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Research article

Archaeological sites in Grand Canyon National Park along the Colorado River are eroding owing to six decades of Glen Canyon Dam operations

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A R T I C L E I N F O

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A B S T R A C T

The archaeological record documenting human history in deserts is commonly concentrated along rivers in terraces or other landforms built by river sediment deposits. Today that record is at risk in many river valleys owing to human resource and infrastructure development activities, including the construction and operation of dams. We assessed the effects of the operations of Glen Canyon Dam – which, since its closure in 1963, has imposed drastic changes to flow, sediment supply and distribution, and riparian vegetation – on a population of 362 archaeological sites in the Colorado River corridor through Grand Canyon National Park, Arizona, USA. We leverage 50 years of evidence from aerial photographs and more than 30 years of field observations and measurements of archaeological-site topography and wind patterns to evaluate changes in the physical integrity of archaeological sites using two geomorphology-based site classification systems. We find that most archaeological sites are eroding; moreover, most are at increased risk of continuing to erode, due to six decades of operations of Glen Canyon Dam. Results show that the wind-driven (aeolian) supply of river-sourced sand, essential for covering archaeological sites and protecting them from erosion, has decreased for most sites since 1973 owing to effects of long-term dam operations on river sediment supply and riparian vegetation expansion on sandbars. Results show that the proportion of sites affected by erosion from gullies controlled by the local base-level of the Colorado River has increased since 2000. These changes to landscape processes affecting archaeological site integrity limit the ability of the National Park Service and Grand Canyon-affiliated Native American Tribes to achieve environmental management goals to maintain or improve site integrity *in situ*. We identify three environmental management opportunities that could be used to a greater extent to decrease the risk of erosion and increase the potential for *in-situ* preservation of archaeological sites. Environmental management opportunities are: 1) sediment-rich controlled river floods to increase the aeolian supply of river-sourced sand, 2) extended periods of low river flow to increase the aeolian supply of river-sourced sand, 3) the removal of riparian vegetation barriers to the aeolian transport of river-sourced sand.

1. Introduction

The archaeological record of desert environments is commonly concentrated near fresh water sources such as lakes and rivers (Anderson and Neff, 2011; Roskin et al., 2014; Lu et al., 2017). These archaeological sites on river terraces or other geomorphic landforms built by river sediment deposits document human use of water, minerals, plants, and animals of riparian ecosystems as resources to live, farm, or temporarily reside (e.g., camp) (Schwartz et al., 1979, 1980; Fairley, 2003; Anderson and Neff, 2011; Roskin et al., 2014; Ferro-Vázquez et al., 2017). In many river corridors today, the archaeological record is at risk, due in large part to environmental alterations arising from human activities including infrastructure and housing development, deforestation of riparian corridors, and construction of dams (East et al., 2016, 2017; Holden et al., 2009). A growing body of scientific literature documents the myriad ways that dams affect the downstream portion of

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river corridors by altering the hydrology, sediment supply, water temperature, and other ecologically important parameters (Collier et al., 1996; Topping et al., 2000; Kennedy et al., 2016; U.S. Department of Interior, 2016a; Glenn et al., 2017). Despite these advances, very little attention has been paid to the effects of dams on archaeological sites embedded within landscapes downstream of dams. In this paper we describe results of research and monitoring spanning three decades and incorporating five decades of available data (Sankey et al., 2023). We focus on understanding the influence of modern river flow and sediment-supply alteration by a large dam (Glen Canyon Dam) on the archaeological sites and cultural landscape of the Colorado River corridor in Grand Canyon National Park, Arizona, USA (Fig. 1).

While archaeological records in river valleys are commonly concentrated in landforms composed of river-deposited sediment, each river system is geomorphically unique with respect to the processes that both create and disturb the landforms. The Colorado River in Grand Canyon is a canyon-bound river system where ephemeral side-canyon tributaries create debris fans that locally constrict the river channel and also cause pools and eddies to form, in which sediment is commonly deposited (Schmidt and Rubin, 1995). The most common types of river-sourced sediment deposits in Grand Canyon are sandbars, channel margins, terraces, and sand dunes (Fig. 2; Burke et al., 2003). The archaeological record within the river corridor in Grand Canyon is commonly documented in terraces built when the river deposited flood sediment during Holocene or earlier time periods, and also in aeolian sand dunes constructed of wind-redeposited river sediment that are situated on top of river terrace or tributary debris-fan deposits (Hereford et al., 1993, 1996). The terraces and sand dunes erode naturally over time by further wind action (deflation) or via gullying (overland water flow) processes when intense rainstorms cause hillslope runoff (Pederson et al., 2006; Collins et al., 2016). The environmental setting of the Colorado River in Grand Canyon is a well-known case that can be used to understand effects of the environmental risk to the archaeological record in other desert landscapes that are also impacted by a combination of fluvial (river), aeolian (wind), and alluvial (hillslope) geomorphic processes (Love et al., 2011; Roskin et al., 2014; Lu et al., 2017).

1.1. *Objective*

In this paper we build on previous geomorphic studies and process-based conceptual models to examine the environmental risk of erosion on archaeological site preservation and to identify environmental management opportunities to help reduce the environmental risk. Our objective is to compile the results of two classification metrics, based on two conceptual models, applied to a population of 362 archaeological sites over multiple decades, along with repeat lidar survey results from a sample of these sites, in order to assess long-term changes to the geomorphic condition of Colorado River archaeological sites along the entire river corridor throughout Grand Canyon National Park. This synthesis approach, combining quantitative data and conceptual understanding of sediment movement throughout the river environment, provides a comprehensive analysis of the effects of Glen Canyon Dam operations on this iconic landscape and its archaeological heritage as the dam reaches its 60th year in use.

1.2. *Background*

1.2.1. *History of human occupation and river-corridor archaeological sites in Grand Canyon*

Human history in Grand Canyon spans at least 10,000 years (Smiley, 2017). Indigenous peoples inhabited the region intermittently throughout that time. European explorers first visited the canyon 480

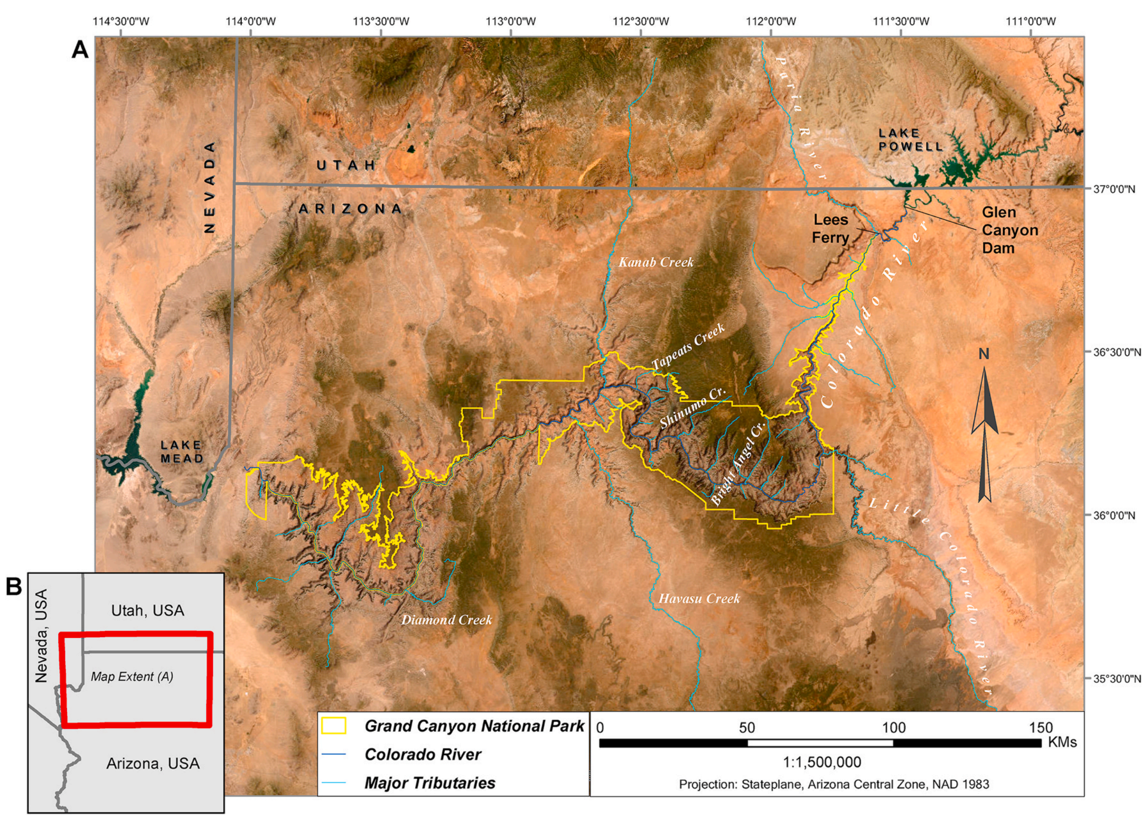

Fig. 1. (A) Map showing the locations of the Grand Canyon National Park, Colorado River, Lake Powell and Lake Mead reservoirs, and Glen Canyon Dam. The study area considered in this paper spans all of the Colorado River corridor from Lees Ferry to the western (downstream) extent of Grand Canyon National Park (yellow line). Note the position of Glen Canyon Dam, 24 km upstream (east) of the Grand Canyon National Park boundary. (B) Map showing location of the map in panel A relative to the states of Arizona, Utah, and Nevada in the southwestern USA.

