JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, F02022, doi:10.1029/2011JF002329, 2012

Effects of river regulation on aeolian landscapes, Colorado River, southwestern USA

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Received 4 January 2012; revised 20 March 2012; accepted 26 March 2012; published 16 May 2012.

[1] Connectivity between fluvial and aeolian sedimentary systems plays an important role in the physical and biological environment of dryland regions. This study examines the coupling between fluvial sand deposits and aeolian dune fields in bedrock canyons of the arid to semiarid Colorado River corridor, southwestern USA. By quantifying significant differences between aeolian landscapes with and without modern fluvial sediment sources, this work demonstrates for the first time that the flow- and sediment-limiting effects of dam operations affect sedimentary processes and ecosystems in aeolian landscapes above the fluvial high water line. Dune fields decoupled from fluvial sand supply have more ground cover (biologic crust and vegetation) and less aeolian sand transport than do dune fields that remain coupled to modern fluvial sand supply. The proportion of active aeolian sand area also is substantially lower in a heavily regulated river reach (Marble–Grand Canyon, Arizona) than in a much less regulated reach with otherwise similar environmental conditions (Cataract Canyon, Utah). The interconnections shown here among river flow and sediment, aeolian sand transport, and biologic communities in aeolian dunes demonstrate a newly recognized means by which anthropogenic influence alters dryland environments. Because fluvial–aeolian coupling is common globally, it is likely that similar sediment-transport connectivity and interaction with upland ecosystems are important in other dryland regions to a greater degree than has been recognized previously.

Citation: Draut, A. E. (2012), Effects of river regulation on aeolian landscapes, Colorado River, southwestern USA, *J. Geophys. Res.*, *117*, F02022, doi:10.1029/2011JF002329.

1. Introduction

[2] Connectivity between fluvial and aeolian sedimentary systems plays an integral, yet little-studied, role in the physical and biological environment of dryland regions. Rivers in arid and semiarid lands commonly serve as sources and sinks of aeolian sediment (Figure 1), but because aeolian and fluvial processes traditionally have been studied separately, relatively little is known about their interaction or consequent links to xeric ecosystems [*Bullard and McTainsh*, 2003; *Belnap et al.*, 2011]. This study of the Colorado River corridor, southwestern USA, examines the coupling between fluvial sand supply and the physical and ecological development of aeolian dune fields. By quantifying important differences in sand-transport rates, active dune area, and ground cover between aeolian landscapes with modern fluvial sediment sources and those with little to no modern sediment supply, this work demonstrates previously unrecognized effects of anthropogenic river regulation.

[3] Interaction between subaqueous and aeolian sedimentary systems occurs widely on the surface of the Earth, spanning spatial and temporal scales that vary according to global and regional climate, among other factors [*Lancaster*, 1997; *Kocurek*, 1998; *Loope and Swinehart*, 2000; *Bullard and McTainsh*, 2003]. The best-studied examples of such connectivity are arguably those from coastal regions, where beach conditions affect sediment supply to aeolian dunes [e.g., *Davidson-Arnott and Law*, 1990; *Nordstrom and Jackson*, 1992; *Sherman and Lyons*, 1994; *Psuty*, 1996; *Marqués et al.*, 2001; *Hesp*, 2002; *Hesp et al.*, 2005, *Bauer et al.*, 2009; *Houser*, 2009; *Houser and Mathew*, 2011], and from desert playas and dry lake beds that act as aeolian dust sources [e.g., *Wopfner and Twidale*, 1988; *Kocurek and Lancaster*, 1999; *Gillette et al.*, 2001; *Reheis et al.*, 2002; *Wiggs et al.*, 2003]. Aeolian deposits also can form as wind reworks sediment from dryland alluvial fans [*Gillette et al.*, 1980; *Reheis and Kihl*, 1995; *Pease and Tchakerian*, 2003] and crevasse-splay deposits at river-mouth deltas [*Xue*, 1993]. Although interactions between rivers and aeolian sedimentary systems occur globally in dryland regions, this topic remains so little studied that several recent papers have emphasized a pressing need for better understanding of

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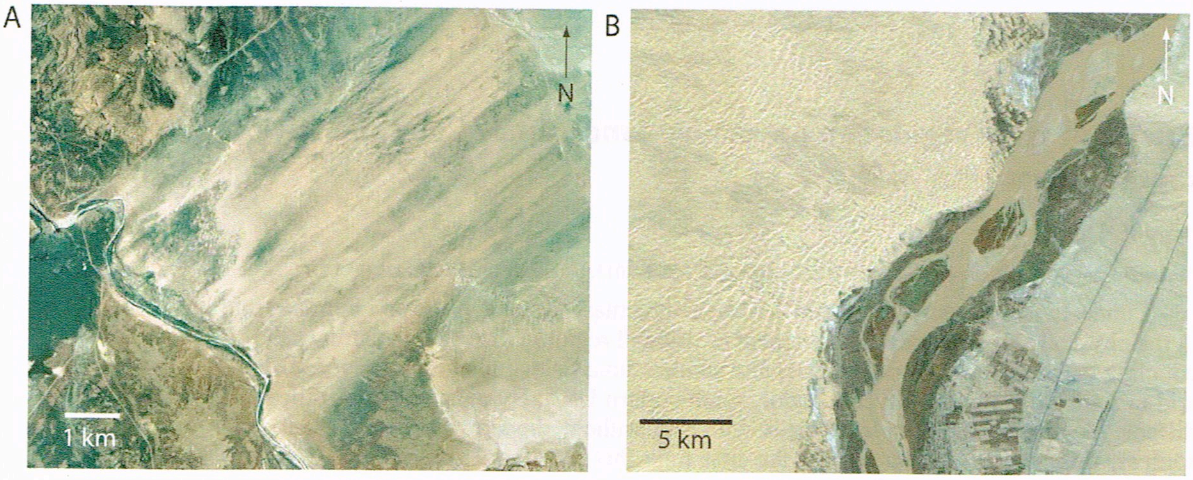

Figure 1. Dryland rivers as sources and sinks of aeolian sediment. (a) An alluvial river channel is a major source of sediment that forms aeolian deposits downwind; regional wind direction at this locality, the Little Colorado River of eastern Arizona, is from southwest toward northeast [*Redsteer et al.*, 2011; *Draut et al.*, 2011]. A dune field (2 km × 1.5 km) is visible in the middle left of the photograph. (b) An alluvial river as a sink for aeolian sediment; in this example, dunes migrate eastward off the Alxa Plateau, Inner Mongolia, into the Huanghe River. Regional wind direction is from west to east [*Yao et al.*, 2007]. Images courtesy of Google Earth, Inc.

fluvial–aeolian connectivity, especially in light of ongoing climatic change and increasing human influence in arid regions [*Field et al.*, 2009; *Belnap et al.*, 2011].

[4] Previous studies of fluvial–aeolian sediment coupling [see reviews by *Langford*, 1989; *Bullard and Livingstone*, 2002; *Bullard and McTainsh*, 2003] have described complex geomorphic and sedimentary interaction between dryland rivers and aeolian deposits [*Grove and Warren*, 1968; *Wopfner and Twidale*, 1988; *Thomas et al.*, 1993; *Loope et al.*, 1995; *Muhs et al.*, 2000, 2003; *Krapf et al.*, 2003], in ancient as well as modern settings [*Middleton and Blakey*, 1983; *Langford and Chan*, 1989; *Jones and Blakey*, 1997; *Ivester et al.*, 2001; *Simpson et al.*, 2008]. Many studies have focused on wind and water as erosive agents causing soil loss [e.g., *Breshears et al.*, 2003; *Visser et al.*, 2004; *Ravi et al.* 2007, 2010] and have discussed gullies, streams, and rivers as sinks for aeolian sediment (Figure 1b) [e.g., *Bridge et al.*, 1986; *Thomas et al.*, 1997; *Sweet et al.*, 1988; *Belnap et al.*, 2011]. There have been fewer detailed investigations of rivers supplying sand to aeolian dune fields (Figure 1a), though it is generally recognized that flood deposits of dryland rivers can be aeolian sediment sources [*Sharp*, 1966; *Williams and Lee*, 1995; *Ramsey et al.*, 1999; *Pell et al.*, 2000; *Bullard and Livingstone*, 2002; *Rendell et al.*, 2003; *Han et al.*, 2007; *Prins et al.*, 2009; *He et al.*, 2011]. In some places, the influence of fluvial sediment on aeolian deposits persists even tens to hundreds of kilometers downwind of a river [*Muhs et al.*, 2003; *Alizai et al.*, 2011]. This present study focuses on the Colorado River as the source for sediment that forms aeolian dune fields within its bedrock canyons, and investigates fluvial–aeolian sediment coupling there to test the hypothesis that river regulation at Glen Canyon Dam, Arizona, influences downstream aeolian sand deposits and associated ecosystems above the fluvial high water line.

1.1. The Colorado River Downstream of Glen Canyon Dam

[5] Although it is well documented that dams and river regulation affect river form and function greatly throughout much of the world [*Dynesius and Nilsson*, 1994; *Syvitski et al.*, 2005], some of the ways in which dams affect geologic and ecosystem properties of river corridors are still being recognized [*Ligon et al.*, 1995; *Ward and Stanford*, 1995; *Poff et al.*, 1997; *Merritt and Cooper*, 2000; *Shafroth et al.*, 2002; *Vörösmarty et al.*, 2003; *Walling and Fang*, 2003; *González et al.*, 2010]. Dams typically block the upstream sediment supply, and river regulation fundamentally alters fluvial hydrology [e.g., *Williams and Wolman*, 1984; *Chien*, 1985] such that dam operations affect downstream fluvial sedimentary processes and deposits [*Galay*, 1983; *Collier et al.*, 1996; *Brandt*, 2000; *Grant et al.*, 2003; *Hazel et al.*, 2006; *Grams et al.*, 2007; *Schmidt and Wilcock*, 2008; *Dade et al.*, 2011]. However, only rarely have those effects been shown to extend above the fluvial high water line. *Germanoski and Ritter* [1988], for instance, reported incision, widening, and headward erosion of tributaries in response to lowered base level on the main stem Osage River, Missouri, after it was dammed. Links between river regulation and aeolian landscapes have not been addressed previously in the scientific literature.

[6] The Colorado River basin drains 637,000 km^2 in an arid to semi-arid region where large dams provide water storage (Figure 2a). Glen Canyon Dam, 216 m tall, impounds the second-largest reservoir in the U.S., Lake Powell. Since the closure of Glen Canyon Dam in 1963, the hydrology and sediment supply downstream in Marble–Grand Canyon, Arizona, have changed substantially (Figure 3) [*Topping et al.*, 2000, 2003; *Rubin et al.*, 2002; *Gloss et al.*, 2005]. The dam has reduced the fluvial sediment supply to upper

