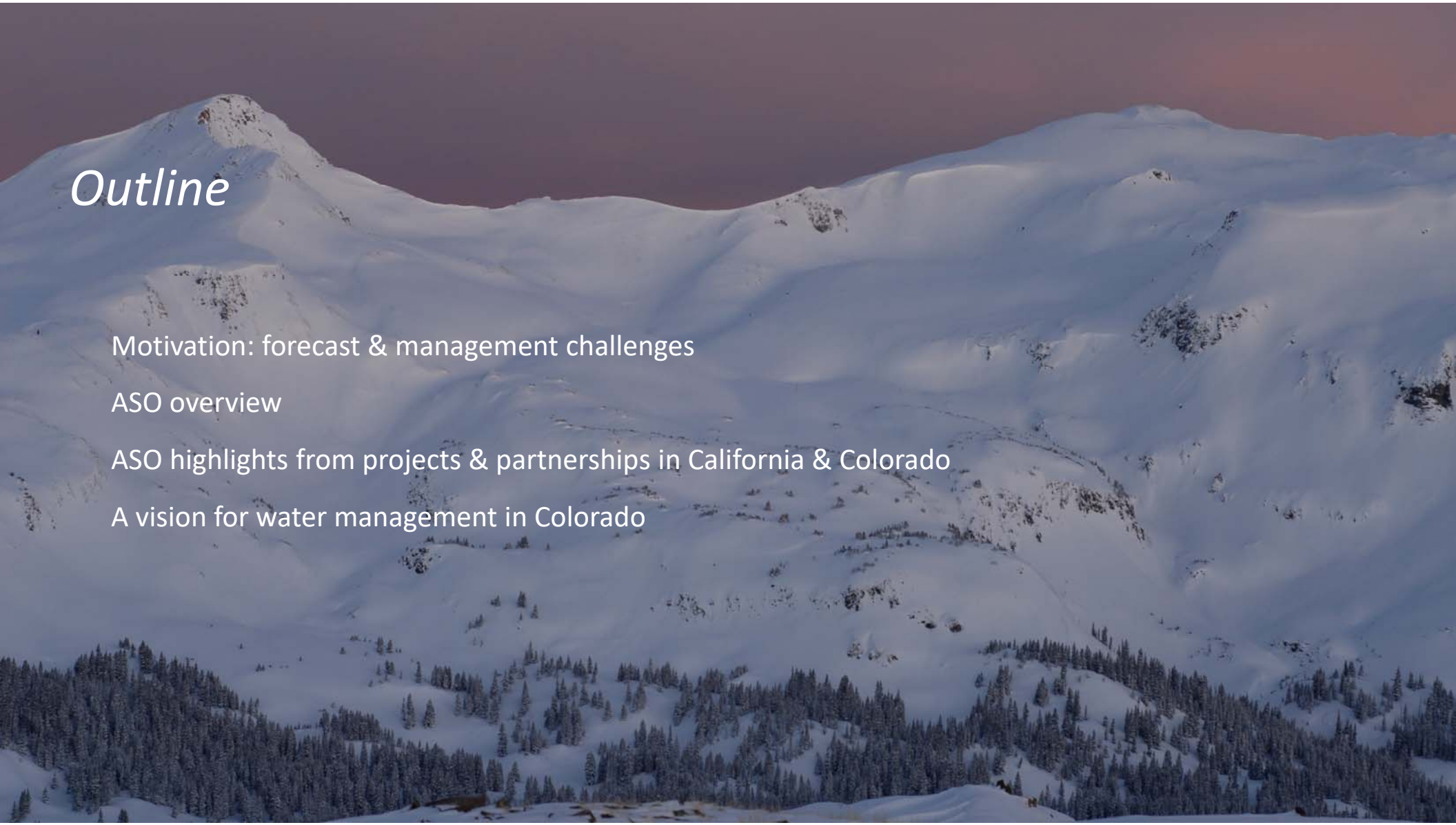
# Mapping mountain snowpacks

*supporting Next Generation Water Management with the Airborne Snow Observatory*

Jeffrey S. Deems
*Airborne Snow Observatories, Inc.*
*Western Water Assessment*
*National Snow and Ice Data Center*
*University of Colorado*



# *Outline*

Motivation: forecast & management challenges

ASO overview

ASO highlights from projects & partnerships in California & Colorado

A vision for water management in Colorado

# CO Collaborators & Partners

CWCB
- Joe Busto

DWR Division 3
- Craig Cotton

CWCD
- Nathan Coombs

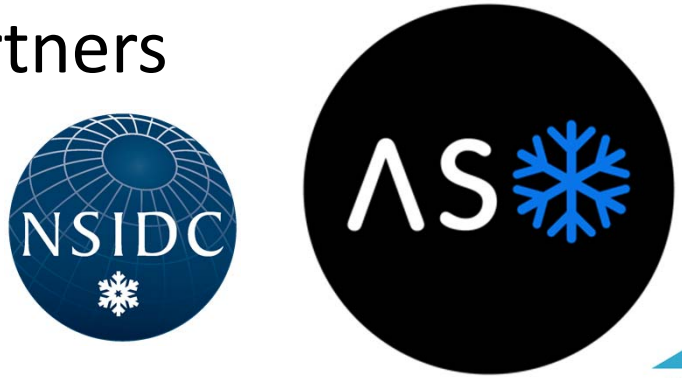
UGRWCD
- Frank Kugel
- Rosemary Carroll

Denver Water
- Nathan Elder
- Laurna Kaatz

NCAR
- Dave Gochis
- Ethan Gutman

City of Aspen
- Margaret Medellin
- Tyler Christoff

DoE/LBNL East River Scientific Focus Area
- Ken Williams
- Rosemary Carroll









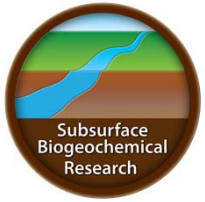


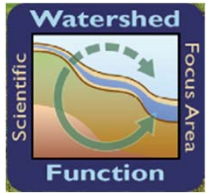

COLORADO
Department of
Natural Resources




Upper Gunnison River
WATER CONSERVANCY DISTRICT



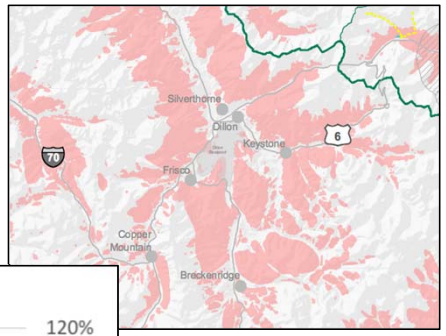



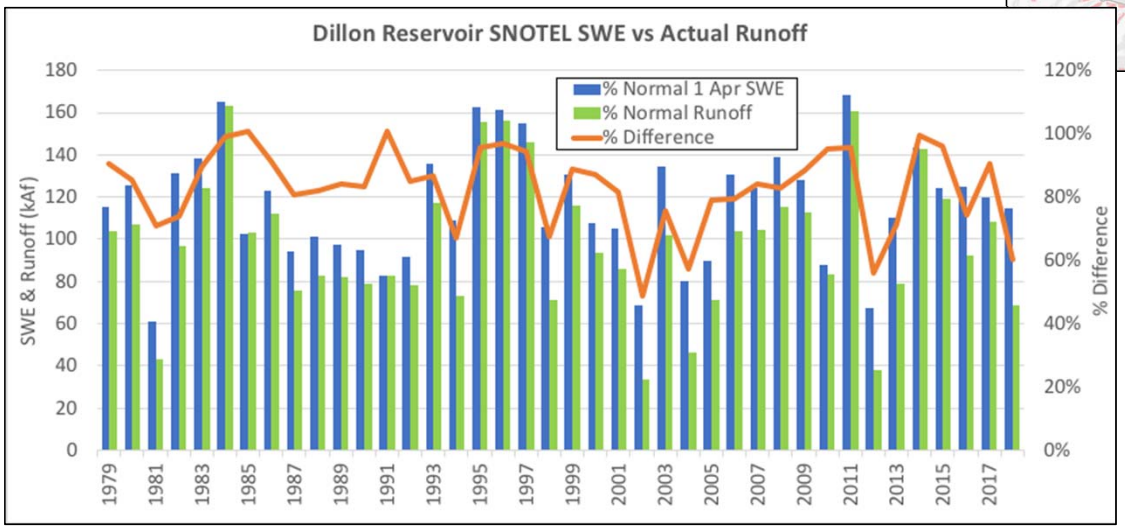

U.S. DEPARTMENT OF
ENERGY

# Some motivation…

Blue River @ Dillon
*Denver Water*

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


| | 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% |

**Forecast > 10% Low**

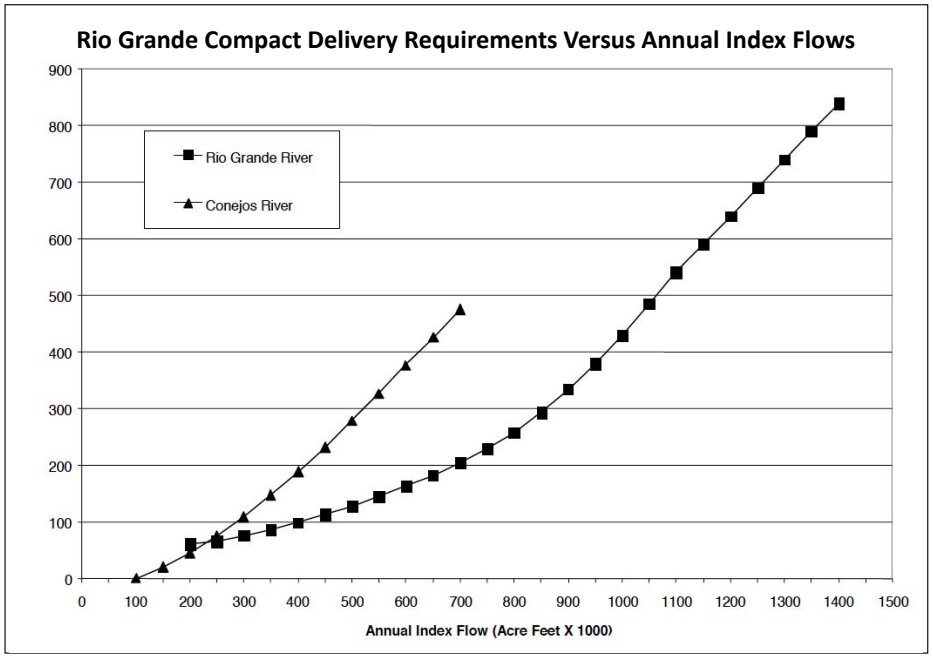
**Forecast > 10% High**

*Data courtesy Nathan Elder, Denver Water*

# More motivation…

Rio Grande @ Del Norte
June Forecast & measured Apr-Sept Volumes

- Over-forecast: risk of compact shortage
- Under-forecast: unnecessary curtailment




Rio Grande @ Del Norte
Apr-Sept forecast vs observed (kAF)

| | June Forecast | Observed | Forecast - Obs | |
|---|---|---|---|---|
| **2005** | 795 | 683 | +112 | 16% |
| **2006** | 350 | 412 | -62 | -15% |
| **2007** | 450 | 593 | -143 | -24% |
| **2008** | 655 | 623 | +32 | 5% |
| **2009** | 490 | 513 | -23 | -5% |
| **2010** | 485 | 455 | +30 | 6% |
| **2011** | 435 | 415 | +20 | 5% |
| **2012** | 352 | 328 | +24 | 7% |
| **2013** | 230 | 344 | -114 | -50% |
| **2014** | 420 | 519 | -99 | -24% |
| **2015** | 385 | 556 | -171 | -31% |
| **2016** | 475 | 566 | -91 | -16% |
| **2017** | 535 | 574 | -39 | -7% |

**Forecast > 10% Low**

**Forecast > 10% High**

*Data courtesy Craig Cotton*
*CO DWR Division 3 Engineer*

# Operational forecasts are vulnerable to unusual conditions…

## *…and conditions are changing*

Statistical streamflow forecast

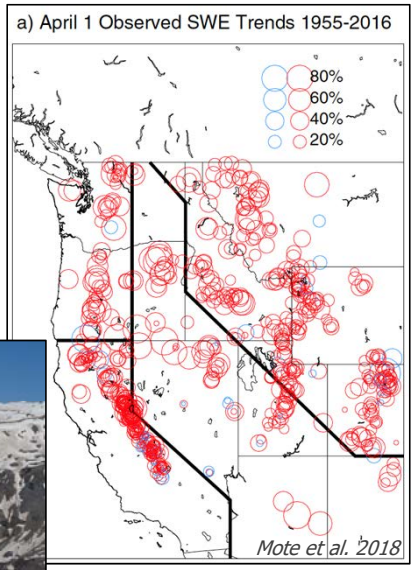
- Regression relates spring SWE to spring/summer flows

