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Gully annealing by aeolian sediment: field and remote-sensing investigation of aeolian–hillslope–fluvial interactions, Colorado River corridor, Arizona, USA☆

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ABSTRACT

Processes contributing to development of ephemeral gully channels are of great importance to landscapes worldwide, and particularly in dryland regions where soil loss and land degradation from gully erosion pose long-term land-management problems. Whereas gully formation has been relatively well studied, much less is known of the processes that anneal gullies and impede their growth. This study of gully annealing by aeolian sediment, spanning 95 km along the Colorado River corridor in Glen, Marble, and Grand Canyon, Arizona, USA, employed field and remote sensing observations, including digital topographic modelling. Results indicate that aeolian sediment activity can be locally effective at counteracting gully erosion. Gullies are less prevalent in areas where surficial sediment undergoes active aeolian transport, and have a greater tendency to terminate in active aeolian sand. Although not common, examples exist in the record of historical imagery of gullies that underwent infilling by aeolian sediment in past decades and evidently were effectively annealed. We thus provide new evidence for a potentially important interaction of aeolian–hillslope–fluvial processes, which could affect dryland regions substantially in ways not widely recognized. Moreover, because the biologic soil crust plays an important role in determining aeolian sand activity, and so in turn the extent of gully development, this study highlights a critical role of geomorphic–ecologic interactions in determining arid-landscape evolution.

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1. Introduction

Erosion of landscapes by ephemeral gully development is a major problem worldwide, particularly in arid and semi-arid ecosystems where the protective presence of vegetation can be scarce (Wainwright et al., 2011; Turnbull et al., 2012; D'Odorico et al., 2013). The causes of gully formation and enlargement have long interested geomorphologists, both from a theoretical standpoint (Bryan, 1925; Patton and Schumm, 1975; Vandaele et al., 1996; Sidorchuk, 1999; Vandekerckhove et al., 2000; Simon and Rinaldi, 2006; Le Roux and Sumner, 2012) and because soil erosion and landscape degradation associated with gullies pose serious land-management concerns in drylands globally (Antevs, 1952; Heede, 1978; Halvorson et al., 1988; Graham, 1992; Casali et al., 1999; Meadows, 2003; Ghimire et al., 2006; Bou Kheir et al., 2007; Zhu, 2012).

For timescales relevant to present-day land managers and in the absence of direct site-specific management efforts, the gully formation process is generally considered unidirectional (non-reversible) once initiated, and the future persistence of gullies on the landscape is considered unavoidable (Patton and Schumm, 1975; Heede, 1978; Graham, 1992; Sidorchuk, 1999; Ghimire et al., 2006; Le Roux and Sumner, 2012). There has been little investigation into how indirect (higher order) linkages between other geomorphic processes might forestall and/or change the trajectory of gully formation or anneal gullies entirely; annealing processes are mechanisms by which gully formation is impeded or reversed (Waters and Haynes, 2001; McIntosh et al., 2004; Xu et al., 2006; Mazaeva et al., 2011). From a purely physically-based perspective, countering the gullying processes requires that sediments accumulate instead of erode from the gully. This can occur when the hillslope processes responsible for gully formation are directly altered and shift from predominantly erosional to depositional, such as when local base level changes within the gully itself (Hereford et al., 1993). This might also occur when external geomorphic processes produce a sediment source, transport mechanism, and depositional setting within the gully that collectively exceed the rate and/or frequency of gullying (McIntosh et al., 2004; Xu et al., 2006; Mazaeva et al., 2011).

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Although many studies have investigated factors that contribute to gully initiation and enlargement, which occurs largely from rainfall-runoff events and can include contribution from subsurface flow (Faulkner et al., 2004; Tebebu et al., 2010; Svoray et al., 2012), few studies have addressed processes of gully annealing. The few literature references to gully and arroyo annealing discuss alluvial cutting and filling episodes related to climate variability and land use (Waters and Haynes, 2001; Mazaeva et al., 2011) but focus primarily on erosion, such that relatively little is known about processes that anneal gullies and therefore impede or counteract their growth. In this paper, we investigate the effectiveness of gully annealing by aeolian sediment activity through a field and remote-sensing study in the semi-arid Colorado River corridor, southwestern USA. In the Colorado River corridor, previous work has demonstrated through measurement of transport processes, rates, and topographic change, that fluvial sand in some locations is transported inland and upslope by aeolian processes to areas affected by gully erosion (Collins et al., 2009, 2012; Draut et al., 2010a; Draut, 2012). In this paper, we evaluate effects of these process interactions at a landscape-scale context and over a large spatial extent. Here, we consider gullies to be channels on the order of 10^0–10^1 m wide and deep that likely formed primarily by ephemeral, rainfall-induced overland flow eroding through Holocene and younger sediment. It has been recognized previously that aeolian sediment can infill gullies of such size, potentially reducing net landscape erosion (McIntosh et al., 2004; Xu et al., 2006), but there have been no systematic studies on the ability of aeolian sediment to limit gully erosion on a landscape scale.

1.1. Objectives

The prevalence of gullies in areas with and without active aeolian sand transport were examined. Gullies were defined topographically as features on hillslopes with the potential to function as overland flowpaths and with concave across-slope shape that could be indicative of sediment transport and erosion by gullying processes. We focused detection of these topographic features characteristic of gullies within and adjacent to geomorphic surfaces comprised of Colorado river-derived sediment that was relatively active or inactive with respect to aeolian transport, and in adjacent surfaces of slopewash (alluvial) parent materials. We defined active aeolian sand as having evidence for contemporary transport, such as wind-rippled surfaces and, locally, slipfaces at the angle of repose (Lancaster, 1994). Sediment surfaces that are inactive with respect to aeolian transport lack those features and, in the Colorado River corridor, contain substantial biologic soil crust and vegetation (Draut, 2012).

The objective of this study was to evaluate whether gully annealing by aeolian sediment may represent an important interaction among hillslope, fluvial and aeolian processes that affects dryland landscape evolution substantially in ways not yet widely recognized (cf. Field et al., 2009; Ravi et al., 2010; Belnap et al., 2011; Sankey et al., 2012a). We refer here to Colorado River flows and sediment as 'fluvial', and to localized, gully-forming, slope-runoff flows and sediment as 'hillslope' or 'alluvial'. This landscape scale, observational study was designed to examine the prevalence of the spatial intersection of aeolian sediment and gullied topography in order to test the following hypotheses: (1) hillslope flowpaths with concave across-slope shape (i.e., topographic features with potential to function as gullies channeling overland flow, henceforth "potential gullies") are more evident in areas where sediment is inactive with respect to aeolian transport; (2) potential gullies terminate more commonly in active aeolian sand; and (3) the historical record contains evidence of gullies that have annealed over time and so are less evident today than in the past.

To evaluate the role of aeolian sediment in gully development and annealing, we examined large reaches of the Colorado River corridor, southwestern USA (Fig. 1). There, dryland sedimentary and geomorphic processes occur over a large landscape scale essentially without anthropogenic disturbance other than river regulation (discussed below); the >300 km-long river corridor is a wilderness area, without roads or other urban development, where gully erosion and aeolian sediment transport are common, important landscape processes (Pederson et al., 2006; Collins et al., 2009; Draut, 2012; Hereford et al., 2014). Sedimentary, geomorphic and ecologic processes of the Colorado River landscape setting are sufficiently representative of many other dryland areas that the links between gullies and aeolian sediment investigated here likely apply well beyond this particular field setting. The extent of gullies through sedimentary deposits and controls on gully development are particular land-management concerns in the Colorado River corridor because gullies erode irreplaceable archaeological sites, and because earlier studies indicated that gully development could be linked to dam operations (Hereford et al., 1993; Thompson and Potochnik, 2000).

