Article

Progress in Physical Geography
1–26

DOI: 10.1177/0309133318795846
journals.sagepub.com/home/ppg
SAGE

Quantifying and forecasting changes in the areal extent of river valley sediment in response to altered hydrology and land cover

Alan Kasprak
US Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, Flagstaff, AZ, USA

Joel B Sankey
US Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, Flagstaff, AZ, USA

Daniel Buscombe
School of Earth and Sustainability, Northern Arizona University, Flagstaff, AZ, USA

Joshua Caster
US Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, Flagstaff, AZ, USA

Amy E East
US Geological Survey, Pacific Coastal and Marine Science Center, Santa Cruz, CA, USA

Paul E Grams
US Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, Flagstaff, AZ, USA

Abstract
In river valleys, sediment moves between active river channels, near-channel deposits including bars and floodplains, and upland environments such as terraces and aeolian dunefields. Sediment availability is a prerequisite for the sustained transfer of material between these areas, and for the eco-geomorphic functioning of river networks in general. However, the difficulty of monitoring sediment availability and movement at the reach or corridor scale has hindered our ability to quantify and forecast the response of sediment transfer to hydrologic or land cover alterations. Here we leverage spatiotemporally extensive datasets quantifying sediment areal coverage along a 28 km reach of the Colorado River in Grand Canyon, southwestern USA. In concert with information on hydrologic alteration and vegetation encroachment resulting from the operation of Glen Canyon Dam (constructed in 1963) upstream of our study reach, we model the relative and combined influence of changes in (a) flow and (b) riparian vegetation extent on the areal extent of

Corresponding author:
Alan Kasprak, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, US Geological Survey, Flagstaff, AZ 86001, USA.
Email: akasprak@usgs.gov

sediment available for transport in the river valley over the period from 1921 to 2016. In addition, we use projections of future streamflow and vegetation encroachment to forecast sediment availability over the 20 year period from 2016 to 2036. We find that hydrologic alteration has reduced the areal extent of bare sediment by 9% from the pre- to post-dam periods, whereas vegetation encroachment further reduced bare sediment extent by 45%. Over the next 20 years, the extent of bare sediment is forecast to be reduced by an additional 12%. Our results demonstrate the impact of river regulation, specifically the loss of annual low flows and associated vegetation encroachment, on reducing the sediment available for transfer within river valleys. This work provides an extendable framework for using high-resolution data on streamflow and land cover to assess and forecast the impact of watershed perturbation (e.g. river regulation, land cover shifts, climate change) on sediment connectivity at the corridor scale.

Keywords
Sediment connectivity, fluvial geomorphology, aeolian geomorphology, hillslope processes, riparian vegetation

I. Introduction

The transfer of sediment among active river channels, near-channel deposits including bars and floodplains, and upland environments, termed *sediment connectivity*, is a vital component of riverscapes worldwide (Bracken et al., 2015; Schmitt et al., 2016). Sediment connectivity is maintained through a combination of transport processes (Figure 1), including fluvial, aeolian, and hillslope (e.g. rainfall runoff or mass failure) mechanisms (Kasprak et al., 2017). During floods, rivers form near-channel sediment deposits, or floodplains, in sufficiently wide valleys. In rivers with narrow valleys or in canyon-bound rivers, where sediment is deposited rather than scoured, flood deposits may take the form of discrete bars (Grams et al., 2007, 2013; Wheaton et al., 2015). Generally, these near-channel environments can be thought of as surfaces lying above the active river channel but below the elevation of regularly occurring floods. The sediment within these near-channel deposits is remobilized by wind (i.e. aeolian transport), water (e.g. fluvial and alluvial processes), and gravity (e.g. colluvial processes including bank failure; Belnap et al., 2011; Langford, 1989; Sankey and Draut, 2014). Uplands, or locations above the stage of regularly occurring river floods (Figure 1), may be further reworked by wind, water, or colluvial (e.g. mass failure; Kasprak et al., 2017) processes and returned to near-channel deposits or the active channel itself. These areas are commonly composed of fluvial terraces in alluvial river valleys, or in dryland river systems may be marked by extensive and active source-bordering aeolian dunefields (Belnap et al., 2011; Draut, 2012; Sankey et al., 2018a, 2018c).

Over the past several decades, the importance of sediment connectivity for the eco-geomorphic function of waterways has been demonstrated (Wohl, 2017; Wohl and Beckman, 2014). Connectivity can be measured, most commonly through direct sediment transport observations, or can be predicted via numerical modeling (Schmitt et al., 2016). As a surrogate for direct measurement of sediment flux, connectivity can be quantified using high-resolution topographic data collection and analysis that allows, through subsequent geomorphic change detection, for the estimation of sediment movement within river valleys (Bangen et al., 2016; Bracken et al., 2015; Kasprak et al., 2015, 2017; Vericat et al., 2017; Wheaton et al., 2009). Recent studies have quantified the morphodynamics of rivers and near-channel deposits, including intra-flood bar and bank evolution (Buscombe, 2017; Grams

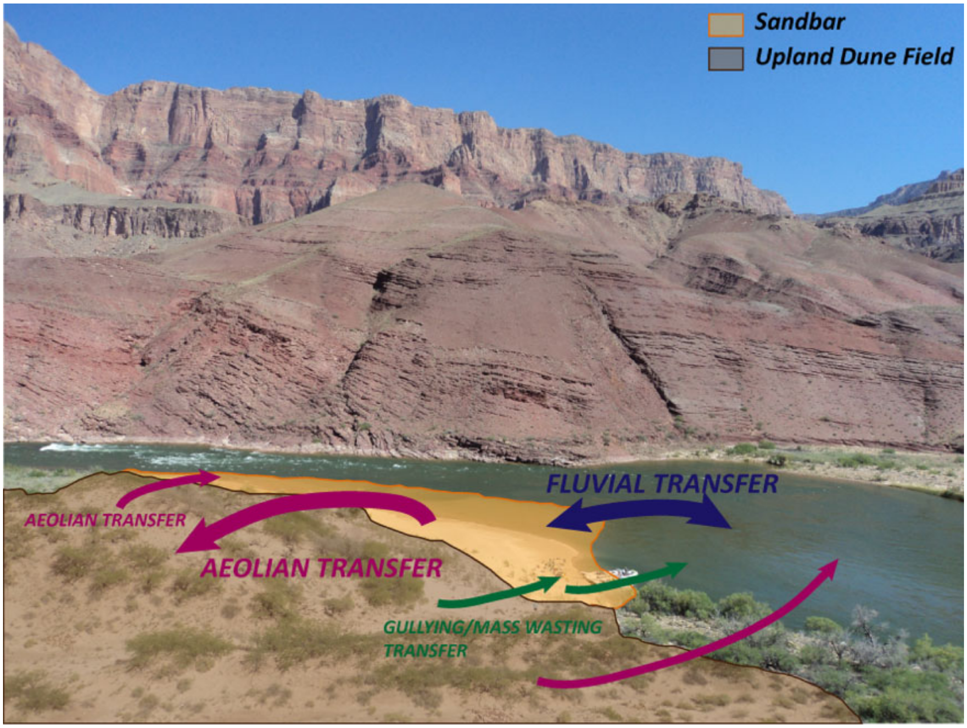

Figure 1. Pathways of sediment connectivity, or transfer, within Grand Canyon. Dominant wind direction at this site is from right to left (river to upland). Sandbars, or near-channel deposits, undergo fluvial deposition during floods, fluvial erosion during and following floods, and aeolian erosion and deposition. Uplands receive sediment via aeolian deposition. Both fluvial and upland deposits undergo gullying and mass wasting. Interactions between sandbars and uplands via fluvial and aeolian sediment connectivity are the main processes described here.

et al., 2013; Konsoer et al., 2016; Leyland et al., 2017) and the progressive building of floodplains. Other recent work has examined sediment transport from near-channel settings to upland areas through aeolian transport and has identified aeolian sediment supply as a key factor controlling gully development and ecosystem properties within source-bordering dune fields (Draut, 2012; East et al., 2016; Sankey and Draut, 2014; Sankey et al., 2018a, 2018c). Apart from physical controls on sediment connectivity in river valleys, the ability of organisms (e.g. elk, beaver, fish, vegetation) to modulate sediment transfer has received particular attention over the past several years (Beschta and Ripple, 2006; East et al., 2017; Macfarlane et al., 2017b; Millar, 2000; Piégay and Gurnell, 1997; Polvi and Wohl, 2012; Tal and Paola, 2007, 2010; Webb et al., 2007).

Although the transfer of sediment between the active channel, near-channel deposits, and uplands is a naturally occurring process in river valleys, the pathways of sediment transport can be modified, or even eliminated. Chief among a variety of such mechanisms are those that modify either the sediment supply or transport competence of rivers, such as shifts in climate, land use, or regulation (i.e. dam construction) that either directly modify the sediment supplied to river reaches or affect fluvial transport capacity through alterations in hydrologic regime (Magilligan and Nislow, 2005; Schmidt and

Wilcock, 2008). Additionally, shifts in land cover, such as vegetation succession or agricultural and urban development on near-channel environments can alter sediment source and sink dynamics (Millar, 2000; Piégay and Gurnell, 1997; Shafroth et al., 2005).

Despite the eco-geomorphic importance and natural background occurrence of interacting sediment transport pathways, most studies of sediment connectivity collect data at the site scale or short reach scale (e.g. several multiples of channel width) and are focused on explaining past, but not predicting future, changes in connectivity. This relatively narrow spatiotemporal scope is largely a function of the field effort and financial cost associated with measuring sediment transport directly, or with conducting high-resolution, repeat topographic mapping to quantify sediment transfer between channels, bars, and uplands. Thus, the baseline, or predisturbance, state of valley-scale sediment connectivity is rarely quantified over appreciable distances in river valleys. This lack of baseline data hinders our ability to predict (i.e. forecast) disruptions in sediment connectivity arising from anticipated landscape change and alterations to hydrology and sediment supply, leading to a knowledge gap which has negative implications for our understanding of river system response to disturbance (Wohl, 2017).

In this paper, we quantify past changes in the areal extent of bare sediment using spatiotemporally extensive datasets that describe river flow and land cover from 1921 to 2016, and subsequently use future predicted streamflow to assess sediment availability over the 20-year period from 2016 through 2036. Our work takes place throughout a 28 km reach of an iconic dryland river corridor, the Colorado River through Grand Canyon National Park, southwestern USA. We synthesize new and previously published data to model the areal extent of sand available for transport by wind and water. This sand is essential for the formation and maintenance of near-channel and upland landscapes, as a function of: (a) altered hydrology owing to river regulation; and (b) increases in near-channel vegetation extent due to changing flow and sediment supply over the last six decades.

For these analyses we leverage one of the most spatially extensive and highest-resolution maps of subaerial and subaqueous sediment coverage in any river system, which allows for arguably the most comprehensive examination to date of sediment availability in fluvial landscapes. Further, the techniques described herein are valuable for quantifying sediment exchange in river valleys, particularly with respect to forecasting the possible effects of alterations in flow and land cover on sediment exchange among the active channel, near-channel deposits, and uplands in riverscapes.