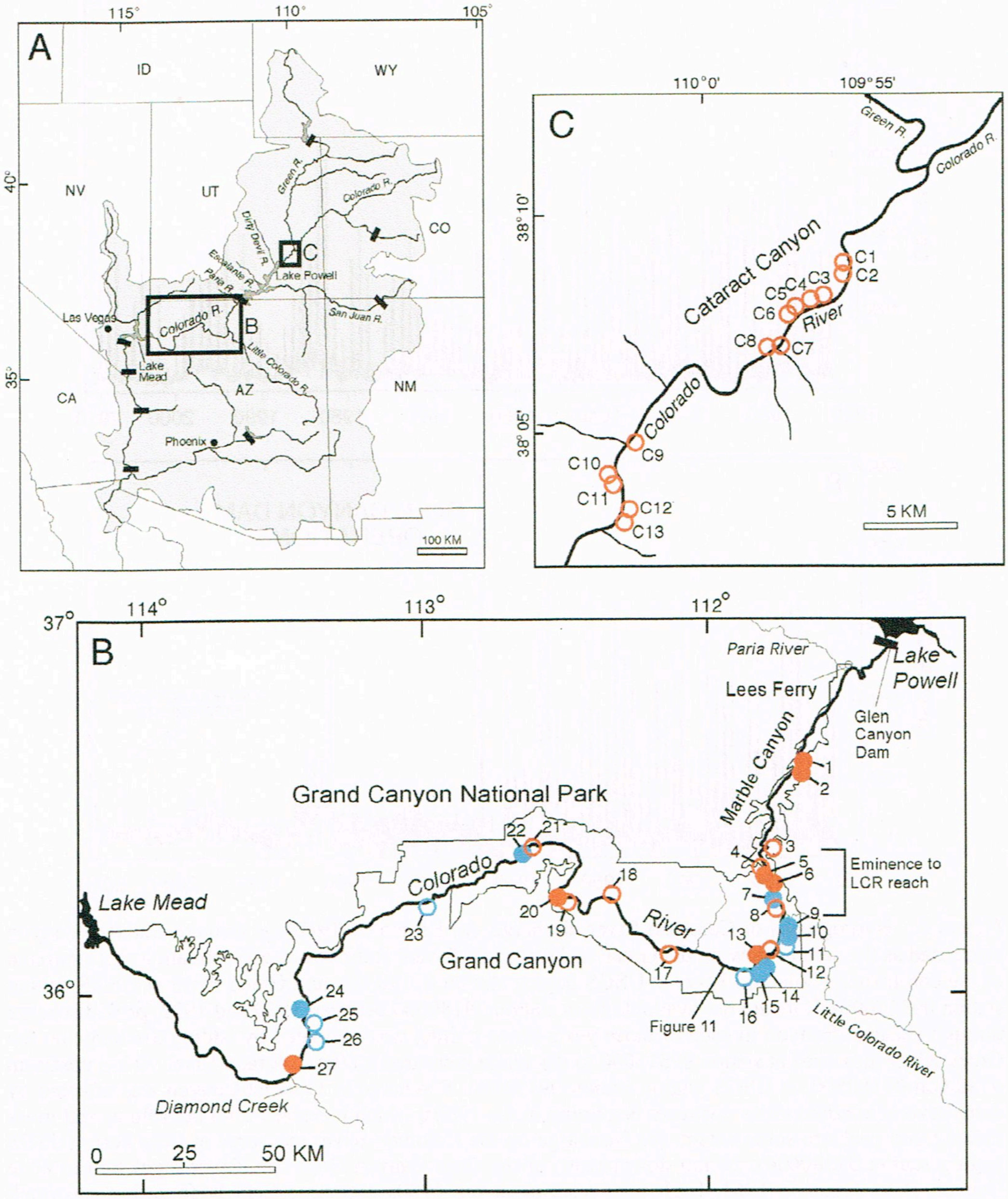

Figure 2. (a) The Colorado River basin, USA. Major dams are shown as black bars. (b) Study area downstream of Glen Canyon Dam, in Grand Canyon National Park, with study sites numbered 1–27 in order from upstream to downstream. The reach of the Colorado River between Lees Ferry and the Little Colorado River confluence is known as Marble Canyon; Grand Canyon begins below the Little Colorado River confluence. (c) Study area upstream of Glen Canyon Dam and Lake Powell, in Cataract Canyon, Utah (Canyonlands National Park), with study sites numbered C1–C13 from upstream to downstream. In Figures 2b and 2c red circles are sites with modern fluvial sediment supply, and blue circles are sites without modern sediment supply. Solid red and blue circles are sites where weather and sand-transport rates were measured. Vegetation and substrate were measured at all sites (solid and open circles).

Marble Canyon (Figure 2b) by about 95% [*Topping et al.*, 2000]. Without natural floods, the river does not deposit fluvial sediment at elevations that received it regularly before dam closure. Owing to the loss of sediment supply and reduction in the magnitude and frequency of floods, and to increased riparian vegetation in the absence of large floods, there has been a systemwide decrease in the size and number of subaerially exposed fluvial sand deposits in Marble–Grand Canyon since the 1960s [*Turner and Karpiscak*, 1980; *Beus et al.*, 1985; *Schmidt and Graf*, 1990; *Kearsley et al.*, 1994;

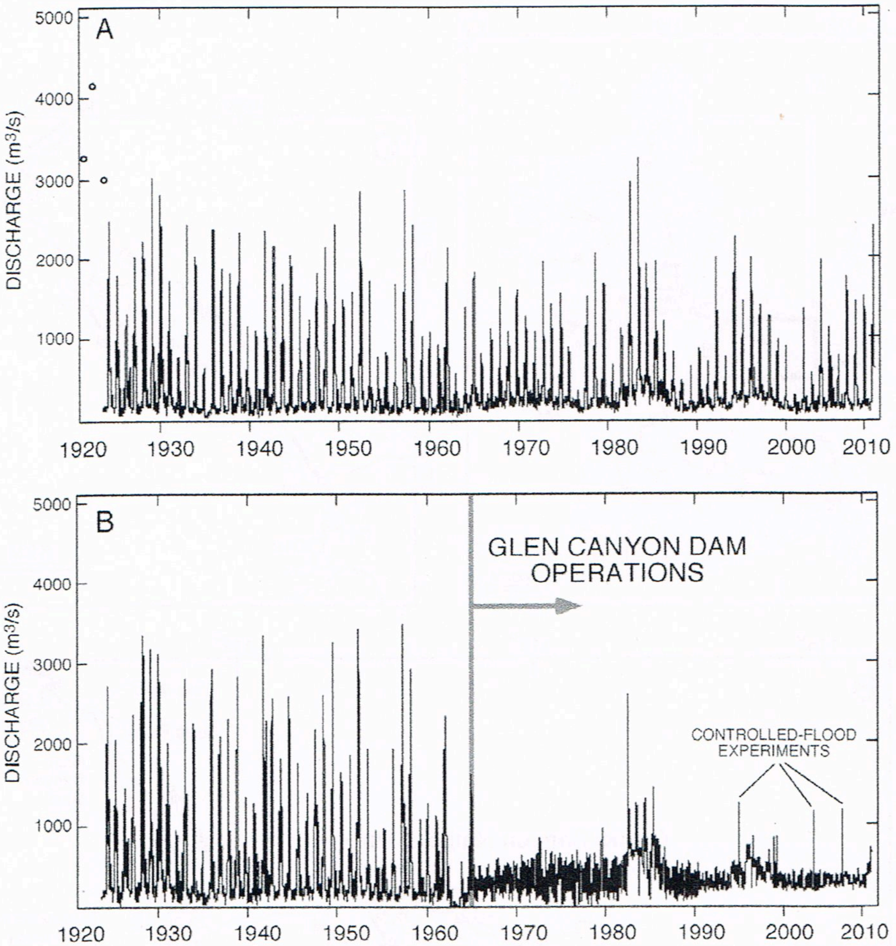

Figure 3. Hydrographs of Colorado River discharge. (a) Estimated discharge through Cataract Canyon calculated as the sum of flow on the Green and Colorado Rivers at the two nearest stream gages upstream of the confluence (Colorado River at USGS gaging station 09180500, and Green River at USGS gaging station 09315000). Data are not available from station 09180500 between 1920 and 1922; peak discharge through Cataract Canyon in each of those years (three points) was estimated by adding discharge on the Green River measured at station 09315000 to discharge measured on the Colorado River 70 km upstream of station 09180500, at USGS gaging station 09153000. Discharge in Cataract Canyon was affected by dams several hundred miles upstream beginning in the 1960s, which increased minimum flows and modulated flood peaks to some extent. (b) Discharge on the Colorado River measured at Lees Ferry (USGS gaging station 09380000), 24 km downstream of the Glen Canyon Dam site. River regulation at Glen Canyon Dam began in 1963. High dam releases in the 1980s accommodated large spring snowmelt flows entering Lake Powell. Controlled floods of 1,160–1,200 m^3/s occurred in 1996, 2004, and 2008 as a management action to rebuild fluvial sandbars in Marble–Grand Canyon.

Cluer, 1995; *Gloss et al.*, 2005; *Hazel et al.*, 2010]. Sandbar decline has been punctuated by episodic aggradation during occasional higher flows such as occurred in 1983–1985, in three controlled-flood experiments discussed below, and by sediment input from tributary floods [e.g., *Hazel et al.*, 2010].

[7] In an effort to rebuild fluvial sandbars, controlled floods were released from Glen Canyon Dam in 1996, 2004, and 2008 (Figure 3b) [*Webb et al.*, 1999; *Patten et al.*, 2001; *Schmidt et al.*, 2001; *Topping et al.*, 2010; *Melis*, 2011]. These controlled floods on the main stem Colorado River mobilized sediment delivered by natural flooding of tributaries that enter the river below the dam (no main stem sediment passes through Glen Canyon Dam). Though sandbar response to controlled floods is a complex function of the amount and grain size of tributary-supplied sand in the main channel, 60-h, 1,160 m^3/s controlled floods can successfully increase sandbar area and volume in Marble–Grand Canyon [*Hazel et al.*, 2010]. However, the magnitudes of the three controlled floods to date (≤1,200 m^3/s) were less than half of the pre-dam mean annual flood peak (2,400 m^3/s) and only one fifth as large as the maximum historic pre-dam flood (5,940 m^3/s, in 1884) [*Topping et al.*, 2003]. Paleoflood-deposit elevations suggest that the pre-dam 1,000-year flood magnitude may have been as great as

8,490 m^3/s [*O'Connor et al.*, 1994; *Topping et al.*, 2003]. The three controlled floods over 12 years therefore did not simulate the frequency or magnitude of natural Colorado River floods and did not inundate many riparian areas that were flooded often before river regulation.

[8] In the Colorado River corridor, as in other dryland areas, subaerially exposed fluvial sediment can be reworked by wind to form aeolian deposits; these are "source-bordering dunes" [*Bullard and McTainsh*, 2003], formed as wind mobilizes flood-deposited sand and redeposits it adjacent to the river channel [cf. *Blount and Lancaster*, 1990; *Lancaster*, 1995; *Nanson et al.*, 1995; *Page et al.*, 1996; *Rendell et al.*, 2003; *Han et al.*, 2007]. Many such aeolian dune fields occur in Marble–Grand Canyon, each covering 10^3–10^4 m^2. The largest aeolian dune fields occur where the river corridor is widest (where the river passes through relatively soft, erodible bedrock or follows major faults), providing space for areally extensive flood deposits and aeolian

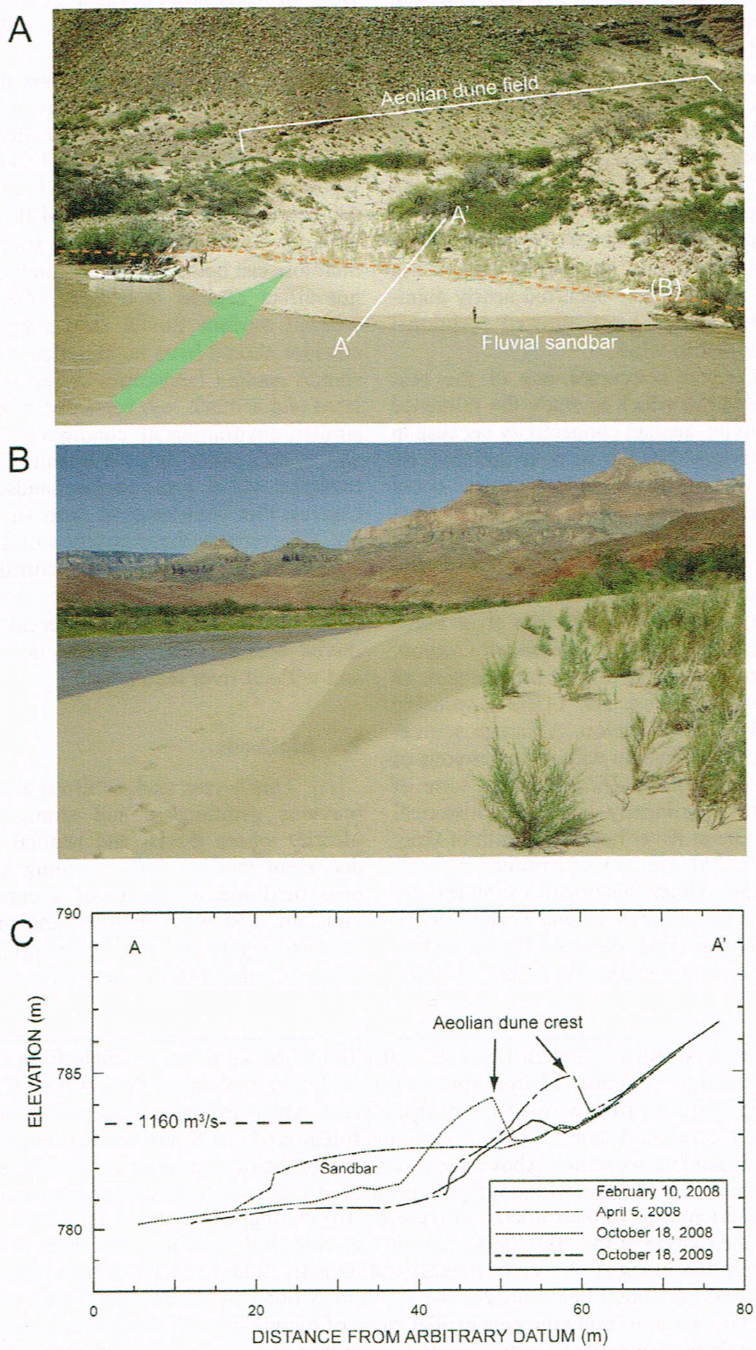

Figure 4

dunes. Maximum elevations of aeolian sand vary according to local topography and wind conditions and can reach tens of meters above the base of any given deposit; in some places, aeolian sand forms a thick mantle on talus slopes at the bases of bedrock canyon walls.

