Aeolian Reworking of Sandbars from the March 2008 Glen Canyon Dam High-Flow Experiment in Grand Canyon

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Abstract

The March 2008 high-flow experiment (HFE) replenished many sandbars along the Colorado River corridor in Grand Canyon downstream from Glen Canyon Dam. Some of those sandbars are source areas from which windblown sand moves inland to feed aeolian (wind-formed) sand dunes. Aeolian movement of sand following HFEs is important because some sand-dune fields in Grand Canyon contain archaeological sites that depend on a supply of windblown sand to remain covered and preserved. At two of nine sites where weather and aeolian sand transport are monitored, HFE sand deposits formed 1-meter-high dunes that moved inland during summer 2008, indicating successful transfer of sand to areas inland of the HFE high-water mark. At the other seven study sites, sand movement in nearby inland dunes was no greater than before the HFE. In order for HFE sand to move inland from sandbars toward aeolian dunes and archaeological sites, (1) sandbars must form upwind from archaeological sites (which requires sufficient sand supply in the Colorado River downstream from Glen Canyon Dam to sustain fluvial sandbar rebuilding through HFE releases); (2) local wind conditions must be strong enough and have the correct direction to move sand inland before subsequent river flows (after normal Glen Canyon Dam operations resume) erode the HFE sandbars; (3) sand transport must be unobstructed by vegetation or topographic barriers; and (4) sandbars must be dry enough for sand to be mobilized by wind.

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Introduction

The March 2008 high-flow experiment (HFE) of 41,000 cubic feet per second (ft^3/s) released from Glen Canyon Dam was intended to rebuild sandbars in the Colorado River corridor through Grand Canyon. This was the third such experimental flow; the earlier two occurred in March 1996 (45,000 ft^3/s; Webb and others, 1999) and November 2004 (41,000 ft^3/s; Topping and others, 2006). Some of the sandbars rebuilt by the HFEs are source areas from which windblown sand moves inland to replenish aeolian (wind-formed) sand dunes. Aeolian movement of sand following HFEs is important because some sand-dune fields in Grand Canyon contain archaeological sites that depend on a supply of windblown sand to remain covered and preserved (Neal and others, 2000; Draut and others, 2008). The U.S. Geological Survey (USGS) monitored aeolian transport of sand at selected study sites before and after the 2004 and 2008 HFEs. This paper discusses the degree to which sandbar enlargement by the 2008 HFE promoted windblown movement of sand inland toward dune fields and archaeological sites and compares the effects of the 2004 and 2008 HFEs on aeolian sand transport.

The 2008 HFE followed above-average input of sand and finer sediment to the Colorado River by the Paria River, 15 miles downstream from Glen Canyon Dam. Unlike in 2004, dam releases following the March 2008 HFE did not include experimental higher daily flow fluctuations like those that rapidly eroded sandbars after the 2004 HFE. Newly rebuilt sandbars, therefore, had not eroded much by the start of the 2008 spring windy season—aeolian sand transport tends to be greatest in Grand Canyon between April and early June—giving us the first opportunity to measure post-HFE aeolian sand transport with large sandbars still present.

Two Types of Aeolian Sedimentary Deposits in Grand Canyon

Previous research by Draut and Rubin (2008) defined two types of aeolian sedimentary deposits in the Colorado River corridor—modern fluvial (river) sourced (MFS) and relict fluvial sourced (RFS) deposits. The two types are distinguishable by their position relative to modern fluvial sandbars (those that formed at river flows of 45,000 ft^3/s or less) that could have provided windblown sand (fig. 1; Draut and Rubin, 2008). MFS dune fields are situated directly downwind from active (post-dam) fluvial sandbars and formed as the wind moved sand inland from sandbars, creating dune fields (fig. 1A). RFS deposits, in contrast, formed as wind reworked sediment from older (pre-dam), higher-elevation flood deposits, forming aeolian sand dunes from sediment left by floods that were larger than any post-dam floods (fig. 1B). RFS dunes may receive some sand from modern sandbars if the wind direction is appropriate, but their major source of sand is older deposits left by floods greater than 45,000 ft^3/s.

