Operational Complete Measurement of our Mountain Snows

~

Thomas H. Painter
Jeff Deems

Airborne Snow Observatories, Inc.

Colorado River Water Users Association
Annual Meeting
14 December 2022

Outline

- Background on snowpack and runoff forecast uncertainties
- Overview of Airborne Snow Observatories
- Forecasting results with ASO updates
- Implementation in Colorado River Basin and elsewhere

The future ain't what it used to be.
– Yogi Berra

Take home messages

The mountain snowpack is the Upper Basin's Lake Mead.

We don't measure it.

… except where ASO is making a quantitative measurement

Covering the entire basin is critical for forecasting improvement and adaptive capacity

Problems for forecasting in snowmelt dominated systems

- Operational forecasts have relied on stable climate
- Accuracy averaged over decades with substantial excursions year to year
- In the absence of climate change, year-to-year forecast errors have increasingly acute impacts
- With climate change, this issue is amplified.
- **Summary: we need to get it right in each year**

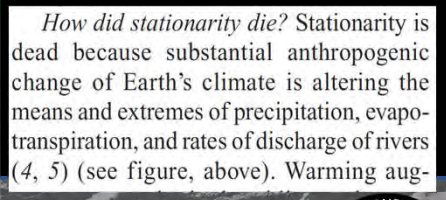
POLICYFORUM

CLIMATE CHANGE

Stationarity Is Dead: Whither Water Management?

Climate change undermines a basic assumption that historically has facilitated management of water supplies, demands, and risks.

P. C. D. Milly,[1]* Julio Betancourt,[2] Malin Falkenmark,[3] Robert M. Hirsch,[4] Zbigniew W. Kundzewicz,[5] Dennis P. Lettenmaier,[6] Ronald J. Stouffer[7]



How did stationarity die? Stationarity is dead because substantial anthropogenic change of Earth's climate is altering the means and extremes of precipitation, evapotranspiration, and rates of discharge of rivers (*4*, *5*) (see figure, above). Warming aug-

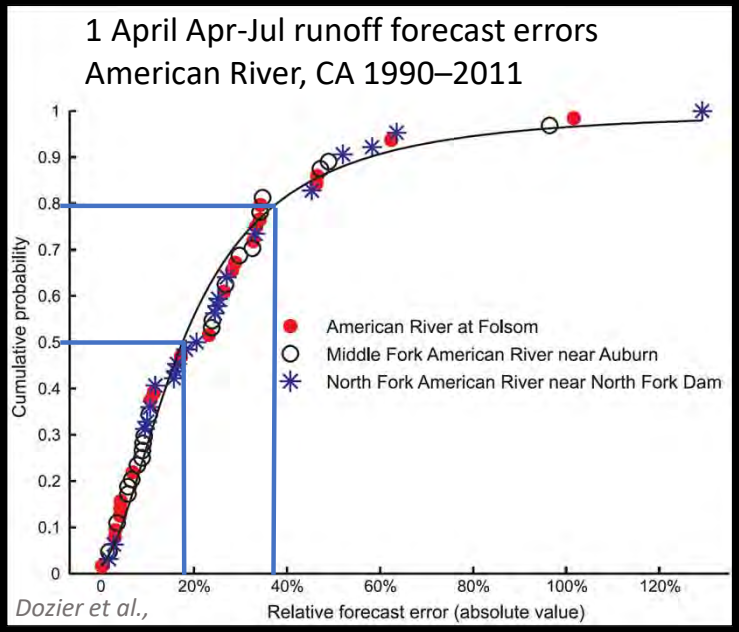
How do we get it right in each year?

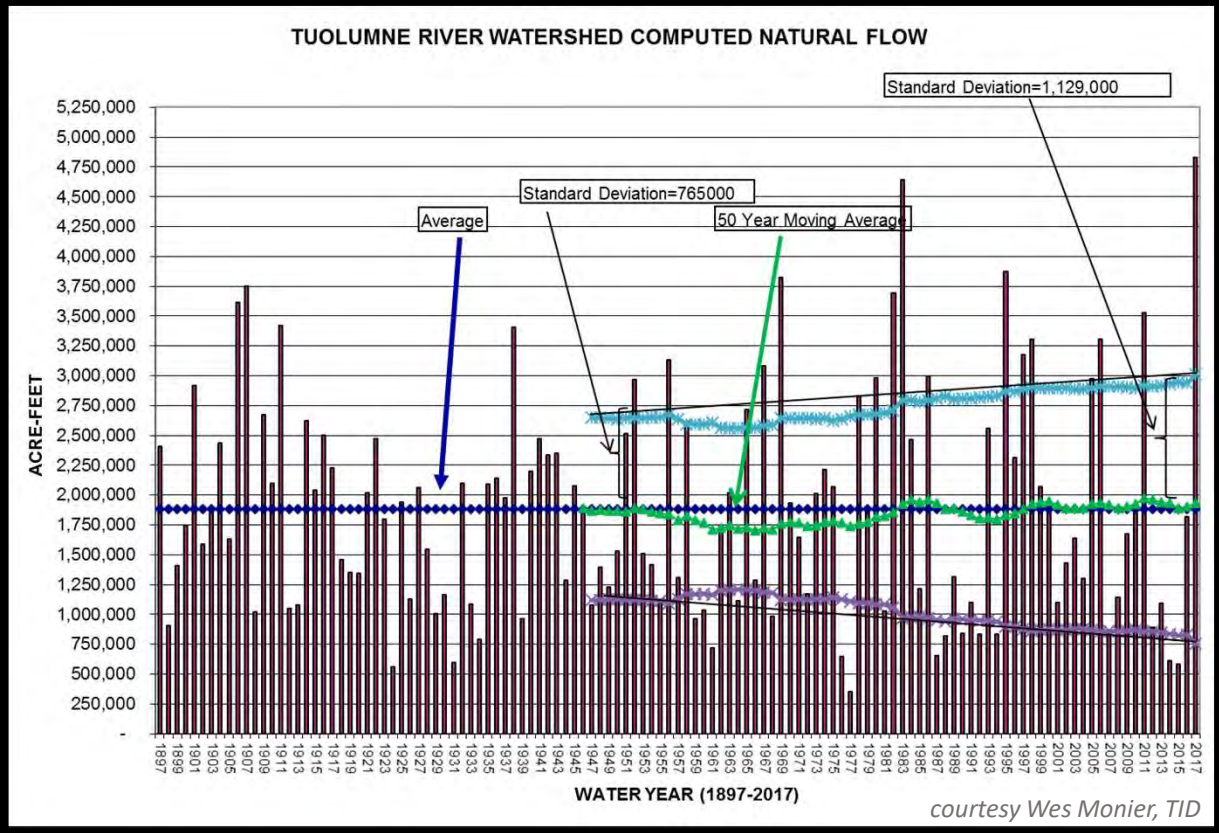
- Distributed models with accurate measurements for the critical components of the water cycle.
- That takes care of components that vary from year to year within a year.
- In snow-dominated systems, accurately measuring the snowpack is the first and arguably most important step in getting it right.

Runoff forecasts: vulnerable in current & future climate

Statistical & index runoff forecasts:

- do not consistently meet accuracy needs
- decreasing reliability in a changing climate

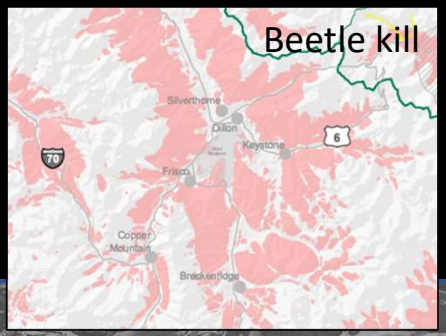




Mote et al. 2018

History is an increasingly poor guide to the present

- forecasts based on historic data assume that calibrations apply to current conditions
- forecast uncertainty demands a wide margin
- accurate & complete SWE mapping is a foundation for reduced forecast uncertainty



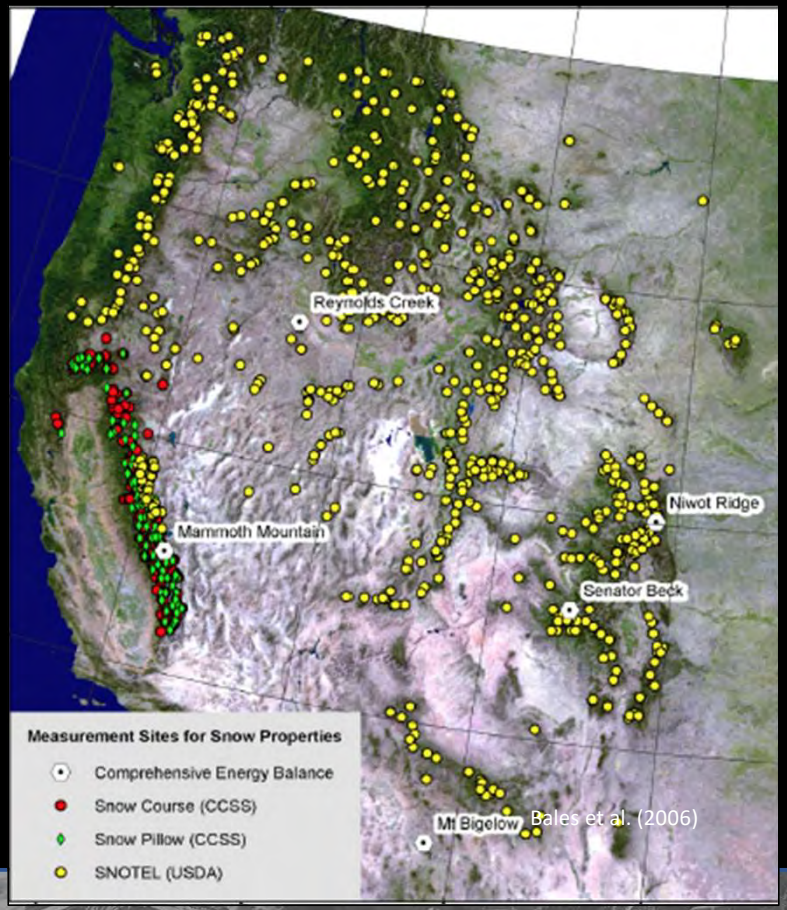
Airborne Sno

	April Forecast	Obs Inflow	% Difference
1999	120		
2000	155		
2001	150		
2002	59		
2003	170		
2004	100		
2005	125		
2006	210		
2007	150		
2008	200		
2009	180		
2010	120		
2011	225		
2012	100		
2013	100		
2014	250		
2015	166		
2016	167		
2017	195		
2018	137		

Forecast > 10% Low | Forecast > 10% High

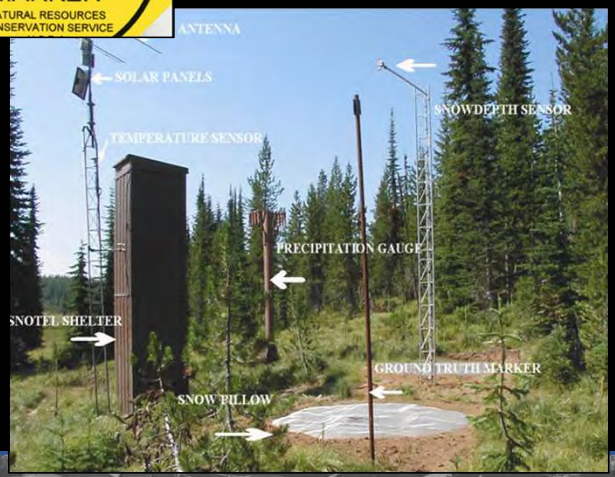
courtesy Nathan Elder, Denver Water

Western US operational snow monitoring



Bales et al. (2006)

