

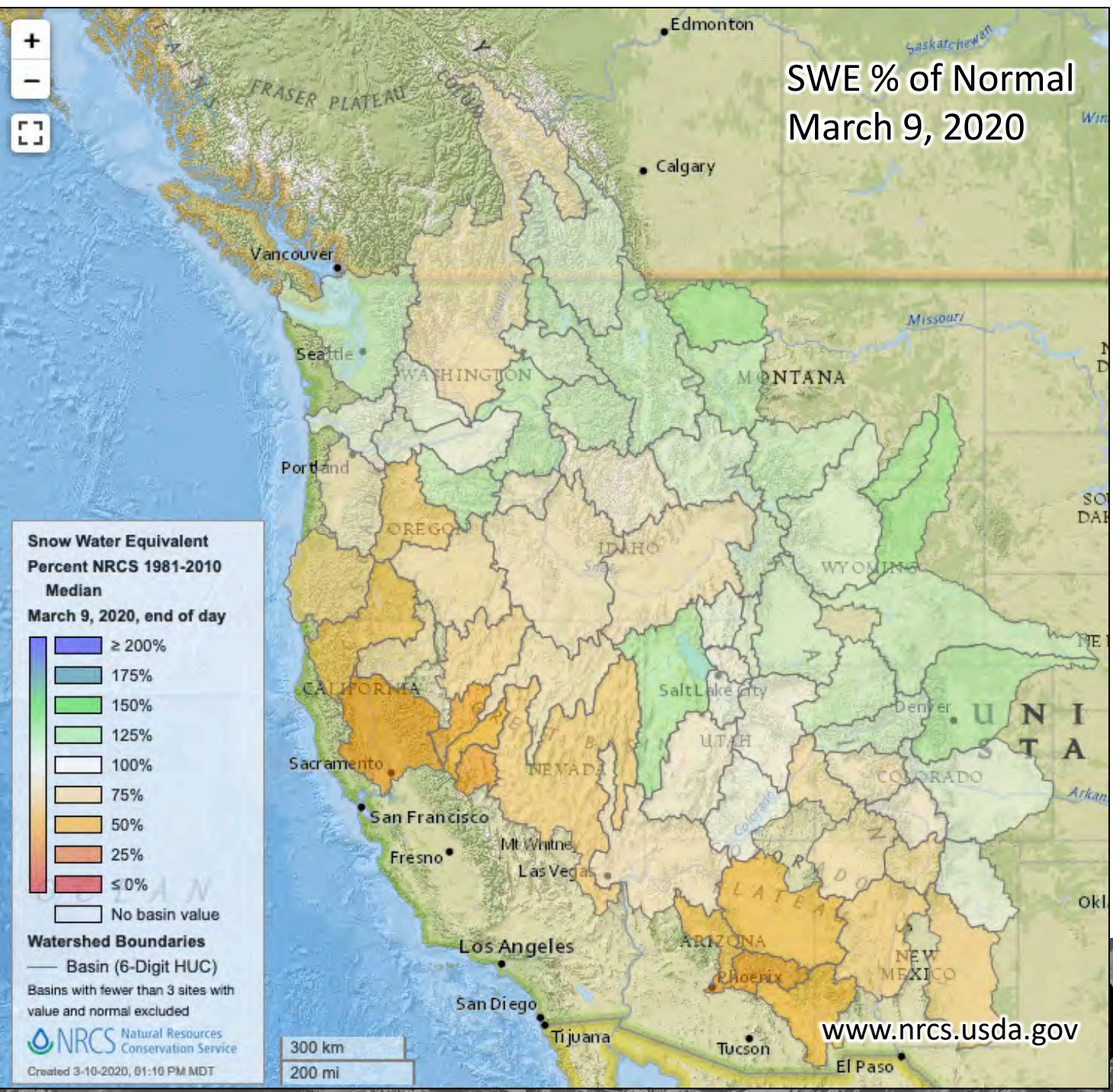
# ASO in Southwest Colorado

## *Water Year 2021*

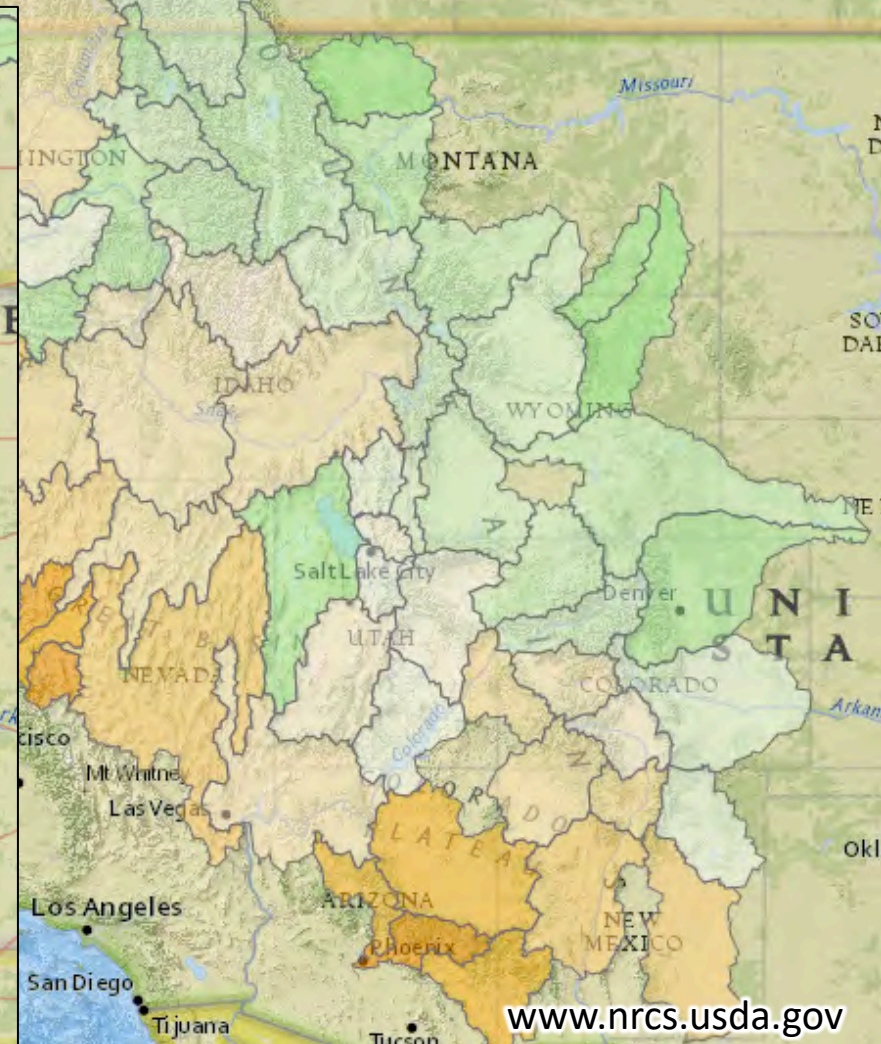
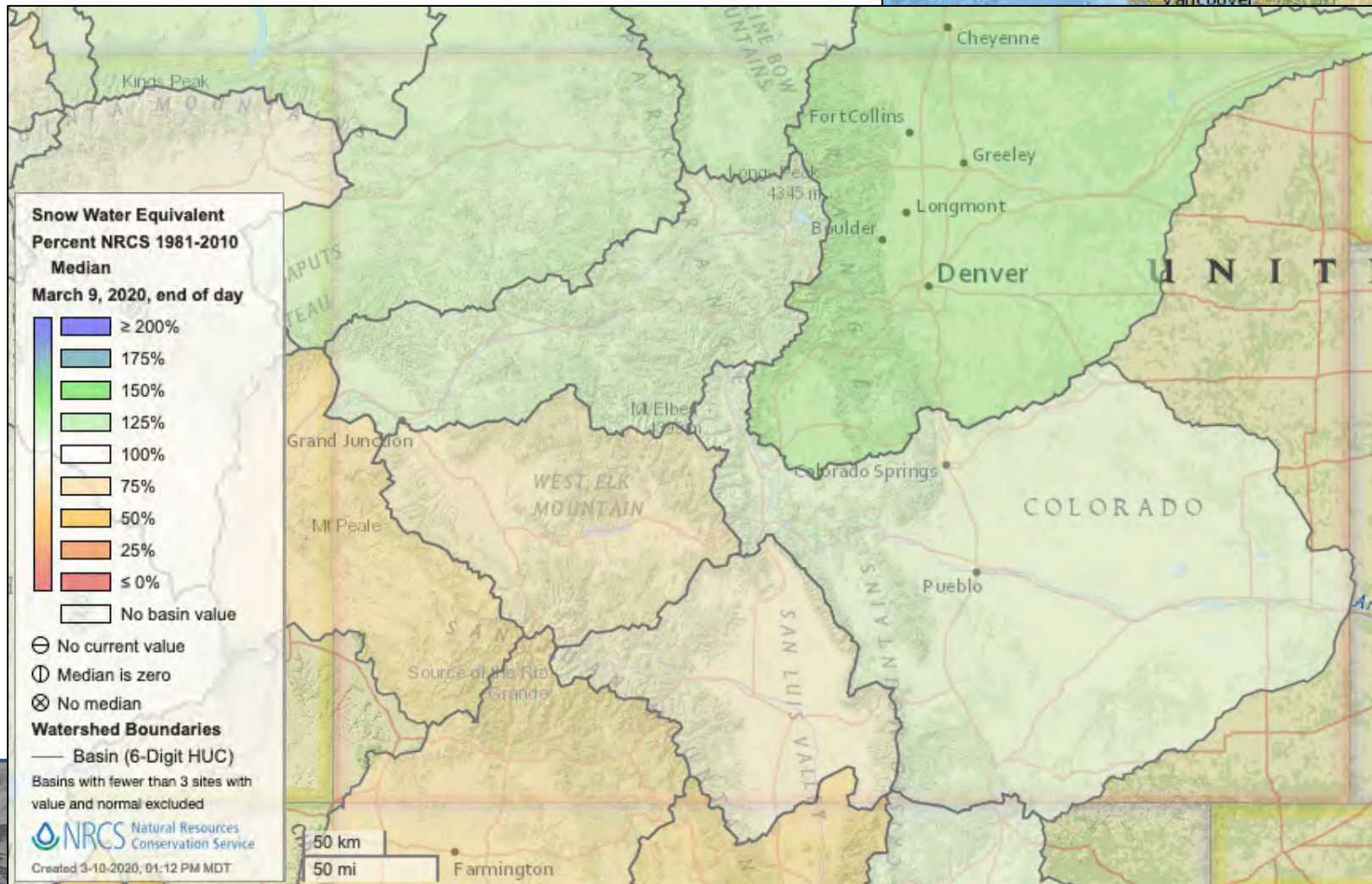
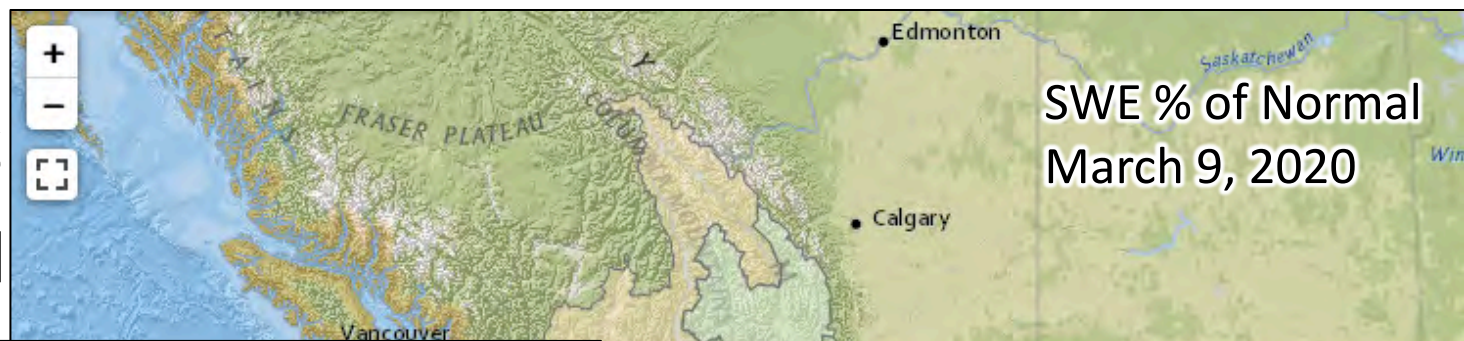
Jeff Deems  
*Airborne Snow Observatories, Inc.*



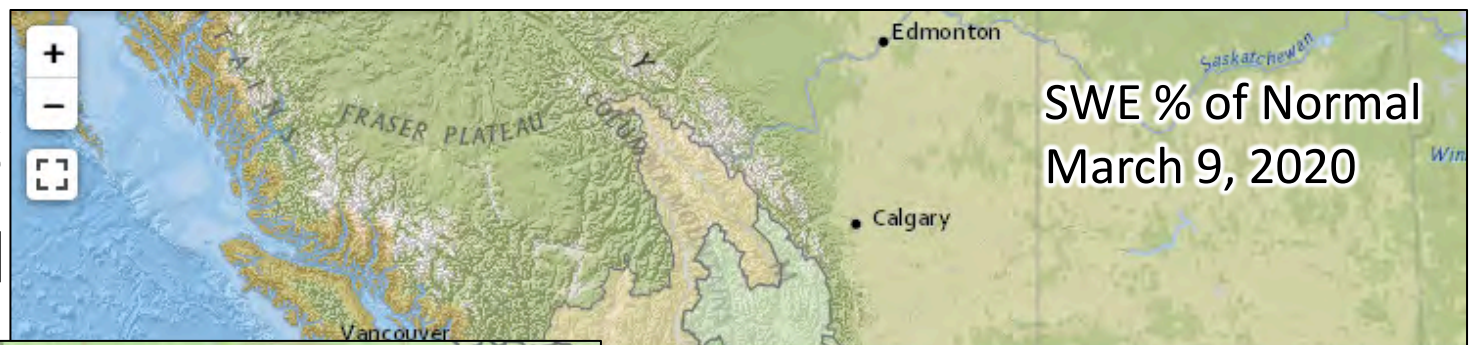
# Basin snowpack status based on station data



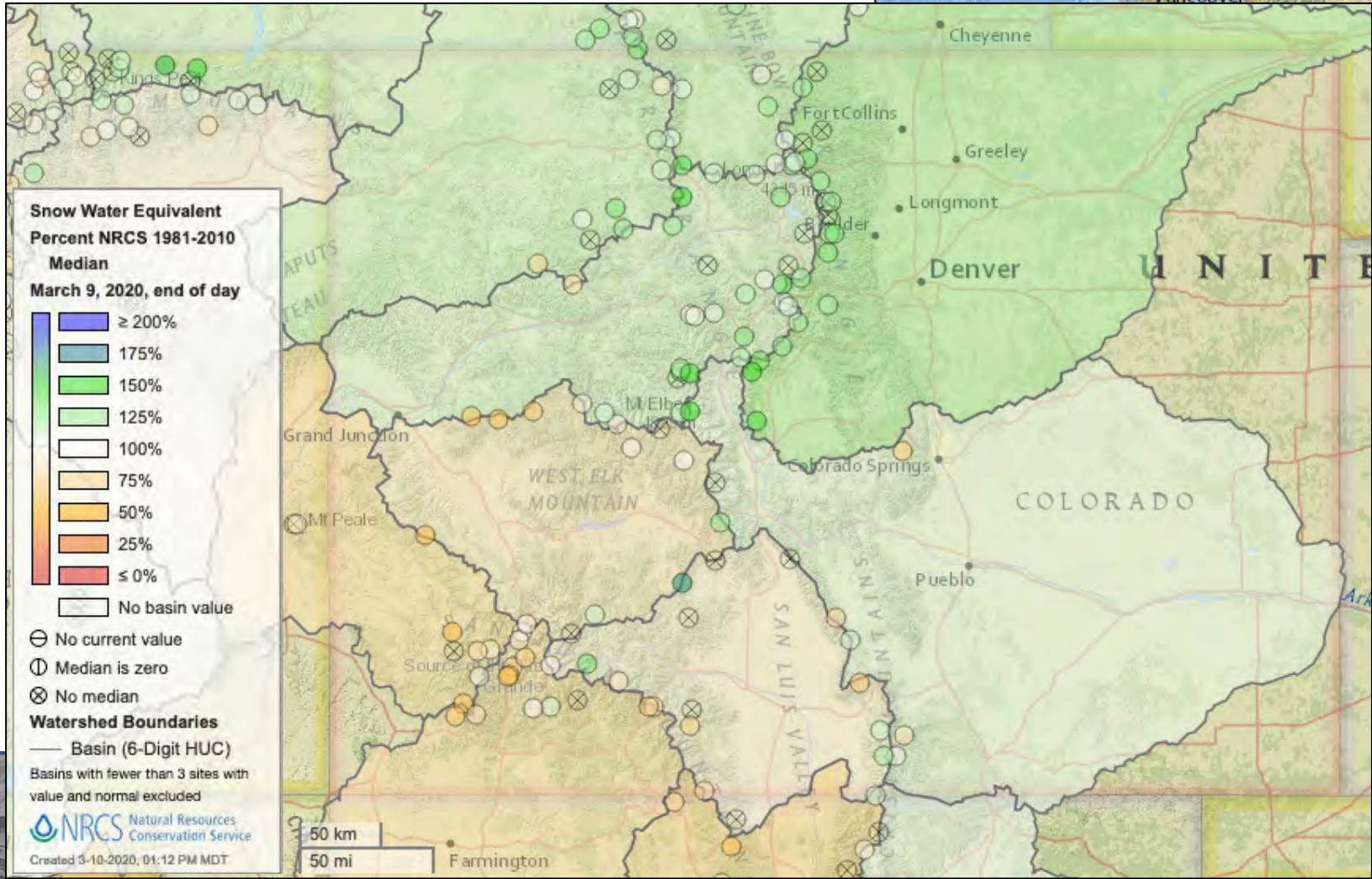
# Basin snowpack status based on station data



# Basin snowpack status based on station data



SWE % of Normal  
March 9, 2020



**Snow Water Equivalent**  
**Percent NRCS 1981-2010**  
**Median**  
**March 9, 2020, end of day**

|                   |                  |
|-------------------|------------------|
| Dark Blue         | ≥ 200%           |
| Blue              | 175%             |
| Light Blue        | 150%             |
| Green             | 125%             |
| White             | 100%             |
| Light Orange      | 75%              |
| Orange            | 50%              |
| Dark Orange       | 25%              |
| Red               | ≤ 0%             |
| White circle      | No basin value   |
| Circle with slash | No current value |
| Circle with dot   | Median is zero   |
| Circle with X     | No median        |

