Airborne Snow Observatory
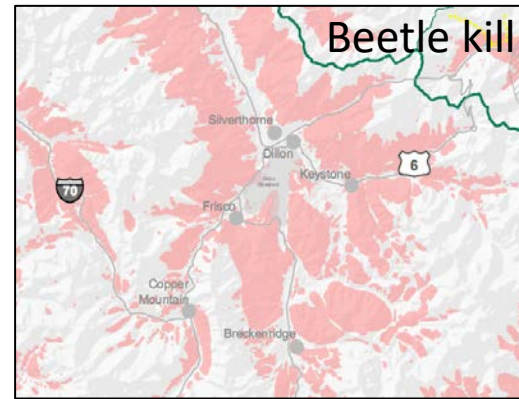## *NASA-Legacy Technology Transfer for Water Management*

Jeff Deems
Airborne Snow Observatories, Inc.

Forecast variation & operational uncertainty

Blue River @ Dillon - Denver Water

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

Dust-on-snow
Arapahoe Basin, May 26, 2009

Beetle kill

Data courtesy Nathan Elder, Denver Water

TUOLUMNE RIVER WATERSHED COMPUTED NATURAL FLOW

	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
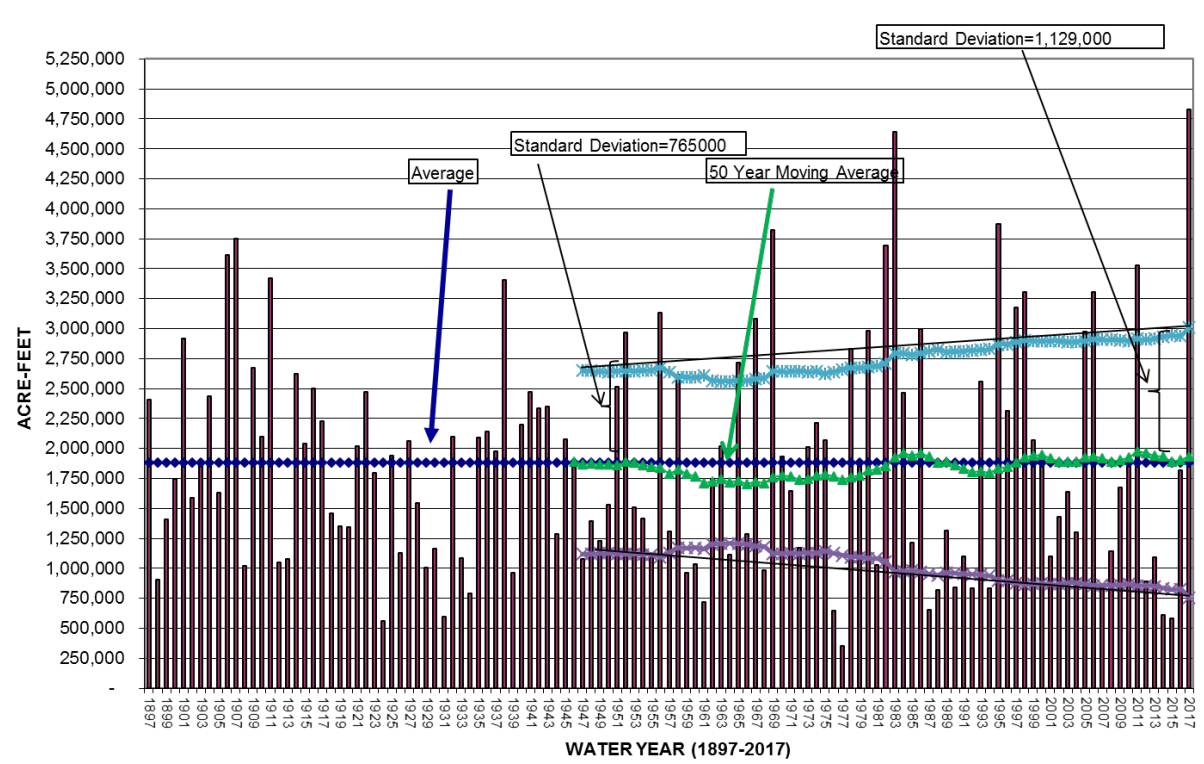
Airborne Sno

A Public Benefit Corporation
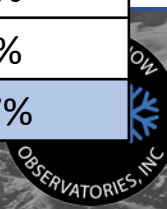
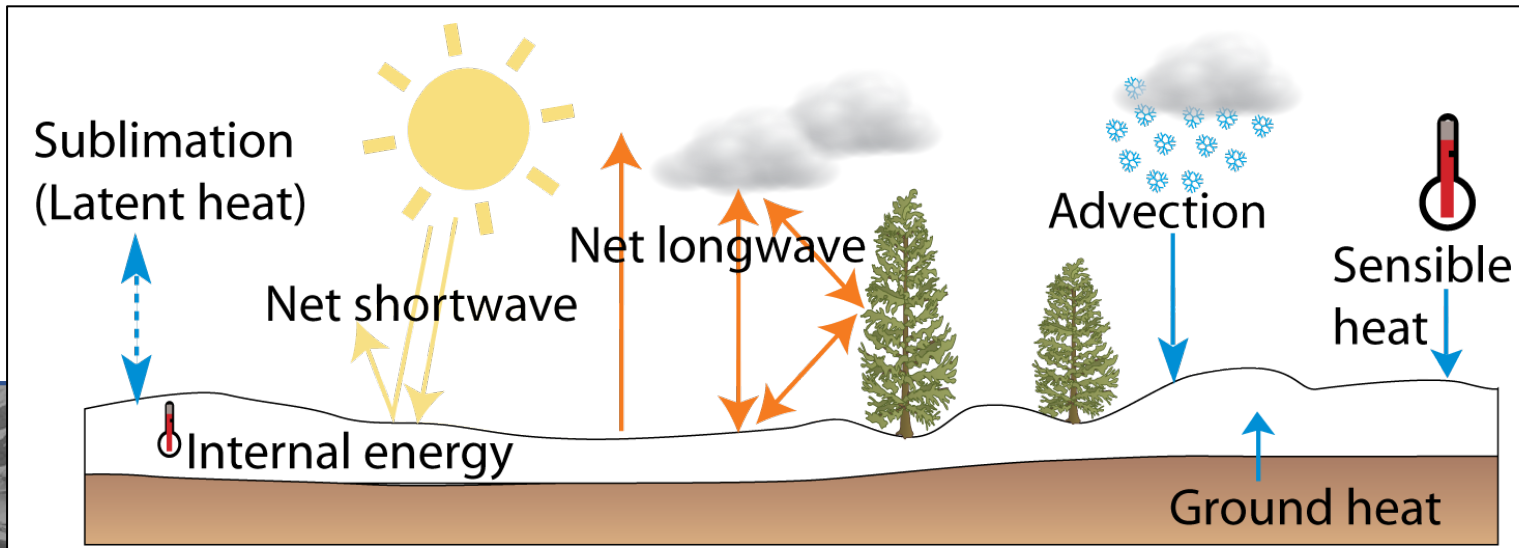# How to support water supply forecasting in these changing conditions?

Decrease reliance on historic record
Increase availability & use of spatial data

- Satellite
- Airborne
- Weather models

Snow accumulation patterns
  drive snowmelt volume & timing

Solar radiation controls snowmelt

These factors can be monitored operationally with remote sensing

How do we get to operational SWE & albedo?
One combination stands out as application-ready

measure snow depth via differential altimetry *(constrained by spectrometer)*

lidar can provide the accuracy in rough terrain & forest
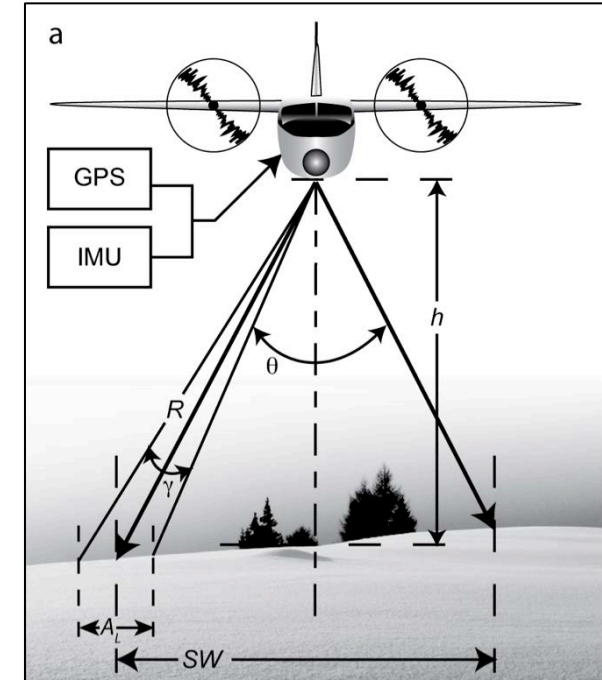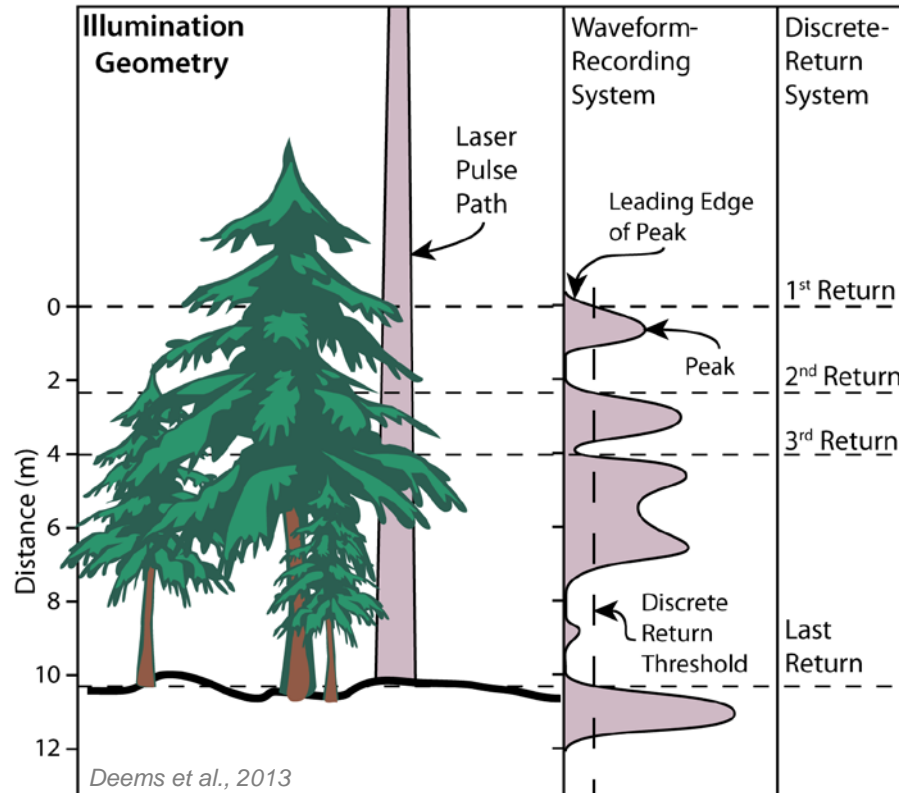
monitor & model snow density

snow depth variation dominates SWE pattern

measure albedo *(constrained by lidar)*

imaging spectrometer retrieves albedo & surface properties

ASO airborne program advantages

- time-nimble

- targetable

- commercial technology

Deems et al., 2013

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
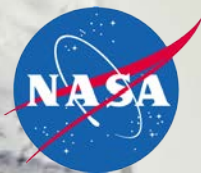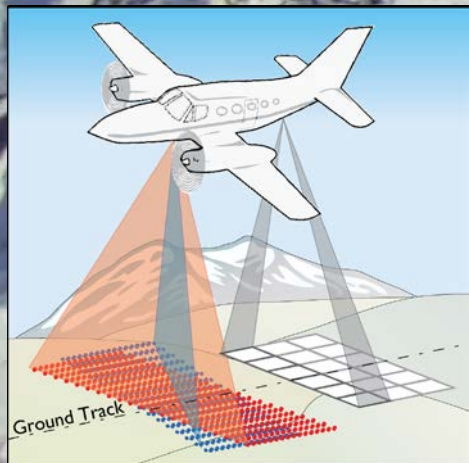
Snow Albedo