Snow Water Equivalent (SWE) measured at manual snow courses & automatic snow pillows



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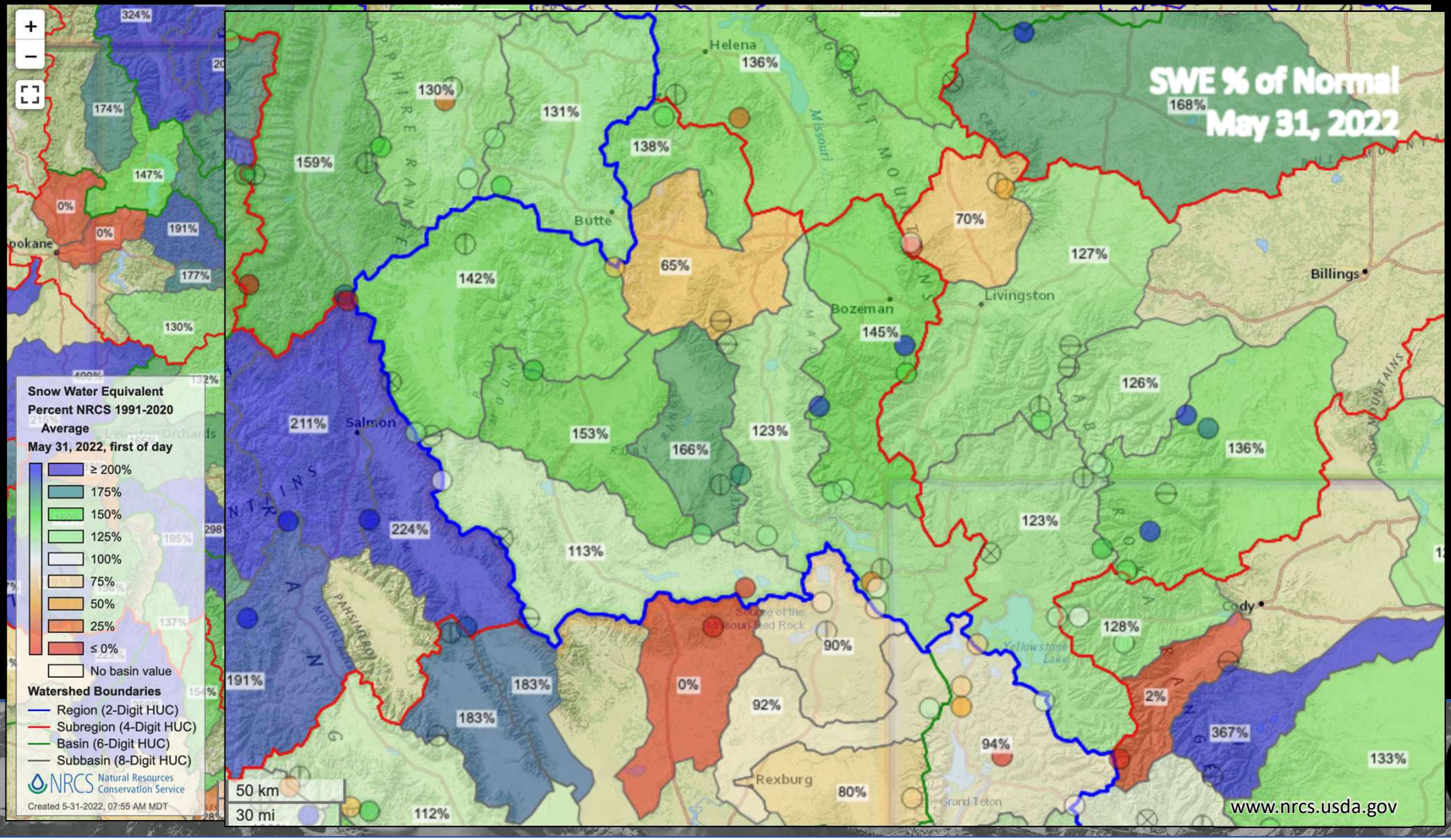
Basin snowpack status based on station data



Basin snowpack indexed using station data

Elk Range
ASO Snow Depth
April 2019

Snow Depth (m)
0 5+

Airborne Snow Observatories, Inc.

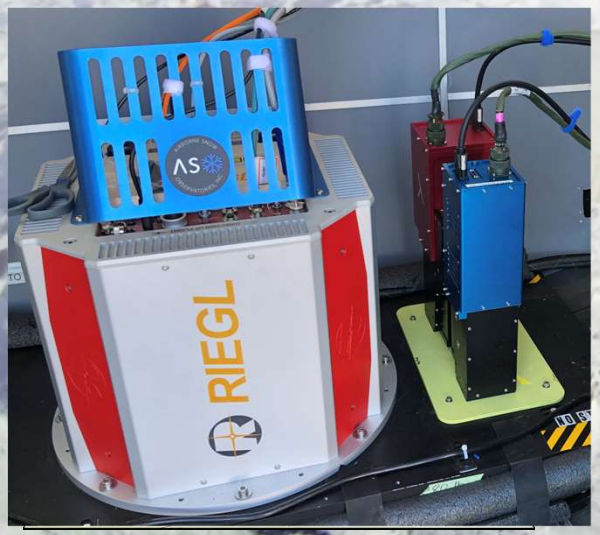
mapping the two most critical snow properties to forecast runoff volume & timing

Snow Water Equivalent

Snow depth from lidar elevation
SWE from coupling with obs & modeled density

Snow Albedo

HySpex VSWIR spectrometers
Albedo & surface properties



Physical Modeling

Coupled lidar & spectrometer
Physical snowpack & runoff modeling

Operations

Unique high-altitude operations
Unique rapid product turnaround

NASA JPL

Airborne Snow Observatories, Inc.

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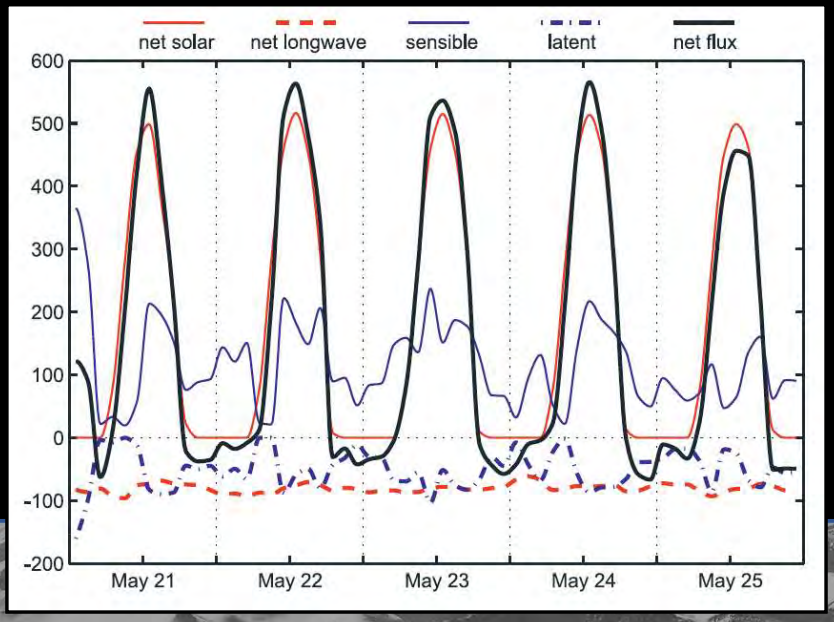
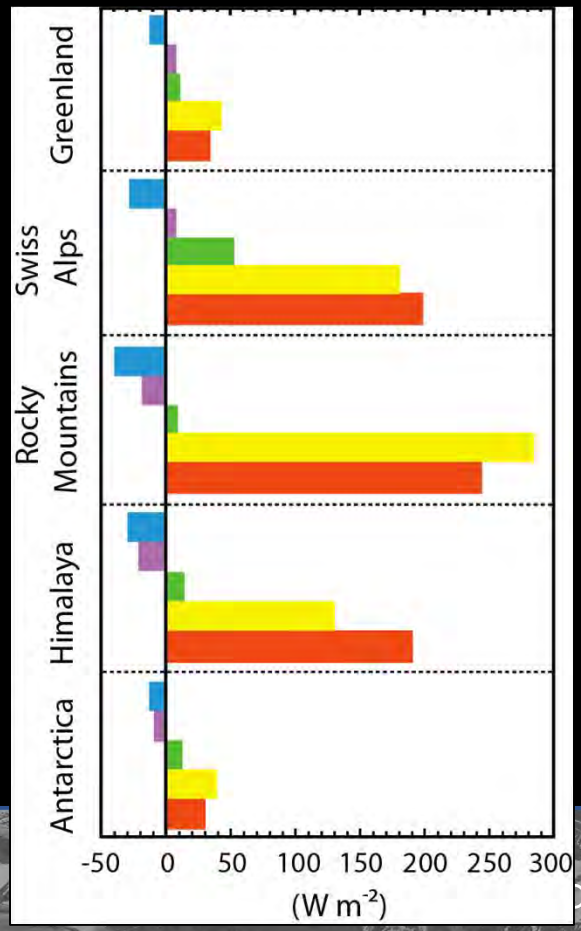
Snow energy balance – net SW dominates

