of all campsites in 1963, and sum of widths in 1991 equals initial width

followed the 1983 and 1984 peak flows (Beus *et al.*, 1985; Schmidt and Graf, 1990). Decrease in campsite size between 1984 and 1991 is either attributable to (1) sediment-starved high flows in 1985 and 1986 or (2) lower fluctuating flows that occurred after 1986.

IMPLICATIONS FOR RIVER MANAGEMENT

Campsite size and capacity are directly linked to the size and number of sand bars. Schmidt and Graf (1990) showed that campsites constitute a subset of the largest and most stable sand bars, and that campsite change alone is not an accurate reflection of the total system-wide behaviour of sand and finer-size alluvial deposits along the Colorado River. Nevertheless, system-wide change of campsites, as described in this paper, is consistent with larger scale geomorphological trends described elsewhere (Beus *et al.*, 1985; Schmidt and Graf, 1990).

The implications of these changes to dam management highlight some dilemmas in restoring campsite capacity to pre-dam conditions. The primary mechanism suggested for campsite rehabilitation is the inclusion of high flows, called 'beach/habitat building flows' intended to entrain bed sediment that would be deposited in eddies at high elevations. The US Bureau of Reclamation (1994) has proposed that these flows have a magnitude of about 1275 m^3/s, approximately equal to the magnitude of flows that occurred between 1984 and 1986, although the exact magnitude is the focus of an adaptive management programme. Such flows would only occur when sediment mass balance calculations and channel bed surveys indicate that an adequate mass of tributary-derived sediment has accumulated on the bed and is available for entrainment (US Bureau of Reclamation, 1994). The integrated perspective of campsite change shown in Figure 9 shows that: (1) rehabilitation can be justified because the number of sites has decreased with time; (2) rehabilitation strategies need not be developed in a crisis atmosphere, because the rate of campsite decline has slowed with time; (3) the 'beneficial' effects of a high discharge may be very short-lived; and (4) the same floods that cause 'benefit' to some sites erode other sites.

The fact that all sites do not respond in the same manner is due to the substantial variability in channel and debris fan geometry (Schmidt and Graf, 1990; Webb *et al.*, 1991) and the fact that progressively more sediment accumulates in the channel in the downstream direction (Randle *et al.*, 1993). Thus any planning for rehabilitation must determine (1) anticipated site response at critical locations, (2) a net change in critical reaches and (3) a net change throughout the Grand Canyon. For example, the inventory data for 1983 show that although many new campsites were formed in Grand Canyon as a whole, there was a net decrease in campsite capacity in two reaches where campsites are presently most limited. The greatest rates of campsite change in the history of Glen Canyon Dam are related to the system-wide response to the 1983 and 1984 high flows. Although we cannot resolve the causal agent for these changes, it is clear that destabilization by high flows caused temporarily high erosion rates that have declined to much slower rates during the period 1984 to 1991. Thus, the 'beneficial' nature of the high flows of 1983 and 1986 is subject to variable interpretation depending on management objectives.

CONCLUSIONS

Loss of Colorado River campsites continues after nearly 30 years of dam operations, but the rate of decline has slowed. No combination of high flows or fluctuating discharges has reversed this process. The pattern of change has been one of initial system-wide decrease in sites (1965–73), variable change during years of regulated high flows (1983–6) and a system-wide decrease in campsites since 1984.

Sand bars in Grand Canyon do not all respond in the same manner to high flows, fluctuating flows or vegetation encroachment, and the response differs between narrow and wide reaches. Despite a system-wide increase in campsites between 1973 and 1983, the carrying capacity of campsites in critical (narrow) reaches decreased. Campsite availability within critical reaches is the limiting factor in determining the river's aggregate physical carrying capacity. Thus, river managers should focus on long-term responses of campsites in critical reaches by implementing strategies that create new or increase the size of sand deposits there. Strategies that lead to net aggregate deposition along the river but which cause net campsite loss in critical reaches will only exacerbate the current problems with concentrated use at the few medium and large campsites remaining in these reaches.