II. Study setting: Lower Marble Canyon, Grand Canyon National Park, Arizona, USA

This research focuses on a 28 km reach of the Colorado River corridor in Lower Marble Canyon. Marble Canyon is within Grand Canyon National Park, and the study reach used here is located from 97 to 125 km downstream of Glen Canyon Dam (Figures 2 and 3). Through this reach, the river valley is marked by steeply sloping to near-vertical canyon walls composed predominantly of Paleozoic limestones, shales, and sandstones. The average wetted channel width at a low-flow discharge of 226 m^3/s is 99 m (Sankey et al., 2015). Whereas the bedrock geology of the Canyon imposes a first-order control on the general planform of the Colorado River through this reach, the river corridor consists of a sand-bedded alluvial channel where tributaries supply the majority of sediment entering the reach. Sandbars form within the channel and along its margins, occurring most commonly within eddy recirculation zones in the lee of tributary debris fans (Figure 1; Hazel et al., 2006; Howard and Dolan, 1981; Melis

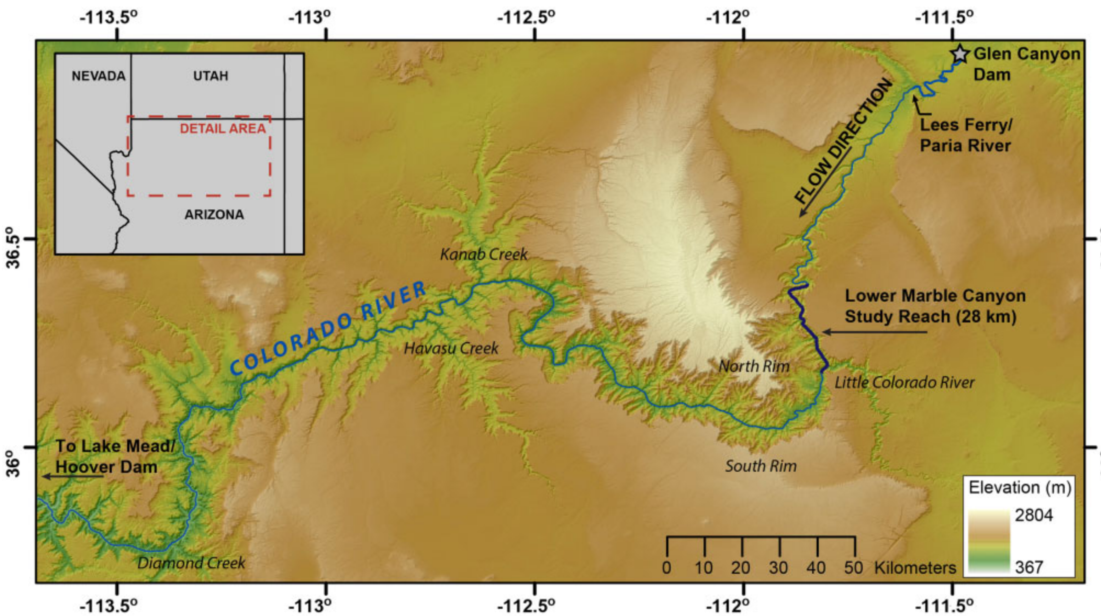

Figure 2. Overview map of the Colorado River in Grand Canyon from Glen Canyon Dam to Lake Mead.

et al., 2012; Schmidt, 1990; Wright and Kaplinski, 2011). At higher elevations, upland areas of the river valley are marked by coarse talus slopes interspersed with finer-grained source-bordering dunefields maintained by aeolian sand winnowed from fluvial sand deposits below (Figure 1; Draut, 2012; Sankey et al., 2018a, 2018c).

1. Study reach alterations in hydrology, sediment supply, and vegetation

The hydrologic and sediment transport dynamics of the Colorado River have been fundamentally altered since 1963 by Glen Canyon Dam, which is operated for both water storage and hydropower generation (Figure 4). The pre-dam flow regime was marked by annual large snowmelt-driven floods during the late spring and early summer (May–July) that often exceeded 2000 m^3/s. During the pre-dam period, these floods were interspersed with flows two orders of magnitude lower (the lowest recorded pre-dam flow was 31 m^3/s in August 1934). In the post-dam period, both the large snowmelt-driven spring/summer floods and the intervening low flows have been eliminated, replaced instead by a flow regime characterized by less-extreme high and low flows, but with daily flow fluctuations for hydropower generation. The post-dam two year flood (Q_2) has a magnitude of 892 m^3/s, a 63% reduction of the pre-dam two-year flood (Q_2) discharge of 2407 m^3/s (Topping et al., 2003). Over the entire pre-dam period of record, the median discharge of the Colorado River was 226 m^3/s, increasing to 357 m^3/s following the closure of Glen Canyon Dam. As a consequence of the loss of both large floods and intervening low flows, channel-proximal areas of the Colorado River have undergone extensive vegetation encroachment during the 54 years since dam construction (Figure 5). Whereas large pre-dam floods commonly scoured existing vegetation and limited the growth of new plants (Grams et al., 2007; Sankey et al., 2015; Schmidt and Rubin, 1995; Turner and Karpiscak, 1980), the present riparian corridor is marked by dense stands of

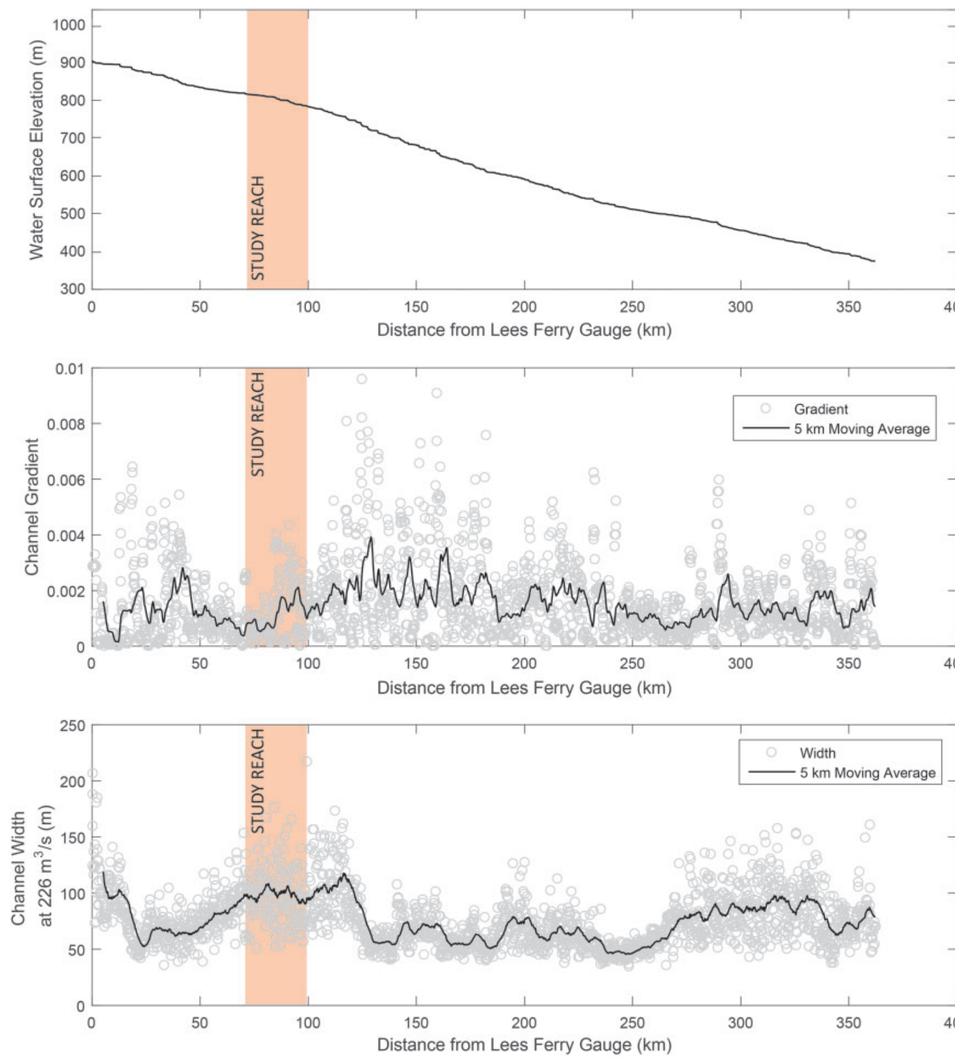

Figure 3. Top panel shows water surface elevation as modeled at a discharge of 226 m^3/s for the Colorado River from Lees Ferry to Diamond Creek. Middle panel shows channel gradient computed over a 1 km window and 5 km moving-average filtered values. Bottom panel shows channel width computed at 0.1 km intervals and smoothed using a moving average filter over a 5 km window. Lower Marble Canyon study reach shown in beige.

vegetation. In particular, woody riparian shrubs such as tamarisk (*Tamarix* sp.), baccharis (*Baccharis* spp.), and arrowweed (*Pluchea sericea*) have expanded considerably and are now present on numerous formerly bare sandbars and channel margins (Sankey et al., 2015; Waring, 1995; Webb, 1996).

In addition to hydrological alteration resulting from Glen Canyon Dam operations, sediment supply has been significantly reduced in the post-dam period. Sediment trapping by Lake Powell Reservoir above Glen Canyon Dam has resulted in a >95% post-dam reduction in fine sediment (sand, silt, and clay) entering Grand

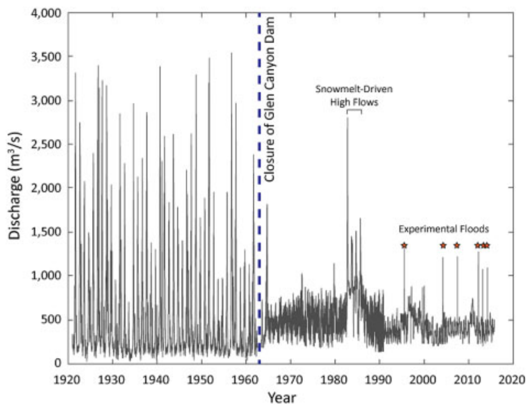

Figure 4. Hydrograph showing discharge of the Colorado River at Lees Ferry (USGS gauge #09380000) from 1921 to 2016. Glen Canyon Dam was completed in 1963.

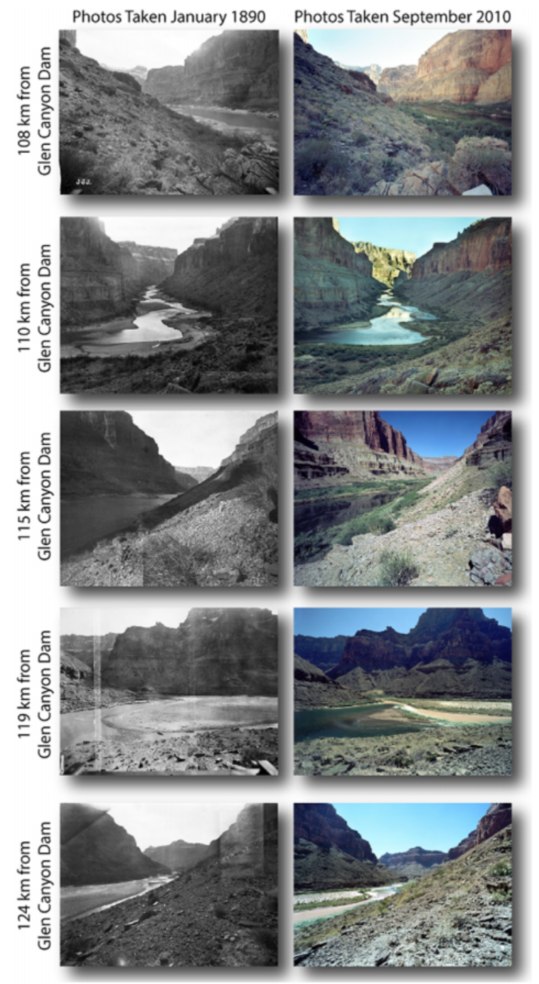

Figure 5. Matched photographs taken in 1890 (credit R.B. Stanton, U.S. Geological Survey) and 2010 (credit J. Mortimer and B. Lemke, U.S. Geological Survey) from five locations in the Lower Marble Canyon study reach. Note general increase in riparian vegetation between the two periods.

Canyon (Hazel et al., 2006; Topping et al., 2000). Today, most of the fine sediment entering the Colorado River in the 140 km between Lees Ferry and the Grand Canyon stream gage (USGS gaging station #09402500) originates from two tributaries, namely the Paria River (at Lees Ferry) and the Little Colorado River (98 km downstream from Lees Ferry), with the remaining sediment inputs delivered from numerous smaller tributaries throughout the reach (Figure 2).