Net Flux | Net Solar | Net Longwave | Sensible Heat | Latent Heat

$$\frac{dU}{dt} + Q_m = (1-\alpha)S + L^* + Q_s + Q_v + Q_g$$

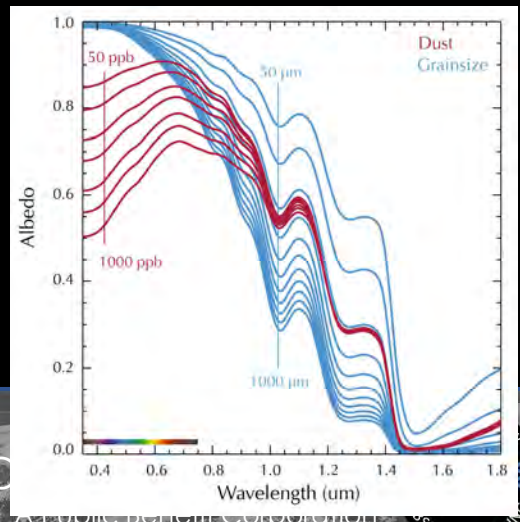


San Juan Mountains, Colorado, 2005

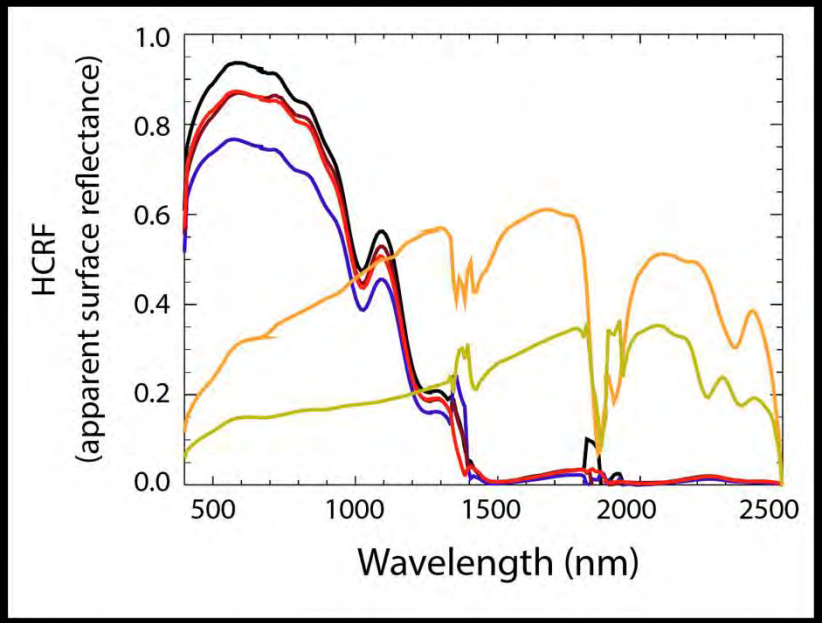


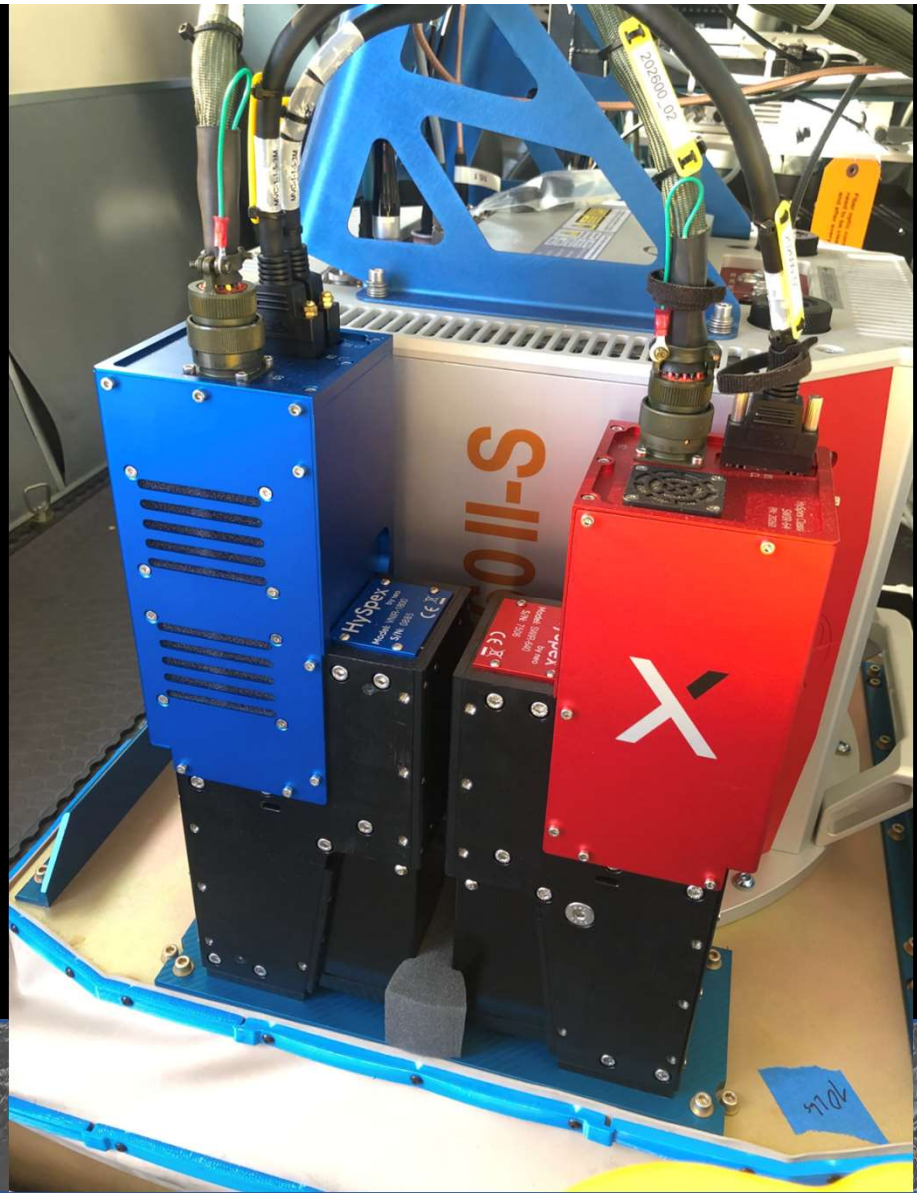
Hence, snow albedo is the dominant snow property in controlling melt. Itself controlled by grain size and LAP

$$\alpha_t = f(GS_t, RF_t, \vartheta_0, E_\lambda)$$



Imaging spectrometers

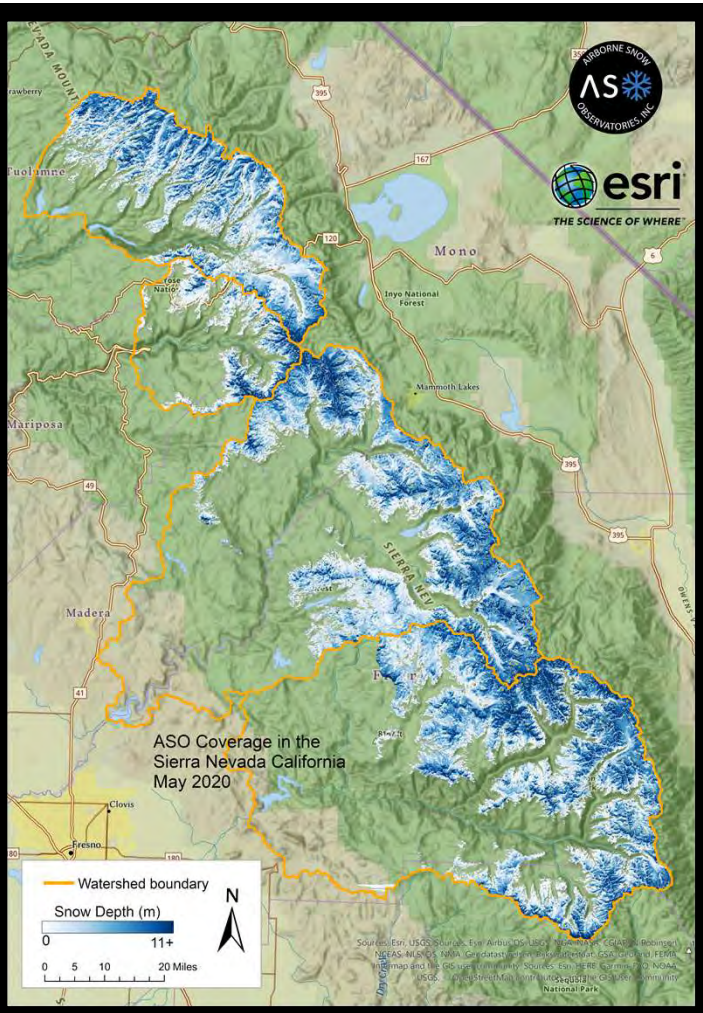




Accuracy is paramount

- To-date, SWE indices & maps have depended on station extrapolation & assumed terrain patterns
- Runoff forecasting literature contains many uncertain relationships between snow **point** measurements & 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)
- Consistent & reliable accuracy provides a strong foundation for robust decision-making



ASO Program Evolution from NASA

Research

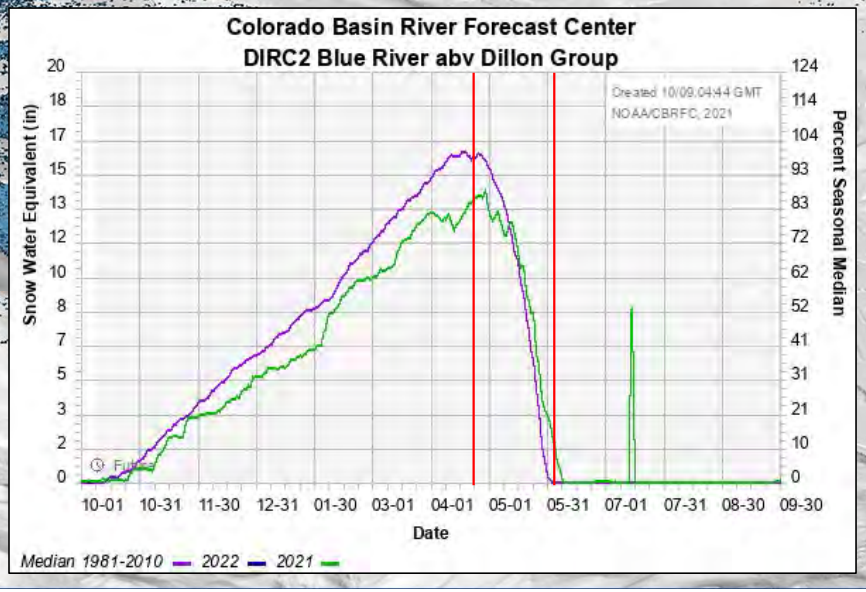
2012 – First flights – partnership with NEON
2013 – First snow flights – NASA HQ support
2013 – JPL Riegl & itres CASI instrument purchases
2013 – Funding support from State of CA
2015 – Funding support from State of CO
2015 – NSIDC begins data archive & distribution
2016 – WSL/SLF Switzerland demo project
2016 – Science support from DoE, USFS
2017 – Southern Sierra Nevada extension

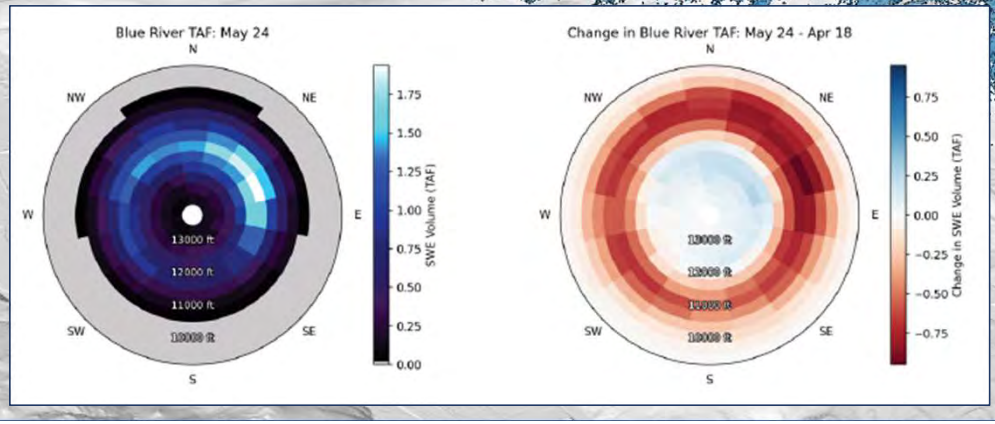
Operations

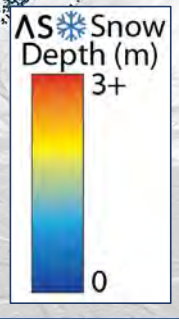
2019 – Transition to Airborne Snow Observatories, Inc., Public Benefit Corp
2019 – Strategic Partnership with M3W
2020 – Strategic Partnership with Esri
2020 – First season as ASO Inc.
2020 – Strategic Partnership with NCAR on WRF-Hydro
2020 – ASO-specific Federal and State (CA) Legislation
2022 – Grew to multiple ASOs
2022 – Added VSWIR imaging spectrometers
2022 – International implementation
2023 – Marked expansion in CA and CO