2. Regional setting and previous work

The Colorado River basin drains 637,000 km^2 in an arid to semi-arid region where large dams provide water storage (Fig. 1). Glen Canyon Dam, 216 m tall, impounds the second-largest reservoir in the US, Lake Powell. Since the closure of Glen Canyon Dam in 1963, the hydrology and sediment supply downstream in Glen, Marble and Grand Canyons, Arizona, have changed substantially (Topping et al., 2000, 2003; Rubin et al., 2002; Gloss and Coggins, 2005b; Hazel et al., 2006). The dam has reduced the fluvial sediment supply to upper Marble Canyon by >90 % (Topping et al., 2000). Without natural floods, the river does not deposit fluvial sediment at elevations that received it regularly before dam closure. Owing to the loss of sediment supply and reduction in the magnitude and frequency of floods, and to increased riparian vegetation without large floods, there has been a system-wide decrease in the size and number of subaerially exposed fluvial sand deposits downstream of Glen Canyon Dam since the 1960s (Turner and Karpiscak, 1980; Beus et al., 1985; Schmidt and Graf, 1990; Kearsley et al., 1994; Gloss and Coggins, 2005a; Hazel et al., 2010). Sand bar decline has been punctuated by episodic aggradation during occasional higher flows, such as occurred in 1983–1985, in controlled floods of 1996, 2004, 2008, 2012 and 2013, and by tributary sediment input (e.g., Hazel et al., 2010). During the controlled floods, intended to rebuild fluvial sand bars, 60-hour flows of 1,160–1,270 m^3/s can successfully increase sand bar area and volume (Hazel et al., 2010; Melis, 2011; Melis et al., 2012). However, the controlled-flood magnitudes (≤1,270 m^3/s) are less than half of the pre-dam mean annual flood peak (2,400 m^3/s) and only one-fifth as large as the maximum historic pre-dam flood (5,940 m^3/s, in 1884; Topping et al., 2003); the largest flood in the stratigraphic record may have been as great as 8,490 m^3/s (O'Connor et al., 1994; Topping et al., 2003). The controlled flooding therefore did not simulate the frequency or magnitude of natural Colorado River floods and did not inundate many riparian areas that were flooded often before river regulation (Turner and Karpiscak, 1980; Magirl et al., 2008).

The loss of fluvial sediment downstream from Glen Canyon Dam substantially decreased the windblown sediment supply to source-bordering aeolian dunes (Draut, 2012). Many such aeolian dune fields occur in the Colorado River corridor, particularly in Marble and Grand Canyons, each covering 10^3–10^4 m^2. In post-dam times, some aeolian-sediment landscapes receive episodic sediment supply after controlled flooding, i.e., those landscapes directly downwind of modern sand bars deposited by controlled floods. However, many aeolian landscapes in this canyon have no modern, controlled-flood sand bar (shoreline) upwind, and therefore receive essentially no aeolian sediment supply today (Magirl et al., 2008; Draut, 2012). Stratigraphy within those dune fields shows that they formed as the wind reworked sediment left by pre-dam floods decades or centuries ago that were larger than any post-dam flows have been (Hereford, 1996; Draut and Rubin, 2008; Anderson and Neff, 2011). River regulation thus reduced sediment sources to aeolian landscapes, largely by eliminating floods but

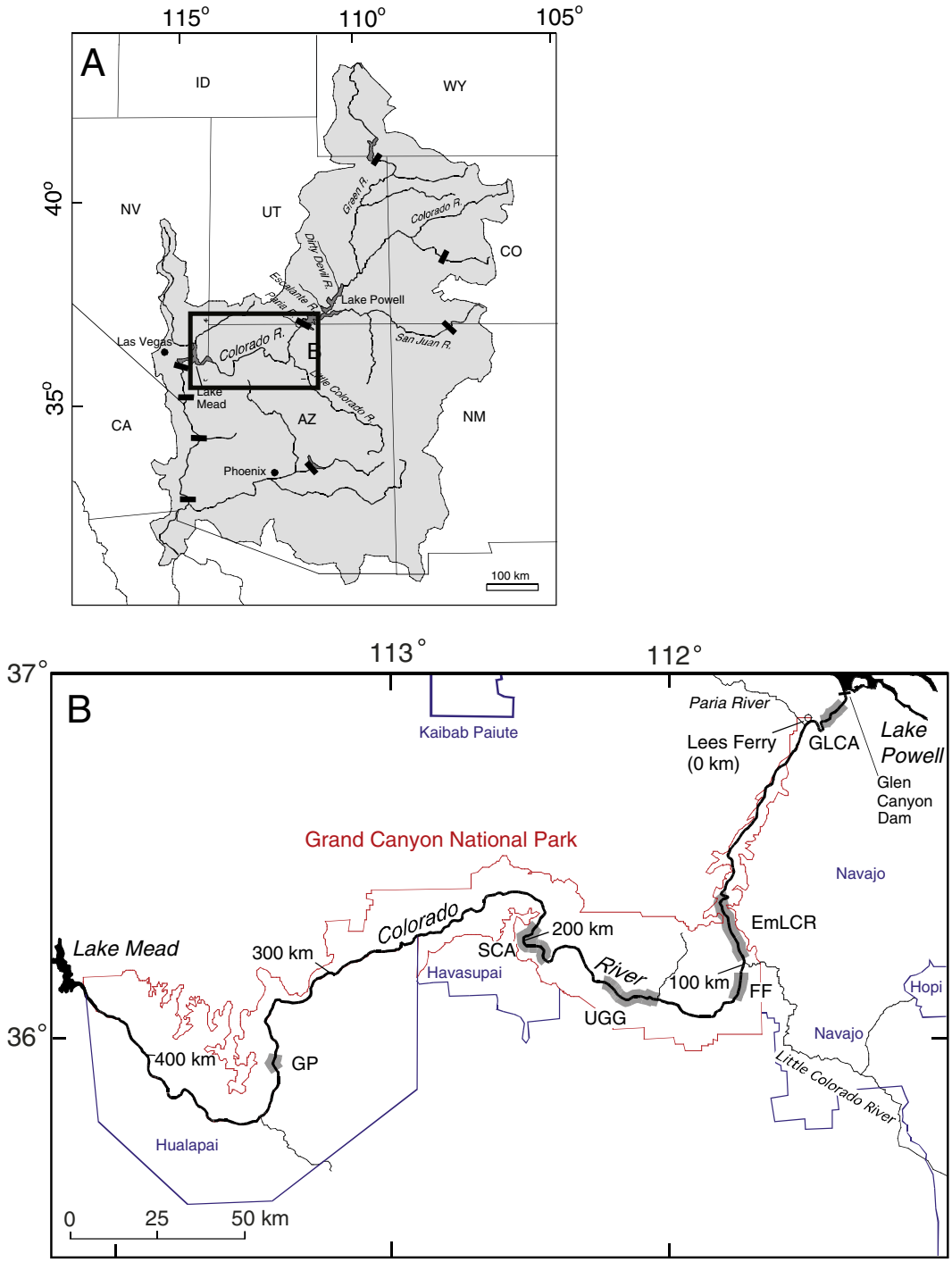

Fig. 1. Location map showing (A) the Colorado River watershed, with major dams indicated by black bars. Box indicates area shown in (B); (B) the Colorado River corridor through Glen, Marble, and Grand Canyon. Glen Canyon Dam is shown at top right; river flow is from northeast toward southwest. Names of study reaches, with their locations in river-km relative to Lees Ferry (by convention in Colorado River research) are abbreviated as: Glen Canyon (GLCA, −24.1 to −9.6 km), Eminence-Little Colorado River (EmLCR, 70.8–98.2 km), Furnace Flats (FF, 106.2–115.9 km), Upper Granite Gorge (UGG, 140.0–159.3 km), Stevens/Conquistador Aisle (SCA, 186.7–206.0), and Granite Park (GP, 333.1–338.0 km). Grand Canyon National Park boundaries are shown in red, tribal reservation lands outlined in blue, in the color version of the figure.

also by eliminating low flows (<100 m^3/s) that would have exposed additional fluvial sediment to wind. Aeolian landscapes in the river corridor that are decoupled from modern sediment supply have significantly more biologic crust cover and less aeolian sand-transport activity than do dune fields that remain coupled to modern fluvial sediment supply (Fig. 2; Draut, 2012). The proportion of uncrusted, active aeolian sand area is substantially lower in the regulated river corridor below Glen Canyon Dam than in a much less regulated reach above the dam (Draut, 2012).

Hereford et al. (1993) and Thompson and Potochnik (2000) proposed that gully incision into Colorado River sediment deposits may be exacerbated by dam operations because the lack of large floods in the dammed system lowered the base level to which gullies grade and also prevented fluvial sediment from filling gullies that naturally form during rainfall events. Gully erosion in many parts of Glen, Marble and Grand Canyon has damaged archaeological sites within and on the surfaces of river-corridor fluvial and aeolian deposits (Balsom et al., 2005; Pederson et al., 2006; Draut and Rubin, 2008; Collins et al., 2009;

