Less Snow

- In Colorado, individual snow course data taken on April 1st since 1950's show 20-60% decline

We know the Earth is warming. We know that will stress water in the West. But we don’t know how.
Recent studies indicate ~3-4% decline in annual runoff in CO for every 1° F of warming.
What we need to know about snow

Practical Applications

• Precipitation
  – Snowfall
• Snow on the ground
  – Depth
  – Density
  – SWE

Hydrologists are most interested in the snow water equivalent (SWE) of snow.
Snow Cover Distribution
Snowpack amount varies in space and time

- Point to Point
- Elevation
- Aspect
- Wind Redistribution
- Vegetation and Interception
- Topography

Figure 5-3. Conceptual representation of snow accumulation versus snow depletion (from Davison, 2004).
SWE Measurement

Ground Observations (in situ = on site)

Snow Pits
Measure vertical profiles of SWE, and other snow pack variables.

Snow Courses with Snow Tube
Transects with snow depth and mass of snow core

Snow Pillows, SNOTEL
Western U.S.
NRCS Snow course

Weigh sample, subtract weight of sample tube, result is SWE in inches of water
Snowcourses

The problems

• only 3-5 data points per year?
• never exact timing.
• always an element of exposure/danger.
• always human error.
• Weather.
• high training overhead.
Anatomy of a SNOTEL site

- Air Temp Sensor
- Solar Panel
- Snow Depth Sensor
- Radio Antenna
- Ground Truth Marker
- Shelter with instrumentation
- Precipitation Gauge
- SWE Pillow
snow station data

snow course measurements
• higher spatial representation/coverage
• lower temporal resolution
• statistics

SNOw TELemetry (SNOTEL)
• lower spatial representation/coverage
• higher temporal resolution

Additional Considerations
• Relevancy to water professionals
• Public Understanding
• Accessibility
• Interpolation/Statistics
• Costs (financial, human resources, instrumentation, maintenance)
Forecast skill has decreased at many forecast points in the West due to increased climate variability.

Stationarity Is Dead: Whither Water Management?

P. C. D. Milly,¹* Julie Botancourt,² Malin Falkenmark,³ Robert M. Hirsch,⁴ Zbigniew W. Kundzewicz,⁵ Dennis P. Lettenmaier,⁶ Ronald J. Stouffer⁷

Systems for management of water throughout the developed world have been designed and operated under the assumption of stationarity. Stationarity—the idea that natural systems fluctuate within an unchanging envelope of variability—is a foundational concept that permeates training and practice in water-resource engineering. It implies that any variable (e.g., annual streamflow or annual flood peak) has a time-invariant (or 1-year–periodic) probability density function (pdf), whose properties can be estimated from the instrument record. Under stationarity, pdf estimation errors are acknowledged, but have been assumed to be reducible by additional observations, more efficient estimators, or regional or paleohydrologic data. The pdfs, in turn, are used to evaluate and manage risks to water supplies, waterworks, and floodplains; annual global invest-

Climate change undermines a basic assumption that historically has facilitated management of water supplies, demands, and risks. That has emerged from climate models (see figure, p. 574).

Why now? That anthropogenic climate change affects the water cycle (9) and water supply (10) is not a new finding. Nevertheless, sensible objections to discarding stationarity have been raised. For a time, hydroclimate had not demonstrably exited the envelope of natural variability and/or the effective range of optimally operated infrastructure (11, 12). Accounting for the substantial uncertainties of climatic parameters estimated from short records (13) effectively hedged against small climate changes. Additionally, climate projections were not considered credible (12, 14).