Blue River 2021

May 24

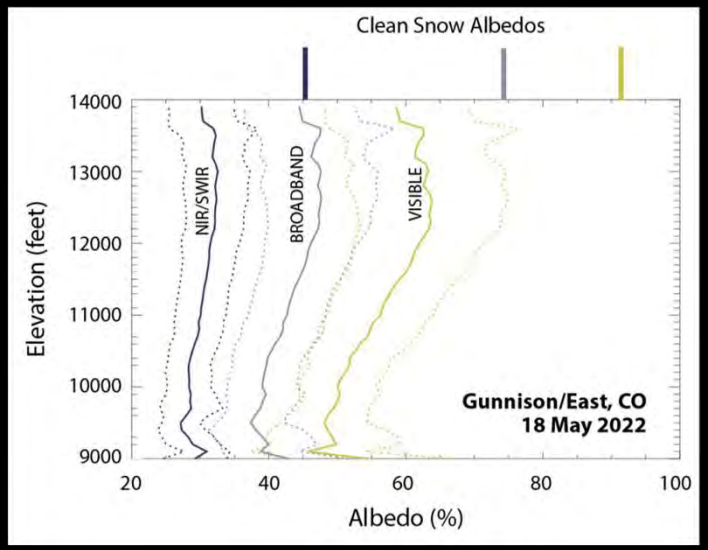


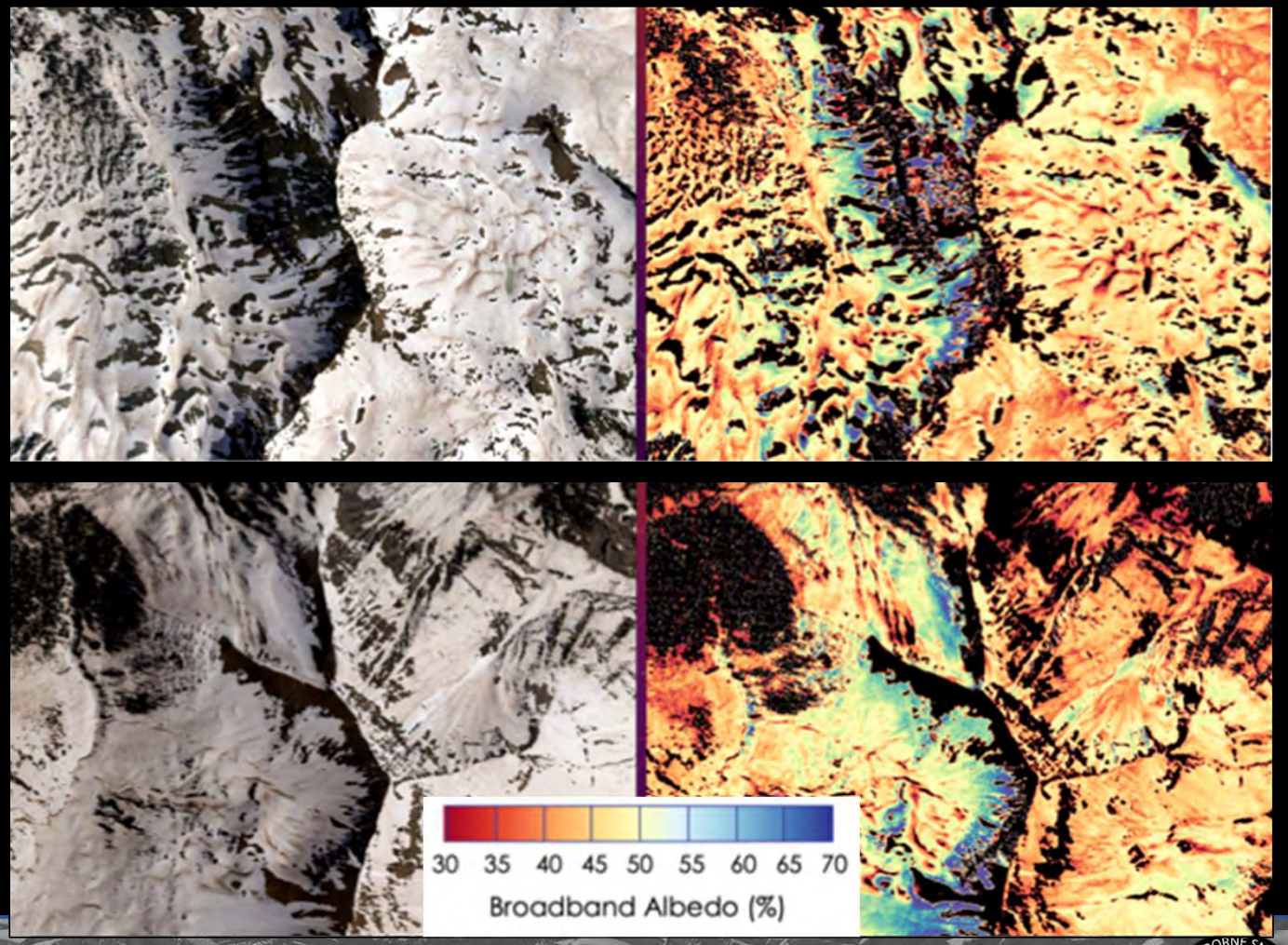




Snow Albedo

East River
May 18, 2022





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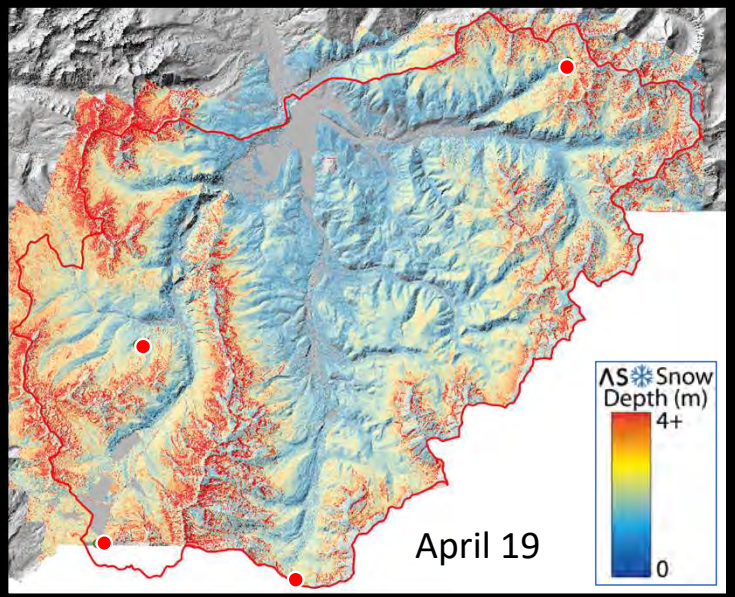
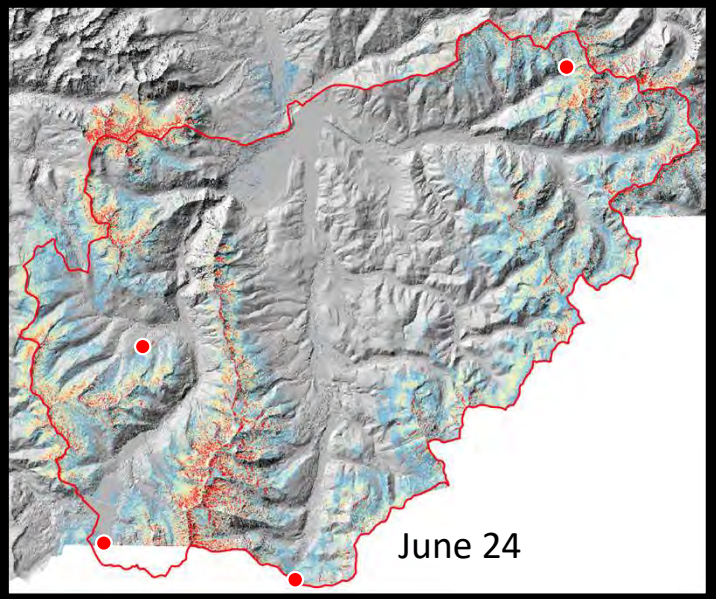
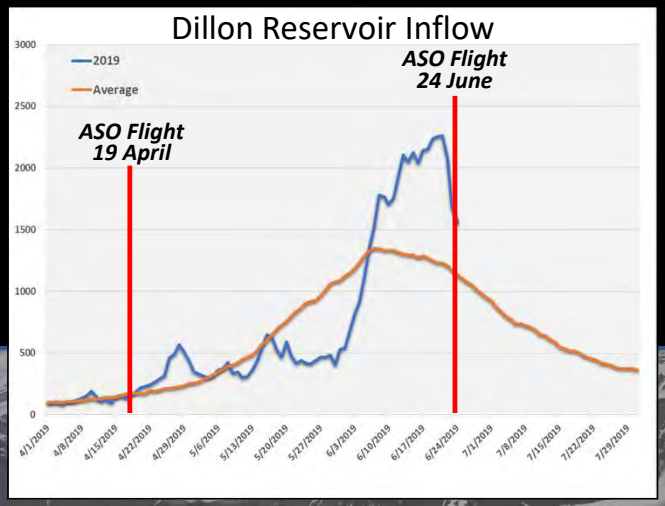
Operational guidance: Peak flow capture