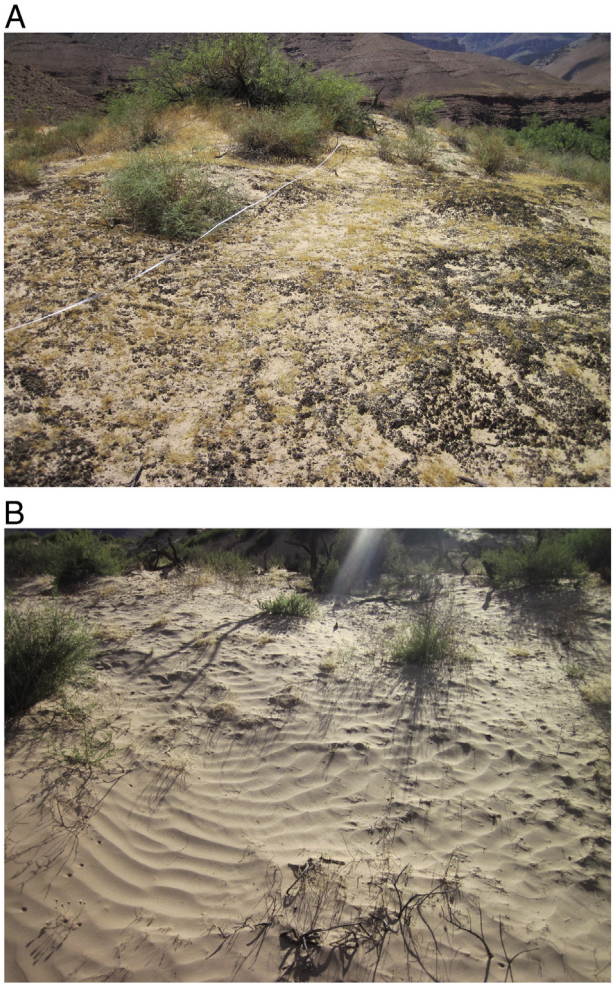

Fig. 2. Photos of inactive and active aeolian sediment deposits in the Colorado River corridor, Marble–Grand Canyon. The landscape in (A) is an example of a sediment deposit considered inactive with respect to recent aeolian transport (sensu Lancaster, 1994); it contains well developed biologic soil crust and vegetative cover, and lacks evidence for recent sediment transport. The landscape in (B) was considered active aeolian sediment on the basis of its wind-rippled surface, which contains some vegetation but largely lacks biologic soil crust.

Anderson and Neff, 2011), representing important losses for Native American tribes and a concern for the federal agencies that manage this river corridor and operate the dam (U.S. National Park Service and Bureau of Reclamation, respectively).

Given that dam operations prevent the large, sediment-rich floods that are thought to have been a major gully-annealing process, the remaining process with potential to anneal gullies or slow their growth is aeolian sediment transport. There have been isolated observations in the Colorado River corridor of gully annealing by aeolian sediment transport (Thompson and Potochnik, 2000; Draut and Rubin, 2006, 2008); one of the goals of the controlled flooding discussed above was to increase aeolian sediment supply that could offset gully erosion and thus reduce the risk of archaeological-site loss (Neal et al., 2000). However, prior to this study there had been no systematic, observational analysis of the effectiveness of aeolian sediment activity on limiting gully development over a landscape scale.

3. Material and methods

Analysis focused on six reaches of the Colorado River between Glen Canyon Dam and Lake Mead (Fig. 1). The reaches studied (what follows is the abbreviation for each reach and river km from Lees Ferry, Arizona which is 24.1 km downstream of Glen Canyon Dam) were: Glen Canyon (GLCA, −24.1 to −9.6 km), Eminence-Little Colorado River (EmLCR, 70.8–98.2 km), Furnace Flats (FF, 106.2–115.9 km), Upper Granite Gorge (UGG, 140.0–159.3 km), Stevens/Conquistador Aisle (SCA, 186.7–206.0) and Granite Park (GP, 333.1–338.0 km).

For each reach, the terrestrial area of Colorado River-derived sediment above the direct effect (i.e., inundation) of the contemporary Colorado River and associated dam and reservoir operations (henceforth "terrestrial area") was identified as the area above stage-elevation 1,270 m^3/s and below the transition of river-derived and slopewash sediment to bedrock or talus. The 1,270 m^3/s stage is the maximum elevation reached by controlled-flood dam operations; its shoreline was determined using a GIS database of shorelines previously developed by coupling a stage-discharge model to a digital elevation model for this reach of the Colorado River with uncertainty of 0.4 m (Magirl et al., 2008). The transition of river-derived and slopewash sediment to bedrock or talus was identified by visual interpretation and delineation in GIS of 22 cm-resolution multispectral imagery acquired in 2009 for the Colorado River corridor between Glen Canyon Dam and Lake Mead (Davis, 2012).

3.1. Aeolian sand mapping

For each reach, aeolian sand deposits above the 1,270 m^3/s river stage and below bedrock and talus were mapped exhaustively on the 22 cm-resolution imagery in the field (i.e., each mapped deposit was delineated and verified during a field visit) in spring and summer 2011–2013. Aeolian sand units were identified as either active or inactive with respect to contemporary aeolian transport (Lancaster, 1994) and these data were transferred into a GIS (i.e., polygons with attributes). The active/inactive classification was defined as described above, following the same method previously described by Draut (2012). A primary defining characteristic was the extent of biologic soil crust establishment on sand surfaces (Fig. 2), which serves to increase threshold friction velocity of the surface and substantially decrease erodibility; in the Colorado River corridor, sand surfaces with biologic crust cover >20% generally are inactive with respect to aeolian sand transport (Draut, 2012).

3.2. Topographic detection of potential gullies

Hillslope flowpaths with concave across-slope shape with potential to channel overland flow ('potential gullies') were detected using a novel combination of overland-flow accumulation and topographic modeling procedures commonly available in GIS and remote sensing software (ArcGIS, ENVI), and a 1 m-resolution digital elevation model (DEM) acquired in 2009 (Fig. 3). The DEM was derived from a 1 m-resolution digital surface model (DSM) produced from automated digital aerial photogrammetry with <0.30 m vertical accuracy (RMSE) (Davis, 2012; P. Davis, United States Geological Survey, personal communication, 2014) and is the highest resolution and most accurate digital topographic dataset available that covers all six of the reaches of the Colorado River. The DEM was constructed by replacing pixels in the DSM that contained vegetation canopies, with elevation interpolated from surrounding bare ground surfaces (IDL routine 'DEM_BAD_DATA_DOIT' in ENVI). Vegetation canopies had been previously identified in classification of coincidentally collected and co-registered multispectral imagery (Davis, 2012) though the majority of the terrestrial area was unvegetated. The first step of the 'potential gully' detection procedure entailed running the overland-flow accumulation model (ArcHydro Tools in ArcGIS) for the DEM to identify thalwegs of possible overland flow paths in terrestrial surfaces (Greenlee, 1987; Jenson and Domingue, 1988; Tarboton et al., 1991). The second step entailed producing a plan convexity product and an RMSE-roughness product for the DEM (IDL routine 'TOPO_DOIT' in ENVI). Thresholds were applied to the flow accumulation and plan convexity raster products using values arrived at heuristically that were confirmed during field visits in winter-spring 2013 to consistently detect