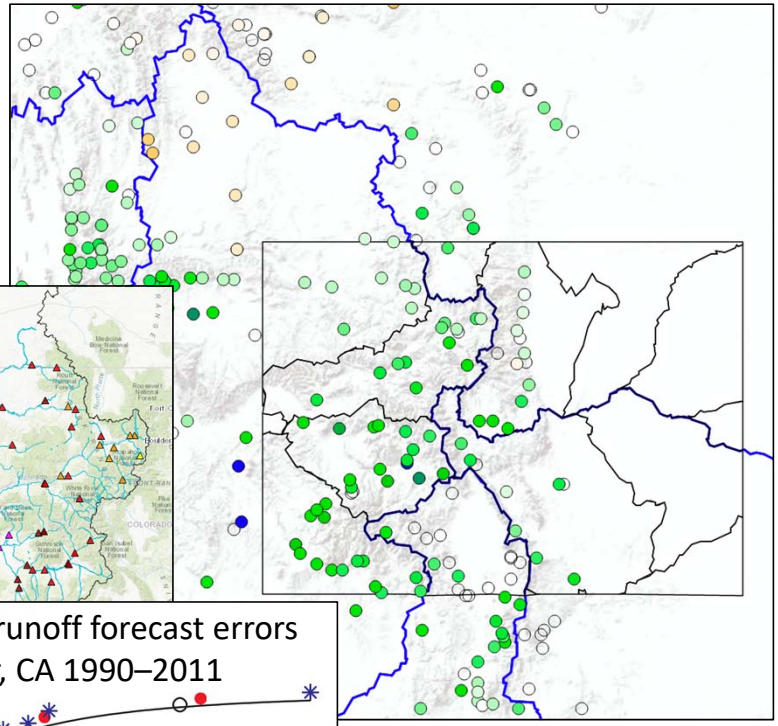
Temperature index runoff forecast

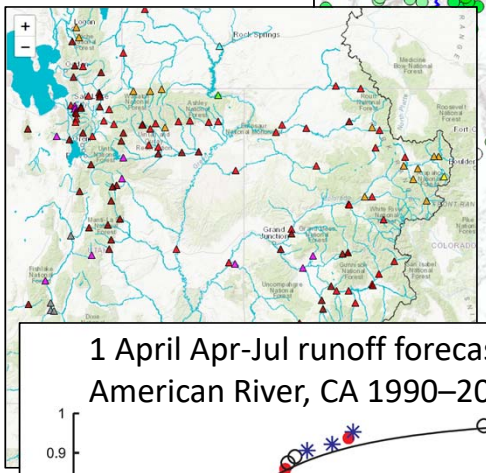
- Calibrated air temperature/snowmelt relationship

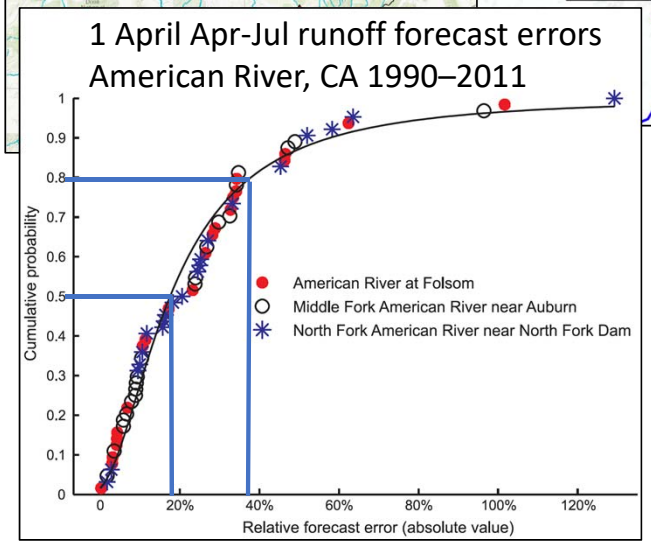
Snow water resources & forecasts affected by:

- Warming temperatures
- Snow season duration
- Rain/snow fraction
- Mid-winter melt
- Rain-on-snow
- Forest change
- Dust on snow








** Period-of-record-based methods assume calibrations apply to current conditions*

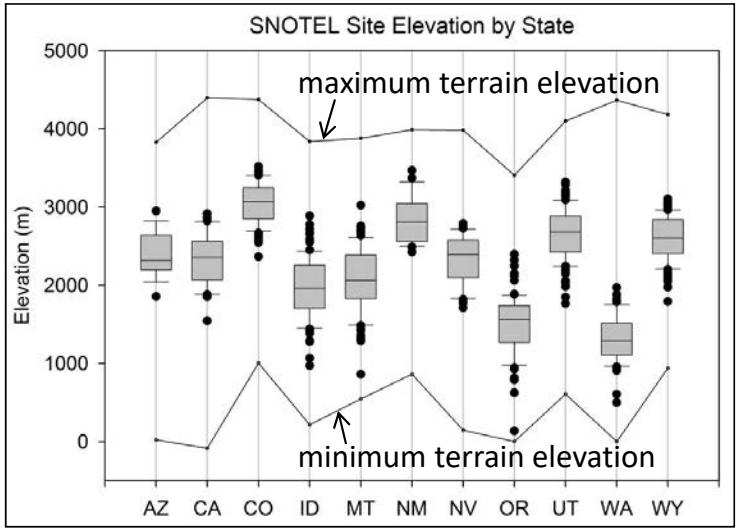
# How do we add resilience to forecast models?

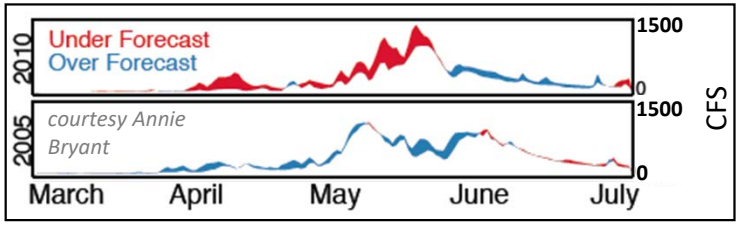
- Decrease reliance on historic record
- Increase availability/use of spatial data
  - Satellite
  - Airborne
  - Mesoscale weather model output

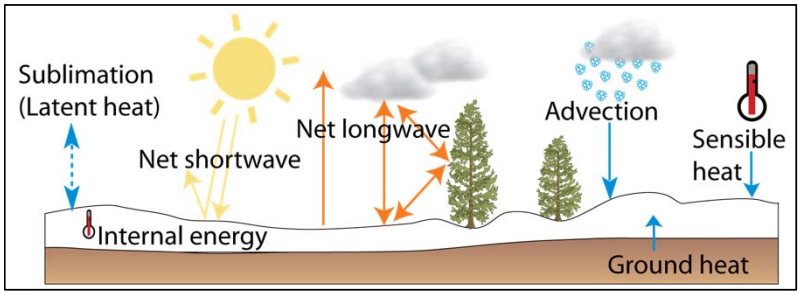
***Snow accumulation patterns drive melt volume & timing***

***Solar radiation controls snowmelt***

** These factors can be monitored operationally with remote sensing*



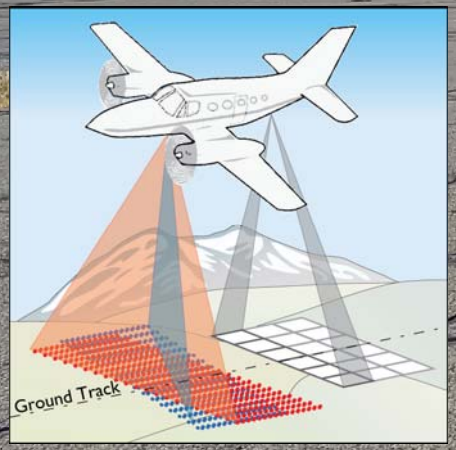
# Pathfinder: The Airborne Snow Observatory

## Snow Water Equivalent

Riegl Q1560 Lidar
1.5m elevation grids

## Snow Albedo

CASI-1500 Spectrometer
2m spatial resolution from 4000m




Map surface elevations: snow-free & snow-on

- Difference gives snow depth

SWE from assimilation of modeled density

- Constrained by observations

Spectrometer maps albedo

# Snow depth & SWE from lidar

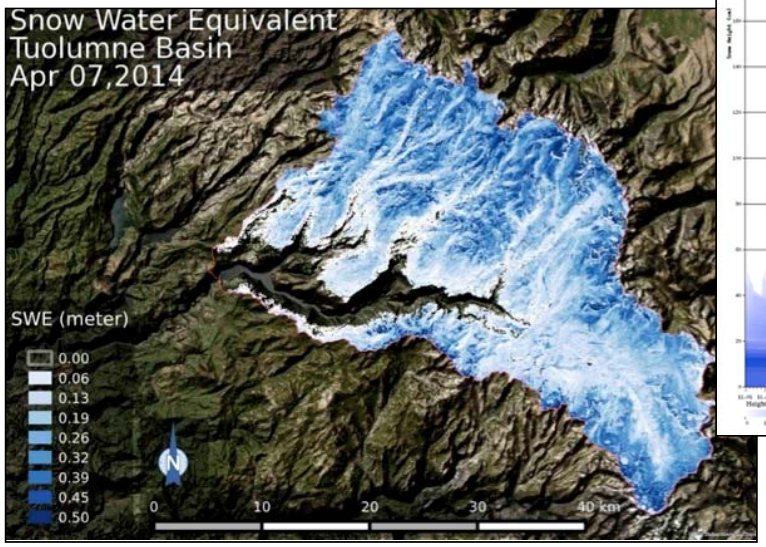
Majority of SWE spatial variability due to snow depth

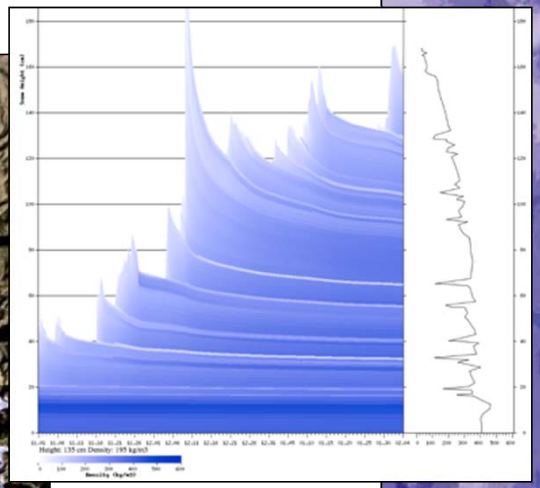
Depth can be measured by subtracting elevations

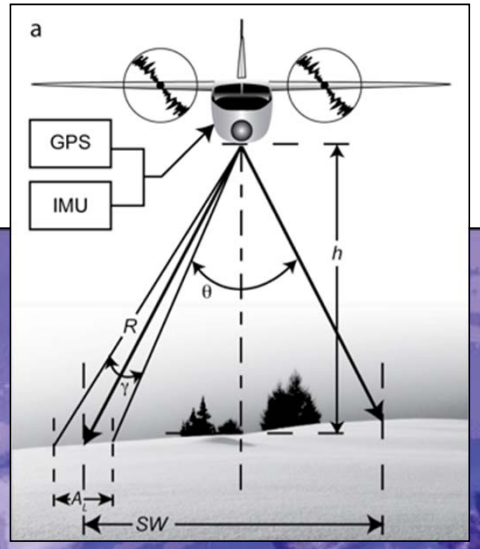
- collect snow-free & snow-covered data sets
- remove vegetation
- subtract snow-free from snow-covered

