Gully annealing by aeolian sediment: Field and remote-sensing investigation in Glen, Marble, and Grand Canyon

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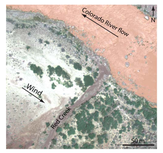
Introduction

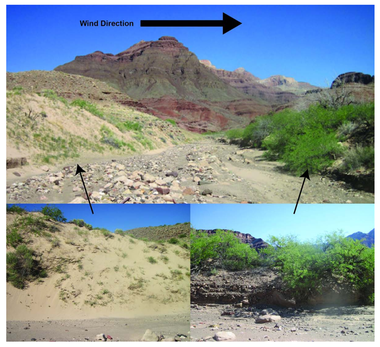
There has been little investigation into how indirect (higher order) linkages between other geomorphic processes might forestall and/or change the trajectory of gully formation. The few literature references to gully and arroyo annealing discuss alluvial cutting and filling episodes related to climate variability and land use but focus primarily on erosion, such that relatively little is known about processes that anneal gullies and therefore impede or counteract their growth. We investigated the effectiveness of gully annealing by aeolian sediment activity.

Aeolian dune migrating into the channel of a small tributary wash of the Colorado River in Grand Canyon

A small gully along the Colorado River in Marble Canyon with terminus annealed by aeolian sand activity.



Aerial image of ephemeral tributary, Red Creek, entering the Colorado River in Grand Canyon 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. 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.



An 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 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.

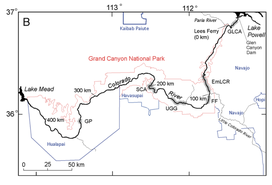
Objectives

We examined the prevalence of gullies in areas with and without active aeolian sand transport.

Hypotheses:

1. Gullies are more evident in areas where sediment is inactive with respect to aeolian transport than in areas with active aeolian transport
2. Gullies terminate more commonly in active aeolian sand than in inactive sand
3. The historical, remotely sensed image record contains evidence of gullies that have annealed over time and so are less evident today than in the past

Study Area

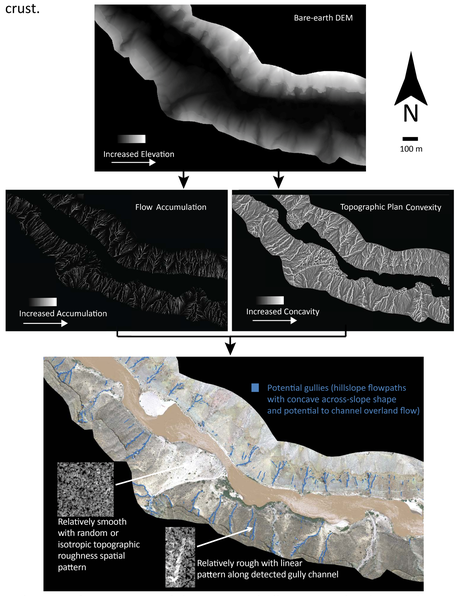


To evaluate the role of aeolian sediment in gully development and annealing, we examined large reaches of the Colorado River corridor, southwestern USA. The extent of gullies through sediment deposits, and controls on gully development, are land-management concerns in the Colorado River corridor because gullies erode irreplaceable archaeological sites and because earlier studies indicated that gully development could be linked to dam operations. Map (A) shows the Colorado River watershed, with major dams indicated by black bars. Box indicates area shown in (B). Map (B) shows the Colorado River corridor through Glen, Marble, and Grand Canyon. Glen Canyon Dam is at top right; river flow is from northeast toward southwest. Study reaches, with locations in river-kilometers relative to Lees Ferry (by convention in Colorado River research) are abbreviated as: Glen Canyon (GLCA, -24.1– -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 red, tribal reservation lands are blue.

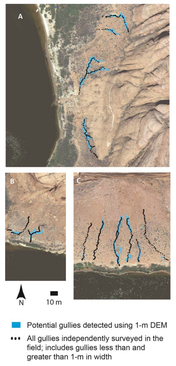
Methods

We defined gullies topographically as features on hillslopes with 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 ("potential gullies") within and adjacent to Colorado river-derived sediment that was relatively active or inactive with respect to aeolian transport, and in adjacent 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. Sediment surfaces that are inactive with respect to aeolian transport lack those features and contain substantial biologic soil crust and vegetation.

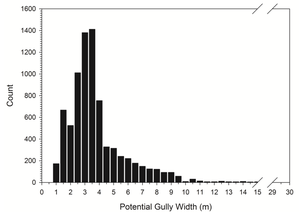
Inactive and active aeolian sediment deposits in the Colorado River corridor, Marble–Grand Canyon. The landscape in the above-left photo is an example of a sediment deposit considered inactive with respect to recent aeolian transport; it contains well developed biologic soil crust and vegetative cover, and lacks evidence for recent sediment transport. The landscape in the above-right photo was considered active aeolian sediment on the basis of its wind-rippled surface, which contains some vegetation but largely lacks biologic soil crust.