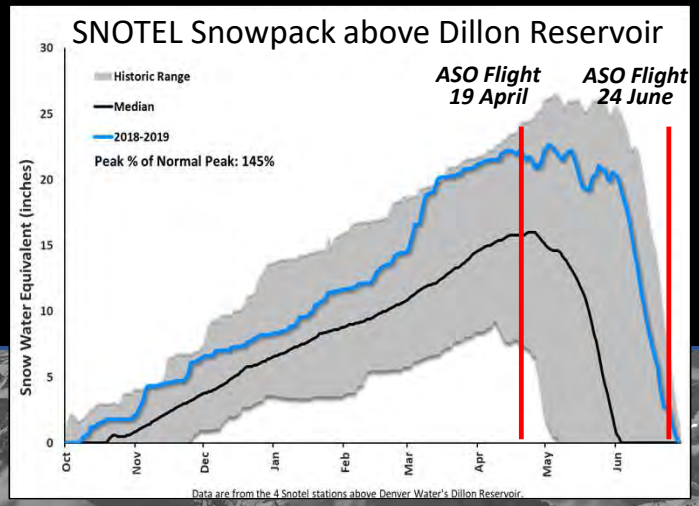
Blue River - Denver Water

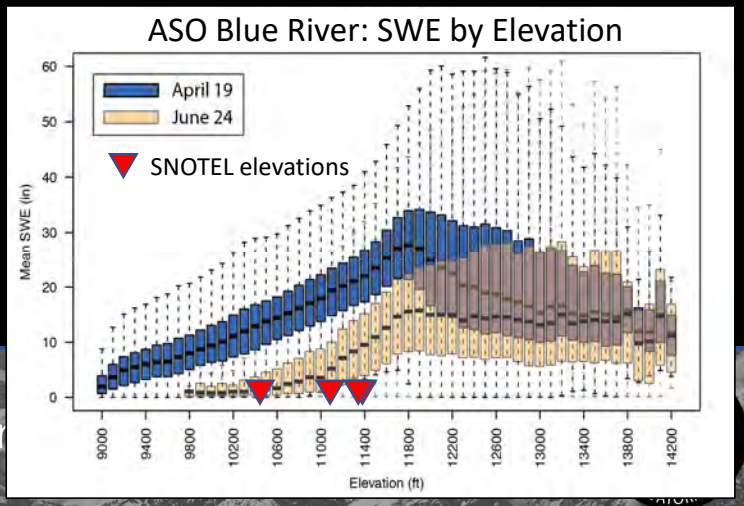
- 2019 Flights: April 19 & June 24
- May + June storms maintained high-elevation snowpack
- SNOTELs snow-free on June 28
- June 24 flight SWE volume: *115 TAF*
  - half of total inflow left to melt
  - enabled response to double flow peak







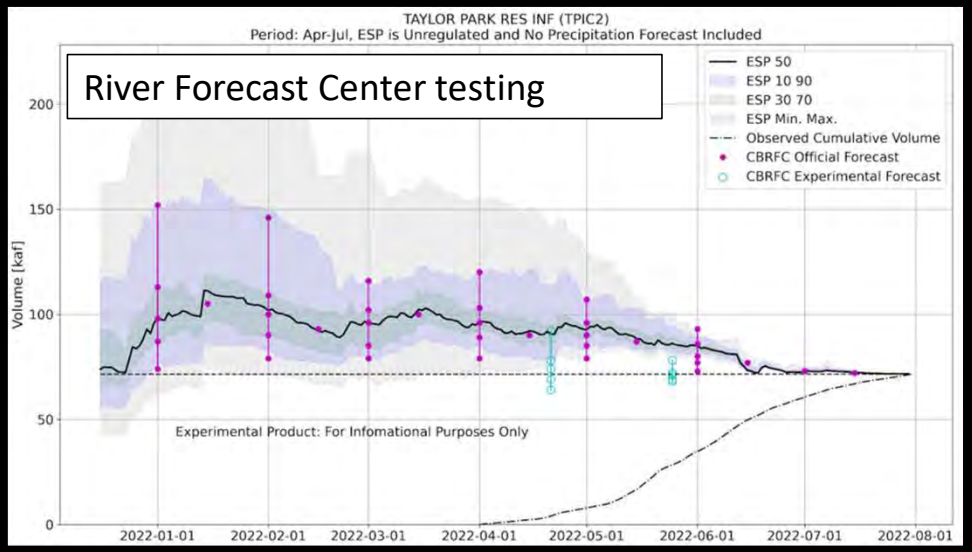


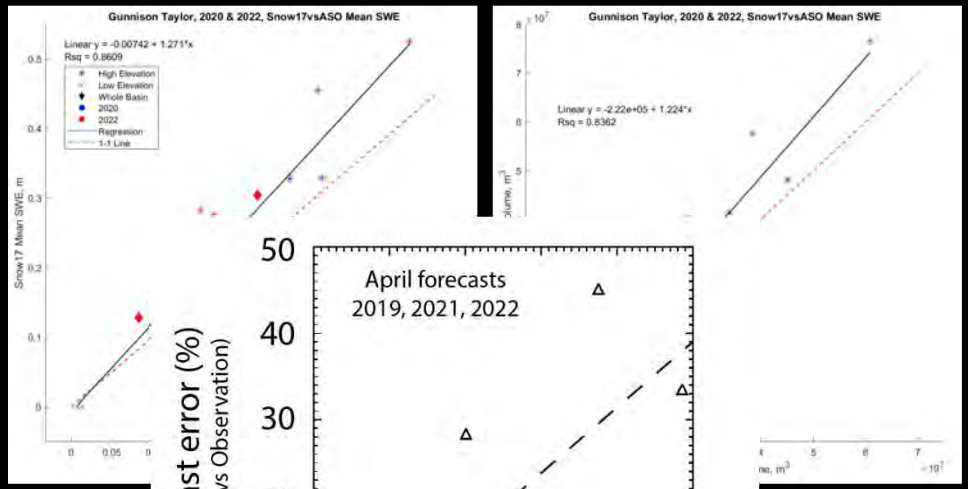


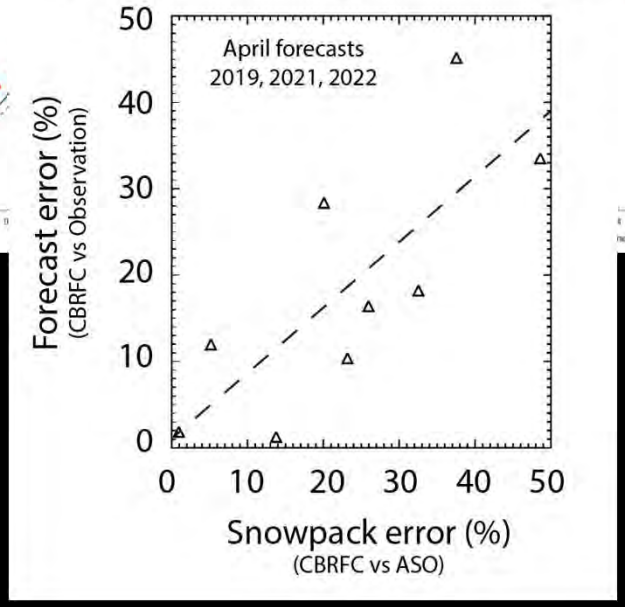
Expanding applications: *operational models*

NOAA River Forecast Center testing/evaluation

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



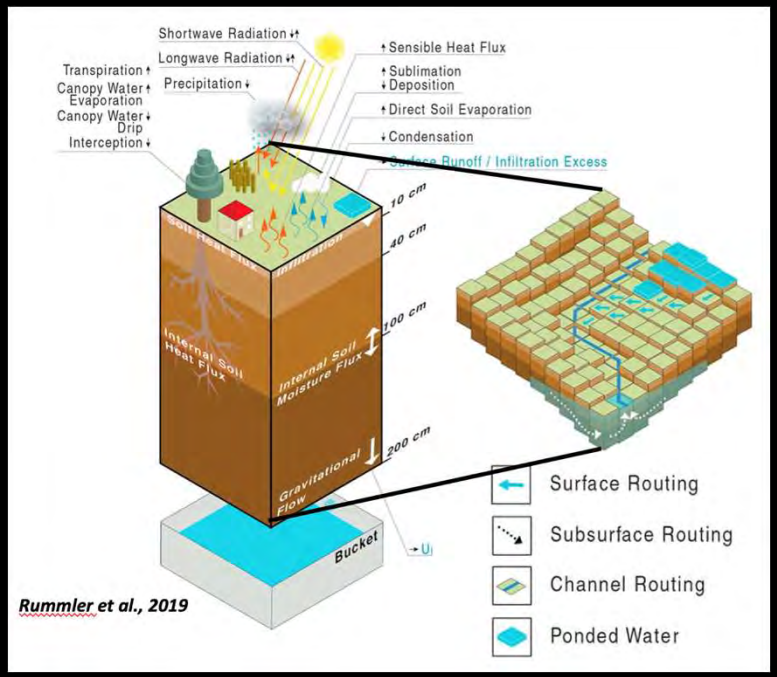




Courtesy Patrick Kormos, CBRFC

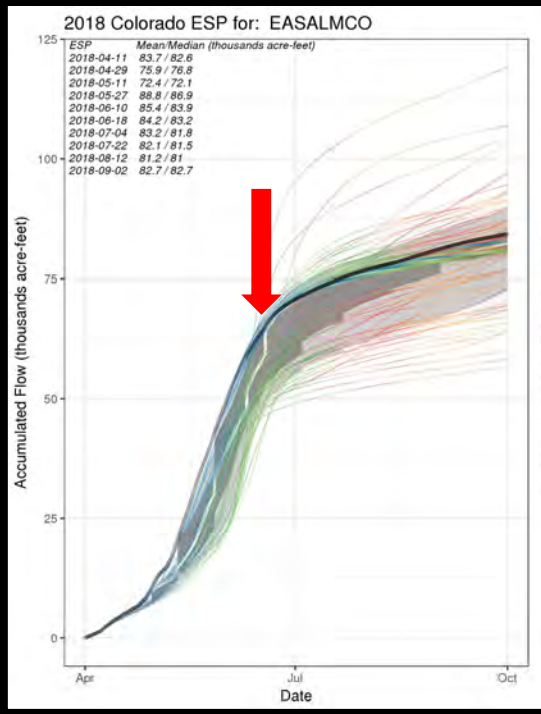
Expanding applications: *operational models*

WRF-Hydro applications data assimilation

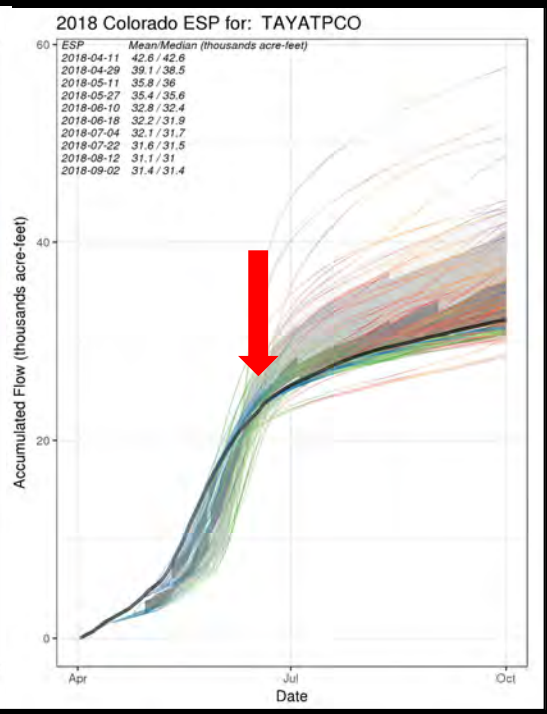


- High elevation snow data from 24 May ASO assimilation reduces low forecast bias in ESP AJRO forecast