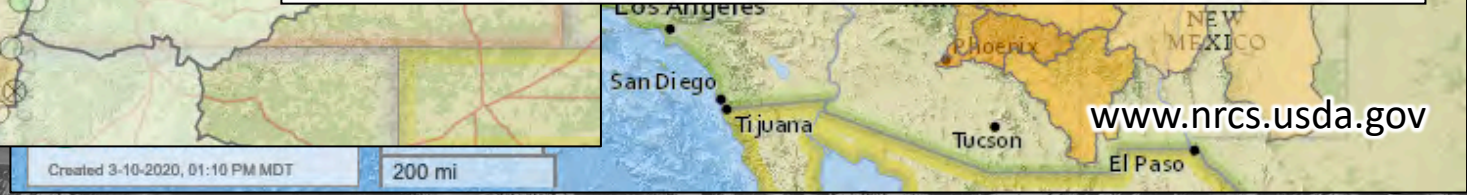
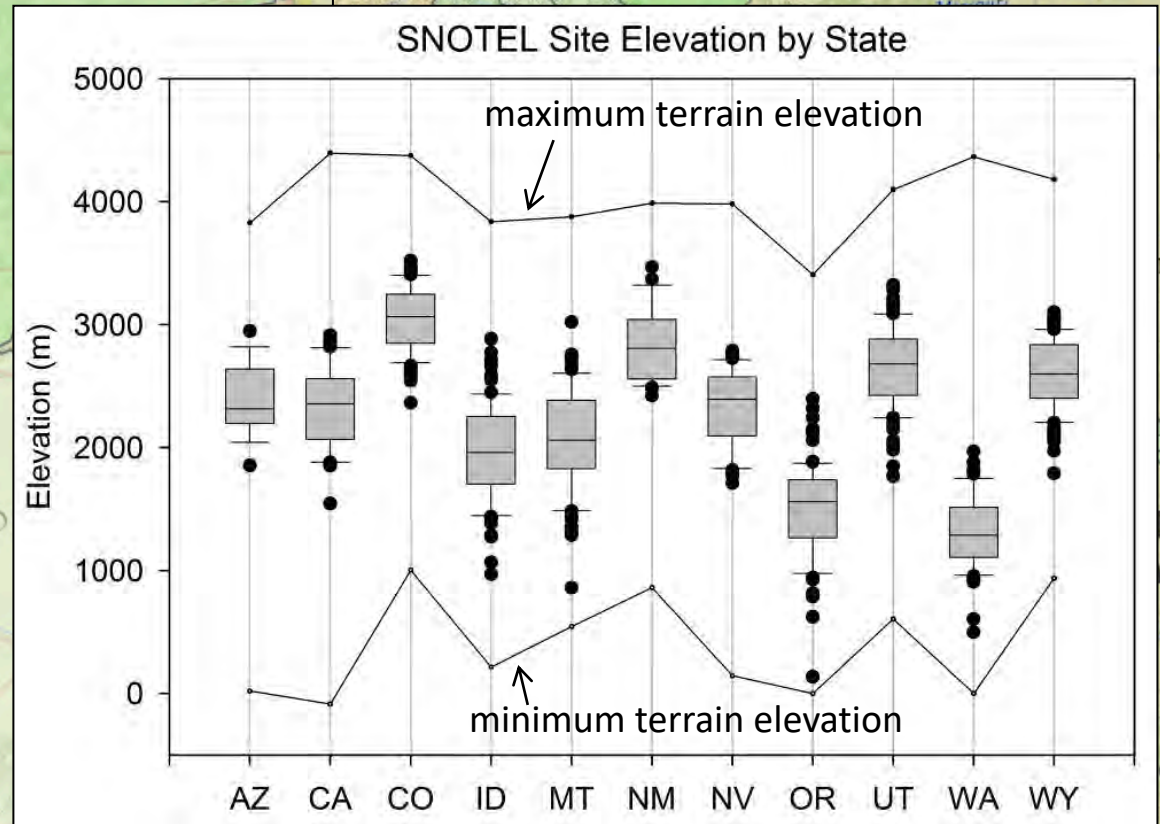
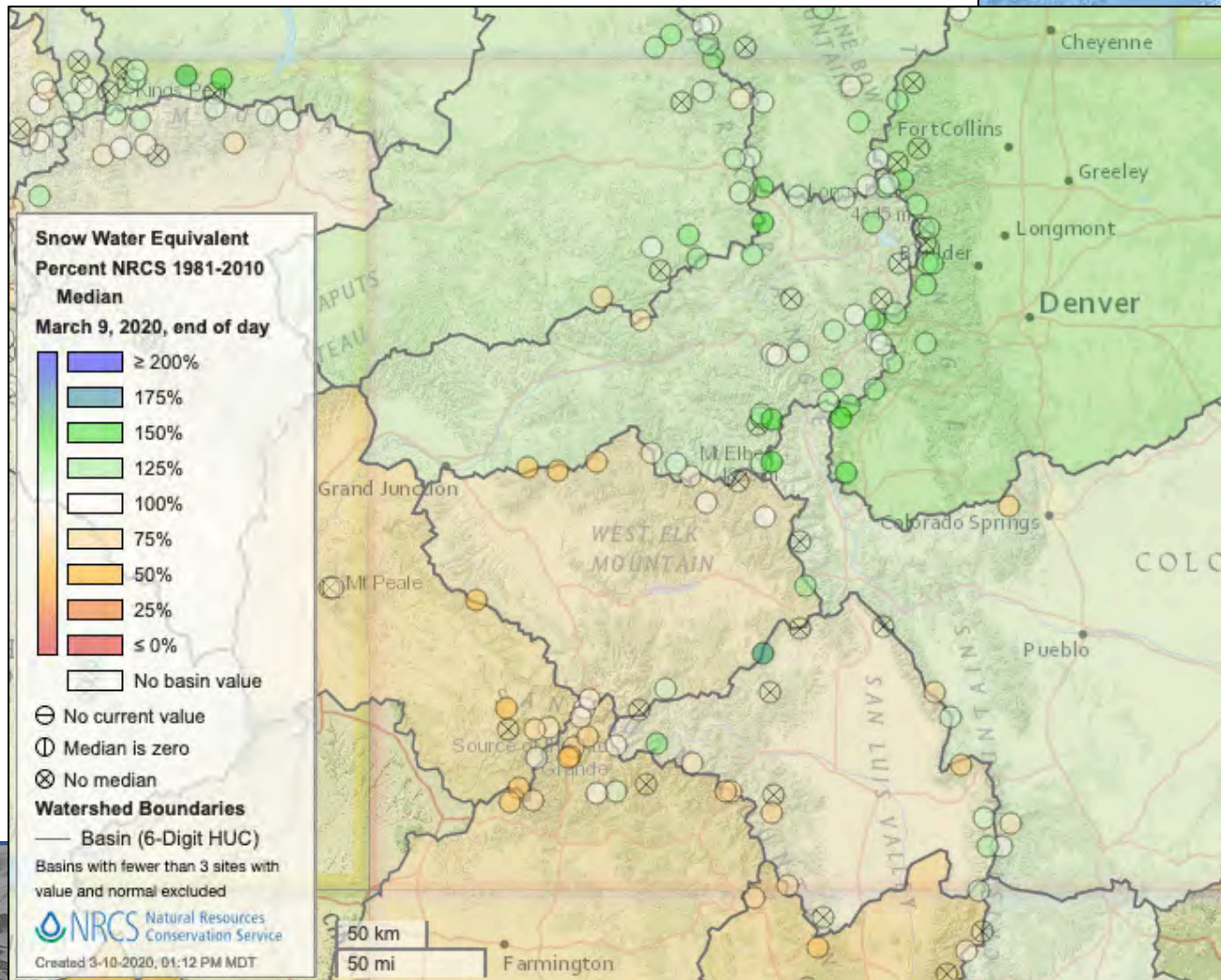
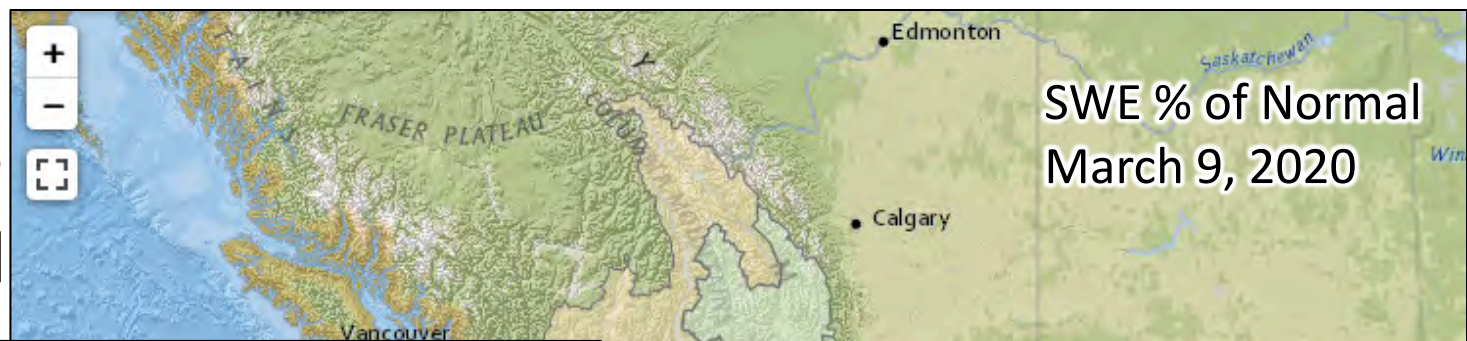
**Watershed Boundaries**  
— Basin (6-Digit HUC)  
Basins with fewer than 3 sites with value and normal excluded

**NRCS** Natural Resources Conservation Service  
Created 3-10-2020, 01:12 PM MDT



[www.nrcs.usda.gov](http://www.nrcs.usda.gov)

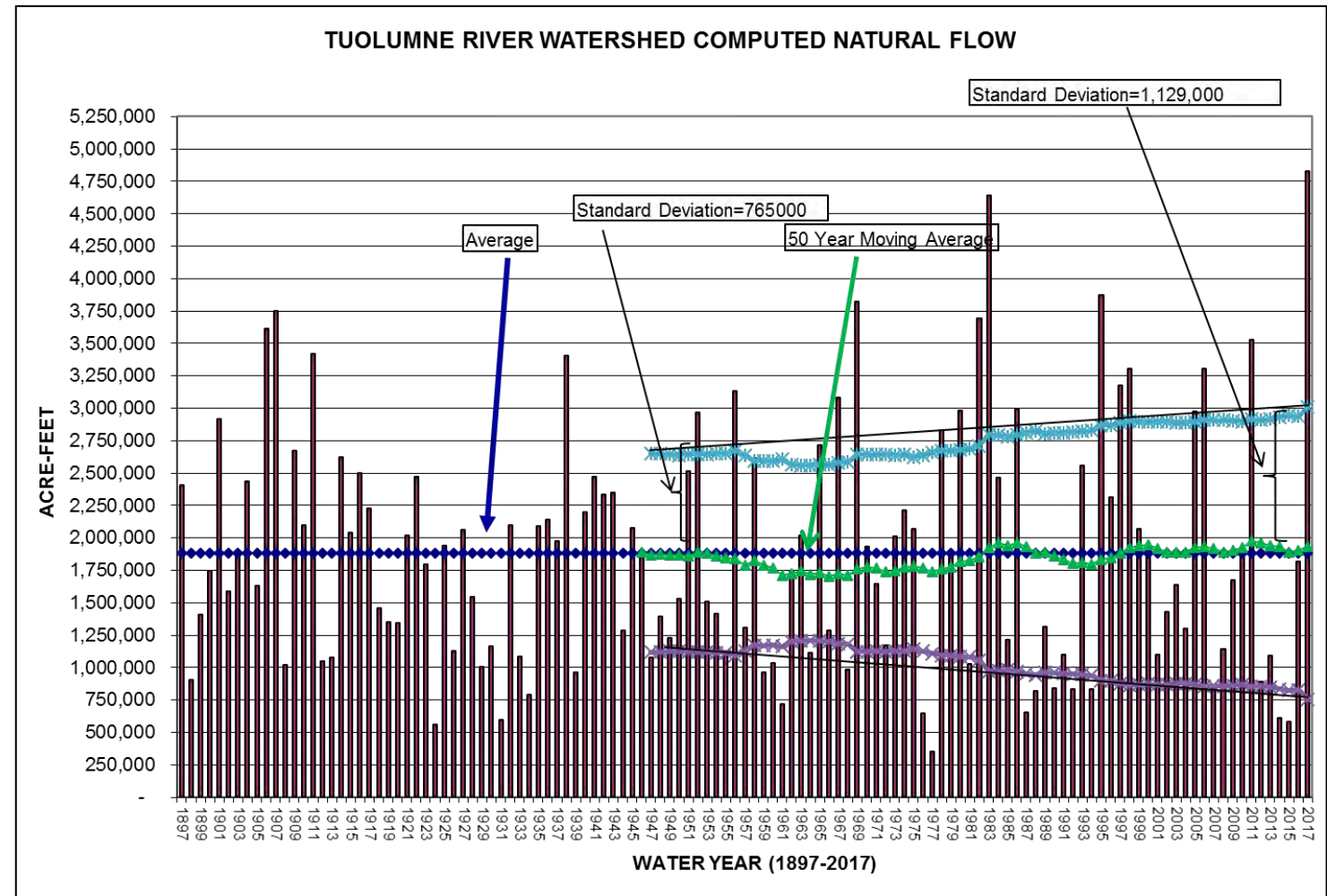
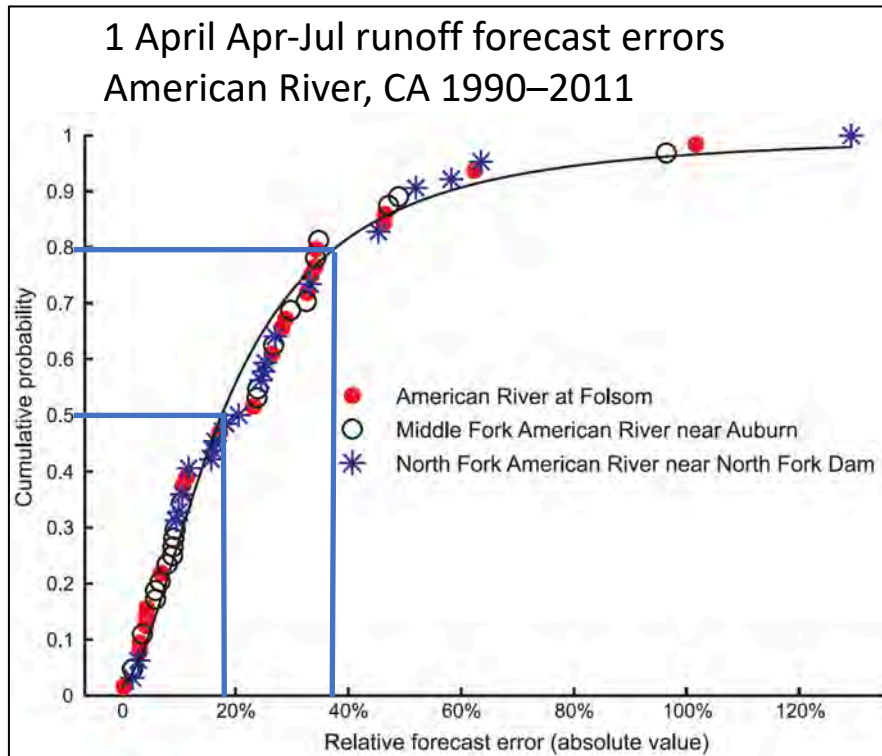
# Basin snowpack status based on station data



# Runoff forecasts: vulnerable in current & future climate

Statistical & index runoff forecasts:

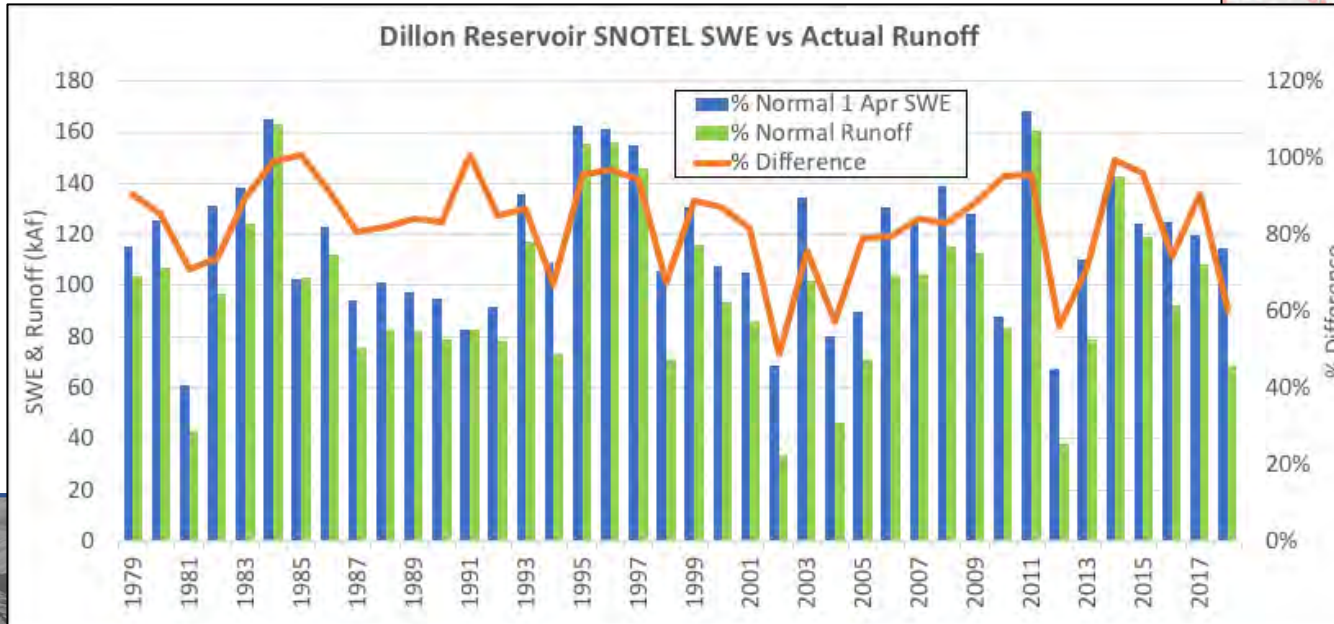
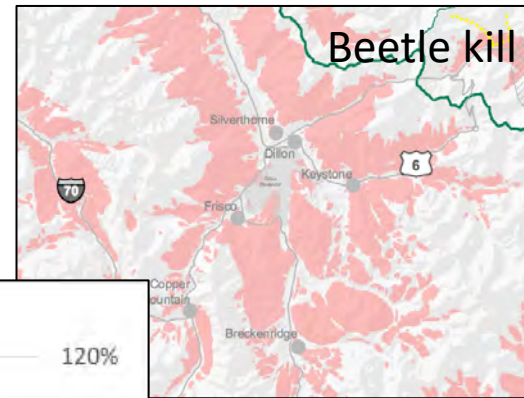
- do not consistently meet accuracy needs
- fail increasingly in a changing climate



# Forecast variation & operational uncertainty

Blue River @ Dillon  
Denver Water

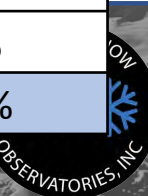
- Changing conditions highlight need for improved snow monitoring
- 4 SNOTEL sites: 10500 – 11400'



Forecast > 10% Low  
Forecast > 10% High

|      | April Forecast | Obs Inflow | % Difference |
|------|----------------|------------|--------------|
| 1999 | 120            | 197        | -39%         |
| 2000 | 155            | 159        | -2%          |
| 2001 | 150            | 146        | 3%           |
| 2002 | 59             | 57         | 4%           |
| 2003 | 170            | 173        | -2%          |
| 2004 | 100            | 78         | 28%          |
| 2005 | 125            | 120        | 4%           |
| 2006 | 210            | 176        | 19%          |
| 2007 | 150            | 177        | -15%         |
| 2008 | 200            | 195        | 2%           |
| 2009 | 180            | 192        | -6%          |
| 2010 | 120            | 142        | -15%         |
| 2011 | 225            | 272        | -17%         |
| 2012 | 100            | 64         | 56%          |
| 2013 | 100            | 134        | -25%         |
| 2014 | 250            | 242        | 3%           |
| 2015 | 166            | 202        | -18%         |
| 2016 | 167            | 157        | 7%           |
| 2017 | 195            | 184        | 6%           |
| 2018 | 137            | 117        | 17%          |

Airborne Snow



# How to make water supply forecasting more robust?

- Decrease reliance on historic record
- Increase availability & use of spatial data and physically-based modeling

*In other words, every year matters,  
not just the average over some decades!*





# Airborne Snow Observatories, Inc.

*mapping the two most critical snow properties to forecast runoff volume & timing*

## Snow Water Equivalent

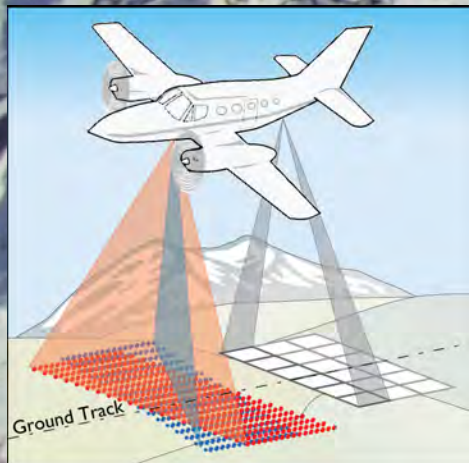
Snow depth from elevation mapping with Riegl VQ1560i  
SWE from insertion of obs & modeled density

