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Dust-on-snow and hydrologic impacts in the Colorado River Basin

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The dust-on-snow phenomenon was all too obvious to visitors to the high mountains of Colorado in late spring 2009 and 2010. Late-lying snowpacks were strikingly dirty, a reddish-brown color that made the slopes resemble cinnamon toast.

The dust's visual impact is actually an insight into a process that has profound implications for snow and water in the Upper Colorado River Basin (UCRB). Several years ago, researchers confirmed that dust loading in the snowpack alters the energy balance of snowmelt, enhancing melt rates and advancing the timing of spring runoff. In September 2010, a new study quantified for the first time the likely impact of recent dust loading on both the timing and amount of runoff across the entire UCRB (Painter et al. 2010). The startling conclusion was that the dust costs the river about 5% of its annual flow, on average—about 800,000 acre-feet, or more than the annual use of the river by Las Vegas, Denver, Phoenix, and Tucson combined. Here, we summarize the findings of that paper, and their implications for future flows on the Colorado River, within the context of both prior and ongoing research on dust-on-snow.

Dust-on-snow in a nutshell

Soil surfaces in arid regions upwind of the Upper Colorado River Basin (UCRB) are naturally resistant to wind erosion, due to biogenic soil crusts common across the Colorado Plateau and Great Basin. Though virtually wind-proof, these crusts are easily disturbed by compressive force, whether from tires, hooves, feet, or bulldozers. Sediment cores from alpine lakes in the San Juan Mountains of Colorado tell us that dust deposition increased six-fold in the mid-1800s, coinciding with increased settlement and grazing animal use of the region (Neff et al. 2008). The deposition decreased somewhat after the late 1800s, coincident with substantial reductions in sheep and cattle herd sizes, but since then has remained at about five times the natural background levels, due to continued disturbance by an increasing array of agents.

Incoming dust tends to precede or accompany the initial precipitation of storms, forming relatively discrete layers that are buried by subsequent snows (Figures 1a and 1b). As the snowpack compacts and melts down in spring, the layers aggregate at the surface. Our own remote-imaging sensors (i.e., our eyes) nicely capture the radiative impact of the dust: the dusty snow appears dark to us because it is strongly absorbing solar energy in the visible spectrum (Figure 2). Clean snow appears white because it reflects back nearly all of

Figure 1: A) (above) Dust deposition event in progress, April 3, 2009, near the Goodwin-Greene Hut south of Aspen, CO. B) (below) Dust layers from three deposition events exposed in a snowpit near the Goodwin-Greene Hut, April 4, 2009. (Photos courtesy Jeff Deems).

the solar energy in the visible wavelengths. Dusty snow can have albedo (reflectivity) values as low as 0.35 – doubling the amount of absorbed solar radiation versus clean snow. This profound difference in energy absorption is what drives the changes in snowmelt, runoff, and the hydrologic regime.

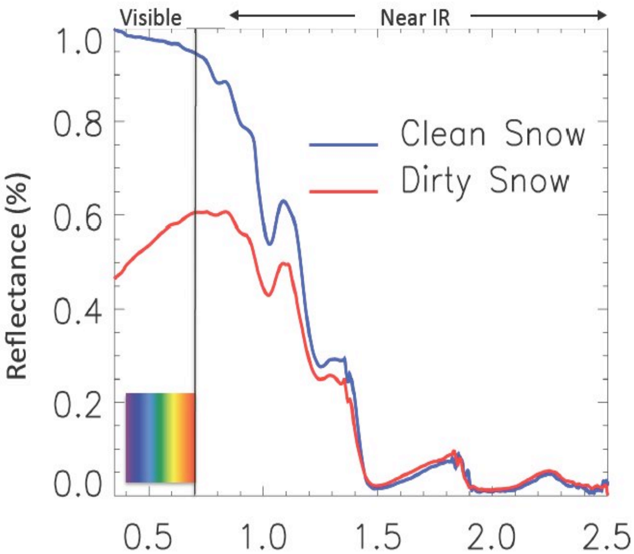

Figure 2. The reflectance spectra for clean snow and dirty snow (with dust loading typical during the snowmelt seasons of 2003-2008). The dirty snow absorbs much more energy at visible wavelengths and in the near-infrared. (After Painter et al. 2007)