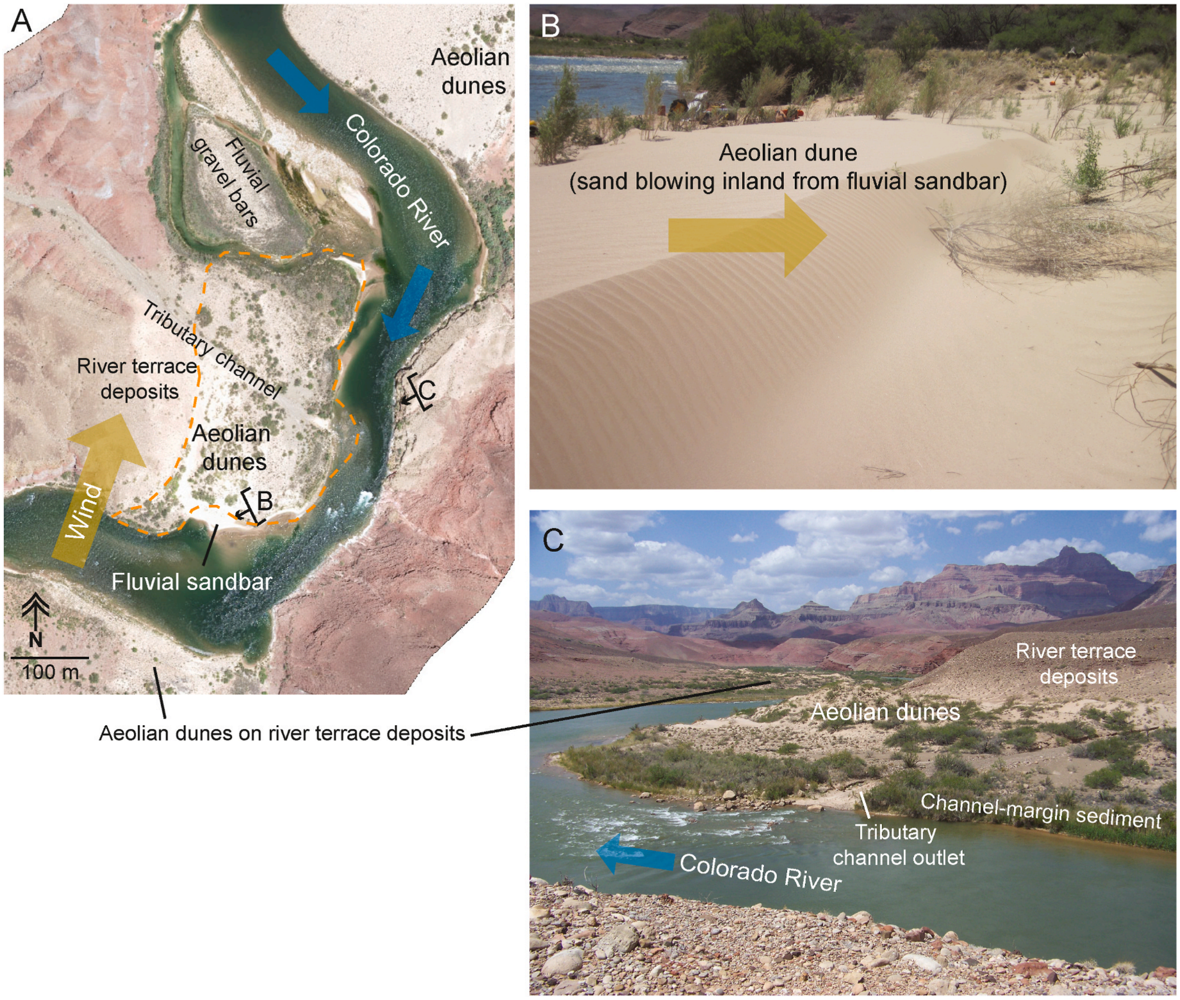

Fig. 2. (A) Overview example of Colorado River-sourced sediment deposits that contain much of the archaeological record along the river corridor in Grand Canyon. Orange dashed line shows approximate extent of tributary debris fan that underlies fluvial and aeolian sediment. (B, C) Ephemeral side canyon tributaries create debris fans that constrict the river channel and also cause pools and eddies to form where sediment is commonly deposited in sandbars, channel margins, terraces, and aeolian sand dunes constructed of wind-deposited river sediment (i.e., debris-fan material underlies the aeolian dunes in the location pictured). The archaeological record is most commonly documented in river terraces built during Holocene or earlier pre-dam time periods, and also in younger aeolian sand dunes that are situated on top of terrace or tributary debris-fan deposits.

years ago. Today, people primarily visit to appreciate the natural and cultural resources and to recreate (e.g., hiking, camping, river rafting). Evidence of the prehistoric occupants and of more recent historic activities is reflected in archaeological sites throughout Grand Canyon National Park (Fig. 3).

Within the riparian corridor of the Colorado River in Grand Canyon National Park, which spans 360 river kilometers of the 637,000 km^2 Colorado River basin, there are hundreds of known prehistoric and historic archaeological sites (Fairley et al., 1994). Many of the archaeological sites are situated on or in river flood deposits and sand dunes formed from sediment derived from the Colorado River (Hereford et al., 1996; Fairley and Hereford, 2002; Anderson and Neff, 2011; Pederson and O'Brien, 2014; East et al., 2016). Prehistoric and historic Native American sites include masonry dwellings, storage structures, ditches, trails, agricultural fields, seasonal campsites, petroglyphs and pictographs, roasting pits, and quarries (Fig. 3A, B, D). The oldest sites in the river corridor date to the Archaic period, which began roughly 9000 B.P., though older sites occur elsewhere in Grand Canyon (Fairley et al., 1994; Smiley, 2017). However, most river corridor sites are associated with Ancestral Puebloan people and date between AD 750 and AD 1250 (Fairley et al., 1994; Fairley, 2003). Other sites date more recently to Pai and Paiute people and their ancestors beginning at approximately AD 1300 and continuing into the historical era (Fairley et al., 1994; Fairley, 2003). Examples of the area's Euroamerican historical sites include remains of cabins, ferry boats and river crossing infrastructure, mining locations, and cowboy camps dating from the 1860s–1950s (Fig. 3C).

1.2.2. *Natural and anthropogenic impacts to archaeological-site integrity*

The Colorado River has exposed and sculpted the landscape of the Grand Canyon and surrounding region for millions of years (Karlstrom et al., 2014). More recently, over the past several thousands of years, it has provided habitat for humans. The physical, ecological, and cultural landscape of the Colorado River has been adjusting to the emplacement of Glen Canyon Dam upstream since it began operating in 1963. The dam traps most of the sediment in the Colorado River, impounding it in the Lake Powell reservoir upstream. Dam operations substantially change the pattern of river flows released downstream, preventing large floods and low summer flows that would occur naturally. These changes to river flow and reductions in sediment supply resulting from the dam's operation have profoundly affected the structure and function of the downstream ecosystem by reducing the size and number of fluvial sandbars (Topping et al., 2000; Rubin et al., 2002; Hazel et al., 2006) and by increasing riparian vegetation in the absence of frequent natural floods (Turner and Karpiscak, 1980; Sankey et al., 2015; Scott et al.,

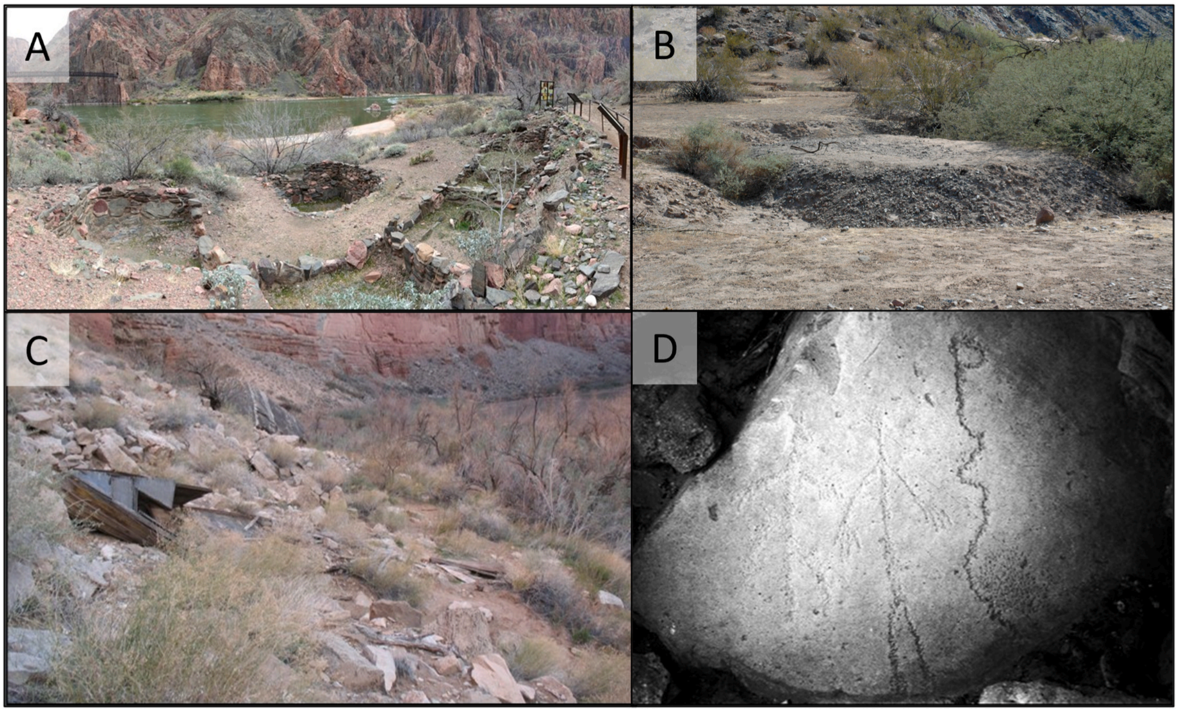

Fig. 3. Examples of different types of archaeological sites that occur along the Colorado River in Grand Canyon: (A) An Ancestral Puebloan multi-room structure that has been previously excavated by archaeologists and partially restored by the National Park Service; (B) Large donut-shaped roasting feature used seasonally to cook local game and plant materials, dating to the late prehistoric or early protohistoric period; (C) The remains of a boat abandoned by historic river runners in 1949; (D) Petroglyphs on a boulder.

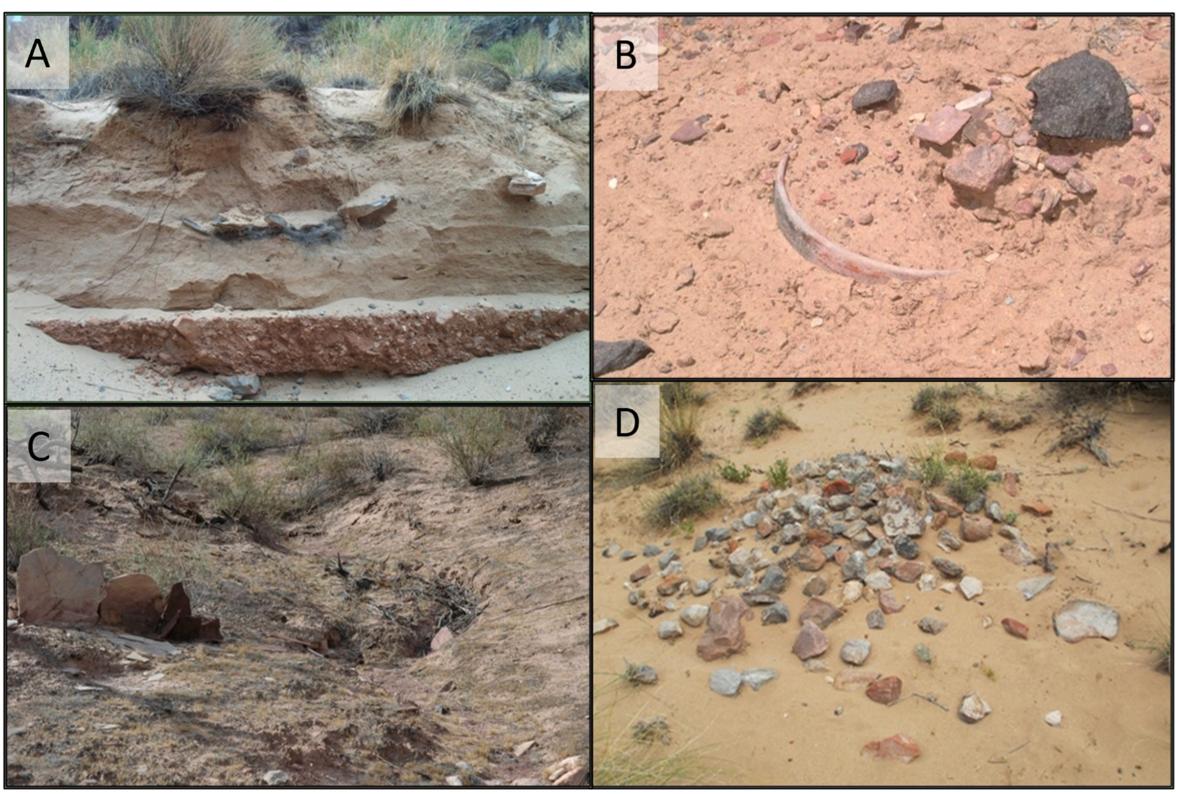

Fig. 4. Examples of different types of erosion that physically degrade archaeological sites along the Colorado River in Grand Canyon National Park: (A) Cutbank erosion in a large alluvial terrace has exposed a prehistoric hearth (buried charcoal lens) in profile; (B) Surface erosion from both water runoff and wind has deflated the archaeological matrix, and in the absence of burial by sand, exposed the rim of a prehistoric bowl; (C) A small gully adjacent to upright slabs forming the base course of a stone and adobe structure; (D) The surface of a roasting feature where wind deflation, coupled with an absence of new sand, has resulted in the loss of the archaeological matrix that once surrounded the fire-altered rock.

