Aeolian landscapes and archaeological sites: 2012 progress and new work plan (Project J)

January 23, 2013

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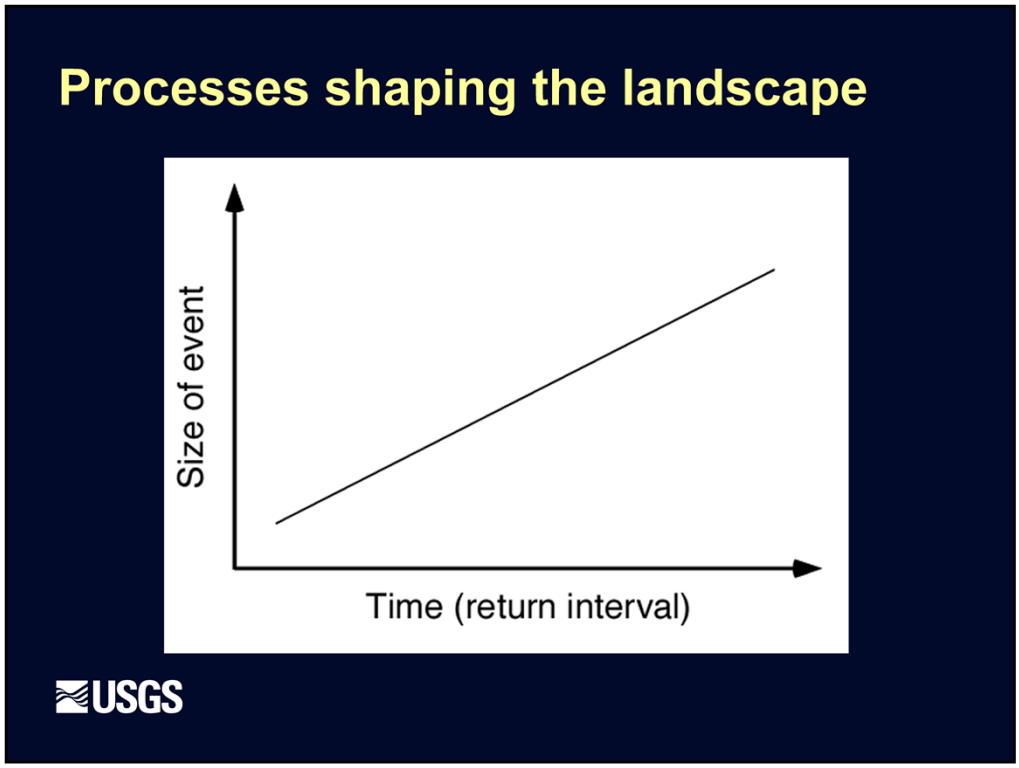
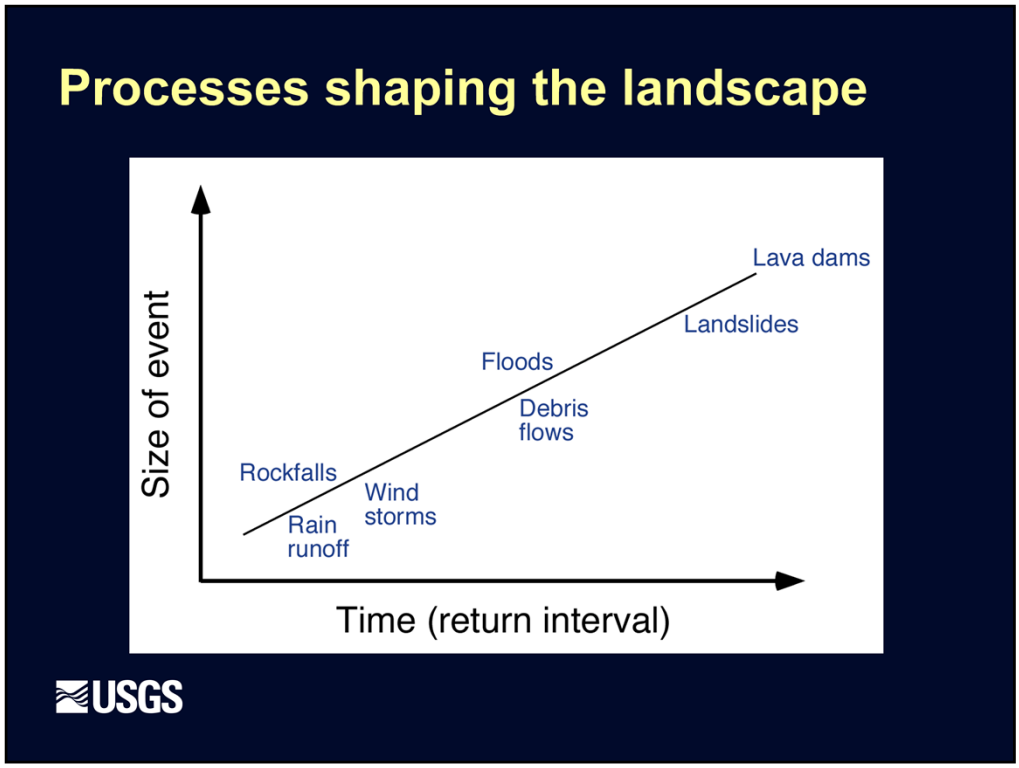
U.S. Department of the Interior
U.S. Geological Survey



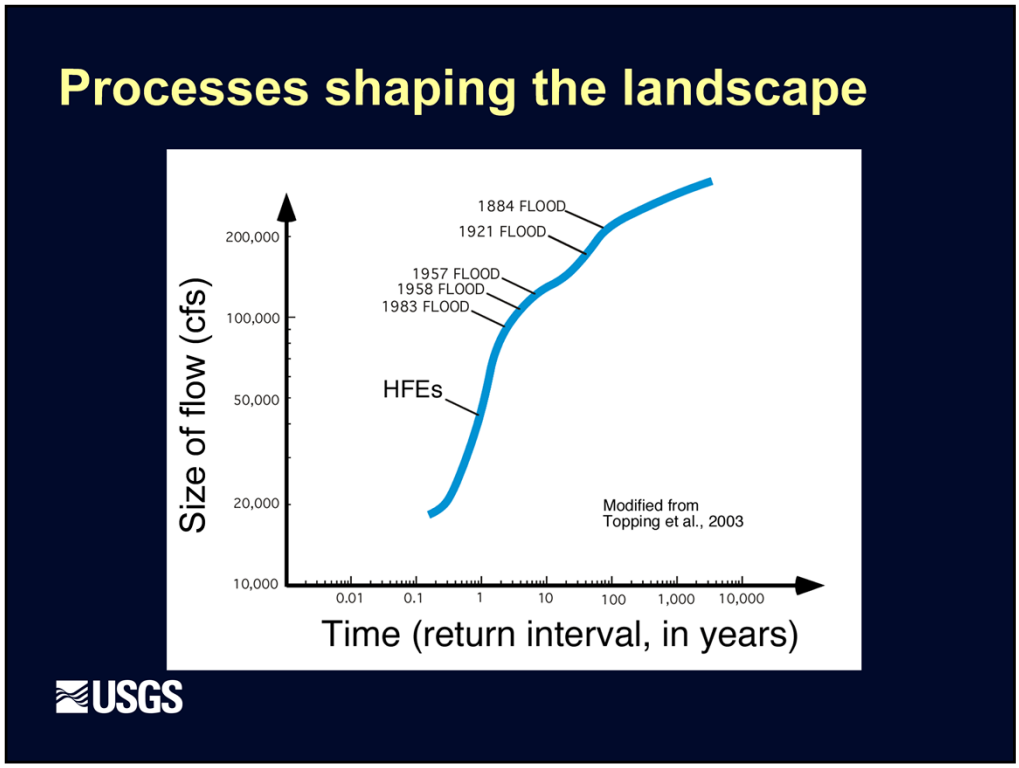
Before I get into specifics of our 2012 progress and the planned work for Project J, I want to make sure we all understand a basic concept behind upland landscapes in GRCA.

There's been a long ongoing debate/discussion in geomorphology in general about whether landscapes respond most strongly to large, extreme events that don't happen very often, or to much smaller events that happen often. [explain schematic graph]. Big, extreme events that don't happen very often, have a lot of time between them, vs. smaller events that happen often, short time between them. In different places, the answer may be different.



In the Colorado River corridor, the structure and function of the landscape result from a suite of different processes that fill the whole spectrum of event size and how often those events occur. On the upper end, we have really huge, extremely rare events (lava dams, huge landslides like Nankoweap or below Deer Creek). Moving down the spectrum we have events that are not quite that catastrophic but still pretty big: large floods, exceptionally large debris flows. Then moving into more common, less extreme, smaller events: smaller floods, storms that produce small debris flows, rockfalls, gullies. So you have the whole spectrum of big and small processes making the landscape what it is.

In the next slide, I want to look at just the floods.



You can make the same kind of diagram for just discharge [don't call it just "floods" because return intervals are shown down to months on this plot]. Topping did this in his 2003 professional paper. This is important because when you talk about aeolian landscapes, it's important to recognize they owe their existence to a range of flood events, many of them quite large. Some aeolian dune fields in the canyon get sand from wind reworking deposits of flows down in the small end of the range, but many cannot. Many, probably most, aeolian dune fields, including the biggest ones with the most extensive arch sites, owe their existence to events up in this big end of the spectrum. Flows closer to 200,000. So for the rest of our discussion about aeolian landscapes, this is the context: although some parts of the landscape are defined by what happens at the low end of the spectrum, much of the appearance and function of aeolian landscapes really depends on large, rare events in a part of the spectrum that dam operations haven't included.

In order to understand what happens at arch sites, have to look both at the small-scale (within the 10 m2 that your site occupies) and the large scale context of the landscape it's in. Understand landscape context and processes affecting it. All of the processes happening in the larger landscape will affect the arch sites ultimately, and it's extremely likely that there are arch sites in the aeolian deposits that we don't know about yet because they aren't yet exposed by erosion. The only way to truly understand and quantify whether and how dam operations affect arch sites, and how much risk they are at, is to integrate observations at small scale (site scale) and large scale bird's eye view. That is what my work evolved into, and is our frame of mind going into Project J.