## Snow Albedo

CASI-1500 Spectrometer  
2m spatial resolution from 4000m

## Operations

Unique high-altitude operations  
Unique rapid product turnaround



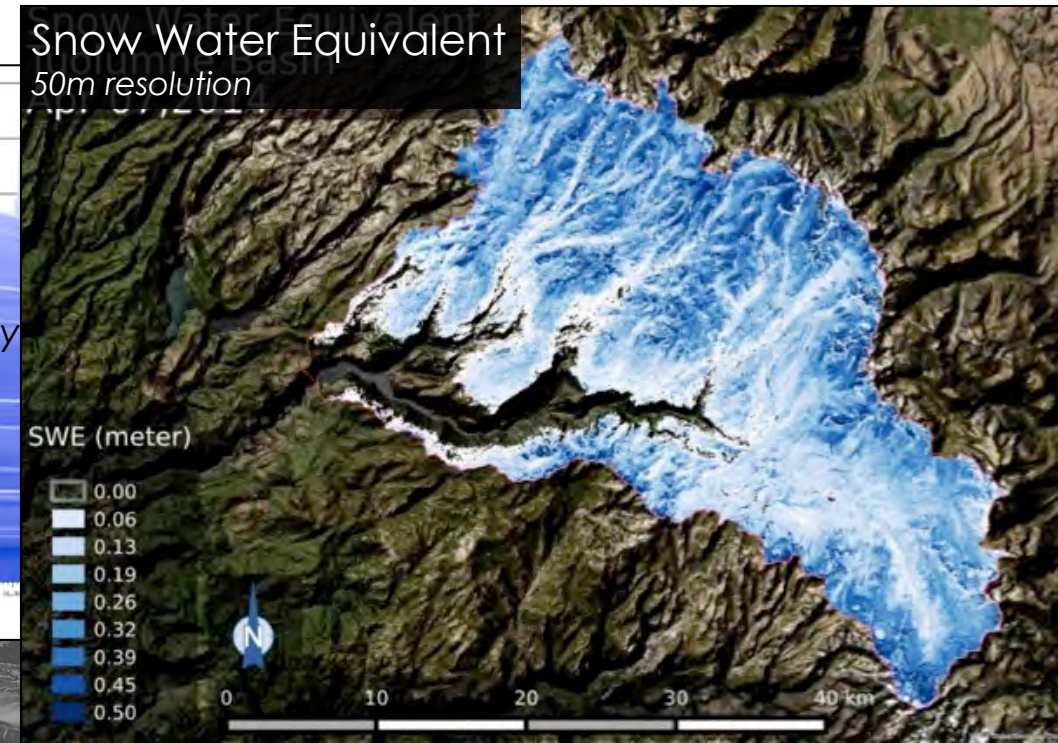
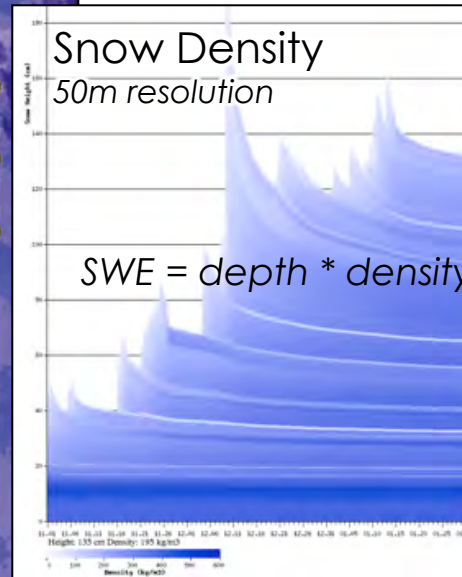
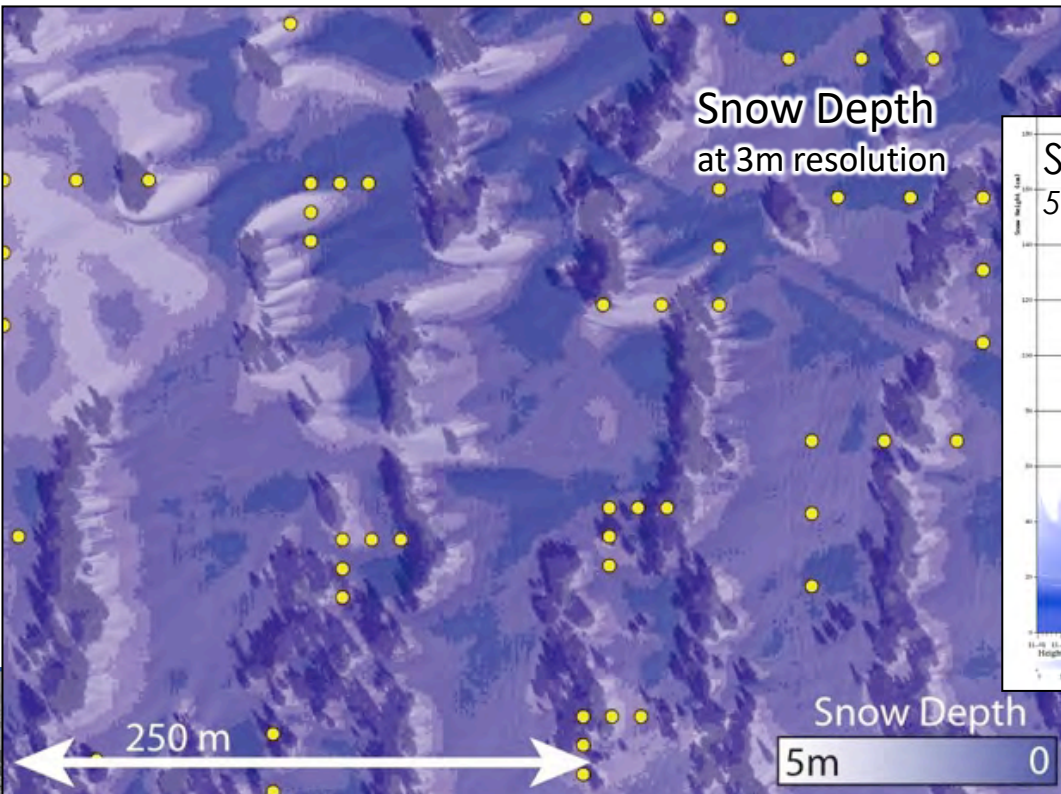
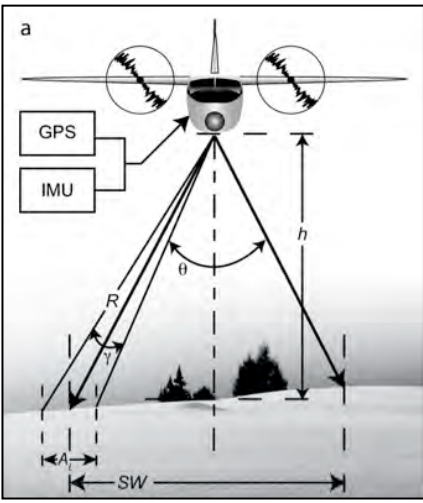
JPL



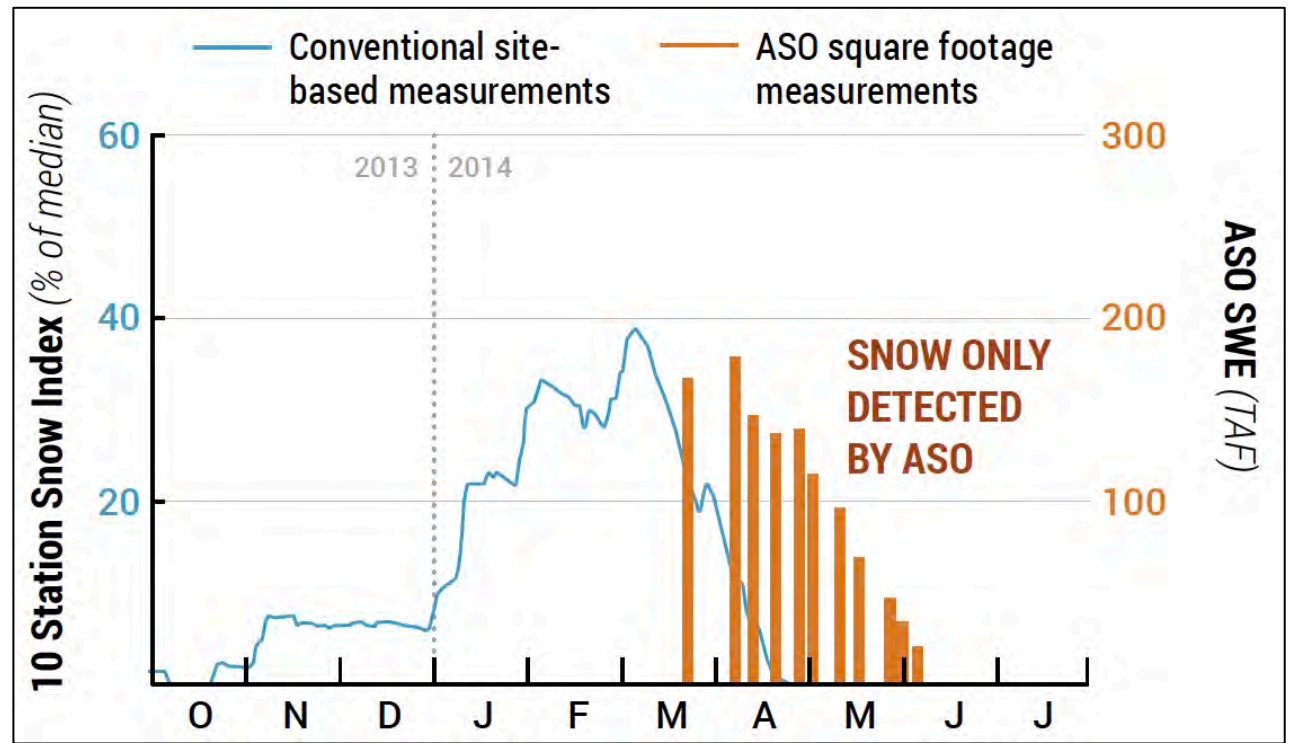
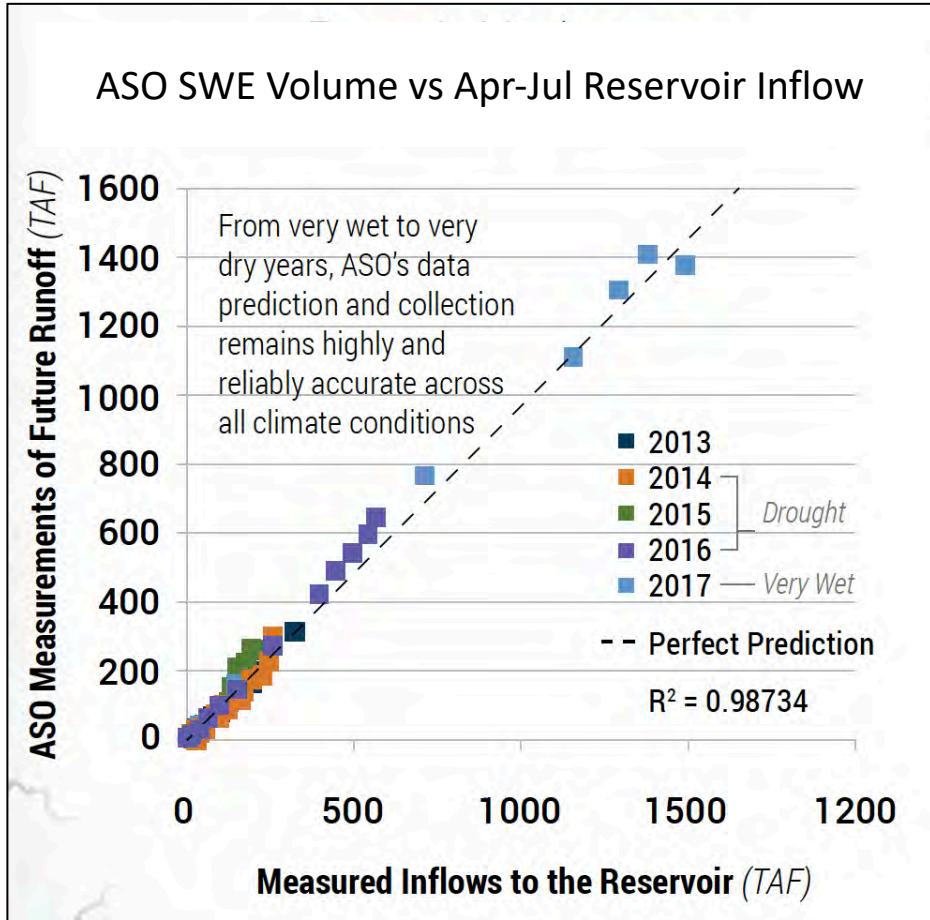
# Snow Depth, Water Equivalent, & Albedo from lidar & spectrometer

ASO's unique process:

- ❄ highly optimized flight design
- ❄ novel integrated data pipeline
- ❄ lidar & spectroscopy experts



# Improvement brings impact ...



“What you’ve done is created new reservoir space and water supply without any impacts to the current physical or environmental paradigms.”

Wes Monier, Chief Hydrologist,  
Turlock Irrigation District

“Having used this technology, it is hard to imagine a future without it.”

Dave Rizzardo, Chief of Snow Surveys  
and Water Supply Forecasting,  
Department of Water Resources

\*content from the ASO Brochure

Airborne Snow Observatories, Inc.  
A Public Benefit Corporation

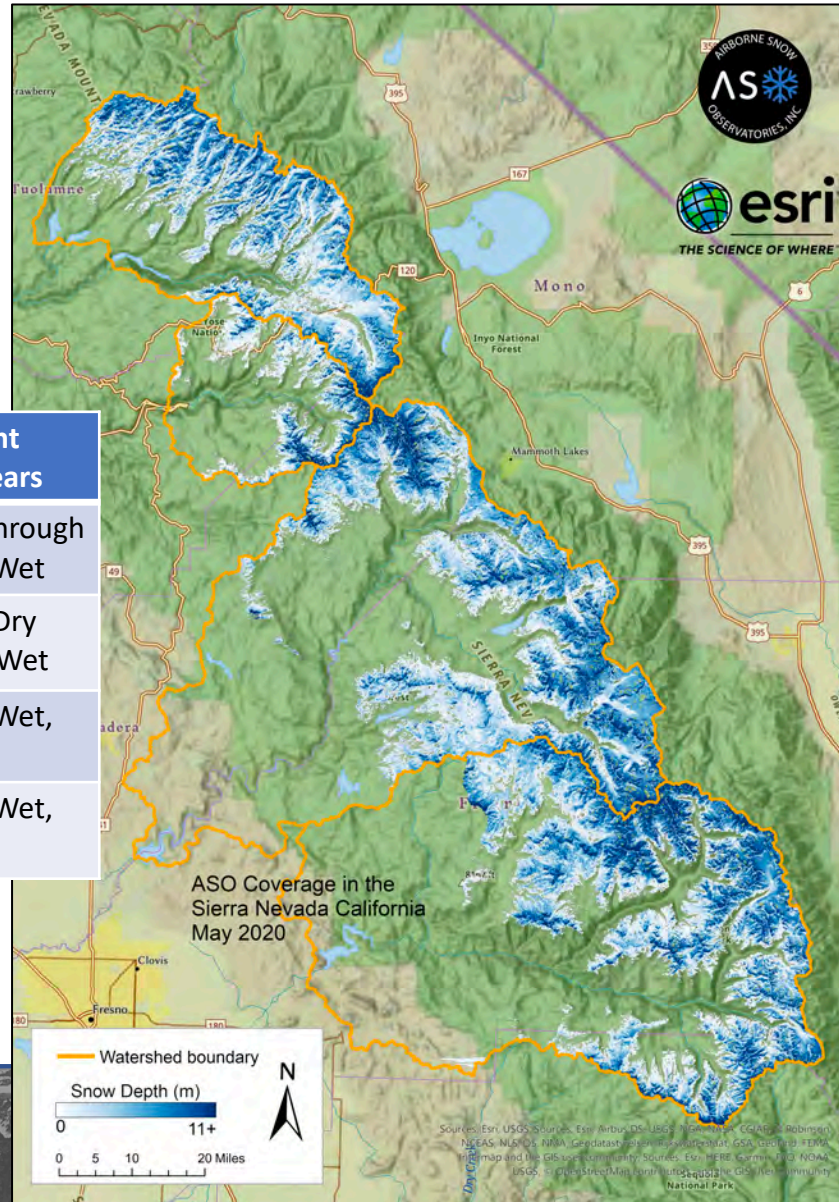
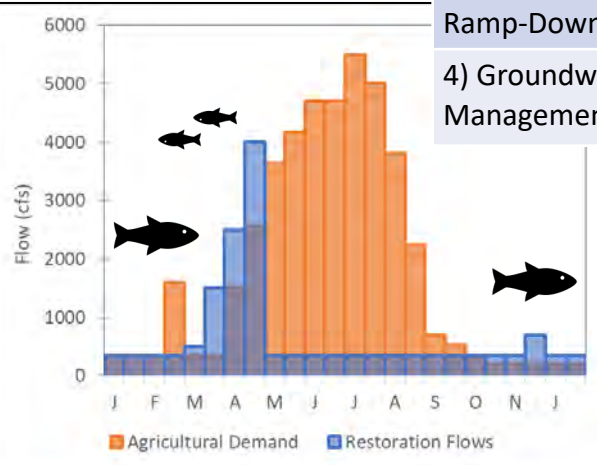


# Operational support: California

## San Joaquin River: Restoration flows for salmon

- ASO data used in forecast for USBR Fish Recovery Program
- Improved accuracy enables restoration flows & re-watering lower San Joaquin
- Early forecast accuracy key to achieving flow factors & summer supply reliability

| Environmental Flow Factor      | Important Water Years       |
|--------------------------------|-----------------------------|
| 1) Restoration Flow Scheduling | Critical through Normal-Wet |
| 2) Temperature Management      | Normal-Dry through Wet      |
| 3) Flood Flow Ramp-Down        | Normal-Wet, Wet             |
| 4) Groundwater Management      | Normal-Wet, Wet             |



## Kings River 2019: Managing supply & flood risk

- Flood declaration: Army Corps takes over Pine Flat Dam ops & operates solely to protect infrastructure
- 2019: ASO forecast allowed KRWA to operate on 10% exceedance

| Forecasts  | Apr-Jul Runoff Forecast Exceedance |         |         |
|------------|------------------------------------|---------|---------|
|            | 10%                                | 50%     | 90%     |
| CA DWR     | 2.1 MAF                            | 1.8 MAF | 1.6 MAF |
| NOAA RFC   | 2.3 MAF                            | 2.1 MAF | 1.9 MAF |
| <b>ASO</b> |                                    | 2.5 MAF |         |

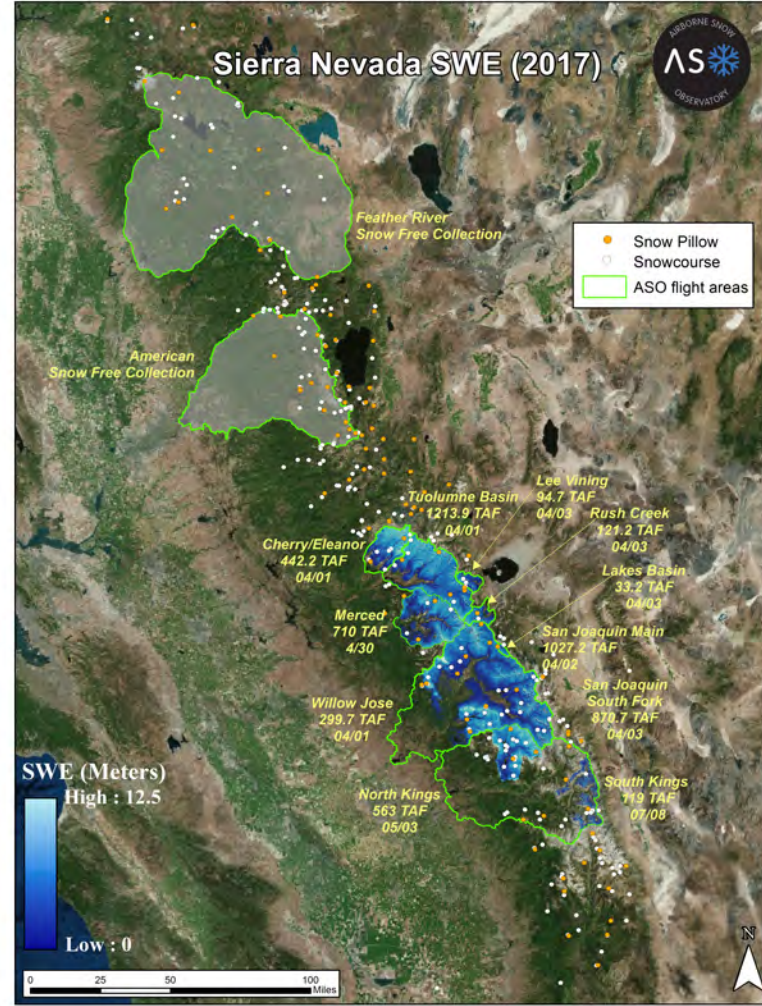
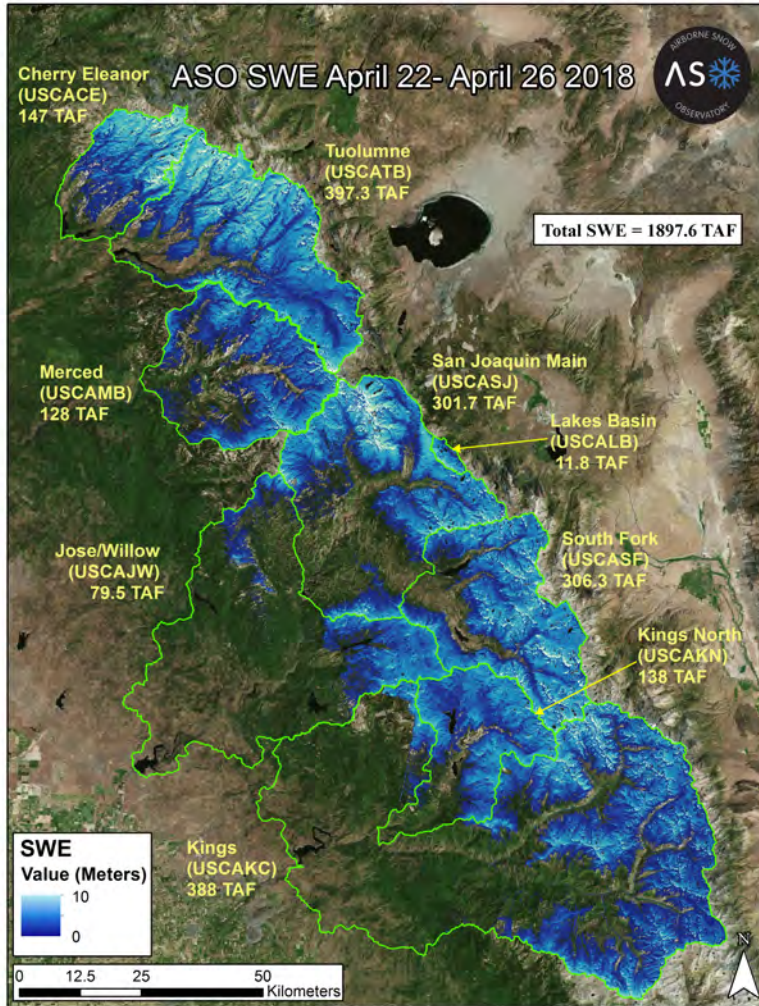
- Saved 100 TAF or **~\$100M** of water

"ASO provides invaluable information that is not otherwise available, most importantly information about the rate of melt that provides a real opportunity to optimize reservoir operations for water supply, flood control, and instream requirements."