Dust and snowmelt

In 2003, Tom Painter, currently a researcher with NASA's Jet Propulsion Laboratory and a WWA team member, began investigating the dust-on-snow phenomenon with an ever-expanding group of collaborators. That same year, Chris Landry, of the Center for Snow and Avalanche Studies in Silverton, CO, developed the Senator Beck Basin Study Area near Silverton. Field studies there, along with simulations based on those observations, confirmed what one would expect from the change in energy absorption—that the "excess" dust (versus the much lower pre-1800s levels) increased the rate of snowmelt and advanced the timing of meltout by about 3–4 weeks (Painter et al. 2007). Furthermore, the dust impact shows year-to-year variation, depending on the amount of dust deposited (affected by drought and disturbance in the source region, and the number of storm events able to carry dust) and also the weather during the spring melt. [For more about this research, see the Feature Article from the July 2008 Intermountain West Climate Summary.]

This research demonstrated the widespread effect of the dust on snowmelt. Hydrographs of runoff in many sub-basins of the UCRB showed earlier-than-average runoff onset and peak runoff during the 2000s, consistent with dust-enhanced melt impacts. These results and observations naturally led to the next question: What are the impacts of dust-driven early snowmelt on runoff timing and volume over the full UCRB?

Dust and Colorado River hydrology – the Painter et al. (2010) study

To examine the impacts of dust-on-snow on Upper Basin runoff, the research team led by Painter and Deems used an advanced hydrology model: VIC, the Variable Infiltration Capacity model, which simulates the balance of water entering into and flowing out of the river basin [see *Additional Resources* below for more information on the VIC model]. They ran the model on the entire UCRB—a scale commensurate with the regional impacts of the dust—under two scenarios: (1) the current dust levels as observed in the field and from satellite imagery from 2003-2008, and (2) the pre-1800s "natural" dust levels as inferred from the lake-sediment studies. The model was run using temperature and precipitation observations for the years 1916-2003 to explore the dust response over a wide variety of annual hydroclimatic conditions, from extreme drought (1934, 1977, 2002) to extreme wet (1983, 1984).

The modeling results indicate that the current (2003-08) dust loadings advance the timing of snowmelt by up to 30 days across the basin (Figure 3), varying with total snow accumulation and forest cover. The shift in timing is greatest above treeline where the radiative forcing of the dust is not lessened by tree cover. Not unexpectedly, the timing of the runoff peak at Lees Ferry, AZ—reflecting the inflows from the entire Upper Basin—is three weeks earlier under the "current dust" scenario, and the annual hydrograph has a steeper rising limb and lower late summer flows (Figure 4). Most critically, the annual (water-year) runoff at Lees Ferry is reduced by 5% under the current dust scenario.

So why does dust decrease the overall runoff in the Upper Colorado River Basin? The VIC modeling, which represents all of the relevant physical processes, tells us that the decline has multiple causes. First, the greater absorption of energy during snowmelt causes more of the snow to sublimate directly into the atmosphere. The primary impact comes from the earlier meltout, which exposes the ground surface to sunlight and warmth earlier—which both allows more evaporation of water directly from the soil, and extends the growing season for plants that then can transpire additional water. It is this combined increase in evapotranspiration that appears to have the most impact on streamflow. The modeling also indicated that the "lost flow" under the current dust scenario varies substantially from year to year, from a low of 2% to a high of over 7%. The greatest loss of flow in both percentage terms and absolute terms (up to 1.5