Recent developments have led us to the opinion that the time has come to move beyond the wait-and-see approach. Projections of runoff changes are bolstered by the recently demonstrated retrodictive skill of cli-
SWE descriptor variables

- **date of peak SWE**
- **cumulative SWE**
- **length of season**

April 1\textsuperscript{st} SWE

- **peak SWE**
- **SWE**
- **length of season**
- **date**
- **date of peak SWE**
Center for Snow and Avalanche Studies
Senator Beck Study Basin
Approximately ~13 miles from the Rio Grande Watershed
Measuring and Modeling our Snow Water Resources
Presented by Jeff Deems & Noah Molotch

Center for Snow and Avalanche Studies
Helping Fill the Monitoring Gap at Higher Elevations

Senator Beck Study Plot
12,186’ (3714 m)

Swamp Angel Study Plot
11,060’ (3371 m)

Upper Colorado River Basin: 50% of streamflow is generated above 9,843’ (3,000 m)

Upper Colorado River Basin: 40% of streamflow is generated above all SNOTEL’s

Snowpack monitoring workshop for drought planning and Streamflow Forecasting: Broomfield, Colorado, September 9, 2015
http://www.colorado.edu/events/workshops/COsnow2015.html
SWE Measurement

Snowpack monitoring

- **SNOTEL**
- **Satellite**
- **Airborne**

**Grid Size**
- 10-50 km
- 1 km
- 1 m
Snow Depth & SWE from LiDAR

- Spectrometer maps albedo
- Majority of SWE spatial variability due to snow depth
- Depth can be measured by differential elevation mapping
  - collect snow-free & snow-covered data sets
  - difference gives snow depth
  - classify & remove vegetation points
  - subtract snow-free from snow-covered
- Apply obs/modeled density
  - SWE = depth * density
  - SNOTEL/manual obs + snow model can estimate density well
Currently lacking the combination of spatial resolution, temporal resolution and depth-integrated metrics
EYES ON THE SNOW

Remote-sensing measurements could finally let scientists monitor Earth's snow resources—which provide drinking water for billions of people. NASA is planning to test various combinations of sensors to see which do best at quantifying how much snow lies on a landscape and how quickly it is likely to melt away.

- Passive microwave detector: To calculate snow depth
- Hyperspectral/multispectral imager: To measure snow cover, albedo, and grain size
- Radar: To calculate snow depth
- Passive visible light/infrared detector: To measure snow cover and albedo
- Lidar (laser altimeter): To calculate snow depth
<table>
<thead>
<tr>
<th>Type</th>
<th>Snow sensing/estimation Technique</th>
<th>Snow Characteristic</th>
<th>Gap Capabilities</th>
<th>Space Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Snow Depth</td>
<td>SWE</td>
<td>Melt</td>
</tr>
<tr>
<td>Lidar</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Ka-band InSAR</td>
<td></td>
<td></td>
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<tr>
<td>Dual band Ku/Ka</td>
<td></td>
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<td></td>
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<tr>
<td>Stereo Photogrammetry</td>
<td></td>
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<td></td>
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<tr>
<td>Wideband Radiometer</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Ku-band SAR</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Passive Microwave</td>
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<td></td>
</tr>
<tr>
<td>L-Band InSAR</td>
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<tr>
<td>Signals of Opportunity</td>
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<tr>
<td>FMCW Radar</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Gamma</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Green – Demonstrated capability. May not work in all areas, but uncertainty is understood. May still benefit from additional research and algorithm development. TRL > 5?

Yellow – Potential capability identified and validated in multiple studies. Research needed to better quantify uncertainty. TRL 3-5?

Orange – Potential capability identified, but uncertainty not quantified. High risk. TRL 1-2?