Post-dam alterations to the hydrology, riparian vegetation density, and sediment supply of the Colorado River substantially affect sediment connectivity within the river corridor, from the active channel to upland environments. Grams et al. (2007) documented widespread incision (2.5 m on average) of the Colorado River channel bed in a 25 km reach downstream of Glen Canyon Dam. Erosion of eddy sandbars was first documented in the 1970s (Dolan et al., 1974; Kearsley et al., 1994; Schmidt and Graf, 1990); sandbar erosion has continued over the past $\sim$25 years, punctuated by short-lived sandbar growth from occasional controlled-flood dam releases of $\sim$1200 m^3/s. These controlled floods have been conducted seven times (1996, 2004, 2008, 2012, 2013, 2014, and 2016) since closure of Glen Canyon Dam. The objective is to redistribute tributary-derived sediment from the bed of the Colorado River into the eddy sandbars that line the channel margins (Grams et al., 2010, 2015; Hazel et al., 2010; Kaplinski et al., 2014; Melis et al., 2012; Mueller et al., 2014). In addition to erosion of sandbars in response to sediment supply reduction following dam closure, daily streamflow fluctuations may also lead to more rapid erosion of bar edges (Alvarez and Schmeeckle, 2013; Dexter and Cluer, 1999). The loss of near-channel fine sediment deposits and the encroachment of vegetation onto remaining sandbars has in turn resulted in the stabilization of upland aeolian dunes, which have become covered by biologic soil crust in the absence of adequate sediment supply to replenish or reactivate these dune fields (Draut, 2012; Sankey et al., 2018a, 2018c). This leaves the upland dune fields and relict pre-dam fluvial sedimentary terraces susceptible to erosion from overland-flow gullying processes (Sankey and Draut, 2014). Gully erosion is a particular concern in those geomorphic settings because hundreds of archaeological sites occur in relict fluvial and aeolian deposits throughout the river corridor that are consequently susceptible to unusually high erosion rates, degrading or destroying cultural resources (Collins et al., 2016; East et al., 2016; Fairley, 2005). Bare sediment is of vital importance for the formation and maintenance of landforms and habitat throughout Grand Canyon (and across dryland rivers in general), ranging from the channel bed to eddy sandbars, to upland aeolian-dominated areas. As such, we believe that a comprehensive analysis of the effect of hydrologic and land cover alteration on the areal extent of sediment available for transport, such as that presented herein, will be valuable for the management and restoration of a variety of landforms and resources in these river valley ecosystems.

III. Datasets

To assess alterations in sediment availability resulting from hydrologic alteration and vegetation encroachment along the Colorado River, we synthesized four existing datasets and analyzed their change through time.

1. Subaqueous sand mapping and bathymetry

Bathymetric data were collected in May 2009 by Kaplinski et al. (2017) below the 226 m^3/s stage (approximately the lowest commonly occurring discharge in the post-dam period) over a 50 km segment of the Colorado River between 48 to 98 km downstream of Lees Ferry (Figure 2). A survey of the same reach was repeated in May 2012 (Grams et al., 2018). Bathymetry was surveyed using a Reson SeaBat 8125 multibeam sonar system, while shallow areas (<2 m depth) were surveyed using an Odom CV-100 single-beam sonar system. Between the 226 m^3/s stage and the modern maximum controlled flood stage of 1274 m^3/s, subaerial sand in sandbars and channel margins was surveyed using conventional total station techniques (Figure 6; Grams et al., 2013; Hazel et al., 2006). The fusion of total station, single-beam sonar, and multibeam sonar datasets provided an initial estimate of all bare sand below the 1274 m^3/s stage during the 2009 survey campaign (Figure 6). The channel bed and near-channel subaerial sand were mapped throughout the study reach, with the exception of rapids, riffles, and large submerged cobble bars, where bathymetry was not mapped either due to safety concerns, known areas of immobile sediment, or because aeration of the water column precludes accurate sonar mapping through these reaches. For full details on the channel mapping methods and uncertainty, see Kaplinski et al. (2017).

Acoustic backscatter data were collected simultaneously with bathymetric data (Kaplinski et al., 2017). Unless otherwise noted, all bathymetric and grain size estimates used here were from the 2009 channel survey, and were sampled on coincident 1 m grids. Backscatter is a measure of the magnitude of the acoustic energy received by the sonar that is the result of interaction with the channel bed with the effects of sonar settings, ensonified areas, and sonic interactions with the

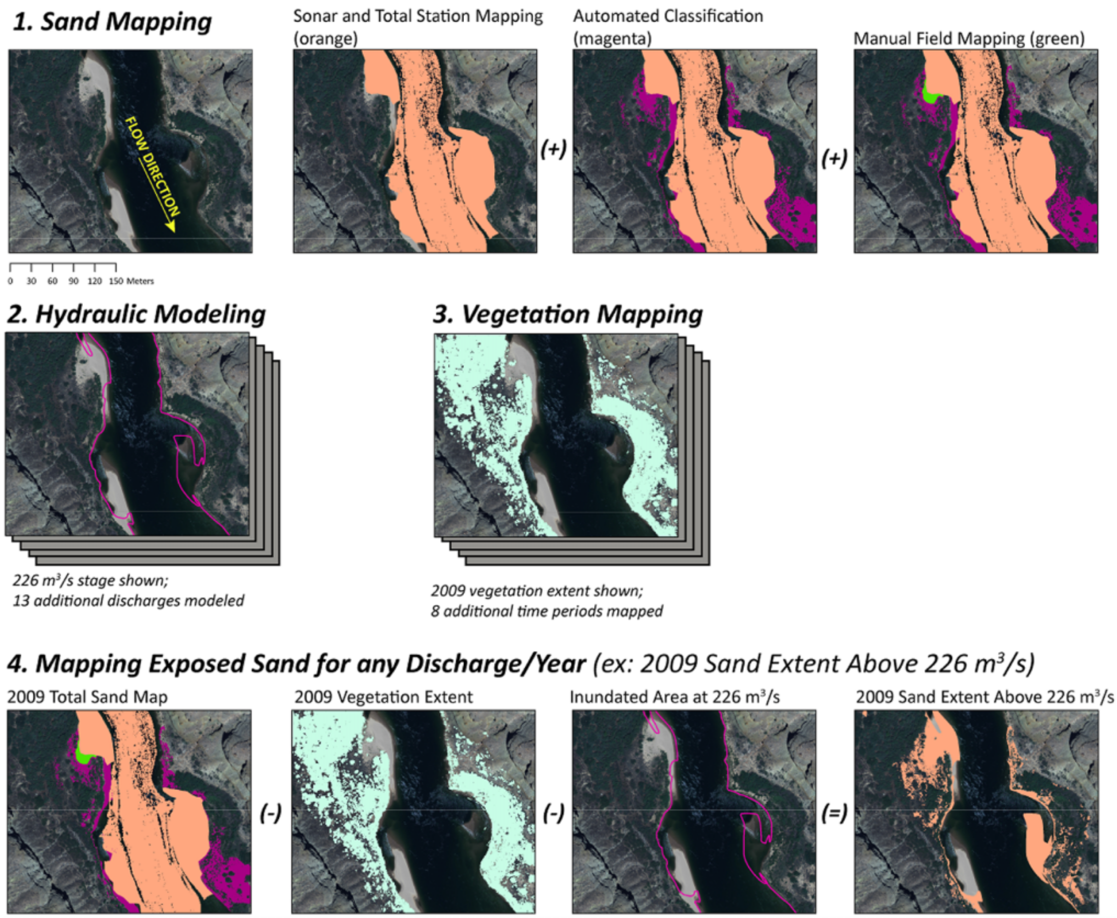

Figure 6. Workflow schematic depicting requisite datasets and geospatial processing routine for (1) generating maps of total bare sand area using 2009 channel mapping data, (2) one-dimensional hydraulic modeling, (3) generating maps of vegetation extent, and finally (4) synthesizing datasets to quantify exposed bare sand areal extent for any given discharge and year combination.

water mass removed (Buscombe et al., 2014a). Using the method of Buscombe et al. (2014b), the amplitude and frequency content of backscatter measurements were used to reliably discriminate among homogeneous sand, homogeneous gravel, and cobble/boulders/bedrock. Predictions were validated using georeferenced images collected with an underwater camera (similar to that described by Rubin et al., 2007) concurrently with channel mapping in 2009 and 2012. This tripartite sediment classification from acoustic backscatter characterized homogeneous sand, gravel, and cobbles/boulders with 95%, 88%, and 91% accuracy, respectively (Buscombe et al., 2014b). Submerged aquatic vegetation is not present in significant quantities in the study reach, nor are significant deposits of clay or silt.

Compared to multibeam sonar, we do not possess a reliable technique to discriminate between channel bed grain sizes using single-beam sonar measurements. Therefore, to map the extent of sand below the 226 m^3/s stage in areas surveyed via single-beam sonar, we combined (a) nearby bed grain size information acquired using the method of Buscombe (2013) from underwater camera imagery, (b) nearby multibeam bed grain size estimates, and (c) those single-beam-mapped areas which were subsequently mapped via multibeam and classified as sand in the 2012 survey. We did not attempt to classify areas unmapped by either multibeam or single-beam sonar. Areas classified as sand from both the multibeam and single-beam sonar mapping campaigns were converted to polygon feature classes in GIS and merged to create a single map of sand below the 226 m^3/s stage for our 28 km study reach.

2. Upland sand mapping

We used datasets describing the extent of bare (i.e. non-vegetated) sand between the 226 m^3/s and 1274 m^3/s stages that were derived via automated supervised classification followed by manual editing and delineation of multispectral bands and band indices of georeferenced 0.2 m resolution aerial imagery collected in May 2009 (Sankey et al., 2018b). This classification was estimated to be 97% accurate based on our field assessments of ground cover during site visits between 2011 and 2014. In addition, the extent of bare sand between 1274 m^3/s and 5947 m^3/s (the inferred flood of record in the pre-dam era; Topping et al., 2003) was mapped in the field in 2011–2012 by East et al. (2016). These field-mapped sand areas were subsequently digitized as polygons within ArcGIS and merged with aerial photo sand mapping to provide a seamless dataset of the extent of upland sand (i.e. at stages > 226 m^3/s) for the 28 km study reach used here (Figure 6).

3. Merged subaqueous and upland sand mapping

We merged the polygon feature classes depicting the extent of sand below 226 m^3/s with the feature classes depicting sand extent from 226 m^3/s to 5947 m^3/s. The result was a single polygon dataset of the bare sand extent in May 2009 from the channel bed up to an elevation corresponding to our best approximation of the historical flood of record over the 28 km study reach (Figure 6).

4. Vegetation mapping

We used maps of vegetation produced from aerial imagery by Durning et al. (2017), Sankey et al. (2015), and Waring (1995) which depict the areal extent of standing vegetation at nine intervals since the construction of Glen Canyon Dam, namely in 1965, 1973, 1984, 1992, 2002, 2004, 2005, 2009, and 2013 (Figure 6). Vegetation maps were completed for five reaches throughout Grand Canyon, ranging from 4 to 21 km in length. While these vegetation maps have not undergone traditional accuracy assessments as were completed for the bare sand maps (Section III.2), the methods included extensive manual image interpretation in addition to image classification, which traditionally produce high classification accuracies (Durning et al., 2017). Two of these vegetation mapping reaches were partially within our 28 km study reach, and combined they covered 11 km, or 39% of our total study reach length.