2018). These changes, in turn, have altered landscape processes in areas of the river corridor above the modern, dam-controlled-flood stage of approximately 1270 m^3/s (45,000 ft^3/s, about half the magnitude of the 2-year natural flood peak), with important implications for historic and prehistoric cultural resources (Hereford et al., 1993, 1996; Draut et al., 2008; East et al., 2016).

The primary objective of environmental management of archaeological sites and associated cultural resources in Grand Canyon National Park is to maintain the National Register integrity of historic properties and preserve them *in situ* (Little et al., 2000; National Park Service, 2006). Integrity is an abstract concept in the historic preservation field that reflects the ability of a site or structure to convey its historical significance. A related but separate concept is physical integrity, whereby the physical components of a historic structure or archaeological site are retained in sufficiently good condition so that their historical significance can be conveyed. Past research using field studies and models in the Colorado River corridor has demonstrated that many archaeological sites have physically deteriorated over time due to erosion from both human and non-human factors (Fig. 4), with cumulative sediment loss tied to regulated river flows being a significant driver of recent site degradation (e.g., Hereford et al., 1993; Pederson et al., 2006; Pederson and O'Brien, 2014; Sankey and Draut, 2014; Collins et al., 2016; East et al., 2016, 2017; Sankey et al., 2018a; Kasprak et al., 2018, 2021).

1.2.3. Conceptual models for assessing Glen Canyon Dam operations impacts to downstream archaeological sites

Two interrelated conceptual models have been proposed by researchers to explain how upstream dam operations affect downstream archaeological site integrity in the Colorado River corridor in Grand Canyon (Hereford et al., 1993; Leap et al., 2000; East et al., 2016, 2017).

One model describes how the absence of episodic sediment-enriched river floods in the era of dam-controlled flows has destabilized sites by removing the key natural process of river sediment deposition that formerly mitigated (counteracted) sediment loss by hillslope run-off erosion. Much of the initial work that studied the effects of Glen Canyon Dam operations on archaeological sites in Grand Canyon focused on how the curtailment of annual sediment-enriched floods (due to dam operations) and the diminishment of aeolian sand cover affected the rate and scope of post-dam gully erosion (Hereford et al., 1993). Because Glen Canyon Dam operations prevent large floods from occurring in the river corridor, shallow gullies that typically form on terrace surfaces during precipitation-driven, monsoon-season water run-off from hillslopes on the margins of the river corridor become progressively deeper, wider, and longer over time (Fig. 5). Eventually the gullies downcut to the stage of the modern river. Once the side drainages become fully integrated with the mainstem river, they then rapidly expand headward and laterally into the underlying terrace deposits that serve as the primary substrate and matrix for many prehistoric and historic archaeological sites in the Colorado River corridor (Fig. 5). Hereford et al. (1993) hypothesized that prior to the construction of

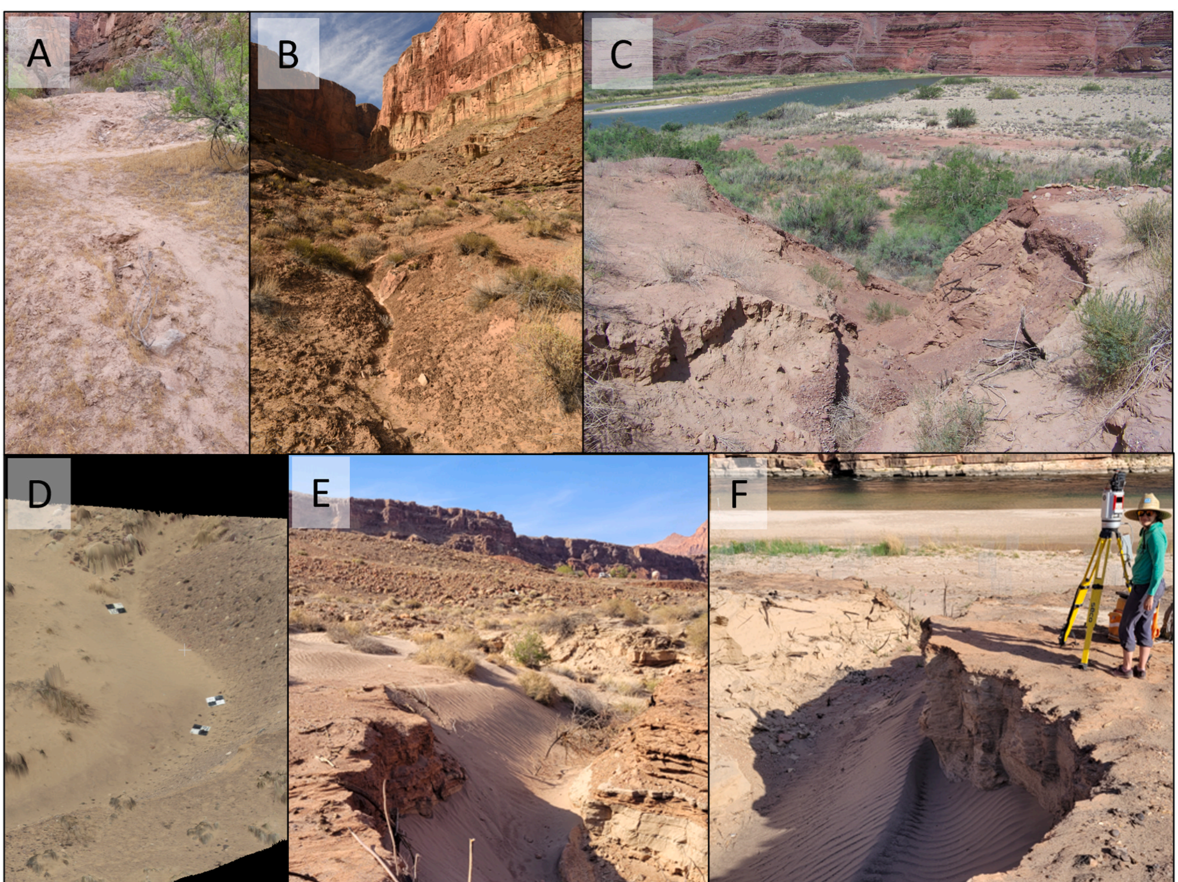

Fig. 5. Examples of different types of gullies eroding archaeological sites located within river sediment deposits along the Colorado River in Grand Canyon National Park: (A, B) Incipient, shallow gullies which have not yet downcut through the terrace sediment to the stage of the modern Colorado River channel; (C) Large gully (arroyo) through a pre-dam river terrace that has downcut to the stage of the modern river, and expanded headward and laterally into the underlying terrace deposits; (D) Shallow gully on a pre-dam river terrace surface that is partially filled in with wind-deposited (aeolian) sand originally sourced from a river deposit; (E, F) Large gully that has downcut through a pre-dam river terrace to the level of a sandbar on the modern river channel, and was partially backfilled with aeolian deposited sand after vegetation was removed by the National Park Service (NPS) from the sandbar for resource-management purposes.

Glen Canyon Dam, gullies rarely had sufficient time to become deeply entrenched before the next sediment-enriched flood would backfill them, since annual floods often overtopped the riverbanks and infilled incipient gullies crossing the fluvial terraces before these gullies became fully integrated with the lower local base level of the mainstem river. The degree to which drainages are present within archaeological-site boundaries and the degree to which those drainages have become integrated with the Colorado River is therefore an indicator of current site condition tied to dam operations (Hereford et al., 1993; East et al., 2017). From this conceptual model, a site classification system – termed the 'drainage classification' – was first implemented by Leap et al. (2000) based on visual surveys during field visits to sites within the river corridor. The purpose of the drainage classification system is to provide a periodic assessment of the degree to which gullies have evolved and become integrated with the mainstem river, as an indicator of archaeological-site erosion, condition, and stability.

A second conceptual model focuses on the role that wind-transported river sand has played in protecting sites from progressive erosion. Because the naturally occurring sediment in the Colorado River is trapped in Lake Powell behind Glen Canyon Dam, downstream sediment supply has been reduced by 85–95% (Topping et al., 2000). Operation of the dam for hydropower generation has altered the flow regime of the river in Grand Canyon by eliminating natural-scale flooding and also low flows that were common before dam construction (i.e., river discharges below 142 m^3/s or 5000 ft^3/s) and that historically exposed large areas of bare sand (U.S. Department of Interior, 2016a; Kasprak