Scientific Context

- Fluvial (river) and aeolian (wind) sediment interactions are common worldwide, but the two processes are rarely studied together
- Scientific community sees need for more integrated studies (e.g., Belnap et al. 2011)
- Effects of river regulation on aeolian sand, upland geomorphology have not been studied elsewhere

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A bit more on scientific context for the cultural and upland geomorphology work: fluvial and aeolian sediment interactions are common in desert areas worldwide but almost no one combines studies of the two. There's a growing awareness among earth scientists that integrating fluvial and aeolian research is necessary, but this program is one of the few places that's ever happened. So the work coming out of this program on these topics is groundbreaking.

2012 paper in Journal of Geophysical Research – Earth Surface

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

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

Amy E. Draut[1]

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

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

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

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2012 paper in Journal of Geophysical Research – Earth Surface

- Significant differences (physical and biological) between aeolian landscapes with and without modern fluvial sand source
- Significant differences between aeolian landscapes of Grand, Cataract Canyons
- Conceptual model: floods, windblown sand supply, upland geomorphology and ecology

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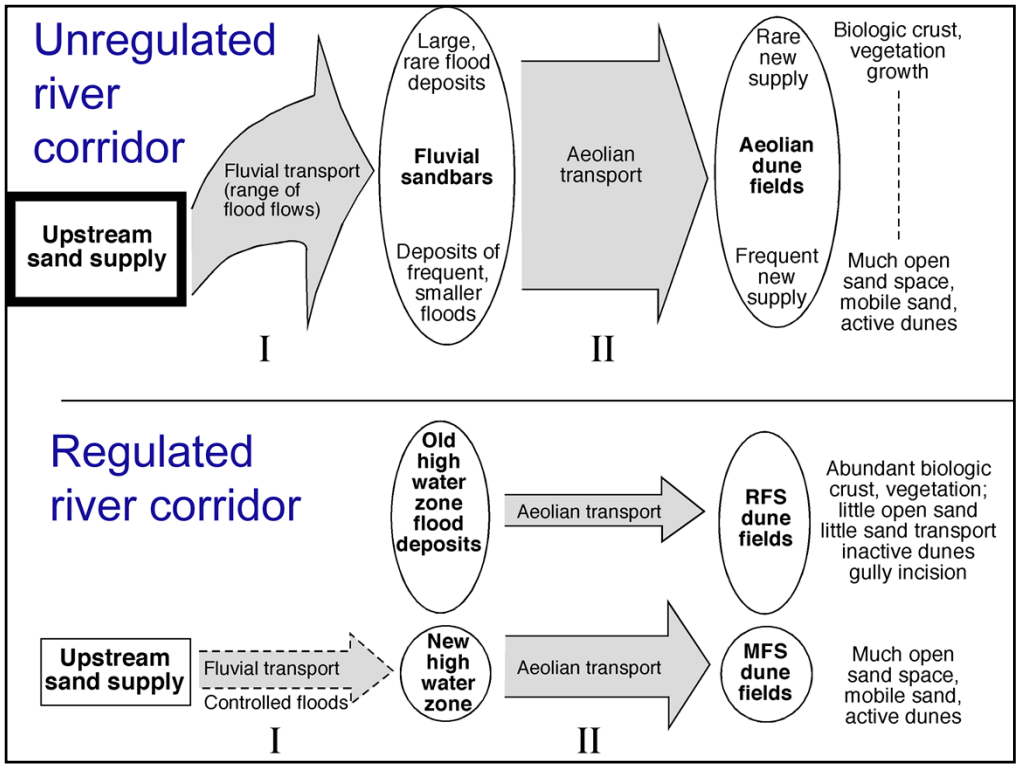
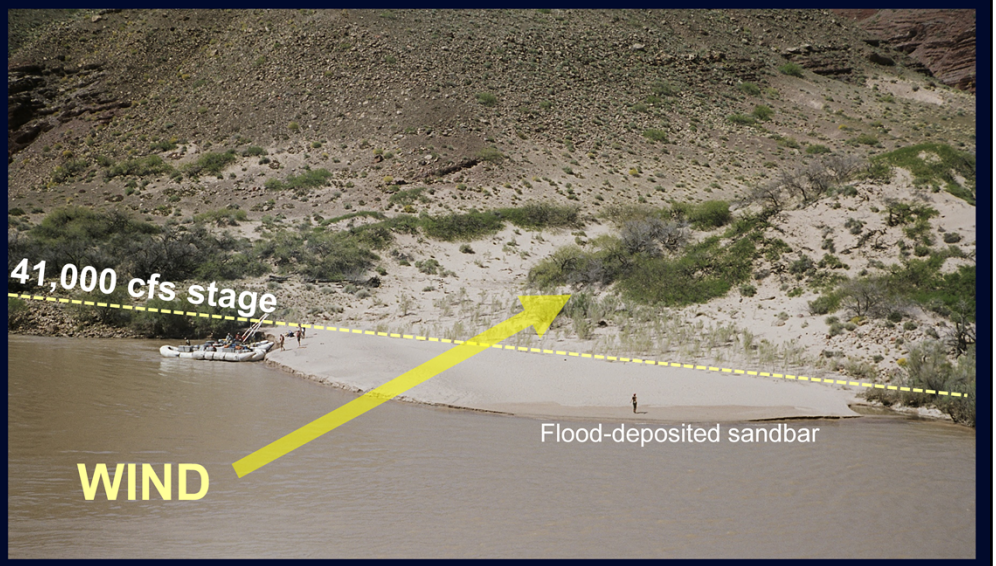
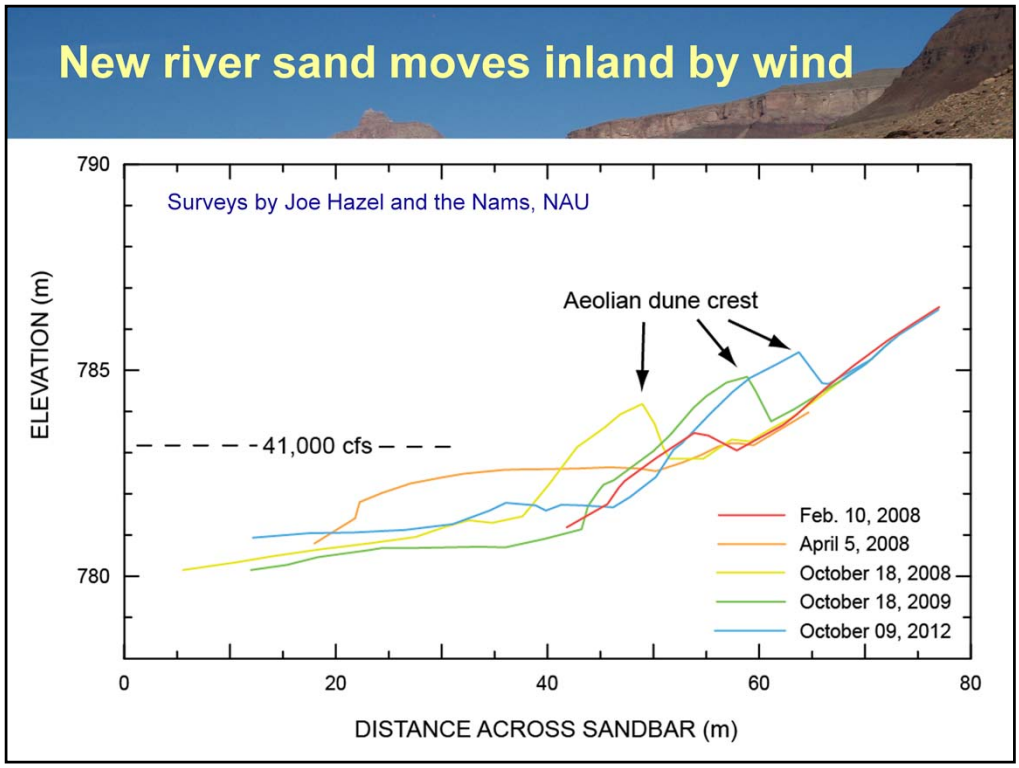


The paper includes a conceptual model that I'll go through in the next few slides, comparing dammed and undammed conditions and linking floods to aeolian reworking of flood deposits. In the dammed era, where we don't have large floods anymore, old flood deposits and the dune fields that depended on them are decoupled from the river, and start to grow lots of biologic crust and the dunes essentially become inactive, no longer migrating and (we think) no longer effectively counteracting gully incision.

Aeolian landscapes form downwind of river sandbars: “source-bordering dunes” (Bullard & McTainsh, 2003)



Controlled floods of the magnitude we've been having can bring sand into aeolian dunes like this one at Basalt, and other places where wind direction is right.