CASI-1500 Spectrometer
2m spatial resolution from 4000m

Physical Modeling

Coupling of lidar and spectrometer measurements
Snowpack process modeling

Operations

Unique high-altitude operations
Unique rapid product turnaround

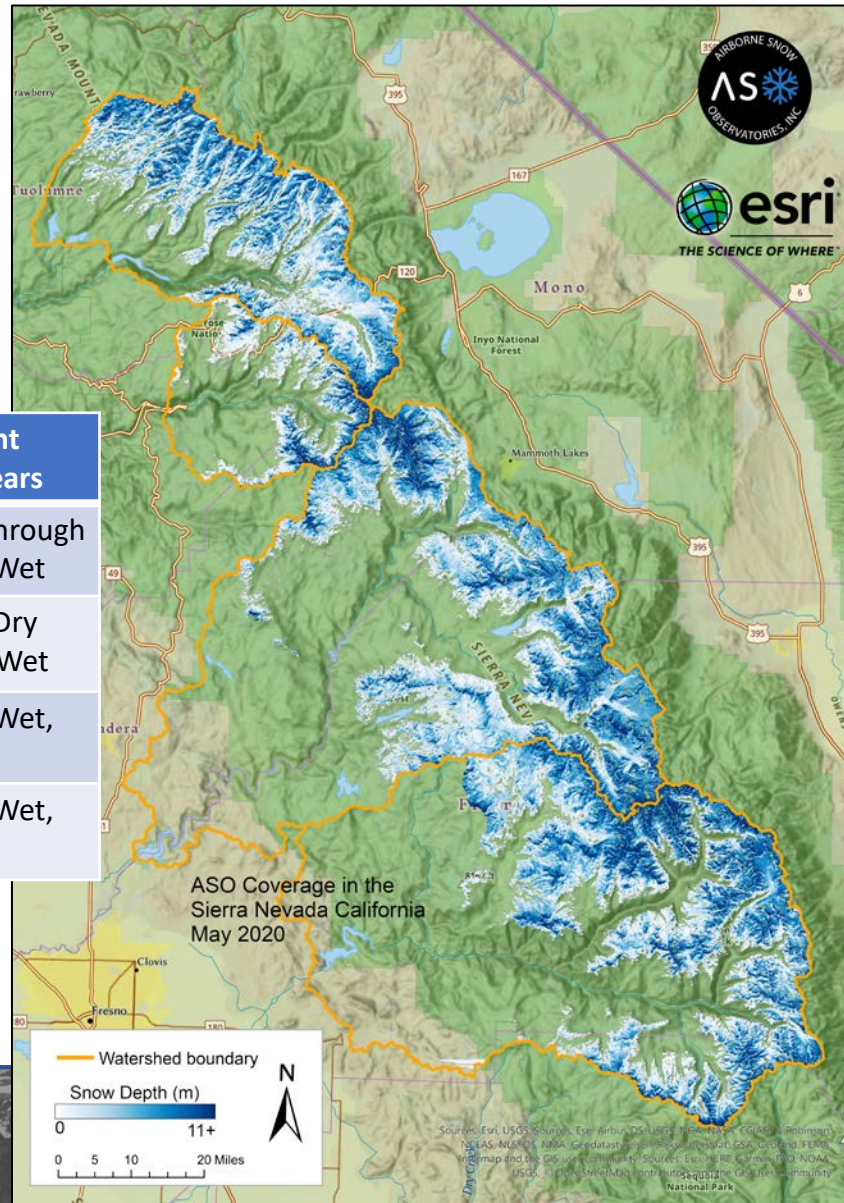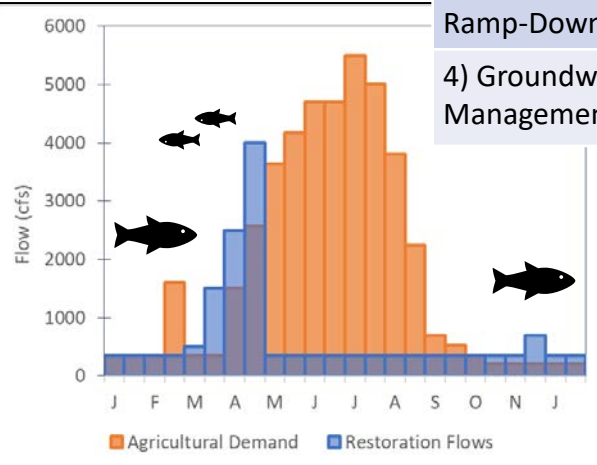Upper Gunnison River
10 June 2019

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

ASO Coverage in the Sierra Nevada California May 2020

Watershed boundary
Snow Depth (m)
0 — 11+
0 5 10 20 Miles
N

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
ASO		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

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)
    Fraser River (USGS)
    Conejos (CWCB)
    Dolores, Animas/Florida/Pinos (CWCB)
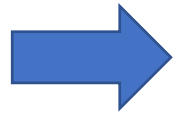
ASO FPMS flow
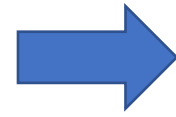
Flight → **P**rocessing → **M**odeling → **S**aaS Analysis & Visualization
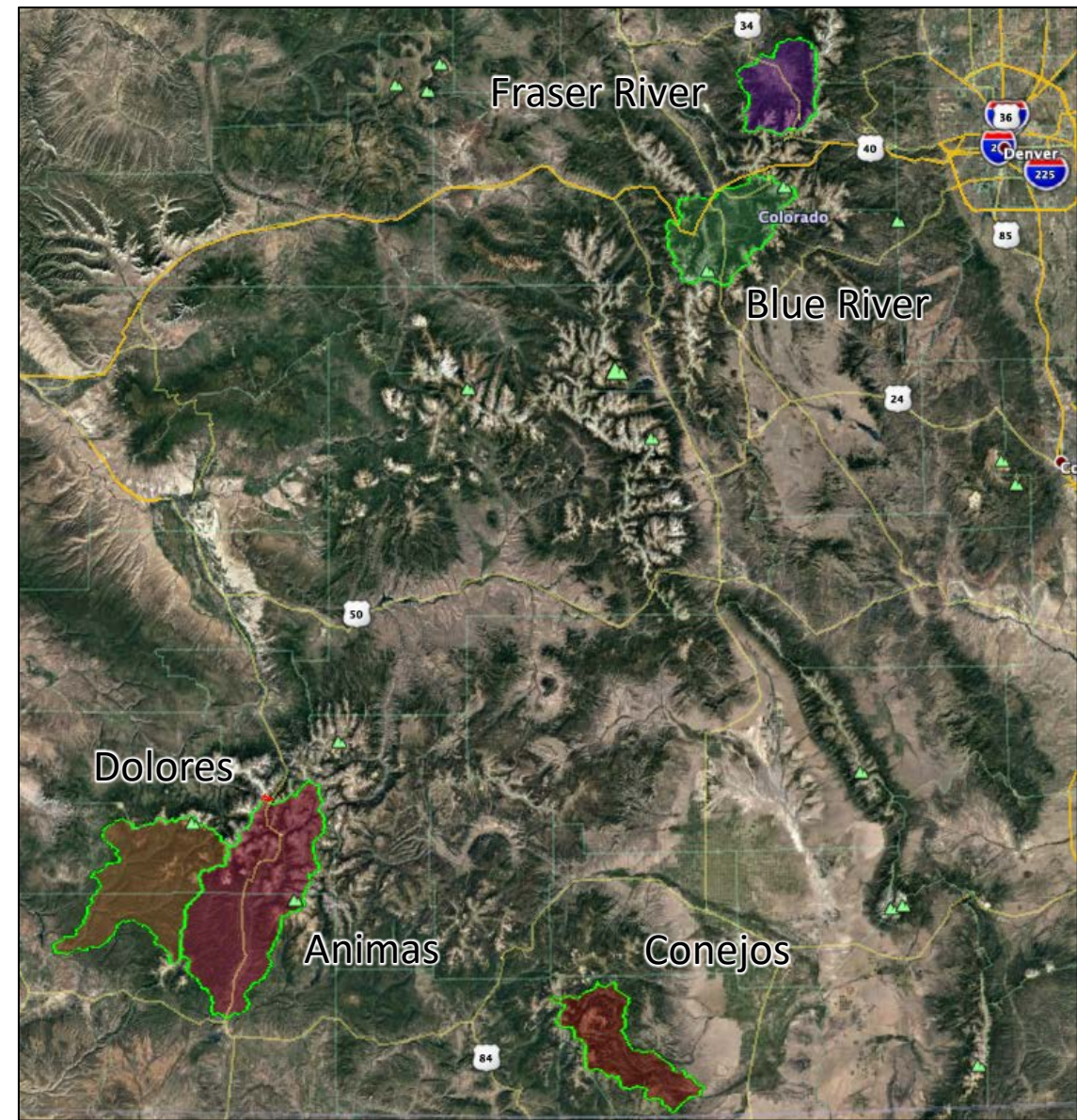
Flight
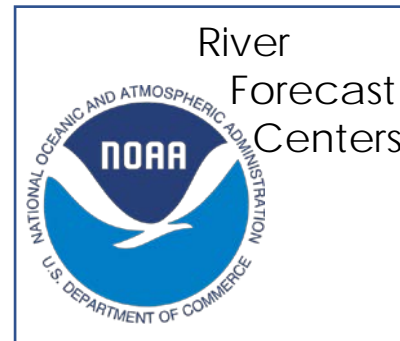- Lidar
- Spectrometer
- (Ka-band radar)

optimized for mountain conditions

Processing
- snow depth
- snow density obs & modeling
- SWE
- snow albedo
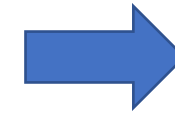- snow grain size
- radiative forcing by dust

< 72 hr turnaround

Modeling
- NCAR
- River Forecast Centers (NOAA)
- Any public or private forecast entity

SaaS Analysis & Visualization
- esri — THE SCIENCE OF WHERE
- U.S. DEPARTMENT OF THE INTERIOR — BUREAU OF RECLAMATION — Regional offices Operations Tech. Serv. Center
- Any public or private decision-maker