[9] In Marble–Grand Canyon, some aeolian dunes have been observed to form directly inland from modern sandbars deposited by controlled floods. After floods recede, in places where the dominant wind direction brings sand inland from the river, new aeolian dunes form above the high water line of the flood (Figure 4) [*Draut et al.*, 2010a]. Other aeolian landscapes in this canyon have no modern, controlled-flood sandbar upwind, and thus receive little to no aeolian sediment supply from modern sandbars. The stratigraphy within those dune fields indicates that they formed as the wind reworked sediment left by pre-dam floods decades or centuries ago that were larger than any post-dam flows have been [*Hereford*, 1996; *Draut et al.*, 2008; *Anderson and Neff*, 2011]. River regulation at Glen Canyon Dam thus reduced the potential sources of sediment to aeolian dune fields, largely by eliminating floods, but also by eliminating low flows (<100 m^3/s) that formerly occurred nearly annually (Figure 3) and that would have allowed additional exposure of fluvial sediment to wind.

[10] Marble–Grand Canyon comprises one of the best localities in North America in which to study the influence of river regulation on fluvial–aeolian connectivity because in no other large-scale setting (>300 km of river corridor) do dryland sedimentary and geomorphic processes occur essentially without anthropogenic disturbance other than those associated with dam operations. The river corridor through Marble–Grand Canyon is a wilderness area within Grand Canyon National Park (Figure 2b) that contains no roads, buildings, or other urban features; the river reach immediately upstream of Lake Powell, in Cataract Canyon, Utah (Figure 2c), is also entirely devoid of urbanization as part of Canyonlands National Park and offers a valuable comparison with Marble–Grand Canyon. Although source-bordering dunes also occur elsewhere within the canyons of the Colorado River and its tributaries [*Elliott*, 2002], some of those mentioned most prominently in early historical records, e.g., along the Green River near the mouth of Gray Canyon, Utah [*Powell*, 1875], are now overprinted by agriculture and urbanization. Other historical examples are submerged beneath Lake Powell [*Powell and Porter*, 1972]. The Columbia River, another large, dammed fluvial system in the arid western U.S., also historically contained large, active aeolian dunes within its bedrock gorge on the Oregon-Washington border [*Gilbert*, 1899; *Toedtemeier and Laursen*, 2008], but although aeolian deposits are still recognizable there (J. E. O'Connor, personal communication, 2012), urbanization complicates interpretation of fluvial–aeolian coupling there to a greater degree than along the Colorado River. Despite human alteration of many arid landscapes, the sedimentary, geomorphic, and ecosystem processes of the Colorado River corridor in Grand Canyon and Canyonlands National Parks are sufficiently representative of many other dryland areas that the linkages investigated by this study likely apply well beyond this particular field setting.

[11] To test the hypothesis that the flow- and sediment-limiting operations of Glen Canyon Dam affect downstream aeolian sand deposits and associated ecosystems, it is necessary to determine whether aeolian landscapes with modern fluvial sediment supply (as in Figure 4) differ from those situated such that dam-regulated flows do not provide them with an upwind fluvial sand source. A null hypothesis therefore can be formulated whereby, if river regulation does not affect aeolian landscapes, the dune fields with and without modern fluvial sand supply in a regulated river corridor should have no significant differences, and neither should aeolian landscapes differ between a strongly regulated and a much less regulated river reach with otherwise similar environmental conditions. To test the hypothesis above, this paper will (1) quantify ground cover and sand transport within some aeolian landscapes of Marble–Grand Canyon that have modern sand supply and others that do not, (2) compare the proportion of active sand-dune area in regions of the Colorado River corridor that are heavily regulated (Marble–Grand Canyon) and much less regulated (Cataract Canyon), and (3) present a conceptual model of fluvial–aeolian sediment interactions in dryland rivers with and without river regulation.

2. Methods

[12] This 8-year study utilized a combination of new and previous geomorphic and stratigraphic observations (to identify where fluvial and aeolian deposits occur, and to document modern dunes forming after controlled floods); new field measurements of ground cover, aeolian sand transport, and wind regimes; the pre- and post-dam flow records (Figure 3); and hydrologic models developed by *Magirl et al.* [2008] to determine the spatial extent of pre-

Figure 4. Reworking of sand from a modern flood deposit into an aeolian dune; example from Grand Canyon after the March 2008 controlled flood (site number 13 from this study). (a) Photograph taken three weeks after the controlled flood, on 5 April 2008, looking at site 13 from across the Colorado River. Arrow indicates local prevailing wind direction. Black dashed line indicates the recent flood stage (1,160 m^3/s). In the foreground is a fluvial sandbar augmented by the controlled flood (person standing on sandbar for scale). Above and downwind of the sandbar is an aeolian dune field with dunes as tall as 10 m. Line (A–A′) shows the location of topographic profiles in Figure 4c. The arrow and parenthetic capital B (right) indicate the location and orientation of the camera in Figure 4b. (b) Photograph taken 29 July 2008, showing a new aeolian dune that formed along the margin of the 2008 flood deposit. Lee-side slipface of the dune faces to the right. (c) Shore-perpendicular topographic profiles along A–A′. Vertical exaggeration is fivefold. In March 2008 a large sandbar formed during the controlled flood; dashed horizontal line indicates the 1,160 m^3/s flood stage. Between February and October 2008 the flood sand was reworked by wind, forming the new aeolian dune of Figure 4b, with slipface orientation indicating migration inland and upslope; river flows also eroded a cutbank into the sandbar. By October 2009, the new dune had migrated inland above the controlled-flood elevation.

and post-dam flood stages. The *Magirl et al.* models used topography from a digital elevation model and agree well with field observations of flood extent based on stratigraphy and driftwood lines [e.g., *Draut et al.*, 2005]. By using these means to determine whether aeolian dune fields receive modern sediment supply and to quantify conditions within those landscapes, this study does not rely on time series records of dune fields in Marble–Grand Canyon before and after river regulation began. Although it would be valuable to compare modern conditions of aeolian dunes with those before 1963 [cf. *Pelletier et al.*, 2009], such records do not exist in detail from pre-dam time. The first detailed geomorphic maps of the river corridor were made in the 1990s, for only a few select areas [*Hereford*, 1996; *Hereford et al.*, 1998, 2000]; this study was the first to focus intensively on aeolian dunes. Historical aerial photographs provide some information about the size and location of fluvial sandbars in the 1960s and earlier [e.g., *Schmidt and Graf*, 1990], but problems of exposure and resolution limit their utility for defining ground cover on dunes. Even without pre- and post-dam measurements on aeolian landscapes, it is nevertheless possible to determine which aeolian dunes have modern fluvial sediment sources, to measure modern conditions within those dune fields, and then to evaluate links among fluvial and aeolian sedimentary processes and dune-field ecosystems in this river corridor. It is also informative to compare the proportion of modern, active sand-dune area in heavily regulated Marble–Grand Canyon with that in the less regulated river corridor of Cataract Canyon, Utah, discussed below.

[13] Ground cover was quantified at 27 sites in aeolian sand deposits of the Colorado River corridor through Marble–Grand Canyon (Figure 2b). At 14 of those study sites, wind, rainfall, and sand transport also were measured directly (section 2.1). Those 14 sites were chosen to inform specific river-corridor management objectives for Grand Canyon National Park [*Draut and Rubin*, 2008] and were not a random sample of aeolian landscapes. The full suite of 27 sites represented the range of dune-field conditions more completely than did the subset of 14 sites where sand transport and weather were measured. Aeolian sand deposits also are present at many other places in the river corridor; the complex logistics necessary to access such a remote area made it impractical to study every occurrence of aeolian sand, except in one relatively short reach (see section 2.2).

[14] At each site, the importance of aeolian sand transport in shaping the landscape was evident from geomorphic characteristics (dune forms and coppice-dune accumulation of sand), and was confirmed by the presence of aeolian sedimentary structures in shallow pits and trenches [*Hunter*, 1977; *Rubin and Hunter*, 1982]. More extensive stratigraphic analyses were conducted at sites 9, 11, and 25 [*Draut et al.*, 2005, 2008]. Sandbar growth from the 2004 and 2008 controlled floods was assessed by direct field observation, including repeat ground-based photography, and, locally, topographic surveys [*Draut and Rubin*, 2005, 2006, 2008; *Draut et al.*, 2009a, 2009b, 2010a, 2010b]; sandbar growth from the 1996 flood was assessed by using aerial photographs in the archives of the USGS Grand Canyon Monitoring and Research Center (GCMRC) in Flagstaff, Arizona. Wind speed and direction were measured directly at 14 sites (section 2.1). At the other 13 sites, the local prevailing wind direction was estimated by measuring orientations of dune slipfaces and sand accumulations behind rocks and vegetation.

2.1. Wind, Rain, and Sand-Transport Measurements

[15] Wind velocity, rainfall, and aeolian sand-transport rates were measured between 2003 and 2010 at weather stations deployed at 14 dune-field sites in Marble–Grand Canyon (numbered 1, 2, 5–7, 9, 10, 13–15, 20, 22, 24, and 27 in Figure 2b). Record lengths at individual study sites ranged from 21 to 69 months [*Draut and Rubin*, 2005, 2006; *Draut et al.*, 2009a, 2009b, 2010a].

[16] Wind speed and direction were measured 2.0 m above the bed at each site, and recorded every 4 min as 4-min averages of 3-s sampling intervals. From 2003 to 2006 the wind measurements were made using Onset™ wind speed and direction sensors and recorded on Onset™ Micro Station data loggers; from 2007 to 2010 they were made using Vaisala™ WXT510/520 multiparameter weather transmitters with SDI-12 interface, recorded on Nexsens™ iSIC data loggers. The Onset™ anemometers measured wind speed with 0.2 m/s resolution, and measured wind direction as vector components with a resolution of 1.4° and an accuracy range of ±5°. These sensors have a 2° blind window between 358° and 0° in which no readings can be made. Vaisala™ WXT510/520 transmitters have accuracy ±0.3 m/s or ±3%, whichever is greater, for wind speeds of 0–35 m/s (no wind gusts >35 m/s were recorded during this study). The wind-direction measurement range for the two-dimensional, acoustic Vaisala™ sensors is 360° with an accuracy of ±3°. An additional error margin as great as 5° is assumed to have been incurred by the user when aligning the transmitter with true north, for a total estimated wind-direction accuracy of ±10° for data collected with Onset™ instruments and ±8° for data collected with Vaisala™ instruments.

[17] Rainfall also was measured at these weather stations with a 4-min sampling interval, using Onset™ tipping-bucket rain gages from 2003 to 2006 (resolution 0.2 mm, with accuracy ±1%) and using the pressure sensor on the Vaisala™ WXT510/520 transmitters from 2007 to 2010 (resolution 0.01 mm, with accuracy ±5%).

[18] Windblown sediment was collected in passive-sampling Big Springs Number Eight (BSNE) sand traps [*Fryrear*, 1986]. Each study site included a set of four BSNE traps deployed on a vertical pole 3–5 m away from the weather station. The bases of the 5-cm-tall trap orifices were set at heights of 0.1, 0.4, 0.7, and 1.0 m above the ground, as the great majority of aeolian sediment transport occurs within 1 m of the bed [*Anderson and Hallet*, 1986; *Sterk and Raats*, 1996; *Zobeck et al.*, 2003]. Sediment was collected from the BSNE traps typically every 4–8 weeks, though some intervals were as short as 2 days [*Draut and Rubin*, 2005] or, rarely, as long as 18 weeks [*Draut et al.*, 2010a]. At the GCMRC laboratory, organic material was removed from the samples by mixing with hydrogen peroxide; sediment was oven-dried overnight at 80°C and weighed. The resulting cumulative mass was divided by the time over which it accumulated in the traps, yielding a transport rate. In total, 378 sediment-flux measurements were made in this way between fall 2003 and summer 2010. The transport measurements included relatively little data from the most active dune fields, because equipment deployed at sites with

the highest sand-transport rates (notably sites 6 and 20) often was damaged by rapid burial and deflation. Because none of the study sites had a slope exceeding 15 degrees upwind of the sand traps, effects of slope on sand transport were considered negligible [*Sherman et al.*, 1998].