Steve Haugen, Watermaster,  
Kings River Water Association



# California: a maturing decision-support program



## California: to-date & Future Plans

- 300+ snow-on flights since 2013 in 10 basins
- Capacity to *operationally* monitor southern Sierra snow water volume
  - data delivery within 72 hours of flight
- Continue program in southern & central Sierra
- Build to regular, full-state coverage over 5 years
- Expand model capacity
- Data service through Esri partnership
- Agency synergies

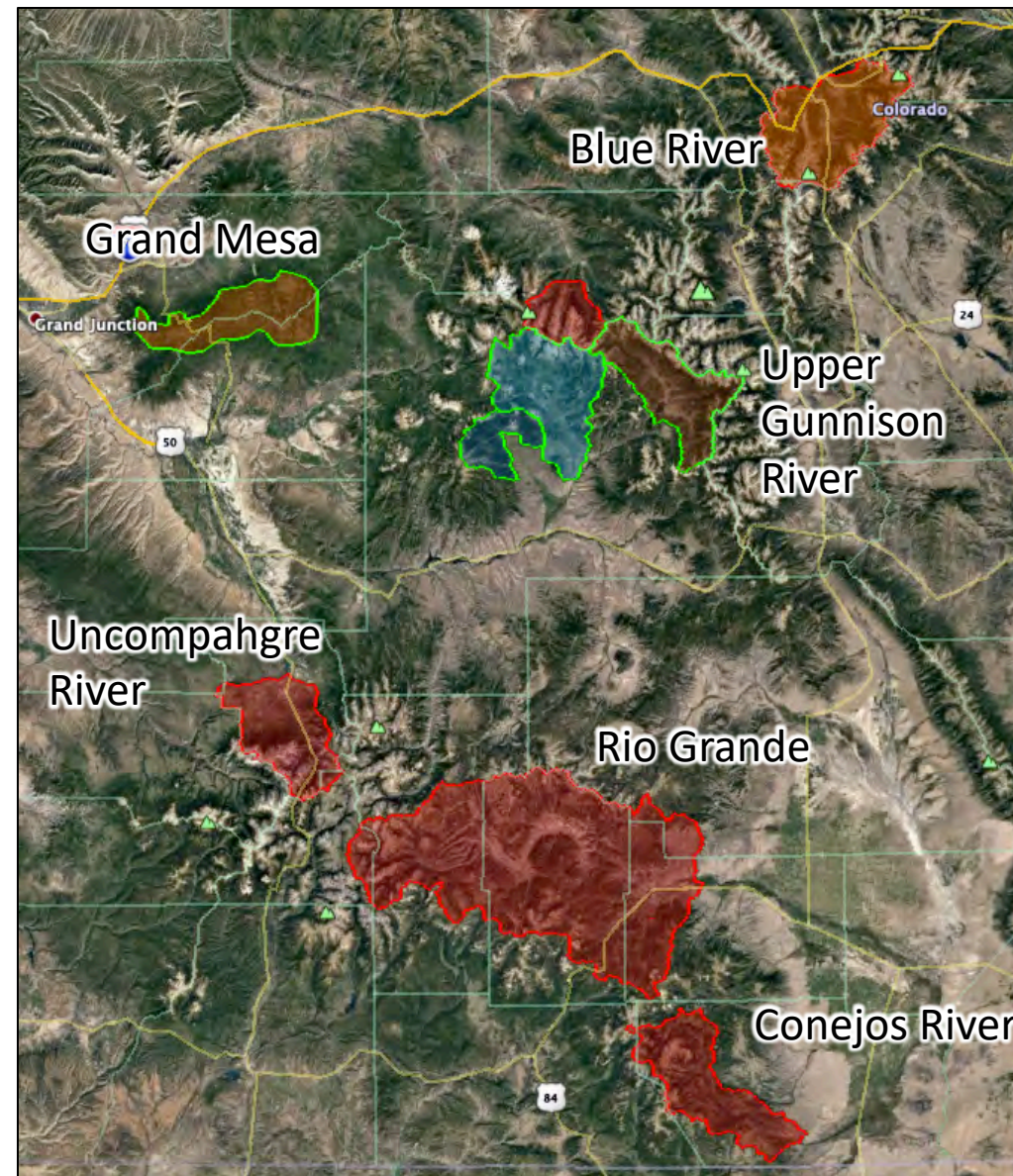
# ASO Colorado Program

## Prior Campaigns:

Uncompahgre River (above Ridgway Reservoir)  
Rio Grande & Conejos Rivers  
Grand Mesa  
Upper Gunnison  
(Taylor/East/Ohio, +Castle/Maroon)  
Blue River (Dillon Res)

## Current 2021 Plans:

Blue River (DW)  
Conejos (CWCB)  
Dolores, Animas/Florida/Pinos (CWCB)



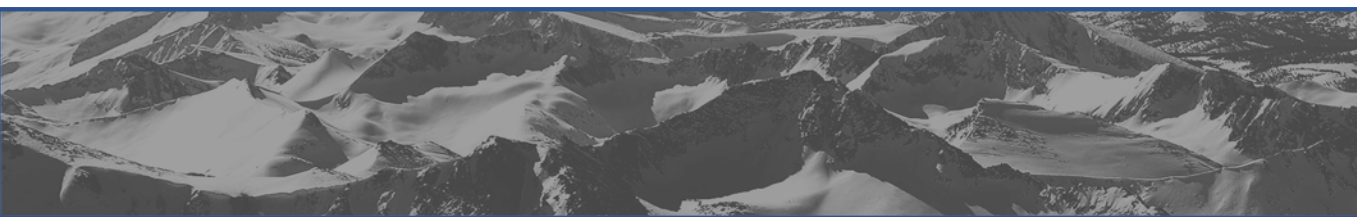
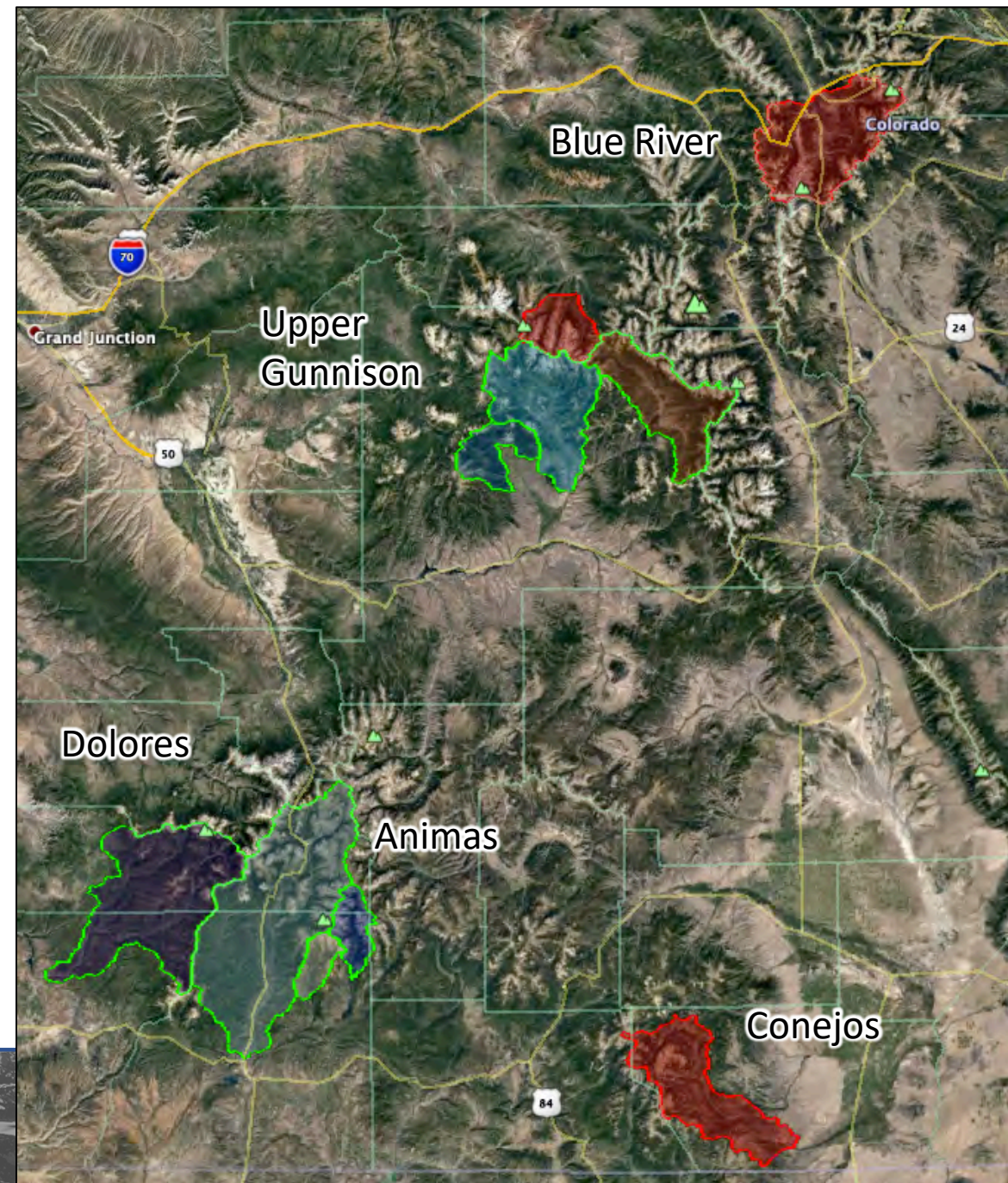
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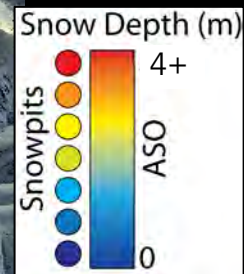
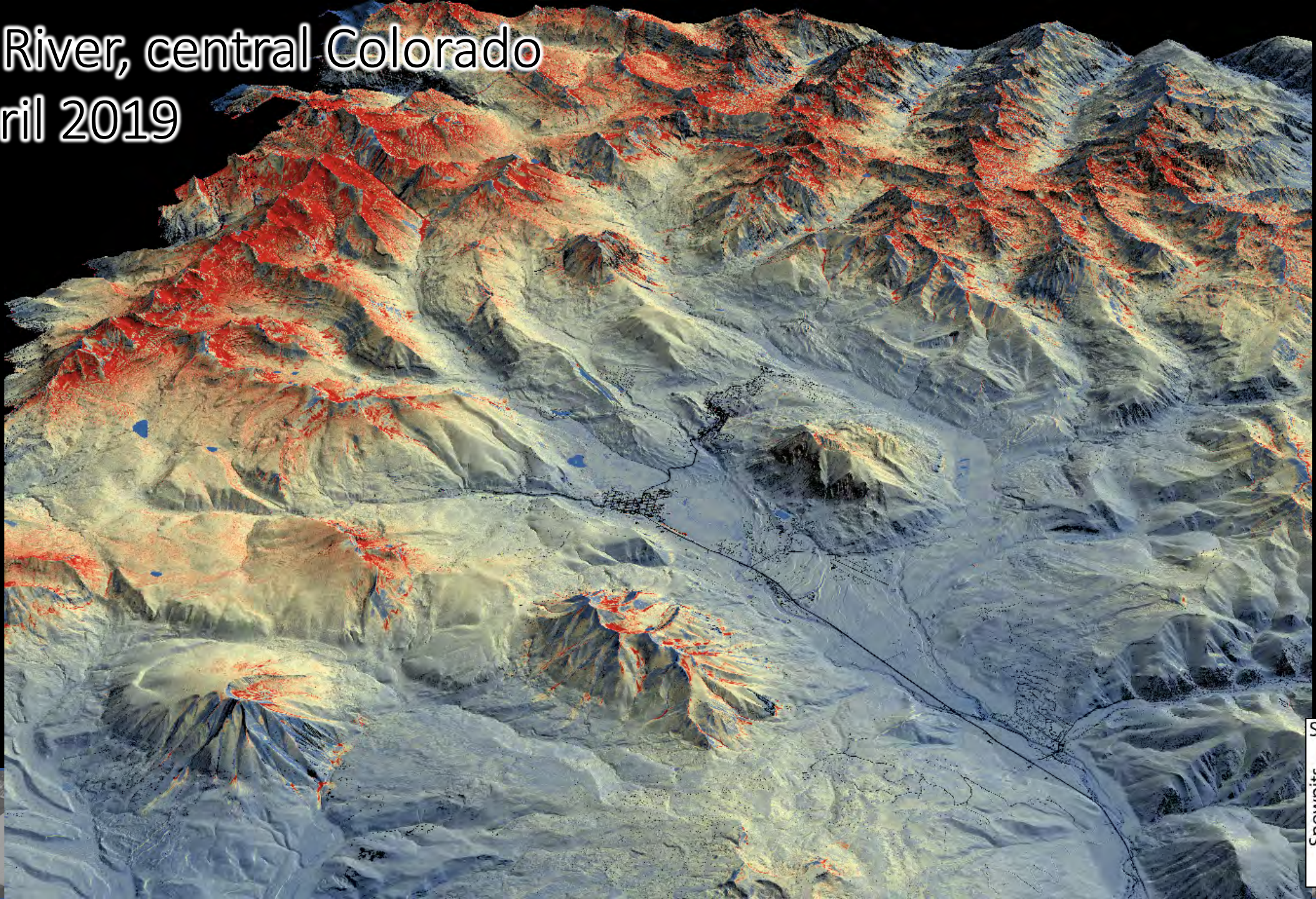
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East River, central Colorado

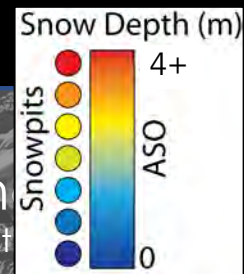
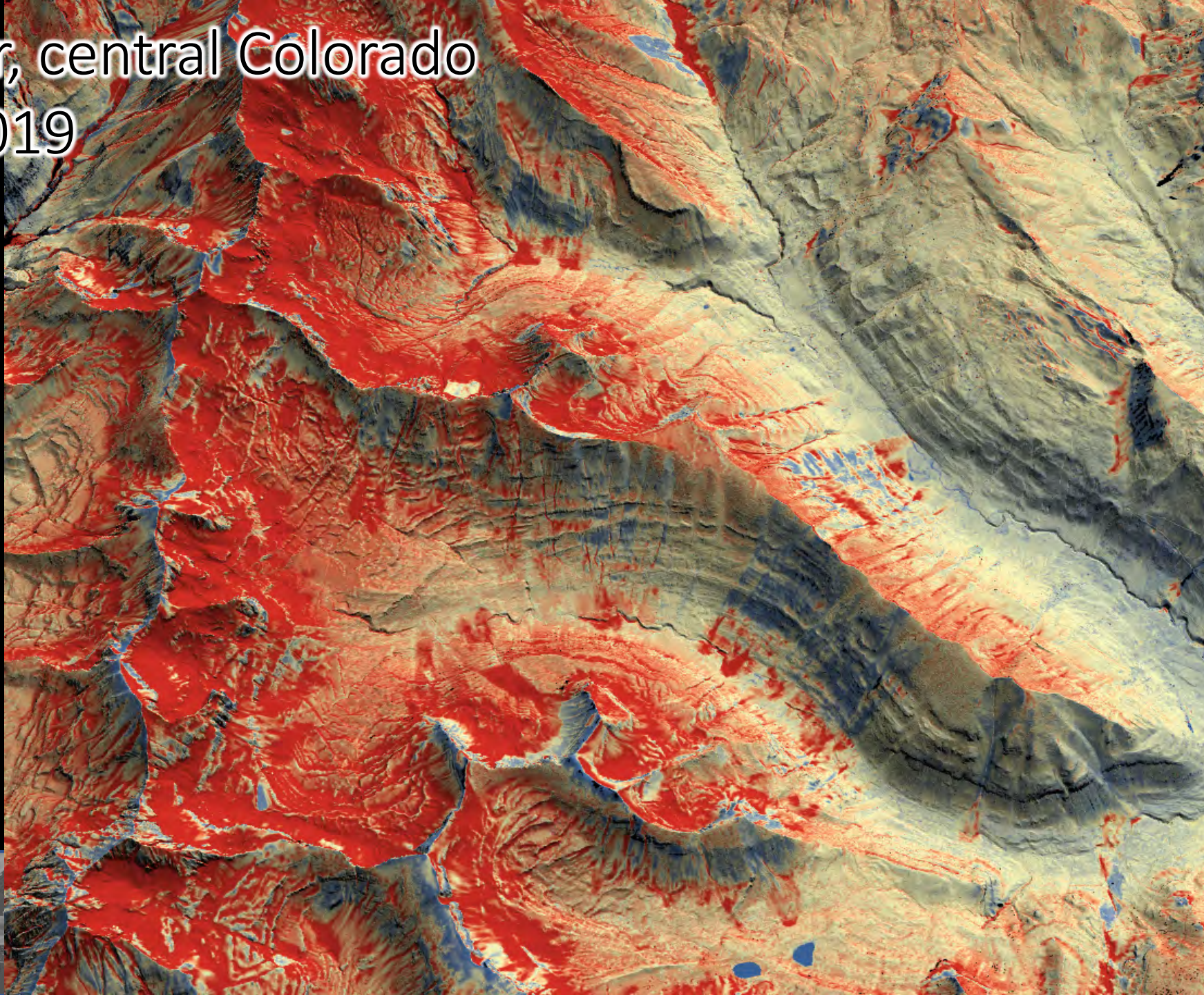
7 April 2019





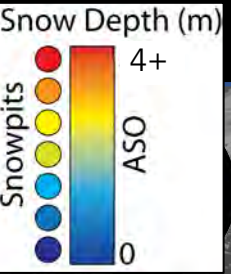
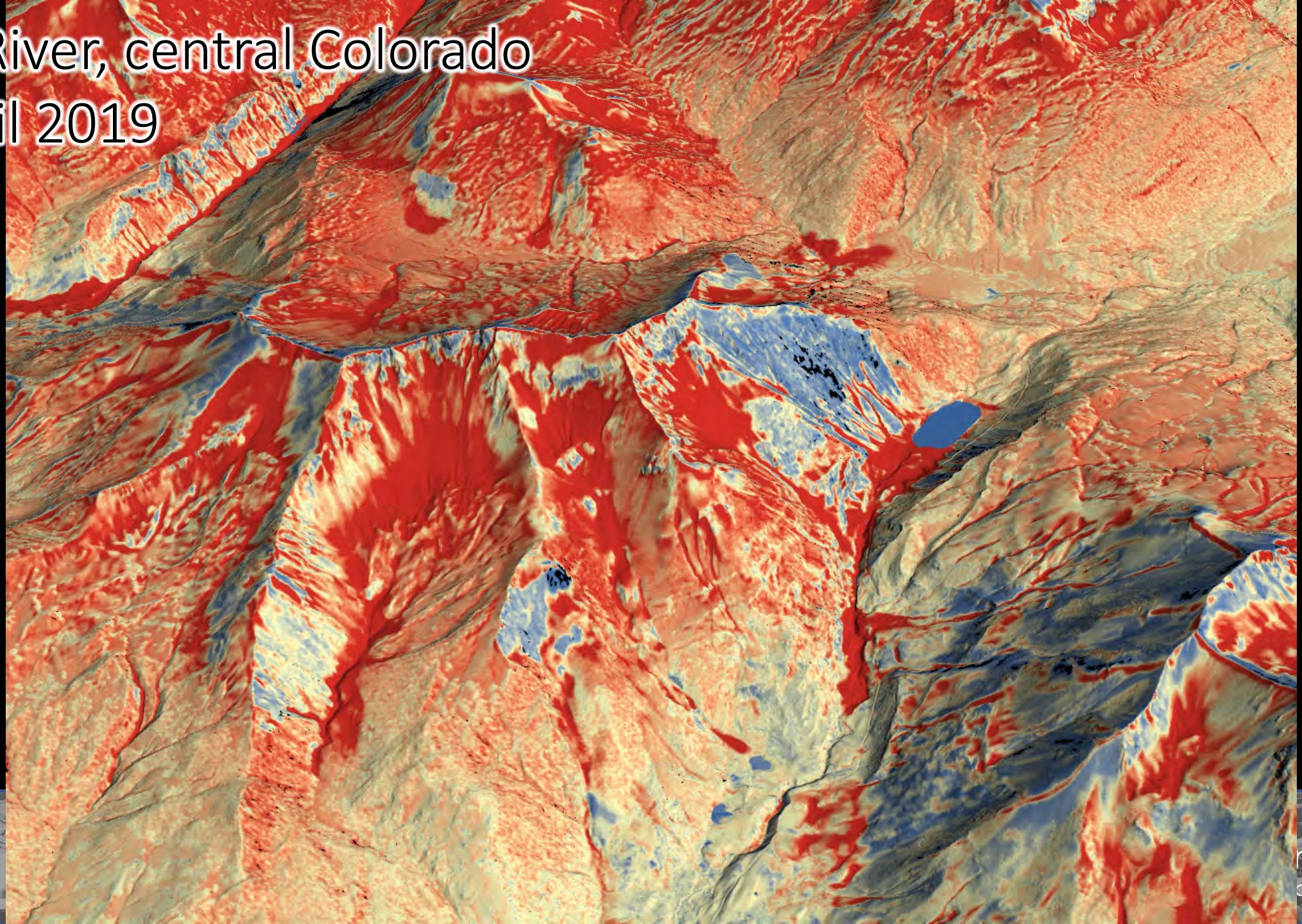
# East River, central Colorado