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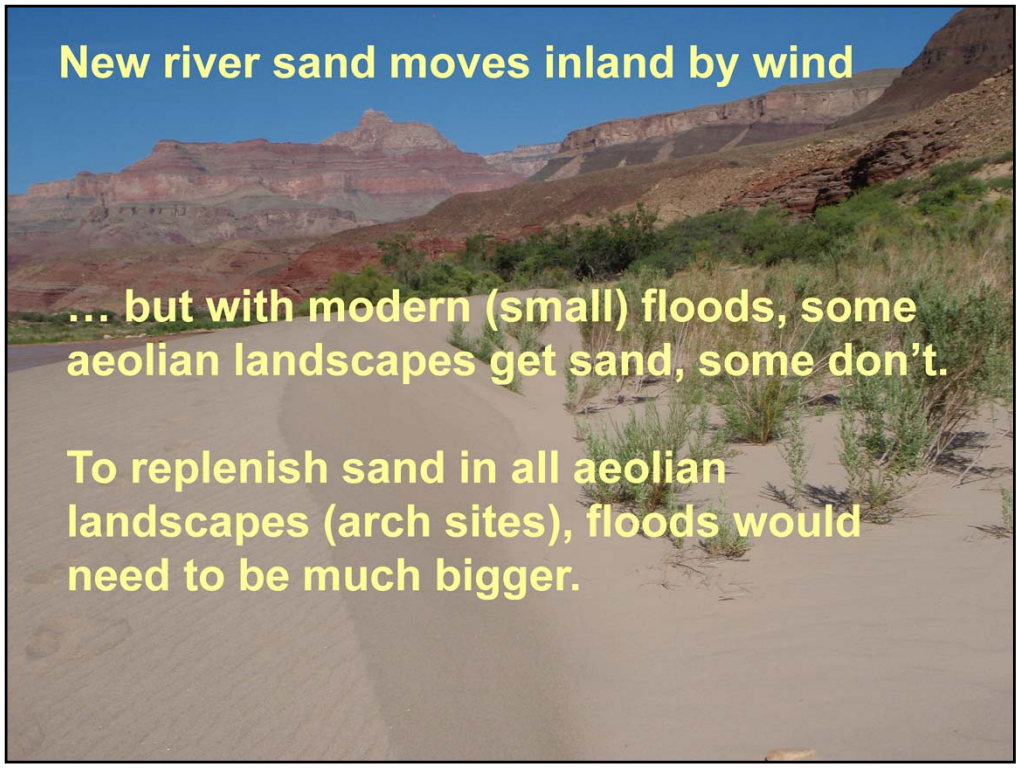
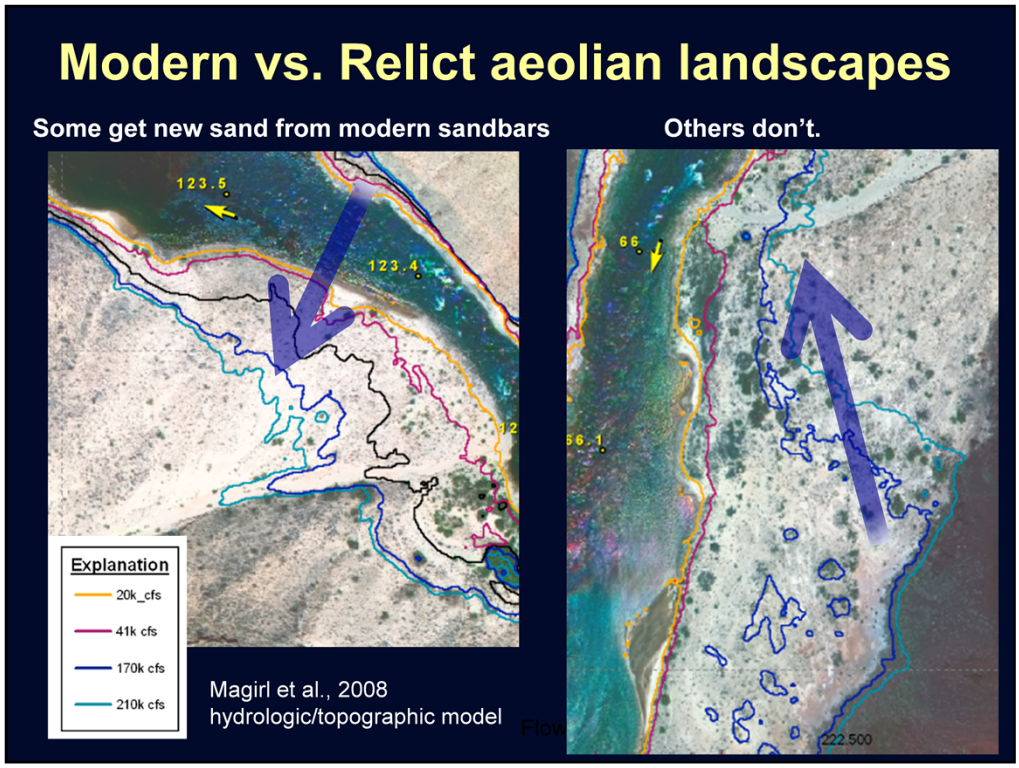
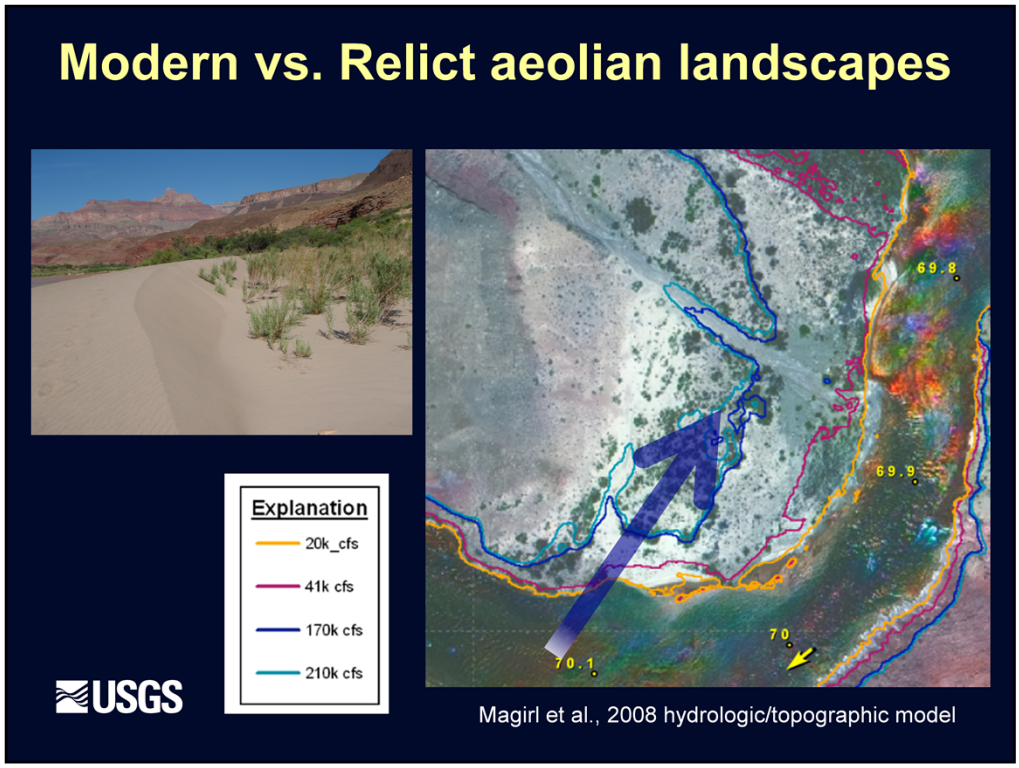

New river sand moves inland by wind
… but with modern (small) floods, some aeolian landscapes get sand, some don't.
To replenish sand in all aeolian landscapes (arch sites), floods would need to be much bigger.



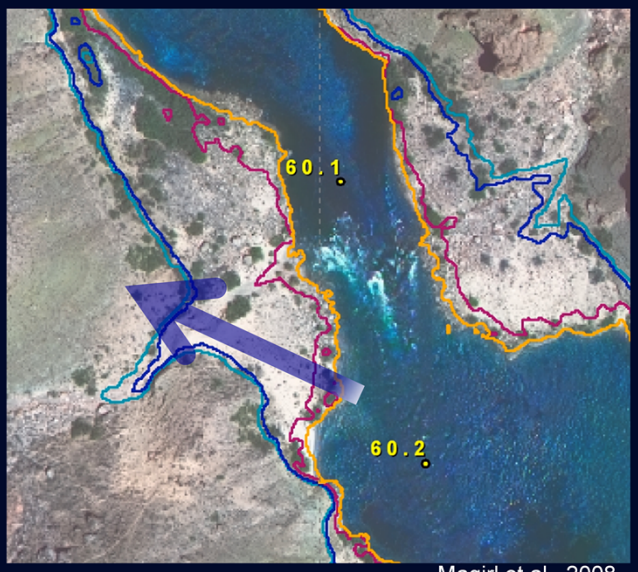
Prevailing wind directions:

1957 flood was 125,000 cfs; 1958 flood was 108,000 cfs.



1957 flood was 125,000 cfs; 1958 flood was 108,000 cfs.

Aeolian landscapes in GRCA largely originated from ‘extreme’ floods



Explanation

- 20k_cfs
- 41k cfs
- 170k cfs
- 210k cfs

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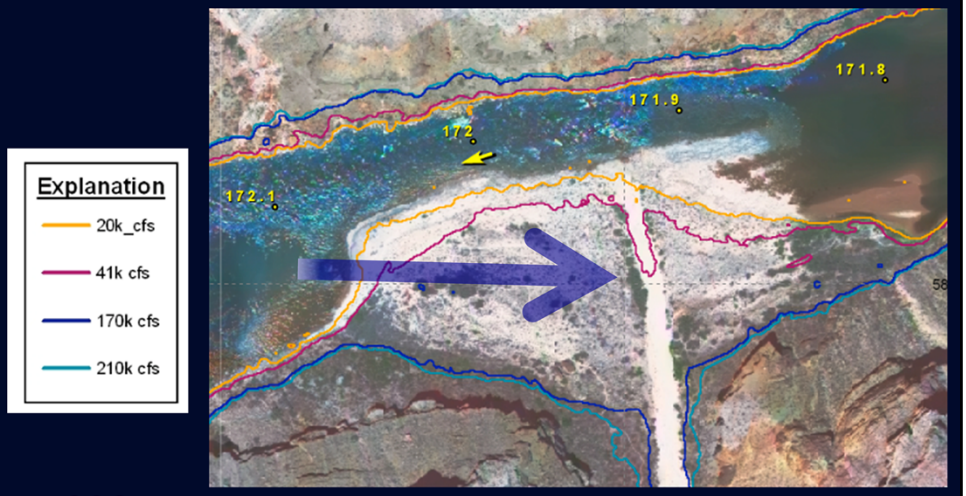
Magirl et al., 2008