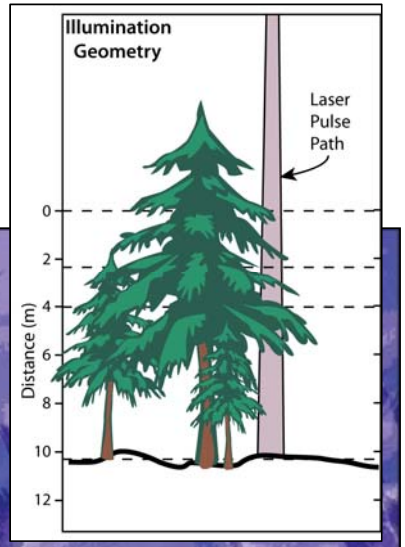
Apply observed/modeled density

SWE = depth * density

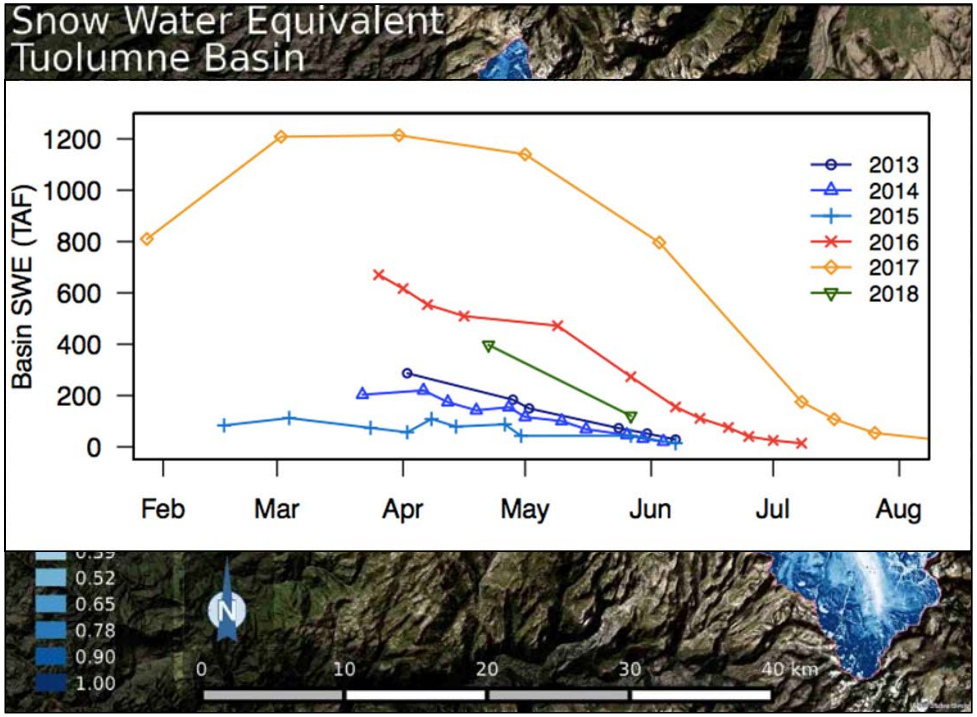


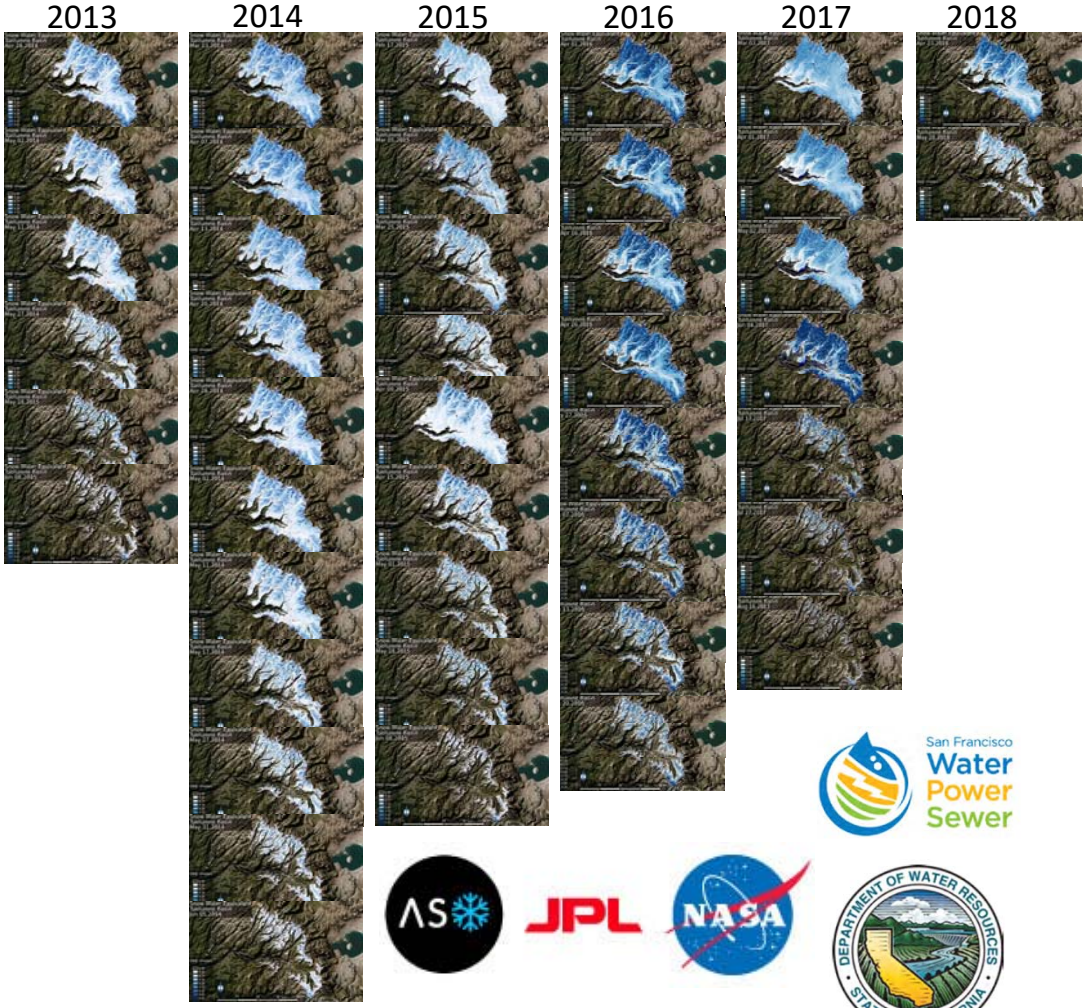





# Building a legacy in the southern Sierra Nevada




Example: Tuolumne River Basin

- utility to operations in a wide range of conditions
- refined data processing for fast data turnaround
- bridge to partnerships in neighboring basins

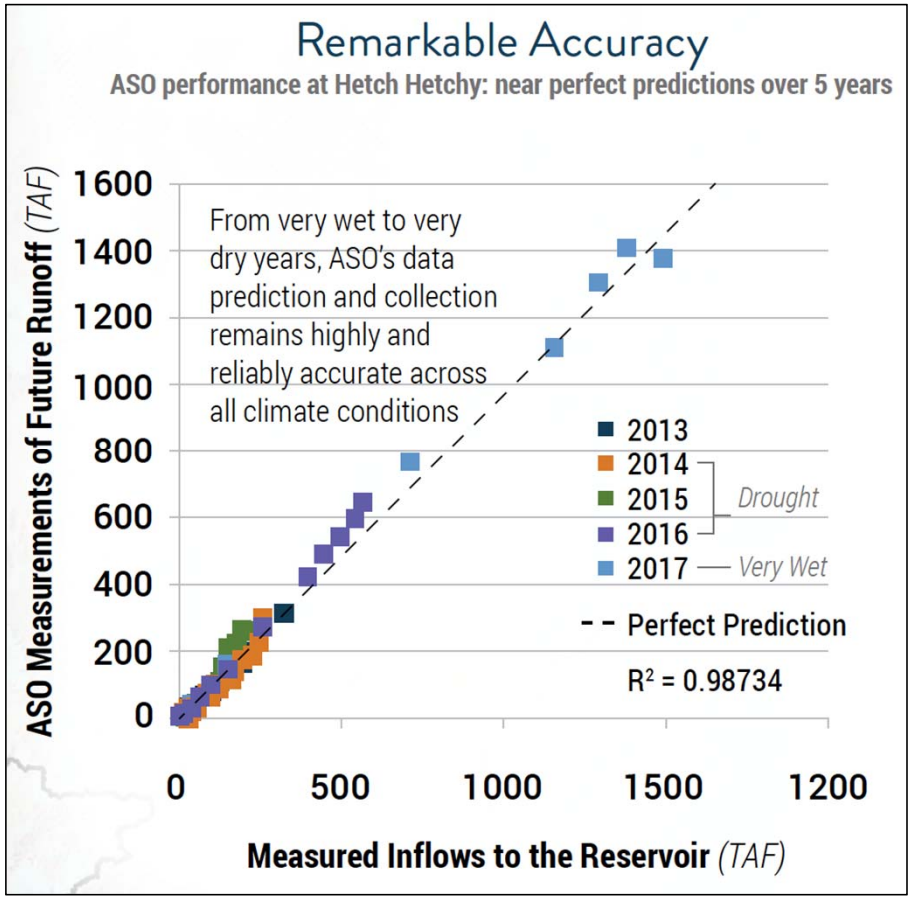
San Francisco Water Power Sewer

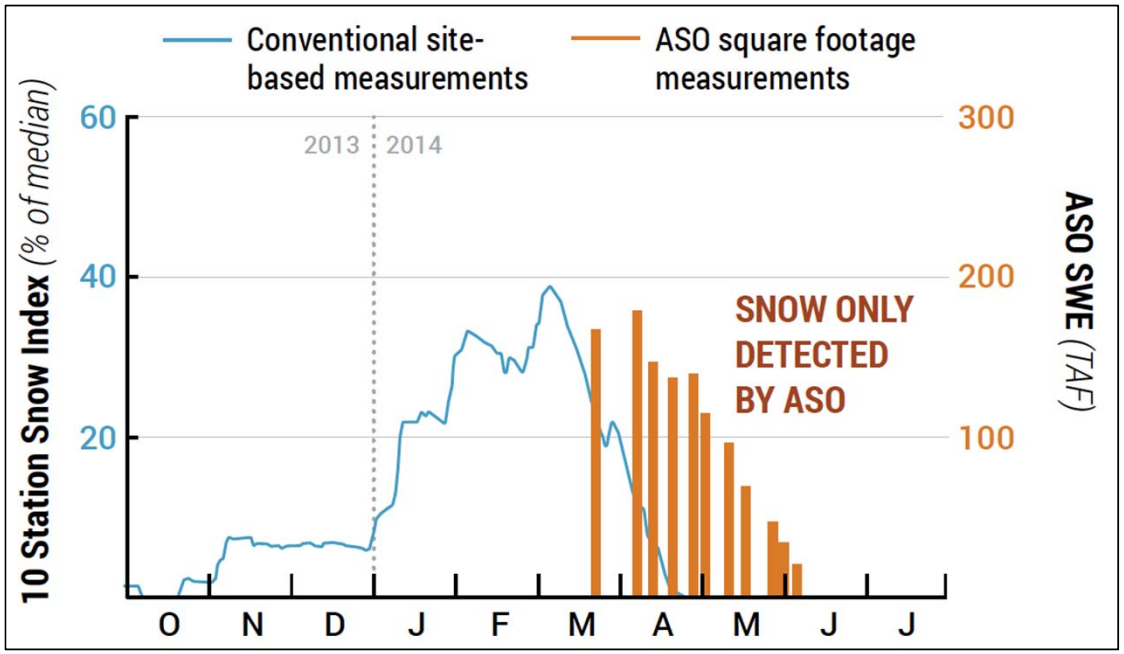
JPL

NASA

DEPARTMENT OF WATER RESOURCES · STATE OF CALIFORNIA ·

# 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."

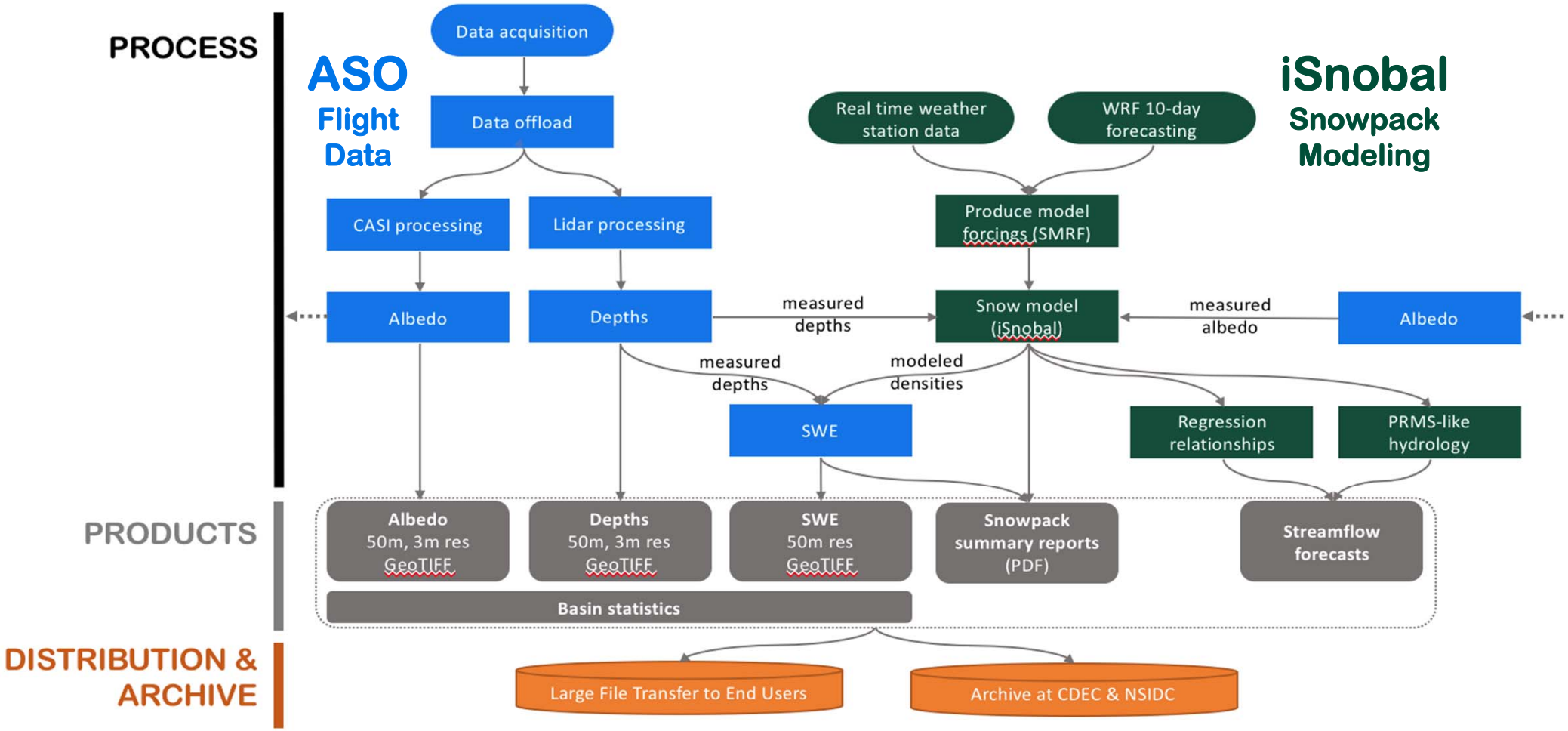
Wes Monier, Chief Hydrologist, Turlock Irrigation District

"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*

# Modeling Flow – Daily to 10-day Forecasting



# Regular monitoring with weekly snow model reports

iSnobal model

continuous monitoring

density model coupled to ASO snow depth maps

DRAFT SUBJECT TO CHANGE

**San Joaquin River Basin Snowpack Summary**

Water Year 2018

May 2 to May 7

USDA Agricultural Research Service, Boise, Idaho
NASA Jet Propulsion Lab, Pasadena, California
*in cooperation with* NRCS National Water and Climate Center, Portland, Oregon
*and* U.S. Bureau of Reclamation, Sacramento, California

**Summary**

This is the San Joaquin River Basin Summary for the period between May 2 and May 7, based on iSnobal model simulation and one ASO depth field update which was applied on April 23.

This report includes station data model inputs from October 1 - November 19, and a hybrid input approach that uses NOAA's High-Resolution Rapid Refresh (HRRR) atmospheric model from November 20 forward, as well as the depth field update from ASO overflights on April 23.

The reporting domain covers the San Joaquin River Basin, and includes the Main San Joaquin, Jose Creek, Willow Creek and South Fork sub-basins. The total amount of water stored in the snowpack as of May 7 is estimated to be **332.5 KAF**, which represents a change of **-137.3 KAF** of snow storage during the reporting period.