[19] Each of the 378 sand-transport measurements was normalized to eliminate the effects of variable wind strength between sites. Each measurement of sand flux was divided by the cumulative flux calculated for that time interval by the *Dong et al.* [2003] aeolian transport equation using wind data measured at the weather stations. Sand flux was calculated in this way for each 4-min time step and summed over the length of each interval during which sediment accumulated in the BSNE traps. It was assumed, based on field observations of several rain events and their aftermath, that negligible transport occurred within 48 h after a rain event. This normalization method, dividing measured sand flux by calculated sand flux, was applied in order to generate dimensionless values representing how much sand transport occurred relative to what could have occurred under local weather conditions in each time step. The *Dong et al.* [2003] transport equation, a modification of the *O'Brien and Rindlaub* [1936] formulation, was chosen because it treats wind strength as a function of velocity rather than shear velocity; to extrapolate shear velocity from having measured wind speed at only one height at each station, as could be done using the Law of the Wall, would introduce unwanted uncertainty. In applying the *Dong et al.* [2003] transport equation, median grain size of sediment at each site was obtained from analyses on a Beckman Coulter LS 100Q laser particle-size analyzer at the GCMRC laboratory; samples were pre-treated with 30% hydrogen peroxide to remove organic matter, with sodium hexametaphosphate as a deflocculant, and were disaggregated by ultrasonication before and during analysis.

2.2. Ground-Cover Measurements

[20] Vegetation and substrate properties were measured once at each of the 27 study sites during 2009 and 2010, using a pattern of circles and linear transects—two 40-m-long orthogonal transects marked out with a measuring-tape reel and five circles with radius 3 m, centered at the intersection of the two transects and at each of the four transect ends; see *Draut and Gillette* [2010]. Along each transect, gap lengths were recorded where the measuring tape crossed bare, open sand that lacked biologic soil crust, leaf litter, rocks, or overhanging plant canopy. This method was modified from *Herrick et al.* [2005], using their criteria to define plant canopy gaps. The proportion of bare, open sand at each site can be estimated by adding all of the measured gap lengths from each transect to compile a cumulative gap length measurement and representing that total gap length as a percentage of the total transect length.

[21] Within each of the five circles at each site, the area occupied by vegetation was measured, as was the proportion of substrate occupied by biologic soil crust, by comparing a disc of known size with the area covered by plants or patches of crust. Biologic soil crust is a common component of desert ecosystems, consisting of cyanobacteria living symbiotically with lichens, mosses, fungi, and algae [e.g., *Belnap and Lange*, 2003], and is recognizable as a dark, rough cover on the ground surface. The uncertainty in ground-cover measurements is estimated to be 5% or less, based on the consistency of measurements made during repeat visits, within the same season, to several test circles.

[22] In addition to the 27 study sites where ground cover was quantified in detail, the locations of which were distributed along 317 km of the river corridor in Grand Canyon National Park, a shorter reach was chosen for more spatially concentrated analysis of the proportion of active and inactive aeolian dunes. This 27-km-long reach in lower Marble Canyon, extending from an area known as Eminence Break (site 3) downstream to the Little Colorado River (LCR) confluence (Figure 2b), was selected because of its similarity to the 27-km-long Cataract Canyon reach of the Colorado River immediately upstream of Lake Powell, discussed below. Everywhere that aeolian sediment occurs in the Eminence–LCR reach, the area occupied by active and inactive dunes was mapped in the field, designating aeolian dunes with evidence for contemporary sand transport (wind-rippled surfaces, and, locally slipfaces at the angle of repose) as "active" [*Lancaster*, 1994]. Areas of active and inactive aeolian sand identified in the field were mapped onto aerial orthophotographs and then digitized in ArcGIS® for geospatial analysis of their coverage and relative proportions.

2.3. Comparative Study in Cataract Canyon, Utah

[23] It is informative to compare aeolian landscapes in the heavily regulated Colorado River corridor through Grand Canyon National Park to those in a canyon with similar scale and climate, but with much less anthropogenic influence on river flow and sand supply. Nowhere in the Colorado River basin with similar discharge to that in Grand Canyon is entirely unregulated, but a reasonable comparison can be made with the Colorado River corridor through Cataract Canyon, immediately upstream of Lake Powell and thus the nearest river reach unaffected by Glen Canyon Dam operations (Figure 2c; see also K. Thompson and A. Potochnik, Alluvial history of Cataract Canyon, Report CANY486/007-026, Resource Management Records Collection, Canyonlands National Park, Moab, Utah, unpublished manuscript, 1998). Although flow and sediment content there are somewhat less than would occur in Grand Canyon (being upstream of the San Juan and Escalante Rivers), and although dams exist far upstream, river regulation affects flow and sediment supply in Cataract Canyon much less than does Glen Canyon Dam in Marble–Grand Canyon (Figure 3a). Cataract Canyon is similar to the Eminence–LCR reach of Marble Canyon in terms of bedrock lithology, both reaches being dominated by Paleozoic limestone, and canyon morphology—14 tributaries large enough to form debris fans enter Cataract Canyon, and 16 enter the Eminence–LCR reach, creating eddies that trap fluvial sand [*Schmidt*, 1990]. Like Marble–Grand Canyon, Cataract Canyon has source-bordering aeolian dunes downwind from modern fluvial sandbars. Cataract Canyon and the Eminence–LCR reach also experience comparable wind magnitude, direction, and seasonality, as well as rainfall (in a comparison of weather data from this study with those from a station 6 km east of Cataract Canyon; U. S. Geological Survey, Southwest climate impact meteorological stations (CLIM-MET), http://esp.cr.usgs.gov/info/sw/clim-met/virginia.html, 2011). River-corridor scale also is directly comparable in the Cataract and Eminence–LCR reaches, with the maximum historic flood stage (5,940 m^3/s, in 1884) being 2.1 to

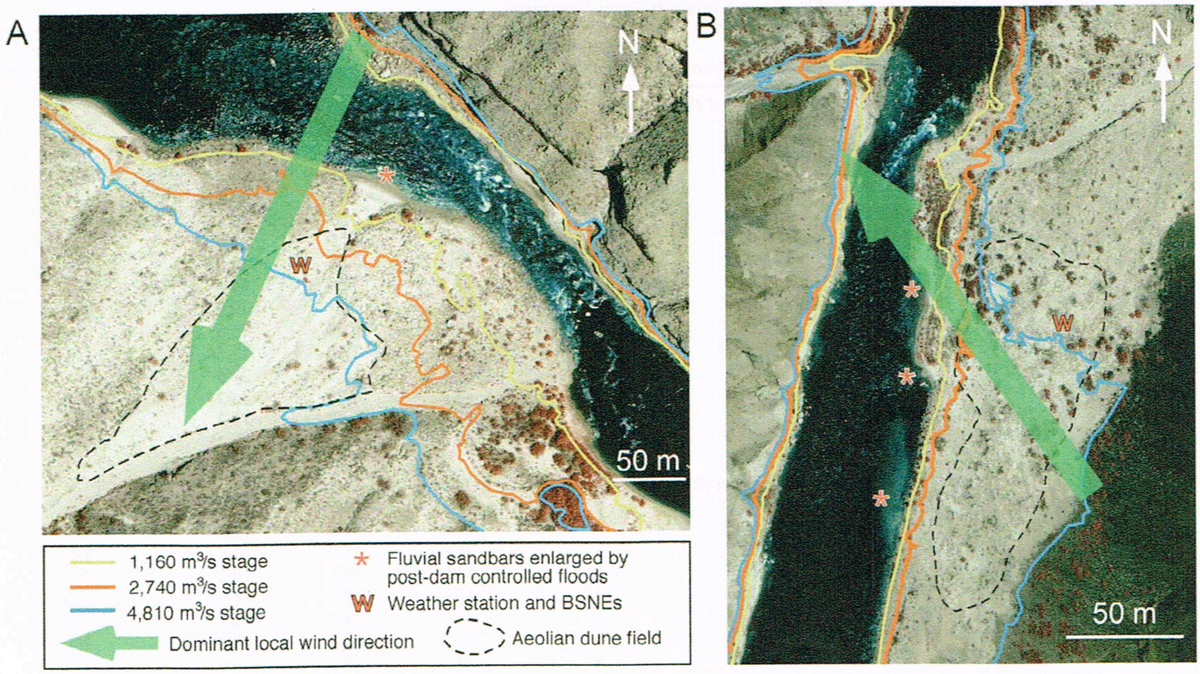

Figure 5. Aerial photographs showing relative positions of fluvial shorelines, aeolian dune fields, and locally dominant wind directions for examples of (a) modern-fluvial-sourced (MFS) aeolian landscapes and (b) relict-fluvial-sourced (RFS) aeolian landscapes in the Colorado River corridor, Grand Canyon. Both photographs were taken in 2004 at a discharge of 227 m^3/s. Colored shorelines show stage reached by post-dam controlled floods (1,160 m^3/s, in 1996, 2004, and 2008), the largest post-dam flood (an anomalous 2,740 m^3/s release in 1983), and the largest twentieth-century flood (4,810 m^3/s, in the spring of 1921) [*Magirl et al.*, 2008]. Figure 5a shows MFS aeolian dunes at site 20 occur on the surface of a broad debris fan. Local wind direction measured there between 2004 and 2006 is strongly from the north-northeast; at this site, there is a 99% probability that wind velocity greater than 5 m/s will come from between 338° and 68°. Relative positions of river shorelines, dunes, and wind direction indicate that aeolian dunes at site 20 could receive windblown sand from fluvial deposits of large pre-dam floods, smaller post-dam controlled floods, and from any low-elevation fluvial sand exposed by pre-dam low flows because the river, at any flow stage, is always upwind of this dune field. Figure 5b shows RFS aeolian dune field at site 9. The locally dominant wind direction is from the southeast, measured there between 2003 and 2010; 71% of wind velocities greater than 5 m/s come from the south and southeast, whereas only 2% come from the direction of the river (203°–293°). The aeolian dune field at site 9 therefore does not receive substantial windblown sand from fluvial sandbars at or below the 1,160 m^3/s controlled-flood stage, nor would it have during pre-dam low flows. Only during large, pre-dam floods would the river have supplied new sand to this dune field; these dunes are within and downwind of the area inundated by the 4,810 m^3/s flood stage.

2.5 times the width occupied by the river at moderate, non-flood flows (230 m^3/s). The available space to store sediment left by large, pre-dam floods in the Eminence–LCR reach is therefore similar to that in Cataract Canyon; elsewhere in Marble–Grand Canyon, the ratio of the river width at pre-dam flood stage of 5,940 m^3/s to non-flood 230 m^3/s ranges from 1 to 7 depending on local bedrock lithology, with accommodation space for subaerial sediment deposits varying accordingly. Because the most substantial difference between the Eminence–LCR reach and Cataract is that Cataract Canyon has annual spring snowmelt floods with magnitudes that vary with hydrologic conditions in the watershed, and that deposit large sandbars there annually, Cataract Canyon is a suitable analog for an unregulated Marble Canyon.