HFE releases of approximately 45,000 ft^3/s that rebuild modern sandbars can, therefore, replenish the sand sources that supply sand to inland MFS dune fields. After the 2004 HFE, at one study site where the new sandbar was not rapidly eroded by high fluctuating flows, aeolian sand-transport rates were significantly higher in the year after the HFE than in the year before (Draut and Rubin, 2008). However, in order to supply substantial amounts of new sand to RFS dune fields, much larger, sand-enriched high flows would have to occur.

The position and extent of MFS and RFS aeolian dunes are related to the magnitude of high flows that recur with sufficient frequency to provide a source of sand. Because all post-dam high flows since 1983 have been approximately 45,000 ft^3/s, the present location of MFS dunes is determined by sandbars deposited by those events. Changes in the high-flow regime could result in a change in the location and extent of MFS dunes. For example, an increase in high-flow magnitude may result in upslope expansion of the area of MFS aeolian dunes. Conversely, a decrease in peak-flow magnitude could result in downslope retreat of MFS dunes and a decrease in the area covered by active aeolian sand.

Aeolian Sand Monitoring Before and After the 2008 HFE

Since early 2007, the USGS has monitored weather conditions and aeolian sand-transport rates at nine aeolian dune fields in the Colorado River corridor where windblown

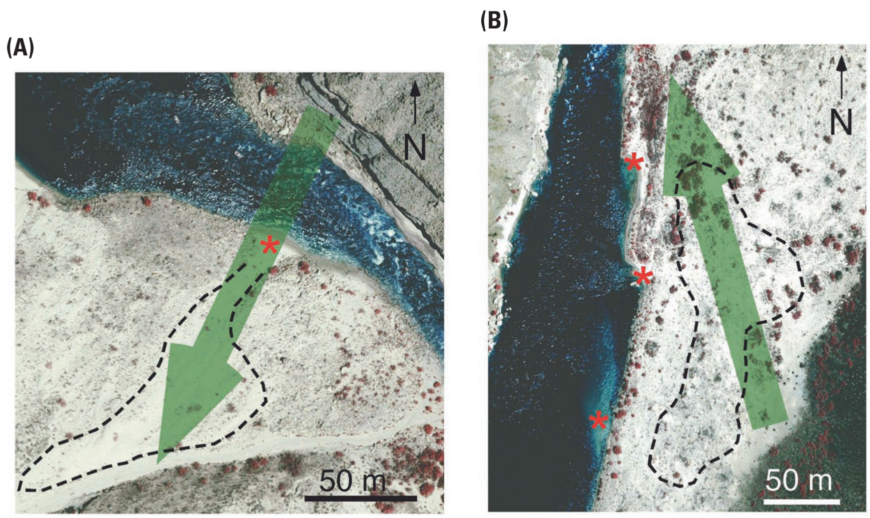

Figure 1. (A) Example of a modern fluvial sourced (MFS) aeolian dune field in Grand Canyon. The dune field (within dashed boundary) is directly downwind from a sandbar formed by flows at or below 45,000 cubic feet per second (asterisk). Here, the dominant wind direction is from the northeast (green arrow), so wind moves sand inland to form the dune field. High flows that rebuild sandbars, such as the March 2008 HFE, could supply new sand that then reaches MFS dune fields by wind transport. (B) Example of a relict fluvial sourced (RFS) aeolian dune field in Grand Canyon. The dune field (within dashed boundary) is not downwind from places where any modern sandbars form (asterisks). Instead, these aeolian dunes formed because the wind reworked sand from older, pre-dam flood deposits on terraces inland of the river (Hereford and others, 1996). The dominant wind direction in this area is from the southwest (green arrow), so sand is unlikely to be blown inland to the dunes from the modern sandbar sites (asterisks), even if those sandbars are enlarged by HFEs.

sand movement is important to the stability and preservation of archaeological sites. To evaluate whether the wind moved sand inland from sandbars that were enlarged by the 2008 HFE, we can compare measured rates of windblown sand transport in those dune fields during the year before and the year after the HFE. Similar records from some of the same sites are available from late 2003 to early 2006, capturing the year before and the year after the November 2004 HFE (Draut and Rubin, 2008). This allows us to compare some effects of the two high flows. In 2008, the size and shape of sandbars at five of the nine study sites were also monitored using topographic surveys (for example, Hazel and others, 2008) and repeat oblique photography before and after the HFE.