Red – No Capability

Images:
- Snow depth (cm)
- Types of snow:
  - Snow depth
  - Tundra
  - Peat
  - Alpine
  - Marine
  - Ephemeral
  - Perennial
- Snow characteristics:
  - New snow
  - Residual snow
  - Fine-grained
  - Medium-grained
  - Coarse-grained
  - Wetted snow
  - Wind slab
  - Depth hoar
  - Ice

Legend:
- Snow depth categories: 0-50, 50-100, 100-150, 150-200, 200-250
Snow melt is driven by surface energy balance

\[ Q_m + \frac{dU}{dT} = (1 - a)S + L^* + Q_s + Q_v + Q_g \]

- Change in internal energy
- Energy available for melt
- Albedo
- Shortwave radiation
- Longwave radiation
- Sensible heat/advection
- Latent heat
- Ground heat

Graph showing differences between regions:
- Greenland
- Swiss Alps
- Rocky Mountains
- Antarctica
- Himalaya
Solar radiation (not air temperature) drives snowmelt!!
Effects of Dust-on-Snow
Snowmelt and River Forecasting

Dust accumulates on surface

Rabbit Ears Pass, Colorado

April, 2009
May, 2009

43 ppmw
52 ppmw
306 ppmw
406 ppmw

Dust-on-Snow Effects
• Timing of snowmelt
• Rate of snowmelt
• Reduce total runoff yields

Near Aspen
April 3, 2009
Silverton
April 3, 2013
Dust-on-Snow Events are Extensive but Not Always Apparent

May 9, 2013 – Hoosier Pass

May 10, 2013 – Berthoud Summit

D8

D6
Knowing the MAGNITUDE and TIMING/INTENSITY of snowmelt runoff requires knowing SNOW WATER EQUIVALENT & SNOW ALBEDO.
Furthermore, it has been shown that variation in the rate at which river flows in the eastern portion of the Upper Colorado River Basin is controlled by variability in dust radiative forcing and not by variations in spring air temperatures [Painter, Skiles, Deems, and others]
Dust forces snowmelt earlier

Swamp Angel Study Site: observed & modeled SWE

<table>
<thead>
<tr>
<th>Year</th>
<th># dust events</th>
<th># spring dust events</th>
<th># days melt advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>4</td>
<td>4</td>
<td>28</td>
</tr>
<tr>
<td>2006</td>
<td>8</td>
<td>6</td>
<td>31</td>
</tr>
<tr>
<td>2007</td>
<td>8</td>
<td>6</td>
<td>30</td>
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<tr>
<td>2008</td>
<td>9</td>
<td>9</td>
<td>26</td>
</tr>
<tr>
<td>2009</td>
<td>12</td>
<td>9</td>
<td>50</td>
</tr>
</tbody>
</table>

Center for Snow and Avalanche Studies
Senator Beck Basin Study Plot
www.snowstudies.org

Early melt shifts hydrograph

Shift in hydrograph toward earlier flows in spring, and diminished flow in late spring and summer

Runoff at Lee’s Ferry, AZ

3 week earlier peak

Steeper rising limb

Daily averages, 1916-2003

Painter, Deems, et al., PNAS (2010)
Longer growing season increases ET

Decrease annual runoff in UCRB by ~ 5% on average

Painter, Deems, et al., PNAS (2010)
Dust from the southern Colorado Plateau—the biggest dust source today in the U.S.

Dust from NE Arizona is deposited on Colorado mountain snow cover.
Dust deposition increased after settlement

Neff et al. (2008) Nature Geosciences
Dust deposition increasing since mid-90’s


Increasing aeolian dust deposition to snowpacks in the Rocky Mountains inferred from snowpack, wet deposition, and aerosol chemistry

David W. Clow a,*, Mark W. Williams b, Paul F. Schuster c

a Colorado Water Science Center, United States Geological Survey, Denver Federal Center, MS 415, Denver, CO 80225, USA
b Department of Geography, University of Colorado at Boulder, UCB 360, Boulder, CO 80309, USA
c National Research Program, United States Geological Survey, 3215 Marine St., Boulder, CO 80303, USA

Soil Erosion In The West Is Getting Worse And The Air Is Getting Dustier

By: Ali Budner • 21 Hours Ago

DIAGRAM
Mountain West

Share · Tweet · Email
Colorado Basin River Forecast Center (CBRFC)
Snowmelt Forecast Errors and Dust

- CBRFC uses SNOW17 temperature-index model
- This approach breaks down when conditions deviate from average
- Dustier than average snowpack brings earlier snowmelt than what SNOW17 predicts
- Larger streamflow prediction errors are correlated with dustier years

Before “cranking up the melt” – sim Q is too low
After “cranking up the melt” – sim Q matches much better

West Gulf RFC: Do not make adjustments based on dust observations.