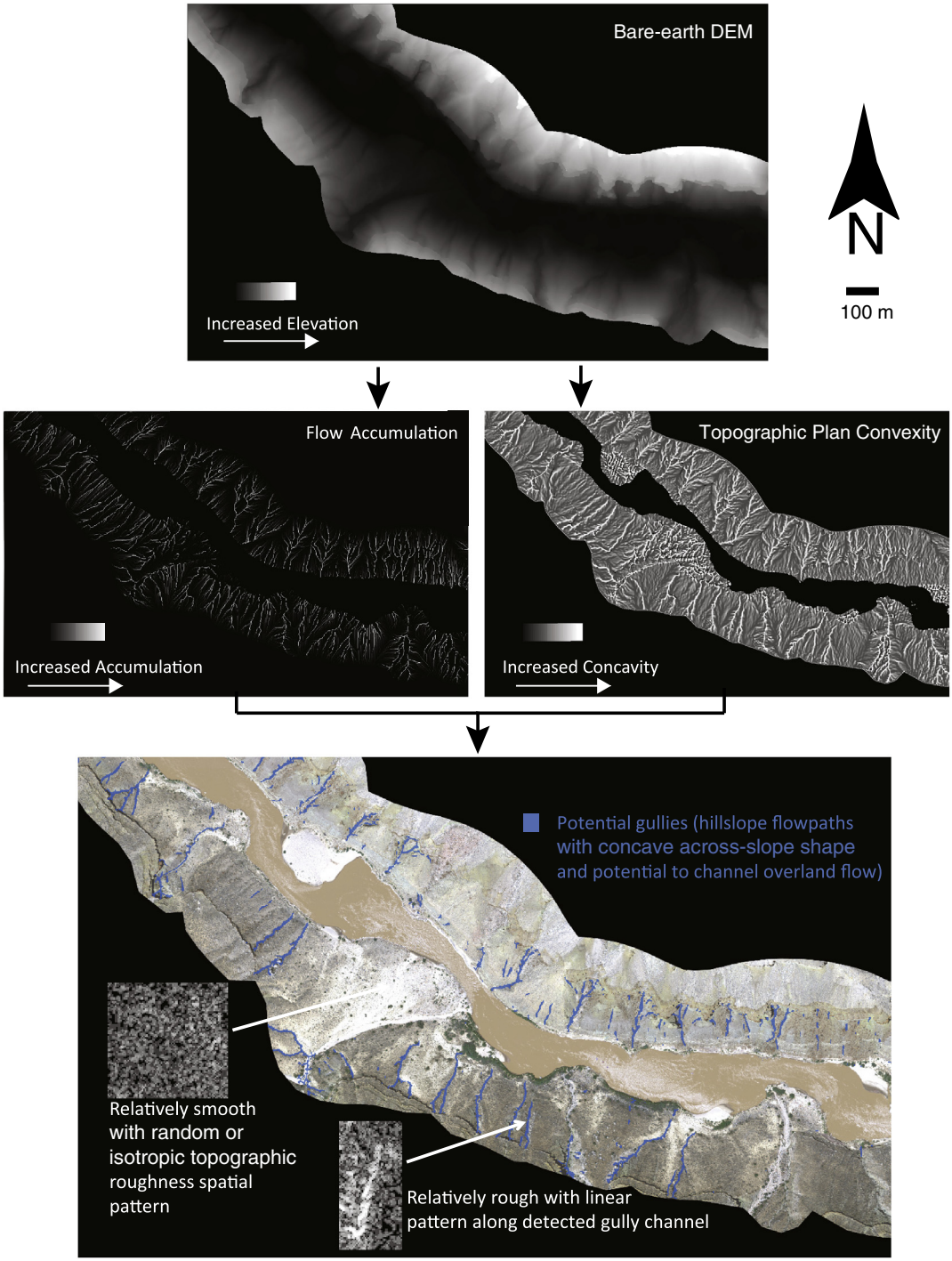

Fig. 3. Schematic for a section of the SCA reach illustrating the data and approach described in Section 3 of the manuscript that was employed similarly in all six reaches of the Colorado River to detect potential gullies. A 1 m-resolution bare-earth DEM was processed for flow accumulation and plan convexity. Threshold values were applied to the flow accumulation and plan convexity, and the resulting products were spatially intersected, to produce polygons of hillslope flowpaths with concave across-slope shape that represented potential gullies. Threshold values of topographic roughness were employed to reduce misclassification of relatively smooth interdune and swale landscape features as potential gullies.

gullies among the six reaches of the river corridor. After applying thresholds, the datasets were spatially intersected in the GIS to produce an intermediate dataset of individual polygons that represented sections of hillslope flowpaths with concave across-slope shape (i.e., potential gullies), many of which were topographically discontinuous. Threshold values of the RMSE-roughness product were applied to the intermediate dataset to reduce the misclassification of topographically smooth interdune swales as potential gullies, resulting in a final dataset of individual polygons of potential gullies (Fig. 3). The same methodology and threshold values for each data type were used for all six reaches of the river corridor (Fig. 1B) to produce datasets that were consistent in terms of degree of flow accumulation, across-slope concave shape, and roughness characteristics considered to be indicative of potential gullies. The final dataset of polygons was subset to the terrestrial area for each reach (i.e., above stage-elevation of 1,270 m^3/s and below the transition to bedrock or talus), thus limiting this consideration of potential gullies to features formed in fine-sediment deposits rather than through coarse talus. The average width of each potential gully polygon in the final

dataset was measured in the GIS to determine the distribution of potential gully sizes and therefore estimate detection limits of the methodology.

The relative ability of the method to detect real gullies was examined for a set of gullies that were independently identified in the field and surveyed with stadia rod and total station in the GLCA reach. The surveyed gullies included segments with sub-meter widths, and the limitations of the methodology to accurately delineate the entire thalweg length of the set which included relatively small and large surveyed gullies was evaluated.

3.3. Statistical analysis and hypothesis testing

The terrestrial area, aeolian sand, and potential gully data were further analyzed in the GIS in several ways to test the hypotheses of the study. The terrestrial area and terrestrial area scaled by reach length were determined for each study reach. The ratio of potential gully area to terrestrial (sediment) area was determined for each reach (henceforth 'potential gully area ratio'). The ratio of active aeolian sand area to the sum of active and inactive sand area was determined for each reach (henceforth 'active sand area ratio'). To test the hypothesis (1) that gullies are more evident in areas where sediment is inactive with respect to aeolian sediment transport, the relationship of the gully area ratio to active sand area ratio was determined with a simple linear regression. Also to test hypothesis 1, the potential gully area within inactive and active sand units were determined for each reach and compared among reaches with a paired t-test where reach was the experimental unit.

To test the hypothesis (2) that potential gullies terminate more commonly in active aeolian sand, the count, ratio of count to sand area, and ratio of potential gully area to sand area were determined for each reach of all potential gullies that entered and subsequently terminated within active and inactive sand units. For this analysis, potential gullies were considered to terminate within sand units if they entered from outside (upslope) and dissipated before passing halfway through the unit. The rationale for considering dissipation that occurred before an individual gully travelled more than halfway through the unit was to (i) use a criterion that was common among gullies and aeolian sediment units and (ii) provide the most spatially unambiguous evidence possible that an individual gully had both entered and terminated within an aeolian sediment unit. The variables for inactive and active sand were compared among reaches with a paired t-test where reach was the experimental unit.

To test the hypothesis (3) that the historical record contains evidence of potential gullies that have annealed over time and so are less evident today than in the past, the entire set of potential gullies that terminate in active and inactive aeolian sand were examined visually relative to archived aerial photographic imagery from 2002 and 1984 to determine the number of gullies that were more pronounced in the earlier imagery and/or exhibited obvious examples of infilling as of 2009. The 1984 black and white image prints were acquired at variable river discharge between 144 and 226 m^3/s, and at map scale of 1:3,000. The 2002 multispectral digital imagery were acquired at steady river discharge of 226 m^3/s and have a 44 cm pixel resolution. In some cases, vegetation encroachment into gullies made it difficult to determine whether infilling had occurred, and the prevalence of these ambiguous situations was recorded separate from, and not included with, examples where infilling was clear. Similarly, the prevalence of examples where vegetation encroachment appeared to have occurred in conjunction with signs of aeolian infilling was also recorded separate from and not included with examples where infilling with aeolian sediment was clear and independent of vegetation encroachment.

While we did not directly experiment with the sediment-trapping efficiency of gullies, we did collect photographic evidence in the field to support the assumption that gully channels are topographic lows that act as natural traps for aeolian sediment in the lee of the prevailing wind; topographic lows in the lee of prevailing wind are thought to be particularly important for trapping saltating or reptating sediment in transport (cf. McIntosh et al., 2004).

4. Results

Fig. 4 provides examples from areas within several reaches of the river corridor of the aeolian sand and potential gully maps. Terrestrial (sediment) area varied greatly among river-corridor reaches, and when scaled by reach length reflected variable canyon morphology in that three of the reaches (EmLCR, FF, and SCA) were relatively wider and three (GLCA, UGG and GP) were relatively narrower sections of the corridor, with less Colorado River-derived sediment available above stage-elevation 1,270 m^3/s (Fig. 5A). The active sand ratio in the UGG and SCA reaches was approximately 2–3 times as large as in the EmLCR and FF reaches, and an order of magnitude larger than in GLCA and GP (Fig. 5B). Results therefore did not appear to follow an obvious relationship of more active aeolian sand in reaches with relatively greater terrestrial area (Fig. 5A,B). This finding was attributed to local variations in prevailing wind direction among the six reaches, verified by several years of high-resolution wind measurements at each of 11 locations in the river corridor (Draut and Rubin, 2006; Draut et al., 2010b). In places where the local prevailing wind direction blows at a high angle to the river (e.g., much of the SCA reach; Draut and Rubin, 2006), providing a means to bring sand from modern fluvial sand bars to inland aeolian dunes, Draut (2012) found that the source-bordering dune fields contain more active aeolian sand than those in other reaches where the wind direction is nearly parallel to the river (Fig. 4; see also Fig. 5 of Draut, 2012).

Comparison of 14 gullies independently surveyed with rod and total station with the relevant potential gullies detected with our method in three sections of the GLCA reach (Fig. 6) reinforced that the method was suitable for detecting portions of real gullies, and that the method was limited for delineating the entire thalwegs of the surveyed gullies that included sections with sub-meter widths. The method detected a portion of all surveyed gullies in the three sections of the GLCA reach (Fig. 6). The method identified 90% of the surveyed thalweg lengths in the first section of the GLCA reach (Fig. 6A), 50% in the second section (Fig. 6B), and 40% in the third section (Fig. 6C), illustrating the relative limitations of the 1 m-resolution DEM data for detecting and delineating the entire thalweg length of small gullies. A total of 11,010 potential gullies were detected among all reaches. The potential gullies detected throughout the six reaches of the Colorado River ranged in maximum width from ~1–30 m, though a majority were ~1–4 m wide (Fig. 7).