Aeolian landscapes in GRCA largely originated from ‘extreme’ floods



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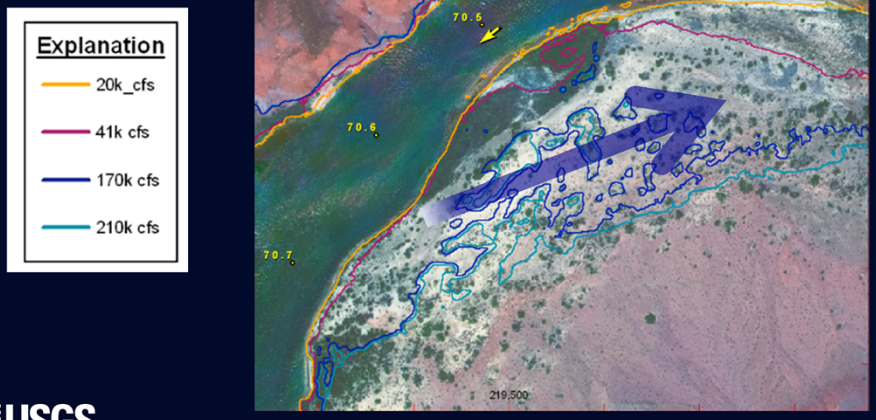
Magirl et al., 2008

Most, and largest, dune fields set by 40-year flood (170,000 cfs)



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USGS

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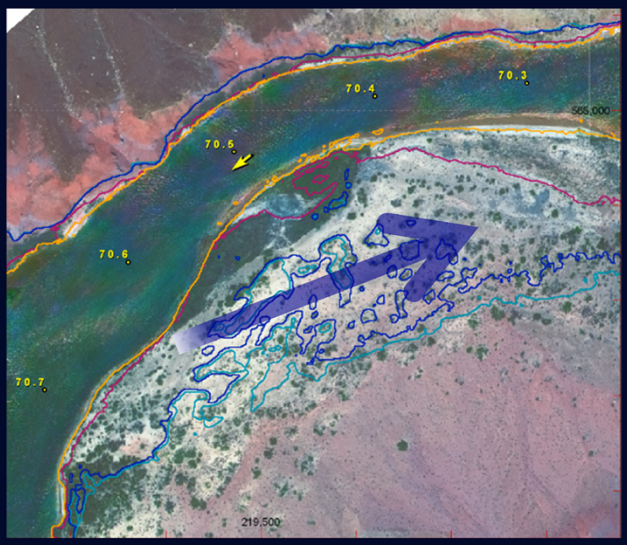
Most, and largest, dune fields set by 40-year flood (170,000 cfs)

- HFEs cover a small proportion of natural (pre-dam) sand source area
- HFE deposits often too small, far away, blocked by riparian vegetation



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Magirl et al., 2008

Aeolian deposits depend on fluvial deposits, as wind reworks the flood deposits. In postdam time, where we don't have big floods anymore and the flood deposits we do have are hard to maintain (by controlled floods), many aeolian dune fields don't get sand anymore, or get a lot less sand than they used to in pre-dam time. Aeolian dunes without modern sand supply start growing much more biologic crust. You get a transition from this (left) to this (right) type of dune field. Having lots of biologic crust prevents dunes from migrating, prevents a lot of aeolian sand transport (= less "active"). In the next phase of work, we are investigating how the transition from this (left) to this (right) consequently influences the landscape being prone to gully incision.

Aeolian dunes without modern sand supply:

Have:

More biologic crust

More vegetation

Less open sand

Less sand transport

Crusts stabilize sand, dunes immobile.

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… compared with places that still get sand supply

More sand transport = dunes shift, migrate.
Artifacts covered/uncovered by dunes

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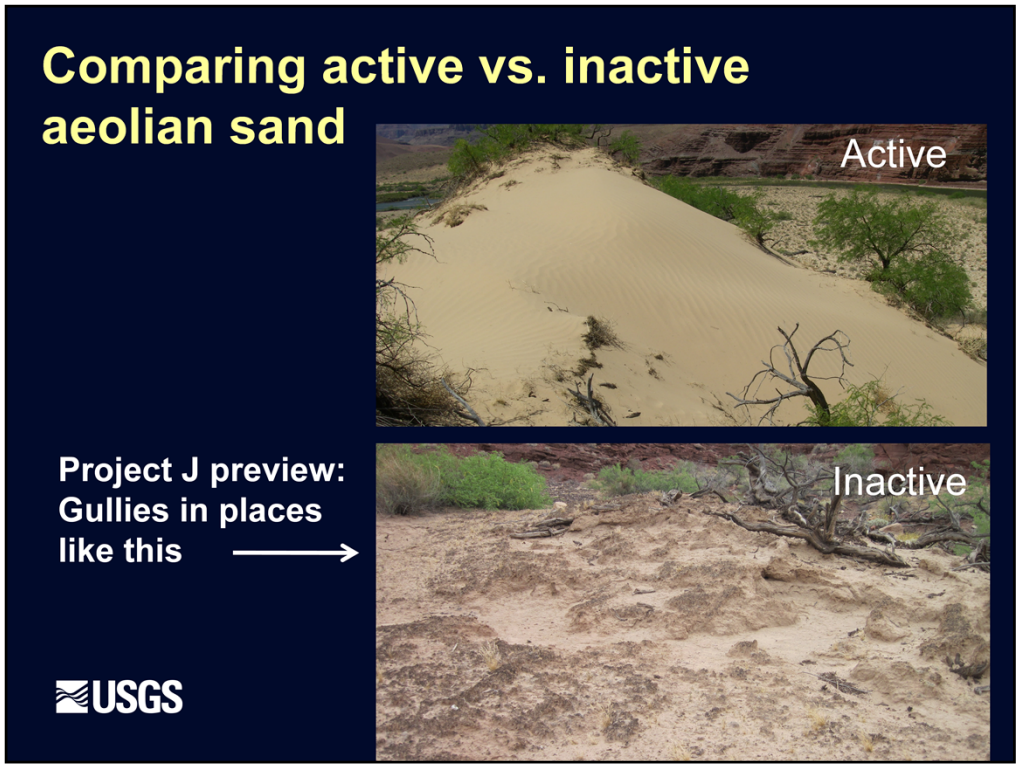
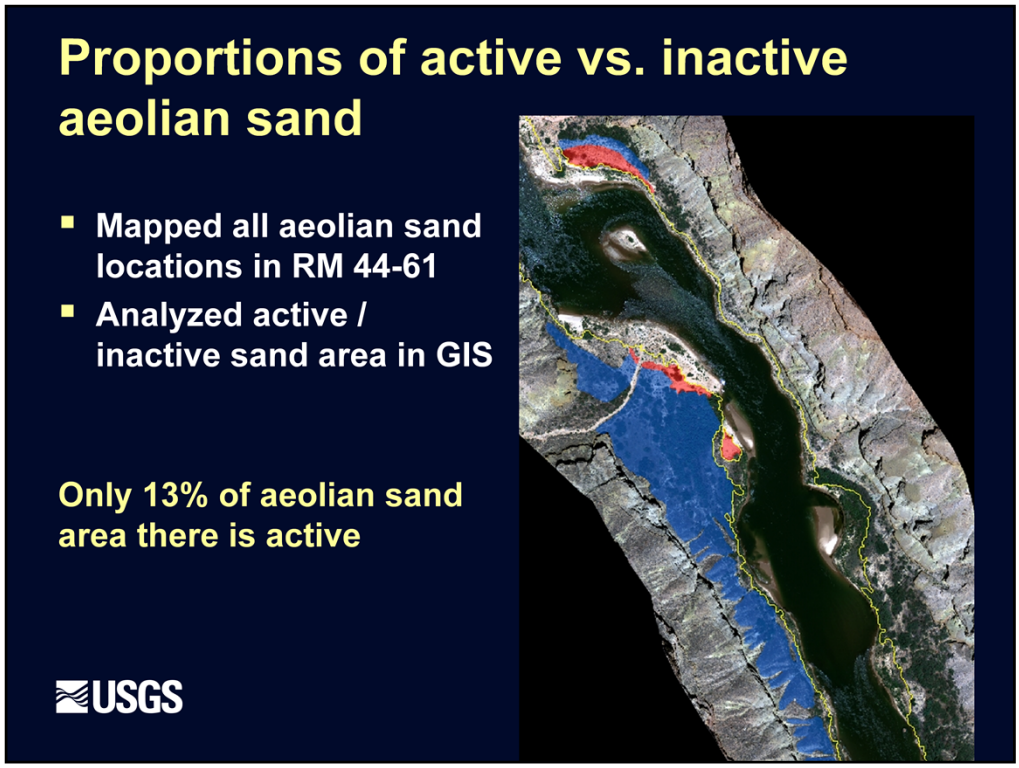
You can learn a lot by mapping out where aeolian deposits are active vs. inactive. Active aeolian deposits are those with evidence for contemporary sand transport (top). Slip faces, nice bedforms. Notice large area without much biologic crust or plant cover. Below, inactive dune is crusted, no ripples.



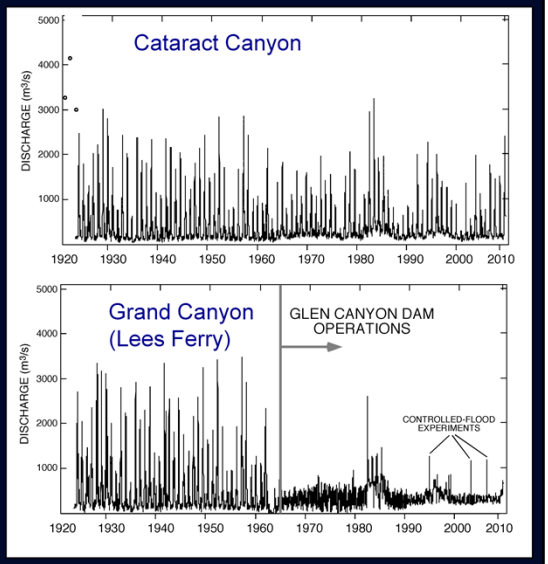
We care about this because gully erosion is almost certainly much more of a problem in aeolian deposits that are inactive, and at arch sites within inactive dunes. I'm fairly confident about that (from observations) but we haven't got much data yet to back up that statement, and we plan to quantify this more completely during Project J.