Airborne Snow Observatories, Inc.
A Public Benefit Corporation

Data product delivery & reports
flight products & weekly model reports

Expanding ASO applications: *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%

courtesy Pat Kormos, CBRFC

WRF-HYDRO applications data assimilation

- High elevation snow data from 24 May ASO assimilation reduces low forecast bias in ESP AJRO forecast
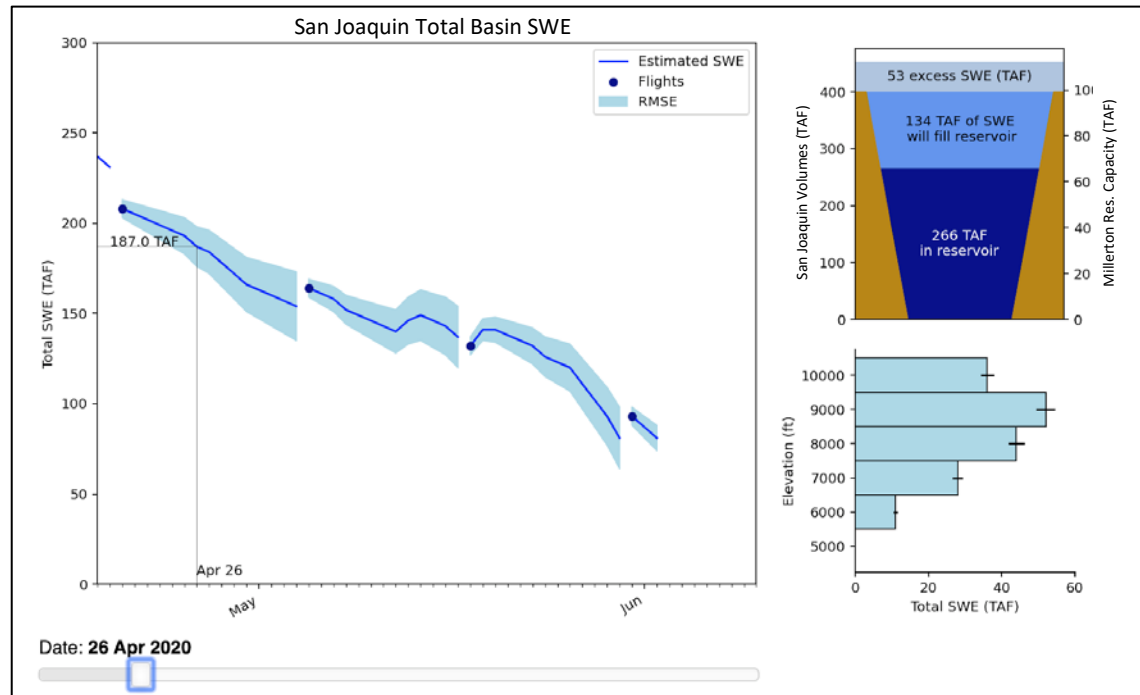
East River @ Almont   **Taylor River @ Taylor Park**

courtesy Dave Gochis, NCAR

Airborne Snow Observatories, Inc.
A Public Benefit Corporation
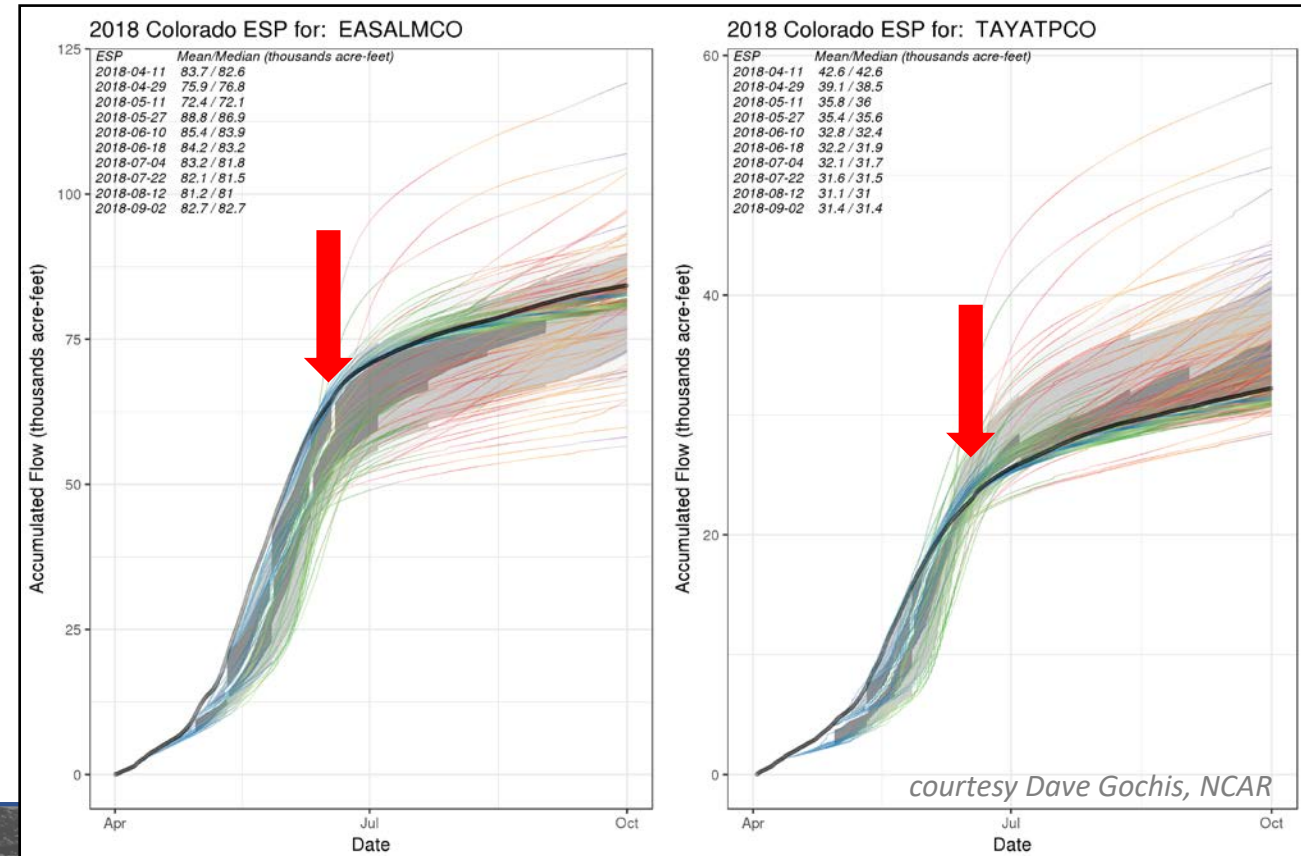
Expanding ASO applications: *data tools*

Building decision-support services
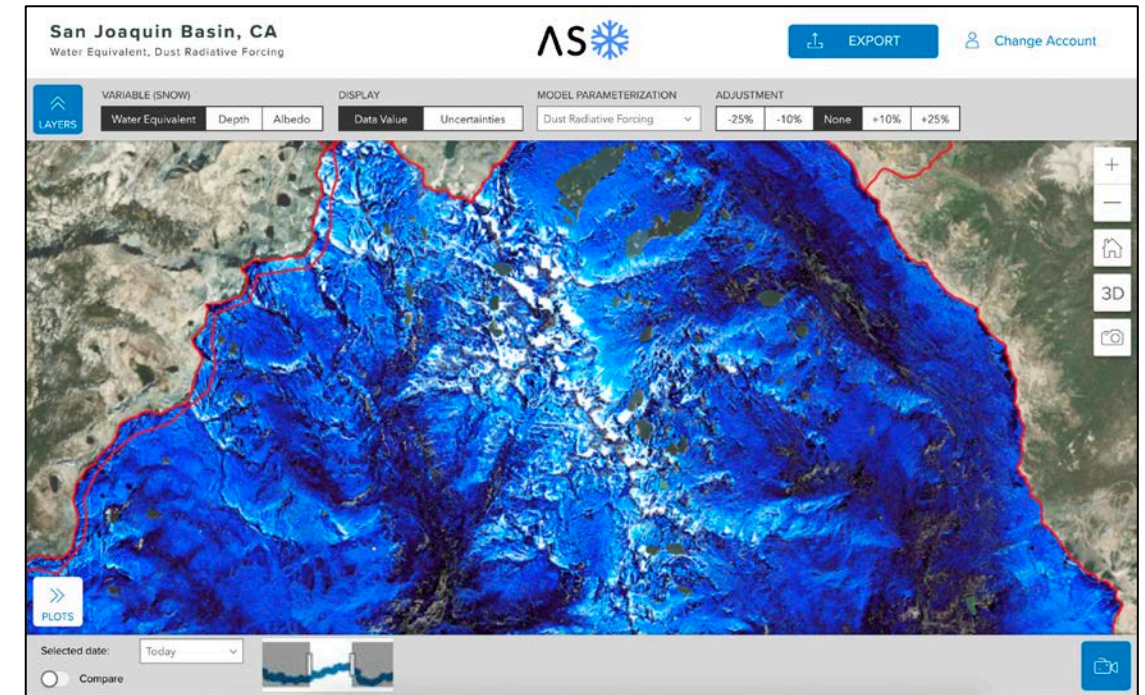
- integration of ASO snow inventory time series with operational needs & workflows
- custom web-app deployment