Credit: plots courtesy B. Bernard (CBRFC)
Eleven Dust-on-Snow Monitoring Sites

WATER YEAR 2020 UPDATES

- February 5, 2020: Weather and Snow Summary, New Assistant, Alamosa Radar Video
- December 18, 2019: Weather and Snowpack Summary, AVy Links, Happy Holidays
- November 27, 2019 Update: Hello Winter, Snow School, Colorado Gives Day
- October 22, 2019 Update: Snow School, SnowEx, IPCC, Etc...

WATER YEAR 2019 UPDATES

- September 21, 2019: WY2019 Season Summary
- June 20, 2019 Update: 1st Precip, Wintry Weekend, Journal Publication
- June 16, 2019 Update: Melt Rates, Plots, Still Lots of Snow
- June 7, 2019 Update: Dust Out, Sun Out, Surf’s Up
- June 4, 2019 CODOS Update: CODOS Tour Part II, Dust Erupted at SASP
Below Slides Not Used
Balance between incoming/emitted terrestrial radiation

Turbulent fluxes

Sum of energy balance terms. Snow at 0°C = Energy for melt

Balance between incoming/emitted solar radiation

Energy in (W/m²)

Energy out (W/m²)
Center for Snow and Avalanche Studies

- Climate and Snow, Past and Future
- Measuring Snow
- Dust-on-Snow
We know the Earth is warming. We know that will stress water in the West. But we don’t know how.