Within the unmapped portion of our study reach, we assumed that changes in vegetation mirrored the trends seen in the 39% of our study reach where vegetation was mapped. We made this assumption because an increase in riparian vegetation between 1965 and 2013 closely mirror those trends found by Sankey et al. (2015) for all five mapped segments along the Colorado River in Grand Canyon National Park, suggesting that this trend is robust and widespread throughout the river corridor, and because the unmapped segment of our study reach does not differ appreciably in valley width, aspect, or channel gradient from the remaining portion of the study reach (Figure 3; data from Mueller et al., 2017b), suggesting that vegetation would have responded similarly to post-dam flows within the unmapped segment as in the mapped area. To approximate the area of vegetation in our 28 km study reach as a function of the vegetation extent seen in the shorter 11 km mapping reach, we multiplied the vegetation area in the 11 km reach by 2.529, to account for the fact that only 39% of the 28 km study reach underwent vegetation mapping.

We related the extent of bare sand with a given discharge from Glen Canyon Dam using inundation-extent polylines produced by Magirl et al. (2008) as part of a one-dimensional hydraulic model for the 364 km of the Colorado River from Lees Ferry to Diamond Creek (Figure 2; this includes our study reach). Magirl et al. (2008) employed a step-backwater model to predict stage elevation at cross sections spaced at 0.16 km intervals. Modeled stages included fourteen discrete discharges between 226 m^3/s and 5947 m^3/s, and assume that channel bathymetry and valley topography are static and based on a digital elevation model created for Grand Canyon in 2002. These model predictions generally agreed with surveyed water surfaces and geomorphic high-flow indicators (e.g. stranded wood, shorelines) to within $\sim$1 m elevation (Magirl et al., 2008). The model predictions were digitized onto 1 m resolution DSMs as polygons to produce a continuous map of inundation extents, or predicted shorelines, corresponding to each of the 14 modeled discharges (Figure 6).

5. Sand availability mapping

5.1. Relating sand coverage to altered hydrology. For each of the 14 discharges modeled by Magirl et al. (2008), we overlaid a polygon of the inundated area on the dataset of bare sand extent (Section III.3) and then eliminated any areas of sand that were inundated for a given flow (Figure 6). We then overlaid the 1965 vegetation extent dataset atop this subaerial sand extent layer and eliminated those areas that were vegetated. This resulted in maps of all sand that was subaerially exposed and thus available to be entrained and transported by wind (Draut, 2012; East et al., 2016) for each of the 14 modeled discharges as it existed in 1965 (i.e. our best approximation of pre-dam conditions). We performed linear interpolation between adjacent modeled discharge points to estimate the extent of bare sand at 28.3 m^3/s, or 1000 ft^3/s, increments across the entire range of discharges examined (Figure 7). Because we performed linear interpolation between pairs of data points, there is no interpolation uncertainty; however, the constituent datasets each contain varying degrees of internal accuracy that may lead to uncertainty in the areal extent of bare sand for any given discharge, and these are described above in the subsection pertaining to each individual dataset.

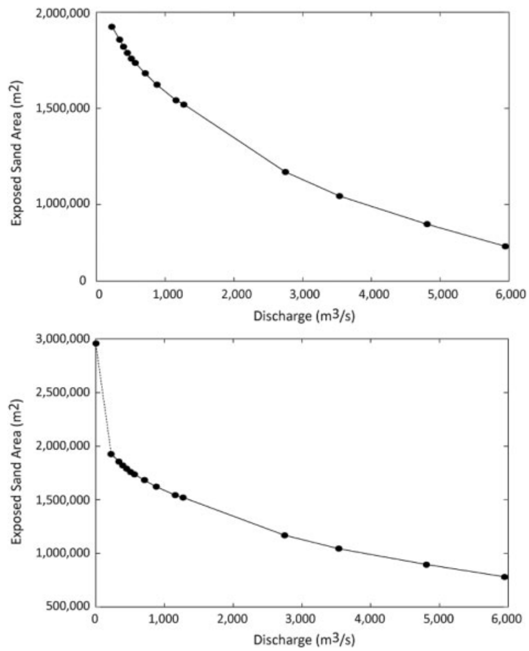

Figure 7. Exposed sand area as a function of Colorado River discharge in the Lower Marble Canyon study reach. Top panel shows exposed sand as inferred in 1965 as a function of each of 14 flows modeled by Magirl et al. (2008), and bottom panel extends this relationship to a discharge of 0 m^3/s (i.e. the entire extent of bare sand inferred in 1965).

Daily discharge measurements have been collected at the Colorado River at Lees Ferry (USGS gauge #09380000) since 1921. To quantify the areal extent of bare sand each day over the period 1963–2016, we used the estimated or measured daily maximum discharge from the gauging record at Lees Ferry (Kasprak et al., 2018). During the period 1921–1963, we used the measured mean daily discharge, as flow variability was minimal over 24-h periods in the pre-dam period. Using this discharge record, we computed the corresponding extent of bare sand for that day, as described above. We used daily maximum discharge to ensure we were including only sand area that had been subaerially exposed for at least 24 h, which provided a simple time cutoff for approximating when sand was dry and able to be mobilized by wind.

5.2. Relating sand coverage to altered vegetation. To quantify the role of vegetation encroachment on bare sand extent in the study reach, we compared the extent of vegetation area computed for each year since 1965 (i.e. the first vegetation mapping following the closure of Glen Canyon Dam) compared to the extent of vegetation in 2009. Because vegetation maps were only produced for nine years since dam closure, and because no information on vegetation extent was available over the entire study reach between these photograph dates, we assumed that vegetation change in the intervening years between any two photographs occurred at a constant rate, and so we performed linear interpolation to estimate vegetation extent during any given year from 1965 to 2016. For the period 1921–1965 (pre-dam and two years immediately following dam closure), we assumed that vegetation extent was identical to that mapped from the 1965 photographs, acquired < 2 years following dam closure. Nevertheless, we acknowledge that there was likely some additional variability in vegetation extent not characterized by the time series of maps we used, as riparian vegetation can respond dynamically (e.g. annually) to intermittent high flows and intervening periods of reduced discharge in river valleys (e.g. Konrad et al., 2012; Shafroth et al., 2002).

The total mapped area of sand and vegetation *(A_T)* in 2009, the only year for which concurrent maps of vegetation extent and sand extent are available, is

$$A_T = A_{SAND2009} + A_{VEG2009} \qquad (1)$$

where A_{SAND} and A_{VEG} are the areal extents of bare sand and vegetation, respectively. Assuming that vegetation exclusively colonizes areas composed of formerly bare sand, a pattern largely consistent with qualitative information from matched photographs (Figure 5) over the last century (Sankey et al., 2015; Turner and Karpiscak, 1980; Waring, 1995; Webb, 1996), A_T remains constant throughout our period of analysis for any given discharge being examined. Therefore, the area of bare sand for any year ($A_{SAND\ YEAR}$) can be computed as a function of that year's vegetation extent ($A_{VEG\ YEAR}$):

$$A_{SANDYEAR} = A_T - A_{VEGYEAR} \qquad (2)$$

Using equation (2), we computed the areal extent of bare sand for any year as a function of discharge for the period 1921–2016, from discharges of 0 m^3/s (i.e. the channel bed) to 5947 m^3/s at 28.3 m^3/s increments. We note that in addition to A_T computed here, the much greater fine sediment supply to Grand Canyon preceding the closure of Glen Canyon Dam in 1963 likely resulted in additional areas of bare sand in our study reach that are not accounted for by the summation of A_{SAND} and A_{VEG} from 2009 aerial photos; this is particularly true in the case of sandbars and channel-margin deposits, which have undergone extensive erosion in the post-dam period (see Ross and Grams, 2015; and Schmidt et al., 2004). However, given that the earliest photograph set used in this analysis was taken after dam closure in 1965, following large-scale reduction of sediment supply, we are unable to estimate pre-dam A_T in the same manner, and note that our estimate computed using 2009 aerial photography and bathymetric grain size analysis is likely a lower-bound estimate of this value.

6. Forecasting changes in future areal extent of sediment

In 2016, the environmental impact statement (EIS) was completed for a 20-year long-term experimental and management plan, which defines the operating criteria for Glen Canyon Dam – and hence sets the river flow and daily discharge variability – over the next two decades (U.S. Department of the Interior, 2016). This EIS is intended to ensure that the operations of Glen Canyon Dam are consistent with the Grand Canyon Protection Act of 1992, which requires protection of physical resources, conservation of threatened and endangered species, and avoiding impacts on cultural resources downstream of Glen Canyon Dam, while ensuring water storage and power generation. As part of this process, seven alternative discharge regimes were proposed and analyzed to determine their impact on physical, cultural, and ecological resources, while also accounting for projected climate-driven shifts in water availability in the Colorado River basin (see http://ltempeis.anl.gov/). Table 1 shows the 24 h maximum discharge for each month under each proposed alternative discharge regime for a year in which 1.02×10^{10} m^3 of water is released from Glen Canyon Dam. This represents the minimum required annual release volume from Lake Powell, although the exact volume will depend on water availability. A brief description of the purpose and benefits of each alternative flow regime is also provided in Table 1. Alternative D was ultimately selected for implementation by the U.S. Department of the Interior, as it was determined to strike the most feasible compromise between maximizing hydropower generation at Glen Canyon Dam and minimizing the eco-geomorphic impacts to the downstream river system (see http://ltempeis.anl.gov/).

To forecast the effect of future hydrologic regime on the areal extent of bare sand throughout the study reach, we developed synthetic daily hydrographs (simply a single-column text file listing daily maximum discharge; see supplemental data) by using the maximum daily discharge for each of the seven alternative scenarios in Table 1 over each month during the 20 year period from 2016 to 2036. We assumed that vegetation encroachment during this period would continue at the same rate seen during the 2009–2013 period. We acknowledge that future changes in climate that may lead to shifts in water availability for plants have the potential to alter vegetation colonization and growth rates. However, changes in river hydrology as influenced by dam operations have been shown to be more important predictors of the areal extent of vegetation than climate-driven changes in rainfall for much of the riparian zone (Sankey et al., 2015); hence, we employed the simplified extrapolation approach described above. We used the computed daily hydrographs corrected for the influence of vegetation encroachment (see Section III.6.2) to model the areal extent of exposed sand on a daily basis for each of the seven alternative discharge regimes in Table 1.

IV. Results

1. Quantifying historical changes in connectivity

Here we present the results of three analyses: (a) the role of hydrological alteration on bare sand extent, (b) the role of vegetation encroachment on bare sand extent, and (c) the combined effect of hydrological alteration and vegetation encroachment on bare sand extent.

1.1. Hydrological alteration. Hydrological alteration owing to the operation of Glen Canyon Dam resulted in a 9% decrease in the areal

Table 1. Description of proposed alternative dam operation regimes from Glen Canyon Dam final environmental impact statement showing monthly maximum flows for a 1.02×10^{10} m^3 release year.