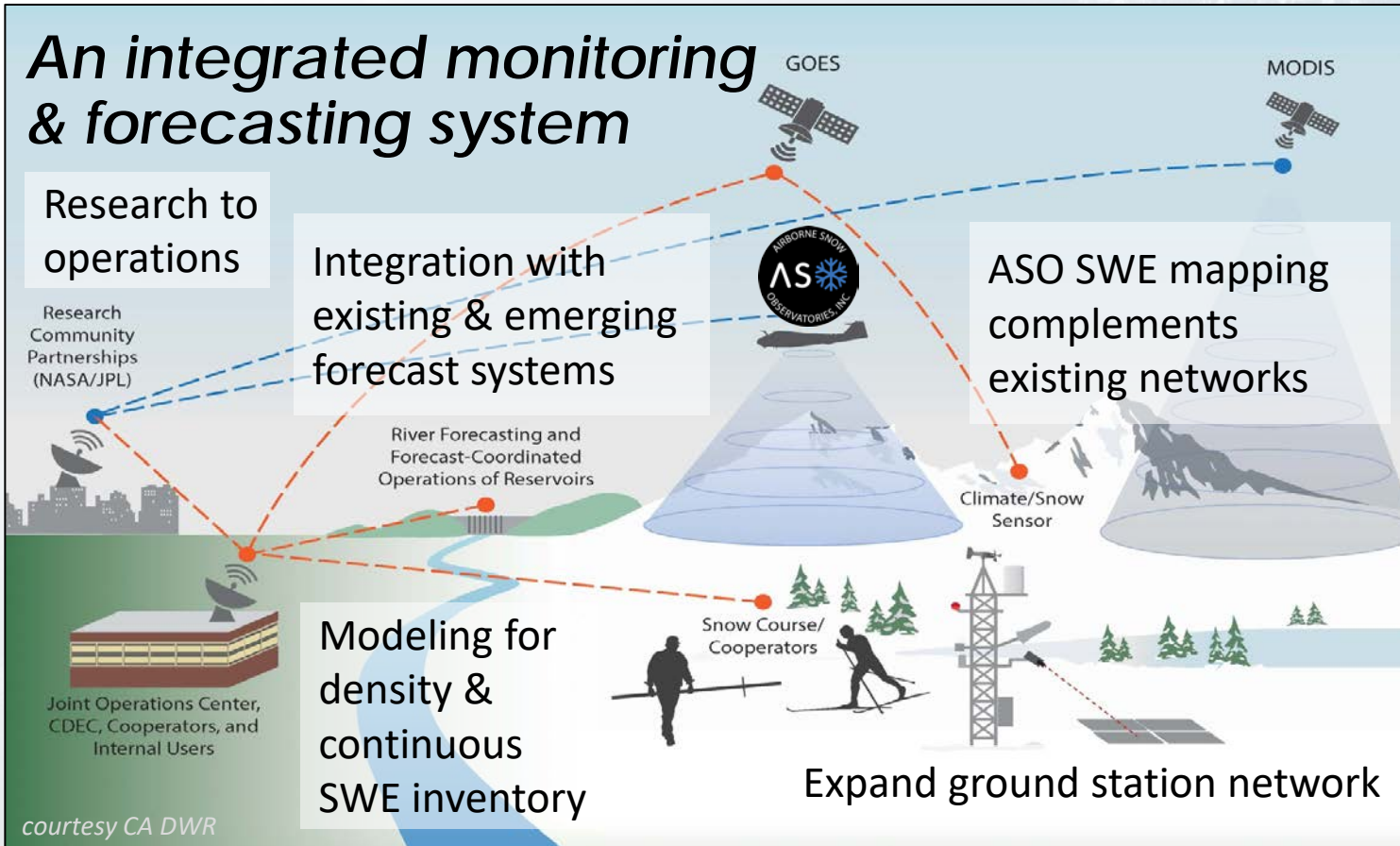## Capitalizing on Esri architectures

- strengthening internal workflow & data management
- integrating with data deployment
- scaling & new program support

Wireframe mock-up of ASO data decision-support tools

Wireframe mock-up of ASO data exploration & subsetting tools

Airborne Snow Observatories, Inc.
A Public Benefit Corporation

Supporting Next Generation Resource Management

An integrated monitoring & forecasting system

GOES

MODIS

Research to operations

Research Community Partnerships (NASA/JPL)

Integration with existing & emerging forecast systems

ASO SWE mapping complements existing networks

River Forecasting and Forecast-Coordinated Operations of Reservoirs

Climate/Snow Sensor

Joint Operations Center, CDEC, Cooperators, and Internal Users

Modeling for density & continuous SWE inventory

Snow Course/Cooperators

Expand ground station network

courtesy CA DWR

Addressing evolving challenges & programs

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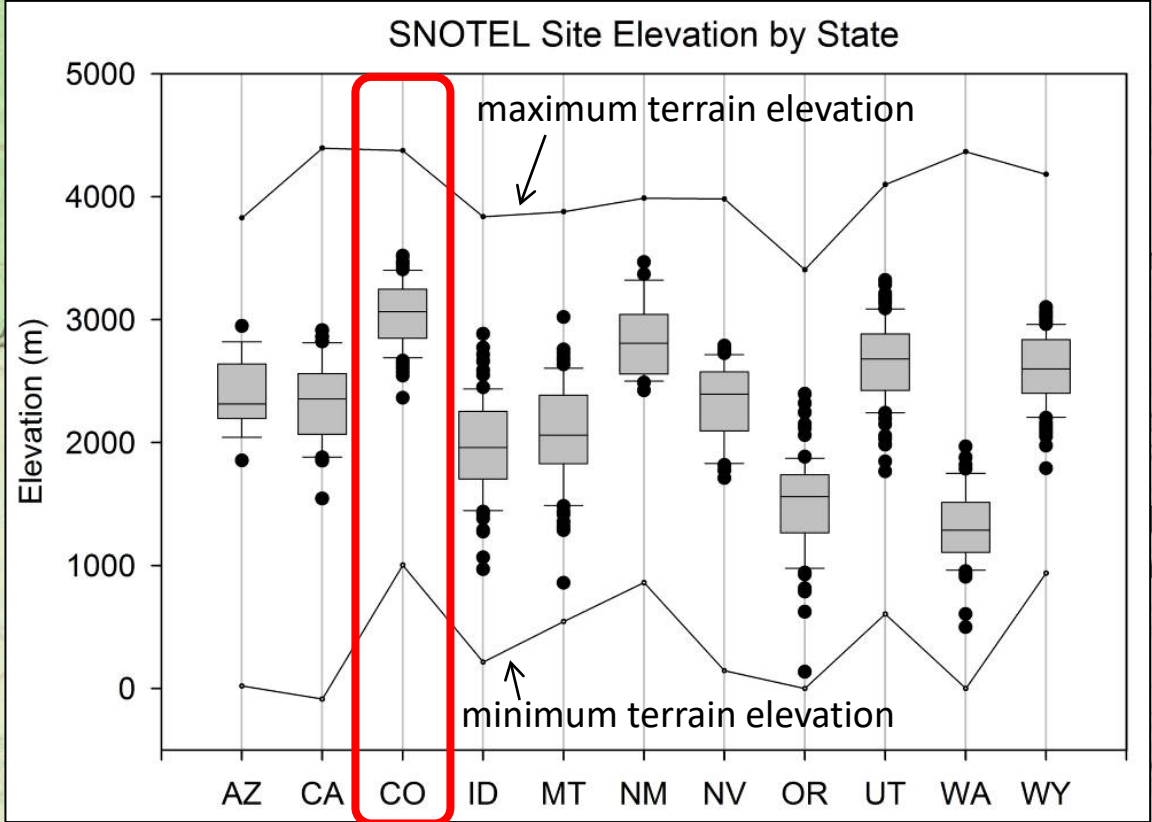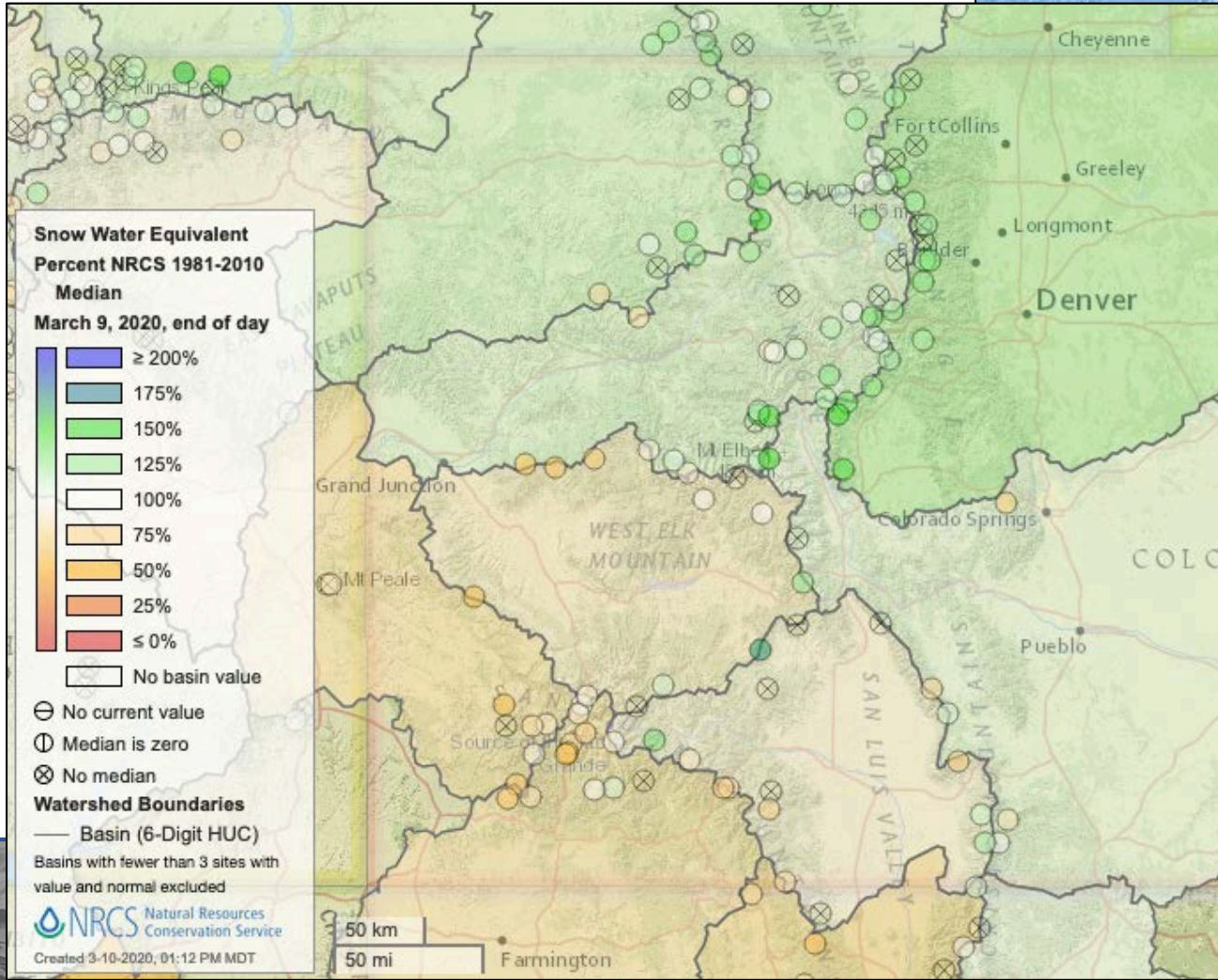- accurate SWE inventory for equitable decision-making

Airborne Snow Observatories, Inc.
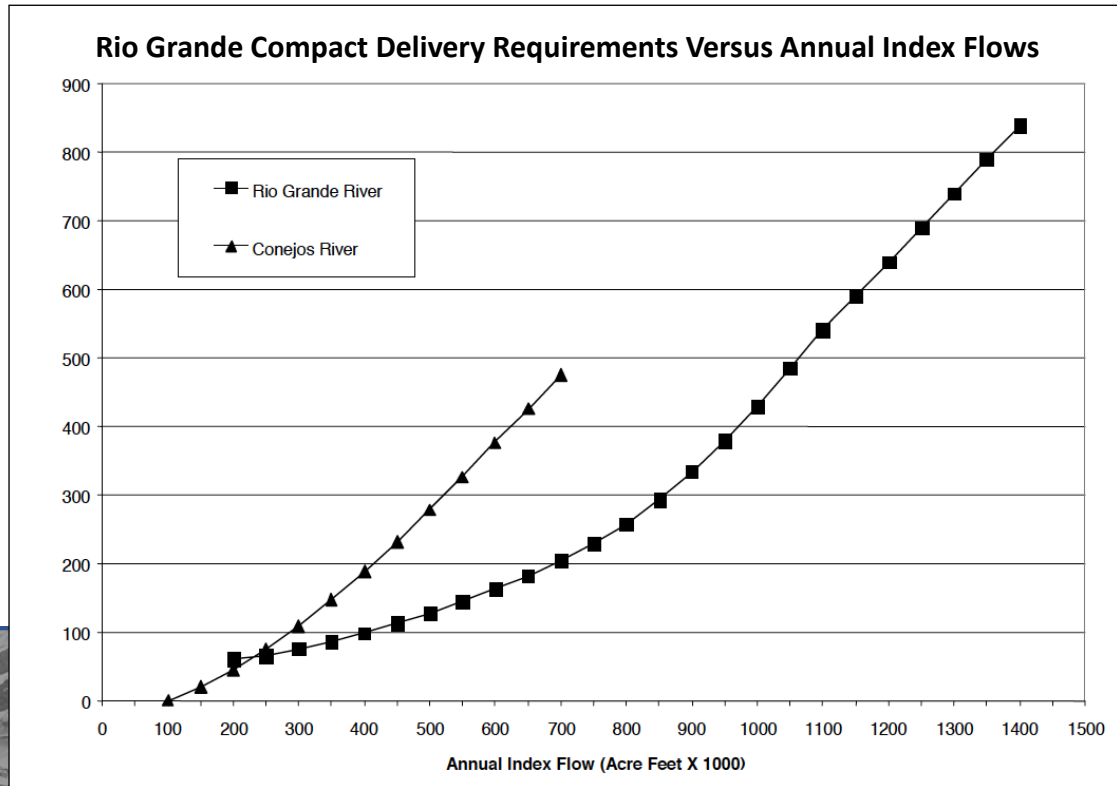A Public Benefit Corporation