The relationship of the potential gully area ratio (Fig. 5C) and active sand area ratio (Fig. 5B) was significant and strong ($R^2 = 0.80$, $p = 0.02$; Fig. 8), and indicated that there was less potential gully area in reaches with more active aeolian sand (Fig. 8). Comparison of the potential gully area within inactive and active aeolian sand (Fig. 9) indicated that there was significantly more potential gully area within inactive sand units than in active sand units (paired t-test $p = 0.03$). Both findings did not refute the first hypothesis that potential gullies are more evident in areas where sediment is inactive as opposed to active with respect to aeolian transport.

A total of 358 potential gullies in the six reaches were identified that terminated in mapped (inactive and active) sand units; as opposed to potential gullies that travelled through aeolian units, and/or ultimately joined other potential gullies or the mainstem river. Comparison of counts and area of potential gullies that terminated in inactive vs. active aeolian sand (Fig. 10) indicated that the total number of potential gullies did not differ significantly (paired t-test $p = 0.11$), but the total number of potential gullies that terminated in sand units scaled by sand area was significantly greater for active vs. inactive sand (paired t-test $p = 0.02$); and the area of potential gullies that terminated in sand units scaled by sand area was significantly greater for active vs. inactive sand (paired t-test $p = 0.06$). (It is necessary to scale by sand area to make a meaningful comparison in potential gully prevalence, because there is

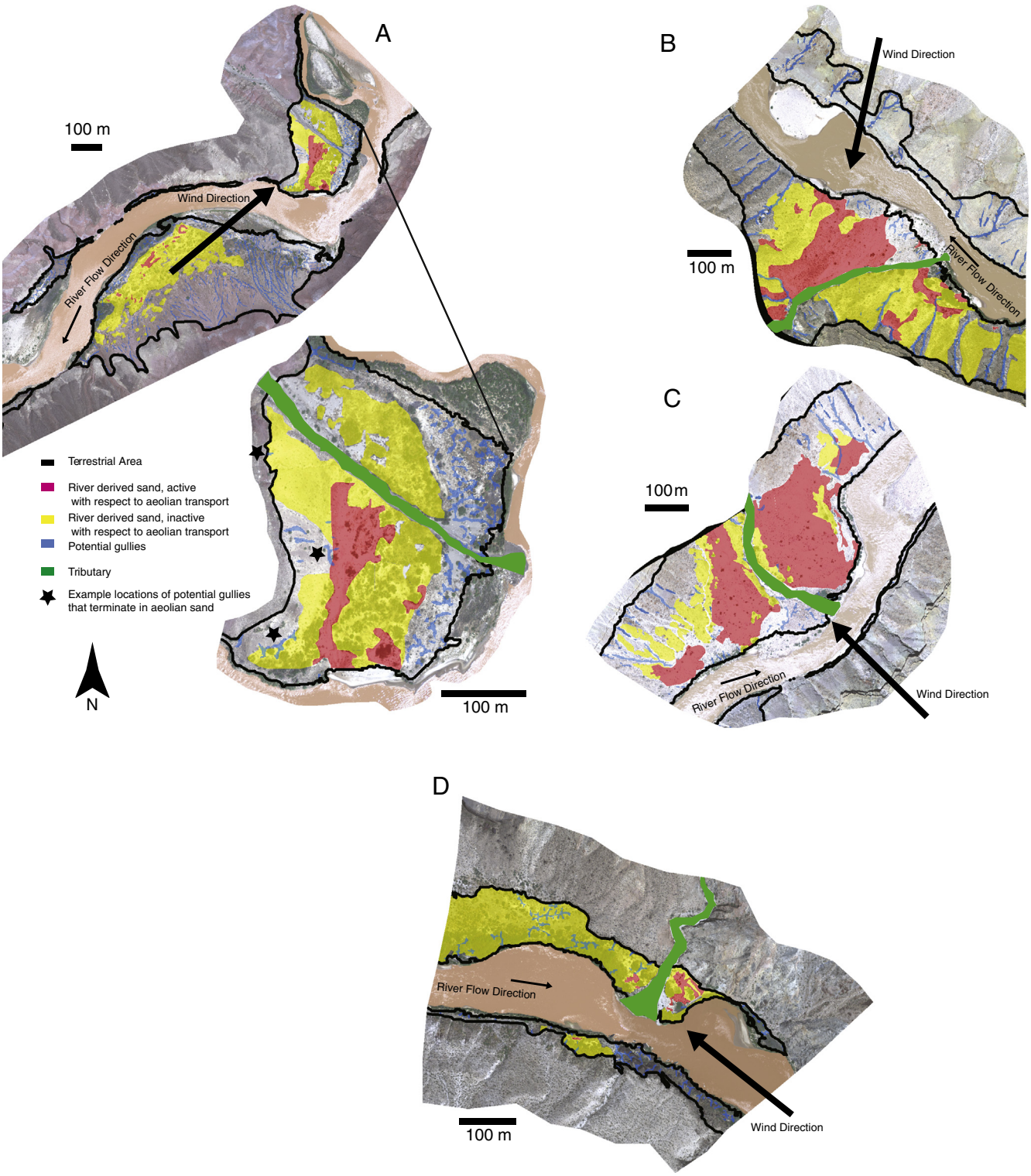

Fig. 4. Examples from four sections of the Colorado River reaches that show the aeolian sand and potential gully mapping data used to test the hypotheses of the study. (A) is in the FF reach, (B) and (C) are in the SCA reach, and (D) is in the GP reach.

substantially less active sand area than inactive sand area in each reach; Fig. 5B.) These findings did not refute the second hypothesis that potential gullies terminate more commonly in active aeolian sand than in inactive sand.

Comparison of historical imagery within our six study reaches from 1984 and 2002 with that from 2009 indicated that as of 2009 a small proportion (~1–3%, or up to 11 total gullies) of the gullies that terminated in aeolian sand showed obvious indication of aeolian annealing (Fig. 11). An additional ~ 1% (3 gullies) showed evidence of aeolian annealing in conjunction with obvious vegetation encroachment (Fig. 11). Approximately 2–10 % of gullies showed evidence of vegetation encroachment within the terminus of the gully, but without obvious evidence of aeolian infilling (Fig. 11). The findings did not refute the third hypothesis that the historical record contains evidence of gullies, although relatively few in this field setting, that have annealed over time and so are less evident today than in the past.

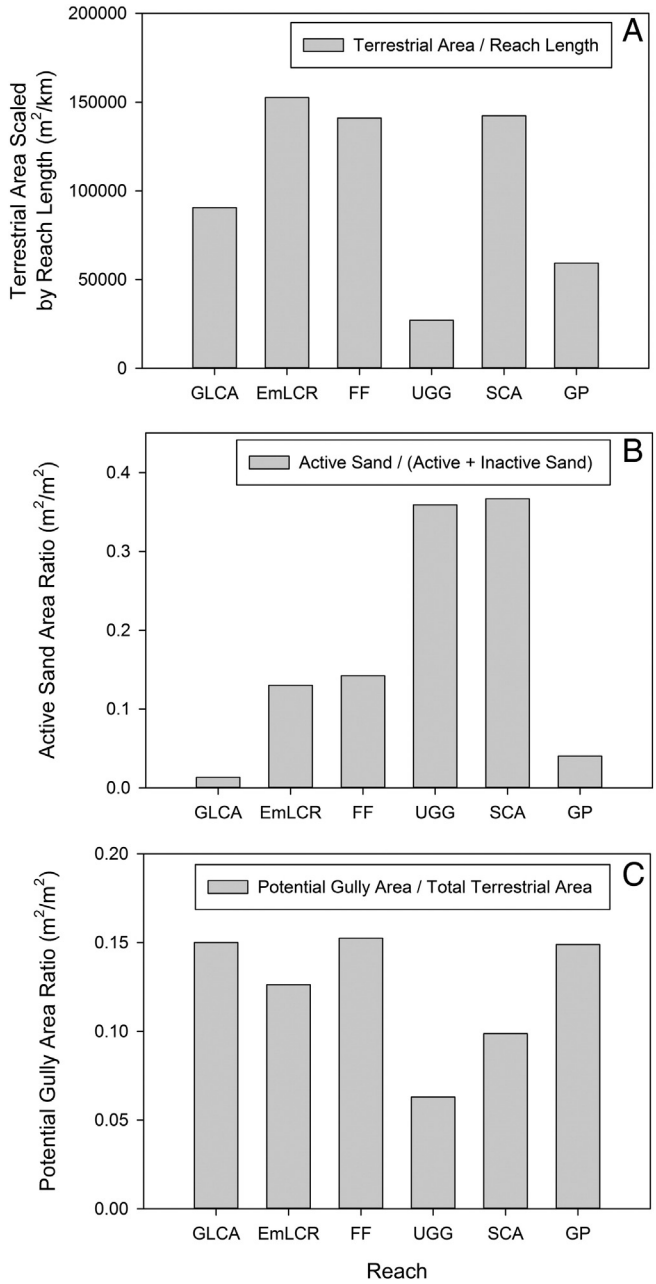

Fig. 5. (A) Terrestrial area of Colorado River-derived sediment between the contemporary active channel of stage-elevation 1,270 m^3/s and the upslope transition to bedrock or talus, scaled by reach length. (B) Active aeolian sand area ratio and (C) potential gully area ratio, summarized by reach. Reach names are abbreviated as in Fig. 1.