In 2012, and the couple years before that, I've been going around in different areas and mapping the proportion of active and inactive aeolian sand. I mapped every aeolian deposit in RM 44-61 (Eminence-LCR), found 13% of the sand area there is active.

That means 87% has extensive crust cover and is likely prone to gully incision, potentially affecting any arch sites within that inactive sand area.

Compare with Cataract Canyon, Utah



65% of aeolian sand area is active (Marble Canyon reach had 13%)

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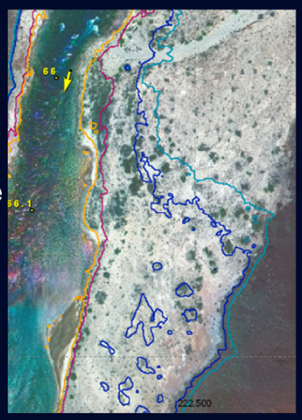
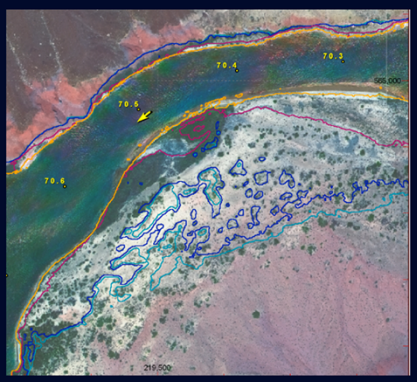
Sand activity in individual dune fields

- Some archaeologically significant dune fields have very little active sand area (mapped RM 66-72 in 2012)
- Influences susceptibility to gully incision

Palisades: 1.6% active sand





70-mile: 4.1% active sand

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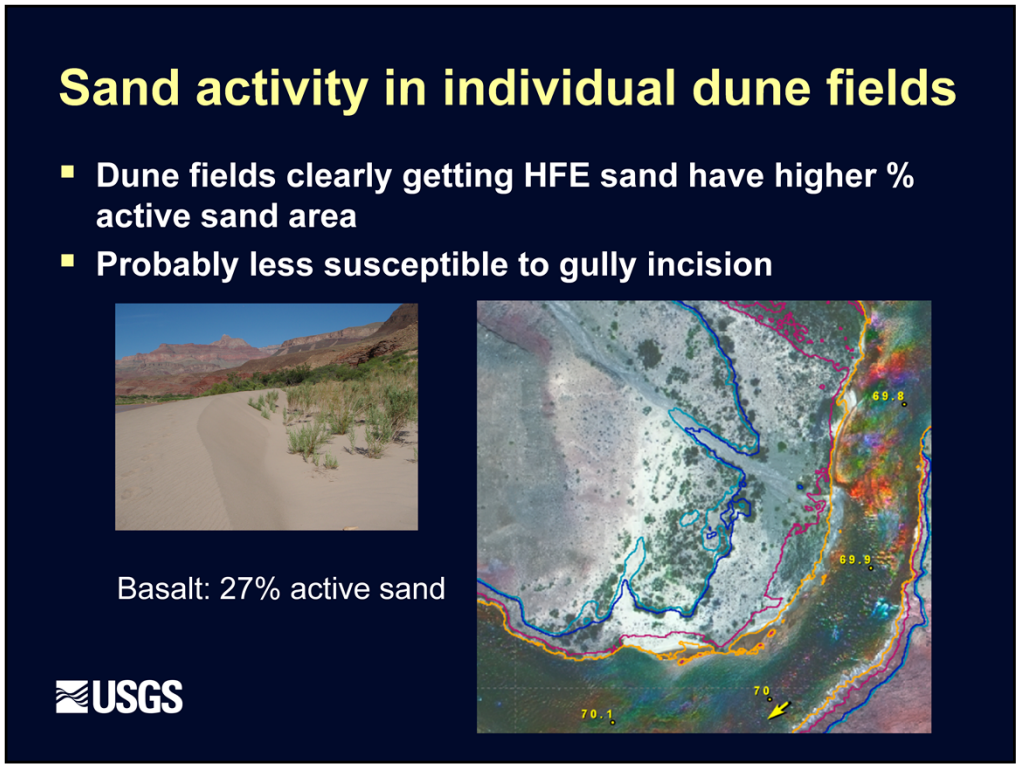

Note that dune fields that are getting HFE sand, like Basalt which we looked at earlier (poster child for HFE sand successfully getting into a dune field) have a lot higher proportion of active sand area. Basalt has about 27% compared to the 1% at Palisades. So the higher prevalence of active sand at a place like Basalt probably means it’s less prone to gully incision, overall, because as we’re going to investigate in Project J, we think gullies don’t tend to get very big in active aeolian deposits.

Project J: 2013-2014
Overview questions

- Do cultural sites erode or change faster or in a significantly different manner than they would if dam operations were different?
- How effective are HFEs at supplying aeolian sand to upland landscapes and archaeological sites, maintaining natural landscape structure and function?

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Project J: 2013-2014

- J1: Cultural-site monitoring in Glen Canyon
- J2: Archaeological site condition, landscape processes at places benefiting from HFE sand
- J3: Large-scale landscape evolution – role of aeolian sand in limiting gully erosion; role of HFEs in maintaining aeolian sand activity

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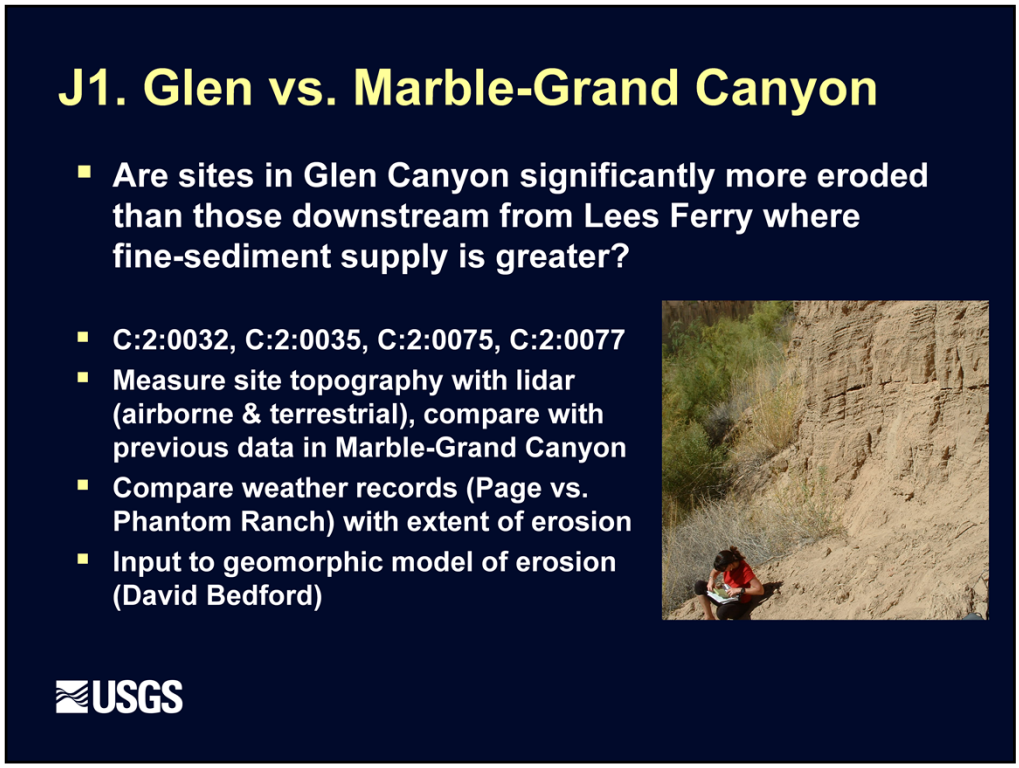


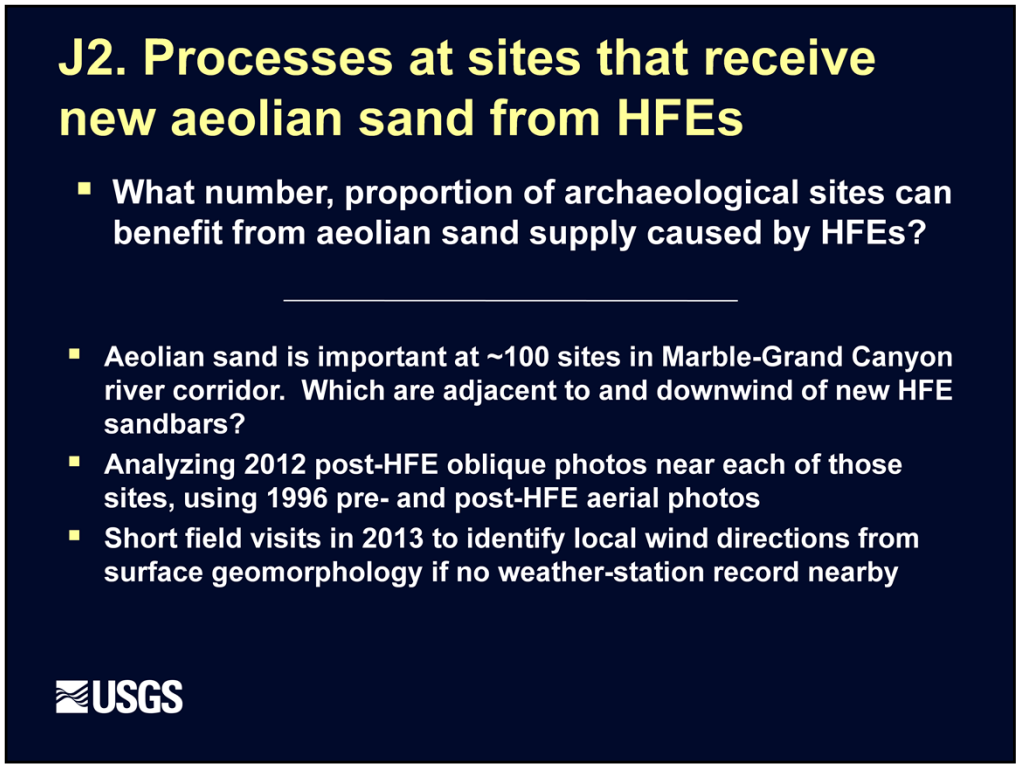
Limitations: we don't have detailed topographic data from every arch site in Marble-Grand Canyon, of course. But should use what we have. There is enough of a range of sites represented from Marble-Grand Cyn (range of site types, condition) that we expect it to yield an informative comparison.