**Snow Storage and Surface Water Inputs**

| Basin | SWE [KAF] | SWE (avail) [KAF] | SWE (mean) [in] | ΔSWE [KAF] |
|---|---|---|---|---|
| San Joaquin | 332.5 | 332.4 | 3.8 | -137.3 |
| Main | 149.4 | 149.4 | 5.3 | -58.4 |
| South Fork | 159.8 | 159.7 | 8.0 | -61.0 |
| Jose Creek | 21.4 | 21.4 | 1.0 | -15.6 |
| Willow Creek | 2.4 | 2.4 | 0.1 | -2.4 |

SWE: Snow Water Equivalent, snow storage in the basin

SWE (avail): amount of snow at 0°C, which will melt with any additional energy inputs

SWE (mean): basin-wide mean SWE, as a depth

ΔSWE: change in SWE during the reporting period

SWI: Surface Water Inputs, the combination of snowmelt and rain that exited the base of the snowpack, and rain on bare ground

ppt (mean): basin-wide mean precipitation, as a depth

Rain: approximate percent of precipitation that fell as rain (*NOTE:* in most cases this is different than %SWI that is attributable to rain)

Cold Content: energy required to bring the snowpack to 0°C

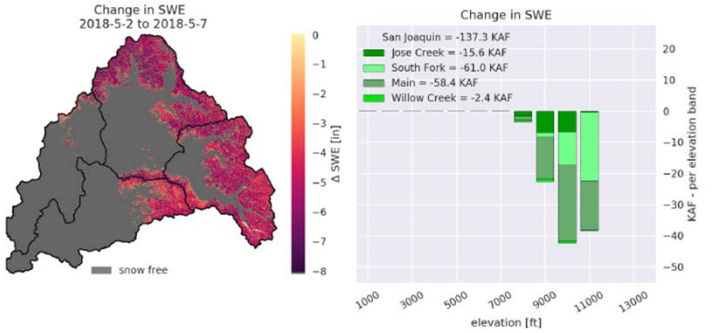



**Figure 1:** Change in SWE during the reporting period, as a depth (left) and as a function of elevation band (right).

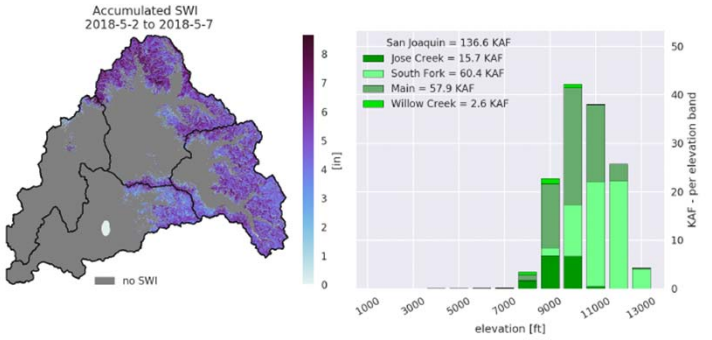
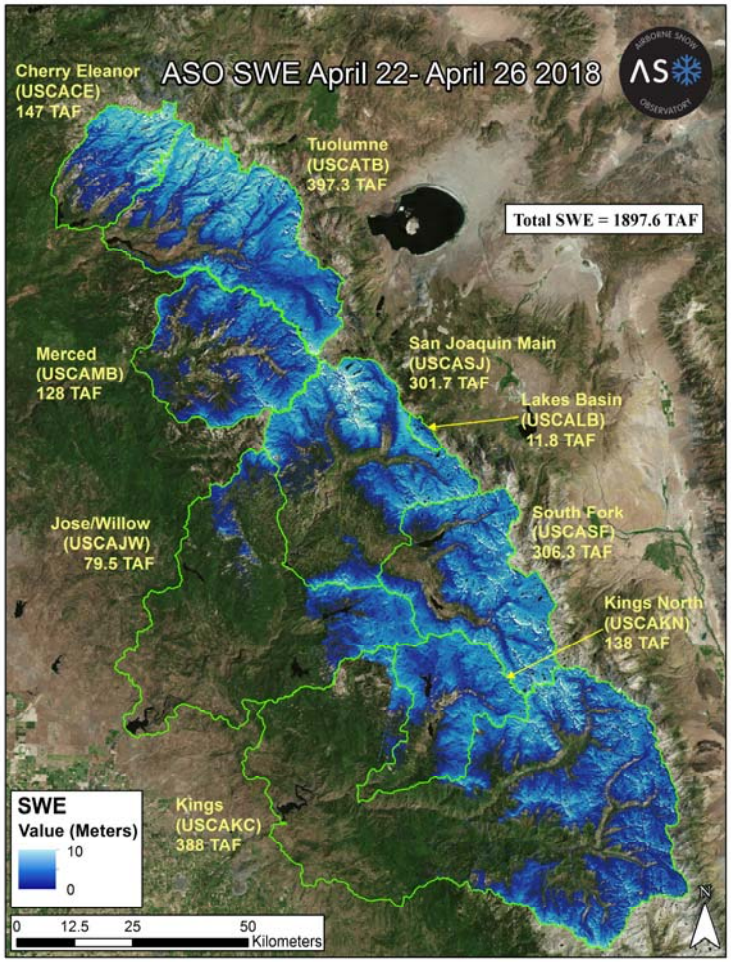
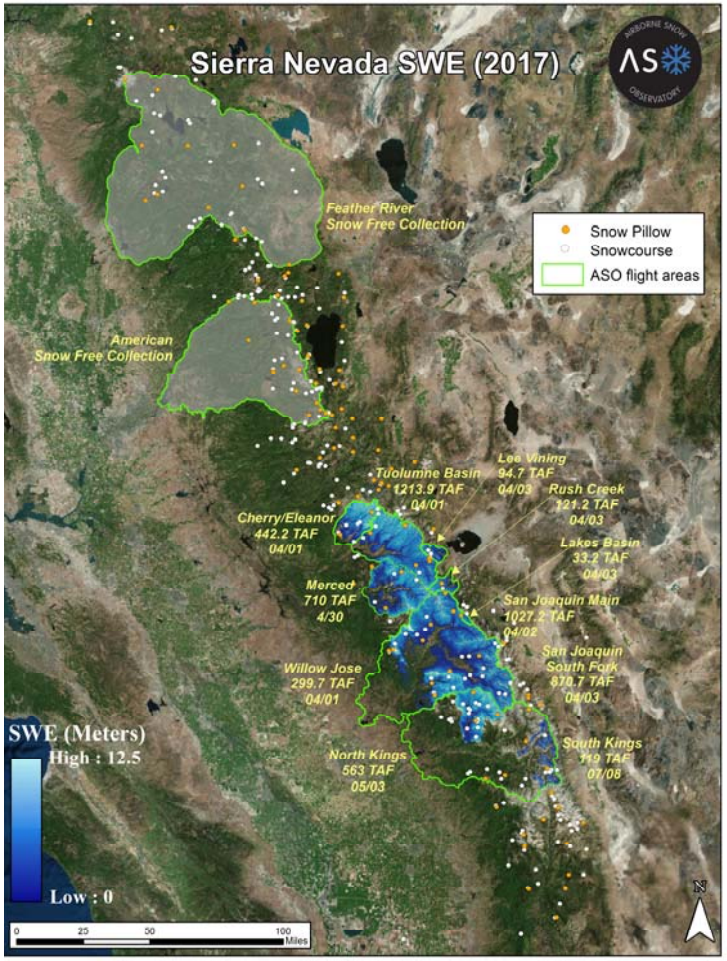



**Figure 2:** Current Surface Water Inputs (SWI) for the reporting period, as a depth (left) and as a function of elevation band (right).

# California: a maturing snow mapping program




**CA to-date & Future Plans**

- 250+ snow-on flights since 2013 in 10 basins
- Daily ARS snow model output in Tuolumne & San Joaquin
- Capacity to *operationally* map southern Sierra snow water volume
- Continue program in southern & central Sierra
- Build to regular, full-state coverage in 5 years
- Expand model capacity
- Data integration with FERIX & CDEC
- Agency synergies

# ASO's Colorado legacy

Uncompahgre River (above Ridgway Res)

- 1-4 Melt season flights since 2013 (NASA HQ)

Rio Grande & Conejos Rivers

- 2 melt season flights 2015, 2016 (CWCB)
- 1 flight 2017

Grand Mesa &
Senator Beck Basin (Red Mountain Pass)

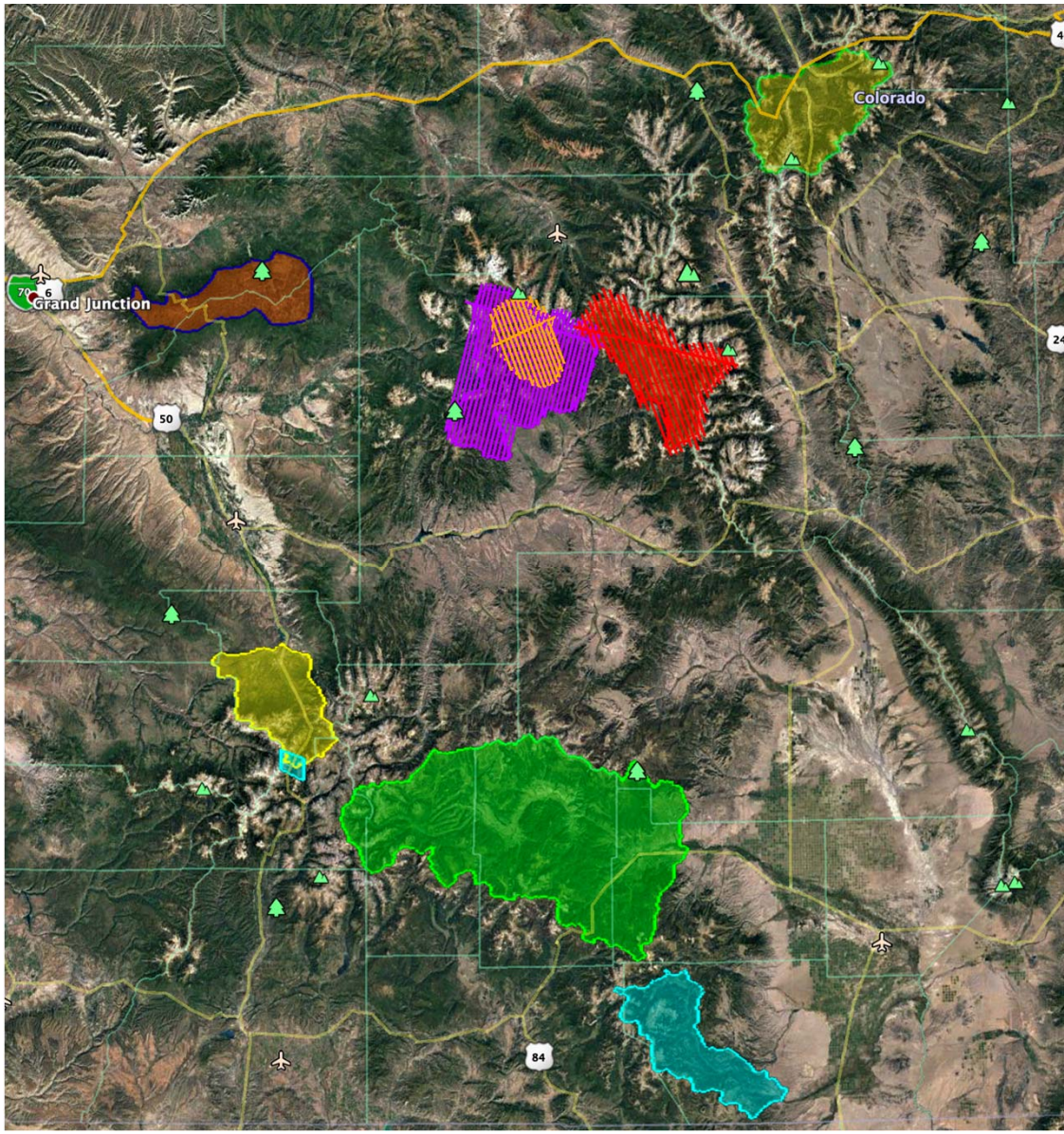
- Multiple high-resolution flights Feb 2017 (NASA SnowEx Campaign)

Upper Gunnison River

- Upper East River 2016 (DoE WFSFA)
- Spring 2018 & 2019:
  East R., Upper Taylor, Upper Ohio (CWCB)

Blue River (above Dillon Dam)

- April & June 2019 (Denver Water)



# Rio Grande Headwaters Project
# RIO-SNOW-FLOW

WRF-Hydro assimilation of novel data sources to improve water supply forecasts in the Upper Rio Grande & Conejos

Comparison & use of ASO SWE maps:

*Evaluation*

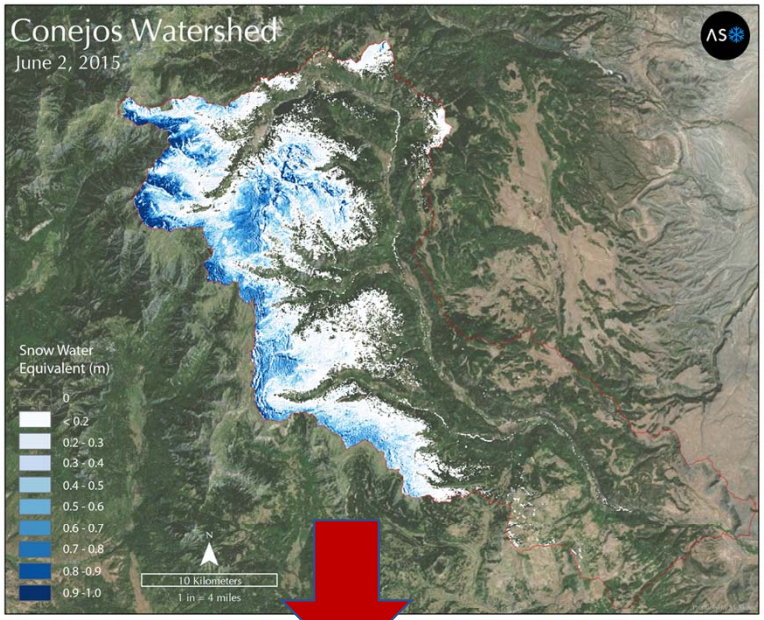
- ASO helped identify:
  - biases in NoahMP/WRF-Hydro & SNODAS (particularly high elevations)
  - basin SWE vs. SCA relations