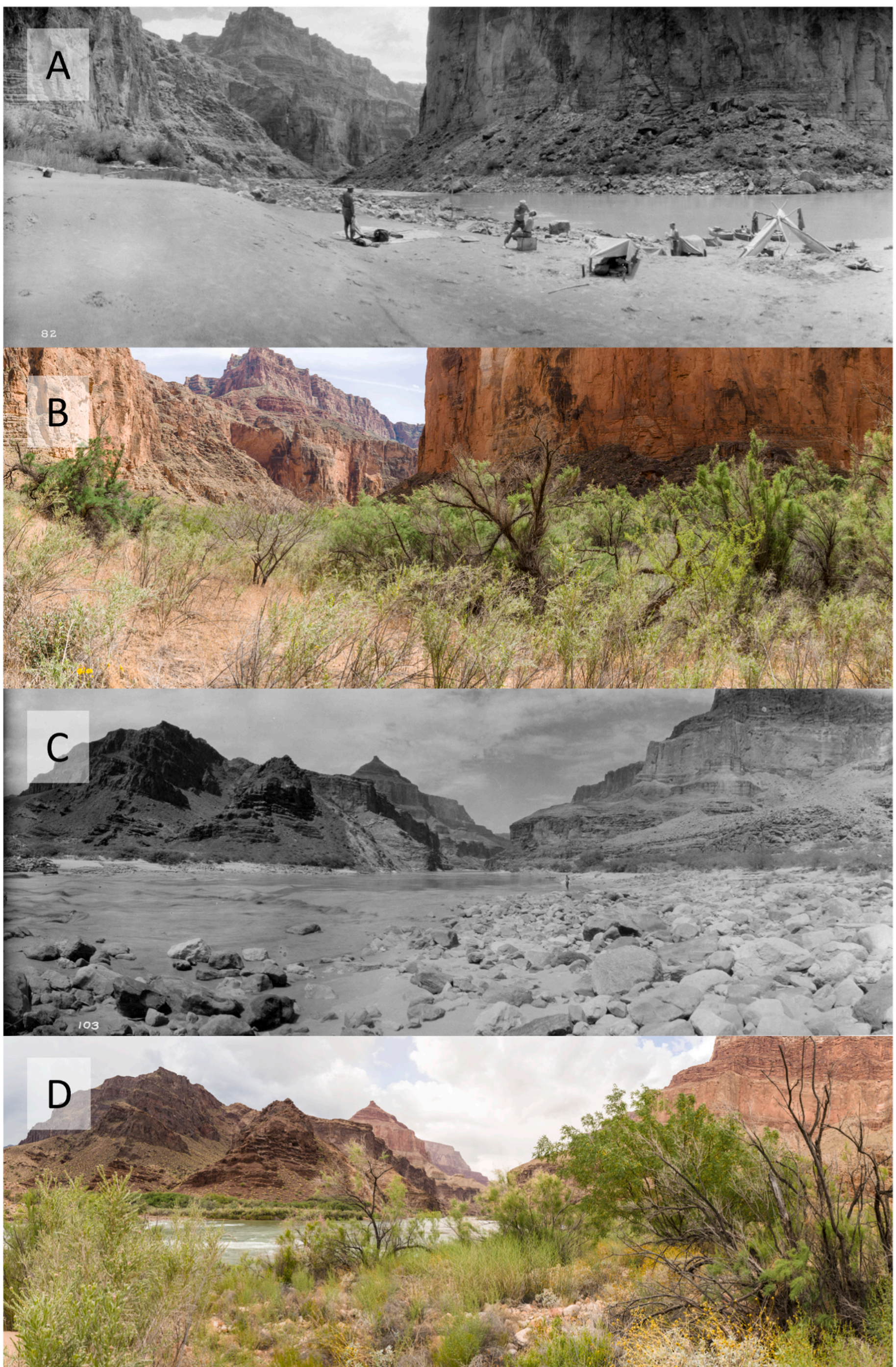

Fig. 6. Matched photos showing areas along the river that formerly served as source areas for wind-blown sand, as they appeared in 1923 compared to 2019 (Photo Credits. Panels A and C: E.C. La Rue, 1923, U. S. Geological Survey Photographic Library, Denver, CO. Panels B and D: A. H. Fairley, May 2019, U.S. Geological Survey). In the top photo match (A–B), taken just upstream of President Harding Rapid, the formerly large open sand bar is now heavily vegetated, with the density of riparian vegetation increasing with closer proximity to the river edge. In the lower photomatch (C–D), taken at the mouth of Palisades Creek and looking across the river towards the mouth of Lava –Chuar Creek, note the significant increase in riparian vegetation along the sandy portions of the opposite river shoreline in 2019 compared to 1923. The areas covered by sand in 1923 were routinely inundated by floods exceeding 2750 m^3/s (Magirl et al., 2008) of the Colorado River prior to regulation by Glen Canyon Dam (pre-1963), whereas the largest post-regulation floods during the early 1980s (up to 2747 m^3/s) inundate only a portion of these sand bars, and the largest floods since then (up to 1274 m^3/s) have only inundated the area of the bars immediately adjacent to the current river banks.

et al., 2018). The combination of elevated low flows coupled with the elimination of large, regularly occurring spring floods in excess of 1982 m^3/s (70,000 ft^3/s) has led to widespread vegetation encroachment along the river (Fig. 6), further reducing the extent of bare, unvegetated sand (Fig. 6A and B; Turner and Karpiscak, 1980; U.S. Department of Interior, 2016a; Sankey et al., 2015). Kasprak et al. (2018) report that the areal coverage of bare sand has decreased by 45% since 1963 due to vegetation expansion and loss of low flows in the river corridor downstream of Glen Canyon Dam. Kasprak et al. (2018) forecast that the areal coverage of bare sand in the river corridor will decrease an additional 12% by 2036. The changes in the flow regime, reductions in river sediment supply and bare sand, and the proliferation of riparian vegetation have affected the condition and physical integrity of archaeological sites. Those changes have resulted in erosion of the upland landscape surface by reducing the fluvial and aeolian transfer of sediment ("sediment connectivity") from sandbars in the active river channel to dunefields on terraces and other older, inactive river sediment deposits in the adjoining landscape that were emplaced by large sediment-rich floods before the dam was built (Fig. 6), and which are where most river-corridor archaeological sites occur (U.S. Department of Interior, 2016a; Draut and Rubin, 2008, 2008; Draut et al., 2008, 2010; Draut, 2012; East et al., 2016, 2017; Kasprak et al., 2018; Sankey et al., 2018a, b; Cook et al., 2019). Many archaeological sites and other evidence of past human activity are now subject to accelerated degradation due to reductions in sediment connectivity under current dam operations and riparian vegetation expansion which are tied to regulated flow regimes (U.S. Department of Interior, 2016a; East et al., 2016, 2017; Cook et al., 2019).

Previous research by East et al. (2016, 2017) and Sankey and Draut (2014) demonstrated that archaeological sites that regularly receive wind-transported sediment derived from nearby sand bars are less susceptible to the damaging effects of hillslope run-off erosion than sites that are disconnected from fluvial sediment source areas. Prior to the construction of Glen Canyon Dam, wind-blown sediment was an important factor protecting sites from erosion by hillslope runoff (overland flow of water that forms gullies). As riparian vegetation has encroached upon open sand bars in response to the elimination of periodic scouring high flows, and as sediment-poor flows have reduced or eliminated many other former sand source areas, many archaeological sites have become disconnected to varying degrees from their former sediment supply (Fig. 7), resulting in increased and progressive erosion and deflation of the surface sediment covering them. East et al. (2016, 2017) developed a site classification system – termed the 'aeolian classification' – that indicates the degree to which archaeological sites can receive wind-blown sediment from fluvial sand bars. This classification is based on a visual assessment of sites' potential influence by dam operations using remotely sensed imagery, coupled with years-long field measurements of wind conditions and field verification of geomorphic context during direct site visits. The classification indicates the degree of sediment connectivity to the river (either from fluvial or aeolian processes, or both) and by extension, relative vulnerability to surface erosion. This classification metric tracks the degree to which sites are maintaining or being disconnected from fluvial sand sources that formerly supplied the wind-blown sediment that covers and protects many sites in the river corridor. As such, it reflects the role that wind-blown sediment derived from fluvial sand bars has played in retaining site integrity.

2. Methods

2.1. Population of Colorado River archaeological sites in Grand Canyon

This study focuses on a population of 362 archaeological sites or site loci (East et al., 2016) located within the Colorado River corridor in Grand Canyon. The 362 sites or loci used here are considered by the Bureau of Reclamation and other signatories to a Programmatic Agreement for Cultural Resources along the Colorado River in Grand Canyon (Bureau of Reclamation, 2017) to be located within the area of potential effect from operations of Glen Canyon Dam (see also Bureau of Reclamation, 2018). Three-quarters of the 362 sites are located within or on top of Colorado River-derived sediment (East et al., 2016) as opposed to substrate from other geologic parent materials. Thus, understanding the potential effects of dam operations at each site first requires characterizing the degree to which a site depends on river-derived sand for maintaining its geomorphic context; the aeolian site classification was developed for this purpose.

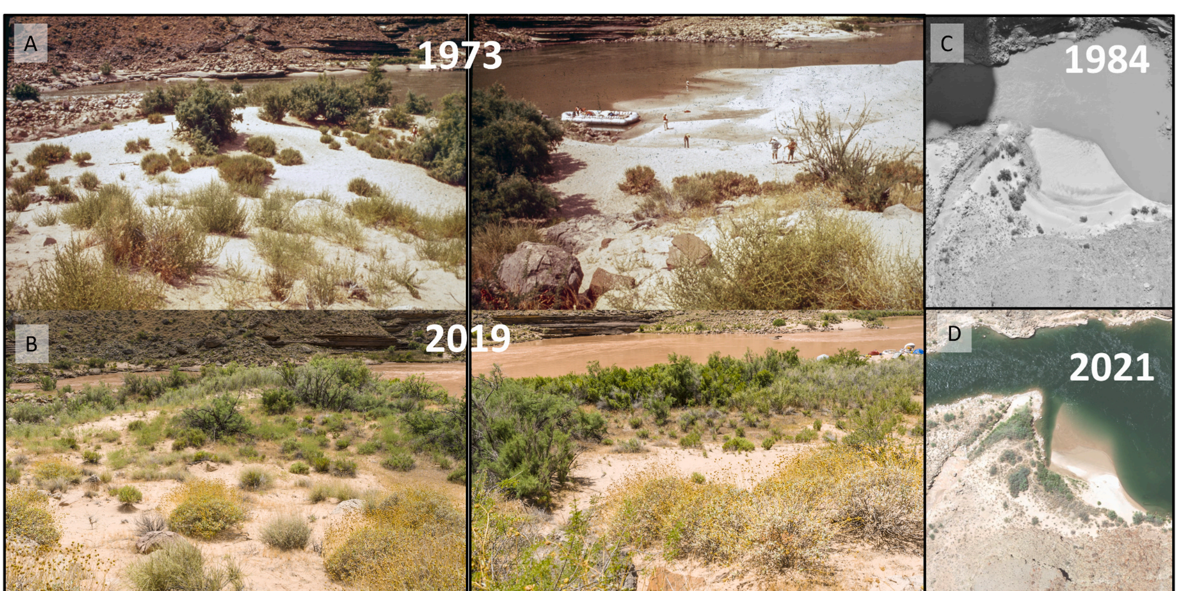

Fig. 7. A river sandbar and downwind aeolian dunefield near an archaeological site area along the Colorado River in Grand Canyon. Note the expansion of riparian vegetation illustrated by the oblique photos matches taken in (A) July 1973 (photo credit, Borden-Weeden research expedition, photographer unknown) and (B) May 2019 (photo credit, A.H. Fairley, USGS), and also by the aerial photos of the same place acquired in (C) 1984 and (D) 2021. The dunefield was formed by river sand blown by wind (i.e., via aeolian transport) from the sandbar. The vegetation creates a barrier to the aeolian sediment transport.

2.2. Archaeological sites fluvial-aeolian sediment connectivity classifications

East et al. (2016) developed a ranked classification of the relative potential for archaeological sites to receive windblown sand from upwind river sandbar deposits, which can help to keep sites buried with a protective cover of sand and offset erosion that may otherwise occur. This classification system focuses on differences in individual site settings that enhance or impede the transfer of fluvial sediment to archaeological sites via the mechanism of aeolian transport; for the sake of simplicity, we refer to it here as the aeolian classification system. The aeolian classification system defines five types of archaeological sites (Fig. 8). Types 1–4 define those sites whose geomorphic context includes river-derived sand as an integral component—either fluvial, aeolian, or both. Type 5 defines those sites at which river-derived sand is absent or, if present, is incidental to the geomorphic context. The site-type definitions are as follows (East et al., 2016, 2017):

Type 1: Sites with an adjacent, upwind, recent subaerial fluvial sand deposit, and where there are no substantial barriers to impede aeolian sand transport from the flood deposit toward the archaeological site.

Type 2: Sites with an adjacent, upwind, recent subaerial fluvial sand deposit, but with a barrier separating the flood deposit from the archaeological site. Barriers were interpreted to limit potential aeolian sand transport from the fluvial deposit toward the archaeological site but may not eliminate sand movement entirely from sandbar to archaeological site. We defined three subtypes:

Type 2a: Vegetation barrier present (may be riparian vegetation or higher-elevation, non-riparian upland vegetation).

Type 2b: Topographic barrier present (most commonly a tributary channel, but in several cases a steep bedrock cliff or large boulder deposit).

Type 2c: Both vegetation and topographic barriers present.

Type 3: Sites at which an upwind shoreline exists for a recent (post-dam) high flow, but where there is presently no open, unvegetated sandbar along the river margin.

Type 4: Sites near which there is no upwind shoreline corresponding to a recent high flow, but whose geomorphic context does involve river-derived sand.

Type 5: Sites at which Colorado River-derived sand is absent or is only incidental to site context, such as sites situated entirely on bedrock or talus.