ACKNOWLEDGEMENTS

We thank the many river guides who assisted in this study, particularly Dennis Silva, Richard Quartaroli, Nancy Brian and Deb Peterson. Earlier versions of this manuscript were reviewed by Larry Stevens, Mike Kearsley, Joe Hazel, Jan Balsom, Nancy Brian, and two anonymous reviewers. Funding and logistical support were provided by the US Bureau of Reclamation's Glen Canyon Environmental Studies program.

REFERENCES

Andrews, E. D. 1986. 'Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah', *Geol. Soc. Am. Bull.*, **97,** 1012–1023.

Andrews, E. D. 1990. 'The Colorado River; a perspective from Lees Ferry, Arizona' in Wolman, M. G. and Riggs, H. C. (Eds), *Surface Water Hydrology. The Geology of North America.* Vol. 0-1. Geological Society of America, Boulder. pp. 304–310.

Beus, S. S., Carothers, S. W. and Avery, C. C. 1985. 'Topographic changes in fluvial terrace deposits used as campsite beaches along the Colorado River in Grand Canyon', *J. AZ-NV Acad. Sci.*, **20,** 111–120.

Beus, S. S., Kaplinski, M. A., Hazel, J. E. Jr, Tedrow, L. A., Mayes, H. B., and Fillmore, R. P. 1993. '100-year flood events from the Little Colorado River: impacts on Colorado River sand bars and implications for sediment storage and sand bar maintenance' [abstract], *Geol. Soc. Am. Annu. Mtg. Prog.*, A142.

Brian, N. J. and Thomas, J. R. 1984. *1983 Colorado River Beach Campsite Inventory*. Division of Resources Management, National Park Service, Grand Canyon National Park, AZ.

Hazel, J. E., Jr, Kaplinski, M. A., Beus, S. S., and Tedrow, L. A. 1993. 'Sand bar stability and response to interim flows after a bar-building event on the Colorado River, Grand Canyon, Arizona: implications for sediment storage and sand bar maintenance' [abstract], *EOS*, **74**(43) (suppl., Fall Meeting Abstracts), 320.

Hirsch, R. V., Walker, J. F., Day, J. C., and Kallio, R. 1990. 'The influence of man on hydrologic systems' in Wolman, M. G. and Riggs, H. C. (Eds), *Surface Water Hydrology. The Geology of North America*. Vol. 0–1. Geological Society of America, Boulder. pp. 329–359.

Howard, A. D. and Doland, R. 1981. 'Geomorphology of the Colorado River in Grand Canyon', *J. Geol.*, **89**, 269–298.

Johnson, R. R. 1991. 'Historic changes in vegetation along the Colorado River in the Grand Canyon' in National Research Council, *Colorado River Ecology and Dam Management*. Proceedings of a Symposium held 24-25 May 1990, Santa Fe, New Mexico. National Academy Press, Washington. pp. 178–206.

Kieffer, S. W. 1985. 'The 1983 hydraulic jump in Crystal Rapid; implications for river-running and geomorphic evolution in the Grand Canyon', *J. Geol.*, **93**, 385–406.

Kieffer, S. W., Graf, J. B., and Schmidt, J. C. 1989. 'Hydraulics and sediment transport of the Colorado River' in Elston, D. P., Billingsley, G. H., and Young, R. A. (Eds), *Geology of Grand Canyon, Northern Arizona: 28th International Geological Congress Field Trip Guidebook T115/315*. American Geophysical Union. pp. 48–66.

Leopold, L. B. 1969. 'The rapids and the pools—Grand Canyon', *USGS Prof. Pap. 669-D*.