7 April 2019



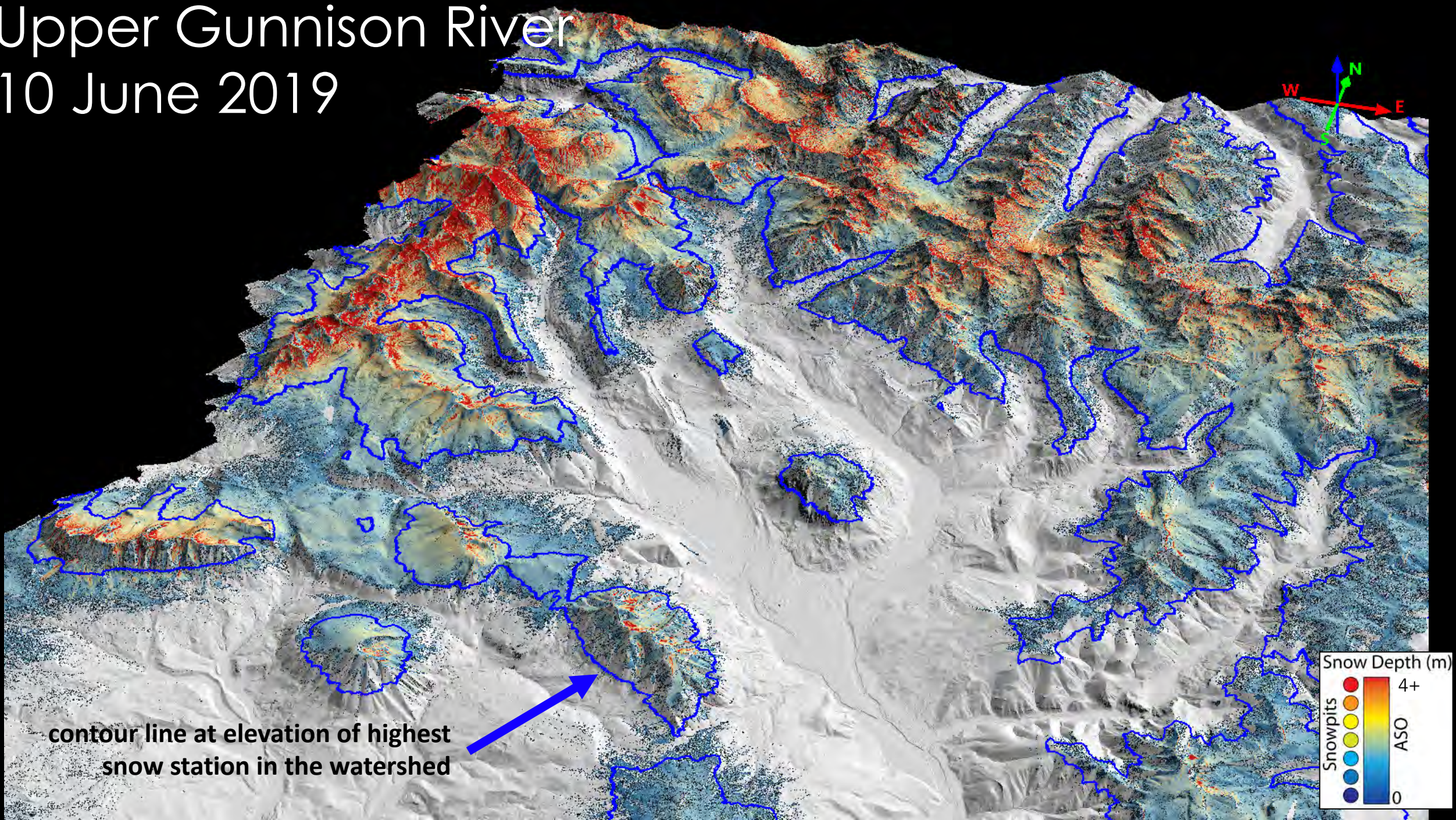
ries, In  
t Corporat

East River, central Colorado  
7 April 2019



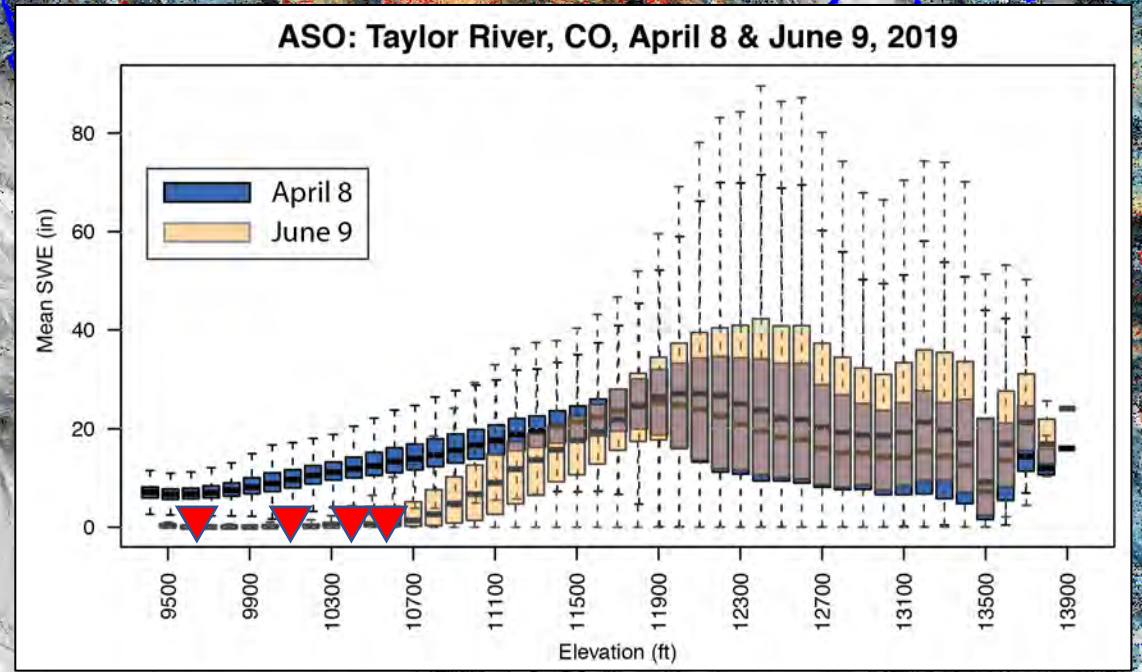
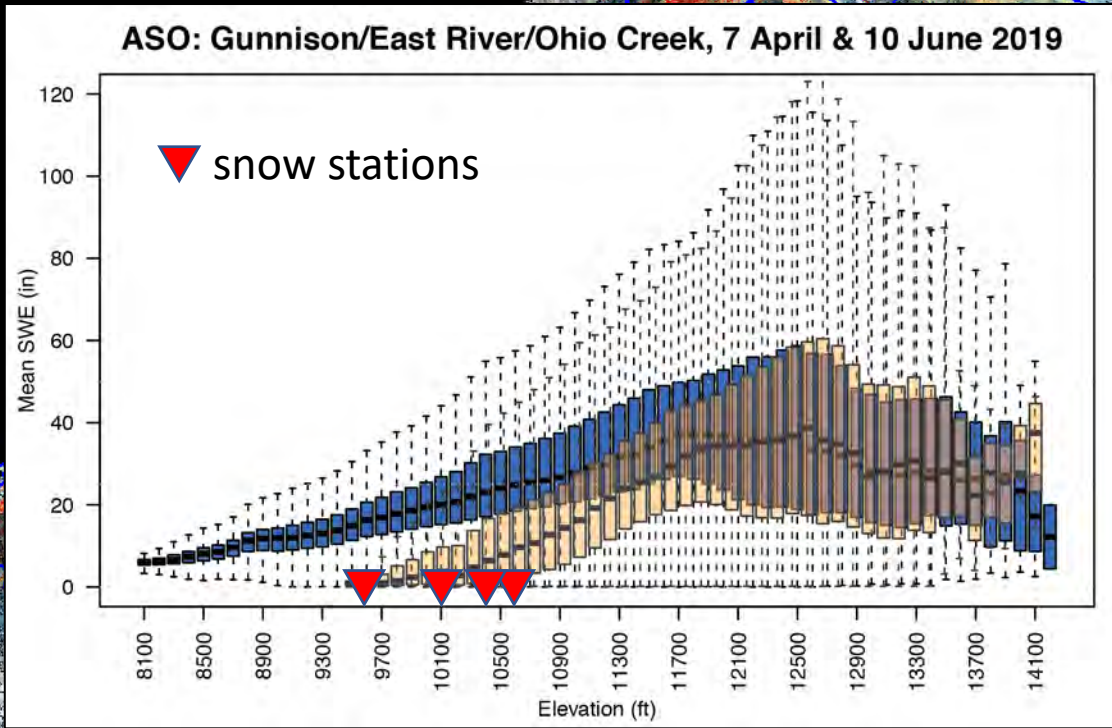
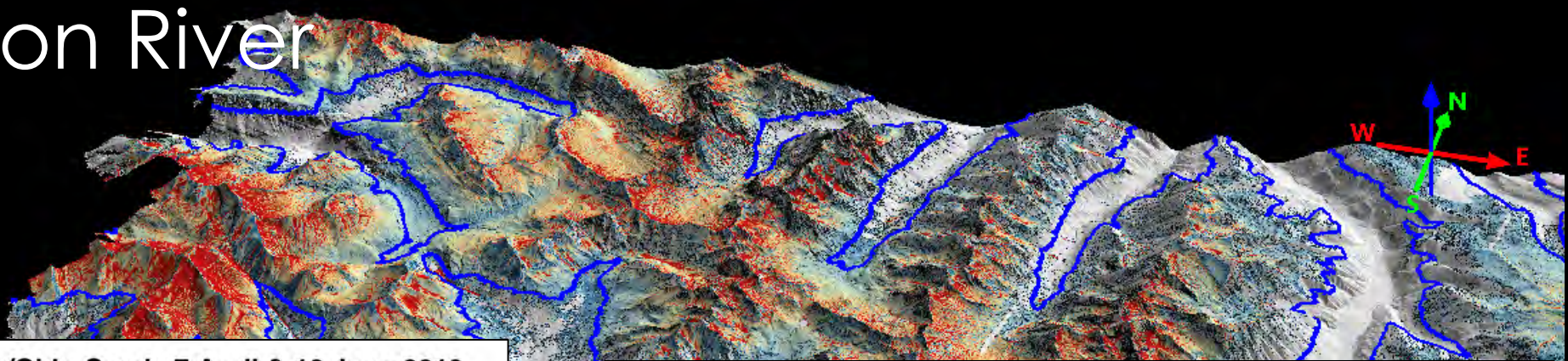
# Upper Gunnison River

10 June 2019

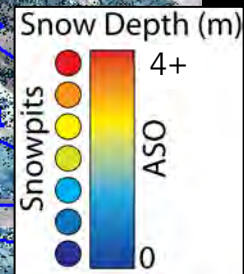
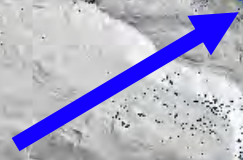


# Upper Gunnison River

10 June 2019



contour line at elevation of highest snow station in the watershed

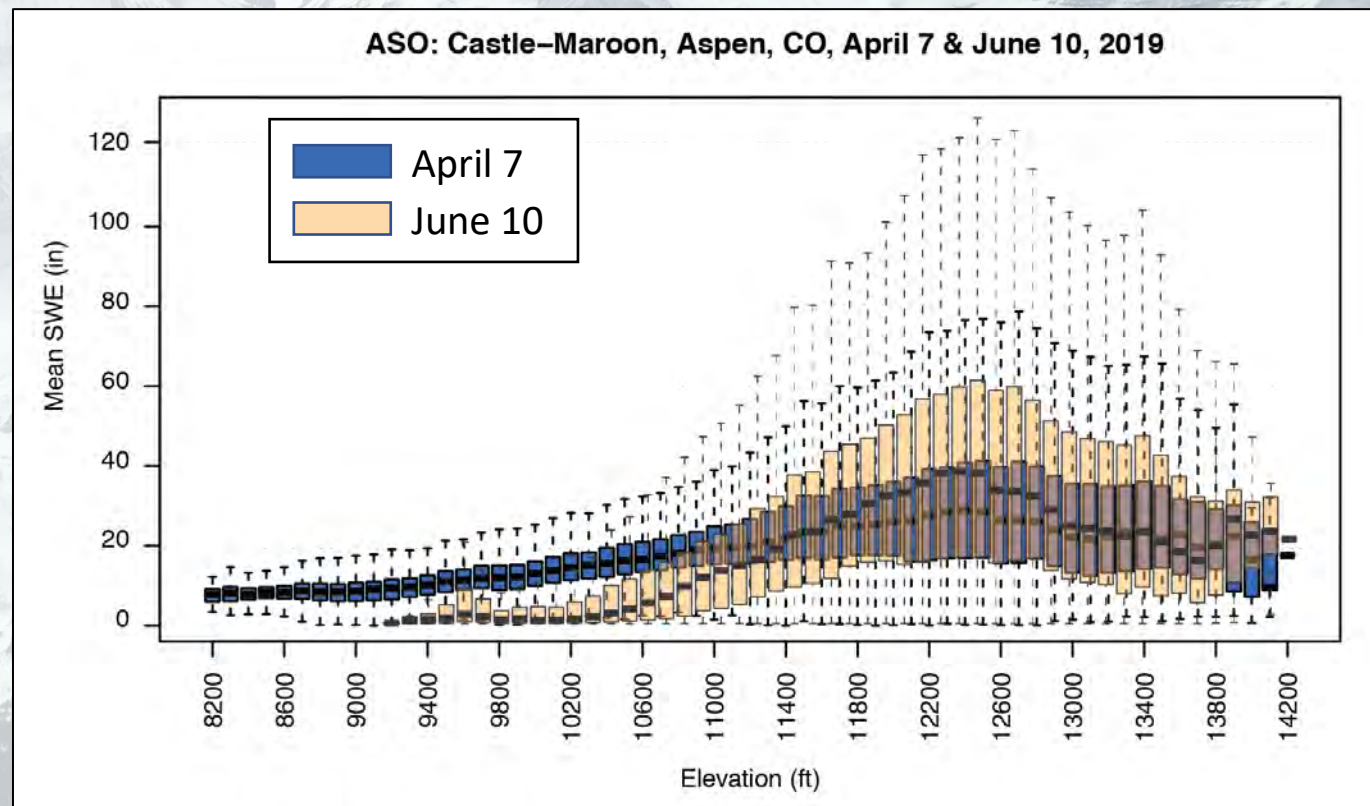
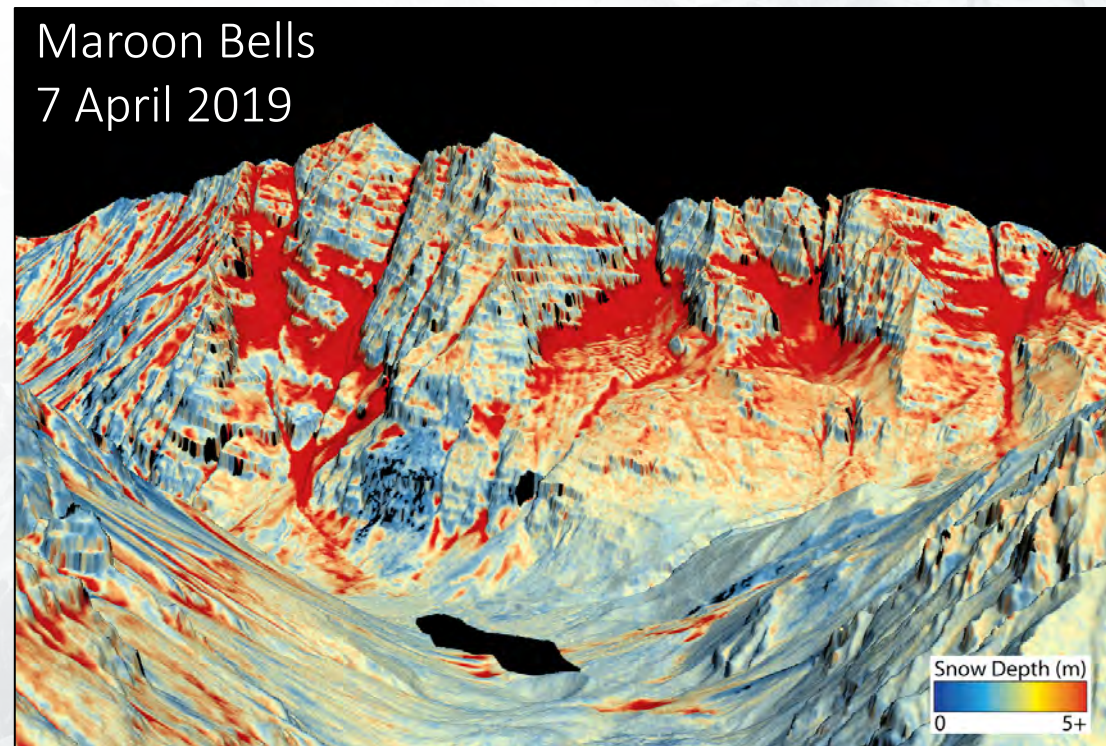


# A new look into Castle & Maroon Creeks

## City of Aspen

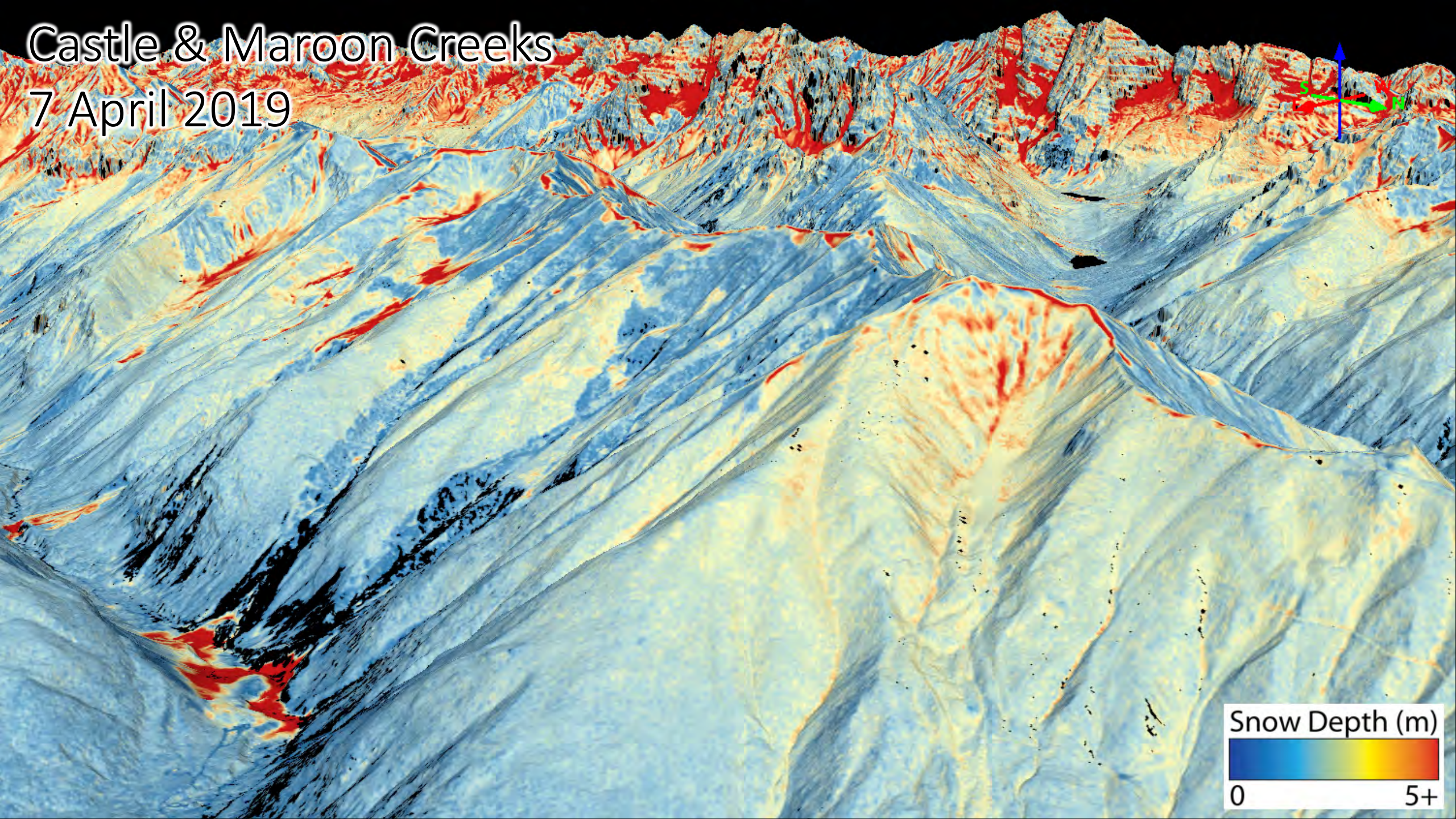
- no snow monitoring stations in the watersheds
- historic link of melt-out elevation & peak runoff
- 2019: April – June maps show low-elevation melt, mid-elevation gains