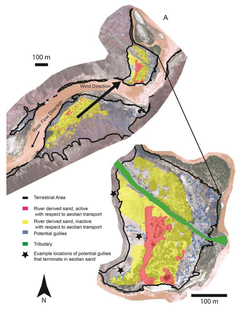
Schematic for a section of the SCA reach illustrating the data and approach that was employed in all six reaches of the Colorado River to detect potential gullies. A 1-m resolution bare-earth DEM was processed for flow accumulation and plan convexity. Threshold values were applied to flow accumulation 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 applied to reduce misclassification of relatively smooth interdune and swale landscape features as potential gullies.

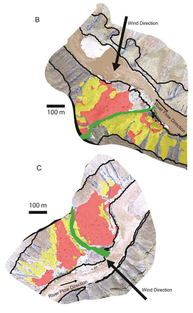


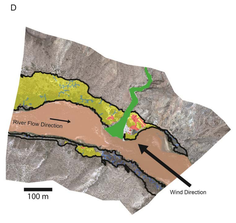
Examples from 3 locations in the GLCA reach that illustrate the strength of the potential gully detection method for detecting real gullies verified in the field; the method detected a portion of all surveyed gullies in (A), (B), and (C). Examples also illustrate the relative limitations of the 1-m resolution 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)



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.



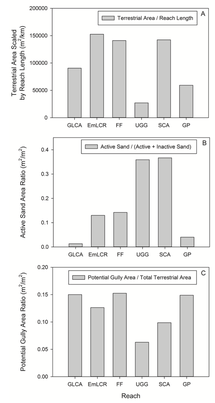




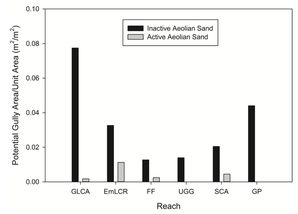
Examples from four sections of the Colorado River reaches that show the aeolian sand and potential gully mapping data used to test the hypotheses of the study. (A) is in the FF reach, (B) and (C) are in the SCA reach, and (D) is in the GP reach.

Results and Discussion

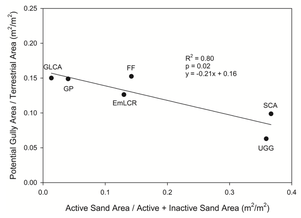
Potential gullies are less prevalent in areas where surficial sediment undergoes active aeolian transport, and have a greater tendency to terminate in active aeolian sand than in sediment that is inactive with respect to aeolian transport. Although not common, examples exist in the record of historical imagery of gullies that underwent infilling by aeolian sediment in past decades and evidently were annealed by aeolian sediment. We thus provide new evidence for an important interaction of aeolian-hillslope-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 extent of gully development, this study highlights a critical role of geomorphic–ecologic interactions in determining arid-landscape evolution.



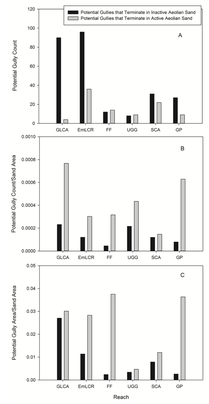
(A) Terrestrial area of Colorado River-derived sediment between stage-elevation 1,270 m^3/s and the upslope transition to bedrock or talus, scaled by reach length. (B) Active aeolian sand area ratio and (C) potential gully area ratio, summarized by reach.



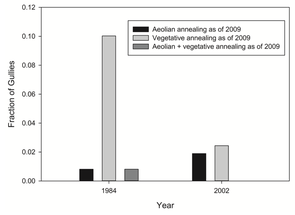
Potential gully area per mapped sand unit (either active or inactive with respect to aeolian transport) summarized by reach.



Relationship of potential gully area ratio and active sand area ratio by reach. Points are labeled by reach names. Relationship demonstrates that reaches with relatively more Colorado River-derived sediment that is active with respect to aeolian transport have less area affected by potential gullies



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 (either active or inactive with respect to aeolian transport) summarized by reach. A total of 358 potential gullies were identified among all reaches that terminated in mapped (inactive and 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. 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.



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.

Summary and Key Points

- Annealing processes are mechanisms by which gully formation is impeded or reversed
- Mechanisms of gully annealing are understudied relative to gully formation
- Gully annealing is driven by aeolian-hillslope-fluvial and ecologic interactions
- Infilling by aeolian sediment transport is an effective annealing mechanism

Acknowledgments

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(Preliminary Data from Sankey and Draut, Do Not Cite)