Basin snowpack status based on station data

www.nrcs.usda.gov

Forecast variation & operational uncertainty

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

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

Rio Grande Compact Delivery Requirements Versus Annual Index Flows

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%

Data courtesy Craig Cotton CO DWR Division 3 Engineer

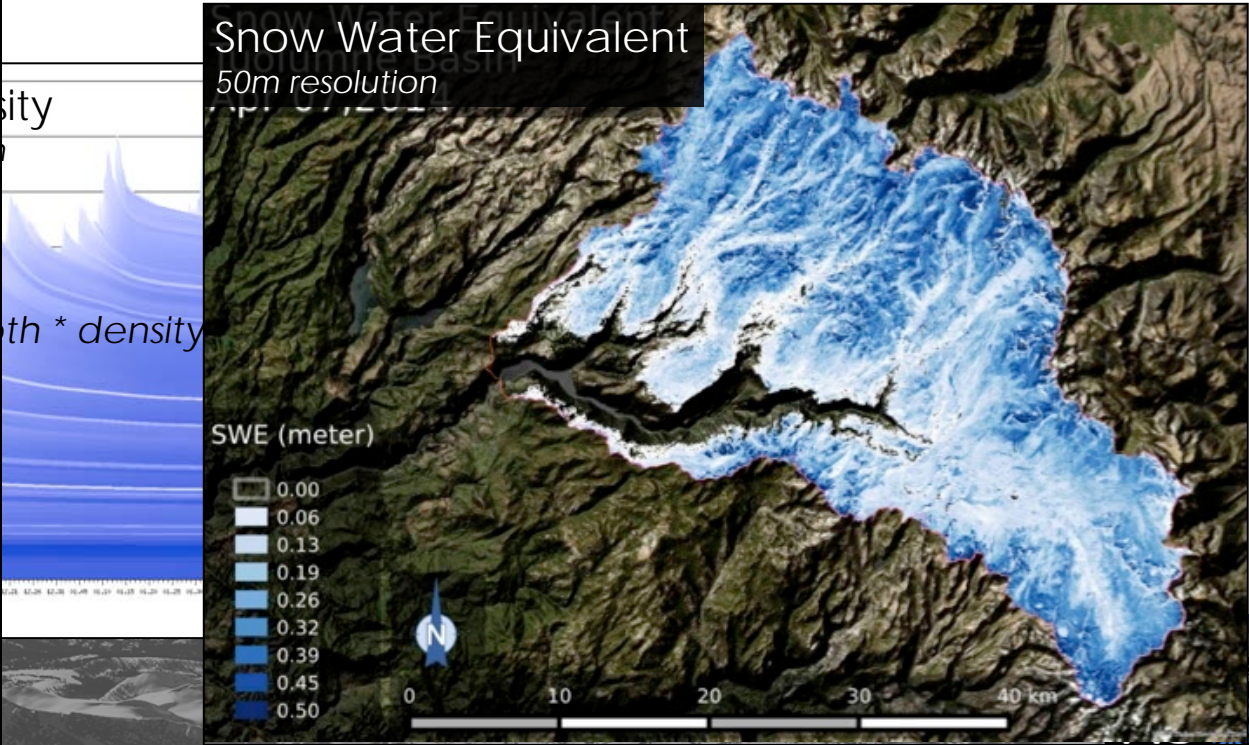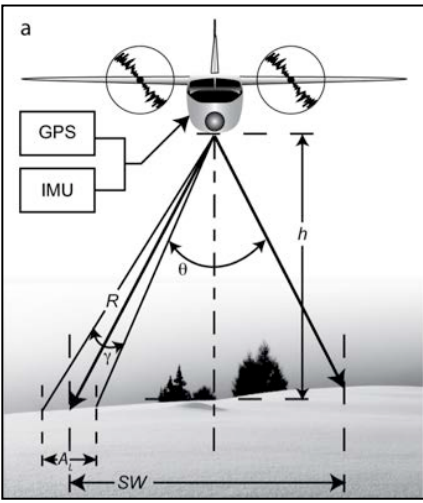| Forecast > 10% Low |
| Forecast > 10% High |

Snow Observatories, Inc.
A Public Benefit Corporation

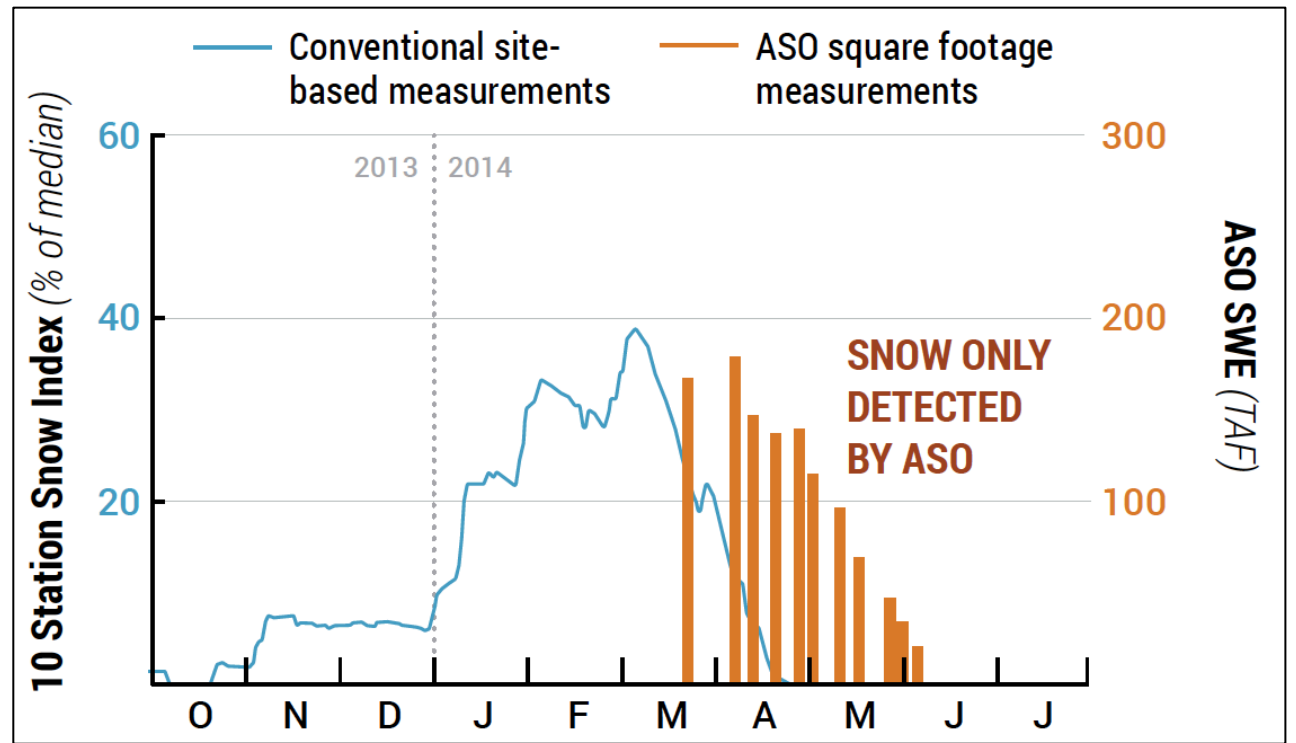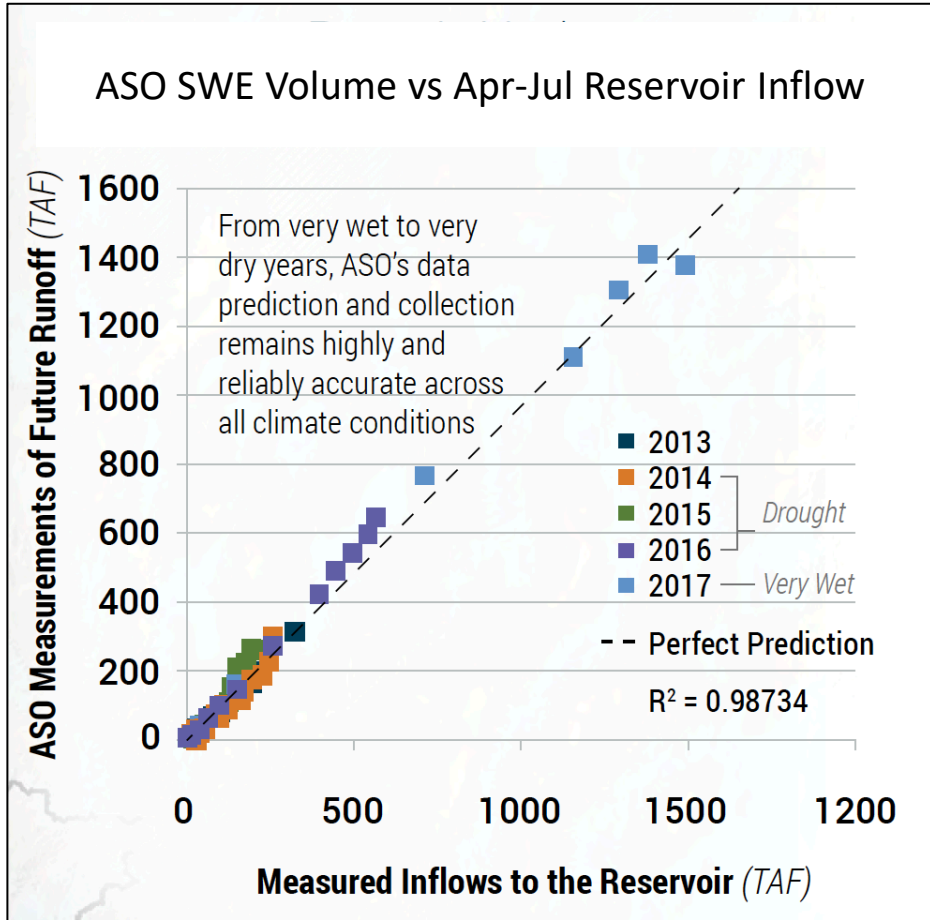# Snow Depth, Water Equivalent, & Albedo
from lidar & spectrometer

ASO's unique process:
* ❆ highly optimized flight design
* ❆ novel integrated data pipeline
* ❆ lidar & spectroscopy experts

Snow Water Equivalent
50m resolution

SWE (meter)
- 0.00
- 0.06
- 0.13
- 0.19
- 0.26
- 0.32
- 0.39
- 0.45
- 0.50

A Public Benefit Corporation

Improvement brings impact ...