Compare with historical precipitation patterns to see if, once you've accounted for any differences in precip between Glen and Grand Canyons, the Marble-Grand Canyon sites are in better shape.

Weather data from Page since 1957, Phantom since 1966. "Painting with a broad brush", can't resolve small, site-scale changes from each event that way, but should at least tell you whether it supports hypothesis that the greater sediment supply could help sites in Marble-Grand Cyn.

Airborne lidar data from GRCA, 2000. Terrestrial in 2010.

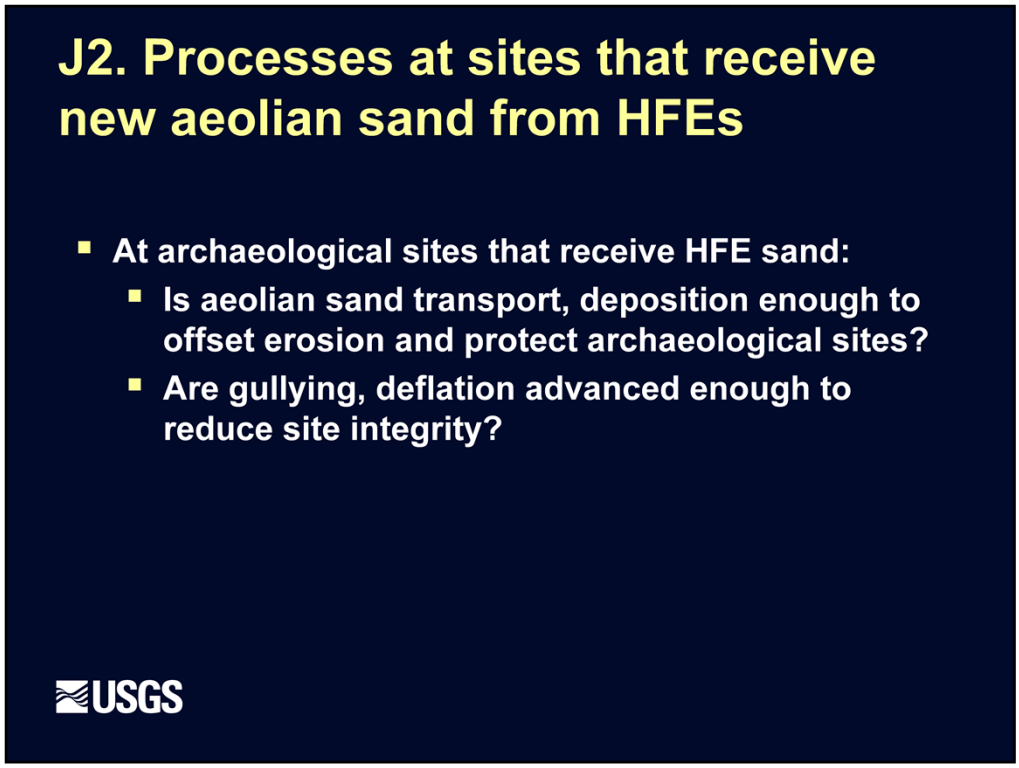
Modeling can be used to evaluate what might happen if you change any of the input parameters: if climate got wetter or drier, or if aeolian sediment supply were to double - ?



J2 deals with understanding site condition in Marble and Grand Canyon, concentrating specifically a few select places that we know do benefit from HFEs.

From our pre-2012-HFE session with the aerial photo books and arch-site GIS, there are approx 100 sites affected by aeolian sand. How many of those ended up with new HFE sandbars upwind, we are trying to figure out with post-flood photos, 1996 photos, and brief stops in 2012 river trip to estimate local wind directions if we don't already know them.

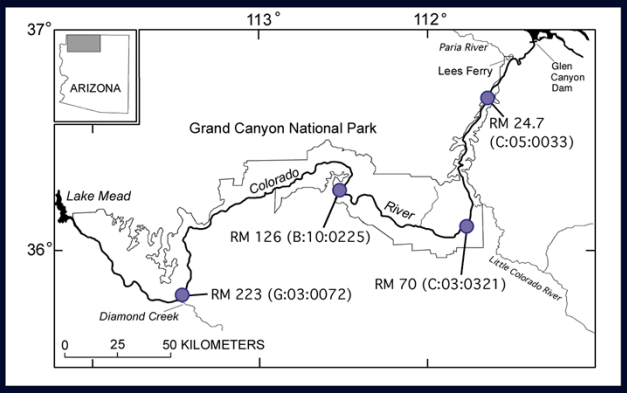
O'Brien and Pederson (2009) listed 232 sites overall.



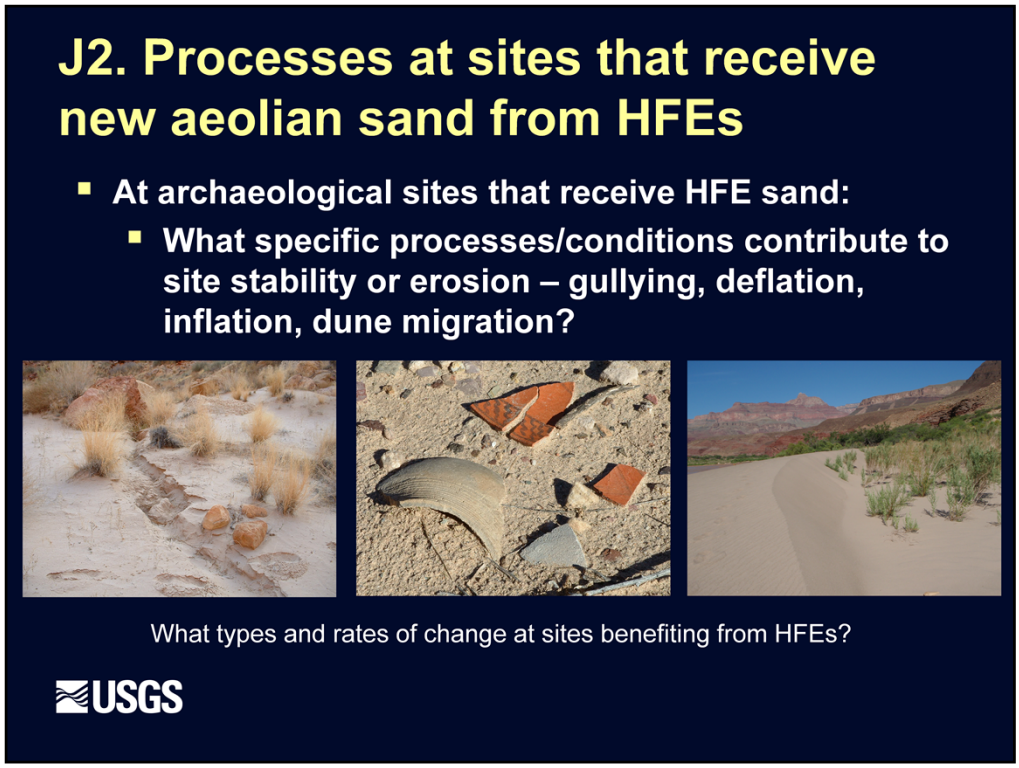
This part of our study concentrates on a few specific places where we know HFEs have an effect. Some dune fields, arch sites get sand after HFEs, others don't. We've talked about that already. But – in the places that do benefit from HFEs, what is happening at those arch sites? We can't assume that just because new sand makes it to an arch site after an HFE that everything is great there now and we never have to worry about erosion of that site again. We're asking – at arch sites that do receive HFE sand, is that aeolian sand transport, deposition enough? Enough to offset erosion, prevent gullying, protect the sites? Or, are gullying and aeolian deflation still enough of a problem at those places to compromise the physical and informational integrity of the site?