*Assimilation*

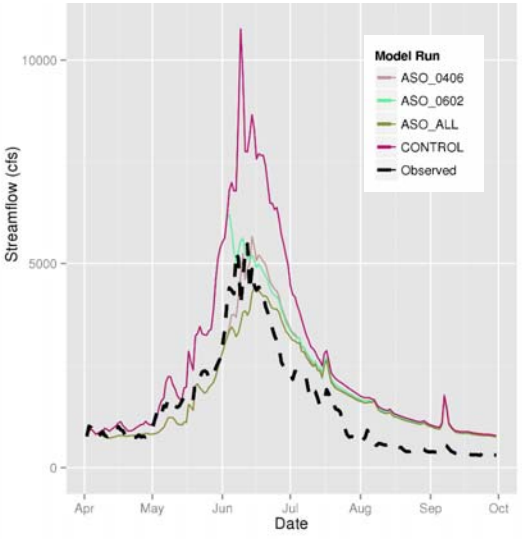
- Assimilation of early April ASO data improved Rio Grande & Conejos snowpack & runoff

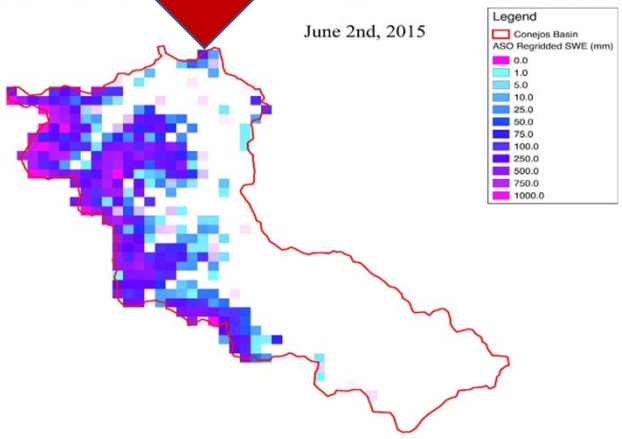
*Precipitation Correction*

- ASO precipitation bias correction shows promise




Rio Grande
ASO Direct Assimilation



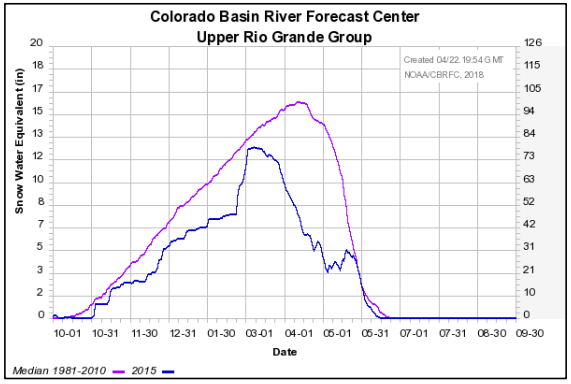



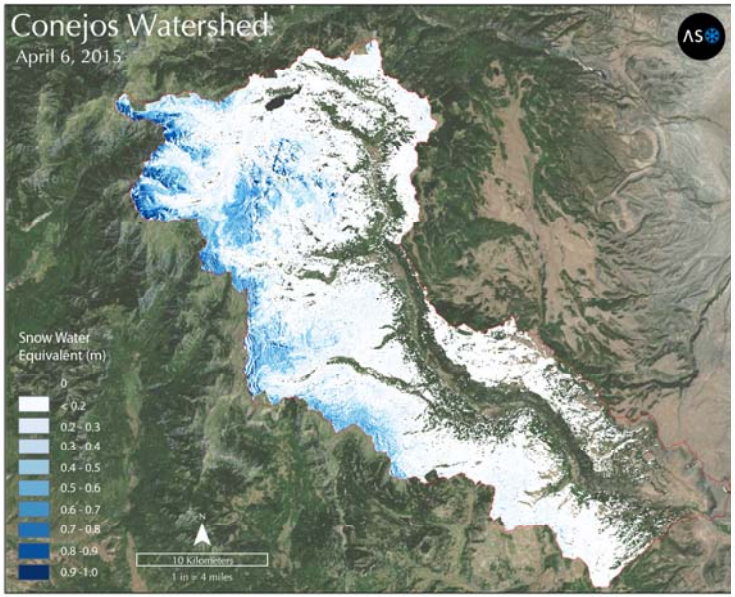

*courtesy Dave Gochis, NCAR*

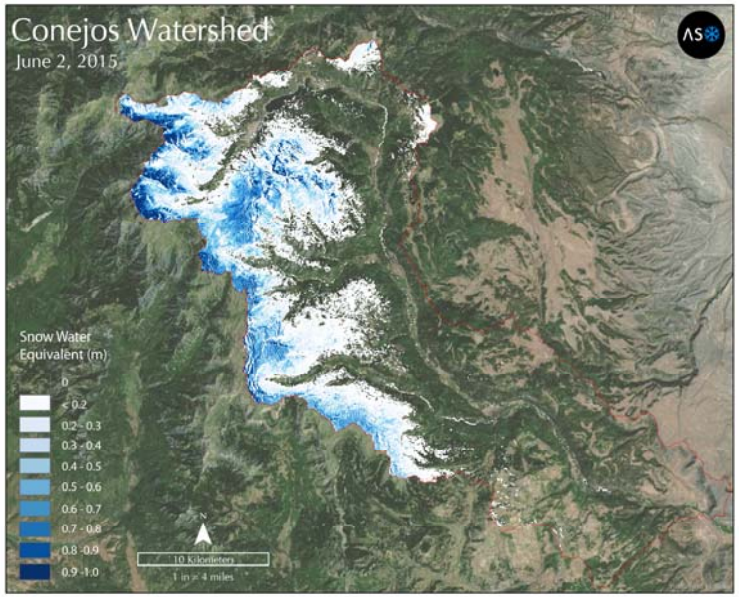
# Conejos River

*"Miracle May" 2015*

- ASO flights:
  - 6 April
  - 2 June
- SNOTELs recorded almost now new snow in that period
- Snow area decreased dramatically
- SWE decreased ~10%

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Exported by swe_at_3_elev_bands.pro
File =U:\ASO_Flight_Data\snowon_2015\LIDAR\p
\CJ20150406_SUPERswe_50p0m_agg
Band 1 =        1158.54 to       2073.17 m
Band 2 =        2073.17 to       2987.80 m
Band 3 =        2987.80 to       9000.00 m

Band          SWE Volume (AF)
SWE Band1          0.0
SWE Band2        405.2
SWE Band3      60346.2
                60751.4
```

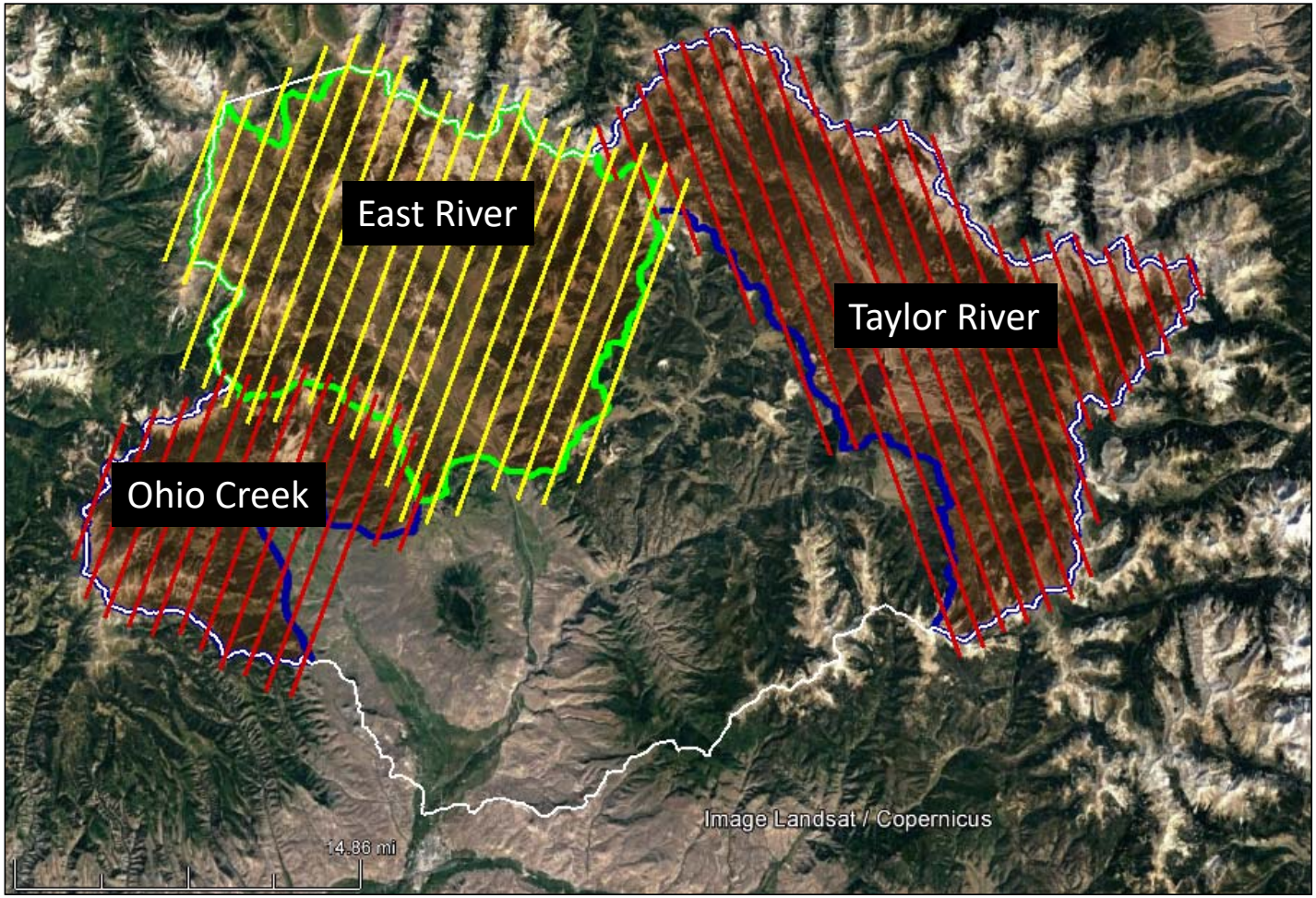
```
Flight: USCOCJ20150406f2a1
Exported by swe_at_3_elev_bands.pro
File =U:\ASO_Flight_Data\snowon_2015\LIDAR\pr
\CJ20150602_SUPERswe_50p0m_agg
Band 1 =        1158.54 to       2073.17 m
Band 2 =        2073.17 to       2987.80 m
Band 3 =        2987.80 to       9000.00 m