Methods

General locations of study sites are shown in figure 2 (exact locations cannot be disclosed, owing to their association with archaeological sites; we report only the site number, not its latitude, longitude, or river mile). At each site, one or more arrays of wedge-shaped, metal passive-sampling sand traps (Fryrear, 1986) catch samples of windblown sand that moves through the dune field. Researchers return to the sites periodically and collect the sand samples. The sample mass that accumulates in the traps over a known interval of time is used to estimate rates of sand flux moving through the dune field. Weather stations at or near each array of sand traps record wind speed and direction every 4 minutes, from which the net direction of probable sand transport can be calculated using vector sums of wind data from times when the wind was strong enough to move sand. The weather stations also record rainfall, temperature, humidity, and barometric pressure, so that we can determine if weather conditions were conducive to windblown movement of sand (wet sand will not blow around in the wind).

Results and Discussion

Of the nine sites where the USGS monitored aeolian sand transport before and after the 2008 HFE, two sites, AZ C:13:0321 and AZ C:13:0365, showed unequivocal evidence that sand deposited on sandbars by the HFE subsequently moved inland by wind action.

At AZ C:13:0321, topographic surveys before and after the 2008 HFE showed that the sandbar area increased by 129 percent and volume increased by 90 percent, owing to new sand deposition by the HFE. During the summer of 2008, sand formed a new aeolian dune 1–2 meters (m) high (fig. 3). The shape and orientation of the dune face implied that it was migrating (and moving sand) inland, toward a well-established dune field consisting of larger, vegetated dunes >10 m tall that are inland above the post-dam high-water elevation. As of October 2008, the new dune was taller (by 1.5 m) than the surface of the sandbar deposited by the HFE, and its crest was approximately 1 m higher than the maximum elevation reached by the HFE water. Because this site was monitored