Maroon Bells  
7 April 2019



# Castle & Maroon Creeks

7 April 2019



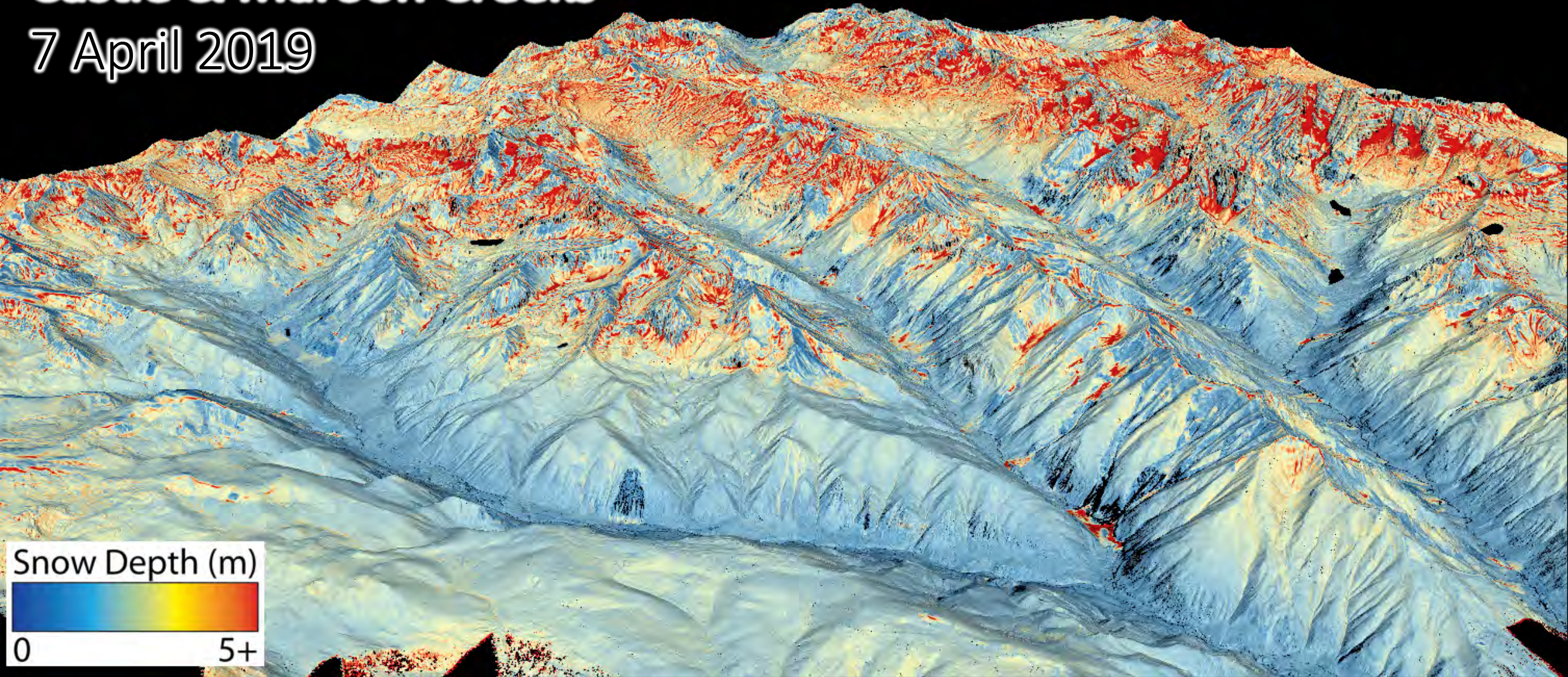
Snow Depth (m)



0 5+

# Castle & Maroon Creeks

7 April 2019



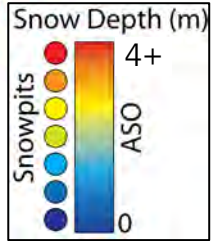
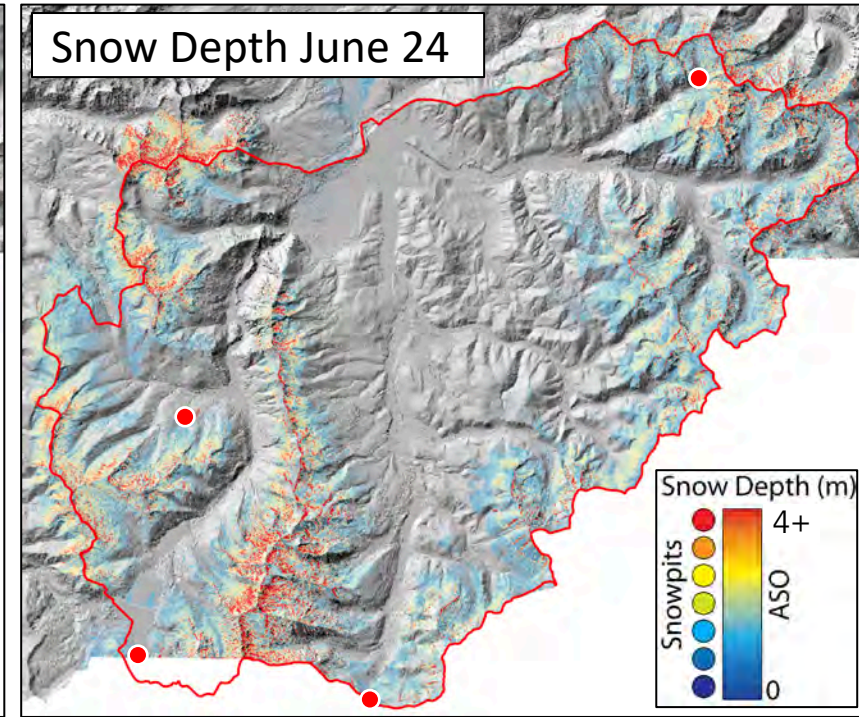
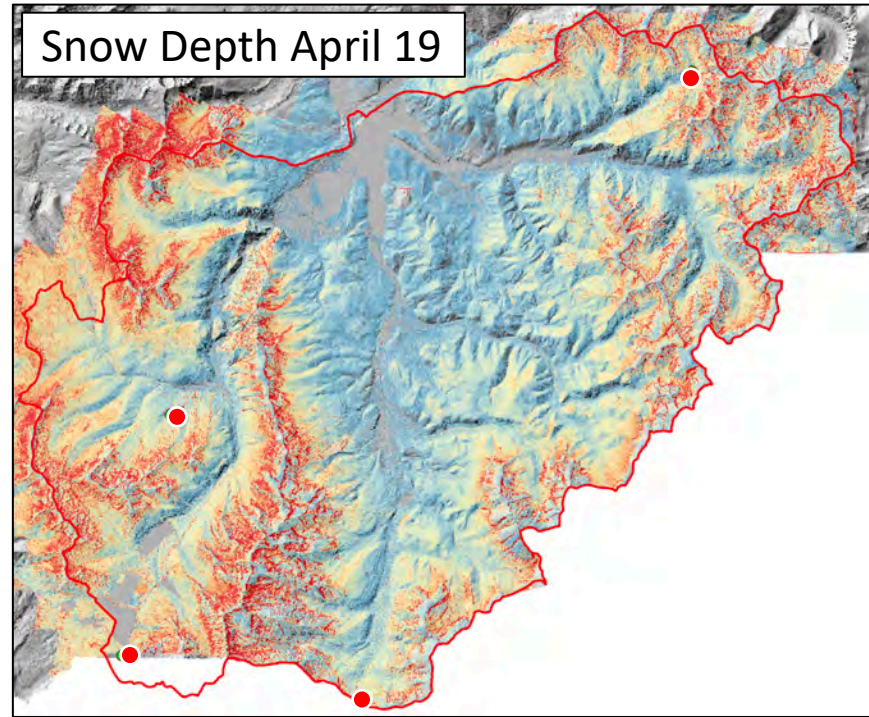
Airborne Snow Observatories, Inc.  
A Public Benefit Corporation



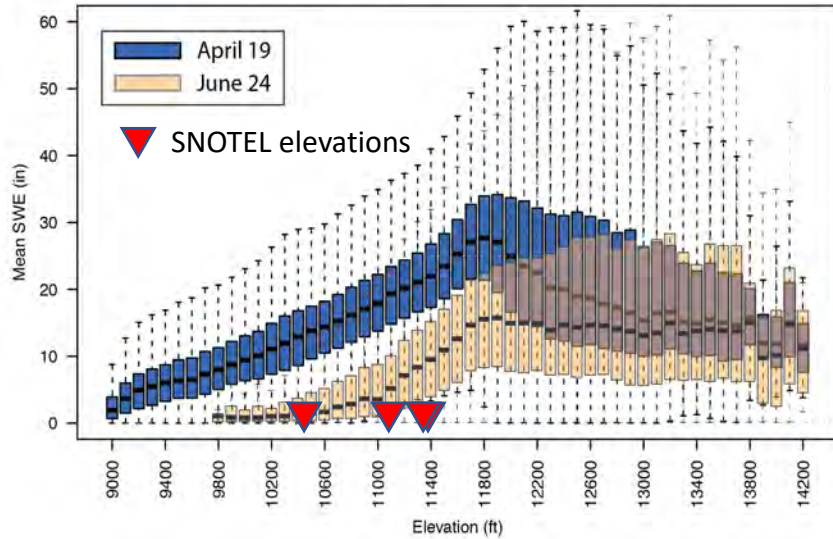
# Blue River Basin

## Denver Water

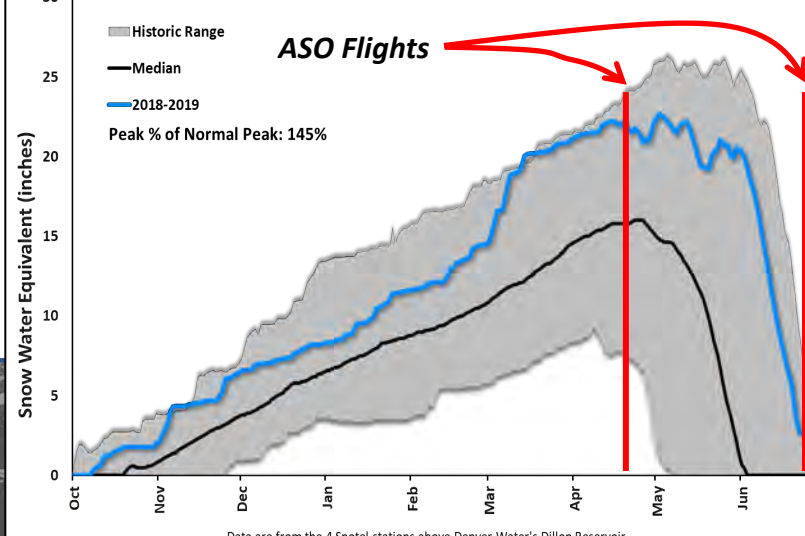
- 2019 Flights: April 19 & June 24
- May + June storms maintained high elevation snowpack
- SNOTELs snow-free on June 28
- June 24 flight SWE volume: *115 TAF*
  - half of total inflow left to melt
  - enabled response to double flow peak



ASO Blue River: SWE by Elevation



SNOTEL Snowpack above Dillon Reservoir



Data are from the 4 Snotel stations above Denver Water's Dillon Reservoir.

Dillon Reservoir Inflow (cfs)



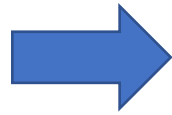


# ASO FPMS flow

## Flight



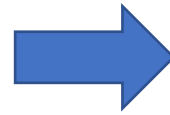
- Lidar
  - Spectrometer
  - (Ka-band radar)
- optimized for mountain conditions**



## Processing



- snow depth
  - snow density
  - obs & modeling
  - SWE
  - snow albedo
  - snow grain size
  - radiative forcing by dust
- < 72 hr turnaround**



## Modeling



## SaaS Analysis & Visualization

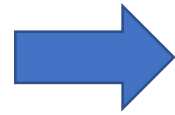


# ASO FPMS flow

## Flight



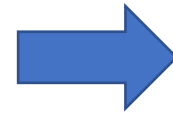
- Lidar
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  - (Ka-band radar)
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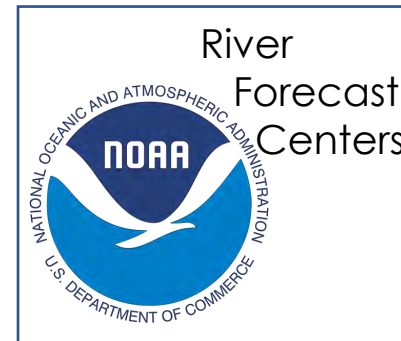
## Processing



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## Modeling



## SaaS Analysis & Visualization

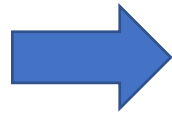


# ASO FPMS flow

## Flight



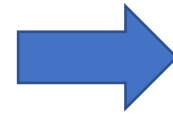
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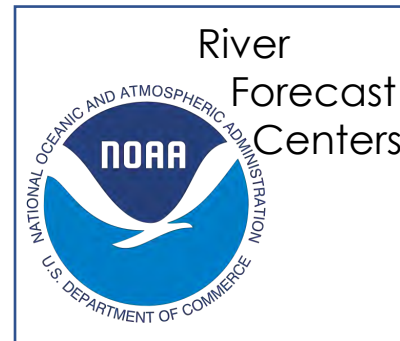
## Processing



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  - SWE
  - snow albedo
  - snow grain size
  - radiative forcing by dust
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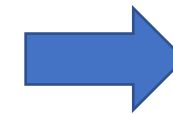
## Modeling



Any public or private forecast entity



## SaaS Analysis & Visualization



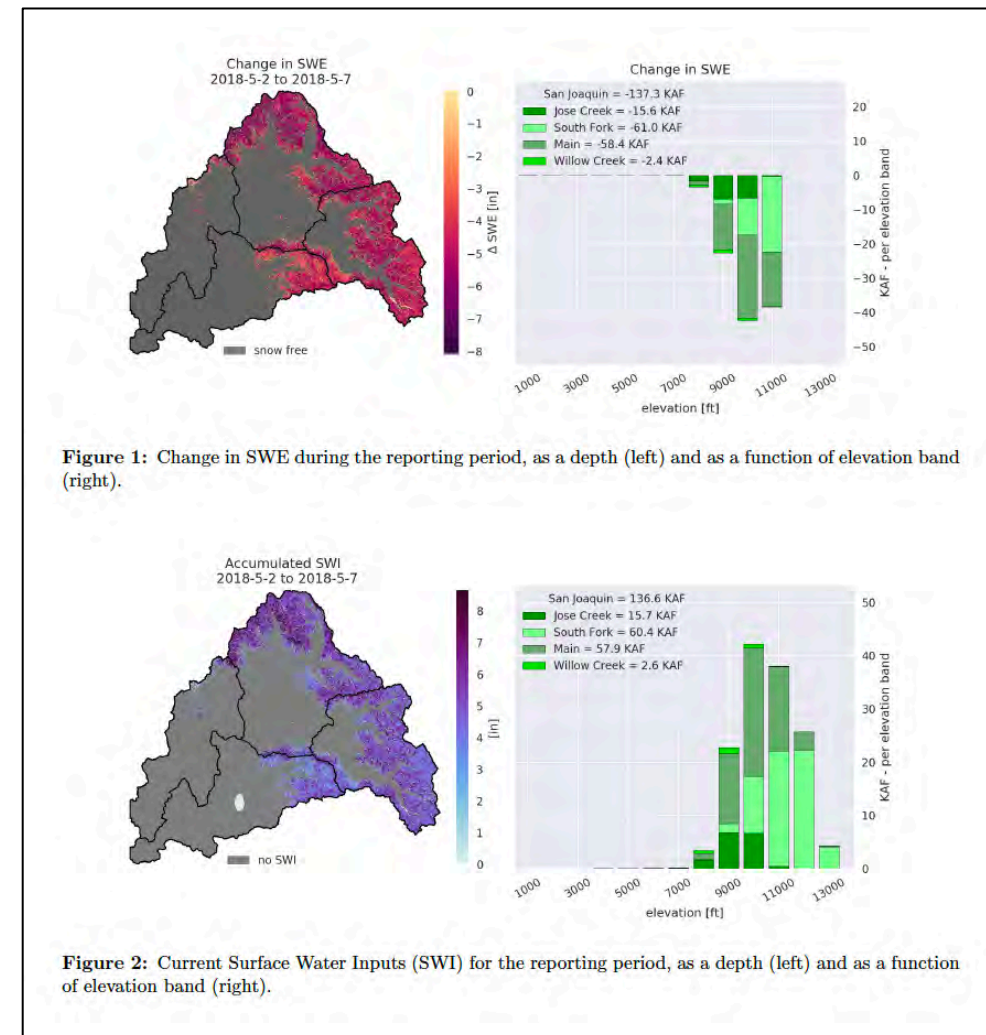
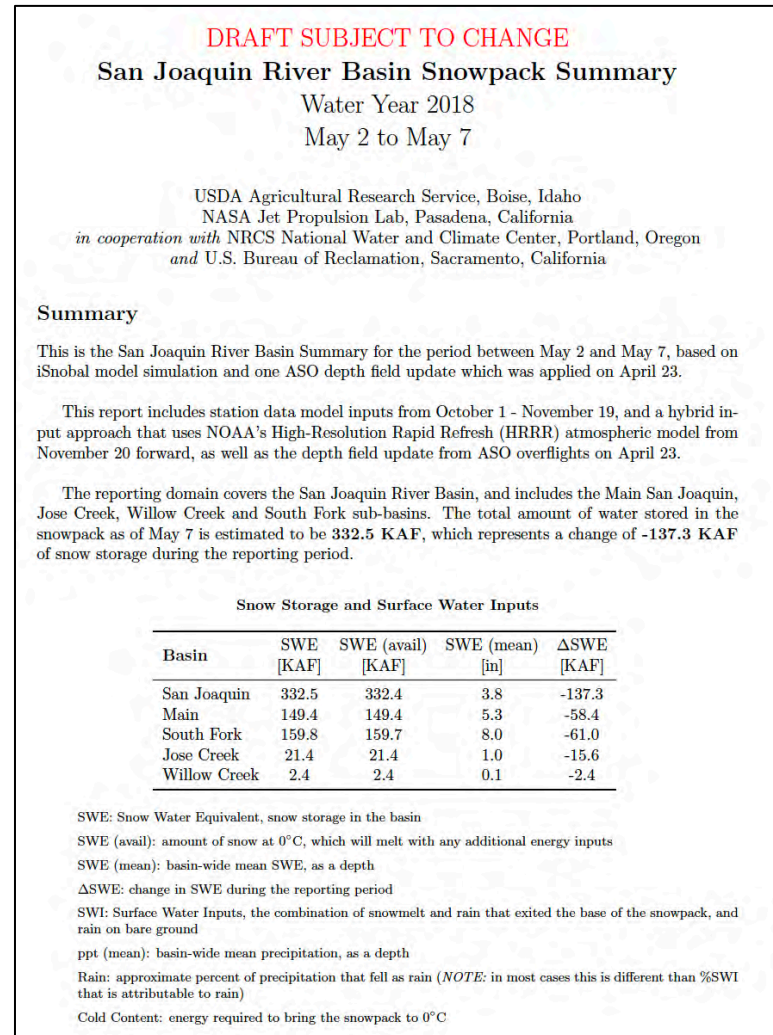
Any public or private decision-maker