ASO SWE Volume vs Apr-Jul Reservoir Inflow

From very wet to very dry years, ASO's data prediction and collection remains highly and reliably accurate across all climate conditions

2013
2014
2015 — *Drought*
2016
2017 — *Very Wet*

- - Perfect Prediction

$R^2 = 0.98734$

Conventional site-based measurements   ASO square footage measurements

SNOW ONLY DETECTED BY ASO

"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

California: a maturing decision-support program
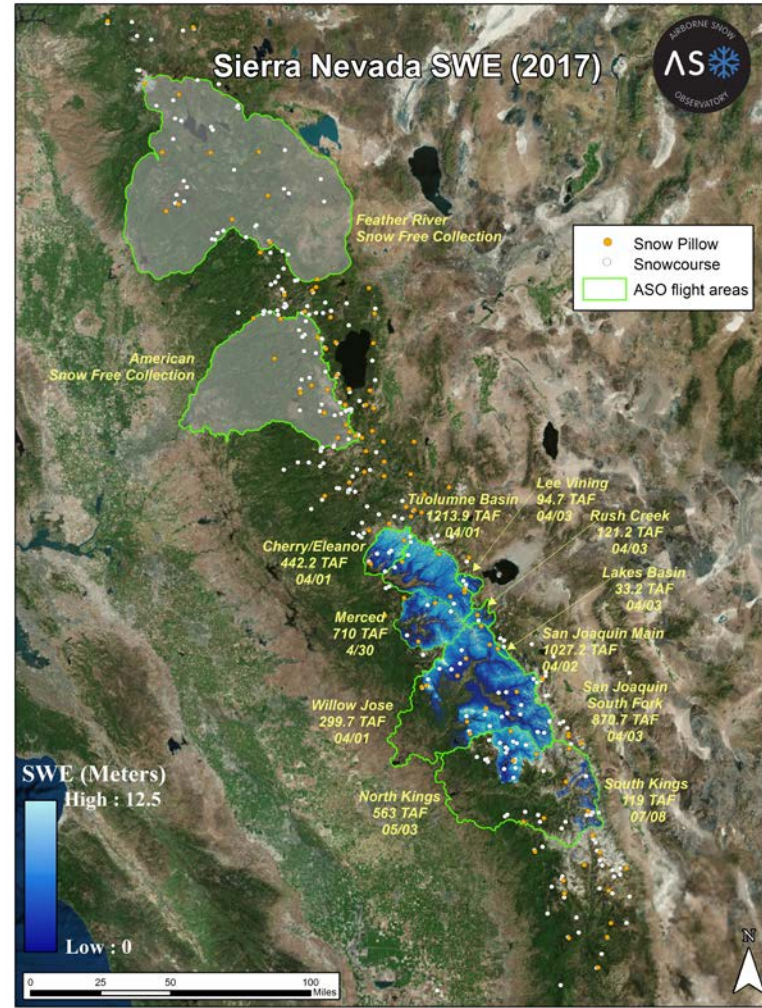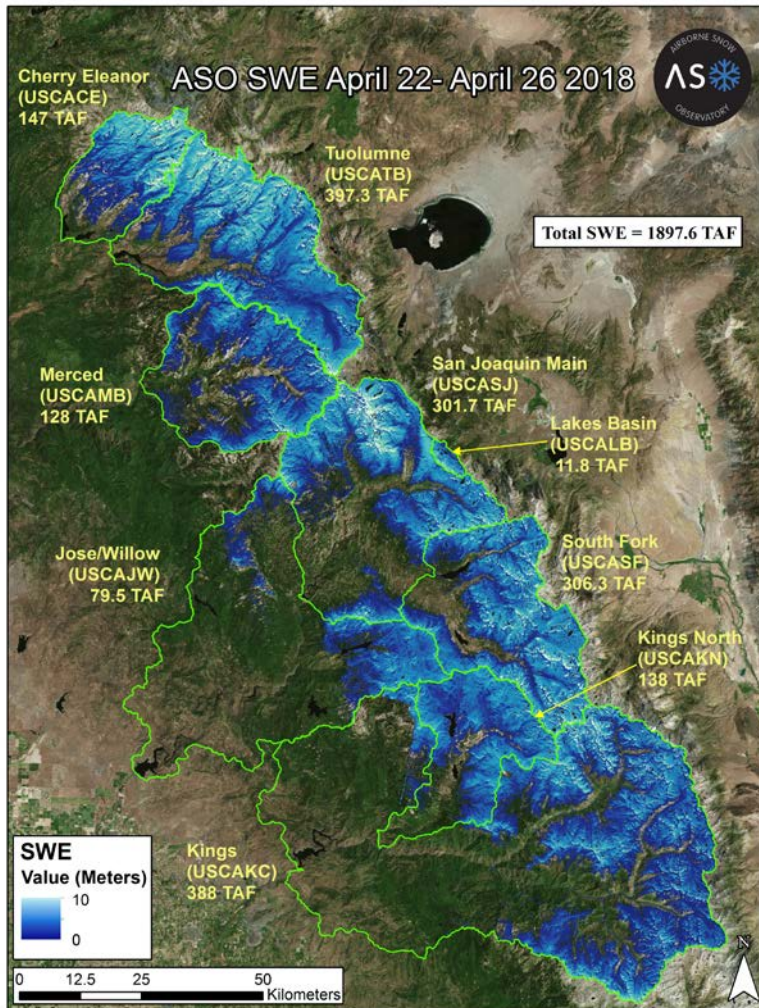

**California:
to-date & Future Plans**

- 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

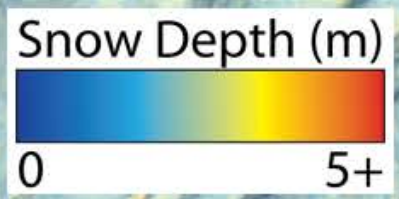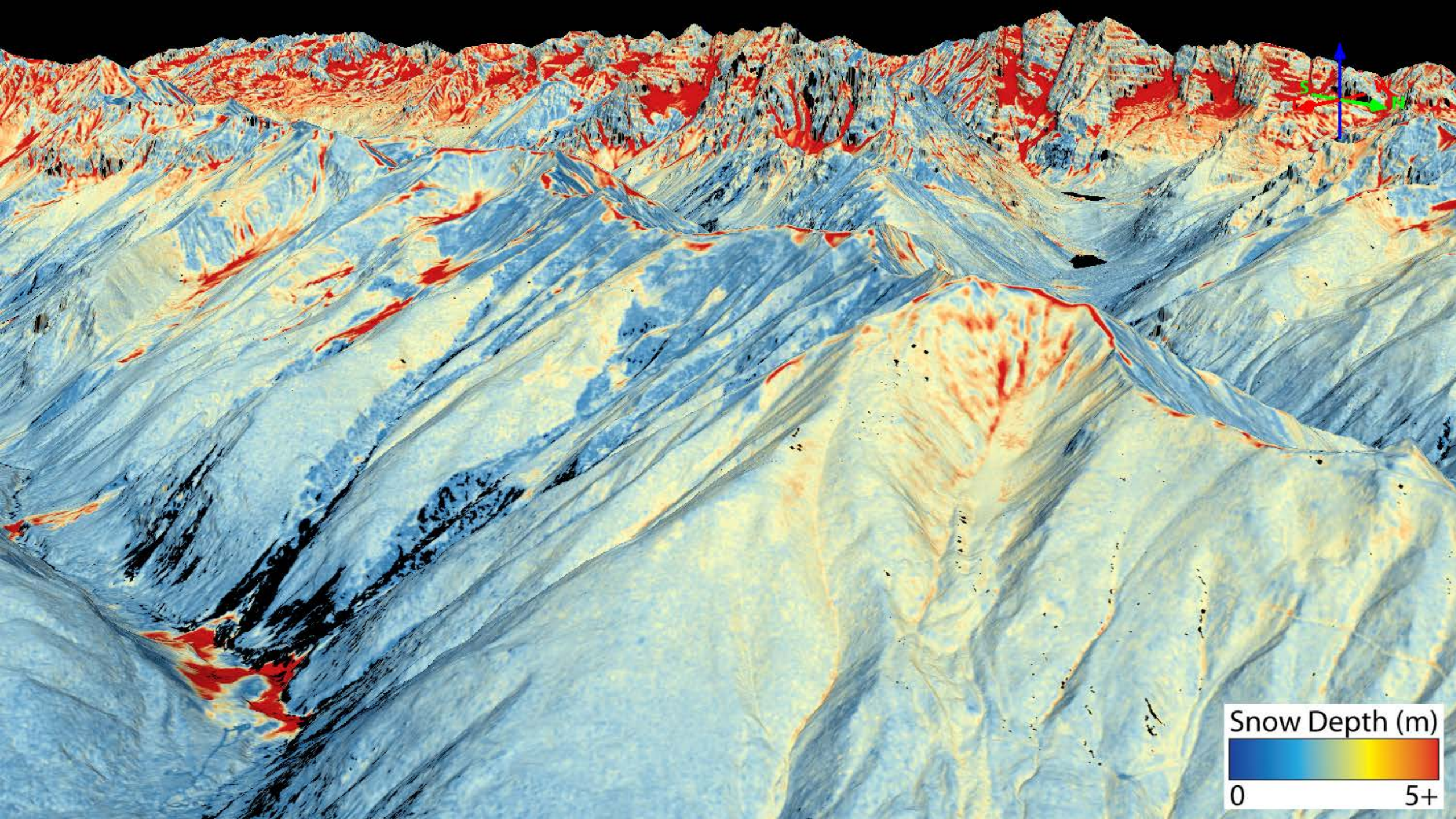- Data service through Esri partnership