	Alternative A: ***No change from current operation regime***	**Alternative B:** ***Maximizing hydropower generation***	**Alternative C:** ***Adaptive flows for invertebrates, fish, and sediment***	**Alternative D:** ***Compromise between power generation and ecology***	**Alternative E:** ***Native fish conservation flows***	**Alternative F:** ***Mirroring pre-dam seasonal flow regime***	**Alternative G:** ***Maximizing sediment conservation***
October	361 m^3/s	390 m^3/s	269 m^3/s	378 m^3/s	387 m^3/s	233 m^3/s	322 m^3/s
November	370 m^3/s	399 m^3/s	276 m^3/s	387 m^3/s	396 m^3/s	233 m^3/s	333 m^3/s
December	482 m^3/s	538 m^3/s	465 m^3/s	421 m^3/s	431 m^3/s	233 m^3/s	312 m^3/s
January	482 m^3/s	538 m^3/s	465 m^3/s	449 m^3/s	470 m^3/s	233 m^3/s	322 m^3/s
February	391 m^3/s	448 m^3/s	445 m^3/s	430 m^3/s	450 m^3/s	311 m^3/s	345 m^3/s
March	361 m^3/s	390 m^3/s	431 m^3/s	419 m^3/s	439 m^3/s	396 m^3/s	322 m^3/s
April	370 m^3/s	370 m^3/s	394 m^3/s	383 m^3/s	401 m^3/s	481 m^3/s	333 m^3/s
May	361 m^3/s	361 m^3/s	397 m^3/s	372 m^3/s	405 m^3/s	566 m^3/s	291 m^3/s
June	394 m^3/s	423 m^3/s	427 m^3/s	409 m^3/s	455 m^3/s	566 m^3/s	333 m^3/s
July	505 m^3/s	533 m^3/s	465 m^3/s	451 m^3/s	483 m^3/s	205 m^3/s	311 m^3/s
August	528 m^3/s	556 m^3/s	369 m^3/s	482 m^3/s	416 m^3/s	205 m^3/s	322 m^3/s
September	385 m^3/s	413 m^3/s	276 m^3/s	362 m^3/s	355 m^3/s	205 m^3/s	322 m^3/s

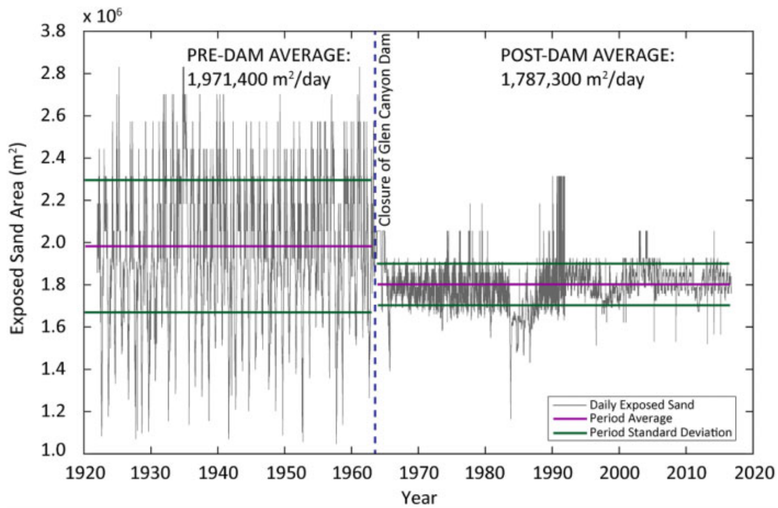

Figure 8. The influence of hydrologic alteration on areal extent of bare sand for the period of discharge record 1921–2016 in the Lower Marble Canyon study reach. Analysis was completed assuming static vegetation extent through the entire period of record, as mapped from 1965 aerial photographs.

extent of bare sand when comparing its average area in the pre-dam period of gauging record (1921–1963) to that in the post-dam period (1963–2016; Figure 8). Bare sand area in the pre-dam period was highly variable, owing to the unregulated nature of the Colorado River during this period and the associated large floods in the late spring and early summer, followed by very low flows for the remainder of the year. The average areal extent of bare sand in the pre-dam period was 1.97×10^6 m^2/day, with a standard deviation of 3.29×10^5 m^2/day and a coefficient of variation of 16.7% (Figure 8). In comparison, the post-dam areal extent of bare sand is less variable, with an average of 1.79×10^6 m^2/day, a standard deviation of 9.60×10^4 m^2/day, and a coefficient of variation of 5.4%. The reduced variability in bare sand extent in the post-dam period is due to relatively small oscillations in stage in the post-dam era (Figure 3). Instances of significantly lower exposed sand area in the post-dam period, during the mid-to-late 1980s and sporadically occurring through the late 1990s are due to large releases from Lake Powell due to high snowpack in the Rocky Mountains in 1983 and 1984 and, more recently, controlled floods from the dam intended to rebuild sandbars (Melis et al., 2012; Mueller et al., 2014; Schmidt et al., 2014). Instances of relatively abundant bare sand area in the early 1990s are due to experimental research flows that periodically released lower discharges from Glen Canyon Dam (around 142 m^3/s; Melis et al., 2012).

1.2. Vegetation encroachment. The areal extent of vegetation has increased for each of the 14 modeled discharges; this increase was most pronounced at the lower discharges (Figure 9) and during the $\sim$30 years immediately following the construction of Glen Canyon Dam as previously bare surfaces were rapidly colonized by emergent vegetation (Sankey et al., 2015). Assuming that vegetation colonizes surfaces that were previously bare sand, across all discharges, bare sand extent was reduced by 45% on average as a result of vegetation encroachment when comparing the pre-dam period (1921–1963) to the post-dam period (1963–2016).

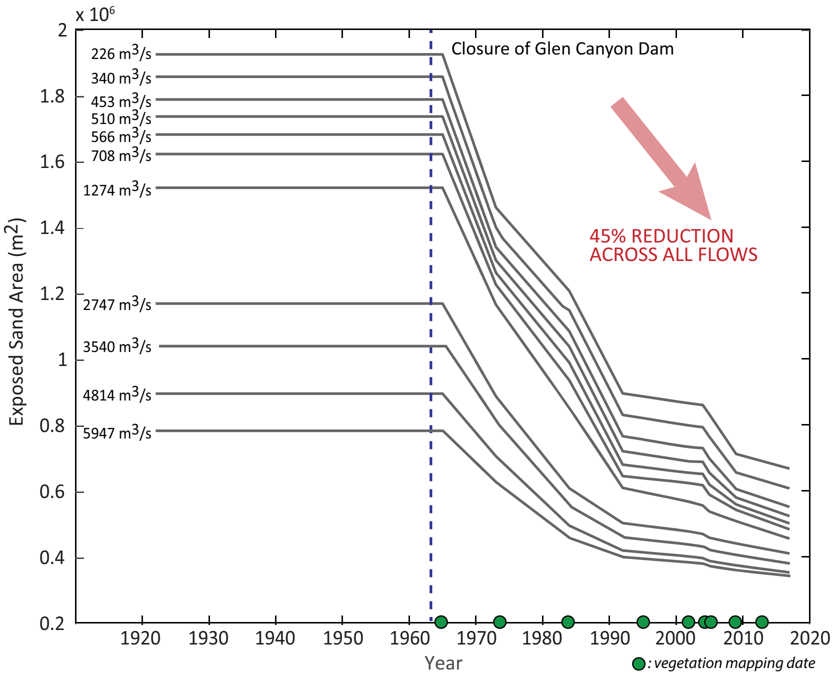

Figure 9. Influence of vegetation encroachment on bare sand extent in the Lower Marble Canyon study reach across the 14 discharges modeled by Magirl et al. (2008).

1.3. Combined effects of hydrologic alteration and vegetation encroachment. Combined, hydrological alteration and vegetation encroachment onto previously bare sand have reduced its areal extent by 49%, which was computed by comparing the average amount of exposed sand on a daily basis between the pre- and post-dam periods (Figure 10; 1.97×10^6 m^2/day in the pre-dam period compared to 1.01×10^6 m^2/day in the post-dam period). However, these time-averaged values mask considerable temporal variability in the manner with which exposed sand area was decreased in the post-dam period: for example, 73% of the reduction in bare sand extent occurred in the 30 years immediately following completion of Glen Canyon Dam. Since the mid-to-late 1990s, the area of bare sand exposed each day has exhibited less variability than during the pre-dam period, while the average area of exposed sand has been considerably reduced compared pre-dam extents (Figure 10).

2. Forecasting changes in future areal extent of sediment

The areal extent of exposed sand on a daily basis under each of proposed future discharge regimes is shown in the top panel of Figure 11, along with the percent change in bare sand area from the current operating protocol of Glen Canyon Dam. While some proposed discharge regimes provide marginal increases in exposed sand area (16.0% and 9.7% increase as compared to current operation regime for Alternatives F and G, respectively), none of the proposed regimes would substantially increase the amount of exposed sand, especially when compared to the 49% reduction in bare sand area that followed the closure of Glen Canyon Dam. The variability in bare sand extent is minimal, with standard deviations in daily exposed sand ranging from 1.60×10^4 m^2/day (Alternative E) to 9.91×10^4 m^2/day (Alternative F). This relatively modest change

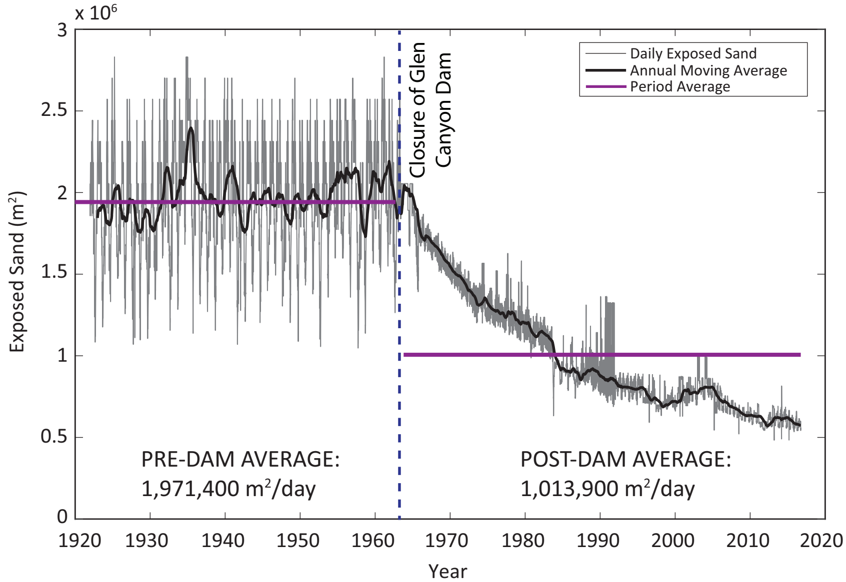

Figure 10. Combined influence of hydrologic alteration and vegetation encroachment on areal extent of bare sand in the Lower Marble Canyon study reach. Grey line shows daily extent of bare sand for the period of discharge record 1921–2016.

in exposed sand area results because none of the alternative operation regimes provide for daily maximum flows < 226 m^3/s, which exert a disproportionate influence on exposed sand area within our 28 km study reach (Figure 6). The bottom panel of Figure 11 depicts the areal extent of bare sand over the next 20 years under the anticipated future discharge regime that will be implemented as the preferred management regime for Glen Canyon Dam (Alternative D) and suggests that the extent of bare sediment will decrease slightly over the next two decades (an additional 12% decrease by 2036 as compared to current bare sand extent).