East River @ Almont



Taylor River @ Taylor Park

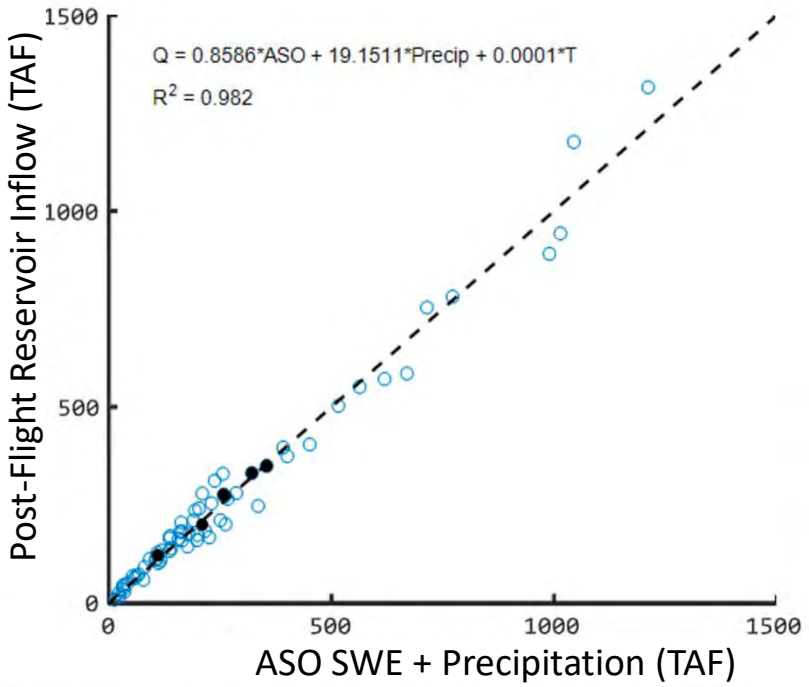


courtesy Dave Gochis, NCAR

Operational guidance: reservoir operations

- ASO data provides high confidence in total seasonal runoff
- Supports multi-objective reservoir operations
- Accuracy persists across years from very dry to very wet

WY 2022 Snowpack and ASO SWE

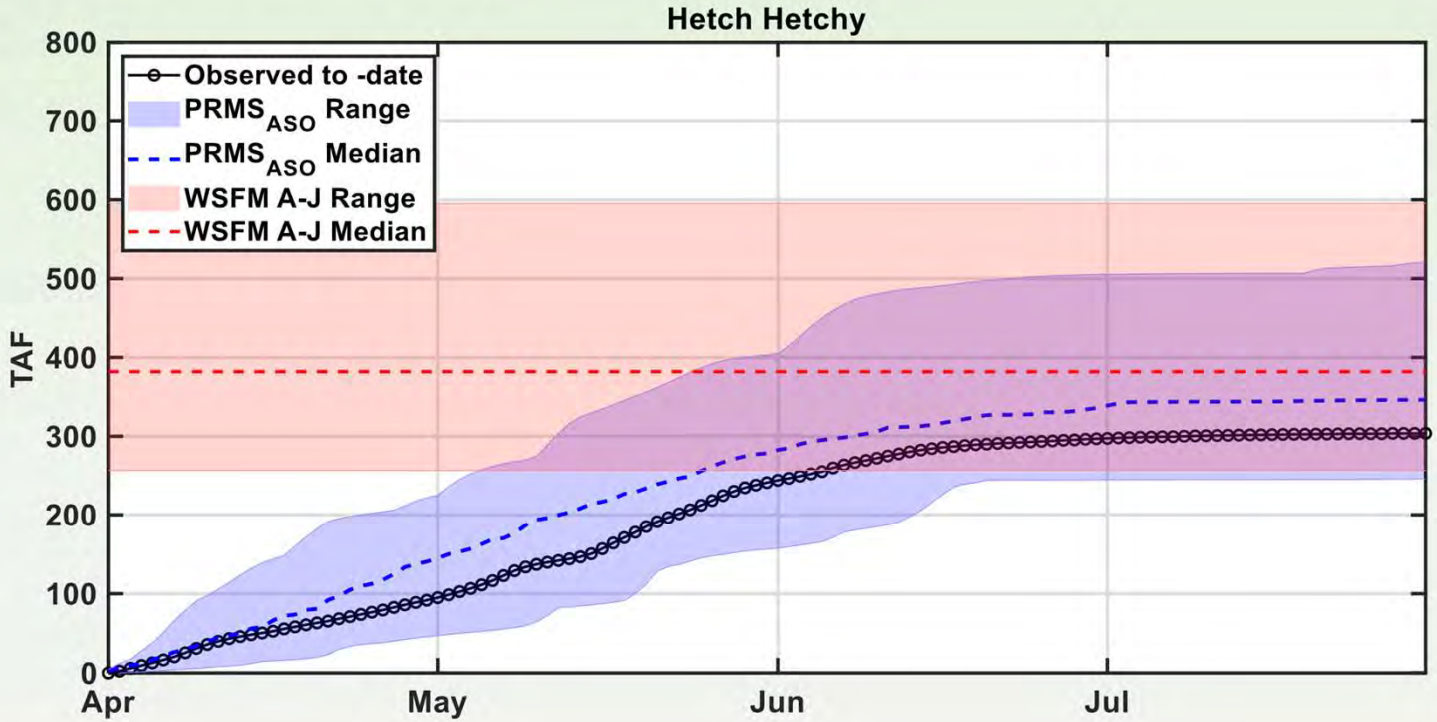


- ASO SWE estimates continue to demonstrate reliable empirical fit to observed runoff at Hetch Hetchy Reservoir
- Tuolumne Meadows precipitation used

courtesy Hetch Hetchy Water & Power

Runoff Forecast Performance at Hetch Hetchy Reservoir

April 1 PRMS_aso forecast provided confidence in lower bounds of statistical Apr-Jul runoff forecast at Hetch Hetchy.



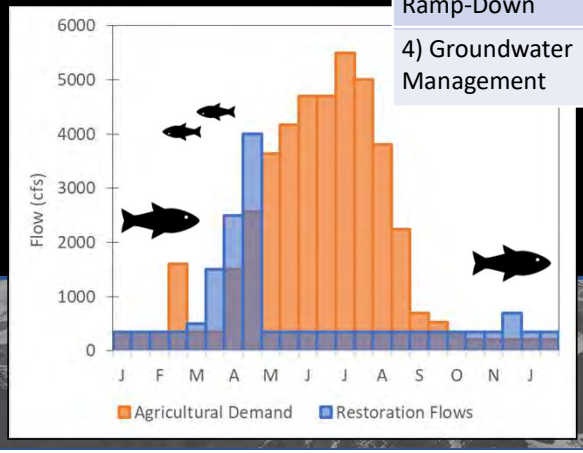
slide courtesy Harrison Forrester, HHW&P

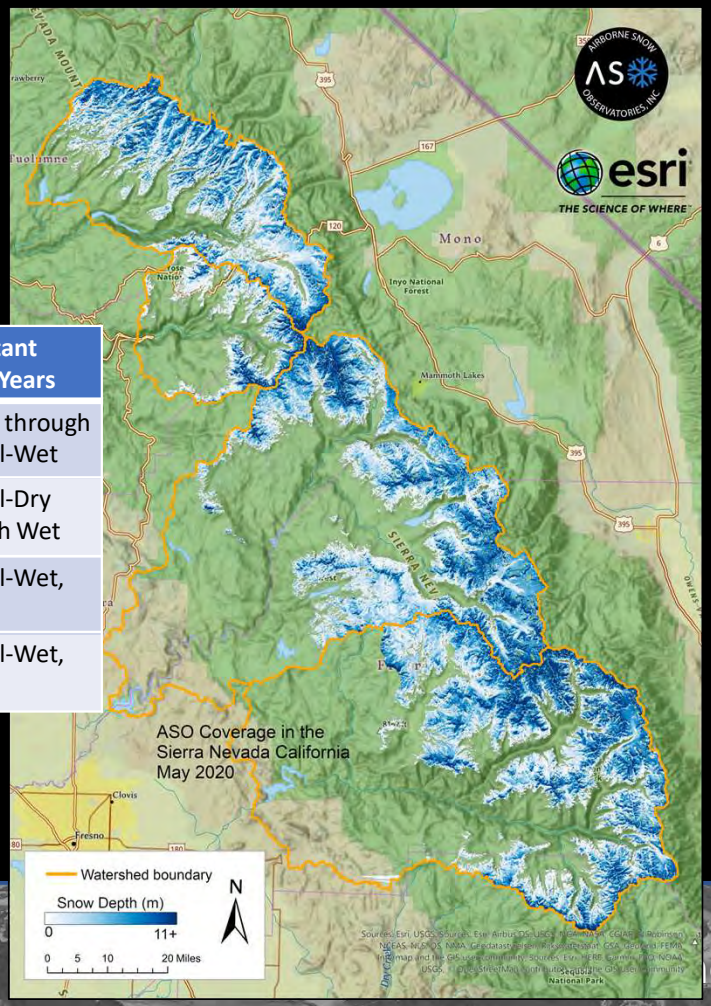
Operational guidance: restoration & flood management

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

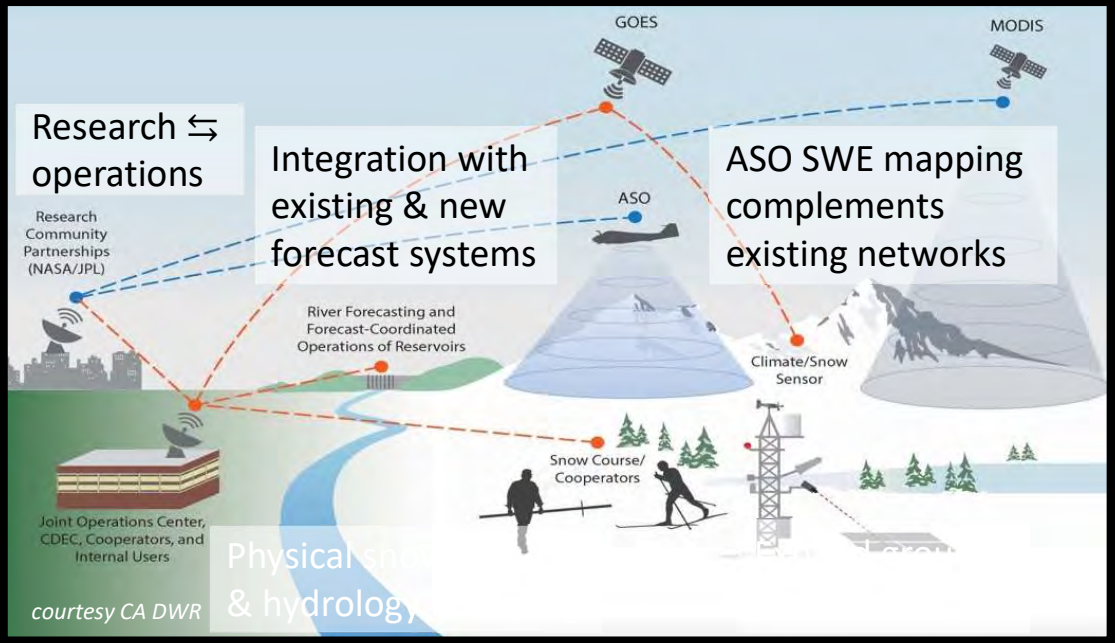
Forecasts	Apr-Jul Runoff Forecast Exceedance		
	10%	50%	90%
CA DWR	2.1 MAF	1.8 MAF	1.6 MAF
NOAA RFC	2.3 MAF	2.1 MAF	1.9 MAF
ASO		2.5 MAF	

- *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

Enabling a resilient & responsive water management paradigm

An integrated monitoring & forecasting system



ASO is the cornerstone of this vision

Integration with Seasonal-to-Subseasonal Program (S2S)