[24] Cataract Canyon field investigations in 2010 had two objectives: (1) to measure ground cover on aeolian dunes immediately downwind of recent flood deposits, in order to evaluate how closely active source-bordering dunes in Marble–Grand Canyon resemble their expected condition in a more natural, less regulated system, and (2) to measure relative proportions of active and inactive aeolian sand area, for comparison with the Eminence–LCR reach in lower Marble Canyon. To address the first goal, vegetation and biologic crust abundance were measured at 13 sites in Cataract Canyon aeolian deposits (Figure 2c) using the same pattern of circles and orthogonal transects described in section 2.2. Study sites were chosen within landscapes that had obvious aeolian landforms (sand dunes, coppice dunes, and sand accumulations behind rocks and

Table 1. Study Sites in Aeolian Dune Fields of the Colorado River Corridor[a]

Site Number	Latitude	Longitude	Wind Direction	Elevation Above River (m)	Total Gap Length (%)	Biologic Crust (%)	Vegetation Cover (%)	Wind and Sand Transport Measured?
A. Modern-Fluvial-Sourced (MFS) Dune Fields Studied in Marble–Grand Canyon								
1	36°34′38″N	111°47′29″W	169–244°	5	61.4	1.20	10.0	Yes
2	36°34′38″N	111°47′29″W	211–244°	12	56.1	3.00	10.0	Yes
3	36°23′14″N	111°51′00″W	274–303°	5	79.3	1.05	23.3	No
4	36°20′14″N	111°51′37″W	74–94°	3	90.8	0	25.1	No
5	36°14′26″N	111°49′27″W	132–154°	5	83.0	0	24.7	Yes
6	36°14′26″N	111°49′27″W	138–156°	15	65.6	14.0	32.6	Yes
8	36°12′49″N	111°48′31″W	121–127°	4	70.4	2.45	13.3	No
12	36°06′10″N	111°49′47″W	205–225°	1	79.3	4.50	12.5	No
13	36°05′40″N	111°50′34″W	175–200°	4	82.2	0	30.0	Yes
17	36°05′53″N	112°11′04″W	284–349°	12	81.3	0.60	15.5	No
18	36°14′15″N	112°20′43″W	250–270°	7	92.6	3.00	11.8	No
19	36°14′42″N	112°30′59″W	21–26°	3	69.5	15.8	29.5	No
20	36°14′50″N	112°31′09″W	21–26°	2	85.9	0.20	4.62	Yes
21	36°22′25″N	112°28′33″W	76–91°	3	85.8	0.30	11.3	No
27	35°47′13″N	113°20′34″W	176–199°	4	49.4	6.02	49.2	Yes
B. Relict-Fluvial-Sourced (RFS) Dune Fields Studied in Marble–Grand Canyon								
7	36°12′49″N	111°48′34″W	121–127°	5	14.9	34.9	51.2	Yes
9	36°08′20″N	111°48′58″W	132–155°	2	42.8	51.0	18.5	Yes
10	36°06′43″N	111°49′45″W	98–153°	3	54.9	18.0	14.8	Yes
11	36°06′37″N	111°49′40″W	98–153°	3	34.9	16.1	19.2	No
14	36°05′35″N	111°50′59″W	244–254°	7	42.6	18.0	34.6	Yes
15	36°05′40″N	111°50′51″W	233–237°	7	44.8	13.6	18.1	Yes
16	36°05′15″N	111°51′54″W	267–289°	6	37.0	6.50	16.4	No
22	36°22′39″N	112°28′53″W	84–97°	6	64.5	43.0	13.0	Yes
23	36°14′07″N	112°58′04″W	229–271°	3	27.6	27.1	18.2	No
24	36°02′49″N	113°21′08″W	194–283°	3	20.9	26.6	63.4	Yes
25	35°58′42″N	113°19′49″W	105–130°	5	0	69.8	58.8	No
26	35°58′05″N	113°19′03″W	190–240°	5	0.71	95.3	30.6	No
C. Modern-Fluvial-Sourced (MFS) Dune Fields Studied in Cataract Canyon								
C1	38°08′52″N	109°55′40″W	190–220°	13	81.5	1.25	12.6	No
C2	38°08′40″N	109°55′44″W	149–183°	10	49.3	2.00	20.7	No
C3	38°08′06″N	109°56′44″W	205–224°	10	69.6	0.55	18.4	No
C4	38°08′07″N	109°56′41″W	205–224°	5	62.5	0.75	14.4	No
C5	38°07′56″N	109°57′08″W	200–235°	9	86.7	1.80	22.1	No
C6	38°07′57″N	109°57′07″W	200–235°	12	32.3	37.4	38.4	No
C7	38°06′46″N	109°57′53″W	265–274°	3	71.2	0	22.1	No
C8	38°06′47″N	109°58′08″W	265–274°	4	47.3	1.50	23.6	No
C9	38°05′00″N	110°02′12″W	240–250°	4	66.0	16.5	23.1	No
C10	38°03′55″N	110°02′40″W	101–165°	4	68.8	3.02	22.4	No
C11	38°03′51″N	110°02′41″W	130–159°	3	68.1	7.42	28.7	No
C12	38°03′22″N	110°02′33″W	175–208°	6	75.8	4.00	29.4	No
C13	38°03′09″N	110°02′35″W	194–230°	7	80.5	2.80	23.1	No

[a] Vegetation and substrate properties were measured once at each site during 2009 and 2010. Aeolian sand transport, wind velocity, and rainfall were measured at 14 Marble–Grand Canyon sites (7 MFS and 7 RFS) between 2003 and 2010 with record lengths ranging from 21 to 69 months. Wind direction at those sites (numbers 1, 2, 5–7, 9, 10, 13–15, 20, 22, 24, and 27) was measured directly and is given in the table as the range of annualized vector sums calculated at the end of each year from 4-min measurements. At all other sites, dominant local wind direction was estimated by measuring orientations of dune slipfaces and sand shadows behind rocks and vegetation. Site elevation is given as the vertical elevation above the river at moderate, non-flood flow of 227 m^3/s. Several dune fields contain more than one study site, to represent a range of conditions observed within some of the larger dune fields: sites 1 and 2 are within one dune field, sites 5 and 6 are within one dune field, sites 10 and 11 are within one dune field, and sites 14 and 15 are within one dune field.

vegetation) within 100 m downwind of sandbars deposited by the spring 2010 flood (1,530 m^3/s), the peak stage of which was readily identifiable from driftwood and debris in wrack lines, and from sandbar morphology. Prevailing local wind directions were estimated by measuring orientations of dune slipfaces and sand accumulations behind obstacles. To address the second objective, using the same methods as described above for the 27-km-long Eminence–LCR reach, the area occupied by active and inactive dunes [*Lancaster*, 1994] was mapped on aerial photographs throughout the Cataract Canyon reach (also 27 km long). Boundaries of active and inactive aeolian sand identified in the field were mapped onto orthophotographs and their area and relative proportions were analyzed with ArcGIS®. This analysis excluded high, old flood-deposited terraces [*Webb et al.*, 2004; Thompson and Potochnik, unpublished manuscript, 1998] that had no evident aeolian landforms.

3. Results

3.1. Aeolian Landscapes of Grand Canyon National Park

[25] Locations of aeolian dune fields in Marble–Grand Canyon relative to fluvial sandbars and wind patterns

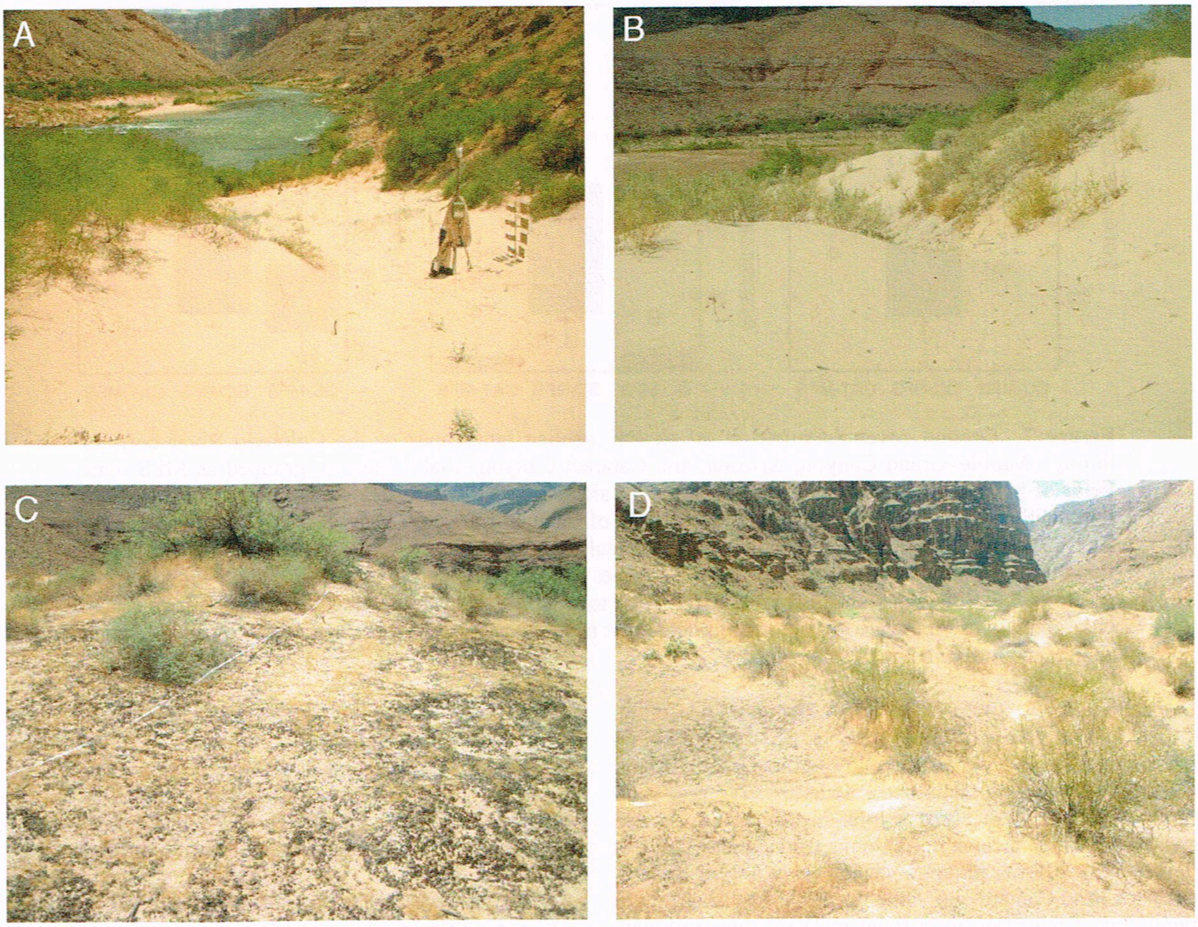

Figure 6. Photographs showing ground cover on (a, b) MFS aeolian landscapes and (c, d) RFS aeolian landscapes in Grand Canyon. All photos were taken above the elevation reached by the largest historic flood (5,940 m^3/s in 1884, a flood with an 80- to 100-year recurrence interval pre-dam) [*Topping et al.*, 2003; *Magirl et al.*, 2008]. Figure 6a shows MFS aeolian dune at site 6, with weather station and BSNE sand traps at right. Figure 6b shows MFS aeolian dunes at site 13. Figure 6c shows site 11, within a 40,000 m^2 RFS aeolian dune field. Dark biologic soil crust appears in the foreground. White measuring tape is visible at left. Figure 6d shows RFS aeolian landscape at site 26.

indicate whether substantial modern, post-dam sediment supply is available to the dunes. Based on their position relative to modern controlled-flood sandbars, pre- and post-dam flood stages (from field studies and hydrologic models [*Draut et al.*, 2005; *Magirl et al.*, 2008]), and local wind directions, the 27 study sites in Grand Canyon National Park can be classified into two groups: (1) modern-fluvial-sourced (MFS) dune fields, which are downwind from the Colorado River no matter what its stage; and (2) relict-fluvial-sourced (RFS) dune fields, which are downwind of places where the river deposited sand only during large, pre-dam floods. Figure 5 shows examples of MFS and RFS aeolian deposits, and the river stages and local wind directions that control their sediment supply. Identification of RFS sites assumes that local prevailing wind directions in pre-dam time were not substantially different from those observed during this study, a reasonable assumption given that aerial photographs show no major geomorphic changes (such as large debris flows) locally since the 1960s that might have altered wind patterns.

[26] At all study sites, aeolian dune sand was derived almost entirely from Colorado River deposits, judging from the similar color and composition of aeolian and fluvial sand in this river corridor. Sediment from the Colorado River is visibly distinct from slopewash deposits derived from local bedrock, which can interbed with aeolian and fluvial deposits—the color, lithic grain content, and angularity of locally derived sediment distinguish it from the buff-colored, mature, quartz-rich Colorado River sediment [*Draut et al.*, 2005]. Any contribution of local bedrock-derived sediment to the aeolian dunes at these study sites evidently was overwhelmed by a much greater supply of sand from Colorado River fluvial deposits [cf. *Hereford et al.*, 1998, 2000].