East et al. (2016) reported on the classification of 362 archaeological sites in the Colorado River corridor in Grand Canyon National Park for the years 1973, 1984–85, 1996, and 2012–14. Their classifications were based on interpretation of historical aerial imagery acquired in 1973, 1984, 1985, 1996, and 2013, as well as site investigations conducted during 2012, 2013, and 2014 (East et al., 2016), and more than 10 years of field measurements of wind speed and direction (e.g., Draut et al., 2010; Caster et al., 2014). More recently, we classified sites for the years 2021–22 based on interpretation of aerial imagery acquired in 2021 and site visits conducted in 2022. In our results for 2021–22 there are additional subcategories of site-types denoted as "*vr*" *(vegetation*

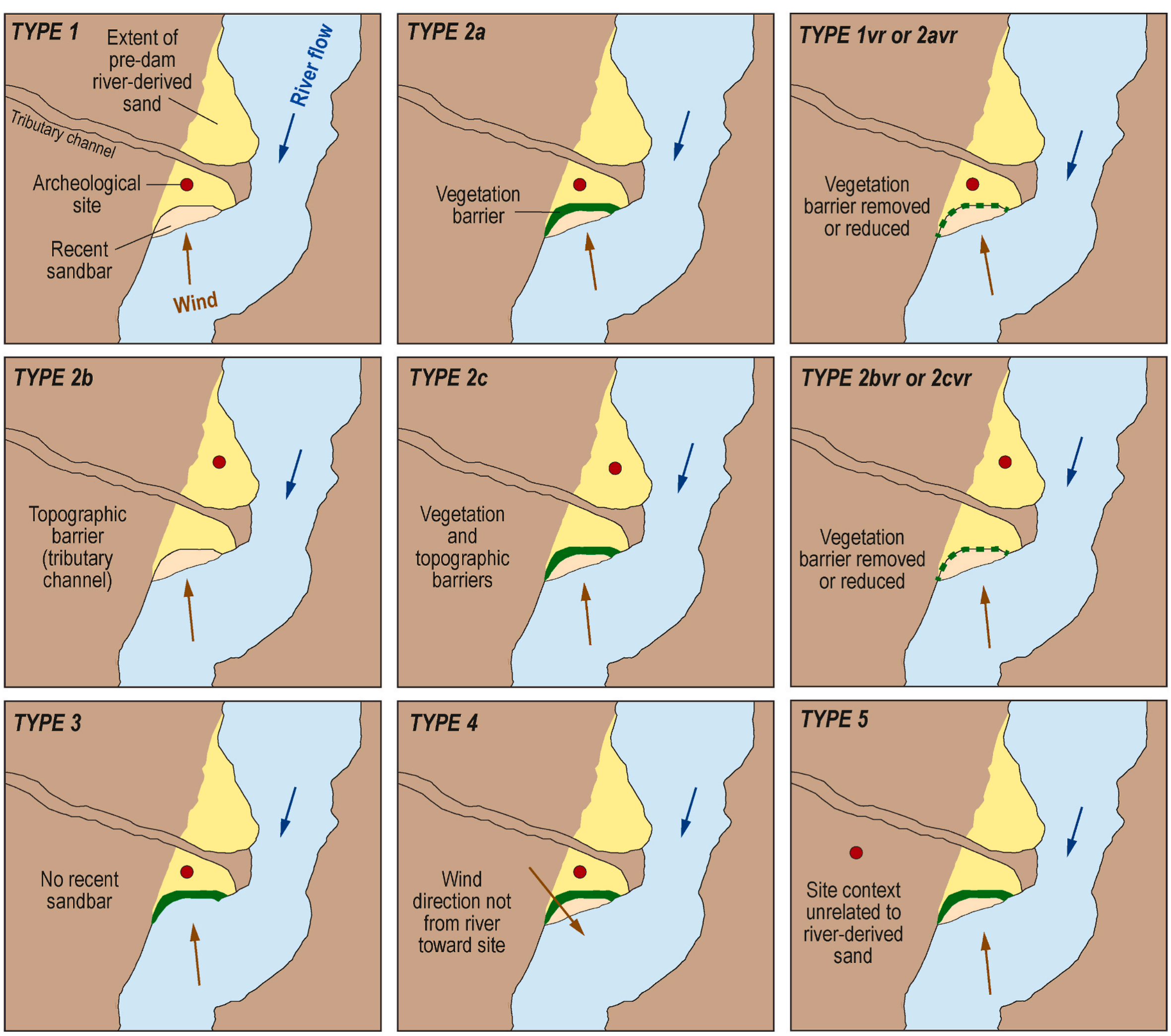

Fig. 8. Schematic diagram illustrating the aeolian classification system (adapted with permission from East et al., 2016, 2017).

removal); these are sites at which the National Park Service has conducted site-specific vegetation management actions between 2019 and 2022 to remove or reduce riparian vegetation barriers to aeolian sand transport (Pilkington et al., 2022, Fig. 8).

Aerial imagery from 2021 to 2013 used in this study and by East et al. (2016) provides coverage of the entire river corridor in Grand Canyon National Park, consisting of 20-cm pixel resolution multispectral digital images acquired in late May to early June at a steady river discharge of 226 m^3/s. Aerial imagery from 1996 consists of black and white as well as color prints at 1:4800 scale acquired in March at a steady river discharge of 226 m^3/s; these images also provide coverage of the entire river corridor. Aerial imagery from 1984 to 1985 were taken in October and June, respectively. The October 1984 aerial photographs are 1:3000 scale black and white prints that were taken at a river discharge of approximately 140 m^3/s and were used to classify most sites. To analyze 20 archaeological sites for which the 1984 aerial images were missing from photographic archives (including where the original flight path missed river segments at the downstream end of the corridor) the June 1985 color prints at 1:4500 scale acquired during river discharge of 850–1020 m^3/s were used. The 1973 images were acquired in June at river discharges ranging from 170 to 368 m^3/s, and are black and white prints at 1:14,400 scale that provide coverage of the locations of the 362 classified sites in the river corridor.

2.3. Archaeological sites drainage classifications

We used the drainage classification system, conceived by Hereford et al. (1993) and adapted by Leap et al. (2000), to identify whether hillslope drainage paths exist at each site that contribute to sediment erosion by overland flow, and, if drainages exist, whether they are integrated with the active river channel or another geomorphic surface (Fig. 9). Drainage classification was completed for 253 Grand Canyon sites by Leap et al. (2000), and those classifications were updated by us and expanded to 362 sites in 2016–17 and again in 2021–22. There were four sites for which Leap et al. (2000) did not distinguish between individual site loci with their classifications, but we chose to do so in 2016–17 and again in 2021–22 as this was consistent with how the aeolian classifications were conducted for those sites. Using aerial imagery and site visits, we evaluated drainage channels (rills, gullies, and arroyos, in order of increasing size) at each of the archaeological sites by noting whether such drainage systems are present within or adjacent to each site. We also documented the downslope extent of the drainage—that is, the base level to which each drainage grades. Sites are binned into one of four categories (East et al., 2017, Fig. 9):

Type D1: no drainages.
Type D2: terrace-based drainages.
Type D3: side-canyon-based drainages.
Type D4: river-based drainages.

The drainage classification system is meant to assess the maximum

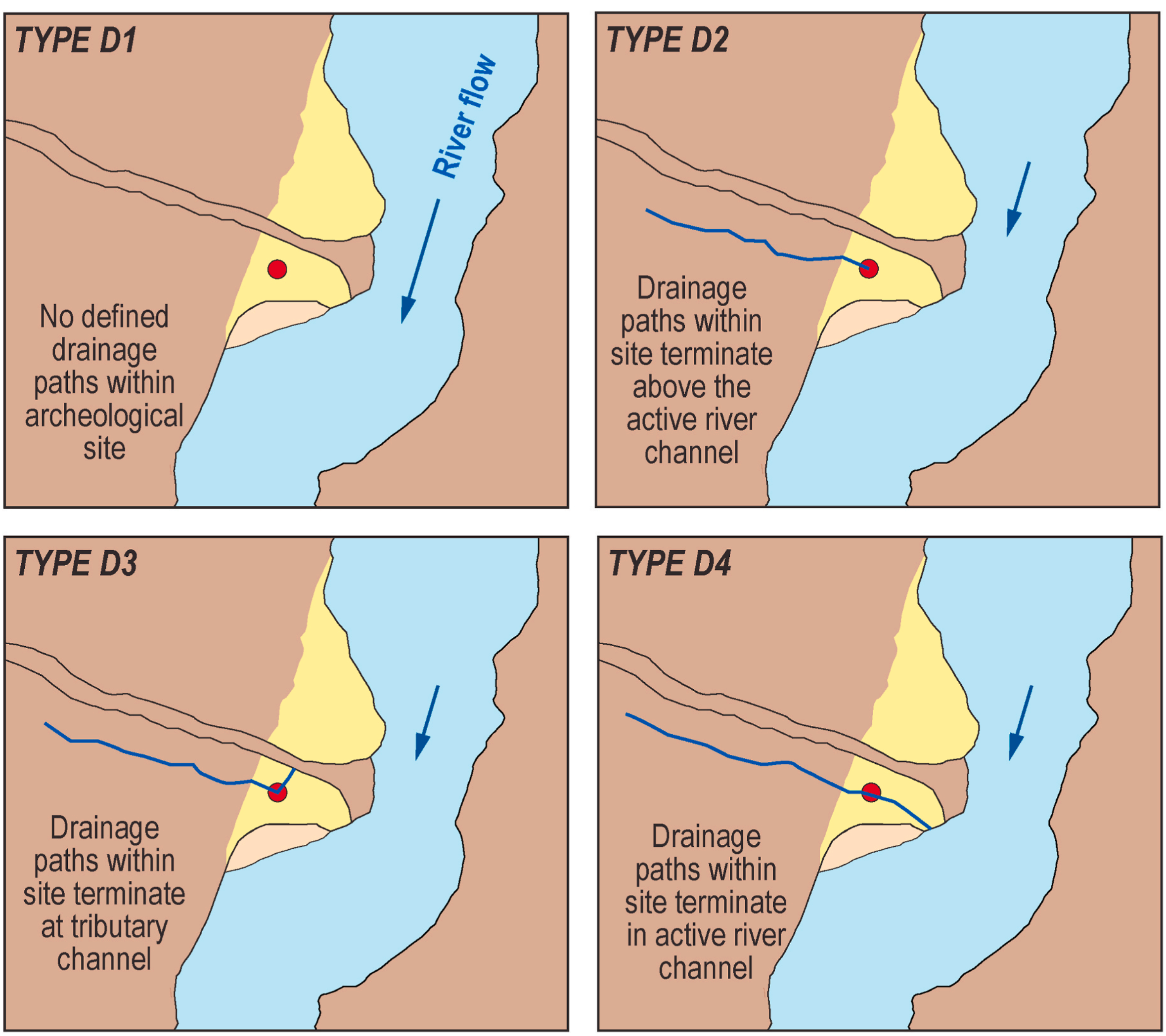

Fig. 9. Schematic diagram illustrating the drainage classification system (adapted with permission from East et al., 2017).

local maturity of drainage networks at a snapshot in time for each field visit or set of aerial photographs. Thus, river-based, and side-canyon-based drainages are graded to the lowest possible base level in this system because they represent the contemporary evolutionary endpoint of drainage development. Terrace-based drainages, on the other hand, represent an intermediate stage of development and may, in the future, become river-based or side-canyon based drainages.

2.4. *Inferring changes in site condition from changes in site type classification over time*

We evaluated changes in archaeological-site condition by analyzing changes in the type classifications for sites over time. Site classification changes from lower numerical values to higher numerical values in the aeolian classification and drainage classifications (for example, aeolian type 1 to aeolian type 2a and drainage type D1 to drainage type D2) represent decreased potential for influx of river sediment via aeolian transport, and increased gullying from overland flow erosion, respectively; we interpret these changes as a transition of site physical condition to a more degraded state with decreased potential for *in-situ* site preservation. Conversely, we interpret site classification changes over time from higher numerical values to lower as a transition to a less degraded state with increased potential for *in-situ* site preservation. Sites that do not change in type classification over time have a stable preservation potential. Interpretations about site preservation potential are made here with respect to impacts by factors assessed using the drainage and aeolian classification systems, but sites could also be impacted by other factors that do not produce gullies, such as rockfall or human activities.