Melis, T. S. and Webb, R. H. 1993. 'Debris flows in Grand Canyon National Park, Arizona—magnitude, frequency, and effects on the Colorado River' in Shen, H. W., Su, S. T., and Wen, F. (Eds), *Hydraulic Engineering '93*. Vol. 2. American Society of Civil Engineering, New York. pp. 1290–1295.

Minckley, W. L. and Deacon, J. C. 1991. *Battle Against Extinction*. University of Arizona Press, Tucson. 517 pp.

National Research Council 1987. *River and Dam Management, A Review of the Bureau of Reclamation's Glen Canyon Environmental Studies*. National Academy Press, Washington.

National Research Council 1991. *Colorado River Ecology and Dam Management, Proceedings of a Symposium May 24–25 1990, Santa Fe, New Mexico*. National Academy Press, Washington.

Pucherelli, M. J. 1986. 'Evaluation of riparian vegetation trends in the Grand Canyon using multitemporal remote sending techniques' Am. Soc. Photogram. Remote Sensing Tech. Pap., pp. 172–181.

Randle, T. J., Strand, R. I., and Streifel, A. 1993. 'Engineering and environmental considerations of Grand Canyon sediment management' in *Engineering Solutions to Environmental Challenges: Thirteenth Annual USCOLD Lecture, Chattanooga, Tennessee*. US Committee on Large Dams.

Rubin, D. M., Schmidt, J. C., and Moore, J. N. 1990. 'Origin, structure, and evolution of a reattachment bar, Colorado River, Grand Canyon, Arizona', *J. Sedim. Petrol.*, **60**, 982–991.

Schmidt, J. C. 1990. 'Recirculating flow and sedimentation in the Colorado River in Grand Canyon, Arizona', *J. Geol.*, **98**, 709–724.

Schmidt, J. C. and Graf, J. B. 1990. 'Aggradation and degradation of alluvial sand deposits, 1965–1986, Colorado River, Grand Canyon National Park', *USGS Prof. Pap. 1493*.

Schmidt, J. C., Rubin, D. M., and Ikeda, H. 1993. 'Flume simulation of recirculating flow and sedimentation', *Water Resour. Res.*, **29**, 2925–2939.

Shelby, B. 1981. 'Research, politics, and resource management decisions: a case study of river research in Grand Canyon', *Leisure Sci.*, **4**, 281–296.

Stanford, J. A. and Ward, J. V. 1979. 'Stream regulation in North America' in Ward, J. V. and Stanford, J. A. (Eds), *The Ecology of Regulated Streams*. Plenum Press, New York. pp. 215–216.

Stephens, H. G. and Shoemaker, E. M. 1987. *In the Footsteps of John Wesley Powell*. Johnson Books, Boulder, CO.

Turner, R. M. and Karpiscak, M. M. 1980. 'Recent vegetation changes along the Colorado River between Glen Canyon Dam and Lake Mead, Arizona', *USGS Prof. Pap. 1132*. 125 pp.

Udall, J. R. 1990. 'A wild, swinging river', *Sierra*, May/June, 22–26.

US Bureau of Reclamation 1994. *Draft Environmental Impact Statement, Operation of Glen Canyon Dam, Colorado River Storage Project*. Bureau of Reclamation, Salt Lake City. 324 pp.

Webb, R. H., Pringle, P. T., and Rink, G. R. 1989. 'Debris flows from tributaries of the Colorado River, Grand Canyon National Park, Arizona', *USGS Prof. Pap. 1492*.

Webb, R. H., Melis, T. S., and Schmidt, J. C. 1991. 'Historical analysis of debris flows, recirculation zones, and changes in sand bars along the Colorado River in Grand Canyon' [abstract], *EOS*, **72** (AGU 1991 Fall Meeting Program and Abstracts), 219.

Weeden, H., Borden, F., Turner, B., Thompson, D., Strauss, C., and Johnson, R. 1975. 'Grand Canyon National Park campsite inventory', *Contract Number CX 001-3-0061 with the National Park Service*. Pennsylvania State University, University Park, PA.