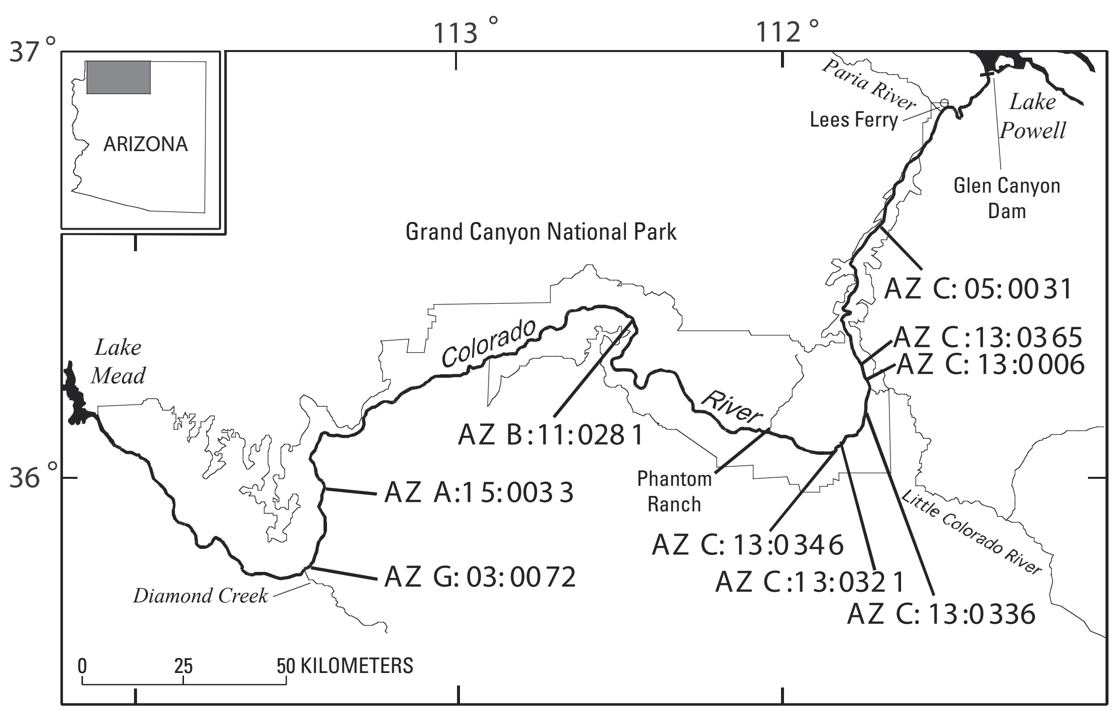

Figure 2. Sites where aeolian sand transport is monitored in the Colorado River corridor, Grand Canyon, Arizona. Site numbers refer to archaeological sites near weather stations and sand traps that measure weather conditions and rates of windblown sand flux in dune fields.