# Regular monitoring with weekly snow model reports

## ISNOBAL model

- run continuously through snow season
- ASO snow depth data assimilated
- produces snow density map for SWE calculation
- enables snow inventory tracking between flights



# Expanding applications with operational models

## NOAA River Forecast Center testing/evaluation

- ASO SWE data nudges RFC forecast close to observed AJRO 2 months earlier than manual tuning

|                         | Source / Run Type          | Volume   | Percent of USGS |
|-------------------------|----------------------------|----------|-----------------|
| Taylor Reservoir Inflow | USGS AJRO Volume (target)  | 29.1 KAF | 100%            |
|                         | CBRFC - unmodified         | 35.2 KAF | 121%            |
|                         | CBRFC ASO 3/31             | 30.2 KAF | 104%            |
|                         | CBRFC ASO 5/24             | 30.0 KAF | 103%            |
|                         | CBRFC ASO both             | 29.2 KAF | 100%            |
|                         | CBRFC FM 3/27 (added swe)  | 35.3 KAF | 121%            |
|                         | CBRFC FM through 4/28 (lz) | 35.1 KAF | 121%            |
|                         | CBRFC FM through 5/15      | 33.3 KAF | 114%            |
|                         | CBRFC FM through 5/25      | 30.8 KAF | 106%            |

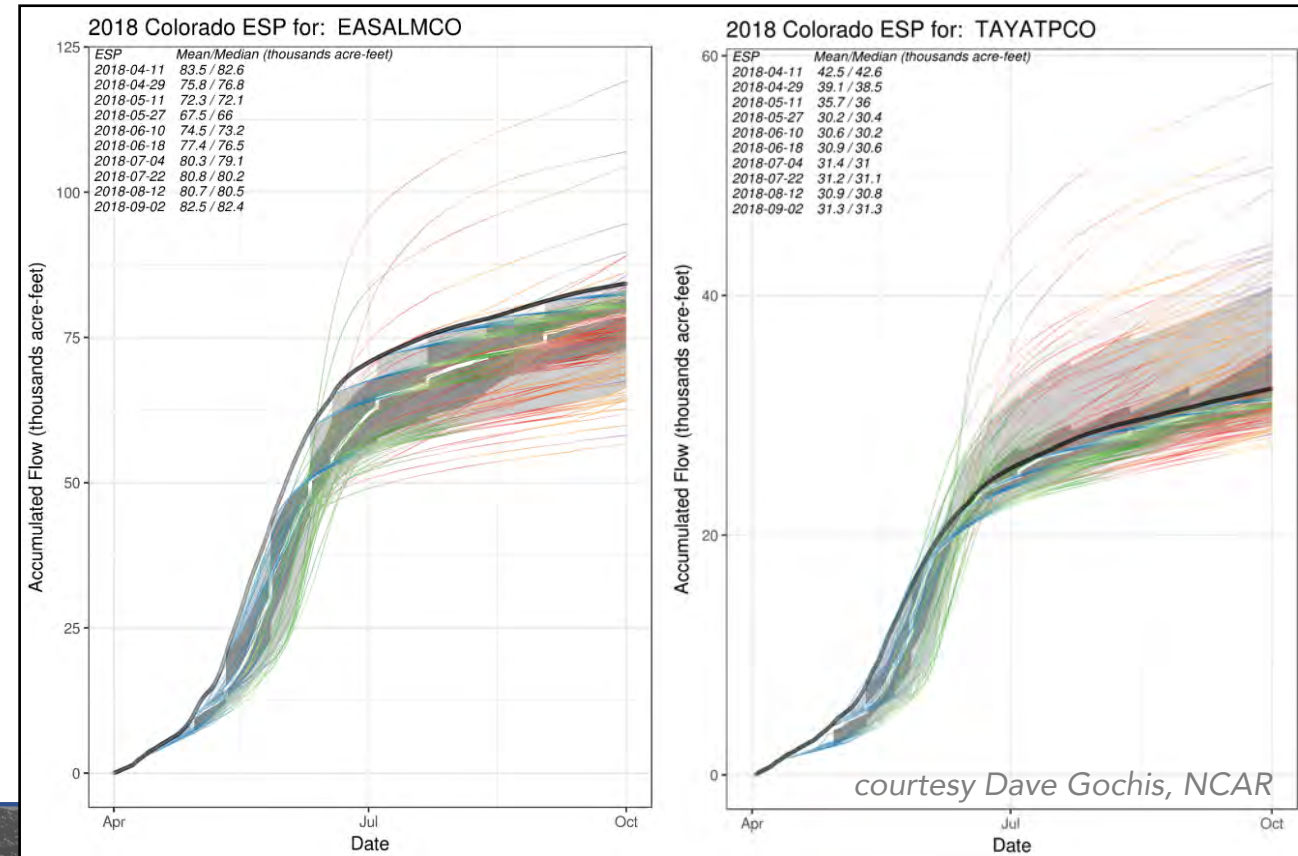
\*preliminary results courtesy Pat Kormos, CBRFC

## WRF-HYDRO/National Water Model assimilation

- High elevation snow data from 24 May ASO assimilation reduces low forecast bias in ESP AJRO forecast

### East River @ Almont

### Taylor River @ Taylor Park



# Expanding applications with operational models

## NOAA River Forecast Center testing/evaluation

- ASO SWE data nudges RFC forecast close to observed AJRO 2 months earlier than manual tuning

|                         | Source / Run Type          | Volume   | Percent of USGS |
|-------------------------|----------------------------|----------|-----------------|
| Taylor Reservoir Inflow | USGS AJRO Volume (target)  | 29.1 KAF | 100%            |
|                         | CBRFC - unmodified         | 35.2 KAF | 121%            |
|                         | CBRFC ASO 3/31             | 30.2 KAF | 104%            |
|                         | CBRFC ASO 5/24             | 30.0 KAF | 103%            |
|                         | CBRFC ASO both             | 29.2 KAF | 100%            |
|                         | CBRFC FM 3/27 (added swe)  | 35.3 KAF | 121%            |
|                         | CBRFC FM through 4/28 (lz) | 35.1 KAF | 121%            |
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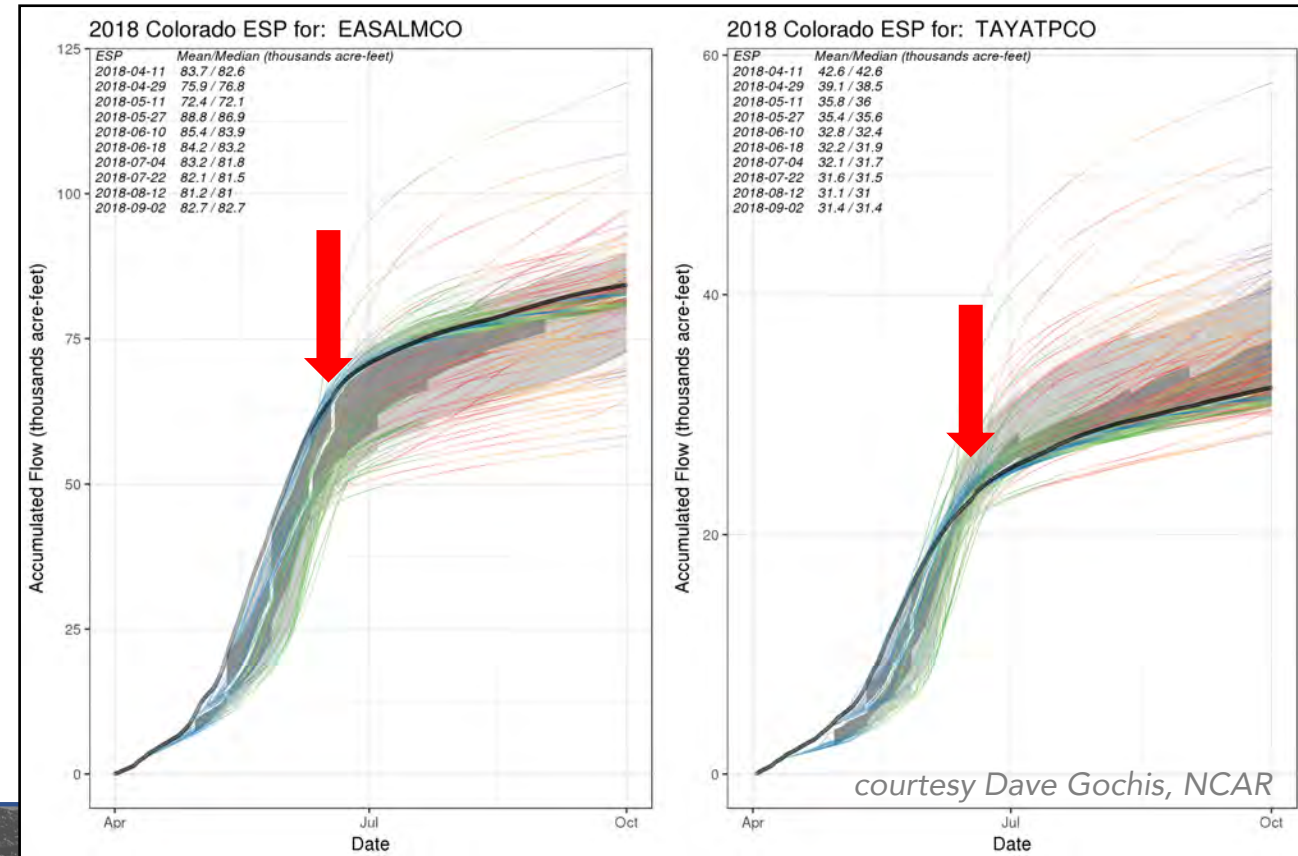
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# Enabling & synergy data sets

## Basin polygons

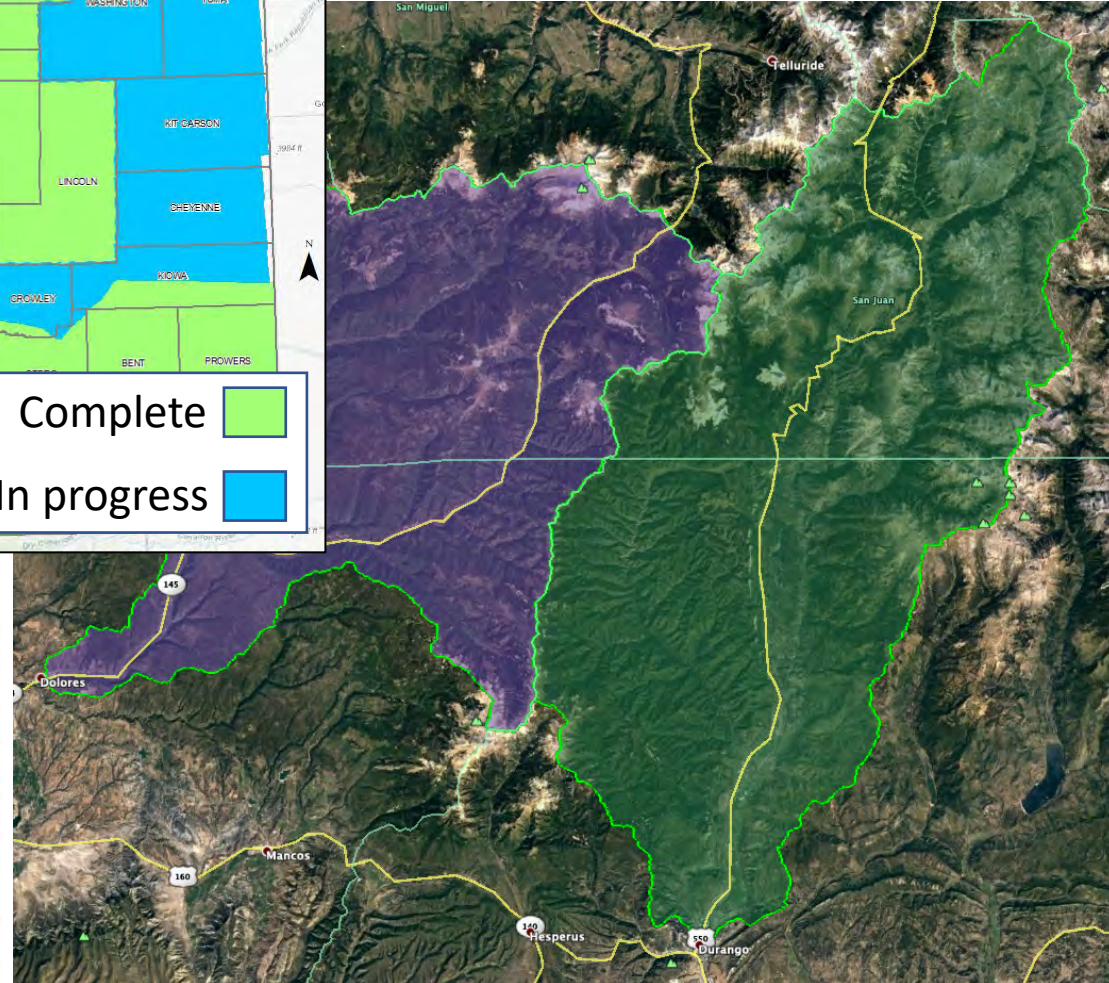
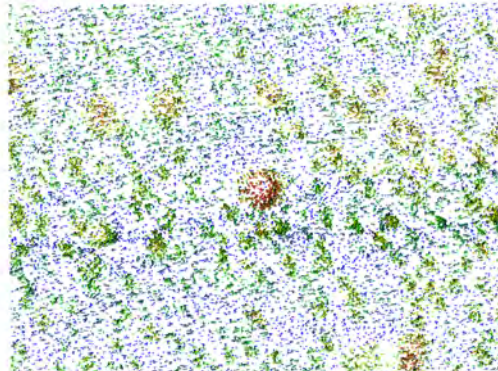
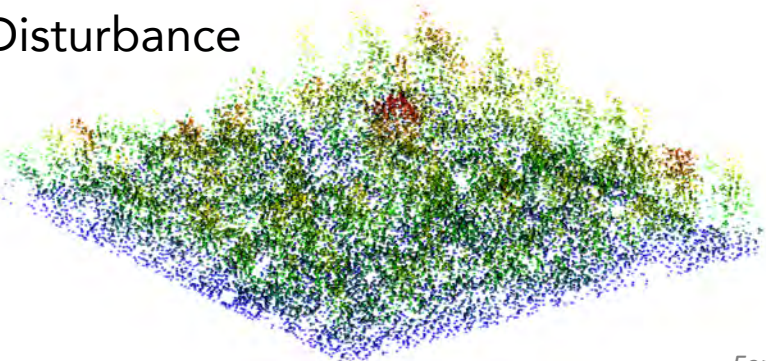
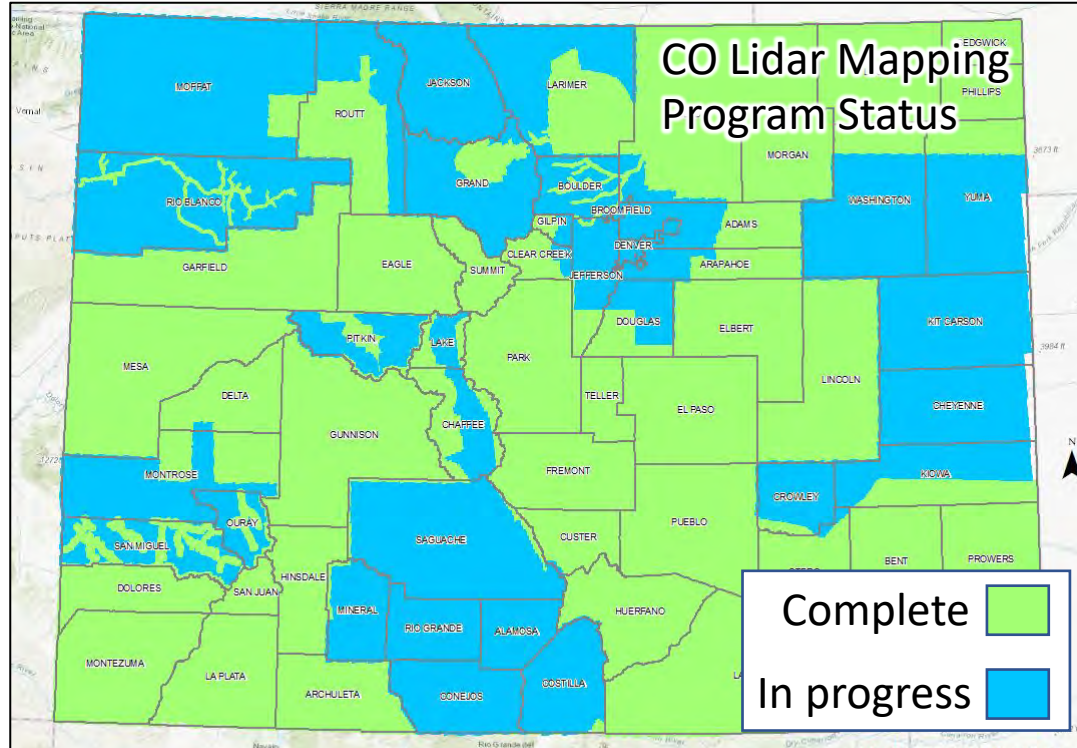
- key forecast points
- constrained to (likely) snow-covered area

## Snow-free reference data

- can be ASO-flown
- can be collected by other agencies (USGS QL2 or better point density)