V. Discussion

Many processes can alter the movement of water and sediment through river networks, in particular changes in climate, land use, or river regulation by dams (Kasprak et al., 2017; Magilligan and Nislow, 2005; Palmer et al., 2008; Schmidt and Wilcock, 2008; Walling and Fang, 2003). These alterations in turn lead to shifts in the transfer of material, or connectivity, between the active channel, near-channel deposits, and uplands (Bracken et al., 2015; Magilligan et al., 2016; McKay et al., 2017; Sankey et al., 2018a, 2018c; Schmitt et al., 2016; Souza et al., 2016; Taylor et al., 1993; Wohl, 2017; Wohl and Beckman, 2014). Whereas the biophysical importance of river valley sediment connectivity is becoming increasingly recognized, most studies of sediment transfer to date have focused on historical changes within short reaches of river or at discrete sites. The logistical complexity in quantifying or predicting sediment connectivity over large spatiotemporal scales often precludes our ability to understand baseline, or pre-disturbance, connectivity in river valleys and thereby assess the magnitude of alteration driven by river regulation. However, the increasing availability of high-resolution data on channel bathymetry, valley topography, land cover, and

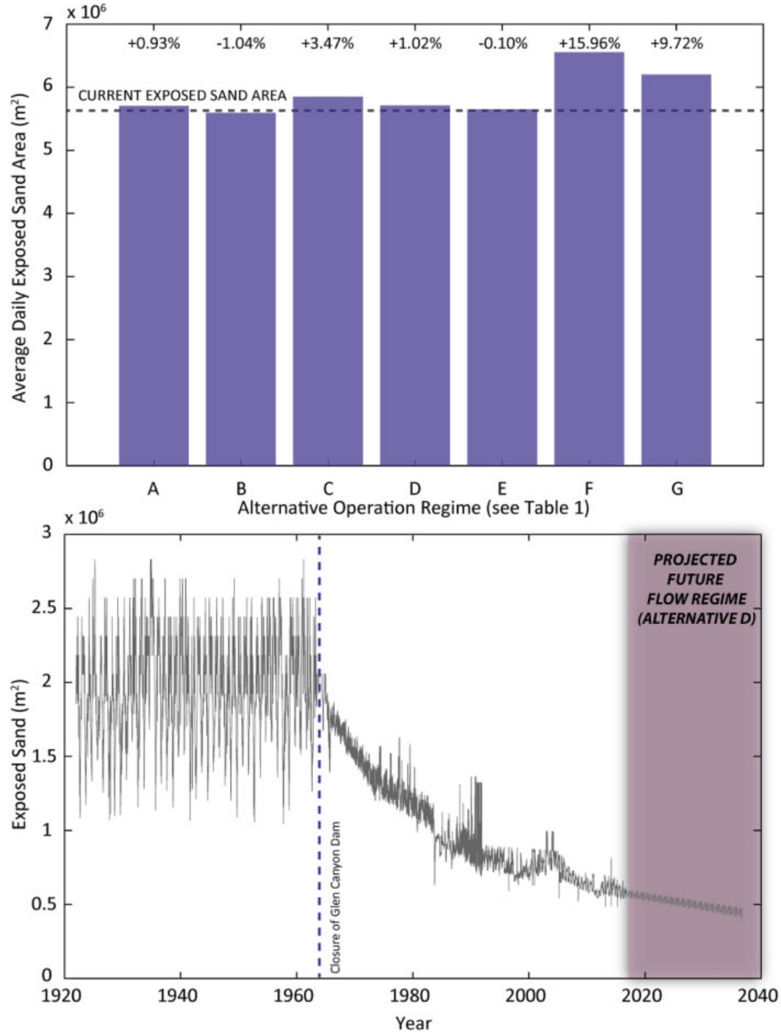

Figure 11. Top panel shows the estimated average daily exposed sand area for the Lower Marble Canyon study reach for each of seven proposed alternative operation regimes for Glen Canyon Dam in the Long Term Experimental and Monitoring Plan Environmental Impact Statement (LTEMP EIS; see Table 1 and http://ltempeis.anl.gov/ for details). Bottom panel shows daily exposed sand area for the study reach projected to 2036 using Alternative D that was adopted by LTEMP EIS stakeholders.

river hydrology (Westoby et al., 2012; Wheaton et al., 2013; Williams et al., 2014) afford the opportunity to explicitly quantify – and in some river systems to even forecast – alterations in sediment availability and thereby reduce this long-standing knowledge gap.

Having analyzed the areal extent of bare sand over the 95-year period from 1921 to 2016 along a 28 km study reach of the Colorado River in Grand Canyon National Park, we find that hydrological alteration (i.e. loss of both large floods and intervening low flows) owing to the operation of Glen Canyon Dam has reduced bare sand areal extent by a reach average of 9%. Vegetation encroachment has reduced bare sand extent by 45%, and the two processes combined to reduce the extent of bare sand by 49%. Bare sand loss due to the two processes is not purely additive (i.e. sand area reduction is 49% and not 54%) because vegetation encroachment and increased baseflow due to hydrological alteration have co-occurred in certain locations (primarily in near-channel areas), with both processes acting together to cover previously bare sand. Thus, the combined effect of hydrological alteration and vegetation encroachment, a 49% reduction in the areal extent of bare sand, represents the *net effect* of the two processes acting in concert throughout the study reach.

The results of our historical analysis emphasize the disproportionate importance of low flows (i.e. < 226 m^3/s) in exposing bare sand (Figures 7 and 8). Because of the widespread increase in riparian vegetation extent following the closure of Glen Canyon Dam in 1963 (Figure 5), more than 60% of the bare sand within this reach is today found at stages associated with discharges < 226 m^3/s (see supplemental data). However, because 226 m^3/s represents the lowest discharges released from Glen Canyon Dam today, this bare sand is almost always submerged and/or saturated, and thus is not available for aeolian transfer to upland landscapes. As indicated by Figure 7, flows below 226 m^3/s have the potential to expose nearly as much bare sand as do alterations in flow between 226 m^3/s and 5947 m^3/s, the latter representing the historic flood of record of the Colorado River in Grand Canyon. The relative importance of low flows can be seen in Figure 8, when research flows of 142 m^3/s released in the early 1990s resulted in increased areal extents of exposed sand. When compared to the most commonly seen post-dam low flows today (226 m^3/s), the 39% increase in exposed sand area gained by the 84 m^3/s change in discharge from 226 m^3/s to 142 m^3/s is nearly equal to the decrease in exposed sand area (−45%) caused by the change in flow from 226 m^3/s to the highest recorded post-dam flow of 2718 m^3/s. Lower flows would allow more of this low-elevation sand to be exposed and transported by wind to upland areas. Over time, such increased sediment supply and connectivity between fluvial and upland regions could likely restore some of the geomorphic and ecological processes disrupted by the reduced sediment supply over the decades of dam operations, given that individual upland areas that have maintained sediment supply throughout the post-dam period continue to exhibit active aeolian evolution, whereas those with reduced sediment supply have become relatively inactive and vegetated (e.g. Draut, 2012; East et al., 2016; Sankey et al., 2018a, 2018c).

It is worth considering the potential effects of using a single map of bathymetric sand, collected in 2009 by Kaplinski et al. (2017); this single map was employed here because channel bed mapping prior to 2009 was not available. With regard to the extent of sand below the 226 m^3/s stage, as mapped from multibeam sonar (Section III.1), we assume that the sand on the channel bed as mapped in May 2009 was representative of the entire period of analysis, from 1921 to 2016. This assumption was necessary given that there are no data describing the areas of the channel bed composed of sand (as opposed to gravel, cobbles, boulders, or aquatic vegetation) prior to 2009 within our study reach. A repeat mapping of the channel bed within our study reach in 2012 revealed widespread consistency in the bed material composition: only 2% of the channel bed areas composed of sand in 2009 changed to non-sand (e.g. gravel/cobble/bolder) in 2012. Annual repeat multibeam surveys at two sites, at the start and end of the present study reach, over the period May 2012 and May 2016, show that the average sand coverage on the bed is stable during modern dam operations, with percent absolute changes of sand area of ±5% and ±7%, respectively (Grams et al., 2018). Thus, for much of the post-dam period (e.g. following equilibration of the channel bed to prevailing sediment supply and discharge; Grams et al., 2007), the 2009 map of sand extent below 226 m^3/s discharge is likely reasonable. However, given that pre-dam bed sediment coverage was likely much greater than in 2009 for much of the period 1921–2009, the 2009 channel bed sediment classification represents a conservative estimate of sand extent below 226 m^3/s. Under these assumptions, the disparity between bare sand extent during the pre- and post-dam periods, computed herein as 49%, is likely to be a lower-bound estimate.

The analyses presented here do not attempt to directly quantify the effect of sediment supply reduction on bare sand area throughout the study reach in the same way that we explored the effects of hydrologic alteration and vegetation encroachment. Topping et al. (2000) demonstrated the large-scale reduction in sediment supply to Grand Canyon following the closure of Glen Canyon Dam. However, directly attributing this sediment supply alteration to the loss of bare sand extent in a spatially explicit manner (i.e. using the same mapping approach that was employed for vegetation extent and inundation extent) is complicated by a lack of time series data on sand coverage, particularly on the bed of the Colorado River, along with the high degree of sediment exchange between the channel bed, near-channel areas such as eddy sandbars, and upland dune fields that occurs within Grand Canyon. Nevertheless, it has been well established that sediment supply reductions have, in a general sense, led to shifts in bare sediment coverage in Grand Canyon, including the loss of sandbar area (Dolan et al., 1974; Kearsley et al., 1994; Schmidt and Graf, 1990) and upland aeolian sand mobility (East et al., 2016; Sankey et al., 2018a, 2018c), and in some cases coarsening of the channel bed (Grams et al., 2007). Schmidt et al. (2004) estimated that sand storage in eddies decreased by ~25% between 1935 and 2001, but these locations have dynamic sediment storage at intra-flood timescales. Although eddy sandbars have undergone widespread erosion following the closure of Glen Canyon Dam, the 1996 controlled flood in Grand Canyon increased sandbar area by 11% on average in Marble Canyon (Schmidt et al., 2004). Because this work was aimed at quantifying the roles of hydrologic alteration and vegetation encroachment (and not sediment supply reduction) on the areal extent of bare sand, eddy sandbar areas were held constant, as represented by 2009 total station surveys and sand mapping in 2009 aerial photographs. Future work in this area should seek to include the dynamic evolution of channel margin and eddy deposits as mapped from field surveys and aerial photographs (e.g. Hazel et al., 2006).

Over the past several decades, increasing importance has been ascribed to transferring geomorphic research into societally relevant predictions, or *earthcasts*, of surface process response to environmental drivers at human timescales, such as climate change or land use alterations (Pelletier et al., 2015; Wilcock and Iverson, 2003). While the historical analysis framework presented here is useful for quantifying the response of river valley sediment connectivity to altered hydrology or land cover following regulation in a post hoc fashion, it is equally important to be able to forecast future changes in sediment connectivity at the river corridor scale. Over the coming decades, many rivers worldwide will undergo shifts in their hydrologic regime, whether as a function of climate change (Palmer et al., 2008), land use alteration (Costa et al., 2003; Hollis, 1975; Kasprak et al., 2013), or river regulation for hydropower development or water diversion. These hydrologic shifts will likely be accompanied or followed by transitions in land cover, such as the vegetation community changes observed in Grand Canyon (Sankey et al., 2015; Turner and Karpiscak, 1980; Webb et al., 2007). The ability to predict the impact of any of these drivers on potential sediment transfer within river valleys is vital for assessing the biophysical impact of river alteration and for taking steps to ameliorate disturbance to waterways. As high-resolution data depicting channel bathymetry, valley topography, land cover, and hydrology are becoming increasingly commonplace in the watershed sciences, we believe that our modeling framework will be readily extendable to other river valleys as well.

Perhaps obviously, the framework developed here benefited from the wealth of topographic, bathymetric, hydrologic, and land cover data available in Grand Canyon. However, similar analyses of sediment availability in response to alteration are possible in other river systems, even at reduced data extent or resolution. For example, emergent technologies for the extraction of topographic, bathymetric, and even sediment grain size data, from aerial or oblique images (Dietrich, 2017; Fonstad et al., 2013; Legleiter, 2016) can provide information on river valley form, while routines for the extraction of sediment grain size data from low-cost sonar data are available freely (Buscombe, 2017). The classification of bare sediment and vegetation from remote sensing data, in particular aerial photographs, is well established (Buscombe et al., 2015; Fu and Burgher, 2015; La Cecilia et al., 2016; Legleiter et al., 2016; Macfarlane et al., 2017a; Sankey et al., 2015). In combination with data on streamflow and relatively simple one-dimensional stage modeling, estimates of sediment availability as a function of discharge can be readily obtained, and perhaps more importantly, impacts to sediment availability arising from anthropogenic or environmental drivers can be predictively modeled using the framework developed here. We believe that in concert with the growing availability of high-resolution data in physical geography, this work will contribute to ongoing progress in the understanding and forecasting of sediment connectivity in river valleys.