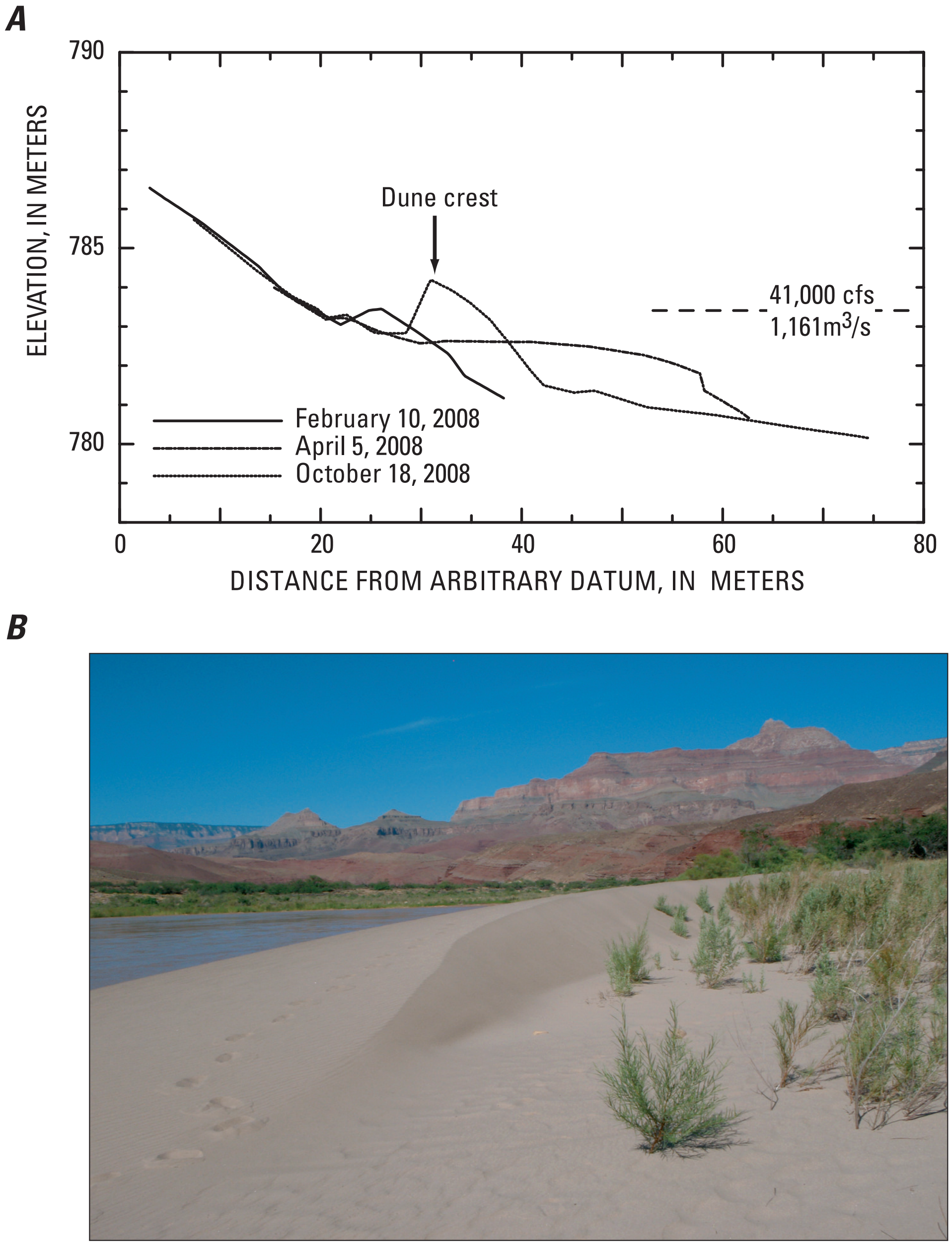

Figure 3. (A) Surveyed cross-section profiles across the sandbar at site AZ C:13:0321 made in February 2008 (1 month before the high-flow experiment (HFE)), April 2008 (1 month after the HFE), and October 2008 (7 months after the HFE). Growth of the sandbar from HFE sand deposition is apparent, as is the formation of an aeolian dune crest between the April and October surveys. The elevation of the dune crest in October was approximately 1.5 m higher than the surface of the sandbar left by the HFE, and nearly a meter higher than the maximum elevation reached by the HFE waters (horizontal dashed line). The orientation of the dune crest and slipface show dune migration (and sand transport) inland. (B) The aeolian dune crest that formed on the HFE sandbar at site AZ C:13:0321 taken on July 29, 2008.

beginning in February 2008, it is not possible to compare sand-transport rates with the year before the HFE, but daily sand flux measured at the site during summer 2008 was similar to that of the most active dune fields in the canyon, at approximately 3 grams per centimeter width.

At site AZ C:13:0365, topographic surveys showed that the HFE caused a loss of sandbar area (by 17 percent) but increased sandbar volume (by 14 percent). During the summer of 2008, one end of the HFE sandbar formed an aeolian dune, similar to the one observed at site AZ C:13:0321. As of July 2008, the dune crest was approximately 1 m higher than the surrounding sandbar, and the dune shape and orientation indicated dune migration inland from the river toward a large MFS aeolian dune field where sand-transport rates are some of the highest known in Grand Canyon (Draut and Rubin, 2008). Wind conditions measured by two weather stations at AZ C:13:0365 were consistent with inland-directed sand transport, as the dominant wind direction blew from the sandbar site inland toward the large dune. In the spring windy season of 2008 (after the HFE), windblown sand transport was greater near river level at this site than at any time measured between mid-2004 and early 2006 (no data are available for this site between January 2006 and February 2008). Higher up in the dune field, sand-transport rates in spring 2008 were similar to those measured between 2004 and early 2006.

At the seven remaining study sites, there was no clear evidence for HFE-deposited sand moving inland by wind. At two of the sites, AZ C:13:0336 and AZ A:15:0033, this was the expected result because aeolian dunes there are RFS sedimentary deposits, the sand sources of which occur at too high an elevation to have been replenished by the March 2008 HFE. At the remaining five study sites, lack of renewed aeolian sand transport to the dunes is attributable to inappropriate wind conditions or to blocking of MFS sand by vegetation or topography. Three of these five study sites (AZ C:05:0031, AZ B:11:0281, and AZ G:03:0072) contain apparently MFS aeolian dunes, which lie downwind from fluvial sandbars capable of being enlarged by HFEs, but had wind conditions after the 2008 HFE that were not effective at moving sand inland. At AZ C:05:0031, increased aeolian sand transport from the sandbar to the dune field was documented after the November 2004 HFE, but no similar response occurred after the 2008 HFE. The 2008 HFE caused some growth of the sandbar there (increasing area by 1 percent and volume by 8 percent). Although the wind commonly blows inland toward the dune field at AZ C:05:0031, between March and June 2008 the wind instead blew predominately upstream, parallel to the river. Wind conditions, therefore, were not conducive to moving sand inland from the new HFE deposit toward the dunes during the 2008 spring windy season. At AZ B:11:0281 and AZ G:03:0072, although the prevailing wind directions from March to June 2008 were oriented from the river margin inland toward dune fields, neither area experienced a significant increase in wind strength during that time of year, so spring sand transport was no higher in 2008 than in 2007. The degree of sandbar growth from the HFE is unknown at those two sites because they were not surveyed.