## Forest metrics

- Hydrologic model input
- Forest health
- Disturbance



# Enabling & synergy data sets

## Basin polygons

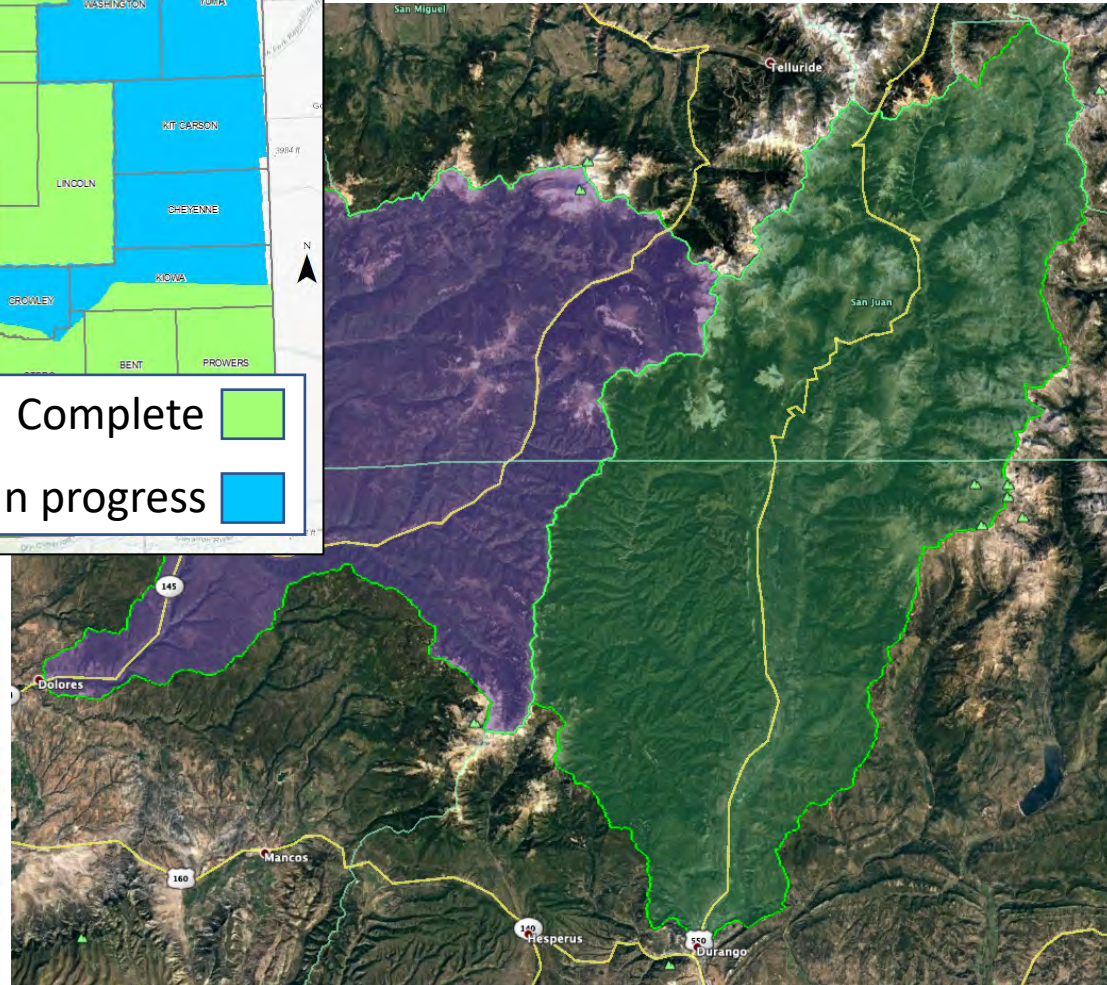
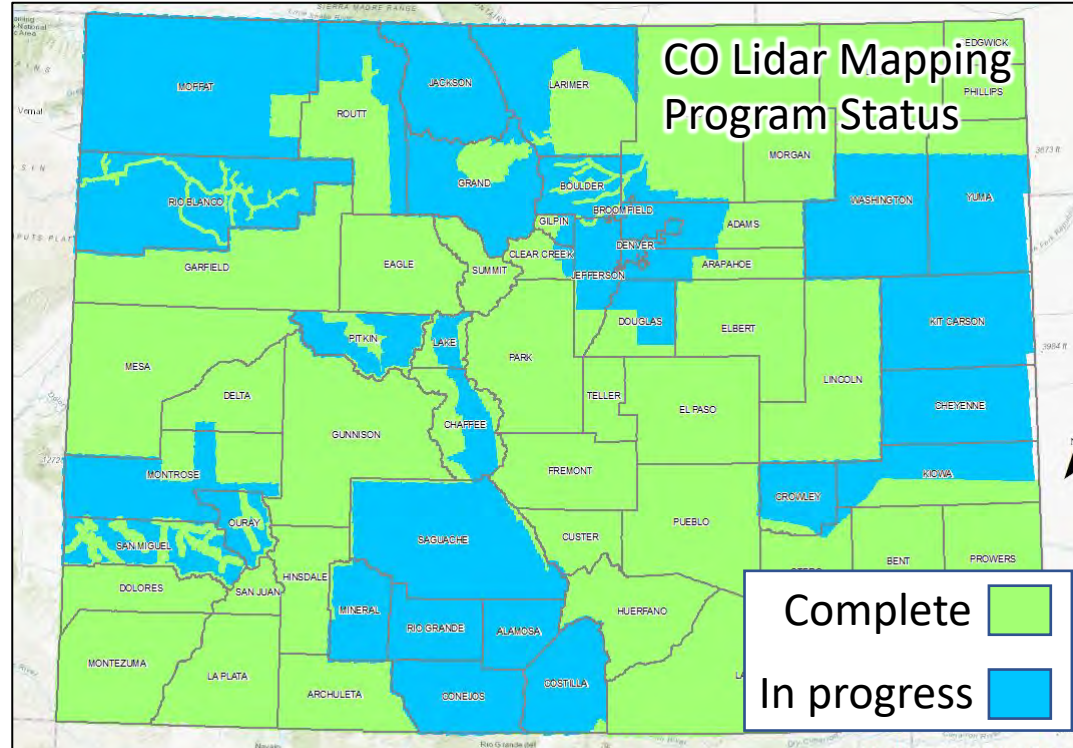
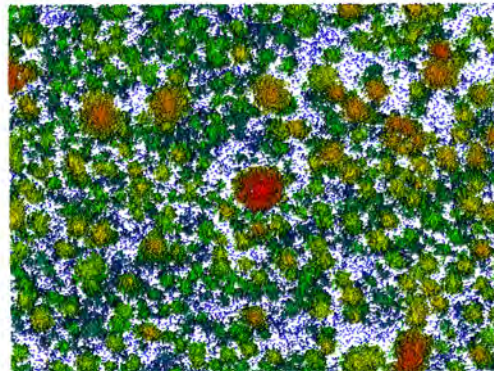
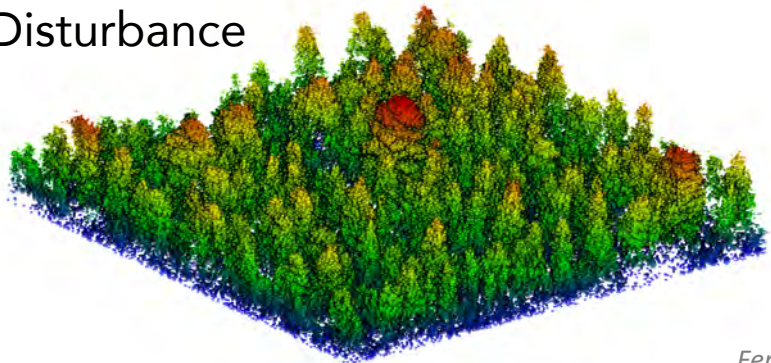
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## Forest metrics

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- Disturbance





# WY 2021 Southwestern program scoping

## **Initial concept:**

### **Flights: 2 per basin**

- 1 near peak SWE (~ April 1)
- 1 mid/late melt season (late May/early June)

### **Snowpack modeling**

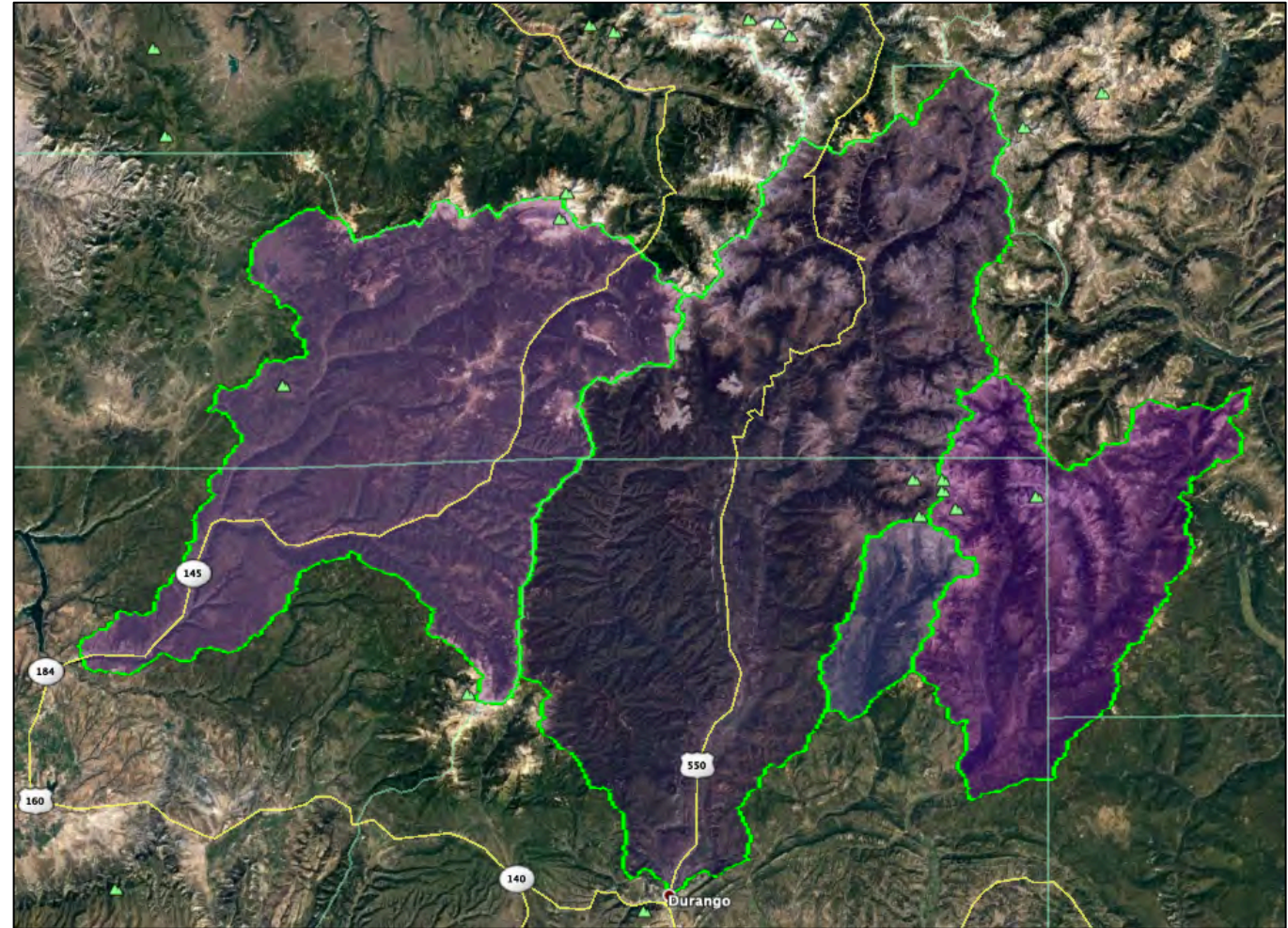
- snow density for SWE conversion
- on-demand state-of-snowpack reports

### **Hydrologic model support**

- NCAR partnership for WRF-HYDRO forecasting
  - e.g. Rio Grande & Gunnison
- ASO data assimilation

### **Data distribution**

- ArcGIS server
- web portal



# WY 2021 Planning options

*all options leverage fixed-cost sharing with Conejos*

## Option 1: full program

- Option 1: 2 flights in Dolores, Animas, Lemon, & Vallecito

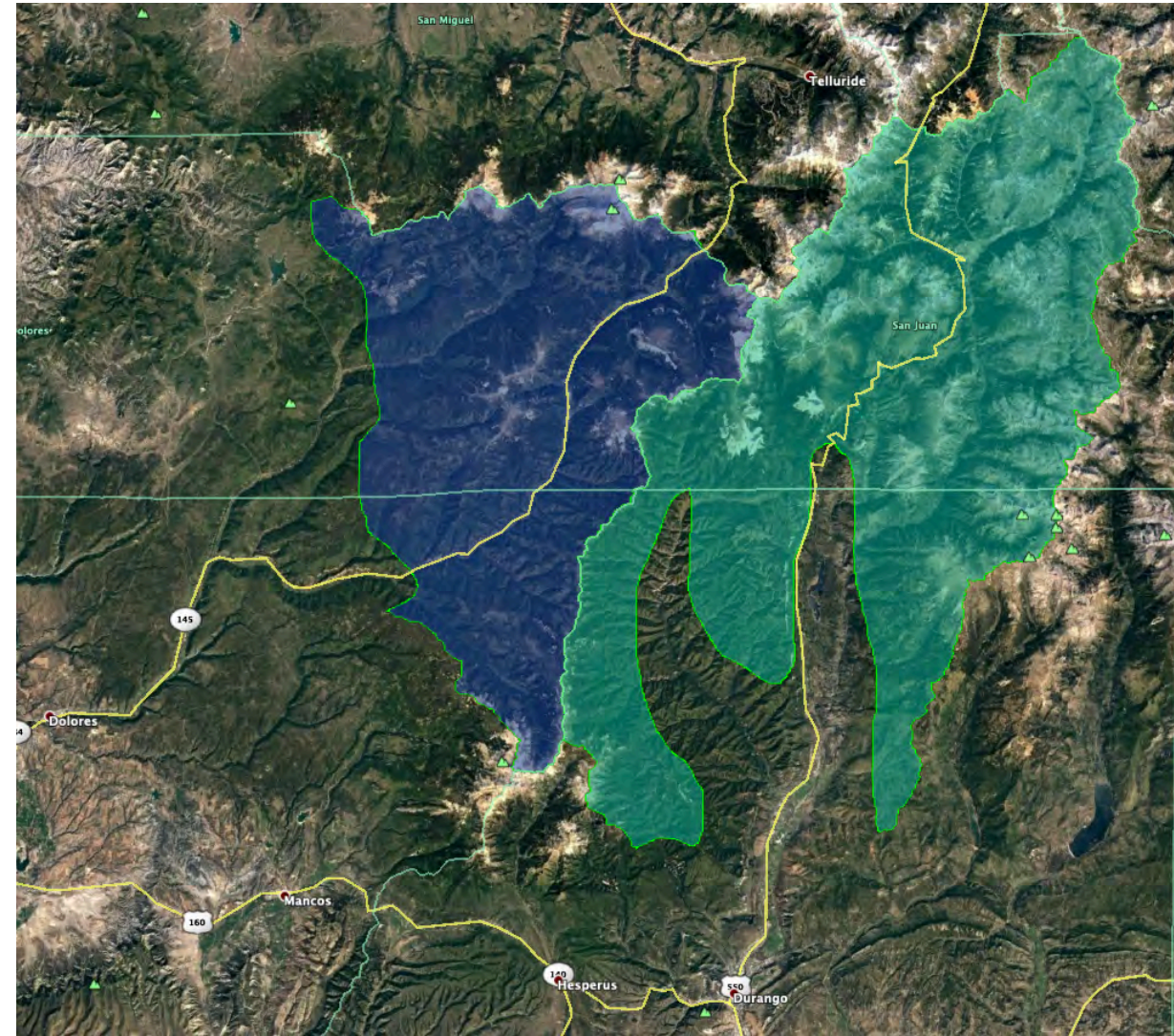
## Options 2-7: reduce area

- Option 2: no Lemon
- Option 3: no Vallecito
- Option 4: no Lemon or Vallecito
- Option 5: Animas & Dolores above 10,000' (incl. L&V)
- Option 6: no Dolores
- Option 7: Dolores only
- Option 8: Animas & Dolores above 10,000' (without L&V)

## Option 9: single flight

- Option 9: 1 flight for full Dolores, Animas, Lemon, & Vallecito

*Options exist without snowpack modeling as well*





# Engagement & Buy-in

## *enthusiastic adoption by water managers*

**RIISING TO NEW CHALLENGES**  
FOR CALIFORNIA'S SNOW FORECASTING PROGRAM

California's History of Leadership in Snow Monitoring

In 1928, the State of California initiated a novel water supply forecasting program that added air measurements of snow in select locations to predict spring and summer runoff into the state's reservoirs. This investment was motivated by the "Yellow Water Run" where the forecasting techniques helped and the long-standing litigation over operation of Lake Tahoe by reducing errors and professional judgment in reservoir operations. Today, this forecasting technique has matured into an indispensable tool for balancing the operations at California's major reservoirs for the benefit of our economy, environment, and public safety. The snow program currently includes 225 monitoring locations that span the watersheds of the Sierra Nevada and Trinity Alps.

The Airborne Snow Observatory (ASO) is an aerial snow monitoring tool that provides precise measurements of depth for every square meter of snow in the watershed. Combined with the conventional network, ASO provides a complete and accurate picture of snow water content that is robust against climate change.

**ASO**

**WHY UPGRADE A WORKING PROGRAM?**

Conventional snow surveys have served an indispensable role in California water management for almost a century, but the state has also changed dramatically over the same period. The demand for water has grown along with the population, which has doubled in the past 40 years alone. We have shared our landscape with urban and suburban growth requiring floodwaters. Changes in social values have required that reservoirs be operated not just for people, but also for downstream species and habitat. With the implementation of the Sustainable Communities Management Act, highly precise water operations will be required to maximize groundwater recharge. Finally, the climate appears to be changing in ways that further strain the state's water resources and how we manage them.

As a result of these changes, mistakes in water management have become more expensive than ever. The conventional snow survey and forecast methods rely heavily on professional judgment and extrapolation with a large margin for error because they use a few point locations to estimate water held in tens of thousands of square miles of snow cover. In the past, water managers have heeded imperfections in the survey by over- or under-estimating water forecasts to avoid flood damage or shorting deliveries. These error-prone practices have begun to pose problems for meeting demands of our urban, agricultural and environmental water users.

Download a PDF of this brochure, here: [http://bit.ly/ASO-brochure-2018](#)

## CALIFORNIA'S OPPORTUNITY TO LEAD

Hydrologists and water managers at state, regional, and unparalleled opportunity to improve the management ability to adopt this technology and harness its benefits.

At present, NASA and research funding for ASO surveys of local and regional water users with a strong belief in emerged to provide gap funding through the 2019 snow Tuolumne, San Joaquin, and Kings river basins. This survey to broadcast the successes experienced by the ASO program to leverage the range of benefits ASO could provide if

## THE SACRAMENTO BEE

VIEWPOINTS

### Changes in climate continue to make surveying watersheds tricky. 'But we can change that'

BY FRANK GEHRKE SPECIAL TO THE SACRAMENTO BEE  
MAY 30, 2019 03:01 AM



"ASO provides invaluable information that is not otherwise available, most importantly information about the rate of melt that provides a real opportunity to optimize reservoir operations for water supply, flood control, and instream requirements."

**Steve Haugen, Watermaster,  
Kings River Water Association**

"Having used this technology, it is hard to imagine a future without it."

**Dave Rizzardo, Chief of Snow Surveys  
and Water Supply Forecasting,  
Department of Water Resources**

**Wes Monier, Chief Hydrologist,  
Turlock Irrigation District**

"Advanced observing systems are critical elements needed to support integrated water management in the 21st Century."

**Mike Anderson,  
State Climatologist,  
Department of Water Resources**

*"[ASO] is, without a doubt, the most significant development in the history of snow surveys."*

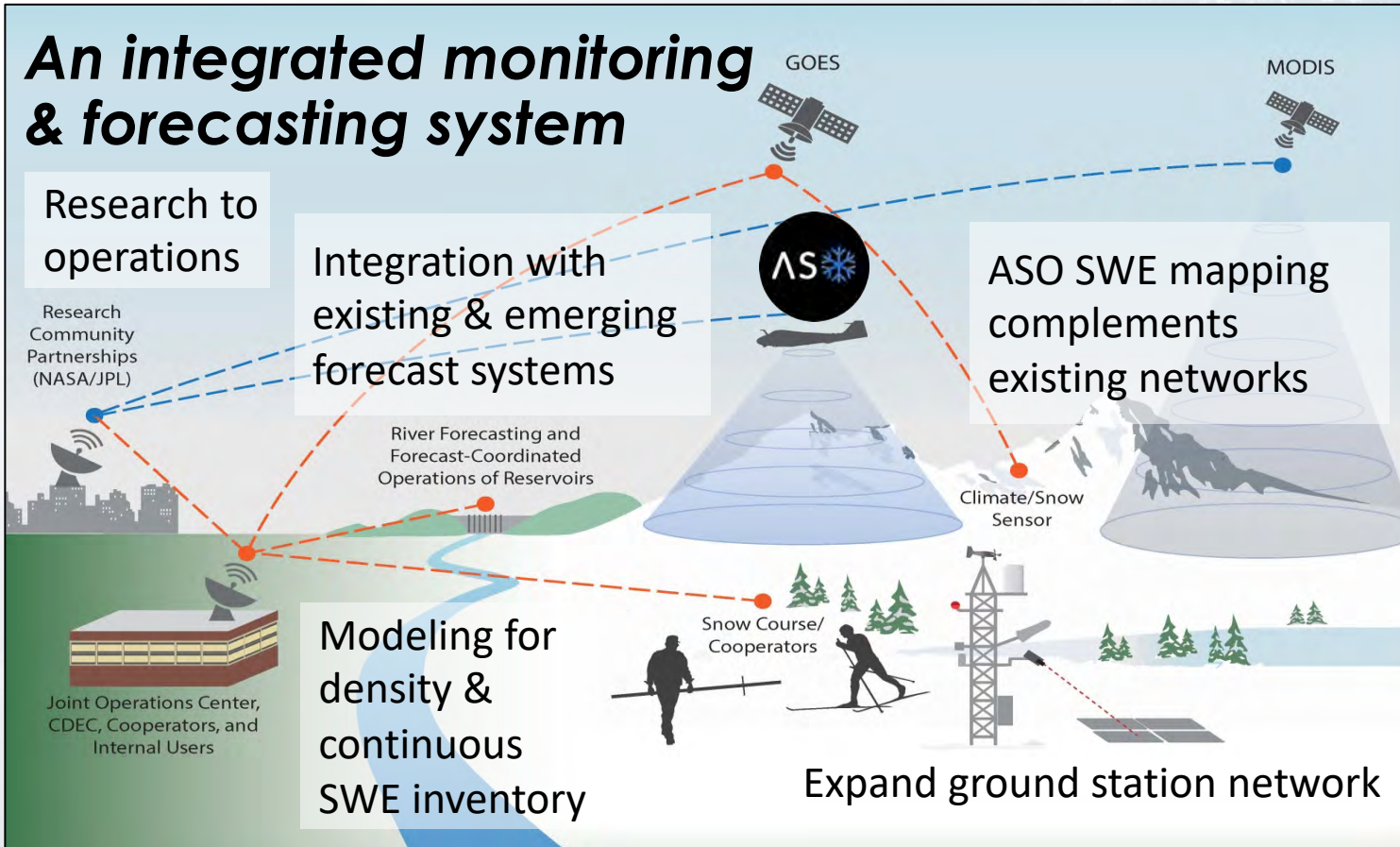
- Frank Gehrke  
Chief of CA Cooperative  
Snow Survey Program (ret.)

*excerpt from the ASO forecasting brochure, produced by CA water management cooperators*

Airborne Snow Observatories, Inc.  
A Public Benefit Corporation



# Supporting Next Generation Resource Management



## Addressing evolving challenges & programs

- decision support information
- providing best snow data to experienced forecast teams
- realizing full potential of advanced model systems
- accurate SWE inventory for equitable decision-making

## Operations support in connected fields

- forecast-informed hydropower production
- forest inventory & management
- transportation infrastructure
- glacier change monitoring

courtesy CA DWR

Airborne Snow Observatories, Inc.  
A Public Benefit Corporation