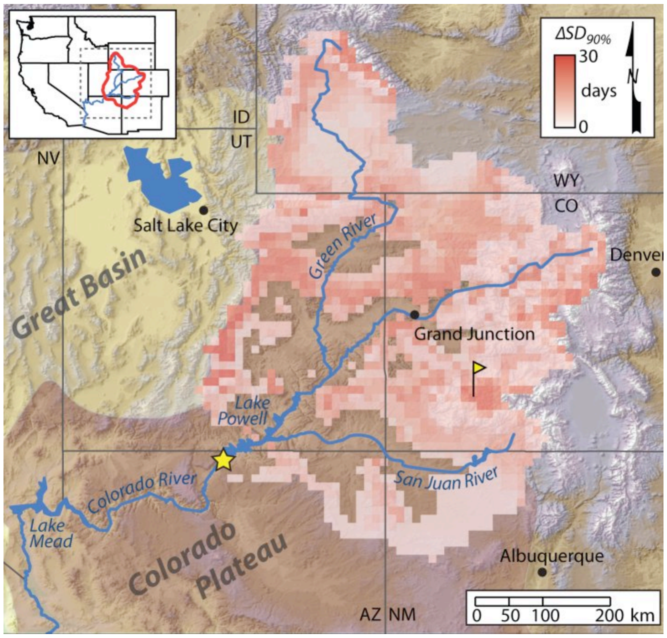

Figure 3. Change in the timing of meltout in the Upper Colorado River Basin under current dust loading vs. pre-1850 dust loading, as modeled using the observed annual climatology from 1916-2003. All grid boxes show an advance in timing, up to 30 days. (Painter et al. 2010)

million acre-feet) comes in the high-flow years, since the more extensive and longer-persisting snowpacks increase the time period over which dust has its impact, producing larger differences in melt-out date between scenarios.

Implications for water and land management

The bad news for water managers and users is that the excess dust loading, as observed from 2003–2008, may "rob" the Colorado River system of an average of 800,000 acre-feet of water annually, which is no small change at a time when the system is operating on such a narrow margin. One should note that this dust-caused loss has likely been of similar magnitude since the early 1900s, so basin-wide water management and planning has been developed under the lower flow regime caused by dust—in other words, the dust impact is embedded in what we consider 'normal'. But the spatial and year-to-year variability in dust loading, and resulting impacts on the hydrograph, complicates the forecasting, storage, and allocation of runoff at all basin scales (see the CODOS program under *Additional Resources,* below).

The good news is that the runoff loss caused by excess dust is potentially reversible, since the primary cause of excess dust entrainment from the Colorado Plateau is disturbance from land uses such as grazing, oil and gas drilling, dryland agriculture, and off-road vehicle use. Changes in land management to promote soil stabilization and revegetation in those areas could decrease dust loading and its hydrologic impact. USGS ecologists and geoscientists led by Jayne Belnap, and WWA researcher Jason Neff, are working to better understand the contributions of each land use to the overall dust picture and how best to ameliorate their impacts.

Even more dust in 2009 and 2010

To assess the impacts of "current" dust loading, the Painter et al. runoff study used data from 2003 to 2008, a period during which the number of major dust deposition events varied from 3 to 9 per year, with an apparent increasing trend. Then, in the winter of 2008–09, 12 events occurred, and in 2009–10, 10 events occurred. But more striking than the number of events in those two years was the huge increase in total dust loading in the snowpack, which in the Senator Beck Basin in the San Juans was roughly an order of magnitude greater in 2009 and 2010 than that observed in 2005–08. Preliminary simulations indicate that the dust loading in 2009 and 2010 advanced snowmelt by about 7 weeks in Senator Beck Basin, compared to 3–4 weeks for 2003-2008.