The same population of 362 archaeological sites was classified using the aeolian classification system in 2012–14 and 2021–22 and using the drainage classification system in 2016–17 and 2021–22. For those time periods and sites, we cross-walked the change results for the aeolian and drainage classification to summarize the proportion of the population of sites that remained stable or transitioned to a less or a more degraded site condition over time.

2.5. *Lidar remote sensing of topographic changes at select archaeological sites*

Caster et al. (2022) reported the results of conducting high-resolution topographic surveys at 31 classified archaeological loci within Grand Canyon using ground-based lidar (also commonly termed terrestrial laser scanning or TLS) between September 2010 and June 2020. Thirteen of the 31 sites studied by Caster et al. (2022) had multiple repeat surveys that permitted comparisons for detecting geomorphic change; their study built on earlier TLS assessments of change at smaller numbers of archaeological sites by Collins et al. (2016) and East et al. (2016). In this paper we summarize the results of Caster et al. (2022) to provide a quantitative assessment of changes in geomorphic condition for the small sample of 13 archaeological sites to complement the site classification results that were completed for the entire population of 362 sites.

Here we provide a brief overview of the lidar remote sensing and geomorphic change detection methods but refer the reader to Caster et al. (2022) for the detailed methods. TLS is a ground-based, line-of-sight survey method that uses infrared lasers to measure distance to objects visible to the instrument. By conducting multiple scans from several station setup points during a survey, the entirety of a study site's topography can be characterized. To ensure accurate registration of the data from multiple location surveys, ground control targets are stationed within the lidar survey area and then surveyed using a total station referenced to the USGS geodetic network within Grand Canyon. Referenced ground-control targets are used to assess proper alignment of topographic measurements and to geographically reference the survey within the Arizona State Plane coordinate projection system. TLS surveys generate a dense set of point measurements, termed a point cloud, that can be used to create a topographic model. A topographic model, such as a digital elevation model (DEM), represents continuous elevation data summarized into raster cells, or pixels, of a given spatial resolution. The resolution of the topographic model is user-defined but is generally based on point density of the point cloud, with the mean point density used to inform appropriate raster cell size. Point density within the overlapping survey areas for all periods are ≥400 points per square meter. This minimum point density provides sufficient data to produce 5-cm (cm) pixel resolution DEMs. Topographic change detection between each consecutive pair of repeat DEMs is performed using Wheaton et al.'s (2010) geomorphic change detection tool (GCD 7; available at http://gcd.riverscapes.xyz) to create a DEM of difference (DoD) that represents spatially continuous inter-survey elevation shifts between two survey DEMs, providing a measure of pixel-by-pixel erosion (i.e., landscape lowering or loss of material) or deposition (i.e., landscape raising or gain of material). Topographic change results from Caster et al. (2022) are summarized for each site as annual mean change in surface elevation normalized by the area of the archaeological site; negative values indicate erosion of the site, whereas positive values indicate aggradation, and thus burial from sediment deposition on the site.

3. Results

3.1. *Aeolian classification changes*

The number of Type 1 sites (those with the highest likelihood of receiving wind-blown sand from fluvial sandbars) decreased over each monitoring interval, from 98 in 1973 to only 4 in 2021–22 (Fig. 10). In 2021–22 there are an additional 7 Type 1*vr* sites that have maintained the Type 1 site characteristics owing to site-specific vegetation management efforts implemented between 2019 and 2022 by the National Park Service (Pilkington et al., 2022); without the vegetation management work, these 7 sites would likely now instead be classified as Type 2 or 3. Most of the sites that were Type 1 in 1973 transitioned over time to Type 2 or 3 sites, primarily due to the expansion of riparian vegetation onto subaerial sandbars throughout the river ecosystem. Riparian vegetation can either create a barrier to aeolian sand transport from sandbars to archaeological sites in the case of Type 2a and Type 2c sites, or it can completely cover the subaerial sandbar deposit such that there is no longer a source area for aeolian sand supply, thus resulting in a site being classified as Type 3. Consequently, many sites that were classified prior to 2021–22 as one of the three subcategories of Type 2 sites, owing to the presence of a riparian and/or topographic barrier to aeolian sand transport, later transitioned to Type 3 sites owing to continued vegetation expansion (Fig. 10) and to alterations of the shoreline geomorphology resulting from the increased vegetation cover on the riverbanks. The number of sites classified as Type 3 increased from 27 in 1973 to 148 in 2021–22 primarily due to this vegetation growth. The sites currently classified as Type 2A*vr* (3), 2b*vr* (3), and 2c*vr* (2) in 2021–22 would all probably instead have the characteristics of Type 3 sites if not for site-specific vegetation management efforts implemented between 2019 and 2022 by the National Park Service (Pilkington et al., 2022).

3.2. *Drainage classification changes*

The proportion of sites without drainages has decreased from 2000 to 2021–22 and the proportion of sites with drainages integrated with mainstem tributaries or the Colorado River channel has increased during that time, indicating an overall increase in sites affected by gullying processes (Fig. 11). For example, from 2016–17 to 2021–22, 16 Type D1 sites developed drainages. A small number of sites transitioned from having terrace-based (Type D2) or river-based (Type D4) drainages in 2000 to not having drainages in 2016–17 owing to fluvial or aeolian

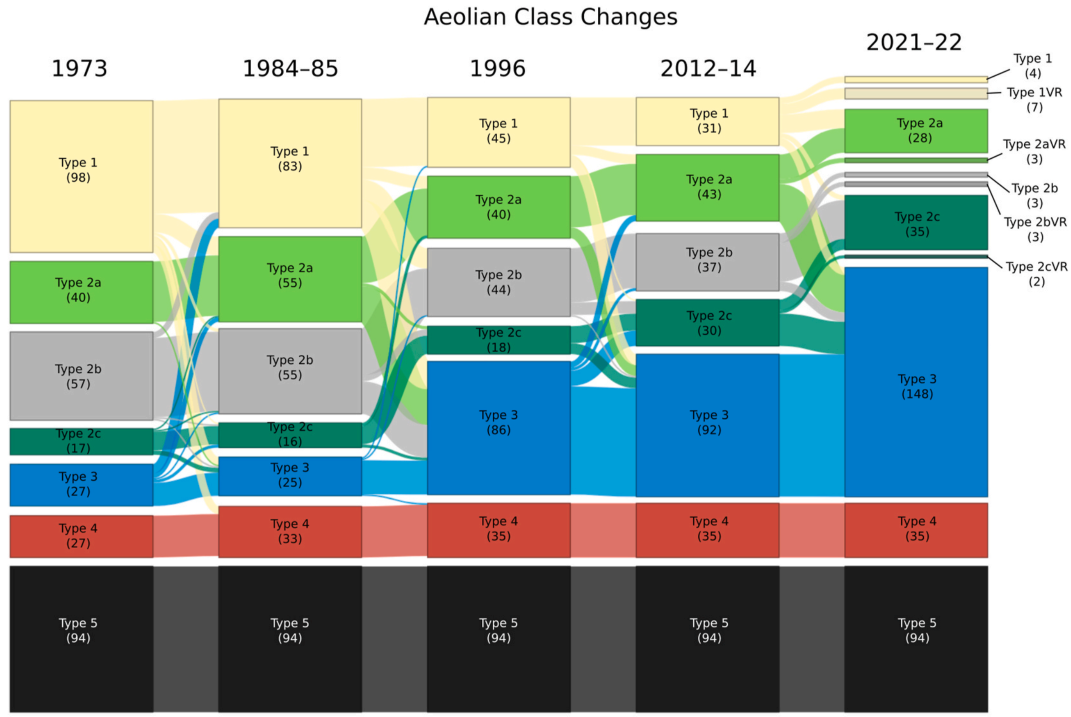

Fig. 10. Sankey diagram of aeolian class changes over time for 362 archaeological sites in the Colorado River corridor, Grand Canyon National Park. Interpretations of site type for 1973, 1984–85, and 1996 were based on examination of aerial photographs; classifications for 2012–14 and 2021–22 were based on a combination of field visits and aerial photographs.

sediment backfilling of the drainages (gully annealing, *sensu* Sankey and Draut, 2014; see also examples in Fig. 5 photos). However, the majority of changes in site classifications indicate the progressive development of new drainages and the downcutting of existing drainages to lower base levels (e.g., terrace to side-canyon or river) over time, indicating increasing erosion and greater future erosion potential for the archaeological site (see examples in Fig. 5 photos). As of 2021–22, 41 sites have side-canyon based drainages and 98 have river-based drainages (Fig. 11). These sites are effectively at the evolutionary endpoint of drainage development because they are graded to the lowest local base level possible for their respective locations, but the drainages could still erode additional sediment by widening and further headcutting (regressive erosion). In 2021–22, 117 sites do not have drainages (Fig. 11) and these sites may or might not be vulnerable to the development of new drainages in the future, depending on the specific geomorphic setting and future storm rainfall. However, 106 sites in 2021–22 have terrace-based drainages that could downcut and become integrated with the base-level of the river in the future; Type D2 sites

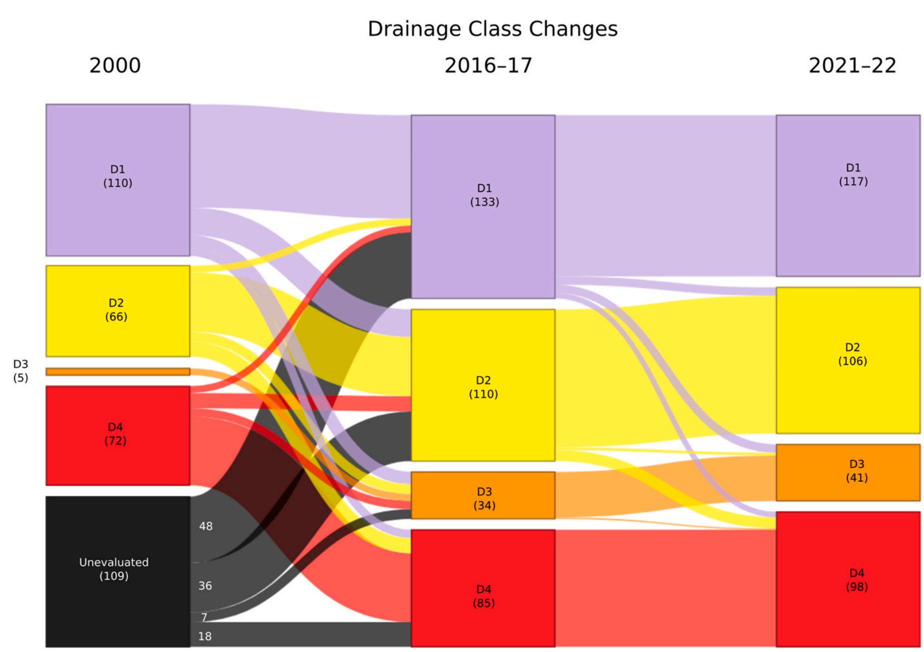

Fig. 11. Sankey diagram of drainage class changes, based on field assessments of archaeological sites in 2000, 2016–17, and 2021–22.

represent the intermediate stage of drainage development in the system.

3.3. Cross-walking the aeolian and drainage classification changes

None of the 362 sites transitioned to a less-degraded site condition based on aeolian and drainage classification change results from 2012–14 to 2021–22 or from 2016–17 to 2021–22, respectively (Fig. 12). We found that 246 of the 362 sites did not change type in either classification system for the same time periods, whereas 89 and 20 of the 362 sites transitioned to a more degraded state with respect to aeolian or drainage classification results, respectively (Fig. 12). Seven of the 362 sites transitioned to a more-degraded state with respect to both classification systems. Sites that transitioned to a more degraded state in both classification systems are eroding from gullying processes and have a decreased potential for influx of windblown river sand that might otherwise help to offset that erosion by infilling gullies (Sankey and Draut, 2014). Thus, the potential for *in-situ* preservation of those seven sites notably decreased during the relatively short time periods of less than one decade.