The final two MFS study sites showed no increase in aeolian sand transport after the 2008 HFE either because sandbars there did not enlarge much or because, although in the past fluvial sand was able to move inland toward these dunes, the dune field at each site is now separated from the associated river-level sand deposits by vegetation and (or) topographic barriers. At AZ C:13:0006, the HFE removed 13 percent of the sandbar area but increased its volume by 15 percent. The typical wind direction at this site is consistent with movement of sand inland toward an MFS aeolian dune field; however, sand-transport rates in the dune field were no higher in 2008 than in 2007. Lack of increased sand flux in the AZ C:13:0006 dune field may be because not much new sand was available on the source sandbar (having lost area) and (or) because sand must cross a side canyon, about 5 m wide, in order to move from the sandbar site into the aeolian dune field. Although this topographic influence (the side canyon) is not new, and windblown sand must have crossed it in the past to form the dune field, it is likely that a much larger sandbar would be required upwind in order for sand transport across the side canyon to increase measurably.

At site AZ C:13:0346, although wind conditions were appropriate to have moved sand inland and upslope toward large dunes, neither of two sand-trap arrays measured any increase in aeolian sand transport in 2008 relative to 2007. Any new HFE sand deposited on sandbars upwind from this dune field is separated from the dunes by a thick band of vegetation parallel to the river, which would have been less of an obstacle during pre-dam time, as this vegetation has grown substantially since the 1960s (apparent in historical aerial photographs). It is likely that although the aeolian dunes at site AZ C:13:0346 can be considered MFS deposits (downwind from sandbars at the 45,000 ft^3/s level), new sand would not readily move toward the dunes unless the vegetation were removed.

Implications for Management

Investigations of the 2004 and 2008 HFEs have shown that under sufficiently sand-enriched condition, HFEs can create new sandbars and enlarge existing ones, at least on time scales of months. Unlike the 2004 HFE sandbars, which quickly eroded because of high fluctuating flows, the 2008 HFE sandbars were present during spring months, the season when windblown sand transport generally is greatest in Grand Canyon.

At two of nine study sites (AZ C:13:0321 and AZ C:13:0365), spring and summer winds reworked the 2008 HFE sand deposits to form new aeolian dunes. The shape of the dunes in both cases indicated sand movement inland toward larger, well established dune fields. At site AZ C:13:0365, measured spring windy-season sand transport near river level was substantially greater after the 2008 HFE than after the 2004 HFE (when sandbars eroded before the 2005 spring windy season).

At the other seven study sites, HFE deposits did not form sizeable aeolian dunes, and sand-transport rates after the 2008 HFE were similar to or lower than in previous years. At several sites, inappropriate wind conditions in spring 2008 likely limited the inland movement of HFE sand; at other sites, lack of increased sand flux is attributable to blocking by vegetation or local topography. Vegetation removal could facilitate the movement of sand inland from sandbars by wind, although this has not yet been attempted in Grand Canyon.

In general, sandbars created or enlarged by HFEs can potentially contribute new sand to MFS dune fields (those downwind from sandbars formed or replenished by the HFE), but these sandbars are not expected to contribute much additional sand to RFS dune fields (which formed as wind reworked sediment left by larger, pre-dam floods). The number and proportion of Grand Canyon archaeological sites that are downwind from MFS sandbars and, thus, could benefit from HFEs are not known precisely, because wind conditions and sediment substrate vary substantially from site to site, and wind conditions and sedimentary history have been studied in detail at only about a dozen sites (this study and Draut and Rubin, 2008). The precise relation between sandbar size, resulting quantity of sand transferred to a MFS dune field, and how long new sand remains in the dune field is uncertain. Recent light detection and ranging (lidar) surveys in the river corridor are providing valuable information about landscape evolution around archaeological sites that will help to address these outstanding questions (Collins and others, 2008).