Earlier Snowmelt

- Climate Change already impacting the basin
  - Temps for sure, maybe precipitation
- Impacts will get Worse
  - “New Normal” inadequate to convey challenges
  - Aridification underway – not a drought
- Plan on...
  - Heat! More and More as the Century Proceeds
  - Shifting runoff patterns
    - South (Dry) and North (Less Dry to Perhaps Wet)
    - Earlier within-year runoff
  - More WX Variability
    - year to year, within-year
  - Substantial Flow Reduction Risk
  - Substantial Megadrought Risk
  - Flood Risks
    - Localized – Likely
    - Basin-wide - ??
  - Higher Water Temperatures
  - Fires
- Opportunity for Change
<table>
<thead>
<tr>
<th>CODOS and Other SNOWTEL Sites - WF 2015 SnowCover Season Summary Data</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Average of Extremes</th>
<th>ECOS</th>
<th>EBEBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>Peak SNIC</td>
<td>% of SNIC Peak</td>
<td>Days in Sat</td>
<td>Peak Area Added SNIC</td>
<td>Peak Area</td>
</tr>
<tr>
<td>Peak SNIC</td>
<td>Start</td>
<td>End</td>
<td>Peak SNIC</td>
<td>Days in Sat</td>
<td>Peak Area</td>
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<tr>
<td>Red Rhino Pass</td>
<td>1/24/2015</td>
<td>20.4</td>
<td>166%</td>
<td>54</td>
<td>5.8</td>
</tr>
<tr>
<td>Klondike Pass</td>
<td>4/13/2015</td>
<td>21.0</td>
<td>164%</td>
<td>45</td>
<td>5.8</td>
</tr>
<tr>
<td>Upper Stampede</td>
<td>4/13/2015</td>
<td>21.0</td>
<td>164%</td>
<td>45</td>
<td>5.8</td>
</tr>
<tr>
<td>Wolf Creek Summit</td>
<td>4/13/2015</td>
<td>21.0</td>
<td>164%</td>
<td>45</td>
<td>5.8</td>
</tr>
<tr>
<td>Redwood</td>
<td>6/23/2015</td>
<td>20.8</td>
<td>164%</td>
<td>60</td>
<td>7.4</td>
</tr>
<tr>
<td>Wizard</td>
<td>6/23/2015</td>
<td>20.8</td>
<td>164%</td>
<td>60</td>
<td>7.4</td>
</tr>
<tr>
<td>Park Creek</td>
<td>6/13/2015</td>
<td>20.8</td>
<td>164%</td>
<td>60</td>
<td>7.4</td>
</tr>
<tr>
<td>Sentinel Pass</td>
<td>6/13/2015</td>
<td>20.8</td>
<td>164%</td>
<td>60</td>
<td>7.4</td>
</tr>
<tr>
<td>Reckless Pass</td>
<td>6/13/2015</td>
<td>20.8</td>
<td>164%</td>
<td>60</td>
<td>7.4</td>
</tr>
<tr>
<td>Independence Pass</td>
<td>6/13/2015</td>
<td>20.8</td>
<td>164%</td>
<td>60</td>
<td>7.4</td>
</tr>
<tr>
<td>Hoover Pass</td>
<td>6/13/2015</td>
<td>20.8</td>
<td>164%</td>
<td>60</td>
<td>7.4</td>
</tr>
<tr>
<td>Kestrel Pass</td>
<td>6/13/2015</td>
<td>20.8</td>
<td>164%</td>
<td>60</td>
<td>7.4</td>
</tr>
<tr>
<td>Wolf Creek Pass</td>
<td>6/13/2015</td>
<td>20.8</td>
<td>164%</td>
<td>60</td>
<td>7.4</td>
</tr>
<tr>
<td>Rabbit Creek Pass</td>
<td>4/13/2015</td>
<td>20.8</td>
<td>164%</td>
<td>60</td>
<td>7.4</td>
</tr>
<tr>
<td>Snow Lake</td>
<td>6/13/2015</td>
<td>20.8</td>
<td>164%</td>
<td>60</td>
<td>7.4</td>
</tr>
</tbody>
</table>

**Notes:**
- The table provides data on the maximum and minimum snow cover for various sites, along with the average of the extremes and the ECOS and EBEBA values.
- The data includes the date, peak SNIC, and other relevant information for each site.

**Diagrams:**
- The diagrams show the relationship between dust and runoff, indicating the impact of dust on runoff space in various seasonal contexts.
Center for Snow and Avalanche Studies
Mountain System Monitoring

- Detecting Regional Climate Change
- Collecting Integrative Datasets
  - Over 10 years of data
  - Data used for hydrologic modeling, satellite (and airborne) ground validation, and forecasting
  - Helping understand mountain meteorology and physics
- Colorado Dust-on-Snow (CODOS) Program
  - Provide water community with updates
    - Presence of dust in snowpack
    - Where dust is located in snowpack
    - When dust emergence will likely occur
  - Improves
    - Timing of snow melt forecasts
    - Rate of snow melt forecasts
    - Total runoff estimates
Water managers: Reservoir is too full

By Gary Harmon
Thursday, August 17, 2017

With Blue Mesa Reservoir nearly full at midsummer, operators of the Aspinall unit of reservoirs say they face a difficult task of reducing the level of Blue Mesa to its winter target.

Blue Mesa this week was brimming at 99 percent full and it was far from alone among Colorado River Basin reservoirs.

Morrow Point and Crystal reservoirs below Blue Mesa on the Gunnison River were 96 percent and 90 percent full, respectively.