3.4. Quantitative assessment of topographic changes at select archaeological sites

Lidar remote sensing for the decade from 2010 to 2020, as documented by Caster et al. (2022), reveals patterns of topographic change at a sample of 13 archaeological sites (Fig. 13). Sites that underwent net erosion during this time frame occur in each of the observed combinations of aeolian and drainage classifications. Specifically, two of the four Type 1 sites, two of the five Type 2 sites, and two of the three Type 3 sites monitored with lidar underwent substantial erosion, as did the one Type 4 site that was monitored. Thus, sites that incurred net aggradation owing to burial by the aeolian deposition of river-sourced sediment most

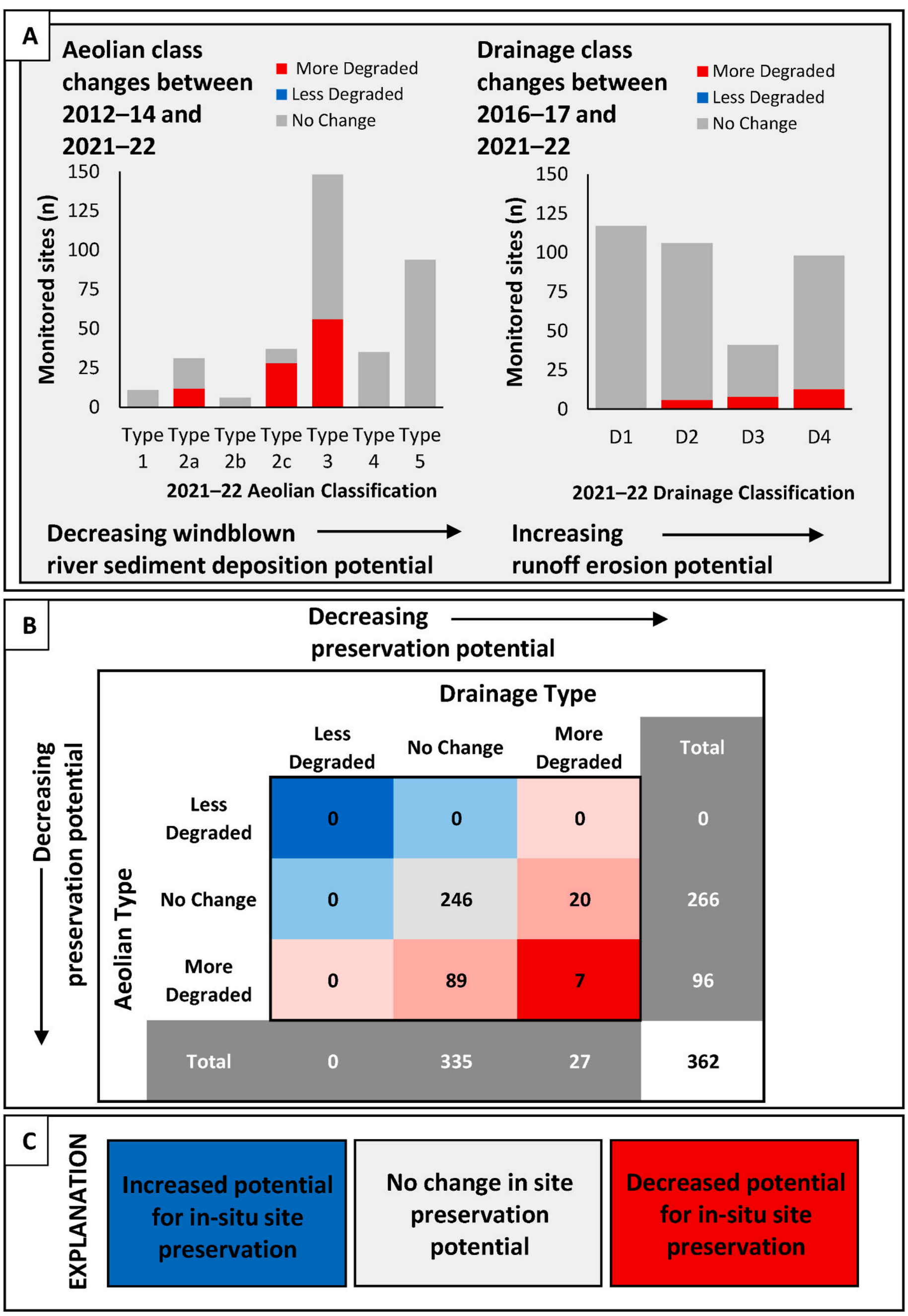

Fig. 12. Bar plots and matrix summarizing recent changes in archaeological site preservation potential owing to site class changes. (A) Aeolian class changes from 2012–14 to 2021–22, and drainage class changes from 2016–17 to 2021–22. (B) Matrix cross-walking the aeolian and drainage classification results from panel A. (C) Interpretative legend for the color-coding scheme used in the matrix in panel B, which illustrates effects of class changes on the management goal to maintain or improve site integrity *in situ*.

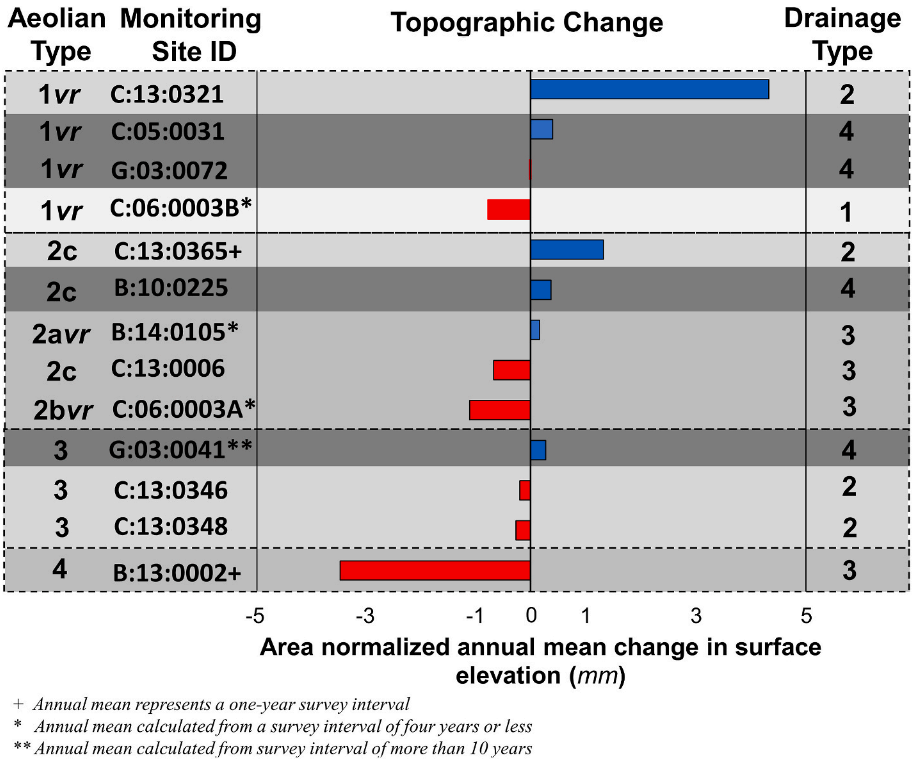

Fig. 13. Topographic changes for select sites derived from repeat lidar surveys conducted between 2010 and 2020, reported by Caster et al. (2022). The topographic changes are expressed as the mean elevation change (in mm) normalized by the area of the archaeological site. Negative values (red) indicate net erosion, whereas positive values (blue) indicate net deposition and thus burial by sediment. Sites are grouped by aeolian and drainage classification determined in 2021–22. Figure reproduced with minor modifications and permission from Caster et al. (2022). The different hues of gray are used to distinguish different combinations of aeolian and drainage type classes.

commonly are Type 1 or 2 aeolian classification sites; this provides support for the conceptual model on which the classification system was derived, namely that wind-transported river sand plays a role in protecting sites from progressive erosion. Previous work with topographic change detection from lidar remote sensing has also shown that many sites have eroded at times during the decade, but those sites that have aggraded tended to be located adjacent to and downwind of river sandbars that are periodically resupplied with sand by controlled river floods and which in turn provide a consistent source of wind-blown sediment supply to downwind archaeological sites (Collins et al., 2016; East et al., 2016; Sankey et al., 2018b).

4. Discussion

4.1. Long-term changes to archaeological sites during the period of dam operations

Grand Canyon National Park was established in 1919 to preserve an iconic landscape. Here we use a record of 50 years of aerial imagery since 1973, and more than 30 years of field investigations since the early 1990s, to describe long-term geomorphic changes to archaeological sites attributed to the effects of the operations of Glen Canyon Dam since 1963 on the Colorado River in Grand Canyon National Park. Of the 362 river-corridor archaeological sites, 268 occur within or on fluvial or originally river-sourced aeolian sediment. Thus, these 268 sites, i.e., three-fourths of the river-corridor archaeological sites in our study area, depend on river-derived sand for their geomorphic context. Findings indicate that, after six decades of changes in river-corridor sediment supply and distribution due to dam operations, the great majority of river corridor archaeological sites are eroding. In the past decade alone – since 2012 – 116 of the population of 362 river corridor archaeological sites (32% of sites) have transitioned to a more degraded condition with increased risk for erosion and decreased potential for *in-situ* preservation (Fig. 12). The increased erosion decreases the tenability of the primary objective of environmental management of archaeological sites and cultural resources in Grand Canyon National Park, which is to maintain the integrity of historic and prehistoric sites *in situ*. This means that mitigation actions such as local site modifications to control erosion, or excavation to record feature information before it is lost to erosion, are likely to become increasingly necessary in the future if trends in landscape changes observed since the closure of Glen Canyon Dam (Figs. 10–12) continue.

Recent decline in site condition is apparent in both the drainage and aeolian classification results. The proportion of archaeological sites without drainages such as gullies (or arroyos) has decreased from 43% of 253 sites in 2000, to 37% of 362 sites in 2016–17, and to 32% in 2021–22. The proportion of sites with drainages has increased from 56% to 63%–68% during that time (2000 to 2016–17 to 2021–22), indicating an overall increase in sites affected by gully erosion processes (Fig. 11). Since 1973, the potential for influx of windblown river sand that can potentially offset the erosion by gullying processes has decreased for almost all archaeological sites, such that as of 2021–22 only four out of 362 sites can receive windblown river-sourced sand from an upwind subaerial sandbar, unimpeded by a barrier of riparian vegetation, and without site-specific management to reduce or remove the vegetation barrier (Fig. 10). Cross-walking the classification results (Fig. 12) demonstrates that many sites are eroding and increasingly starved of sand inputs that can potentially slow down or offset erosion, either by maintaining aeolian sand deposits or annealing gullies that develop from overland-flow erosion. However, the classification results do not indicate quantitatively by how much individual sites change topographically owing to erosion or deposition of sediment. Lidar-derived topographic change detection at a subset of sites during the decade from 2010 to 2020 suggests that wind-transported river sand plays a key role in protecting sites from progressive erosion (Caster et al., 2022), as the sites in Fig. 13 that experienced new deposition gained that sediment from aeolian deposition. It is important to note that the sites in the subset investigated with lidar were not a random sample of the population but instead were selected based on geomorphic activity and membership in specific aeolian and drainage class categories, to examine those processes in detail (Caster et al., 2022).