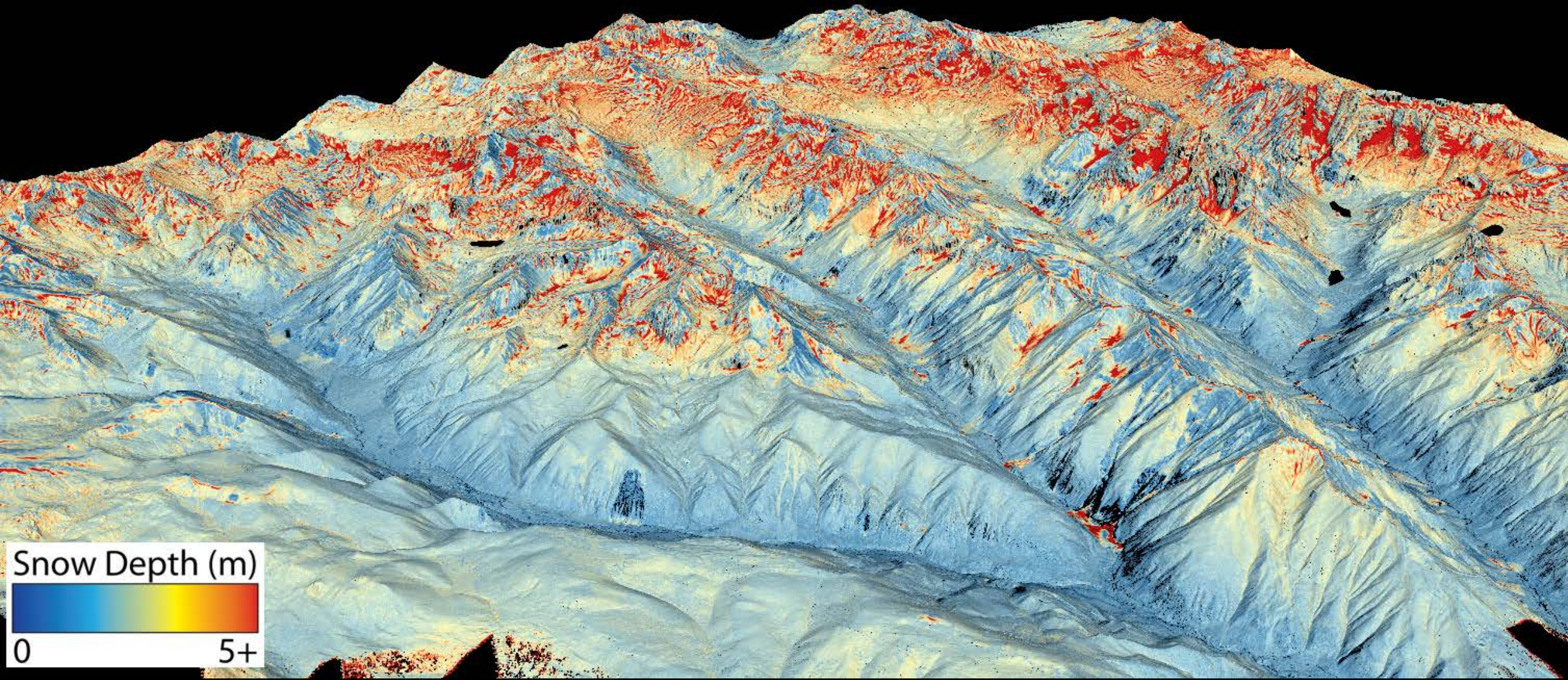- Agency synergies

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

ASO: Castle–Maroon, Aspen, CO, April 7 & June 10, 2019

Snow Depth (m)

0   5+

Snow Depth (m)

0   5+
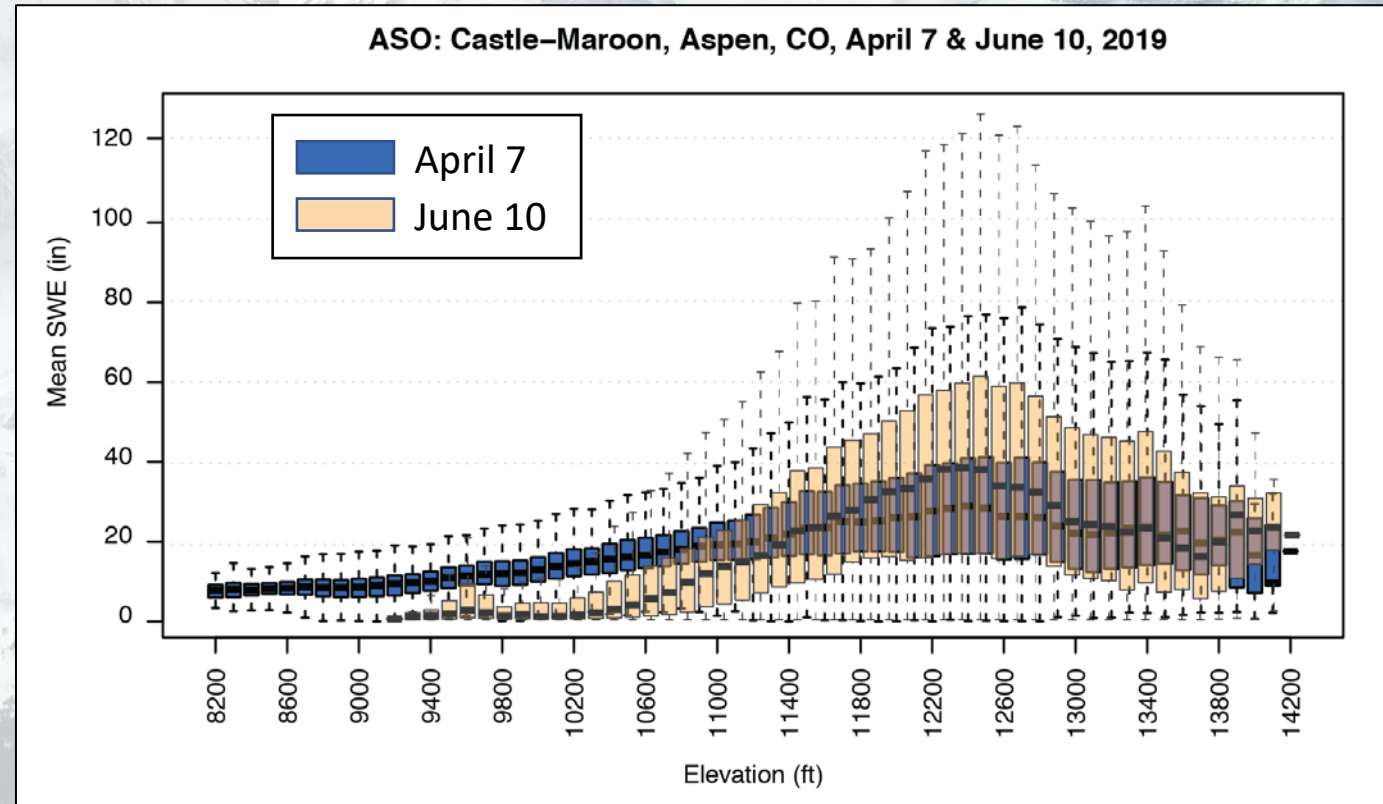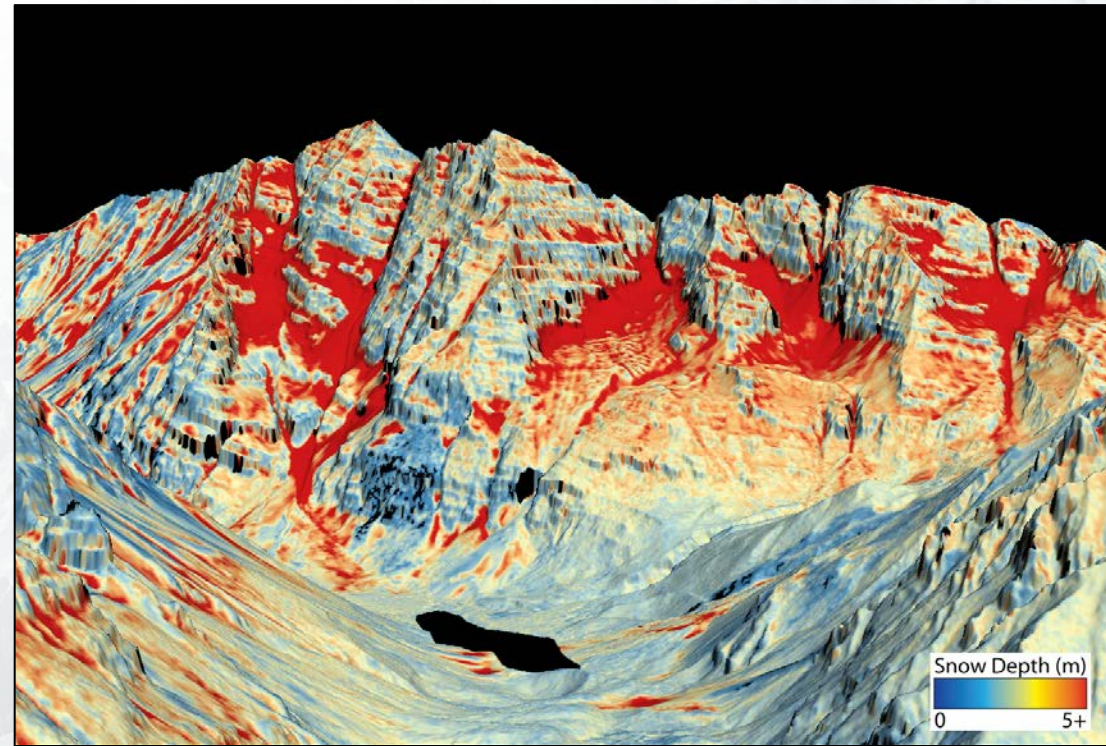
Airborne Snow Observatories, Inc.

A Public Benefit Corporation
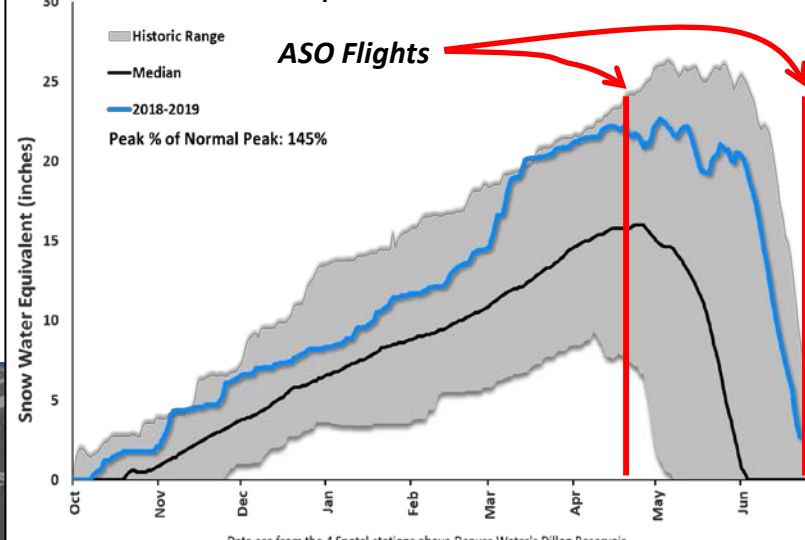
Blue River Basin
Denver Water

- 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
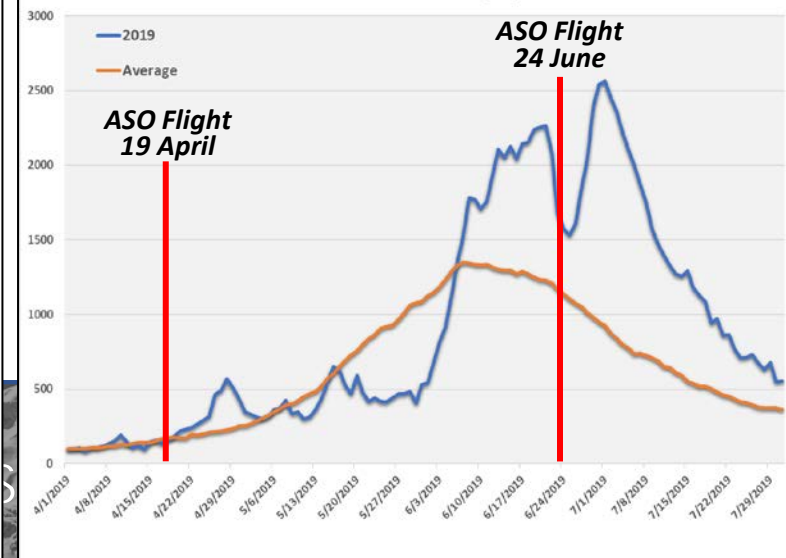 - enabled response to double flow peak