Integration with Forecast-Informed Reservoir Operations (FIRO)

Integration with Sustainable Groundwater Management Act (SGMA)

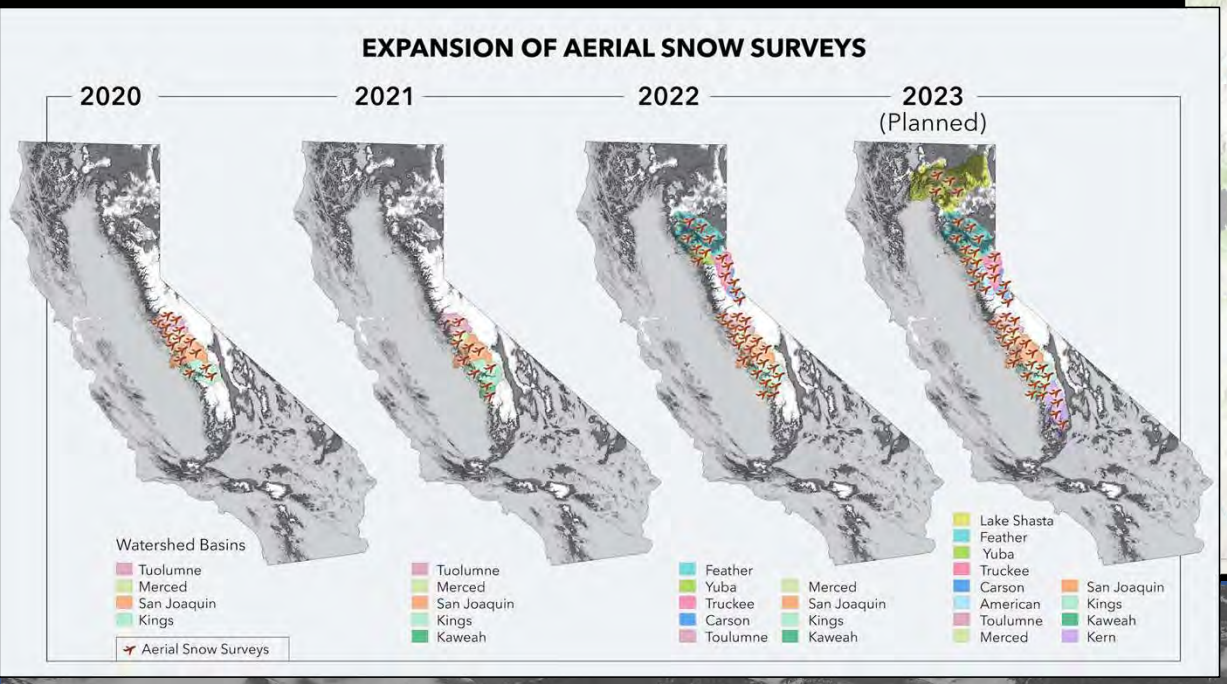
California Cooperative Snow Survey members estimated value of ASO forecast improvements (2018)

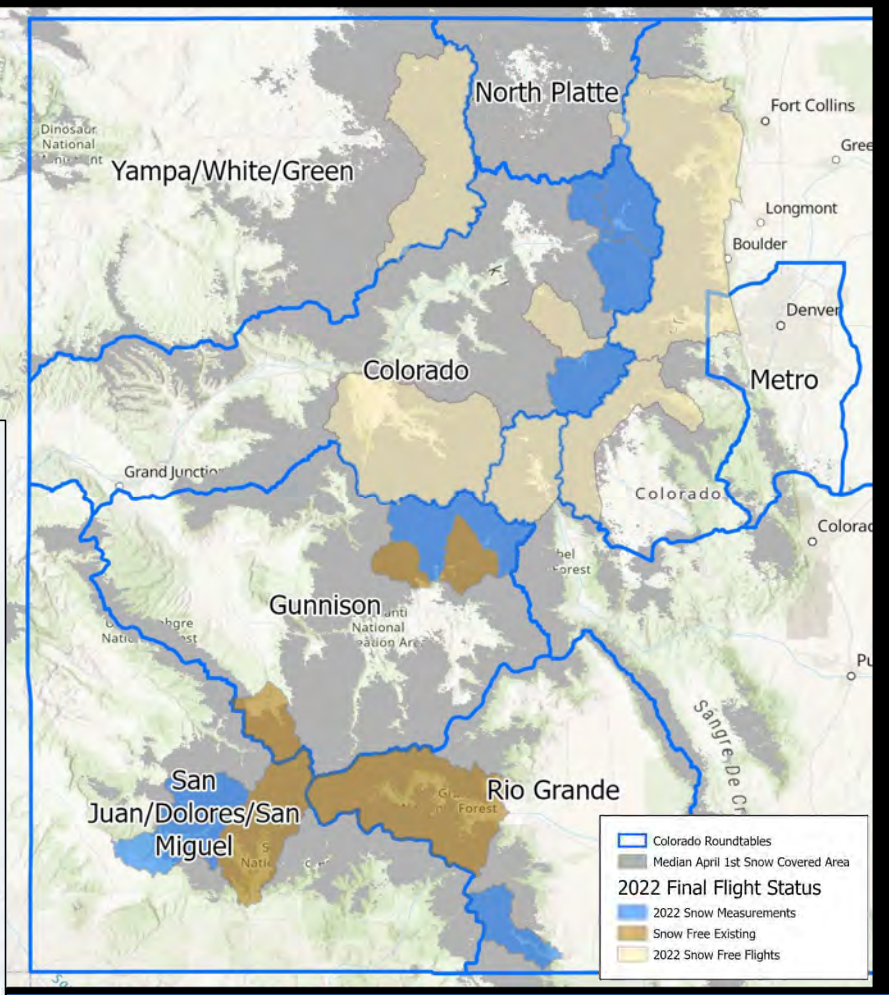
> **40:1** Return on Investment annually for water supply only or ($600M)

> **80:1** Annual ROI for supply, hydro, recharge, ecosystem, operational flexibility ($1.25B)

ASO Program expansion

- CA: base funding for sustained full-state program
- CO: stakeholder-led expansion & development
  - CASM: **coloradosnow.org**
- US Federal program support & grants
- International: programs in Alps & Norway





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Reclamation Program for Snow Measurement to Improve Runoff Forecasting

Congressional Record

By Mrs. FEINSTEIN (for herself and Ms. HARRIS):

S. 4530. A bill to establish a Snow Water Supply Forecasting Program within the Department of the Interior, and for other purposes; to the Committee on Energy and Natural Resources.

Mrs. FEINSTEIN. Mr. President, I rise to speak in support of the Snow Water Supply Forecasting Program Authorization Act, which I introduced today with Senator HARRIS. Representatives JOSH HARDER, JOHN GARAMENDI, JERRY MCNERNEY, GRACE NAPOLITANO, T.J. COX, and AMI BERA—all Democrats from California—and DIANA DEGETTE and JOE NEGUSE—both Democrats from Colorado—have introduced identical companion legislation in the House.

Airborne snow observatory, ASO, technology is a snow monitoring tool that provides precise measurement of depth and water content for every square meter of snow in a watershed. The technology measures snow depth and water content using an airplane-mounted light detection, LiDAR, instrument coupled with an imaging spectrometer.

When combined with conventional snow surveys, ASO provides a near-perfect picture of snow water content.

CONGRESS.GOV Advanced Searches | Browse

Legislation [2020-09-08 TO 2020-09-08] MORE OPTIONS

Home > Legislation > 116th Congress > S.4530

S.4530 - Snow Water Supply Forecasting Program Authorization Act

116th Congress (2019-2020)

BILL Hide Overview

Sponsor: Sen. Feinstein, Dianne [D-CA] (In

Committees: Senate - Energy and Natural Res

Latest Action: 08/13/2020 Read twice and refer on measure: CR S5410) (All Acti

Tracker: Introduced

— BUREAU OF — RECLAMATION

Emerging Technologies in Snow Monitoring

Report to Congress

U.S. Department of the Interior November 2021

— BUREAU OF — RECLAMATION

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Reclamation provides $2.5 million to improve snow water supply forecasting

Media Contact: Peter Soeth 303-445-3615 psoeth@usbr.gov

The new projects will:

- **Expand Airborne Snow Observatory (ASO) snow surveys in various regions.**
- **Develop an integrated remote-sensing and physical-modeling approach to deliver high-resolution, modeled SWE in near real-time.**
- Assess the use of new satellites to advance state-of-the-art snow and water-supply forecasting in river basins.

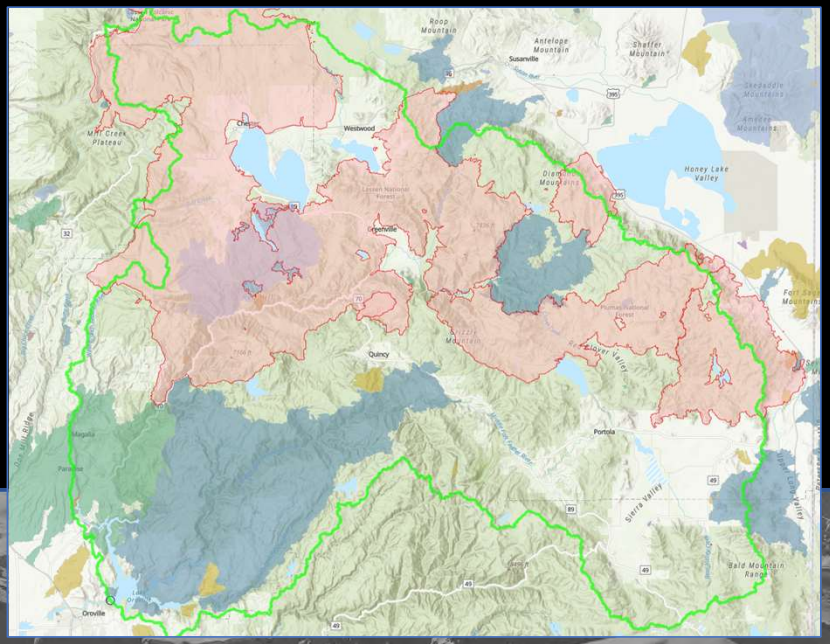
ASO supports post-wildfire forecasting & recovery

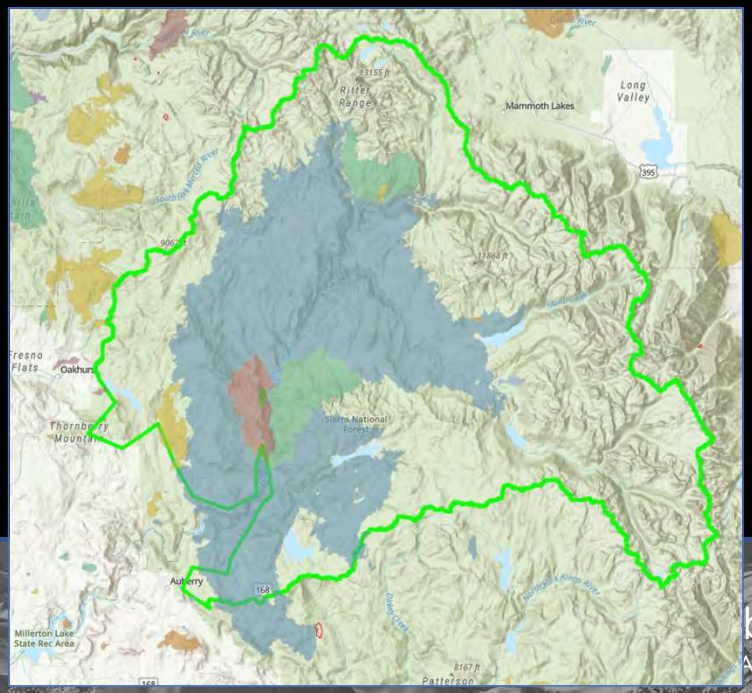
Forecast challenges due to divergence from historic conditions