VI. Conclusions

We synthesized data quantifying the extent of bare sand from the channel bed to the historic flood of record continuously throughout a 28 km reach of the Colorado River in Grand Canyon, Arizona, USA. In combination with maps of vegetation extent derived from nine aerial photograph sets captured between 1965 and 2013 and one-dimensional hydraulic modeling outputs showing the inundation extent of fourteen discrete discharges from Glen Canyon Dam, we modeled the areal extent of bare sand as a function of hydrological alteration and vegetation encroachment during the period from 1921 to 2016. Our results indicated that throughout this study reach, bare sand area has decreased by 49% owing to the combined influence of these two alterations; individually, hydrological alteration has reduced exposed sand area by 9% while vegetation encroachment has reduced exposed sand area by 45%. The two processes are not strictly additive because vegetation encroachment onto bare sand surfaces negates any additional influence of hydrological alteration in inundating or exposing sand at that location. At the same time, these two alterations are undoubtedly related, as hydrologic alteration has led to increased vegetation extent through increased baseflow and the elimination of large scouring floods (Sankey et al., 2015), while vegetation may promote increased sediment deposition, bar aggradation, and the establishment of additional vegetation in a positive feedback (Mueller et al., 2017a). We used the results of the 91-year historical analysis and the projected future river discharge regime to forecast the response of sediment availability to hydrological alterations through the year 2036. We predict that sediment availability will decrease under the planned river discharge regime during this time frame by an additional 12%.

Our modeling framework may prove useful in many river systems where a lack of connectivity between riverine and upland areas creates management issues, as it allows rapid hind- or forecasting of the influence of river discharge and land cover on sediment transport processes and the propensity for the maintenance of landscapes such as sandbars, source-bordering aeolian dunefields, and terraces along spatially extensive river corridors. Although the approach employs several assumptions and simplifications relating to bed sand coverage and vegetation encroachment dynamics by necessity, future work aimed at understanding the dynamic nature of bed sediment coverage and the controls on vegetation encroachment onto a variety of substrates hold the potential to improve the accuracy of our predictions. In combination with work aimed at understanding alterations to riverine habitat through eco-hydraulic habitat availability/suitability relationships, the framework presented here has the potential to better forecast controls on biophysical processes in river corridors at meaningful spatiotemporal scales.

Acknowledgements

Grand Canyon National Park provided permission to conduct river trips for field data collection. We thank Joseph Hazel and Matthew Kaplinski (Northern Arizona University) for collecting nearly 30 years of data on sediment dynamics in Grand Canyon, along with Laura Durning and Geoff Chain (USGS GCMRC) for completing archival maps of sand and vegetation coverage for our study reach. We also thank the numerous boat operators in Grand Canyon who made data collection possible, along with Terry Arundel and Tom Gushue for data archiving and geospatial data support, respectively. Christopher Magirl (USGS AZ WSC), Helen Fairley (USGS GCMRC) and Jack Schmidt (Utah State University) provided valuable insight regarding this manuscript. Data and scripts used in this manuscript can be accessed at https://doi.org/10.5066/P9SX3MGY. The use of trade and company names in this publication is for descriptive purposes only and does not constitute endorsement by the US Government. This manuscript is submitted for publication with the understanding that the US Government is authorized to reproduce and distribute reprints for Governmental purposes.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research was funded by the U.S. Bureau of Reclamation's Glen Canyon Dam Adaptive Management Program, with additional funding from the National Center for Earth Surface Dynamics at the University of Minnesota. Alan Kasprak was supported by a Mendenhall Postdoctoral Research Fellowship from the USGS.

ORCID iD

Alan Kasprak http://orcid.org/0000-0001-8184-6128

Supplemental material

Supplemental material for this article is available online at www.sciencebase.gov.

References

Alvarez LV and Schmeeckle MW (2013) Erosion of river sandbars by diurnal stage fluctuations in the Colorado River in the Marble and Grand Canyons: full-scale laboratory experiments. *River Research and Applications* 29: 839–854.

Bangen S, Hensleigh J, McHugh P, et al. (2016) Error modeling of DEMs from topographic surveys of rivers using fuzzy inference systems. *Water Resources Research* 52(2): 1176–1193.

Belnap J, Munson SM and Field JP (2011) Aeolian and fluvial processes in dryland regions: the need for integrated studies. *Ecohydrology* 622: 615–622.

Beschta RL and Ripple WJ (2006) River channel dynamics following extirpation of wolves in northwestern Yellowstone National Park, USA. *Earth Surface Processes and Landforms* 31(12): 1525–1539.

Bracken LJ, Turnbull L, Wainwright J, et al. (2015) Sediment connectivity: a framework for understanding sediment transfer at multiple scales. *Earth Surface Processes and Landforms* 188: 177–188.

Buscombe D (2013) Transferable wavelet method for grain-size distribution from images of sediment surfaces and thin sections, and other natural granular patterns. *Sedimentology* 60(7): 1709–1732. DOI: 10.1111/sed.12049.

Buscombe D (2017) Shallow water benthic imaging and substrate characterization using recreational-grade sidescan-sonar. *Environmental Modelling and Software* 89: 1–18.

Buscombe D, Grams PE and Kaplinski MA (2014a) Characterizing riverbed sediment using high-frequency acoustics. 1. Spectral properties of scattering. *Journal of Geophysical Research: Earth Surface* 119(12): 2674–2691.

Buscombe D, Grams PE and Kaplinski MA (2014b) Characterizing riverbed sediment using high-frequency acoustics. 2. Scattering signatures of Colorado River bed sediment in Marble and Grand Canyons. *Journal of Geophysical Research: Earth Surface* 119(12): 2692–2710.

Buscombe D, Grams PE and Smith SM (2015) Automated riverbed sediment classification using low-cost side-scan sonar. *ASCE Journal of Hydraulic Engineering* 138: 642–652.

Dexter LR and Cluer BL (1999) Cyclic erosional instability of sandbars along the Colorado River, Grand Canyon, Arizona. *Annals of the Association of American Geographers* 89(2): 238–266.

Collins BD, Bedford DR, Corbett SC, et al. (2016) Relations between rainfall-runoff-induced erosion and aeolian deposition at archaeological sites in a semi-arid dam-controlled river corridor. *Earth Surface Processes and Landforms* 41(7): 899–917.

Costa MH, Botta A and Cardille JA (2003) Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. *Journal of Hydrology* 283(1–4): 206–217.

Dietrich JT (2017) Bathymetric Structure-from-Motion: extracting shallow stream bathymetry from multi-view stereo photogrammetry. *Earth Surface Processes and Landforms* 42(2): 355–364.

Dolan R, Howard A and Gallenson A (1974) Man's impact on the Colorado River in the Grand Canyon: the Grand Canyon is being affected both by the vastly changed Colorado River and by the increased presence of man. *American Scientist* 62(4): 392–401.

Draut AE (2012) Effects of river regulation on aeolian landscapes, Colorado River, southwestern USA. *Journal of Geophysical Research: Earth Surface* 117(F2): F02022.

Durning LE, Sankey JB, Chain GR, et al. (2017) Riparian vegetation classification of the Colorado River Corridor, Grand Canyon, Arizona 2013-Data. U.S. Geological Survey dataset. DOI: 10.5066/F7K64GJF.

East AE, Collins BD, Sankey JB, et al. (2016) Conditions and processes affecting sand resources at archeological sites in the Colorado River corridor below Glen Canyon Dam, Arizona. Professional paper 1825. Reston, VA: U.S. Geological Survey.

East AE, Jenkins KJ, Happe PJ, et al. (2017) Channel-planform evolution in four rivers of Olympic National Park, Washington, USA: the roles of physical drivers and trophic cascades. *Earth Surface Processes and Landforms* 42(7): 1011–1032.

Fairley HC (2005) Cultural resources in the Colorado River corridor. In: Gloss SP, Lovich JE and Melis TS (eds) *The State of the Colorado River Ecosystem in Grand Canyon*. Reston, VA: U.S. Geological Survey, 177–192.

Fonstad MA, Dietrich JT, Courville BC, et al. (2013) Topographic structure from motion: a new development in photogrammetric measurement. *Earth Surface Processes and Landforms* 38(4): 421–430.

Fu B and Burgher I (2015) Riparian vegetation NDVI dynamics and its relationship with climate, surface water and groundwater. *Journal of Arid Environments* 113: 59–68.

Grams PE, Hazel JE, Schmidt JC, et al. (2010) Response of sandbars to the March 2008 high flow experiment on the Colorado River downstream from Glen Canyon Dam. In: *Proceedings of the joint federal interagency conference* 2010, Las Vegas, NV, 27 June – 1 July 2010.

Grams PE, Kaplinski MA, Buscombe D, et al. (2018) Sand budget of Lower Marble Canyon: 2009 to 2012. U.S. Geological Survey data release.

Grams PE, Schmidt JC and Topping DJ (2007) The rate and pattern of bed incision and bank adjustment on the Colorado River in Glen Canyon downstream from Glen Canyon Dam, 1956–2000. *Geological Society of America Bulletin* 119(5–6): 556–575.

Grams PE, Schmidt JC, Wright SA, et al. (2015) Building sandbars in the Grand Canyon. *EOS, Transactions of the American Geophysical Union* 96: 1–11.

Grams PE, Topping DJ, Schmidt JC, et al. (2013) Linking morphodynamic response with sediment mass balance on the Colorado River in Marble Canyon: issues of scale, geomorphic setting, and sampling design. *Journal of Geophysical Research: Earth Surface* 118(2): 361–381.

Hazel JE, Grams PE, Schmidt JC, et al. (2010) *Sandbar Response in Marble and Grand Canyons, Arizona, Following the 2008 High-Flow Experiment on the Colorado River*. US Geological Survey Scientific Investigations Report, 2010-5015. p. 52.

Hazel JE, Topping DJ, Schmidt JC, et al. (2006) Influence of a dam on fine-sediment storage in a canyon river. *Journal of Geophysical Research* 111(F1): F01025.

Hollis GE (1975) The effect of urbanization on floods of different recurrence interval. *Water Resources Research* 11(3): 431–435.

Howard A and Dolan R (1981) Geomorphology of the Colorado River in the Grand Canyon. *The Journal of Geology* 89(3): 269–298. DOI: 10.1086/628592.

Kaplinski M, Hazel JE, Parnell R, et al. (2014) *Colorado River campsite monitoring, Grand Canyon National Park, Arizona, 1998–2012*. Open file report no. 2014-1161. Reston, VA: U.S. Geological Survey.

Kaplinski M, Hazel JE Jr, Grams PE, et al. (2017) *Channel mapping river miles 29–62 of the Colorado River in Grand Canyon National Park, Arizona, May 2009*. Open file report no. 2017-1030. Reston, VA: U.S. Geological Survey.

Kasprak A, Caster J, Bangen SG, et al. (2017) Geomorphic process from topographic form: automating the interpretation of repeat survey data in river valleys. *Earth Surface Processes and Landforms* 42(12): 1872–1883.

Kasprak A, Magilligan FJ, Nislow KH, et al. (2013) Differentiating the relative importance of land cover change and geomorphic processes on fine sediment sequestration in a logged watershed. *Geomorphology* 185: 67–77.

Kasprak A, Sankey JB, Buscombe D, et al. (2018) River valley sediment connectivity data, Colorado River, Grand Canyon. U.S. Geological Survey data release. DOI: 10.5066/P9SX3MGY.

Kasprak A, Wheaton JM, Ashmore PE, et al. (2015) The relationship between particle travel distance and channel morphology: results from physical models of braided rivers. *Journal of Geophysical Research: Earth Surface* 120(1): 55–74.

Kearsley LH, Schmidt JC and Warren KD (1994) Effects of Glen Canyon Dam on Colorado River sand deposits used as campsites in Grand Canyon National Park, USA. *Regulated Rivers: Research & Management* 9(3): 137–149.

Konrad CP (2012) Reoccupation of floodplains by rivers and its relation to the age structure of floodplain vegetation. *Journal of Geophysical Research: Biogeosciences* 117: G00N13.

Konsoer KM, Rhoads BL, Langendoen EJ, et al. (2016) Spatial variability in bank resistance to erosion on a large meandering, mixed bedrock-alluvial river. *Geomorphology* 252: 80–97.