“It’s going to take a lot of work” to reduce Blue Mesa’s level to 70 percent of full, or 580,000 acre-feet of water, U.S. Bureau of Reclamation hydrologist Eric Knight said Thursday.
Measuring Snow

- Precipitation
  - Snowfall
- Snow on the ground
  - Depth
  - Density
  - SWE
Dust-on-Snow
Stages of the Snowpack

- Accumulation
  - Increase in pack

- Densification
  - Metamorphism
  - Compaction

- Ablation
  - Sublimation
    - Loss to vapour phase
  - Snowmelt
    - Contribution to runoff
North Slope Alaska
Tundra Travel and Snow Data
May 2009 from Peak 13,510' at Senator Beck Study Basin

May 2013 at Wolf Creek Pass
Akumulace vody na nepropustné vrstvě ledové krusty

Preferenční cesty

Jeff Dozier / UCSB / The COMET Program
Animas River at Durango, CO

- Storm May 16-18 with 2.3" of precipitation, big albedo reset
- Storm May 8-10
- Storm April 29-May 1
- Storm April 9-14, albedo reset
- Warm/dry, D3 exposed
- Storm 19-23, D3/D4 coalescing
- Storm June 15-22
- Sunny/dry, D2-D7 exposed
- Rain
- D2-D7 emerged
- D3-D6 emerged
- Storm May 26-30

Legend:
- Orange: Median daily statistic (106 years)
- Green: Period of approved data
- Blue: Daily mean discharge
- Pink: Period of provisional data
- Red: Estimated daily mean discharge
**Statistical water supply forecast**
- e.g. NRCS
- \( Q = f(SWE) \)
- Regression based
- Relates winter/spring SWE obs to spring/summer streamflow
- Calibrated to years in period of record

**Temperature index runoff model**
- e.g. CBRFC; SAC/SNOW-17
- \( Q = f(SWE, T_{air} \cdot \text{melt factor}) \)
- Calibrated relationship between air temperature and snowmelt
- Calibrated to observations

**Physically-based hydrology model**
- e.g. PRMS
- \( \frac{dU}{dt} + Q_m = (1 - \alpha)S + L + Q_s + Q_v + Q_g \)
- Common research
Assessing recent declines in Upper Rio Grande River runoff efficiency from a paleoclimate perspective

Flavio Lehner¹, Eugene R. Wahl², Andrew W. Wood¹, Douglas B. Blatchford³, Dagmar Llewellyn⁴

¹Research Application Laboratory, National Center for Atmospheric Research, Boulder, USA
²Paleoclimatology Group, NOAA’s National Centers for Environmental Information, Boulder, USA
³Lower Colorado Regional Office, Bureau of Reclamation, Boulder City, USA
⁴Albuquerque Area Office, Bureau of Reclamation, Albuquerque, USA

Corresponding author: Flavio Lehner (flehner@ucar.edu)

Key Points:

- The decreasing runoff efficiency trend from 1986-2015 in the Upper Rio Grande River basin is unprecedented in the last 445 years
- Very low runoff ratios are 2.5 to 3 times more likely when temperatures are above-normal than when they are below-normal
- The trend arises primarily from natural variability but runoff sensitivity to temperature implies further declines should warming continue
How warming drives reductions in streamflow
Berghuijs et al. (2014), Bamhart et al. (2016), Deem et al. (2013)

- Fall and spring precip falls as rain instead of snow = less efficient runoff
- Higher sublimation loss from snowpack
- Earlier snowmelt = slower melt = less efficient runoff (from dust too)
- Soils exposed by earlier meltout = more evaporation
- Vegetation has longer growing season = more transpiration

Most recent studies indicate ~3-4% decline in annual runoff in CO for every 1°F of warming
Record warm March, Lower elevation snowmelt

Stormy period, 3-4" gain in SWE, albedo reset, Streamflow decreases

No precipitation first half of April

Received precipitation Albedo reset

June 1-7 = sparse precipitation. Then, 23 days without precipitation

Snow gone at SASP

May = observed precipitation 14 out 31 days, numerous albedo resets and added SWE