It is not clear why the dust loading was so much greater in 2009 and 2010 than the previous several years, nor whether these two years reflect a new "dust regime" more representative of future conditions. The Colorado Plateau region has been experiencing persistent drought conditions since 2000, which may have progressively reduced annual vegetation cover. At least some

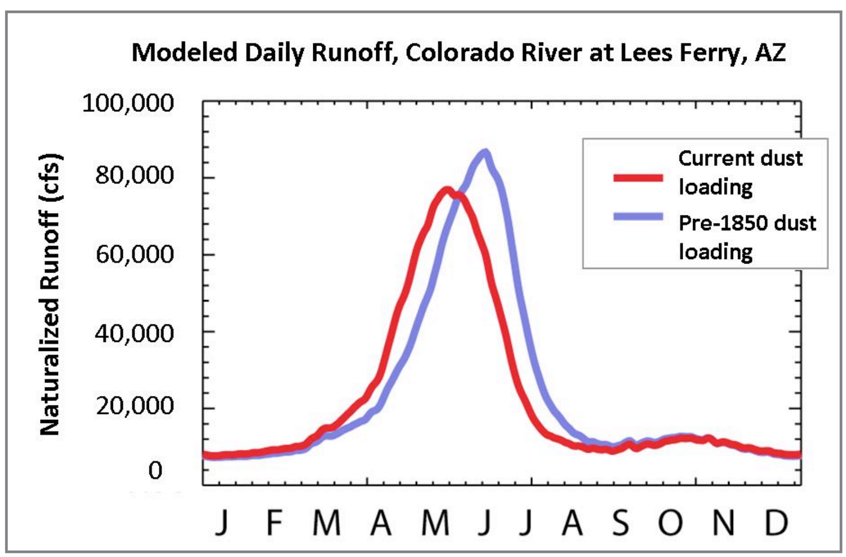

Figure 4. Modeled daily naturalized runoff for the Upper Colorado River Basin, under two dust-on-snow scenarios. Under current (2003–2008) dust loading, the hydrograph has an earlier (by 3 weeks) and lower peak, a steeper rising limb, and lower annual flow. (After Painter et al. 2010)

land disturbances, such as road building for oil and gas drilling, are likely to have increased during this same time span. Given projections of enhanced drought and continued disturbance in the dust source regions, the 2009 and 2010 dust loadings could well be an indication of future conditions. The researchers who produced the Painter et al. study are now updating their modeling and analyses to assess the impact of the 2009 and 2010 dust loading, and potential interactions with climate warming.

Dust and future climate change

Projections of climate change from global climate models, when coupled with hydrologic modeling using VIC or other models, have suggested that the warming projected for the UCRB will decrease average annual flow at Lees Ferry by 7–20% by mid-century under mid-range emissions scenarios. But these modeling exercises did not account for the potential for enhanced dust impact to snowpacks like the events of 2009 and 2010. Even the "current" (2003–08) dust loading represents a radiative forcing on snowpack that is much larger than the greenhouse gas forcing on global climate. So what happens to the hydrology of the Colorado River when the current dust loading occurs in a warmer climate? And what flow fractions could potentially be recovered in a future climate by making dust reduction a land management goal?

Deems' and Painter's ongoing projects, funded by the Western Water Assessment and NASA, are intended to answer these questions. The VIC hydrology model is again being used to simulate snowpacks, snowmelt, and runoff across the Colorado River Basin, under the projected climate changes plus the two dust scenarios used in the Painter et al. (2010) study. Preliminary results indicate that the additional advance in the timing of peak runoff from climate warming is actually less under the "current dust" scenario than under cleaner conditions, since the radiative forcing from dust is vastly greater than the sensible heat and longwave radiation forcings from warmer temperatures. The upshot of the results so far is that the hydrologic impact of dust-on-snow now is comparable to that expected from just from climate change in 30 to 50 years. Their combined impacts will not be strictly additive, but certainly worse than those from climate change or dust alone.