[27] Table 1 and Figures 6–8 summarize ground-cover and sand-transport measurements from all study sites. Full suites of data are available online from the U.S. Geological Survey

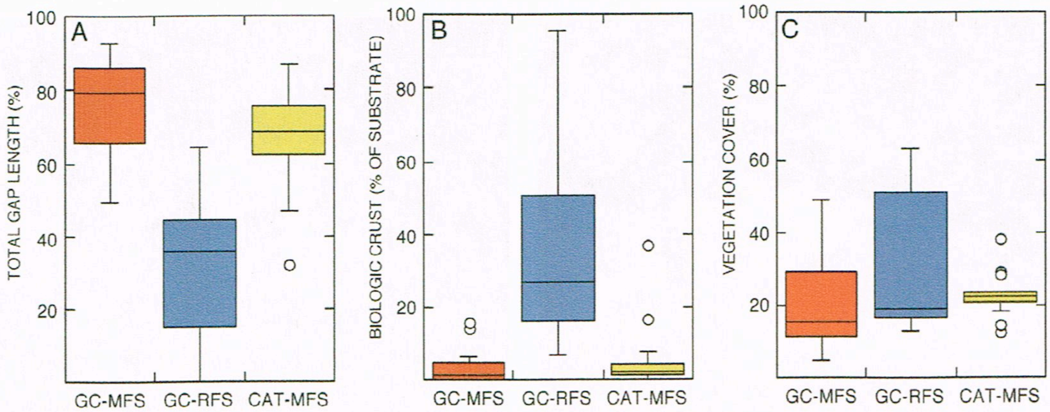

Figure 7. Ground cover measured at 40 sites in aeolian landscapes of the Colorado River corridor through Marble–Grand Canyon, Arizona, and Cataract Canyon, Utah. Sites are grouped as MFS dune fields of Marble–Grand Canyon (GC-MFS; n = 15 sites, red), RFS dune fields of Marble–Grand Canyon (GC-RFS; n = 12 sites, blue), and MFS dune fields of Cataract Canyon (CAT-MFS; n = 13 sites, yellow). Boxes span the interquartile range of data; horizontal line through each box is the median value. Circles show outlier points with values more than 1.5 times the interquartile range, and whiskers show highest and lowest non-outlier points. (a) Proportion of the total length of linear transects comprising gaps where only open, bare sand was present; (b) biologic crust abundance measured in circular plots; (c) vegetation abundance measured in circular plots.

[*Draut and Rubin*, 2005, 2006, 2008; *Draut et al.*, 2009a, 2009b, 2010a; *Draut and Gillette*, 2010; *Draut*, 2011]. Substantial differences are evident in Marble–Grand Canyon between MFS aeolian landscapes, which receive new sand supply under modern river regulation, and RFS aeolian landscapes, which receive trivial to no sand supply (Table 1, Figures 6–8). All four photographs in Figure 6 were taken in Marble–Grand Canyon above the historical maximum flood stage (that of the 5,940 m^3/s flood in 1884), but landscape characteristics of the MFS dunes (Figures 6a and 6b) downwind of modern sand sources differ visibly from those of the RFS dunes (Figures 6c and 6d). Open, bare sand constitutes a greater proportion of the ground cover on MFS dunes than on RFS dunes (Figure 7a; a *t* test shows the mean total gap length on MFS and RFS dune fields to be significantly different, $p < 0.000005$), and bare sand patches on MFS dunes are, on average, more than twice as large as those on RFS dunes.

[28] MFS sites in Marble–Grand Canyon have substantially less biologic soil crust than do RFS dune fields. The median value for biologic crust as a proportion of the substrate on dune fields is more than 20 times greater for RFS landscapes than for MFS landscapes in Grand Canyon National Park (27% versus 1.2%; Figure 7b), and the means of the two populations are significantly different ($p < 0.005$). All but one of the MFS dune fields studied in Grand Canyon had less than 20% biologic crust cover, and most of the RFS sites had more crust cover than that. However, within each dune field some areas contain more active sand than others, with evidence for recent aeolian sand activity [*Lancaster*, 1994] occurring generally in places with <20% crust cover—some MFS sites had small regions (1–10 m^2) with crust cover locally as high as 70% (e.g., site 6), and some RFS sites had 1–10 m^2 patches without biologic crust (e.g., sites 9, 10, 14, 22).

[29] Measurements of vegetation abundance yielded higher median values for RFS dune fields (15.5% for MFS, 18.9% for RFS), and higher maximum values at RFS sites (Figure 7c). A *t* test comparing mean vegetation cover at MFS and RFS sites yields $p = 0.07$, falling between two commonly used thresholds of significant difference (0.05 and 0.1).

[30] Differences in ground cover between MFS and RFS sites apparently are not related to the elevation above the river where measurements were made. The elevations of MFS and RFS study sites above the non-flood Colorado River stage of 227 m^3/s show no significant difference (from Table 1; $p > 0.1$).

[31] Consistent with the ground-cover results, aeolian sand-transport rates are much lower on RFS dunes than on MFS dunes (Figure 8). To avoid introducing uncertainty, the measured sand fluxes (Figure 8a), which were obtained from samples collected in BSNE traps, have not been extrapolated all the way down to the bed; thus, obviously, the measurements do not account for the absolute total mass flux from each site, but the relatively greater transport within MFS dunes than within RFS dunes is nevertheless clear from these data. The transport measurements of Figure 8a were normalized as described in section 2.1 to account for variability in weather conditions at different times and between sites (Figure 8b). The pattern showing greater sand transport at MFS sites remains even after the measured sand-transport rates have been normalized (Figure 8), and normalized transport rates in the two dune-field populations are significantly different ($p < 0.05$).

[32] Geospatial analysis of active and inactive aeolian sand area in the Eminence–LCR reach of lower Marble Canyon indicated that of the 797,204 m^2 of aeolian sand mapped, 119,072 m^2 (13.0%) consisted of active dunes.

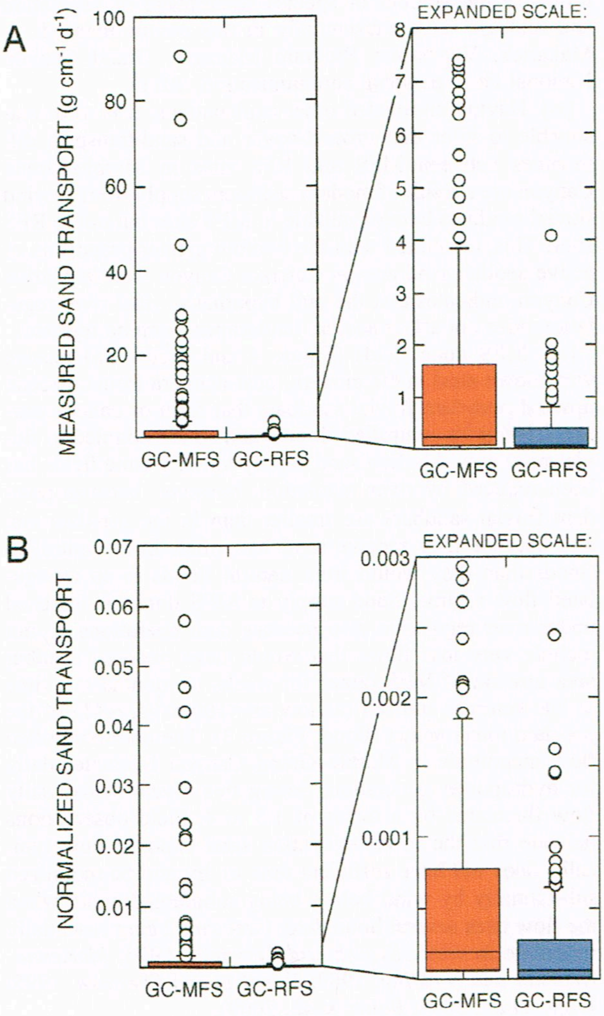

Figure 8. Aeolian sand transport measured between 2003 and 2010 at 14 sites in Marble–Grand Canyon (filled circles in Figure 2b). Sites are grouped as modern-fluvial-sourced (GC-MFS; n = 210 measurements at 7 sites, red) and relict-fluvial-sourced dune fields (GC-RFS; n = 168 measurements at 7 sites, blue). (a) Measured sand flux, in g/cm width d^{-1}. (b) Normalized, dimensionless sand flux, calculated by dividing each measurement in Figure 8a against the sand flux predicted for that time interval by the *Dong et al.* [2003] sand-transport equation, using wind velocities measured at each site, and assuming no transport within 48 h after a rain event.

3.2. Comparison with Cataract Canyon, Utah

[33] Aeolian dune fields in Cataract Canyon range from those with abundant open, bare sand (immediately downwind of recently replenished fluvial sandbars) to those with extensive biologic crust and vegetation atop older, higher flood deposits. On the 13 dune-field study sites in Cataract Canyon immediately downwind of sandbars left by a 1,530 m^3/s spring flood in 2010 (analogous to MFS dune fields in Marble–Grand Canyon), the proportions of open, bare sand and biologic crust abundance are very similar to those on MFS landscapes of Marble–Grand Canyon, and vegetation cover is also within the range seen in Marble–Grand Canyon MFS dunes (Figure 7). No significant differences were found between MFS dune ground cover in Marble–Grand Canyon and Cataract Canyon ($p \gg 0.05$ for comparison of MFS open sand, biologic crust, and vegetation abundance).

[34] The proportion of active aeolian sand area is much greater in Cataract Canyon than in the Eminence–LCR reach downstream of Glen Canyon Dam. Of the 63,451 m^2 of aeolian landscape area mapped in Cataract Canyon and digitized into ArcGIS® coverage, 41,314 m^2 (65.1%) consisted of active dune sand.

4. Discussion

[35] As shown above, ground cover and sand transport within aeolian landscapes that receive modern, fluvial sand supply from controlled floods in the Colorado River corridor of Grand Canyon National Park are significantly different than those measured there in aeolian landscapes with essentially no modern fluvial sediment source. The proportion of active aeolian sand in the Eminence–LCR reach of lower Marble Canyon, where river regulation profoundly limits flow and sediment supply, is only one fifth of that upstream of Glen Canyon Dam in Cataract Canyon, where large floods deposit sandbars annually.

[36] The association at RFS sites of low sand-transport rates with extensive ground cover (biologic crust and vegetation) is consistent with the findings of many previous studies on factors that inhibit aeolian sand transport. Biologic crust corresponds negatively with aeolian sand mobility and transport [*Leys and Eldridge*, 1998; *Belnap and Lange*, 2003; *Goossens*, 2004; *Zhang et al.*, 2008; see also *Argaman et al.*, 2006, on salt crusts]—soil crust armors the ground surface, limiting sand entrainment by wind, and, conversely, the photosynthesizing organisms in biologic crust are damaged by burial or abrasion by windblown sand [*Belnap and Lange*, 2003]. Vegetation abundance also is well known to inhibit sand transport in most situations [*Musick et al.*, 1996]—plants reduce the transport capacity of wind near the bed by covering a portion of the ground surface, physically blocking sediment motion, and forming porous, flexible roughness elements that extract momentum; plants do not thrive in active dune fields where they are abraded, buried, or have their roots exposed by deflation [e.g., *Ash and Wasson*, 1983; *Buckley*, 1987; *Raupach et al.*, 1993; *King et al.*, 2005, 2006; *Okin et al.*, 2006].

[37] Before concluding that the differences in sand transport and ground cover between MFS and RFS dune fields are caused by modern fluvial sand supply being available to the MFS sites, other explanations—such as the possibility of wind strength being coincidentally greater at all the MFS sites, or grain-size effects—must be ruled out. That the difference in relative sand-transport rates between MFS and RFS sites persists even after measured sand fluxes are normalized (Figure 8) indicates that the greater sand transport within MFS dunes must be a result of greater sediment availability or mobility rather than wind strength; wind magnitude and seasonality are, in fact, comparable at all measured sites [*Draut and Rubin*, 2005, 2006; *Draut et al.*, 2009a, 2009b, 2010a]. If sediment grain size within MFS

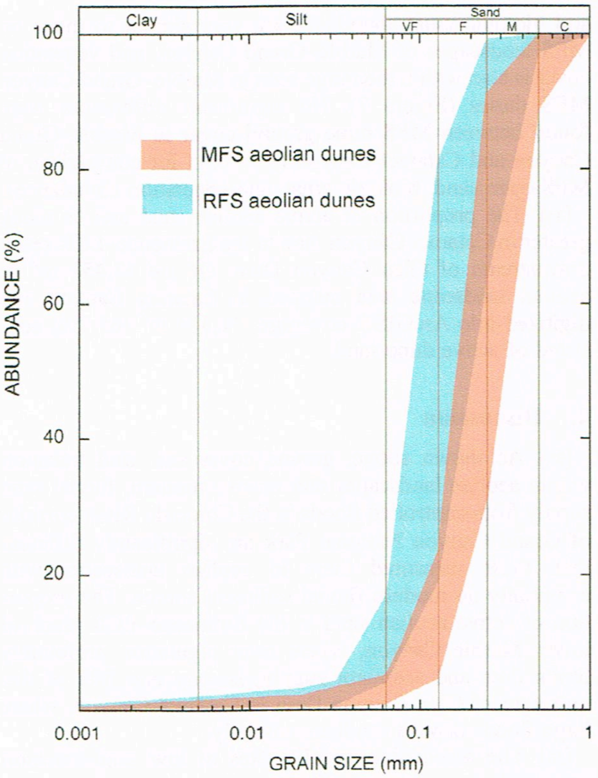

Figure 9. Grain-size distributions in sediment samples collected from the ground surfaces (uppermost 3 cm) of the aeolian dune fields in Marble–Grand Canyon where wind and sand transport were measured. VF, F, M, and C refer to very fine, fine, medium, and coarse sand.