La Cecilia D, Toffolon M, Woodcock CE, et al. (2016) Interactions between river stage and wetland vegetation detected with a seasonality index derived from LANDSAT images in the Apalachicola Delta, Florida. *Advances in Water Resources* 89: 10–23.

Langford RP (1989) Fluvial–aeolian interactions. Part I. Modern systems. *Sedimentology* 36: 1023–1035.

Legleiter CJ (2016) Inferring river bathymetry via image-to-depth quantile transformation (IDQT). *Water Resources Research* 52(5): 3722–3741.

Legleiter CJ, Stegman TK and Overstreet BT (2016) Spectrally based mapping of riverbed composition. *Geomorphology* 264: 61–79.

Leyland J, Hackney CR, Darby SE, et al. (2017) Extreme flood-driven fluvial bank erosion and sediment loads: direct process measurements using integrated Mobile Laser Scanning (MLS) and hydro-acoustic techniques. *Earth Surface Processes and Landforms* 42(2): 334–346.

Macfarlane WW, McGinty CM, Laub BG, et al. (2017a) High-resolution riparian vegetation mapping to prioritize conservation and restoration in an impaired desert river. *Restoration Ecology* 25(3): 333–341.

Macfarlane WW, Wheaton JM, Bouwes N, et al. (2017b) Modeling the capacity of riverscapes to support beaver dams. *Geomorphology*, 277: 72–99.

Magilligan FJ and Nislow KH (2005) Changes in hydrologic regime by dams. *Geomorphology* 71(1–2): 61–78.

Magilligan FJ, Graber BE, Nislow KH, et al. (2016) River restoration by dam removal: enhancing connectivity at watershed scales. *Elementa: Science of the Anthropocene* 4: 108.

Magirl C, Breedlove MJ, Webb RB, et al. (2008) *Modeling water-surface elevations and virtual shorelines for the Colorado River in Grand Canyon, Arizona.* Scientific investigations report no. 2008–5075. Reston, VA: U.S. Geological Survey.

McKay SK, Cooper AR, Diebel MW, et al. (2017) Informing watershed connectivity barrier prioritization decisions: a synthesis. *River Research and Applications* 33(6): 847–862.

Melis T, Korman J and Kennedy T (2012) Abiotic & biotic responses of the Colorado River to controlled floods at Glen Canyon Dam, Arizona, USA. *River Research and Applications* 776: 764–776.

Millar R (2000) Influence of bank vegetation on alluvial channel patterns. *Water Resources Research* 36(4): 1109–1118.

Mueller ER, Grams PE, Hazel JE, et al. (2017a) Variability in eddy sandbar dynamics during two decades of controlled flooding of the Colorado River in the Grand Canyon. *Sedimentary Geology*. Epub ahead of print 10 November 2017. DOI: 10.1016/j.sedgeo.2017.11.007.

Mueller ER, Grams PE, Schmidt JC, et al. (2014) The influence of controlled floods on fine sediment storage in debris fan-affected canyons of the Colorado River basin. *Geomorphology* 226: 65–75.

Mueller ER, Hazel JE, Ross RP, et al. (2017b) Colorado River eddy sandbar dynamics data. U.S. Geological Survey data release. DOI: 10.5066/F7HD7SSW.

Palmer MA, Reidy Liermann CA, Nilsson C, et al. (2008) Climate change and the world's river basins: anticipating management options. *Frontiers in Ecology and the Environment* 6(2): 81–89.

Pelletier JD, Murray AB, Pierce JL, et al. (2015) Forecasting the response of Earth's surface to future climatic and land use changes: a review of methods and research needs. *Earth's Future* 3(7): 220–251.

Piégay H and Gurnell AM (1997) Large woody debris and river geomorphological pattern: examples from S.E. France and S. England. *Geomorphology* 19: 99–116.

Polvi LE and Wohl E (2012) The beaver meadow complex revisited – the role of beavers in post-glacial floodplain development. *Earth Surface Processes and Landforms* 37(3): 332–346.

Ross RP and Grams PE (2015) Long-term monitoring of sandbars on the Colorado River in Grand Canyon using remote sensing. In: *Proceedings of the 3rd joint federal interagency conference on sedimentation and hydrologic modeling*, Reno, NV, 19–23 April 2015.

Rubin DM, Chezar H, Harney JN, et al. (2007) Underwater microscope for measuring spatial and temporal changes in bed-sediment grain size. *Sedimentary Geology* 202(3): 402–408.

Sankey JB and Draut AE (2014) Gully annealing by aeolian sediment: field and remote-sensing investigation of aeolian–hillslope–fluvial interactions, Colorado River corridor, Arizona, USA. *Geomorphology* 220: 68–80.

Sankey JB, Caster J, Kasprak A, et al. (2018a) The response of source-bordering aeolian dunefields to sediment-supply changes 2: controlled floods of the Colorado River in Grand Canyon, Arizona, USA. *Aeolian Research* 32: 154–169.

Sankey JB, Chain GR, Solazzo D, et al. (2018b) Sand classifications along the Colorado River in Grand Canyon derived from 2002, 2009, and 2013 high-resolution multispectral airborne imagery. U.S. Geological Survey data release. DOI: 10.5066/P99TN424.

Sankey JB, Kasprak A, Caster J, et al. (2018c) The response of source-bordering aeolian dunefields to sediment-supply changes 1: effects of wind variability and river-valley morphodynamics. *Aeolian Research* 32: 228–245.

Sankey JB, Ralston BE, Grams PE, et al. (2015) Riparian vegetation, Colorado River, and climate: five decades of spatiotemporal dynamics in the Grand Canyon with river regulation. *Journal of Geophysical Research: Biogeosciences* 120(8): 1532–1547.

Schmidt JC (1990) Recirculating flow and sedimentation in the Colorado River in Grand Canyon, Arizona. *The Journal of Geology* 98(5): 709–724. DOI: 10.1086/629435.

Schmidt JC and Graf JB (1990) Aggradation and degradation of alluvial sand deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona. Professional paper 1493. Reston, VA: U.S. Geological Survey.

Schmidt JC and Rubin D (1995) Regulated streamflow, fine-grained deposits, and effective discharge in canyons with abundant debris fans. In: Costa JE, Miller AJ, Potter KW, et al. (eds) *Natural and Anthropogenic Influences in Fluvial Geomorphology*. Geophysical Monograph 89. Washington, DC: American Geophysical Union.

Schmidt JC and Wilcock PR (2008) Metrics for assessing the downstream effects of dams. *Water Resources Research* 44(4): 1–19.

Schmidt JC, Topping DJ, Grams PE, et al. (2004) *System-wide changes in the distribution of fine sediment in the Colorado River corridor between Glen Canyon Dam and Bright Angel Creek, Arizona*. Final report, submitted to Grand Canyon Monitoring and Research Center, U.S. Geological Survey.

Schmidt JC, Webb RH, Valdez RA, et al. (2014) Science and values in River Grand Canyon. *Bioscience* 48(9): 735–747.

Schmitt RJP, Bizzi S and Castelletti A (2016) Tracking multiple sediment cascades at the river network scale identifies controls and emerging patterns of sediment connectivity. *Water Resources Research* 52(5): 3941–3965.

Shafroth PB, Cleverly JR, Dudley TL, et al. (2005) Control of Tamarix in the Western United States: implications for water salvage, wildlife use, and riparian restoration. *Environmental Management* 35(3): 231–246.

Shafroth PB, Stromberg JC and Patten DT (2002) Riparian vegetation response to altered disturbance and stress regimes. *Ecological Applications* 12(1): 107–123.

Souza JOP, Correa ACB and Brierley GJ (2016) An approach to assess the impact of landscape connectivity and effective catchment area upon bedload sediment flux in Saco Creek Watershed, Semiarid Brazil. *Catena* 138: 13–29.

Tal M and Paola C (2007) Dynamic single-thread channels maintained by the interaction of flow and vegetation. *Geology* 35(4): 347–350.

Tal M and Paola C (2010) Effects of vegetation on channel morphodynamics: results and insights from laboratory experiments. *Earth Surface Processes and Landforms* 35(9): 1014–1028.

Taylor P, Fahrig L, Henein K, et al. (1993) Connectivity is a vital element of landscape structure. *Oikos* 68: 571–573.

Topping DJ, Rubin DM and Vierra LE (2000) Colorado River sediment transport. 1. Natural sediment supply limitation and the influence of Glen Canyon Dam. *Water Resources Research* 36(2): 515–542.

Topping DJ, Schmidt JC and Vierra LEJ (2003) Computation and analysis of the instantaneous-discharge record for the Colorado River at Lees Ferry, Arizona – May 8, 1921, through September 30, 2000. Professional paper 1677. Reston, VA: U.S. Geological Survey.

Turner RM and Karpiscak MM (1980) Recent vegetation changes along the Colorado River between Glen Canyon Dam and Lake Mead, Arizona. Professional paper 1132. Reston, VA: U.S. Geological Survey.

U.S. Department of the Interior (2016) *Glen Canyon Dam Long-Term Experimental and Management Plan Final Environmental Impact Statement*. Salt Lake City, UT: U.S. Department of the Interior Bureau of Reclamation.

Vericat D, Wheaton JM and Brasington J (2017) Revisiting the morphological approach: opportunities and challenges with repeat high-resolution topography. In: Tsutsumi D and Laronne JB (eds) *Gravel-Bed Rivers: Process and Disasters*. Chichester, UK: John Wiley & Sons, 121–158.

Walling DE and Fang D (2003) Recent trends in the suspended sediment loads of the world's rivers. *Global and Planetary Change* 39(1–2): 111–126.

Waring GL (1995) *Current and historical riparian vegetation trends in Grand Canyon, using multitemporal remote sensing analyses of GIS sites*. Final report to Bureau of Reclamation, Glen Canyon Environmental Studies, and National Park Service. Flagstaff, AZ: Northern Arizona University.

Webb RH (1996) *Grand Canyon, a Century of Change: Rephotography of the 1899–1890 Stanton Expedition*. Tucson, AZ: University of Arizona Press.

Webb RH, Leake SA and Turner RM (2007) *The Ribbon of Green: Change in Riparian Vegetation in the Southwestern United States*. Tucson, AZ: University of Arizona Press.

Westoby MJ, Brasington J, Glasser NF, et al. (2012) 'Structure-from-Motion' photogrammetry: a low-cost, effective tool for geoscience applications. *Geomorphology* 179: 300–314.

Wheaton JM, Brasington J, Darby SE, et al. (2009) Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. *Earth Surface Processes and Landforms* 35(2): 136–156.

Wheaton JM, Brasington J, Darby SE, et al. (2013) Morphodynamic signatures of braiding mechanisms as expressed through change in sediment storage in a gravel-bed river. *Journal of Geophysical Research: Earth Surface* 118(2): 759–779.

Wheaton JM, Fryirs KA, Brierley G, et al. (2015) Geomorphic mapping and taxonomy of fluvial landforms. *Geomorphology* 248: 273–295.

Wilcock PR and Iverson RM (2003) *Prediction in Geomorphology*. Monograph 135. Washington, DC: American Geophysical Union.

Williams RD, Brasington J, Vericat D, et al. (2014) Hyperscale terrain modelling of braided rivers: fusing mobile terrestrial laser scanning and optical bathymetric mapping. *Earth Surface Processes and Landforms* 39(2): 167–183.

Wohl E (2017) Connectivity in rivers. *Progress in Physical Geography* 41(3): 345–362.

Wohl E and Beckman ND (2014) Leaky rivers: implications of the loss of longitudinal fluvial disconnectivity in headwater streams. *Geomorphology* 205: 27–35.

Wright SA and Kaplinski M (2011) Flow structures and sandbar dynamics in a canyon river during a controlled flood, Colorado River, Arizona. *Journal of Geophysical Research: Earth Surface* 116(F1): 1–15.