J2. Processes at sites that receive new aeolian sand from HFEs

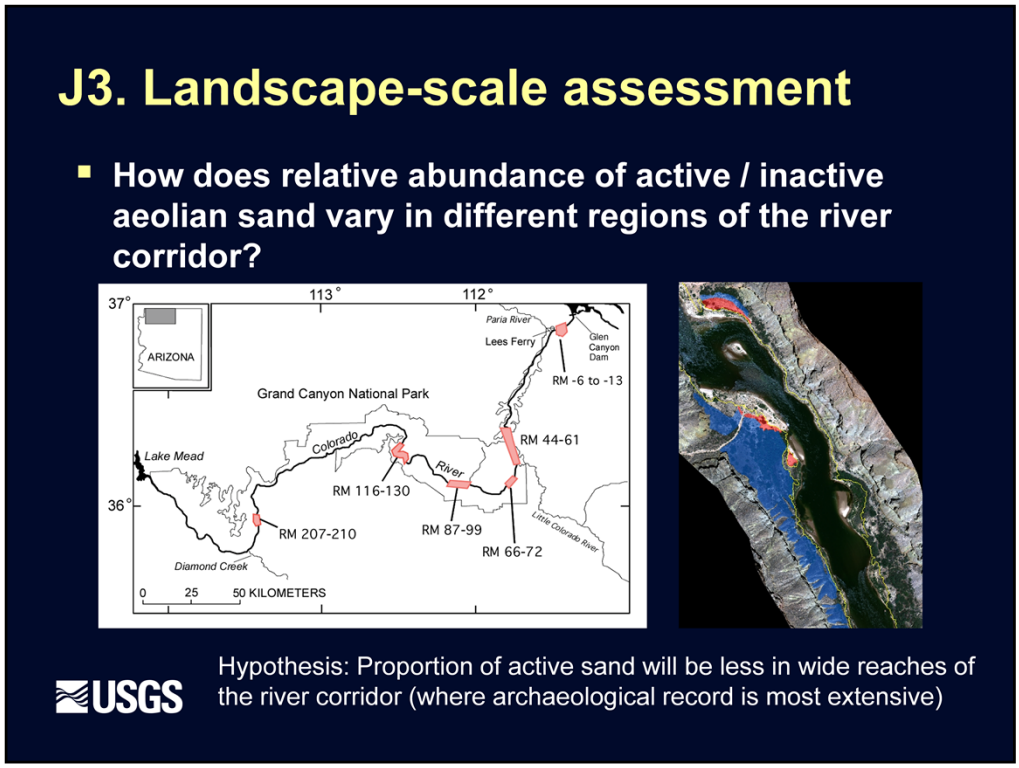
- Measure rainfall, wind at weather stations at 4 sites
- Terrestrial lidar scanning in 2013, 2014
- Stationary cameras for daily record of site conditions



We picked these 4 areas to focus on: 24.5 mile, Basalt, Fossil, and 223 mile. Our goal is to measure, quantify topography and landscape processes at those places by means of instrument stations (wind, precipitation), lidar scanning to quantify topographic change between 2013 and 2014, and stationary cameras taking a picture each day. With the combination of that information, you would be able to tell if, for instance, these sites were in such good shape, so resilient to erosion, that a huge storm comes along, carves big gullies into the dunes, and a couple days or weeks later the gullies have annealed.



So basically, the information we get from those places will tell us: what specific processes contribute to site stability or erosion EVEN THOUGH the HFEs are doing what we intended they would do at those places? How much is site condition altered by gullies, deflation or inflation, dune migration? Once we know that, helps determine what if any mitigation measures will be most effective.



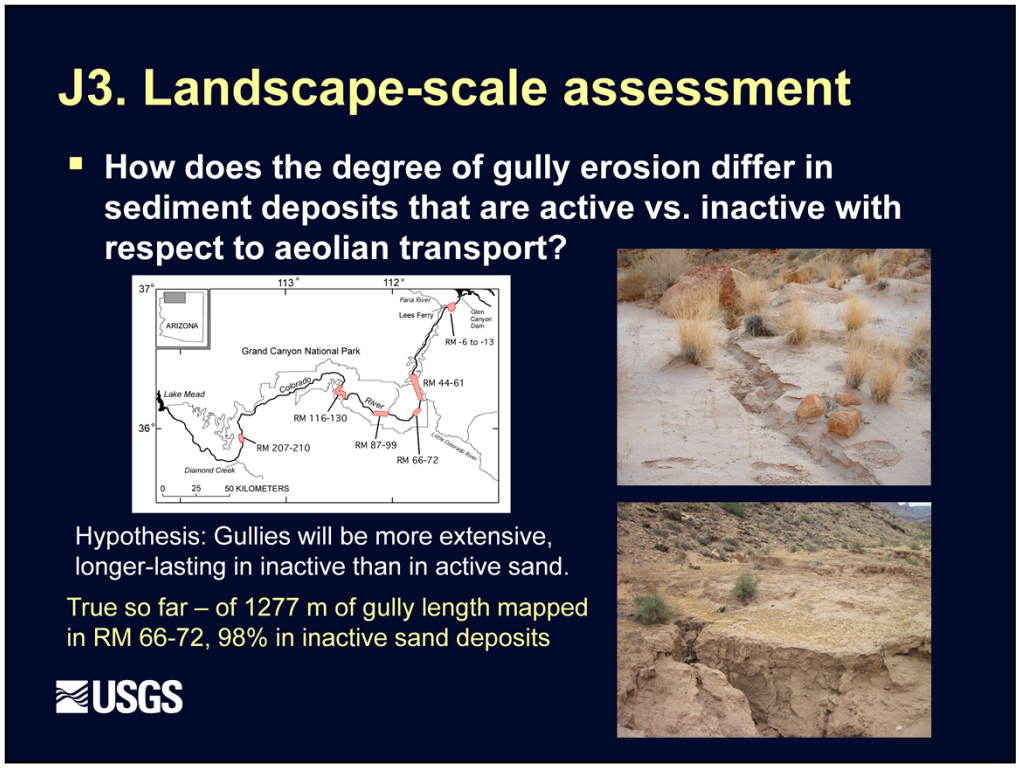
Lastly, J3 incorporates what we learn from individual sites into a larger, landscape-scale assessment.

First question… My hypothesis is that…

The reason I think this could be the case is that in wide sections there is more space to store large, old flood deposits that become aeolian dunes, i.e., a greater width was inundated by the large, 200,000 cfs floods pre-dam, and so a larger proportion of aeolian landscape that's not getting recharged in post-dam time.

The implication here is that inactive sand area is probably more prone to large-scale gully incision, and we are concerned that the largest dune fields, the widest parts of the canyon, with the highest concentration of archaeological sites, could also be the most prone to gully incision.

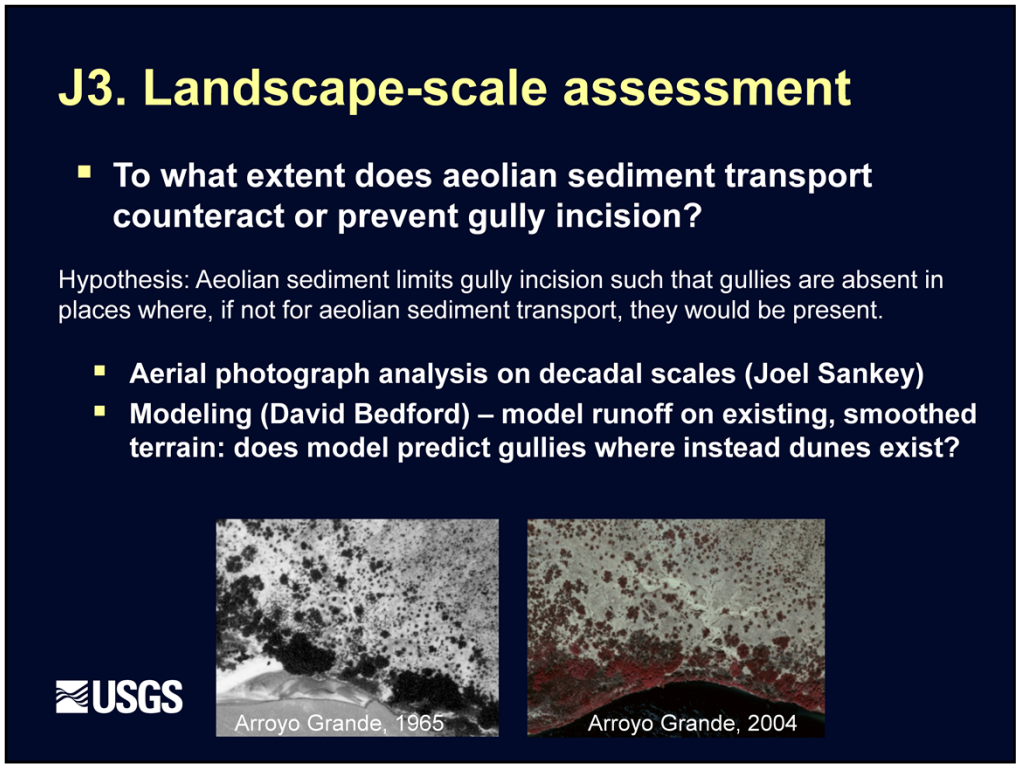
This leads directly into the next question J3 is addressing…



[read it]

We know gullies can occur in active aeolian dunes, after very big storms, but just from observations they appear not to last very long or to get very big. [example from 24.5 mile, lasted a few months]. Aeolian sand transport fills them in. Whereas in inactive dunes, without enough aeolian transport to anneal the gullies, they get much larger and last a long time. These are observations, but haven't been quantified.

Early results: from 2012 – I mapped



How effective, overall, is aeolian sediment transport at preventing or counteracting gully incision? We hypothesize that it's effective enough to have stopped gullies or annealed gullies in places where they otherwise would be present today.

[read hypothesis]

Looking for any examples in aerial photo record where gullies used to exist but are gone later. This analysis will also tell us whether vegetation growth seems to have affected gully extent. Joel Sankey helped develop some techniques to detect vegetation changes from remote-sensing imagery.

Bedford will employ a landscape-evolution model (LEM) already vetted, tested, published, applied to the DEM of river corridor from 2002. Are there places where a robust LEM predicts gullies should be there, but they are not, and aeolian dunes are there instead? IF so, how common are instances like that? If we find NO cases where gullies have annealed on a large scale or are absent where it's likely they'd be present, we'd have to conclude that even though aeolian sand can anneal small gullies or parts of them at smaller spatial and time scales, over the large scale and long term aeolian transport in the post-dam era isn't substantially preventing gully incision.