Higher elevations get in the game with increased snowmelt

D3/D4 on surface

D3/D4 re-surfaces

CONMOGCO • Historic Average (Based on 109 years of record) • Discharge Measurements
A comparison of early (1982-1995) and late (2002-2015) time series using snowcourse as well as SNOTEL data reveals:

- Both slopes agree in the relationship between the two time series.
- Locations with more SWE have experienced a greater rate of decrease in SWE.
Assessing recent declines in Upper Rio Grande runoff efficiency from a paleoclimate perspective

Flavio Lehner, Eugene R. Wahl, Andrew W. Wood, Douglas B. Blatchford, Dagmar Llewellyn

First published: 05 April 2017 | https://doi.org/10.1002/2017GL073253 | Cited by: 16

Historical and Projected Colorado Temperatures
Comparisons to 1971–2000 Averages

The twenty-first century Colorado River hot drought and implications for the future

Bradley Udall1,2 and Jonathan Overpeck2,3

JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
AMERICAN WATER RESOURCES ASSOCIATION

OBSERVED CHANGES IN CLIMATE AND STREAMFLOW IN THE UPPER RIO GRANDE BASIN

Shaleene B. Chavarria and David S. Gutzler
Winter and spring temperatures have increased (study period 1958-2015)
Decline in snowpack (~25%)
Shift in hydrograph toward earlier flows in spring, and diminished flow in late spring and summer months
Streamflow declined slightly
Average and variability of precipitation in April and May has increased, masking effects of declining snowpack, accounting for much of the unpredicted streamflow variance in recent decades
Changes in snowpack-runoff relationship and increased precip variability = impact ability to predict streamflow on seasonal basis.
‘Dust’ Publications


More pubs ...


• In Western US over the last 40 years snowpack has diminished by 41% since early 1980’s
• In Colorado individual snow course data taken April 1st since 1950’s show 20-60% decline
  • In the Upper Rio Grande snowpack decline is 25%
  • Shift in hydrograph toward earlier flows in spring, and diminished flow in late spring and summer months
  • Snow season has become 34 days shorter on average
Plant Community Monitoring

- Snow amount and distribution greatly influences vegetation composition, abundance, and distribution.
- Alpine regions are considered one of the most vulnerable ecosystems in the face of climate change, yet we have very few sites with quantitative data.
D3/D4 on surface, snowpack isothermal at SASP

D3/D4/D5 under 7” snow

Atmospheric river, 1.7” precip at SASP, D3/D4 buried

D3/D4/D5/D6 under 4” snow at SASP, emerging in exposed areas

D3 on surface, snowpack isothermal at SASP

D3/D4/D5/D6 under 7” snow

Last winter storm, 11” new snow at SASP

D3-D7 emerging at SASP

D3-D7 re-emerged

D7 deposited

Snow gone at SASP

Snow gone at SBSP

0.5” rain at SASP

D3/D4/D5 under 7” snow

D3/D4/D5/D6 emerging at SASP

Snow gone at SASP

0.5” rain at SASP

Median daily statistic (59 years)  
Period of approved data  
Daily mean discharge  
Period of provisional data  
Estimated daily mean discharge
D3/D4 on surface. Snowpack isothermal at SASP.


Atmospheric river. 1.7" precip at SASP.

D3/D4 buried.

D3/D4/D5/D6 under 4" snow at SASP, emerging in exposed areas.

D7 deposited.


Snow gone at SASP.

Snow gone at SBSP.

0.5" rain at SASP.

D3-D7 emerging at SASP.

D3-D7 re-emerged.

Last winter storm, 11" new snow at SASP.

Snow gone at SASP.

Snow gone at SBSP.

0.5" rain at SASP.

D3/D4/D5/D6 under 4" snow at SASP, emerging in exposed areas.

D3/D4/D5/D6 under 4" snow at SASP, emerging in exposed areas.

D3/D4 on surface. Snowpack isothermal at SASP.