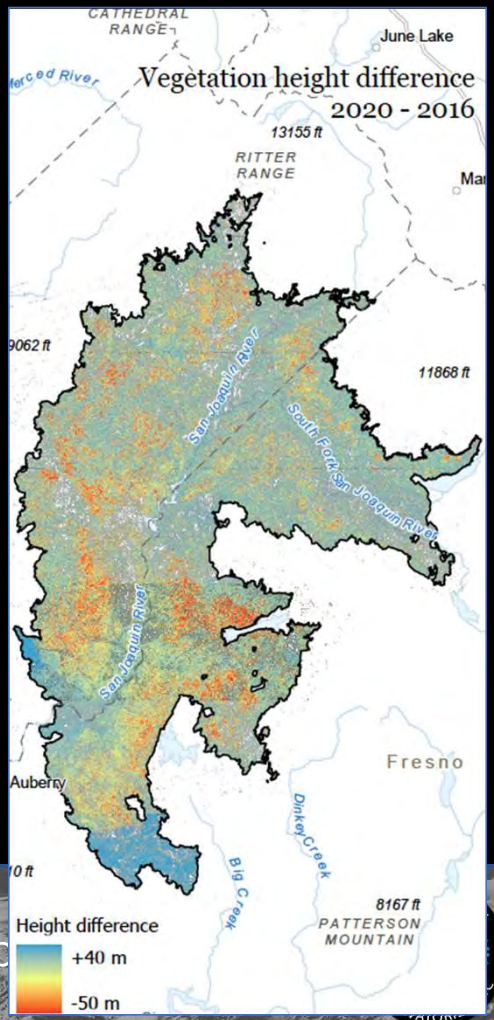
- major wildfires – change snow accumulation patterns & energy balance
- hydroclimate – changing seasonality, precipitation, & temperature

ASO data captures forest structure change & snow response

- lidar & spectrometer data quantify & document forest condition
- forecast model support







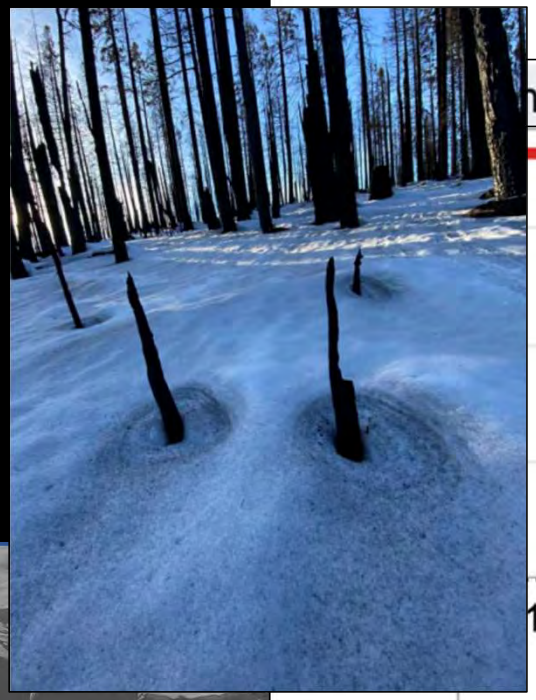
Adaptation in practice: Feather River, CA, 2022

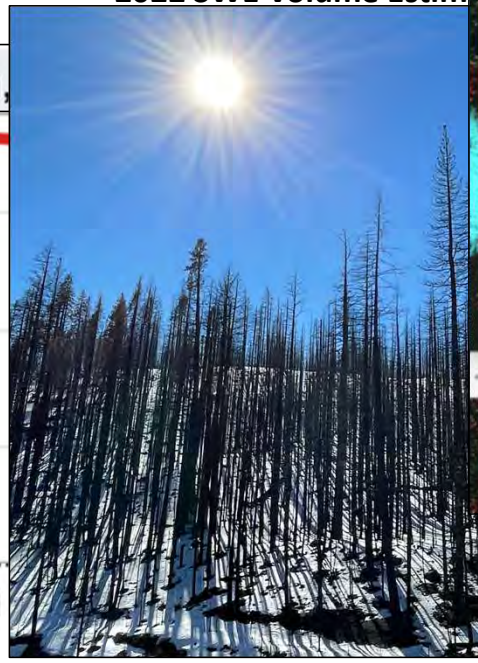
Early warning of low snowpack

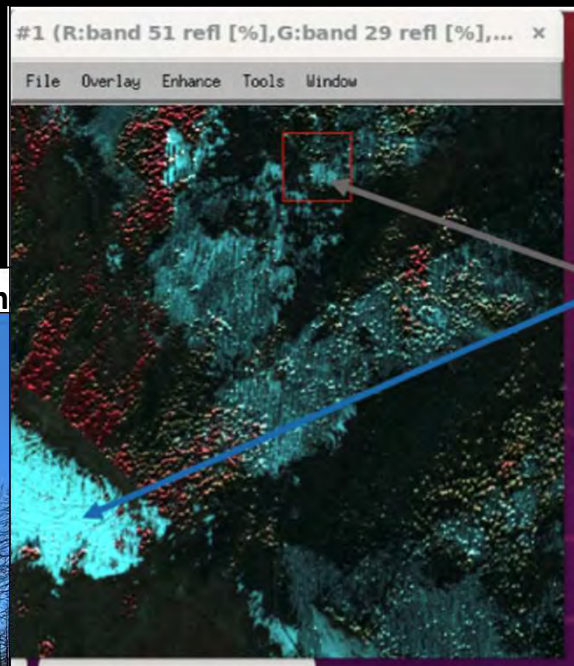
- snowpack peaked Jan 1st
- overestimated by conventional products

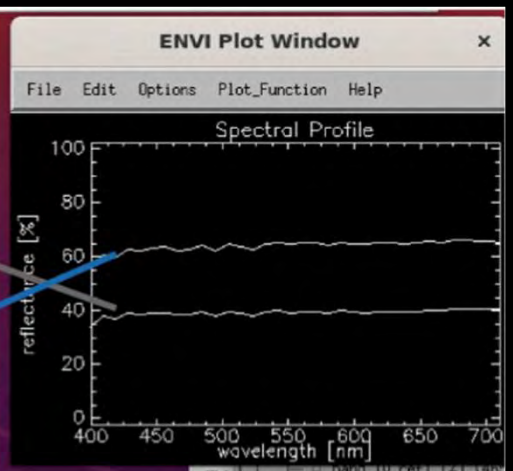
Wildfire impacts on hydrology

- >60% of basin burned in 4 years
- Large snow albedo reduction from soot









Clean snow

Soot-laden snow

50% increase in net solar radiation

2022 SWE Volume Estim

Water Year 2022

Take home messages

The mountain snowpack is the Upper Basin's Lake Mead.

We don't measure it.

… except where ASO is making a quantitative measurement

Covering the entire basin is critical for forecasting improvement and adaptive capacity

Airborne Snow Observatories, Inc.

A Public Benefit Corporation

Error budget for forecasting

$$\varepsilon(forecast) = \varepsilon(current\ mass) + \varepsilon(future\ precip) + \varepsilon(energy\ fluxes) + \varepsilon(soil\ moisture) + \varepsilon(meteorology)$$

Realizing value in accurate snowpack monitoring

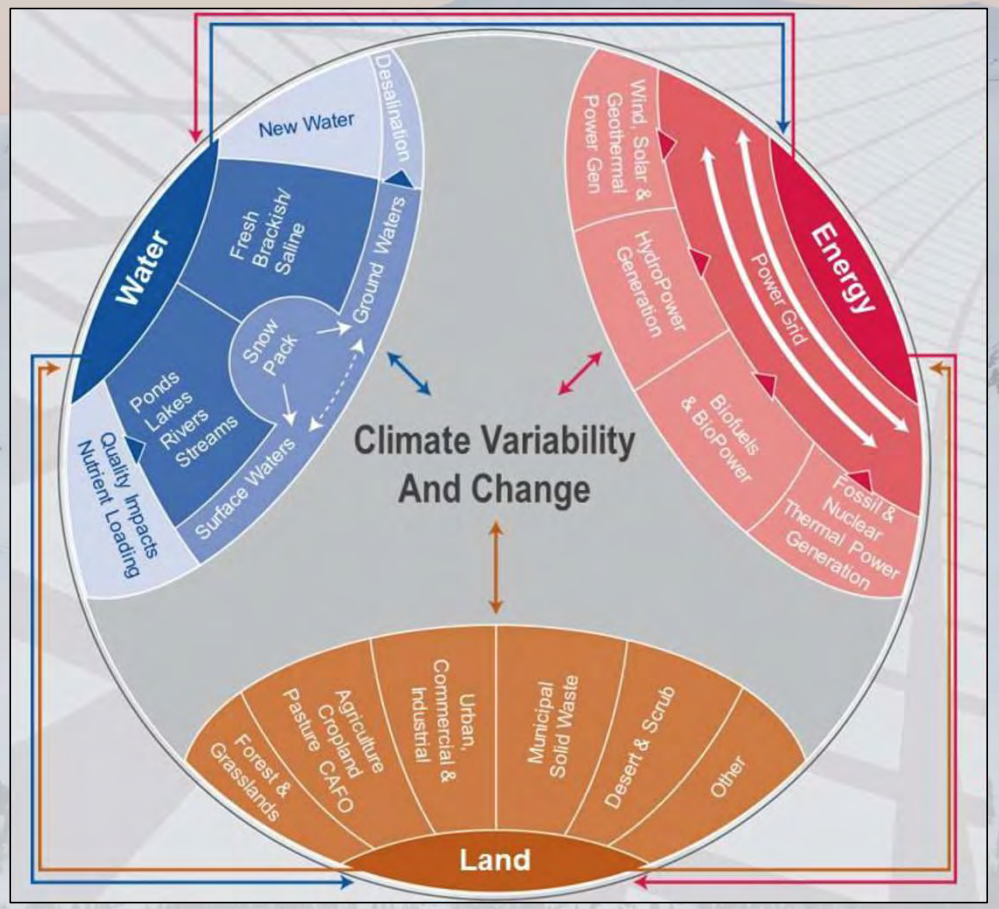
operational resilience & reliability:

- optimized & increased hydropower production
- ecologic flow reliability
- groundwater recharge

avoided costs:

- reducing/avoiding flood impacts
- unforeseen water leasing or use curtailment
- water temperature & quality impacts from low flows
- groundwater over-reliance/overdraft

NOT measuring the snowpack reservoir is expensive!



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