dunes were finer than that within RFS dunes, that difference might permit greater transport at MFS sites, but such is not the case. Grain size is similar in MFS and RFS dunes, with both groups containing almost entirely well sorted fine sand, but is slightly finer at RFS sites (Figure 9). Although pre-dam flood deposits in Grand Canyon commonly are finer than post-dam controlled-flood deposits (30%–70% silt and clay pre-dam, compared to <20% silt and clay post-dam), a result of dam-imposed fine-sediment-supply limitation [*Rubin et al.*, 1998; *Topping et al.*, 2000; *Draut et al.*, 2008, 2010b], the wind winnows flood deposits such that sediment in RFS aeolian dunes contains only 4%–6% silt and clay, and thus the difference in grain size between dune fields of each group is much less than the difference in grain size of the flood deposits that supplied their respective sediment (Figure 9) [see also *Hereford*, 1996; *Hereford et al.*, 1998, 2000]. That RFS sites have slightly finer sediment than MFS sites is the opposite of what would be expected if grain-size differences were the cause of the greater sand transport within MFS dunes, and so cannot explain the sand-transport patterns observed (Figure 8). It is also unlikely that the slightly finer sediment in RFS dunes affects those sites by providing substrate more conducive to ground-cover growth; the $\sim$3% greater silt and clay content in RFS than in MFS dunes (Figure 9) is considered not large enough to influence the amount or species assemblage of vegetation and biologic crust substantially in this environment (L. J. Makarick, Vegetation Program Manager, Grand Canyon National Park, personal communication, 2011).

[38] Having eliminated other explanations, it is most reasonable to infer that ground-cover and sand-transport differences between MFS and RFS sites in Marble–Grand Canyon are a result of modern sediment supply from upwind fluvial sandbars being available to MFS sites but not to RFS sites. This, combined with the fivefold greater proportion of active aeolian sand area in Cataract Canyon than in Marble Canyon, indicates that the null hypothesis—that river regulation does not affect aeolian landscapes—can be rejected.

[39] MFS dune fields (Figure 4 and Figure 5a) receive windblown sand in the modern, post-dam era from adjacent, upwind post-dam fluvial sandbars that form or enlarge during 1,160 m^3/s controlled floods, and so are coupled to fluvial processes. Modern sand supply to MFS dune fields has been reduced by river regulation, however, because post-dam fluvial sandbars are smaller than in the pre-dam era, and because they receive sand less often from controlled floods than they would from natural floods in an unregulated flow regime. Sand supply to MFS dunes is lessened under river regulation also because dam operations do not include very low flows that would have exposed sandbar area upwind of MFS dunes for weeks to months at a time in late summer and fall (as low as $<$100 m^3/s, $\sim$4% of the pre-dam mean annual flood; Figure 3). The dam-controlled flow magnitude in Marble–Grand Canyon fluctuates daily for hydropower generation; during this 8-year study, daily flow fluctuated by a factor of 1.5 to 4. Field observations indicate that the lowest-elevation sand exposed now typically does not have sufficient time to dry and be mobilized substantially by wind before being submerged again when the flow rises several hours later (wet sand being essentially immobile in wind; *Svasek and Terwindt*, 1974; *McKenna-Neuman and Nickling*, 1989; *Namikas and Sherman*, 1995; *Wiggs et al.*, 2004; *Bauer et al.*, 2009).

[40] RFS dune fields, having no modern sandbar adjacent and upwind, do not receive any substantial sand supply post-dam (Figure 5b) and so are "discoupled" [sensu *Brunsden*, 1993] from fluvial processes. Aeolian sand in RFS dunes was derived primarily from deposits of pre-dam floods that were larger than any post-dam flows have been [*Hereford*, 1996; *Hereford et al.*, 1998, 2000; *Draut et al.*, 2008]. Even the 2,740 m^3/s flood of 1983, anomalously high for the post-dam era (Figure 3b), would have been only a 3-year flood in the natural hydrograph and was not high enough to bring substantial new sand to areas upwind of most RFS dune fields (e.g., Figure 5b; flood-frequency estimate by *Topping et al.*, 2003). Most of the relict aeolian landscapes instead formed atop and downwind of extensive (10^4 m^2) alluvial deposits by wind reworking of sediment deposited by pre-dam floods $\geq$4,800 m^3/s [*Hereford*, 1996; *Draut et al.*, 2008; *Magirl et al.*, 2008].

[41] The similarities in ground cover on MFS dunes in Marble–Grand Canyon and Cataract Canyon suggest that the controlled floods in Marble–Grand Canyon, though less frequent and utilizing less sand than in pre-dam time, have still supplied enough sand to effectively simulate near-natural ground-cover conditions on MFS dunes downwind

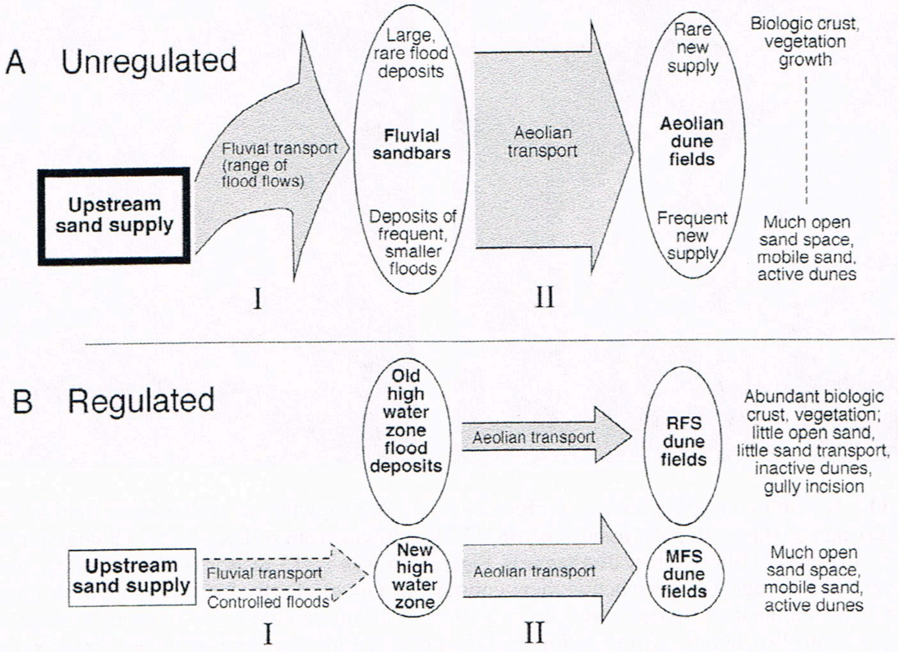

Figure 10. Conceptual model of sand transport and deposition in a dryland river corridor under conditions of flow and sand supply that are (a) natural and (b) regulated, as in the Colorado River through Marble–Grand Canyon. (See text for a detailed explanation.) For clarity, this figure omits sand-transport pathways that do not contribute sand ultimately to aeolian dune fields. Those include, in step I, fluvial sand deposited at elevations too low ever to be subaerially exposed, and suspended sand that is exported downstream out of Grand Canyon (to Lake Mead, in the modern, regulated era). In step II, depending on local wind patterns, the wind also may transport sand from fluvial sandbars back into the river or to other places on land in amounts small enough that its deposits do not form dune fields.

of the 1,160 m^3/s flood elevation. It is interesting to note that the total aeolian-sand area is much greater (by a factor of 12) in the Eminence–LCR reach than in Cataract Canyon. There are two likely reasons for this: first, although river-corridor morphology and dimensions are otherwise similar in the two reaches, the Eminence–LCR reach contains several debris fans and landslide deposits at the mouths of tributary canyons that are larger than any in Cataract Canyon. Those major debris deposits at the mouths of Saddle, Nankoweap, and Kwagunt canyons (77 km, 85 km, and 90 km downstream of Lees Ferry, respectively) affect Colorado River flow by creating large eddies downstream that, especially in the pre-dam era of substantial floods and sediment load, could trap large amounts of sand during high flows, providing ample sand for aeolian transport into dune fields. Second, because the geospatial analysis of aeolian landscapes necessarily had to include only areas above the recent flood stage and with evident dune morphology, and because the recent flood stage in Cataract Canyon (1,530 m^3/s in 2010) was higher and more recently attained than that in Marble–Grand Canyon (1,160 m^3/s in 2008), Cataract Canyon simply has more of its river corridor occupied by recent fluvial deposits not yet modified by wind. Despite the difference in total area occupied by aeolian sand within the two reaches, the geospatial mapping comparison clearly indicates that the proportion of active sand-dune area in heavily regulated Marble Canyon is substantially smaller than in the much less regulated Cataract Canyon reach upstream of the dam (13.0% versus 65.1%).

5. Conceptual Model and Implications

[42] A conceptual model is proposed to describe connectivity among fluvial sandbars, downwind aeolian deposits, and associated xeric ecosystems (Figure 10). In any unregulated river corridor with coupled fluvial and aeolian deposits, the frequency with which sand is supplied to aeolian dunes should be a function of the flood-frequency distribution. In this conceptual model, therefore, aeolian dunes that are downwind of high-elevation flood deposits left by rare, large floods (e.g., the 100-year flood) receive new sand supply less often than do aeolian dunes that are downwind of lower-elevation sandbars exposed after smaller, more frequent floods (e.g., the 2-year flood) and sand area exposed by low flows (Figure 10a). During intervals between floods, biologic soil crust and vegetation fill in open sand space to the extent that they can grow without being hindered by abrasion, burial, or root exposure owing to windblown sand. Thus, unless a rare, large flood has recently occurred, biologic crust and vegetation will be most abundant (and sand mobility lowest) in dunes downwind of large-flood deposits. In the Colorado River below Glen Canyon Dam (Figure 10b), controlled floods smaller than the pre-dam 2-year flood occasionally supply sand to the so-called new high water zone at and below the 1,160 m^3/s stage. MFS aeolian

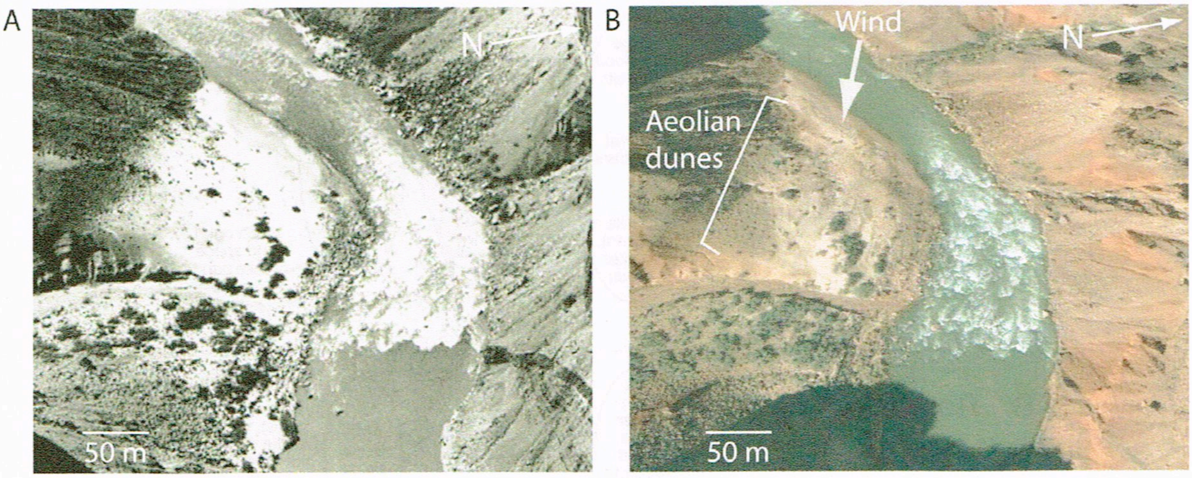

Figure 11. (a) Oblique aerial photograph from 24 June 1965 showing an aeolian dune field at the river-left (south) side of Hance Rapid, Grand Canyon, 125 km downstream of Lees Ferry. Photograph is reproduced from *Leopold* [1969]. River discharge in Figure 11a was 1,313 m^3/s. (b) The same location on 17 November 2006 (image and perspective view courtesy of Google Earth, Inc.). Discharge in Figure 11b was 308 m^3/s; the aeolian dunes extend up to >30 m in elevation above the 1,160 m^3/s stage reached by modern controlled floods. Arrow in Figure 11b shows the locally dominant wind direction, inferred from field observations of dune-crest orientation and sand accumulations behind vegetation.

dunes receive new windblown sand from those sandbars and thus remain coupled to the fluvial system, although sand supply to MFS dunes is less than in pre-dam time because exposed fluvial sand area is smaller, a result of sandbar erosion by the river, loss of natural low flows, and vegetation growth, and because increased riparian vegetation in many places [*Turner and Karpiscak*, 1980] can serve as a barrier and roughness element limiting sand transport from sandbars toward aeolian dunes. Areas formerly inundated by large, pre-dam floods—the so-called old high water zone—and RFS dunes on and downwind of those flood deposits are now decoupled from river processes. Some aeolian sand transport still occurs on pre-dam flood-deposit surfaces and in RFS dune fields, but sand-transport rates are substantially lower in RFS than in MFS dunes as biologic crust and vegetation limit sand mobility. In Cataract Canyon, annual sediment-rich floods promote stronger coupling of fluvial and aeolian processes than occurs in Marble–Grand Canyon, such that a greater proportion of aeolian landscape area consists of active dunes without biologic cover (as in Figure 10a). This model considers the condition of aeolian dunes to be dependent on a subaqueous (fluvial) sand source in a manner similar to the coupling of subaqueous and aeolian sand recognized in coastal settings [*Psuty*, 1996; *Hesp*, 2002; *Houser and Mathew*, 2011].