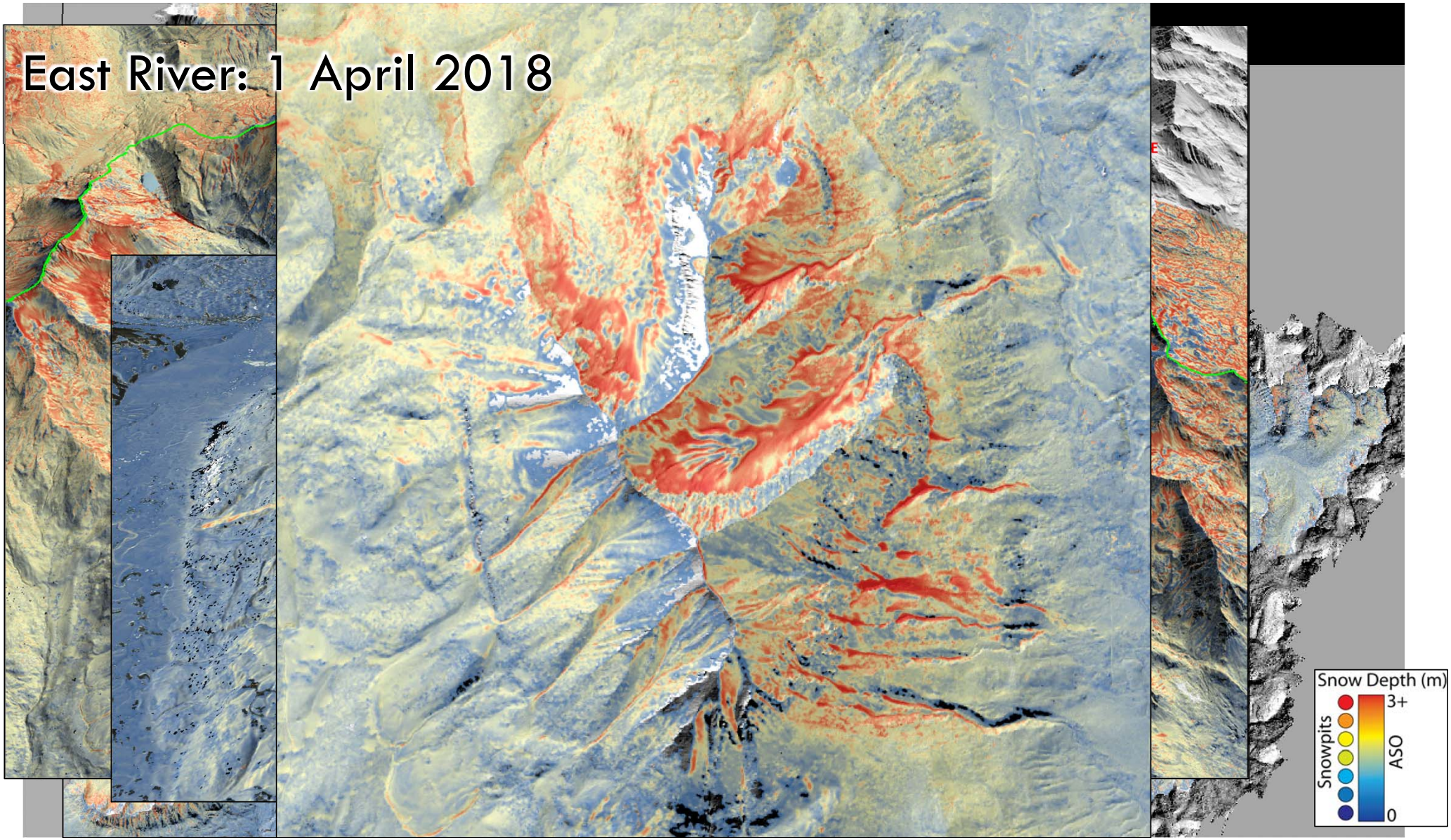
Band          SWE Volume (AF)
SWE Band1          0.0
SWE Band2         14.6
SWE Band3      54236.5
                54251.1
```

SWE difference: -6.5 kAf

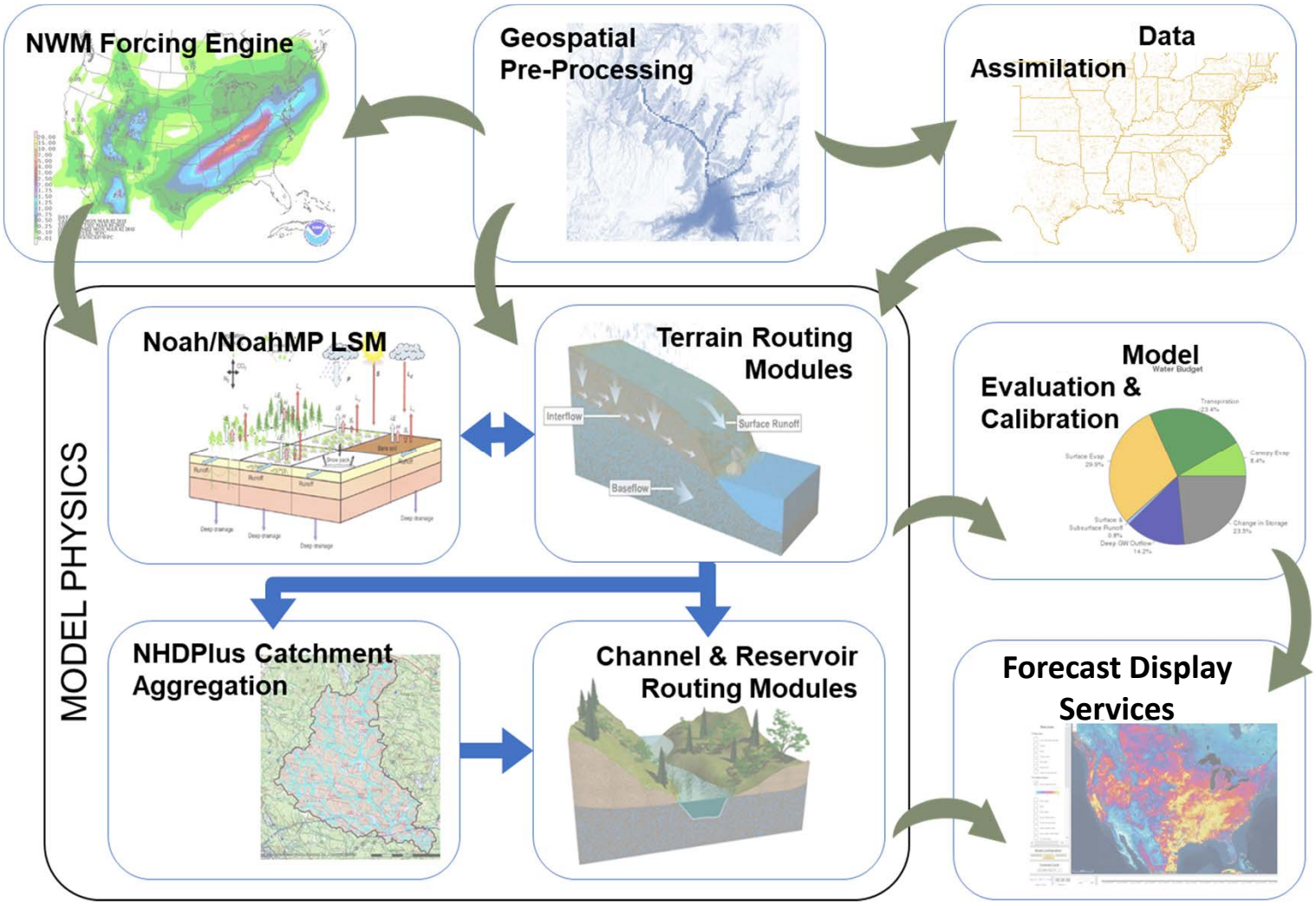
# 4 years of collaboration in the Upper Gunnison

- CWCB $$ support
- Collaborators:
  - UGR WCD
  - DoE SFA
  - NCAR WRF-HYDRO
- ASO flights
  - 1 Spring 2016
    East R.
  - 2 Spring 2018 & 2019
    East/Ohio/Taylor




East River: 1 April 2018
Snow Depth (m)
Snowpits
3+
ASO
0

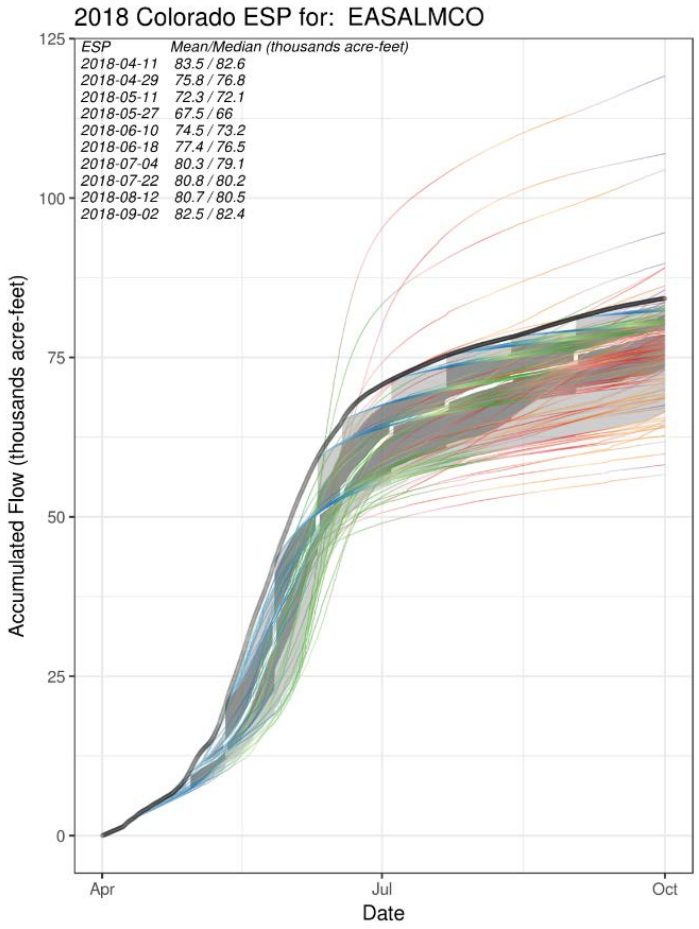
# Full WRF-Hydro / NWM Ecosystem



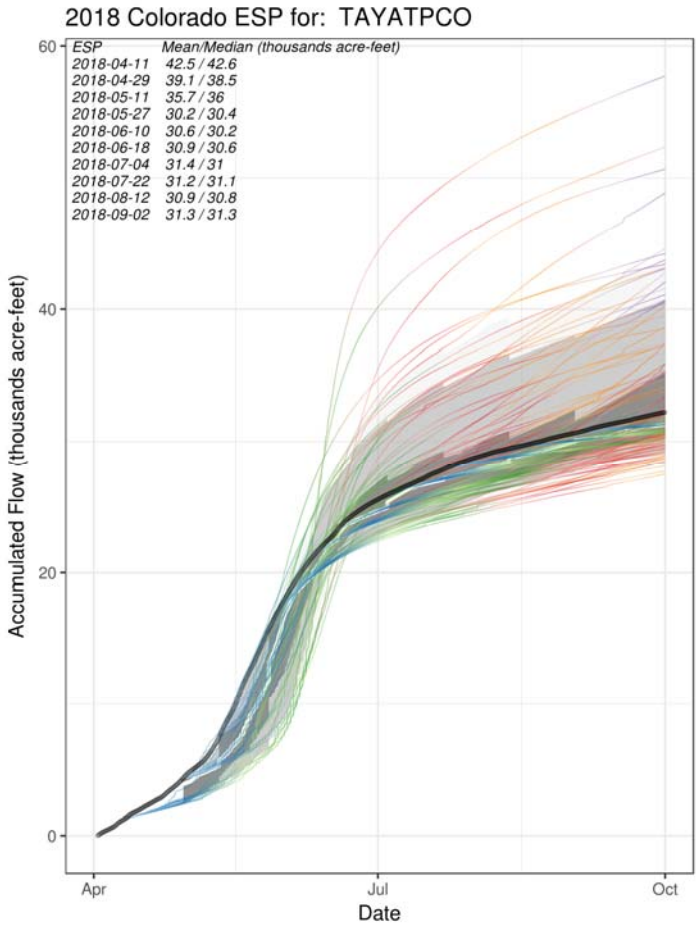

*courtesy Dave Gochis, NCAR*

# 2018 Water Year – ESP Forecast Results: No ASO assimilation

## East River @ Almont




## Taylor River @ Taylor Park

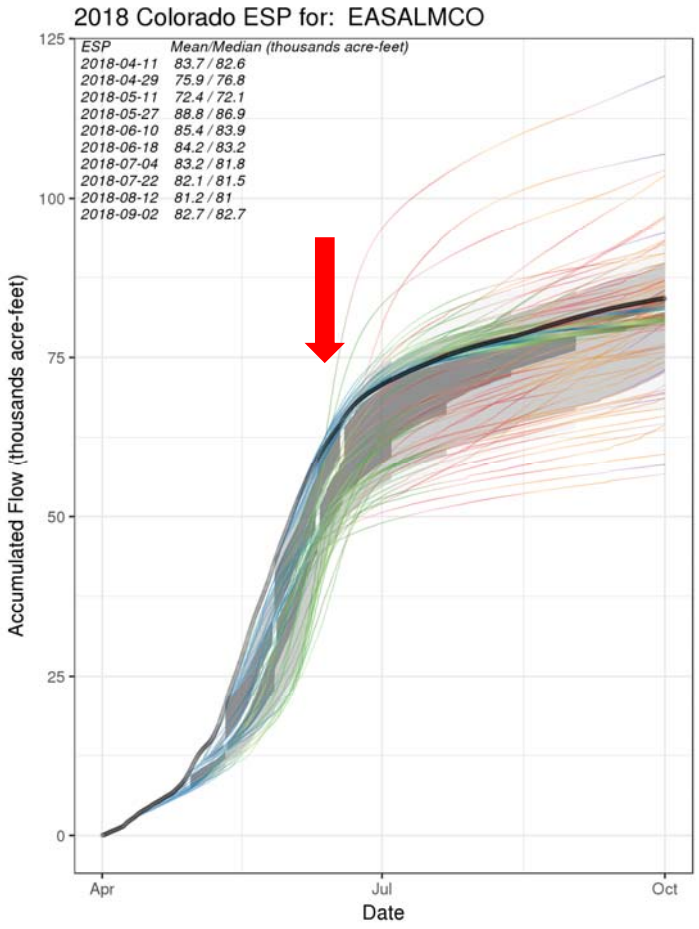



*courtesy Dave Gochis, NCAR*

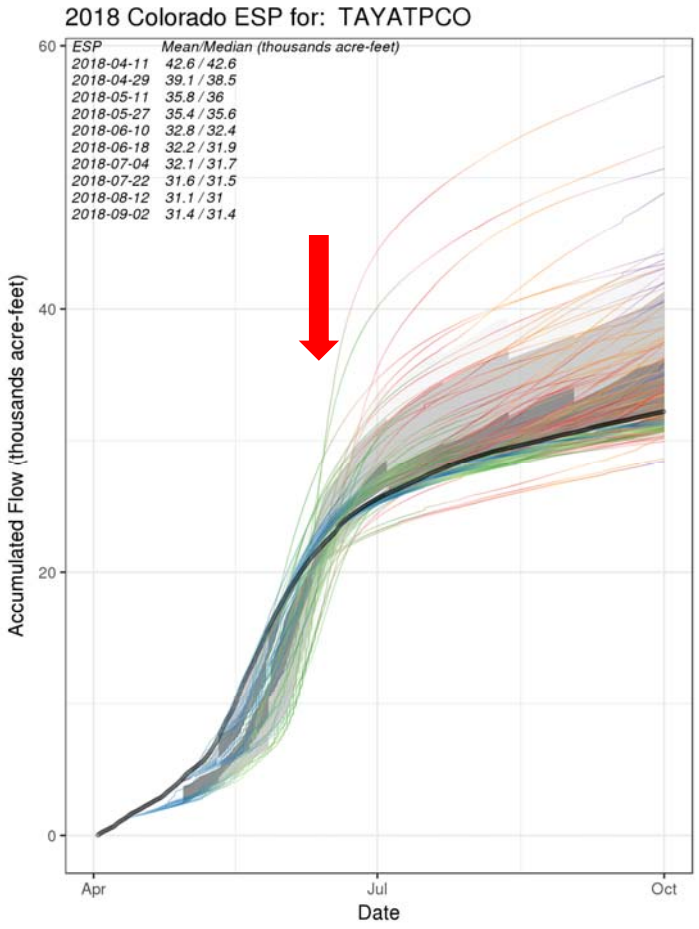
# 2018 Water Year – ESP Forecast Results: ASO assimilation

- 24 May assimilation Reduces low forecast bias