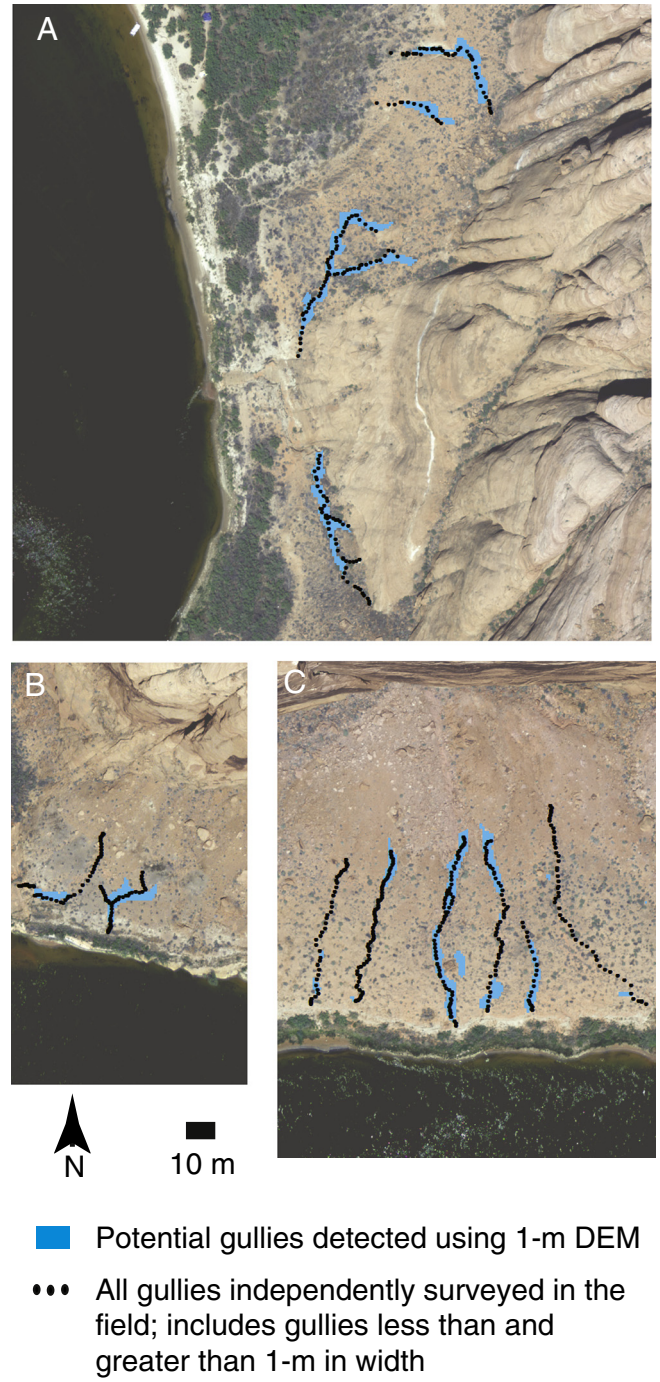

Fig. 6. Examples from 3 locations in the GLCA reach that illustrate the strength of the potential gully detection method (described in Section 3 of the manuscript and Fig. 3) for detecting real gullies verified in the field; the method detected a portion of all surveyed gullies in (A), (B), and (C). Examples also illustrate the relative limitations of the 1-m resolution DEM data for detecting sub-meter portions of gullies and delineating the entire thalweg length of small gullies; the method identified 90% of the surveyed thalweg lengths in (A), 50% in (B), and 40% in (C).

Contemporary oblique and aerial photographs from the Colorado River corridor illustrated the ability for concave topographic features that channel overland flow (e.g., gullies, arroyos and large tributary channels) to capture aeolian sediment (Fig. 12). The photos provided examples from several observed locations where unconsolidated, active aeolian sand filled a gully that thus terminated in an active aeolian deposit, and also evidence of the larger-scale but analogous phenomena where tributary channels of the Colorado River contain aeolian dune sand migrating into the upwind side, but not out of the downwind side, of the ephemerally flowing alluvial channel. Photos highlighted that aeolian dunes commonly had clearer dune morphology (steep, well defined slipfaces) and contained more active sand on the upwind side of a tributary channel (Fig. 12B,C), with slipfaces indicating dune migration into the tributary channel (Fig. 12C). Aeolian dunes observed in these contexts were less pronounced and contained less active sand area on the downwind side of the same tributary channel (Fig. 12B, C).

5. Discussion

Landscape evolution in dryland regions depends strongly on connectivity between fluvial, aeolian and hillslope (including alluvial) systems, although these modes of sediment transport are rarely studied in

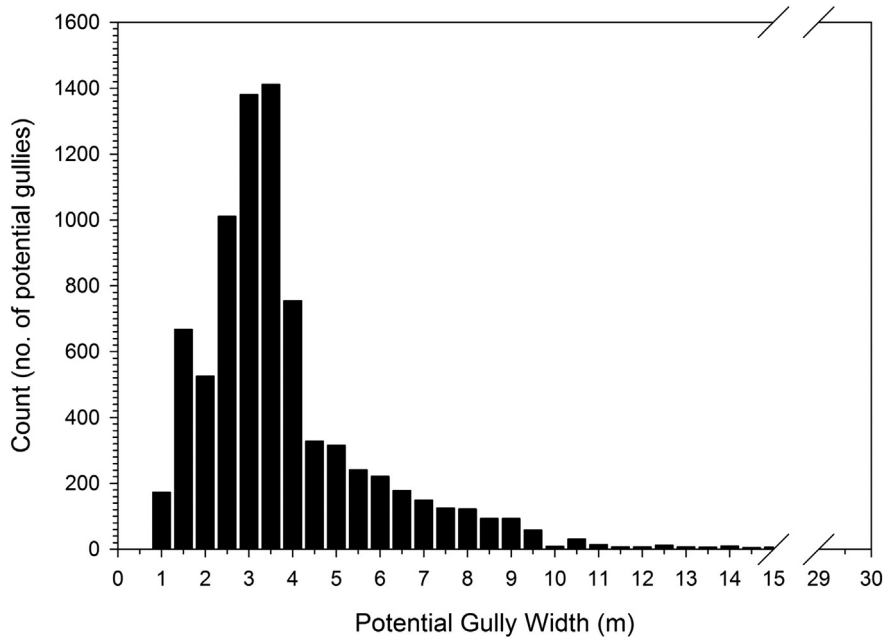

Fig. 7. Distribution of average widths for all potential gullies (n = 11,010) delineated and examined in the study. Potential gullies detected ranged in width from ~1–30 m, though a majority occupied a much smaller range of widths.

combination (Bullard and Livingstone, 2002; Bullard and McTainsh, 2003; Field et al., 2009; Ravi et al., 2010; Belnap et al., 2011; Sankey et al., 2012a, 2012b). Understanding factors that enhance or impede ephemeral gully development, a concern throughout dryland regions globally (Antevs, 1952; Heede, 1978; Halvorson et al., 1988; Graham, 1992; Casali et al., 1999; Meadows, 2003; Ghimire et al., 2006; Bou Kheir et al., 2007; Zhu, 2012), depends on recognizing not only the roles of hillslope (alluvial) runoff and substrate parameters in forming gullies, but also of aeolian sediment transport in counteracting gully erosion. In the case of this study, the role of the mainstem Colorado River in generating fluvial sediment that is central to the aeolian sediment supply is likely important as well. While this was not a direct study of aeolian sediment transport, our methods provided an effective proxy for analyzing the role of aeolian sediment transport in annealing and impeding the expansion of gullies that has gone largely unrecognized or commented on in the literature (e.g., Xu et al., 2006). Our observations of annealing are particularly significant considering that the regulated Colorado River system that we studied has less than natural aeolian sediment supply to its river-corridor landscapes (Draut and Rubin, 2008), and less than natural prevalence of active aeolian sand surfaces (Draut, 2012). It would be informative to compare the results of this study with gully-annealing efficacy of aeolian sediment in a dryland environment with natural sediment supply, unaffected by river regulation. While we are not aware of a similarly large-scale dryland river corridor entirely free of river-regulation or other human influence, there are certainly examples globally (e.g., in Asia and Northeast China (see for example, Han et al., 2007), or possibly the Orange River corridor, southwestern Africa, downstream from its dams) of relatively undeveloped segments of large river corridors with prominent aeolian sediment supply that might inform on this problem.