Snow Depth April 19

Snow Depth June 24

Snow Depth (m)
Snowpits | ASO
4+
0
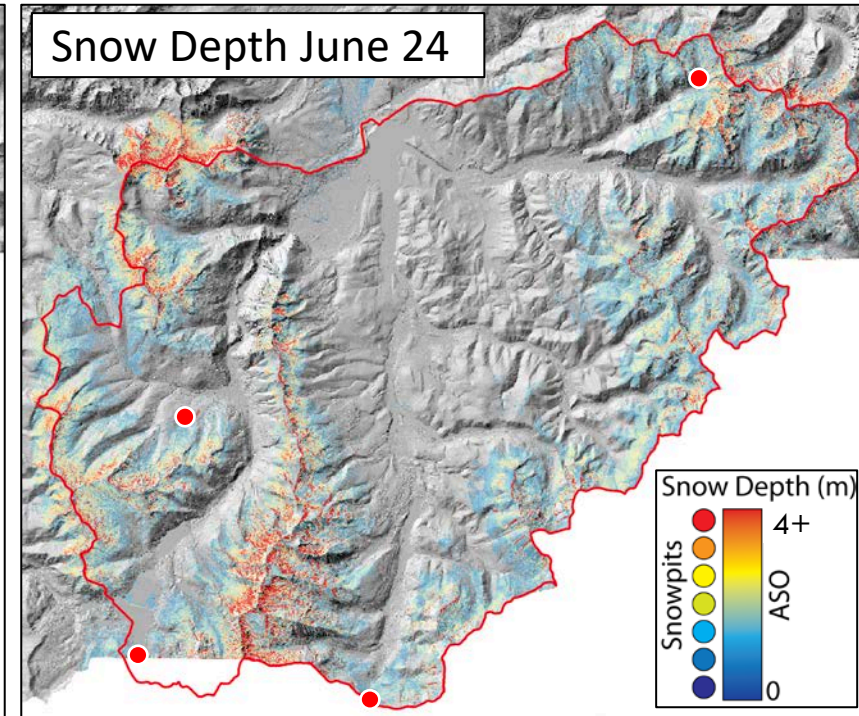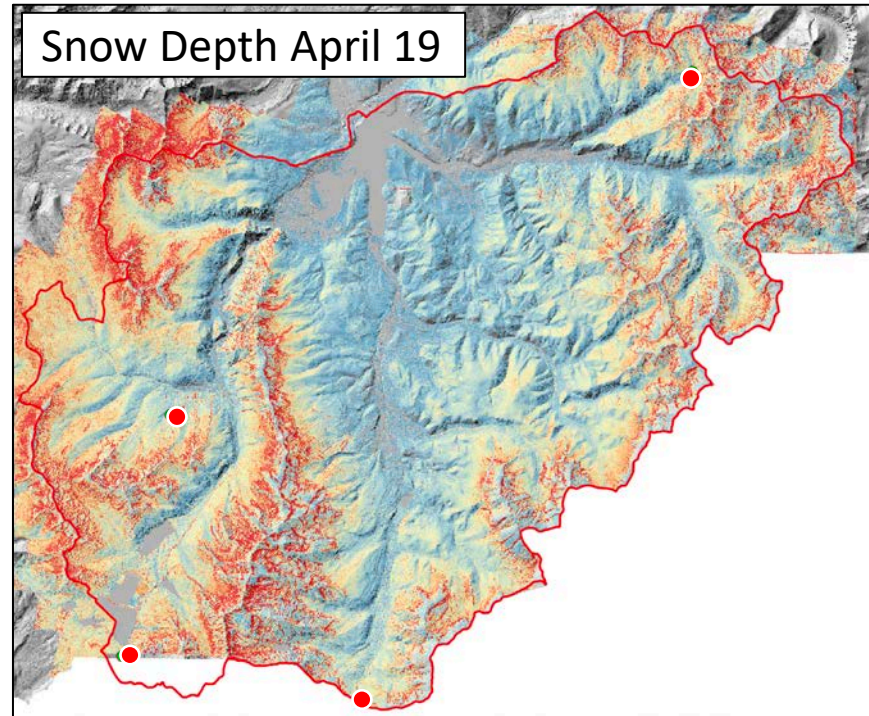
ASO Blue River: SWE by Elevation
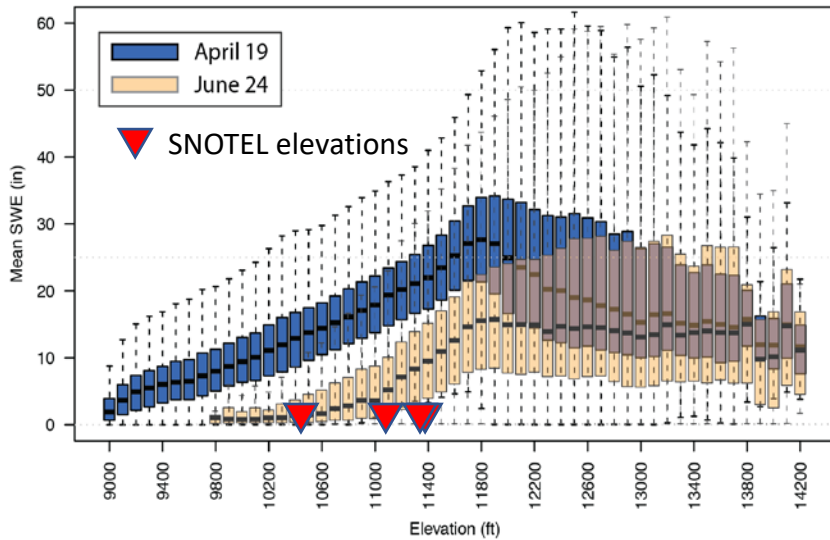
SNOTEL Snowpack above Dillon Reservoir

ASO Flights

ASO Flight 19 April

Historic Range
Median
2018-2019
Peak % of Normal Peak: 145%

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

Dillon Reservoir Inflow (cfs)

2019
Average

ASO Flight 24 June

ASO Flight 19 April

ASO is not just another hopeful SWE & albedo product

- Runoff forecasting literature contains many uncertain relationships between snow **point** measurements & total SWE + runoff

- ASO is the **first, highly accurate, spatially-complete measurement of snow depth, snow water equivalent, & snow albedo**
  - Depth accuracy (±1 cm at 50m), Density (±3-6% at 50m)
  - SWE accuracy (±1% across basin)

- Enables forecast accuracy improvement from 50-90% to 96-99%

- California Cooperative Snow Survey members estimate value of ASO forecast improvements
  - > $600M annual for water supply only or > 40:1 ROI
  - > $1.25B annual for supply, hydro, recharge, ecosystem, operational flexibility

ASO Coverage in the Sierra Nevada California May 2020

Watershed boundary

Snow Depth (m)
0   11+

0   5   10   20 Miles
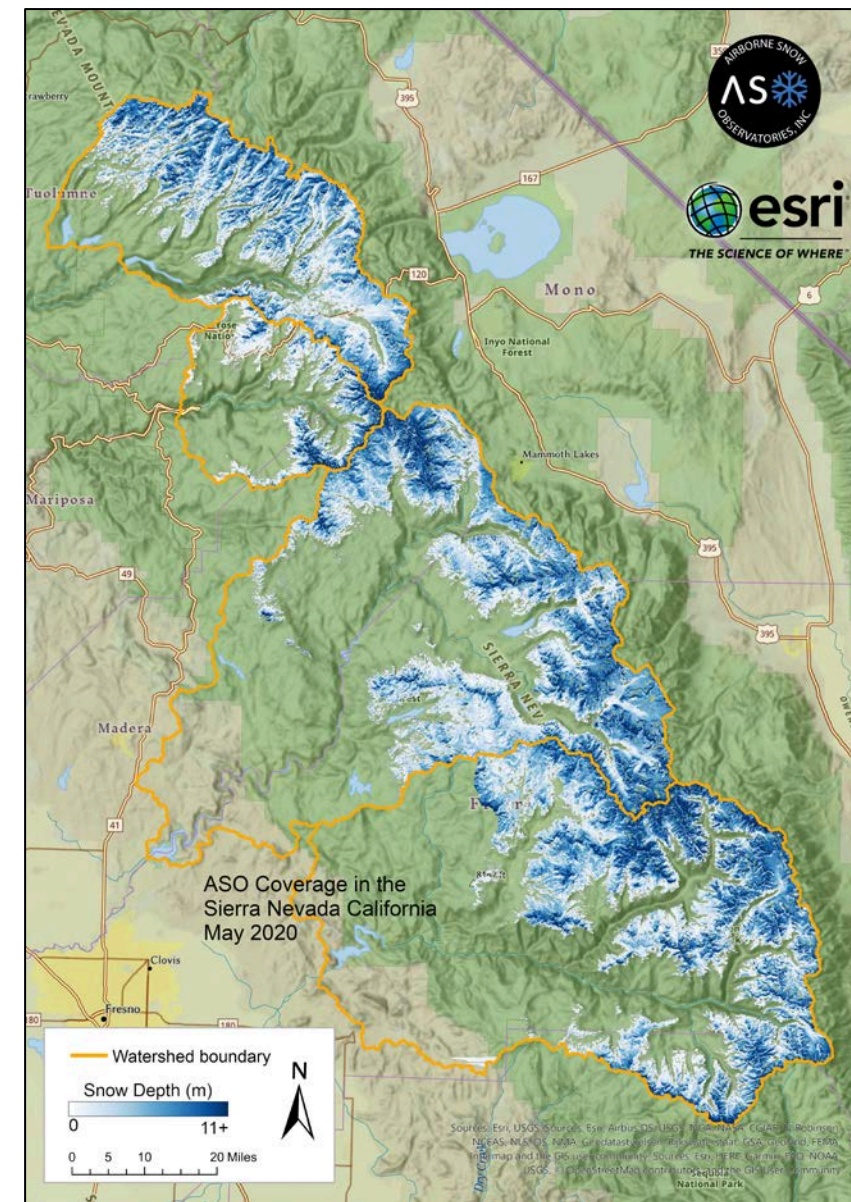
Engagement & Buy-in
enthusiastic adoption by water managers

RISING TO NEW CHALLENGES
FOR CALIFORNIA'S SNOW FORECASTING PROGRAM

California's History of Leadership in Snow Monitoring

CALIFORNIA'S OPPORTUNITY TO LEAD

Hydrologists and water managers at state, regional, a[nd]
unparalleled opportunity to improve the management
ability to adopt this technology and harness its benef[its]

At present, NASA and research funding for ASO surve[ys]
of local and regional water users with a strong belief i[n]
emerged to provide gap funding through the 2019 sno[w]
Tuolumne, San Joaquin, and Kings river basins. This s[...]
to broadcast the successes experienced by the ASO p[...]
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."

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"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

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

CO Lidar Mapping Program Status

Complete
In progress

Ferraz, Saatchi, Bormann, & Painter, 2018