4.2. Environmental management for in-situ preservation of archaeological sites

There are opportunities for resource managers to increase the potential for *in-situ* preservation of archaeological sites. One environmental management opportunity in Grand Canyon National Park is the use of dam-controlled river floods, which when conducted consecutively, on an annual basis, have been shown to cumulatively increase the deposition of windblown sand from river sandbars at some archaeological sites (Sankey et al., 2018b) and anneal gullies formed by overland-flow erosion (Sankey and Draut, 2014; Collins et al., 2016). Deposition of sediment provides a protective cover to archaeological materials that reduces surface weathering (Ferring, 1986). A second opportunity is the implementation of periodic low river flows, which when conducted over a period of as short as 2–3 consecutive days to allow previously inundated sediment to dry – especially during the spring or summer windy seasons – have the potential to expose and entrain large volumes of aeolian sediment (Sankey et al., 2022), thus increasing the potential for transport and deposition of sediment within archaeological sites. In simple terms, implementation of periodic low river flows could transition numerous Type 3 sites (Fig. 8) to Type 2 sites, simply by virtue of exposing large open sand surfaces adjacent to the site which are currently inundated by the river.

A third opportunity is site-specific vegetation management to remove the barriers to aeolian sediment transport from the river channel toward archaeological sites created by unnaturally large amounts of vegetation encroaching on river sandbars in the absence of major floods (Pilkington et al., 2022). There are analogous examples to this vegetation management in coastal aeolian dune landscapes around the world. In New Zealand, for example, the occupation of coastal landscapes by ancestral Maori people is documented in archaeological sites buried within dunefields (Hilton et al., 2018; Hilton and Konlechner, 2021). In the 20th and 21st centuries, invasion by Marram Grass (*Ammophila* spp.) on foredunes and beaches reduced the windblown transport of beach sand to the dunefields, causing archaeological sites to emerge and erode due to aeolian deflation of the dunefields under the sand-starved conditions (Hesp and Hilton, 2013; Hilton et al., 2018; Hilton and Konlechner, 2021). Repeat annual herbicide applications to kill Marram Grass were successful to increase the aeolian sand transport from beaches to dunes and keep archaeological sites buried by sand (Konlechner et al., 2014; Hilton and Konlechner, 2021). In the Netherlands, coastal foredunes invaded by Marram Grass were mechanically altered using an excavator to dig the grass out of the dunes and at the same time reshape the dunes to create blowouts that would function as erosional features to supply sand to downwind dunefields (Arens et al., 2013; Konlechner et al., 2014). The Netherlands applied-geomorphology work has been ongoing since the 1990s in adaptive science and management aimed at restoring coastal dunefields to a more natural and biologically diverse ecosystem state (Arens et al., 2013; Konlechner et al., 2014).

In Grand Canyon, seven of the 11 sites currently classified as best-case-scenario Type 1 sites with the greatest potential for influxes of windblown river sand are only so by virtue of experimental vegetation removal treatments on sandbars, which have been implemented by the NPS in conjunction with the USGS annually since 2019 (Pilkington et al., 2022). The experimental design underlying that vegetation management project is testing the hypothesis that the combination of controlled river floods and site-specific vegetation removal will increase the preservation potential of sites located in aeolian sediment deposits (Pilkington et al., 2022). However, owing to policy changes and perceived threats from invasive fish species and drought in the river basin, a controlled river flood has not been implemented since 2018, and thus the combined effects of controlled flooding and vegetation removal have yet to be evaluated.

A potential future avenue for increasing the *in-situ* preservation potential of archaeological sites that warrants additional research is the construction of erosion-control structures (checkdams) within gullies. In the 1990s and early 2000s, the NPS and their Tribal partners constructed rock and brush checkdams in numerous gullies at archaeological sites in Grand Canyon. Pederson et al. (2006) subsequently studied 25 gullies at 9 archaeological sites over a two-year period and concluded that some checkdams did reduce erosion, at least for short periods of time. However, Pederson et al. (2006) also concluded that continued maintenance of the erosion-control structures is imperative, because a checkdam that is damaged – for example by a large rainfall-runoff event or by human visitors – can actually increase erosion in the gully. The Pederson et al. (2006) study did not distinguish the site-specific geomorphic conditions that contributed to successful erosion control management outcomes. For example, it has been anecdotally observed in subsequent years that effective checkdams tend to be located at sites where connectivity to aeolian sand supply has been maintained. Currently the NPS monitors existing checkdams to ensure there is no additional channel development or exposure of cultural materials, conducting maintenance as needed. Additional future research could help to determine the specific geomorphic circumstances in which checkdams of various types are most effective at controlling gully erosion.

In addition to environmental management aimed at increasing the *in-situ* preservation potential, archaeological site excavations are a final option to record site characteristics and document site information before it is lost to erosion, though this is a last resort if *in-situ* preservation efforts are unsuccessful. The NPS and their partners have conducted excavations in past years to mitigate the effects of dam operations and other sources of impacts on archaeological sites in the Colorado River corridor in Grand Canyon (Pederson et al., 2011; Neff et al., 2016) and additional excavations are being considered (U.S. Department of Interior, 2020).

4.3. Summary and ways forward

We conclude that most of the river-corridor archaeological sites are eroding owing to complex effects of geomorphic process interactions initiated by dam operations that began in 1963. However, environmental management options could be applied to a greater extent to slow the observed site degradation. In the present flow regime, controlled floods do not simulate the magnitude or frequency of natural floods, which formerly supplied sand that, when remobilized by wind, covered and maintained the geomorphic context at three-quarters of the river-corridor archaeological sites in Grand Canyon. Floods of 4800 m^3/s and greater would be necessary to deposit sediment on most terraces that contain archaeological sites, as shown by discharge-elevation models (Magirl et al., 2008; Sondossi and Fairley, 2014). The last flood to attain a discharge of 4800 m^3/s occurred in 1921. That 1921 flood had an estimated return interval of 40 years in the pre-dam Colorado River hydrology (Topping et al., 2003). Dam-controlled floods have been implemented episodically since 1996 with discharges $\leq$1274 m^3/s, which are not large enough to deposit sand at elevations that were typically flooded at annual to decadal intervals in pre-dam time. Although those controlled floods can rebuild sand bars at lower elevations (Grams et al., 2015), and these bars can then serve as source areas for aeolian sand to transport inland to higher-elevation areas where most archaeological sites are located (East et al., 2016; Sankey et al., 2018b), the relatively small dam-controlled floods cannot deliver new sand directly to archaeological-site locations that would receive fluvial sand deposition from floods on the scale of 4800 m^3/s.

For archaeological sites that depend upon river-derived sand for their geomorphic context, the elevated erosion risk inferred from our long-term site classification change results is due to a combination of reduced sand supply (both fluvial and aeolian) through: (1) the lower-than-natural flood magnitude, frequency, and sediment supply of the controlled-flooding and other current flow-operation protocols; (2) inconsistency in the implementation of controlled floods (magnitude, seasonality, and frequency); (3) reduction of open, dry sand area available for wind redistribution under current normal (non-flood) dam operations, which do not include flows as low as natural seasonal low flows and do include substantial daily flow fluctuations; (4) infrequency of controlled floods and low flows (i.e., 2 and 3 in this list) during the spring or summer windy seasons; and (5) impeded aeolian sand entrainment and transport owing to increased riparian vegetation growth.

If dam operations were to increase the supply of sand available for windblown transport—for example, through more frequent controlled floods, or increased subaerial exposure of sandbars by low flows during the dry, windy seasons—and if resource managers were to continue targeted efforts to decrease riparian vegetation, the prevalence of active aeolian sand could increase over time, and the propensity for unmitigated gully erosion could decrease. Over the past few centuries, river-derived sediment forming the substrate and cover for many archaeological sites resulted from relatively rare (multidecadal) return-interval floods, and their complete absence in the post-dam era means that the geomorphic context of some archaeologically-rich areas of the canyon cannot be restored by the much smaller ($\leq$1274 m^3/s) controlled floods that have been conducted since 1996 (Draut, 2012; East et al., 2016). Additional alterations of the natural landscape processes and sand movement in the river corridor result from the lack of seasonal low flows. River discharges below 226 m^3/s commonly occurred in both wetter and drier water years during the pre-dam period. For example, flows below 226 m^3/s occurred more than 20% of time in the higher water year of 1927 and approximately 85% of the time in the lower water year of 1934 (U.S. Geological Survey, 2022). The expansion of dense stands of riparian vegetation on sandbars and channel margins during the first five decades of dam operations that increased the area covered by riparian vegetation by factors of two or three (Sankey et al., 2015) and created barriers to aeolian transport of river-sourced sand is another major impact to natural landscape processes and sand movement in the river corridor. However, some combination of sediment-rich flows above 1270 m^3/s, extended periods with consecutive daily flows below 226 m^3/s, and riparian-vegetation removal would likely increase the preservation potential for sand-dependent archaeological resources in the Colorado River corridor.

5. Conclusion

This assessment of the condition of 362 river-corridor archaeological sites marks the 60th anniversary of the closure of Glen Canyon Dam, which imposed drastic changes to river flow, sediment supply and distribution, and riparian vegetation in the Colorado River corridor through Grand Canyon National Park. We have drawn on 50 years of evidence to make this assessment and compile inferences for the environmental management of the risk of erosion of irreplaceable cultural resources: aerial photographs dating back to 1973, and more than 30 years of field observations and measurements of archaeological-site topography and wind patterns since the early 1990s. We find that most archaeological sites in Grand Canyon National Park along the Colorado River are eroding, and at increased environmental risk of erosion, from six decades of operations of Glen Canyon Dam.

Three-quarters of the river-corridor archaeological sites in Grand Canyon National Park depend on river-derived sand for their geomorphic context and the vast majority of those are now deprived of sand resupply in the modern, dam-controlled river system. Results of an aeolian geomorphology-based site classification show that the wind-driven supply of river-derived sand, essential for covering sites and maintaining their geomorphic context, has decreased for most archaeological sites since 1973 owing to effects of long-term dam operations on river sediment supply and riparian vegetation expansion on sandbars. Results of a drainage geomorphology-based site classification show that the proportion of sites affected by gullying processes controlled by the base-level of the Colorado River in Grand Canyon has increased since 2000. These fundamental changes to landscape processes affecting archaeological site context and integrity limit the ability of the National Park Service to achieve environmental management goals to maintain or improve site integrity *in-situ*.

Archaeological site monitoring illustrates some of the negative impacts of human river management and gully erosion on site condition and the physical integrity of prehistoric and historic archaeological sites. Monitoring and research demonstrate that windblown river sand can help to offset erosion impacts on archaeological site condition. Targeted riparian vegetation removal may provide an environmental management opportunity to increase windblown sand supply from sandbars to archaeological sites, and thus increase *in-situ* preservation potential on a site-specific basis. The effectiveness of vegetation management might theoretically be increased when coupled with controlled river flooding to rebuild sandbars, or with periodic low river flows to expose sandbars, which in both cases are the sources of windblown sediment supply; however, these experimental management actions have yet to be implemented in combination in the same year in Grand Canyon. Barring environmental management actions to increase *in-situ* preservation potential, sites along the Colorado River will continue to erode, leaving site-specific excavations as the only remaining option for preserving archaeological site information before it is lost, although this approach falls short of stated environmental-management goals.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used for this investigation will be made openly available in a USGS data release published at the time of journal publication of the article: Sankey, J.B., East, A., Caster, J., Fairley, H., Dierker, J., Brennan, E., Pilkington, L., Bransky, N., Kasprak, A., 2023. Aeolian and Drainage Classification Data for Various Archaeological Sites in Grand Canyon National Park along the Colorado River from 1973 to 2022. U.S. Geological Survey data release. doi:10.5066/P9X9ZDPK.

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