- Attributed to addition of late season high elevation snowpack

## East River @ Almont

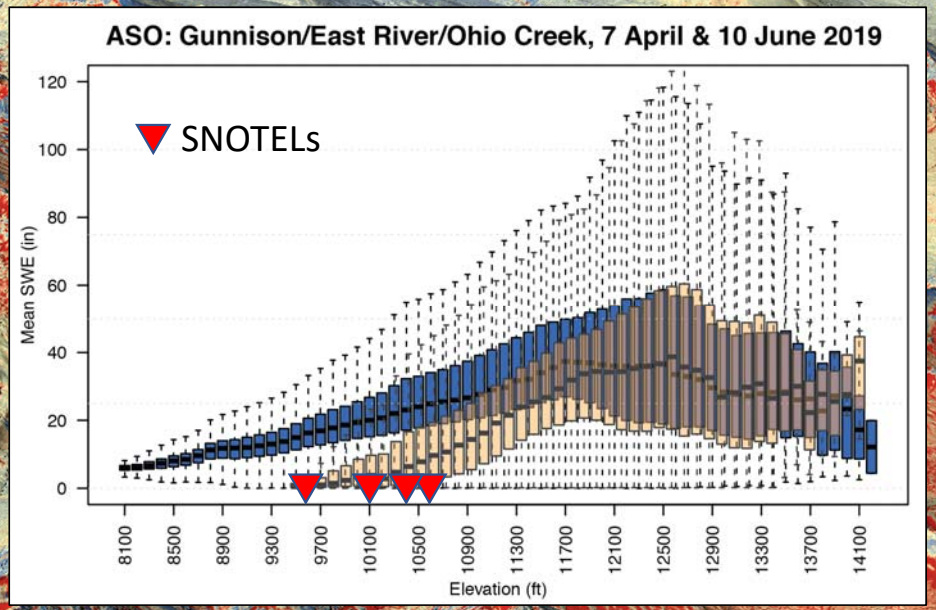


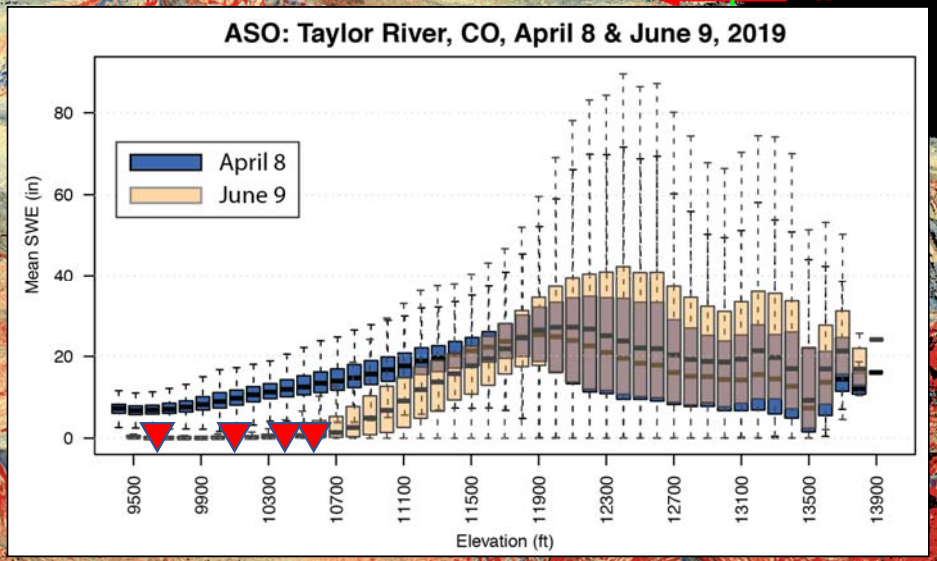

## Taylor River @ Taylor Park

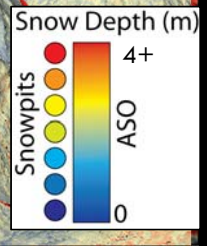



*courtesy Dave Gochis, NCAR*

# East River: 7 April 2019

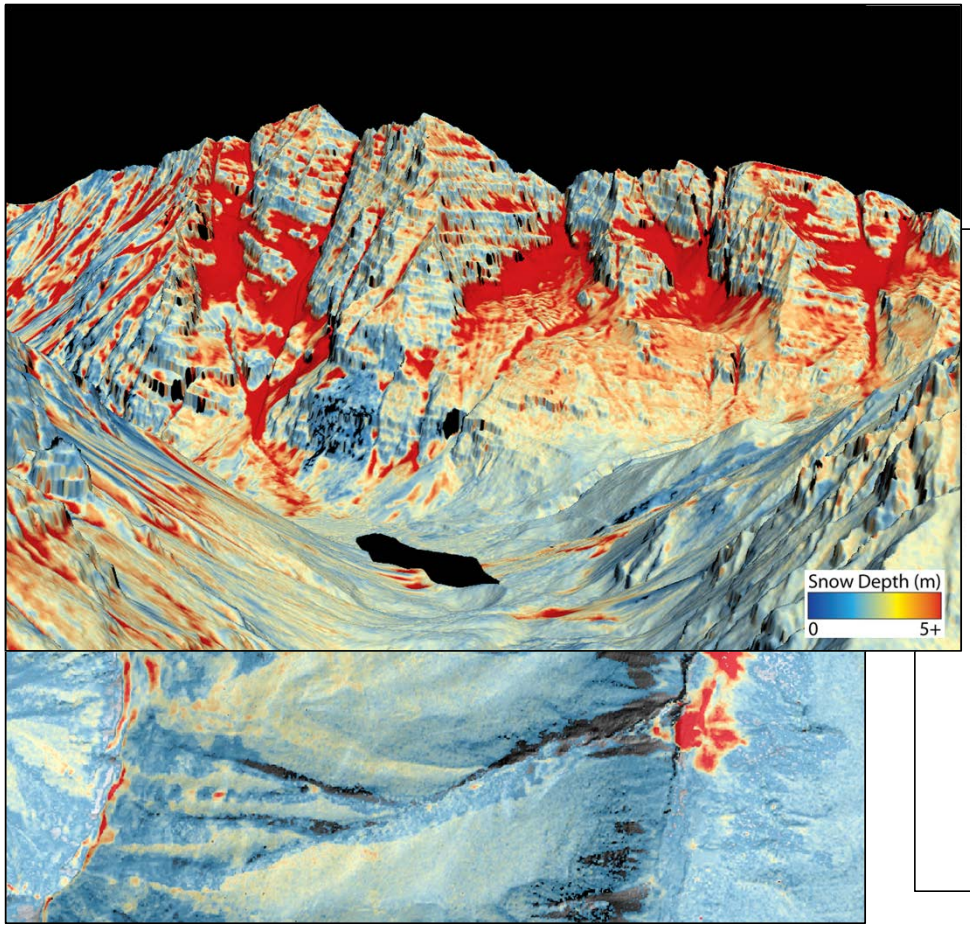


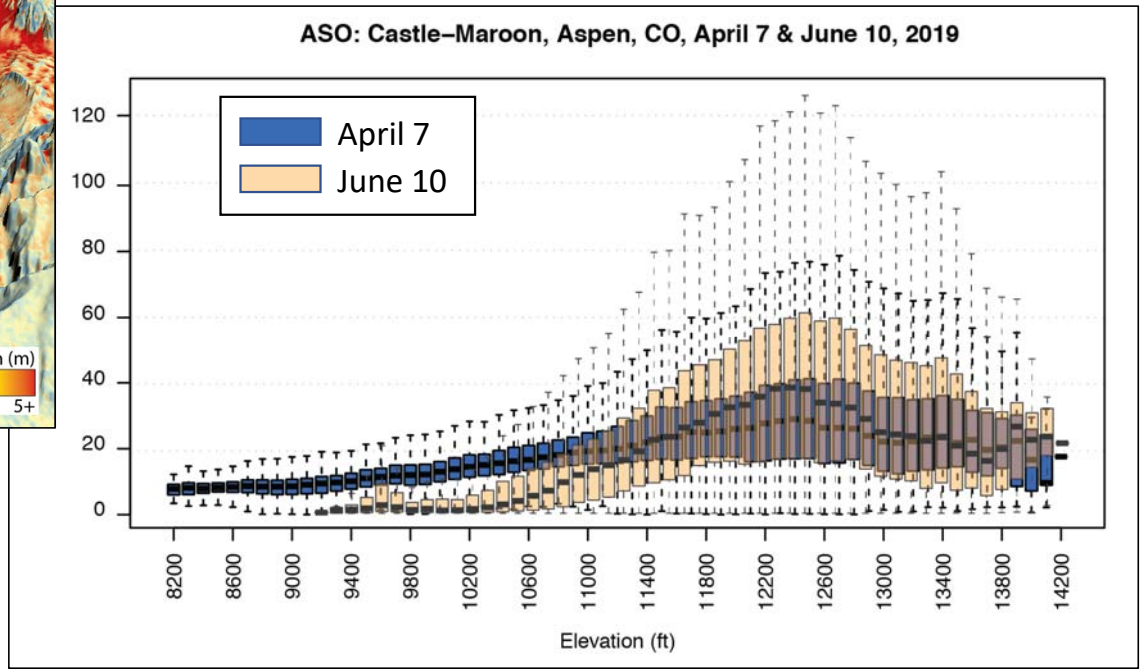



# A new look into Castle & Maroon Creeks

*City of Aspen*

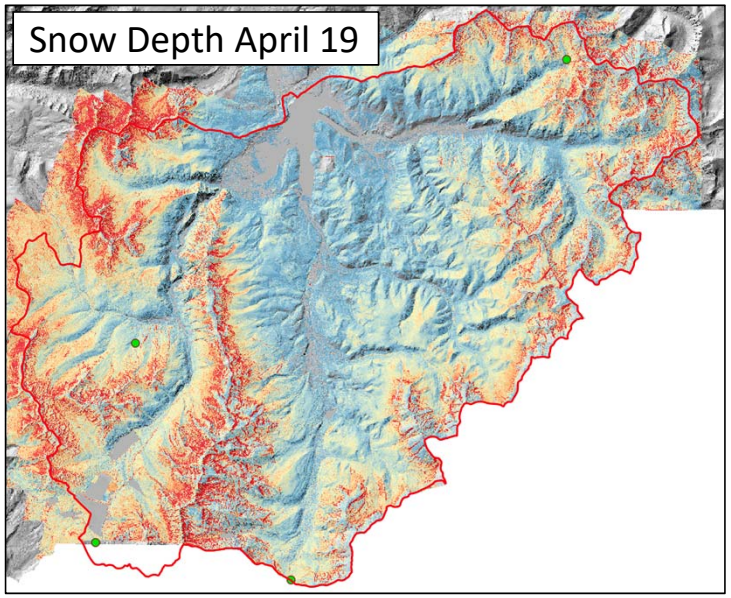


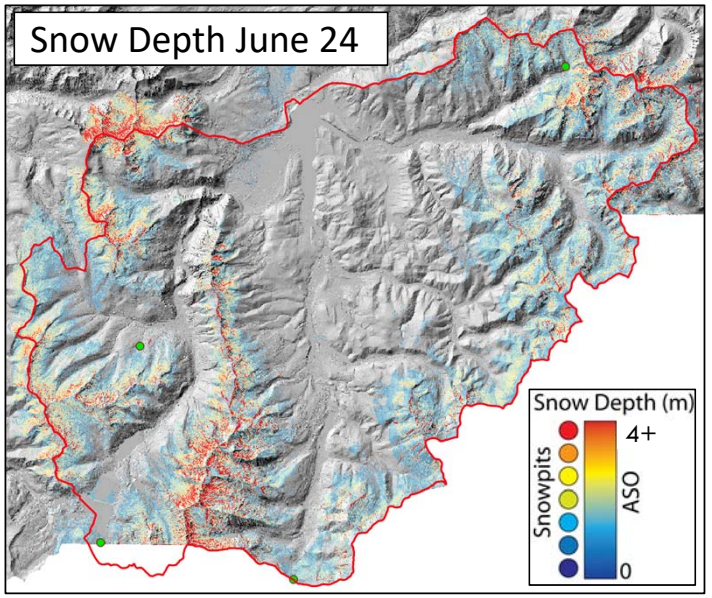

- no snow monitoring stations in the watersheds
- historic link of melt-out elevation & peak runoff
- 2019: April – June maps show low-elevation melt, mid-elevation gains

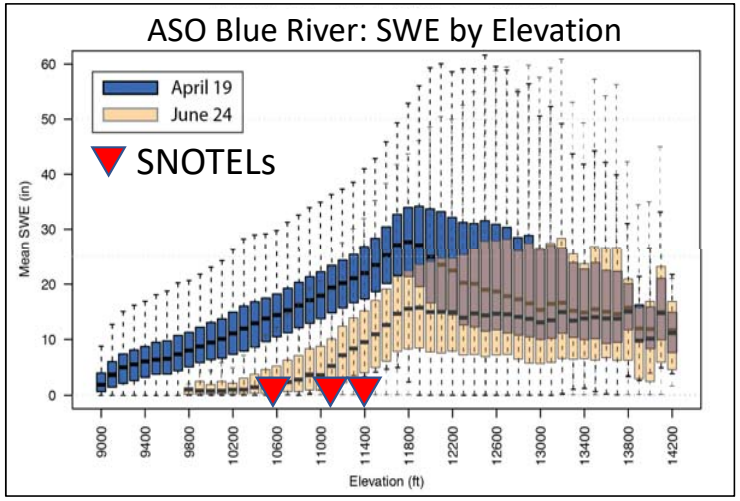


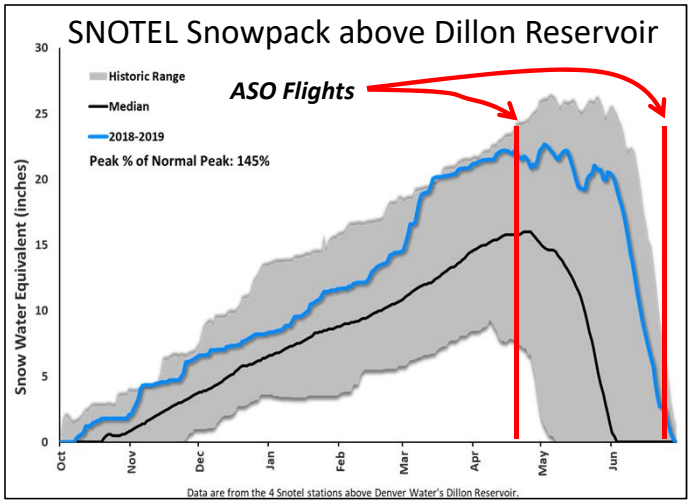
# Blue River Basin
## *Denver Water*

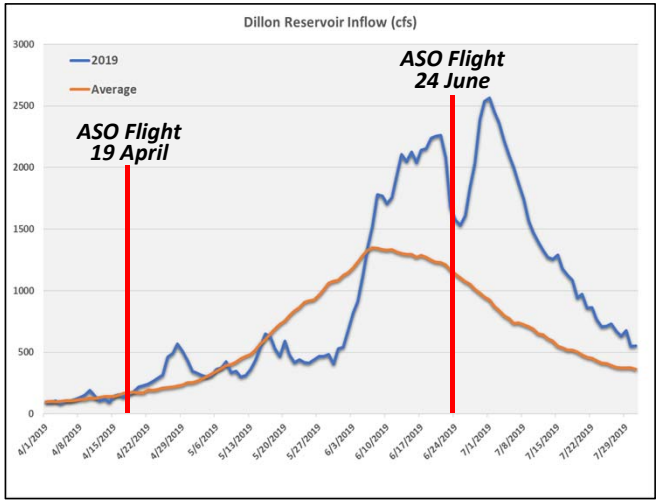
- 2019 Flights: April 19 & June 24
- May + June storms maintained high elevation snowpack
- SNOTELs snow-free on June 28
- June 24 flight:
  - half of total inflow left to melt