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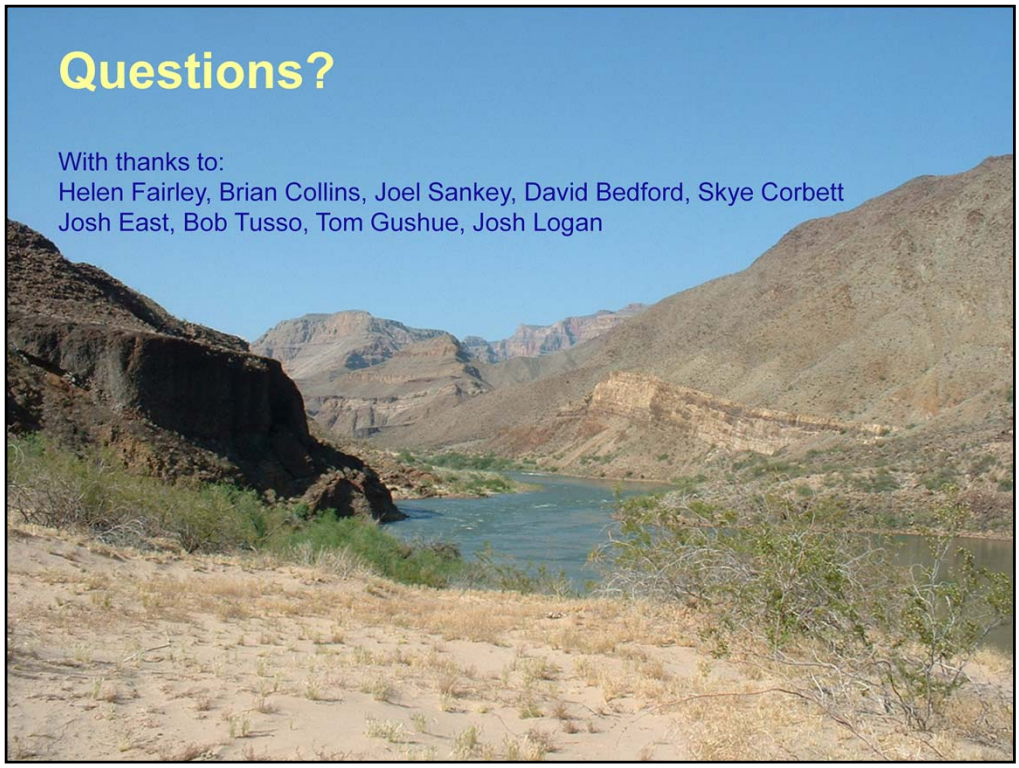

Questions?
With thanks to:
Helen Fairley, Brian Collins, Joel Sankey, David Bedford, Skye Corbett
Josh East, Bob Tusso, Tom Gushue, Josh Logan

Ecosystem role of biologic crust

- Lichens, moss, cyanobacteria, fungi, algae
- Changes soil chemistry, nutrientes, plants, herbivore diet & abundance
- Loss of aeolian sand supply translates into upland ecosystem

Heavily crusted dunes at Granite Park

USGS

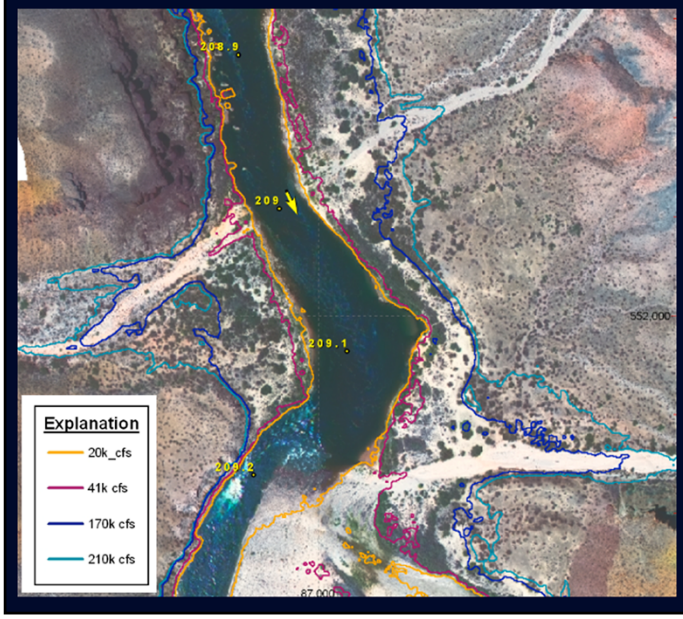
Given the pronounced differences in biologic crust abundance between dune fields that get modern sand supply and those that don't, it is highly likely that soil chemistry and nutrient content of plants also differ between aeolian landscapes with and w/o modern sed supply, and that the effects of dam operations on aeolian sand propagate quite far into the ecosystem.

What about loss of low flows?

- Loss of low flows post-dam means wind can't mobilize sand from fluvial sandbars that were exposed in late summer/ fall
- Less important than loss of flood sand, because timing of low flows and driest, windiest weather didn'tcoincide. Pre-dam spring winds mostly reworked last year's flood sand
- Low flows don't expose sand upwind of large, archaeologically important dune fields

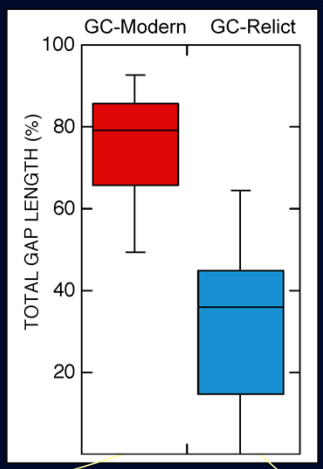
USGS

Most, and largest, dune fields set by 40-year flood (170,000 cfs)



- HFEs cover a small proportion of natural (pre-dam) sand source area
- HFE deposits often too small, far away, blocked by riparian vegetation

Open, bare sand space



These sites get modern wind-blown sand supply after HFEs

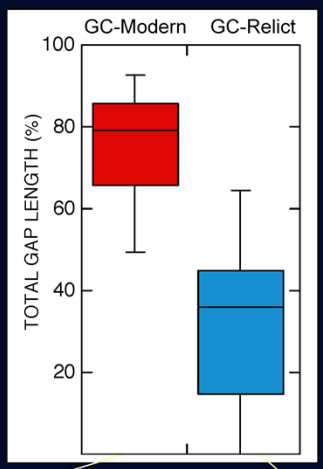
These don't

USGS

Box-and-whisker plots:

Outliers: any points > 1.5 times the inter-quartile range (box length)

Open, bare sand space



These sites get modern wind-blown sand supply after HFEs

These don't

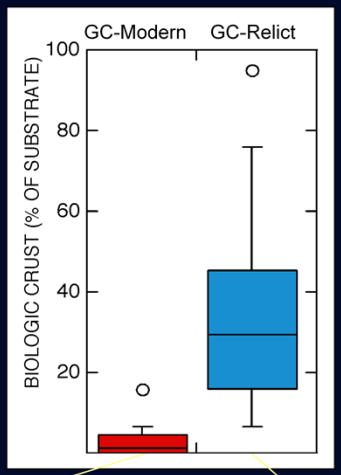
***t*-test → *p* value**

Low *p* values mean the two groups are significantly different

$p < 0.00001$

USGS

Biologic soil crust



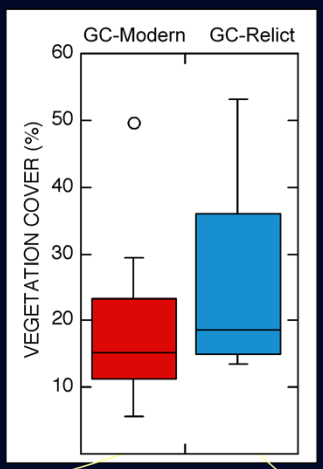
$p < 0.005$

These sites get modern wind-blown sand supply after HFEs

These don't

USGS

Vegetation cover



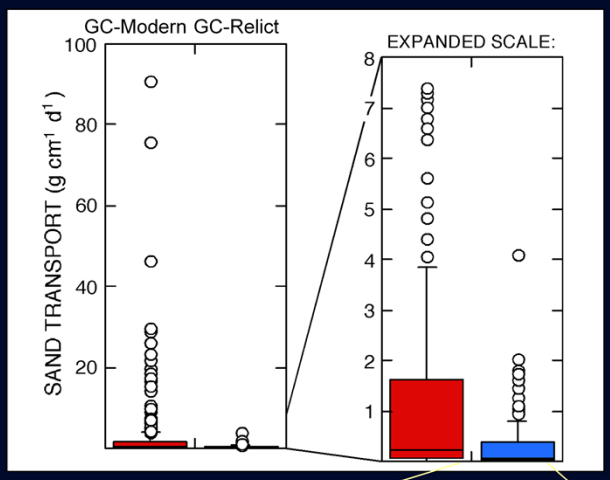
$p < 0.07$

These sites get modern wind-blown sand supply after HFEs

These don't

USGS

Sand transport by wind: raw data



378 measurements

at 14 sites

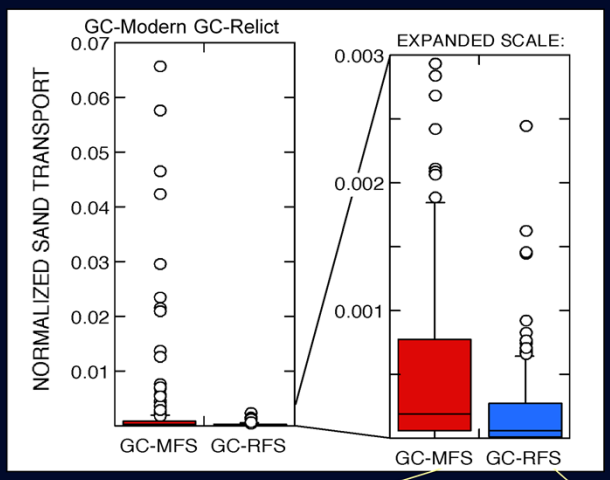
2003 - 2010

These sites get modern wind-blown sand supply after HFEs

These don't

USGS

Sand transport by wind: normalized



$p < 0.05$

These sites get modern wind-blown sand supply after HFEs

These don't

USGS

In work I've done since 2003 we are basically asking, what is the influence of GCD operations ON LANDSCAPES AND THE ARCH SITES WITHIN THEM above the pre- and post-dam high water line? To address this we have to understand fluvial/aeolian interactions.

Example of gully filled by wind-blown sand from a controlled-flood deposit

Head of gully

Middle of gully

Terminus of gully

USGS

Riparian vegetation growth will inhibit aeolian sand supply inland

USGS

Riparian vegetation growth will inhibit aeolian sand supply inland