[43] It is worthwhile to define the time scale over which the suppression of large floods begins to affect aeolian landscapes in a regulated river. Local topography around the relict aeolian landscapes in this study is such that a flood of 4,800 m^3/s could supply new sand upwind of them (based on discharge-elevation models of *Magirl et al.* [2008]; see Figure 5b). A flood of that magnitude on the Colorado River through Marble–Grand Canyon, before dam operations began, had an estimated return interval of 40 years [*Topping et al.*, 2003], and this can be considered the time frame beyond which artificial flood suppression affected aeolian landscapes there. Given that the last flood of that magnitude occurred more than 90 years ago, in 1921, the RFS landscapes in Marble–Grand Canyon have gone more than twice as long as is natural without receiving new sand.

[44] In addition to limiting aeolian sand supply by suppressing floods, Glen Canyon Dam operations also reduce aeolian sand supply by eliminating low flows that naturally occurred nearly annually (<100 m^3/s; Figure 3), and that could have supplied additional sand to MFS dunes [*Wiele and Torizzo*, 2005]. The resulting loss of subaerially exposed sandbar area limits windblown sand supply on shorter (annual) time scales than those over which flood suppression became relevant. Loss of aeolian sand supply from low-flow sandbars is likely less important than loss of flood sand deposition, though, because the timing of pre-dam low flows and the greatest aeolian sand transport did not coincide. Flows <100 m^3/s occurred between mid-June and February, and most commonly in August and September, as still occurs in Cataract Canyon (Figure 3), whereas the most windblown sand transport happens in April and May when high wind velocity and typically dry weather cause 3–15 times more sand transport than in other seasons [*Draut and Rubin*, 2008; *Draut et al.*, 2009a, 2009b, 2010a]. Strong winds in April-May thus would have reworked primarily high-flow rather than low-flow sand, including deposits left by the snowmelt flood the previous year, which usually peaked in June.

[45] This study and the proposed conceptual model did not rely on time series records of dune fields in Marble–Grand Canyon before and after river regulation began, because such information is very scarce. Although the pre-dam condition of dune fields is largely unknown, the presence of abundant biologic soil crust and vegetation on dune morphology at RFS sites is consistent with sand supply having been reduced

relative to some time in the past, suggesting an absence of aeolian sedimentation and decrease in dune mobility relative to past times when the supply and transport of aeolian sand were great enough to form dunes [cf. *Lancaster*, 1994, 1995; *Lancaster and Baas*, 1998]. Of the rare extant photographs that show Marble–Grand Canyon dune fields several decades ago, the best example, from a field party led by L. B. Leopold in 1965 (two years after dam closure), shows an aeolian landscape lighter-colored and less vegetated than in photographs taken four decades later (Figure 11), suggesting that biologic crust and plant cover do indeed occupy more of the aeolian sand area in this river corridor now relative to earlier times.

[46] River regulation has been shown here to influence not only some downstream sedimentary and geomorphic processes above the high water line, but also the abundance of biologic soil crust. The greater proportion of inactive, crust-covered dunes in heavily regulated Marble–Grand Canyon than in the more natural environment of Cataract Canyon implies that different factors ultimately will control aeolian-sand stability in a regulated dryland river corridor than in an unregulated one. In one sense, biologic crust stabilizes relict dune surfaces by preventing sand transport that otherwise would cause dunes to migrate downwind over time [cf. *Warren*, 2003; *Belnap et al.*, 2009]. However, instead of destabilizing by dune migration, aeolian landscapes covered with biologic crust can destabilize by intensive gully incision as rainfall runs off of bedrock walls and talus slopes onto sand deposits that, even with biologic crust cover, are relatively erodible. Whereas small gullies that form in active dune fields tend to be short-lived, being soon filled and healed by windblown sand, gullies that incise into inactive, crusted dunes with little aeolian sand transport can grow into large, deep arroyo networks [*Draut and Rubin*, 2006, 2008]. The greater abundance of crust-covered dunes in a heavily regulated river corridor than in a less regulated one implies that dune migration probably has decreased and gully erosion increased in Marble–Grand Canyon since pre-dam time [cf. *Hereford et al.*, 1993]. Because aeolian sediment is important as a cover that protects some archeological sites from erosion [*Davis et al.*, 2000; *Draut et al.*, 2008], a transition from active, migrating dunes toward non-migrating, crusted dunes incised by gullies would have had substantial implications for geomorphic alteration not only of sediment deposits but also of archeological sites in the river corridor downstream of Glen Canyon Dam. Gully erosion, which typically washes sediment downslope into the Colorado River [*Hereford et al.*, 1993], is now one of the foremost challenges to preservation of archeological sites in Grand Canyon National Park, many of which occur in and on heavily crusted relict aeolian and fluvial sediment deposits [*Hereford et al.*, 1993; *Balsom et al.*, 2005; *Pederson et al.*, 2006; *Draut et al.*, 2008; *Collins et al.*, 2009; *Anderson and Neff*, 2011].

[47] In addition to its influence on landscape stability, biologic soil crust forms an important component of xeric ecosystems worldwide. Biologic crusts compose up to 70% of living ground cover in parts of the Colorado River basin, where they include multiple species of lichens, mosses, cyanobacteria, fungi, and green algae [*Harper and Belnap*, 2001; *Webb et al.*, 2004]. Crust organisms fix atmospheric nitrogen and release it into soil [*Macgregor and Johnson*, 1971]; vascular plants growing in crusted areas are substantially enhanced in nitrogen, bioavailable metals, and other elements critically important to herbivorous animals [*Harper and Belnap*, 2001; *Belnap et al.*, 2001; *Belnap and Lange*, 2003]. Given the pronounced differences in biologic crust abundance between MFS and RFS dune fields, it is highly likely that soil chemistry and nutrient content of plants also differ between aeolian landscapes with and without modern sediment supply, and that the effects of river regulation on aeolian sand supply thus propagate quite far into the ecosystem. This study therefore provides an initial example of links between fluvial and aeolian processes affecting upland ecosystems, a topic about which very little is presently known [*Belnap et al.*, 2011] and that would be an important direction for future research.

[48] Many studies have demonstrated interconnections between aquatic and subaerial parts of riparian ecosystems, but those discussed here are of a type not previously described. It is known, for instance, that nutrients and anthropogenic contaminants in rivers move into terrestrial soils and food webs [*Ben-David et al.*, 1998; *Walters et al.*, 2008; *D'Amore et al.*, 2011] and that dams impede natural connections between the aquatic and terrestrial riparian zone (e.g., by blocking fish migration; *Hilderbrand et al.*, 1999; *Helfield and Naiman*, 2001; *Duda et al.*, 2010). Those processes generally depend upon organic-matter decomposition or predation and scavenging by animals, and so differ from the ecosystem links discussed here in that the impact of river regulation on desert soils above the high water line begins not through biologic processes, but instead through geologic, sediment-transport processes. The interconnections shown here among river flow and sediment, aeolian sand transport, and biologic communities in aeolian dunes thus represent a newly recognized means by which river regulation alters dryland environments. Such connectivity among fluvial and aeolian sedimentary systems and ecosystems likely prevails in many other arid and semiarid regions globally, given that fluvial–aeolian interactions, though seldom described, are common [*Bullard and Livingstone*, 2002; *Bullard and McTainsh*, 2003] and that the sediment-transport processes and biota at the study sites discussed here are not unique to the Colorado River corridor. Better understanding of fluvial–aeolian connectivity will be particularly important as climate change and anthropogenic influence increasingly affect the physical and biological environment of dryland regions.

6. Conclusions

[49] Fluvial–aeolian sediment interactions play an important role in the physical and biological processes of the Colorado River corridor, and in many other dryland environments worldwide. Wind can move sediment from flood-deposited sandbars into aeolian dunes above the high water line of the flood that formed the sandbars; locations and elevations at which a river deposits sand are functions of the flow regime. In the Colorado River downstream of Glen Canyon Dam, as in many regulated rivers, floods are much smaller and less frequent than in pre-dam time. In Marble–Grand Canyon, rare controlled floods of 1,160 m^3/s deposit fluvial sand upwind of some, but not all, of the aeolian dune fields in the river corridor, and thus only

some of the aeolian landscapes there (modern-fluvial-sourced dune fields) remain connected to fluvial processes. Other dune fields are not downwind of places where fluvial sandbars form at flows of $\leq 1{,}160$ m^3/s, but instead lie atop or downwind of fluvial deposits of larger, pre-dam floods that have never been replenished by dam-controlled flooding. These relict-fluvial-sourced dune fields, decoupled from fluvial processes in the post-dam era, have significantly greater biologic ground cover, and significantly less aeolian sand activity, than do aeolian landscapes that receive modern sediment supply.

[50] Significant differences in ground cover and sand transport in dune fields with and without modern sand supply in the heavily regulated Colorado River corridor in Marble–Grand Canyon, together with a fivefold greater proportion of active aeolian dune area in the much less regulated Cataract Canyon reach, indicate that river regulation affects sedimentary and ecosystem processes above the fluvial high water line. These interconnections among river flow and sediment, aeolian sand transport, and biologic communities in aeolian landscapes represent a newly documented means by which anthropogenic river regulation alters dryland environments. Given that fluvial–aeolian interactions are common globally, it is likely that similar sediment-transport connectivity and interaction with upland ecosystems are important in other dryland settings to a greater degree than has yet been recognized.

[51] **Acknowledgments.** Fieldwork in Grand Canyon National Park was supported by the U.S. Bureau of Reclamation through the USGS Grand Canyon Monitoring and Research Center (National Park Service study GRCA-00208). Fieldwork in Canyonlands National Park was supported by the U.S. Geological Survey (NPS study CANY-00035). Many thanks to D. M. Rubin, H. C. Fairley, T. S. Melis, and J. C. Schmidt for their important contributions throughout, and to R. E. Hunter, L. J. Makarick, D. J. Topping, R. H. Webb, and S. W. Young for additional discussions. Research assistance was provided by S. Baden, C. Fritzinger, E. R. Gillette, C. Nelson, L. Roeder, J. S. Weisheit, G. Woodall, and more than 50 others from the USGS and the nonprofit organization Grand Canyon Youth of Flagstaff, Arizona. Topographic surveys in Figure 4c were produced by J. E. Hazel Jr. and are reprinted from *Draut et al.* [2010a]. T. Dealy, T. Gushue, and J. Logan assisted with GIS analyses. Thanks to J. E. O'Connor for valuable discussions and a field trip to aeolian deposits in the Columbia River gorge. W. Emmett provided information on historical photography by L. B. Leopold's field crew. F. Urban of the USGS measured wind velocity in Canyonlands National Park. B. O. Bauer, J. Belnap, D. M. Rubin, J. C. Schmidt, D. Sherman, P. W. Swarzenski, J. A. Warrick, S. A. Wright, B. Yanites, and 3 anonymous reviewers provided many comments that improved the manuscript.

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