  - enabled response to double flow peak



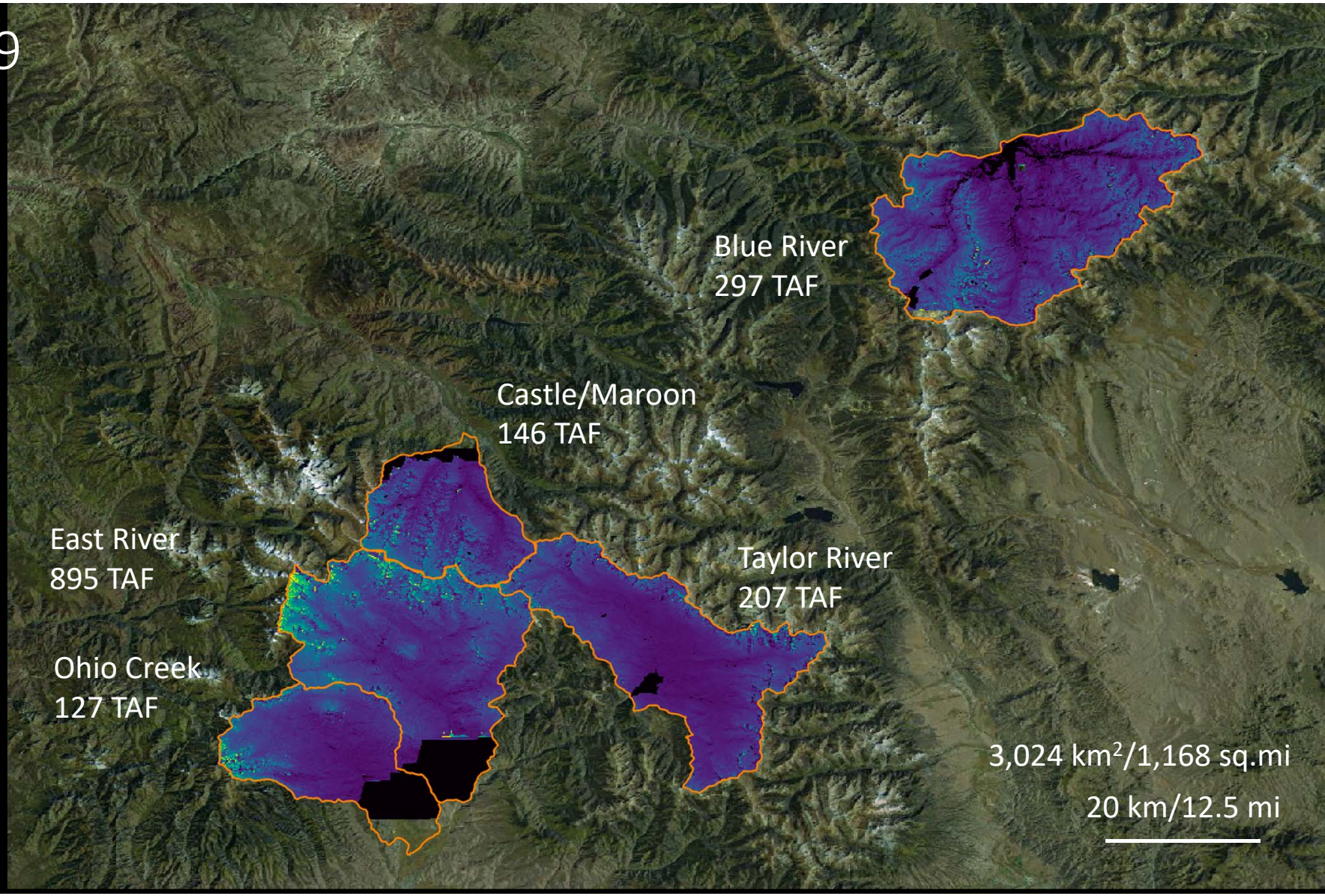



# April 2019 SWE Colorado



# Ongoing & future work

Integrate data with forecasts

- CBRFC project
  - CRCHWG support
  - leverage CA/CNRFC dataset
- NWM/WRF-Hydro
  - Taylor & East Rivers
  - Rio Grande
  - Blue River
- CA DWR Bulletin 120

Expand snow modeling

Maintain & expand partnerships in CO & the Upper CO River Basin

- Identify priority basins in CO

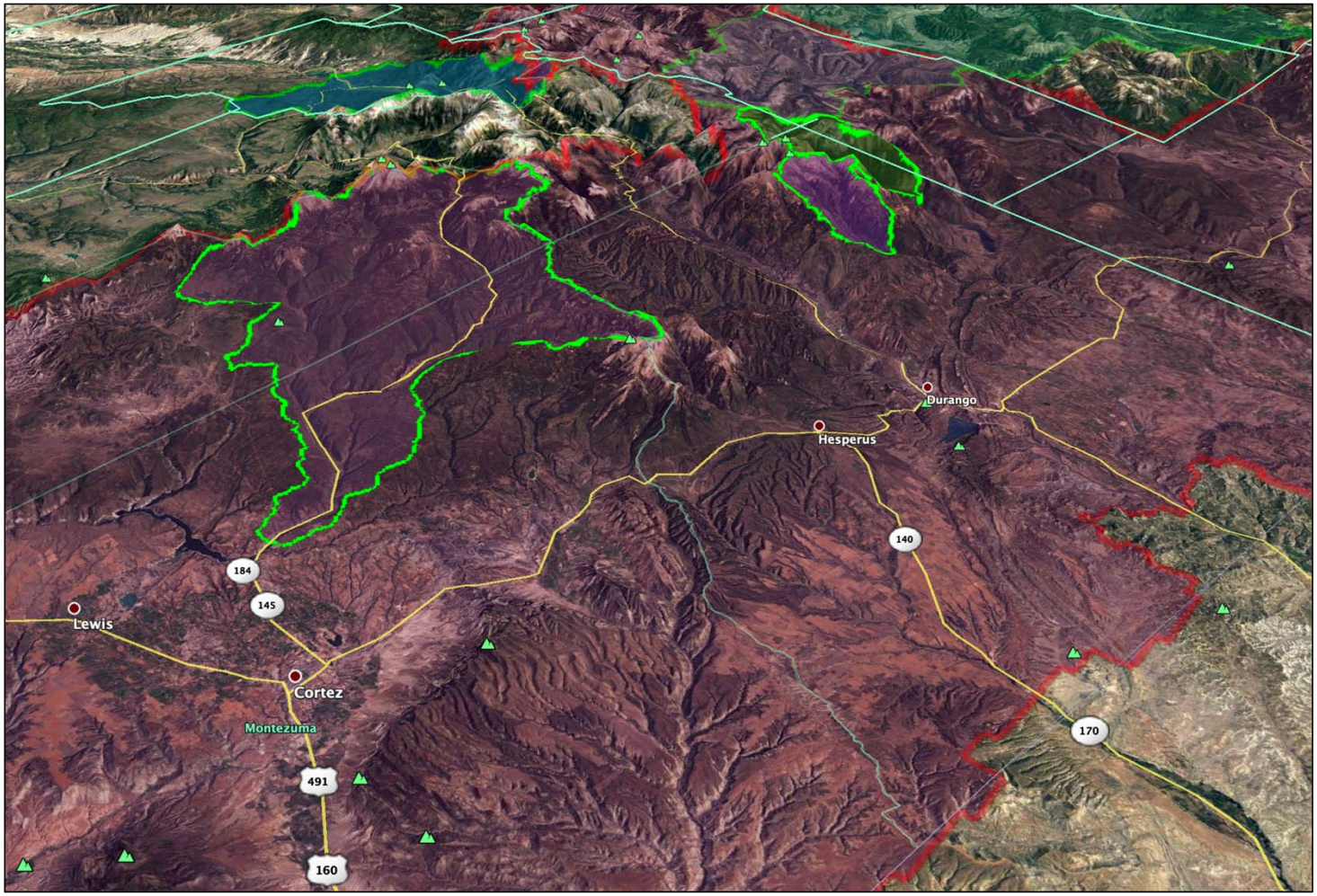
# Emerging opportunities in the SWCD

**Foundation**

- Sept 2019 snow-free lidar data sets cover majority of SWCD counties
- WRF-Hydro model cutout

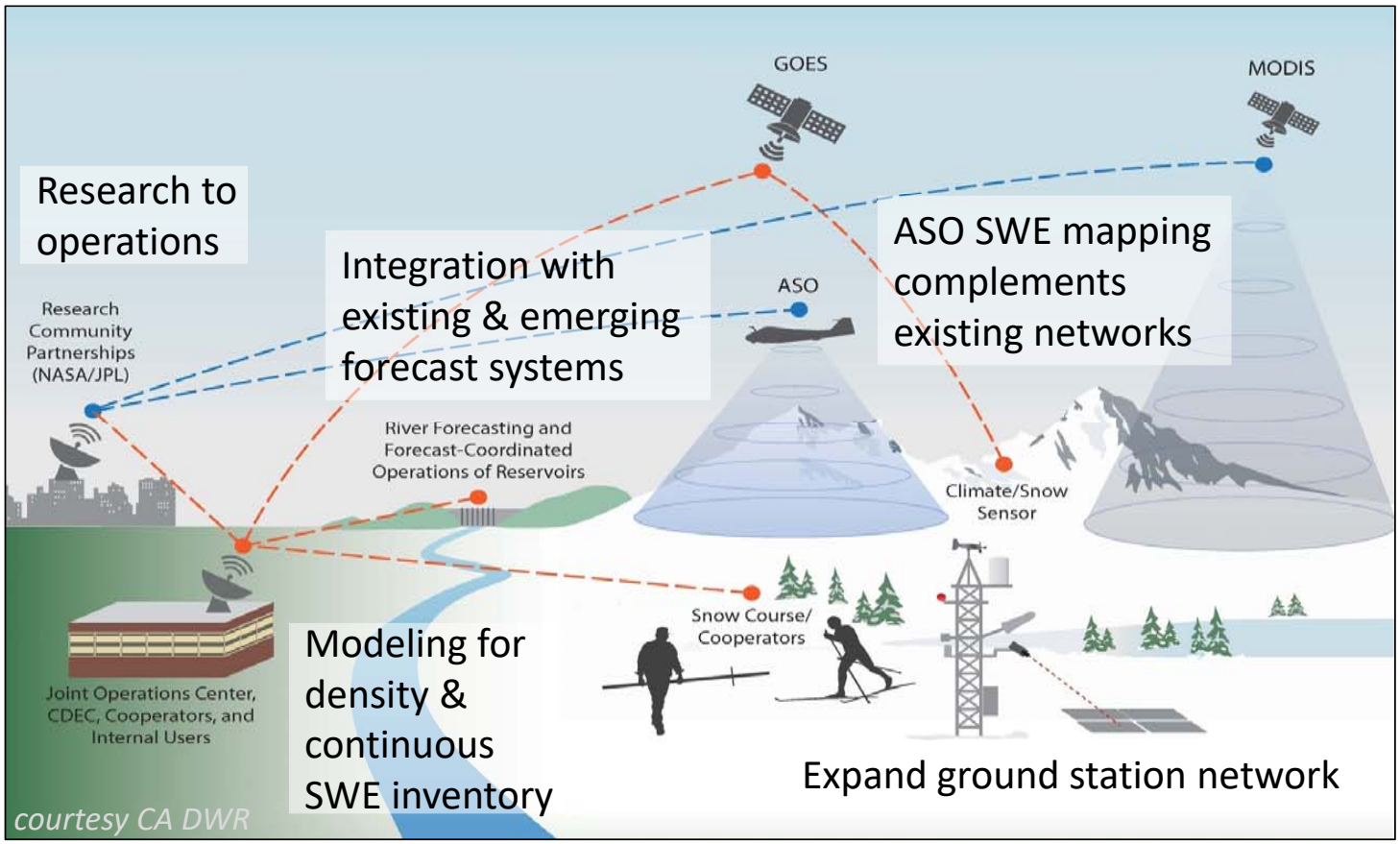
**Potential**

- Dolores above McPhee
- Lemon/Vallecito
- Integration with San Juan, Gunnison, & Rio Grande



# *Next Generation Water Management: CO River Basin*

## *An integrated monitoring & forecasting system*




## *Supporting evolving challenges & programs*

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