The most definitive characteristic of aeolian transport potential in this system, in addition to direct observations of sand transport and mobility, is the lack (or presence, conversely) of biologic soil crusts (Draut, 2012). Biologic soil crusts are known to play a critically important role in arid ecosystems (Harper and Belnap, 2001; Belnap, 2012; Elbert et al., 2012), and also evidently in the physical evolution of landscape surfaces, affecting the potential for aeolian sediment entrainment, overland flow effects, and gully annealing or persistence. Water infiltration rates are lower on biologic soil crusts than on many other sediment surfaces

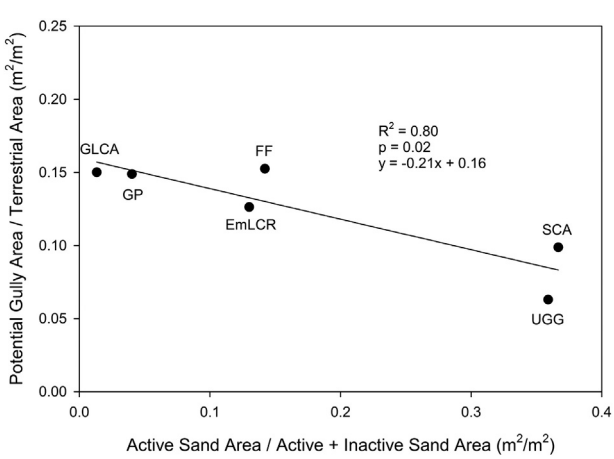

Fig. 8. Relationship of potential gully area ratio and active sand area ratio by reach. Points are labeled by reach names which are abbreviated as in Fig. 1.

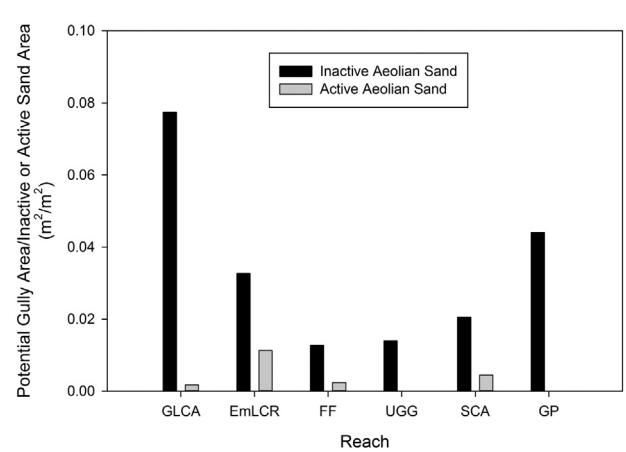

Fig. 9. Potential gully area per mapped sand unit (active or inactive, respectively) summarized by reach. Comparison of the potential gully area within inactive and active aeolian sand indicated that there was significantly more potential gully area within inactive sand units than in active sand units (paired t-test p = 0.03).

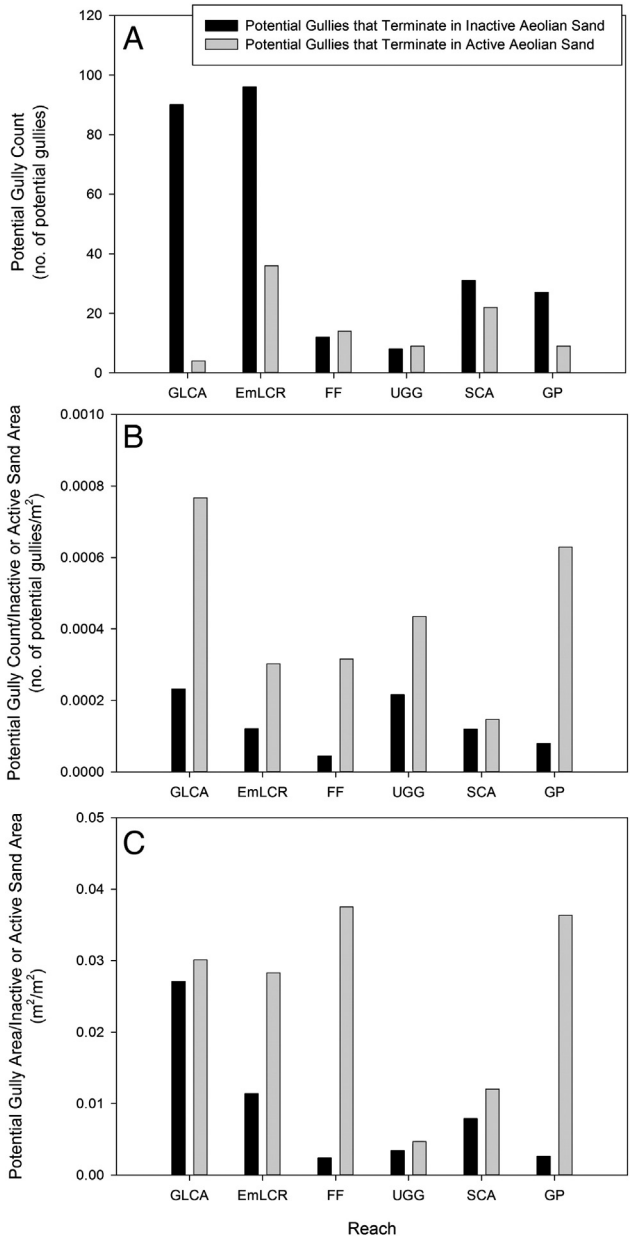

Fig. 10. The count (A), count divided by sand area (B), and area divided by sand area (C) of potential gullies that terminated in mapped sand units (active or inactive aeolian sediment, respectively) summarized by reach. A total of 358 potential gullies were identified among all reaches that terminated in mapped (inactive or active) sand units. Simply comparing counts of potential gullies that terminated in inactive vs. active aeolian sand (A) indicated that the total number of potential gullies did not differ significantly (paired t-test p = 0.11). However, there was proportionately more inactive aeolian sand relative to active sand in all reaches, and when the counts and areas of potential gullies that terminated in mapped sand units were normalized by the sand area (B and C, respectively) results indicated that potential gullies terminated more commonly in active aeolian sand than inactive sand (paired t-test p = 0.02 and 0.06, respectively, for tests of results presented in B and C).

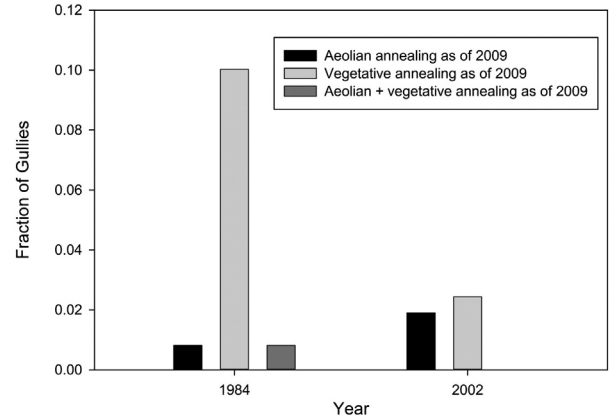

Fig. 11. Fraction of gullies (n = 358 among all reaches) that terminated in mapped aeolian sand units that showed evidence of aeolian annealing as of 2009 relative to historical aerial imagery from 1984 and 2002.

(Chamizo et al., 2012; Rodríguez-Caballeroa et al., 2012). Biologic soil crusts substantially reduce the aeolian transport potential of sediment surfaces (McKenna Neuman et al., 1996; Belnap et al., 2007; Dong et al., 2011) in addition to reducing erodibility by water (Finlayson et al., 1987; Kidron et al., 2012; Rodríguez-Caballeroa et al., 2012). Our results indicate that gullies are less evident in areas that are more active with respect to aeolian transport. Conversely, our results suggest that more extensively bio-crusted sand surfaces, which are less active with respect to aeolian transport and wind erosion, are also surfaces that show greater evidence of gully erosion. It might seem counterintuitive to suggest that gullies are more likely to occur, and therefore hillslope erosion processes are more evident, in areas that are more biocrusted. However, our findings likely reflect the differences in hydrologic characteristics of the two distinct types of sediment surfaces and their biologic crust characteristics. Although biologic soil crusts can enhance surface 'stability' in one sense by limiting aeolian transport potential and in some places also limiting erodibility by overland flow, once that crust is disturbed (e.g., by overland flow with sufficient shear stress, or that in combination with biocrust disturbance by human or animal trails), gullies that do form through biocrusted sediment persist and enlarge because they are not readily annealed by subsequent aeolian transport. As a result, biocrusted surfaces might be considered 'stable' with respect to aeolian entrainment potential, but much less 'stable' with respect to their propensity for gully incision. The evidently greater susceptibility of inactive, biocrusted sediment surfaces to extensive gully erosion with little aeolian annealing potential could therefore be hypothesized to contribute to degradation of sediment deposits and associated archaeological sites in the Colorado River corridor (Pederson et al., 2006; Collins et al., 2009, 2012).