The greatest potential for inland sand movement after HFEs is in the spring, when weather commonly includes stronger winds with less rain likely than at other times of year; dam operations that maintain large sandbars in spring months, therefore, provide the best chance for sand to move inland by wind toward MFS dunes and any associated archaeological sites.

The effectiveness of HFEs to supply new sand to MFS aeolian dunes depends on the following:

1. The formation or enlargement of sandbars upwind from the dunes. This requires a sufficient sand supply in the Colorado River downstream from Glen Canyon Dam to sustain fluvial sandbar rebuilding through HFE releases (Wright and others, 2008).

2. The dominant local wind direction and intensity after the HFE near each sandbar.

3. Windblown sand moving from a sandbar to a dune field without being blocked by vegetation or topography.

4. Dryness of sandbars after the HFE. Even high winds cannot transport sand if rain or daily flow fluctuations keep the sandbar surfaces wet.

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References Cited

Collins, B.D., Brown, K.M., and Fairley, H.C., 2008, Evaluation of terrestrial LIDAR for monitoring geomorphic change at archeological sites in Grand Canyon National Park, Arizona: U.S. Geological Survey Open-File Report 2008–1384, 60 p., accessed June 8, 2010, at *http://pubs.usgs.gov/of/2008/1384/*.

Draut, A.E., and Rubin, D.M., 2008, The role of eolian sediment in the preservation of archaeologic sites along the Colorado River in Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1756, 71 p., accessed June 8, 2010, at *http://pubs.usgs.gov/pp/1756/*.

Draut, A.E., Rubin, D.M., Dierker, J.L., Fairley, H.C., Griffiths, R.E., Hazel, J.E., Jr., Hunter, R.E., Kohl, K., Leap, L.M., Nials, F.L., Topping, D.J., and Yeatts, M., 2008, Application of sedimentary-structure interpretation to geoarchaeological investigations in the Colorado River corridor, Grand Canyon, Arizona: Geomorphology, v. 101, no. 3, p. 497–509.

Fryrear, D.W., 1986, A field dust sampler: Journal of Soil and Water Conservation, v. 41, no. 2, p. 117–120.

Hazel, J.E., Jr., Kaplinski, M., Parnell, R.A., and Fairley, H.C., 2008, Aggradation and degradation of the Palisades gully network, 1996 to 2005, with emphasis on the November 2004 high-flow experiment, Grand Canyon National Park, Arizona: U.S. Geological Survey Open-File Report 2008–1264, 14 p., accessed June 8, 2010, at *http://pubs.usgs.gov/of/2008/1264*.

Hereford, R., Thompson, K.S., Burke, K.J., and Fairley, H.C., 1996, Tributary debris fans and the late Holocene alluvial chronology of the Colorado River, eastern Grand Canyon, Arizona: Geological Society of America Bulletin, v. 108, no. 1, p. 3–19.

Neal, L.A., Gilpin, D.A., Jonas, L., and Ballagh, J.H., 2000, Cultural resources data synthesis within the Colorado River corridor, Grand Canyon National Park and Glen Canyon National Recreation Area, Arizona: Flagstaff, AZ, SWCA, Inc., submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, Cultural Resources Report 98–85.

Topping, D.J., Rubin, D.M., Schmidt, J.C., Hazel, J.E., Jr., Melis, T.S., Wright, S.A., Kaplinski, M., Draut, A.E., and Breedlove, M.J., 2006, Comparison of sediment-transport and bar-response results from the 1996 and 2004 controlled-flood experiments on the Colorado River in Grand Canyon, *in* Federal Inter-Agency Sedimentation Conference, 8th, Reno, Nevada, 2006, CD-ROM Proceedings, 8 p.

Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., 1999, The 1996 controlled flood in Grand Canyon—Scientific experiment and management demonstration: Washington, DC, American Geophysical Union, Geophysical Monograph Series, v. 110, 367 p.

Wright, S.A., Schmidt, J.C., Melis, T.S., Topping, D.J., and Rubin, D.M., 2008, Is there enough sand? Evaluating the fate of Grand Canyon sandbars: Geological Society of America Today, v. 18, no. 8, p. 4–10.