A more troubling aspect of the future-climate-change/dust-on-snow combination is the likelihood that climate change will increase the potential for dust loading. As temperatures warm, higher evapotranspiration will tend to dry out the soils and plants in the dust source region and further stress the vegetation cover holding the dust in place. Furthermore, precipitation in the southern Colorado Plateau region is expected to decrease, though the direction and magnitude of change are much more uncertain than the temperature change. Should climate change drive persistently higher dust loading on the snowpacks, on the order of 2009 and 2010 or beyond, that would effectively overwhelm climate change's direct impact on snowpacks and hydrology.

Other aspects of the future environment for dust-on-snow that remain uncertain and deserve further study include:

- Will snowpack accumulation (snowfall) increase or decrease across the Colorado River basin?
- Will the amount of cloudiness in spring change in a future climate, changing the radiative input to the snowpack?
- How will dust-on-snow impacts interact with the effects on forest cover and hydrology of the ongoing mountain pine beetle (MPB) infestation? [See the Feature Article in the May 2010 IWCS for more on the hydrologic impacts of the MPB infestation.]

So far, the winter of 2010–2011 has provided a nice respite from the chronic low-snow and low-flow years of the 2000s in the Upper Colorado River Basin. As of January 16, the basin-wide snow-water equivalent (SWE) was 131% of the long-term average, the highest value for this date since 1997. No dust-on-snow events have been observed in the basin yet this winter, but most events occur after March 1. La Niña events are typically associated with below-average precipitation in the dust source region during spring (see Figure 2c in the Feature Article, October 2010 IWCS), and this tendency is reflected in the seasonal outlooks for spring 2011 issued by NOAA CPC. Should the unusually high snowpacks persist until the melt season, and dust loadings at least to the level of 2003–08 occur, we may be able to evaluate the expectation from the Painter et al. (2010) study that the greatest loss of flow will occur in the high-snowpack years.

Additional Resources

Center for Snow and Avalanche Studies (CSAS):
http://www.snowstudies.org

Description of the Senator Beck Basin Study Area at CSAS:
http://www.snowstudies.org/sbbsa1.html

Colorado Dust-on-Snow (CODOS) program at CSAS – CODOS conducts dust-on-snow monitoring throughout the Colorado mountains, enabling water managers to include the effects of dust-on-snow into their forecasts of snowmelt timing and intensity:
http://www.snowstudies.org/codos1.html

USGS Dust Monitoring project – the USGS Flagstaff office is monitoring dust emission events, and providing satellite imagery of emission events:
http://sgst.wr.usgs.gov/dust_monitoring/

Dust Collection Network – Jason Neff, WWA team member

with the Geological Sciences Department at the University of Colorado, maintains a website detailing his team's dust monitoring efforts on the Colorado Plateau:
http://moab.colorado.edu/BSNE/Dust2Dust/Home.html

Variable Infiltration Capacity (VIC) Macroscale Hydrological Model Homepage, University of Washington:
http://www.hydro.washington.edu/Lettenmaier/Models/VIC/

References

Neff, J. C., A. P. Ballantyne, G. L. Farmer, N. M. Mahowald, J. L. Conroy, C. C. Landry, J. T. Overpeck, T. H. Painter, C. R. Lawrence and R. L. Reynolds. 2008. Increasing eolian dust deposition in the western United States linked to human activity. Nature Geoscience, 1, 189-195.

Painter, T. H., A. P. Barrett, C. C. Landry, J. C. Neff, M. P. Cassidy, C. R. Lawrence, K. E. McBride and G. L. Farmer. 2007. Impact of disturbed desert soils on duration of mountain snowcover. Geophysical Research Letters, 34. DOI:10.1029/2007GL030284.

Painter, T. H., J. Deems, J. Belnap, A. Hamlet, C. C. Landry, and B. Udall. 2010. Response of Colorado River runoff to dust radiative forcing in snow. Proceedings of the National Academy of Sciences, published ahead of print September 20, 2010, doi:10.1073/pnas.0913139107.