We also observed that gullies that initiate outside (upslope) of aeolian surfaces are more likely to terminate within active aeolian sediment units than in inactive ones. The observation of gullies that terminate within aeolian sediment units is likely an indication that the gullies either existed on the landscape prior to the deposition of (and stabilization by) aeolian sediment and some portions were subsequently infilled by aeolian sand (Thompson and Potochnik, 2000; McIntosh et al., 2004; Xu et al., 2006) or these gullies formed upslope of aeolian sand units but were subject to reduced potential to expand once entering into the aeolian sand unit due to changes in infiltration and runoff capacity. Of these two mechanisms, we did find evidence of the first in our analysis of historical imagery. Specifically, aeolian sand had infilled the termini of a small but detectable proportion (1–3%) of gullies we analyzed. Although this constitutes a relatively uncommon fate for gullies in our field setting (at least over the time frame from 1984 to 2009), that it occurs at all is consistent with the ability for gullies and other concave topographic features to capture aeolian sediment (Fig. 12). It is plausible that some of the gullies we examined might have filled in, excavated, and then re-filled between the relevant dates of analysis. For example, previous work within some of our project reaches has measured relatively rapid aeolian dune crest migration (e.g., >10 m y^{-1}) that occurs directionally from fluvial to upland settings (Draut et al., 2010a), as well as very high spatial resolution topographic change in which gully erosion and aeolian deposition occur within close spatial proximity, at high temporal frequency (months-years) (Collins et al., 2009, 2012). Nonetheless, in this and other environments the presence of aeolian sediment filling channels in the sedimentary record has been described

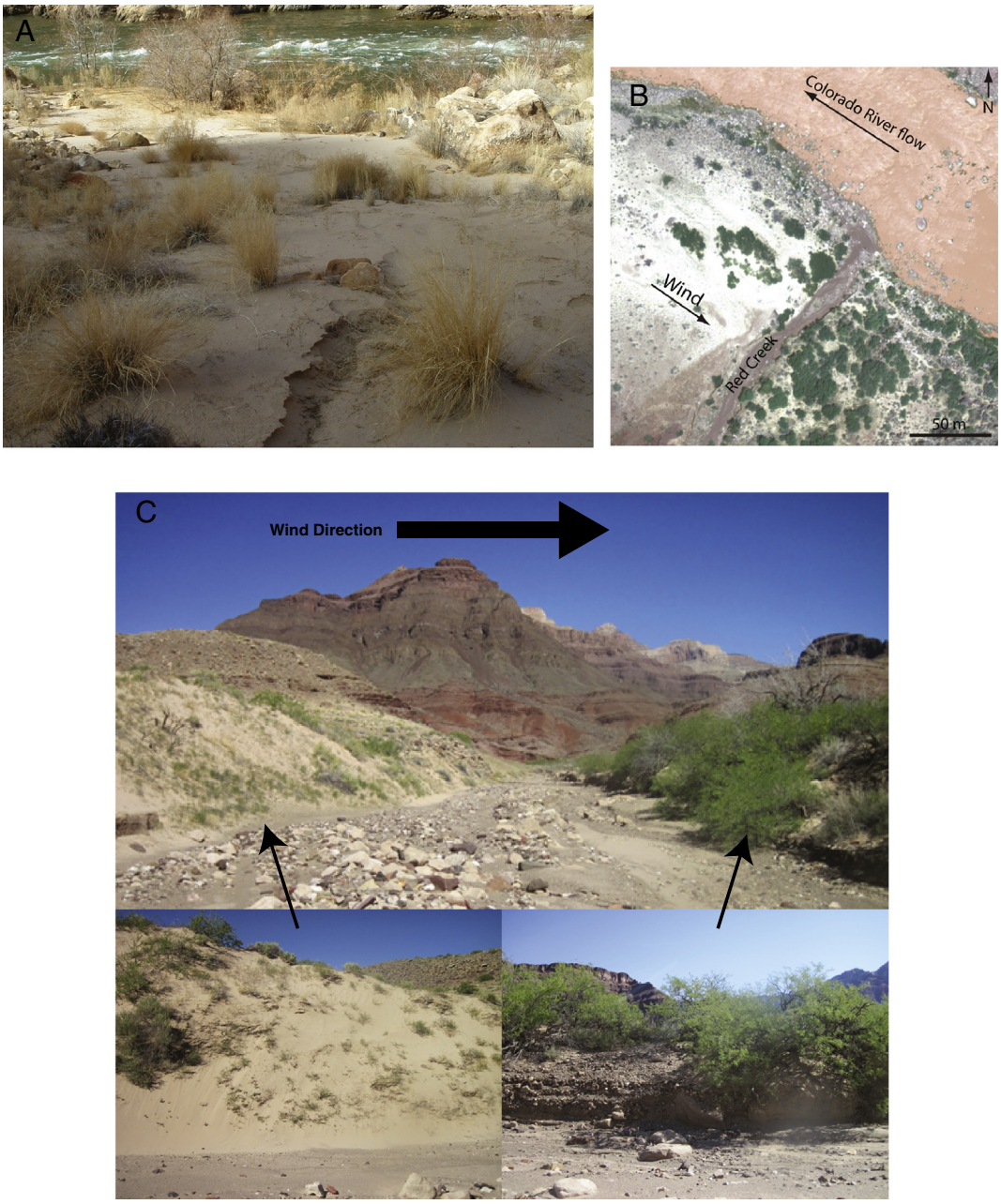

Fig. 12. Examples of interactions between aeolian sediment and topographic depressions in Marble–Grand Canyon. (A) a small gully observed at river km 39, with terminus annealed by aeolian sand activity. (B) aerial image of an ephemeral tributary, Red Creek, entering the Colorado River at Hance rapid (river km 123). Local prevailing wind direction is toward upstream with respect to the Colorado River (toward southeast). River-derived sediment formed source-bordering aeolian dunes along the southern (river-left) side of the river corridor. Note the abundance of bright (high albedo), active aeolian sand on the upwind side of the tributary channel, whereas sediment on the downwind side of the tributary channel comprises inactive dunes that are biocrusted and heavily vegetated. (C) another ephemeral tributary channel (Basalt Creek), which joins the Colorado River at river km 116, showing aeolian infilling on the upwind (photo left) side of the channel. Close-up photos of the up- and down-wind sides, respectively, of the tributary channel in (C) show a lee-side dune slipface migrating into the tributary channel, yet so little aeolian sediment exits the tributary-channel depression on its downwind side that no dune forms are apparent when facing downwind at this location.

for a range of geologic settings and timescales (Thompson and Potochnik, 2000; Krapf et al., 2003; Loope et al., 2004; McIntosh et al., 2004; Xu et al., 2006; Draut and Rubin, 2008; Mazaeva et al., 2011) and examples abound in the Colorado River corridor of topographic depressions, that range in size from small gullies to large ephemeral tributary channels, capturing aeolian sediment.

6. Conclusion

In this study, we provide the first systematic, landscape-scale observations and analyses of the role of aeolian sediment transport in annealing and impeding the expansion of gullies. Aeolian sediment activity appears to be significant as a gully-annealing mechanism, even in the Colorado River corridor where aeolian sediment supply is limited owing to upstream dam operations. Our analyses over 95 km of this river corridor show that gullies are less prevalent in sediment deposits that undergo active aeolian transport, and that gullies are more likely to terminate in active aeolian sand than in sediment that is inactive with respect to aeolian transport. Although not common, examples exist in the record of historical imagery of gullies having been infilled by aeolian sediment. We thus provide new evidence for potentially important interaction of aeolian, hillslope (alluvial) and fluvial processes, which could affect dryland regions substantially in ways not widely recognized. Moreover, because biologic soil crust plays an important role in

determining aeolian sand activity, and so in turn the potential for gully annealing, this study highlights a critical role of geomorphic–ecologic interactions in determining arid-landscape evolution. The potential for aeolian annealing is of great management importance in the Colorado River corridor because it provides a means to offset gully erosion and reduce the risk of loss of culturally valuable archaeological sites; the aeolian sediment supply needed to enhance gully annealing is potentially manageable with dam operations that maximize the size of fluvial sand bars which supply sediment to downwind aeolian deposits. We suggest that future research address the importance of these processes in other regulated and unregulated dryland river corridors worldwide, where fluvially deposited sediment is important for aeolian sediment supply that in turn can contribute to gully annealing.

Acknowledgements

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