Median daily statistic (59 years)
Record warm March, lower elevation snowmelt.

Stormy period, 3-4” gain in SWE, albedo reset, streamflow decreases.

No precipitation first half of April.

Received precipitation, albedo reset.

June 1-7 = sparse precipitation. Then, 23 days without precipitation.

Snow gone at SASP.

D3/D4 on surface.

D3/D4 re-surfaces.

Higher elevations get in the game with increased snowmelt.

May = observed precipitation 14 out of 31 days, numerous albedo resets and added SWE.

Data Source: Co. Division of Water Resources.
Streamflow, Mid-Day Broadband Albedo, and Air Temperature

Senator Beck Basin Study Area, Spring 2017

[Graph showing various data trends such as Mid-Day Broadband Albedo, Air Temperature, and Mean Daily Discharge over the period of March 1, 2017 to June 30, 2017 with different markers for specific locations and measurements.]
Streamflow, Mid-Day Broadband Albedo, and Air Temperature
Senator Beck Basin Study Area, Spring 2018

- SAP BB Albedo (elevation 11,060')
- Uncompahgre River Near Ridgway
- Putney Daily Average Air Temperature
- Putney Daily Min Air Temperature
- Putney POR Average Air Temperature
Energy Budget of the Snowpack
Sensible Heat

• Is related to changes in temperature of a gas or object with no changes in phase.
• Heat flux largely due to convection between air and snowpack.
Phase change from solid to liquid, latent heat absorbed

Phase change from gas to liquid, latent heat is released
Shortwave (visible & ultraviolet)

- Both direct beam and scattered solar radiation
- Affected by latitude, aspect, vegetation, albedo
- Increases in intensity in spring and summer

Longwave (infrared)

- Reflected from the sky, clouds, vegetation (tree wells)
- Near perfect blackbody – absorbs all the longwave radiation, emits maximum radiation allowed by its surface temperature. Emissivity between 0.97-1.0
- During clear skies and cold temperatures, may be a net loss to the pack
- Very important source in spring, especially from vegetation
• Needs warm, moist air masses for condensation.
• Much of the snowmelt during “rain on snow events” is actually from condensation.
• Massive energy transferred to the snowpack, 640 calories/gram instant heat. Condensation of water vapor causes a huge amount of heating!!
• 1 gram of condensate will melt 7.5 grams of SWE.
• Usually overrated!!

• At rain temperature of 10°C (50°F), it would take 8 inches of rain to melt 1 inch of SWE in an isothermal snowpack.

• Cold rain can warm snowpack more than warm rain
EYES ON THE SNOW

Remote-sensing measurements could finally let scientists monitor Earth’s snow resources—which provide drinking water for billions of people. NASA is planning to test various combinations of sensors to see which do best at quantifying how much snow lies on a landscape and how quickly it is likely to melt away.

- Passive microwave detector: To calculate snow depth
- Hyperspectral/multispectral imager: To measure snow cover, albedo and grain size
- Lidar (laser altimeter): To calculate snow depth
- Radar: To calculate snow depth
- Passive visible light/infrared detector: To measure snow cover and albedo

Conejos Watershed
April 6, 2015

Snow Wather (mm)

Snow Water Equivalent (mm)

3-12

0-3

-3 - 0

-12 - 3

Map data: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aeros, IGN, IGP, swisstopo, and the GIS user community
Plant Community Monitoring

- Snow amount and distribution greatly influences vegetation composition, abundance, and distribution.
- Alpine regions are considered one of the most vulnerable ecosystems in the face of climate change, yet we have very few sites with quantitative data.
Operational forecasting

- Statistical streamflow forecast (e.g. NRCS)
  - Regression-based
  - Relates winter/spring SWE obs to spring/summer streamflow
- Temperature index runoff forecast (e.g. CBRFC)
  - Calibrated relationship between air temperature & snowmelt

*Both methods assume calibrations apply to current conditions*