Using NASA-INSTAAR Satellite Data, with Statistical and AI-Based River Hydrology Models, to Improve Operational Western US Seasonal Water Supply Forecasts

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Inventing the future

"To improve assessments of snow accumulation, melt, and runoff, scientists and community planners can take advantage of two emerging trends: (1) an ability to remotely sense snow properties from satellites at a spatial scale appropriate for mountain regions (10- to 100-meter resolution, coverage of the order of 100,000 square kilometers) and a daily temporal scale appropriate for the dynamic nature of snow and (2) The Fourth Paradigm [Hey et al., 2009],which posits a new scientific approach in which insight is discovered through the manipulation of large data sets as the evolutionary step in scientific thinking beyond the first three paradigms: empiricism, analyses, and simulation."

- Jeff Dozier, 2011, 'Mountain hydrology, snow color, and the fourth paradigm,' Eos Transactions

Remotely sensed snow data + AI-driven hydrologic prediction models = Progress

Status?

- From 30,000 feet the view looks pretty good
- Down in the trenches, there are gaps:
  - In operational flood & water supply forecast systems at governmental service-delivery organizations (SDOs; Serafin et al.), remotely sensed snow data are mainly used for qualitative guidance, and hydrologic models don’t use AI
  - In both research and practice, very few examples of remotely sensed snow data driving AI-based streamflow models for seasonal water supply forecasting
- Here: in the context of the generations-old US West-wide NRCS operational water supply forecast system, test a new remotely sensed snow dataset as forcing to a new AI-driven hydrologic model

Water supply forecasts (WSFs) in the US West

Forecasts, issued once or more per month, beginning in winter, of upcoming spring-summer total flow volume for a given river, performed by SDOs having strict accountabilities to end users, including the general public, around reliable forecast product generation

- Examples: California DWR Bulletin 120, NOAA NWS RFC ESPs, NRCS regression models
- Foundational to western water management: crop selection, water rights rentals, hydropower optimization, legal/treaty obligations, etc.
- > $1T of water managed annually in the Colorado Basin alone
- Modest WSF accuracy gains worth > $100M/yr in hydropower generation in the Columbia Basin

Sprague River, Upper Klamath Basin (S.W. Fleming/US Department of Agriculture NRCS NWCC)

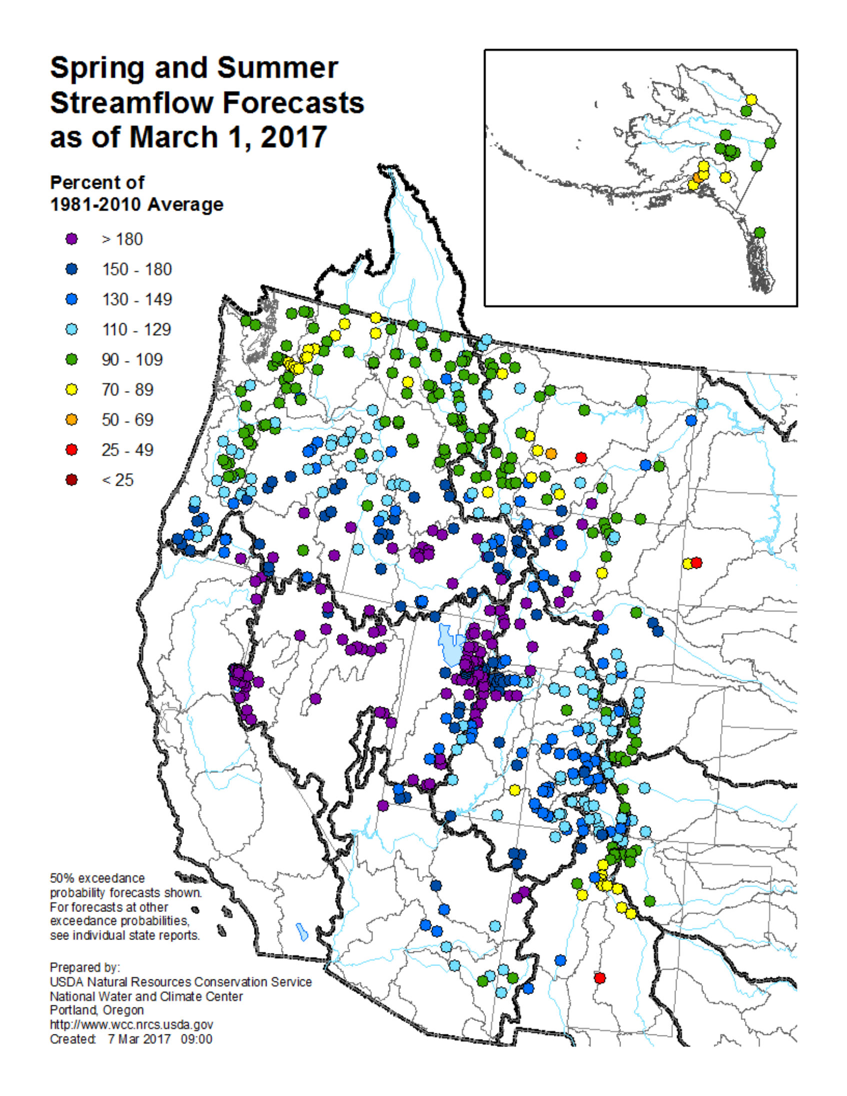
Role of seasonal snowpack

- How are months-ahead WSFs possible if weather is predictable only weeks ahead? Lags between meteorological forcing & hydrologic response
- Precipitation over much of the US West falls predominantly in winter & as snowfall: snowpack is a massive de facto reservoir producing runoff in spring & summer, when it’s most needed
- Snowpack data are a powerful (but not sole) predictor/boundary condition in watershed hydrology models used for WSF
- Classically, in situ data: manual snow surveys, telemetered snow pillows (e.g., SNOTEL)

www.nrcs.usda.gov/wps/portal/nrcs/detail/id/newsroom/releases/?cid=NRCS144P2_048215

NRCS Snow Survey & Water Supply Forecast program

- USDA NRCS has measured snow & predicted water supply in the region since the 1930s
- Manual snow surveys + SNOTEL network
- Largest stand-alone operational WSF system in the US West
- Several statistical models & physics-oriented process models are used by NRCS
- Core method: principal component regression (PCR), a linear statistical model introduced to WSF by NRCS/David Garen in early 1990s
- Now transitioning to an AI-based approach (M^4)



US Department of Agriculture NRCS NWCC

M4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Assessing the new Natural Resources Conservation Service water supply forecast model for the American West: A challenging test of explainable, automated, ensemble artificial intelligence

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ABSTRACT

Western US water management is underpinned by spring-summer water supply forecasts (WSFs) from hydrologic models forced primarily by winter mountain snowpack data. The US Department of Agriculture Natural Resources Conservation Service (NRCS) operates the largest such system regionally. NRCS recently developed a next-generation WSF prototype, the multi-model machine-learning metasystem (M4). Here, we test this ensemble artificial intelligence (AI)-based prototype against challenging theoretical and practical criteria for accepting a ...

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Simplified Cross-Validation in Principal Component Regression ... Machine Learning for Water Supply Forecastin...

Sean W. Fleming, and David C. Garen

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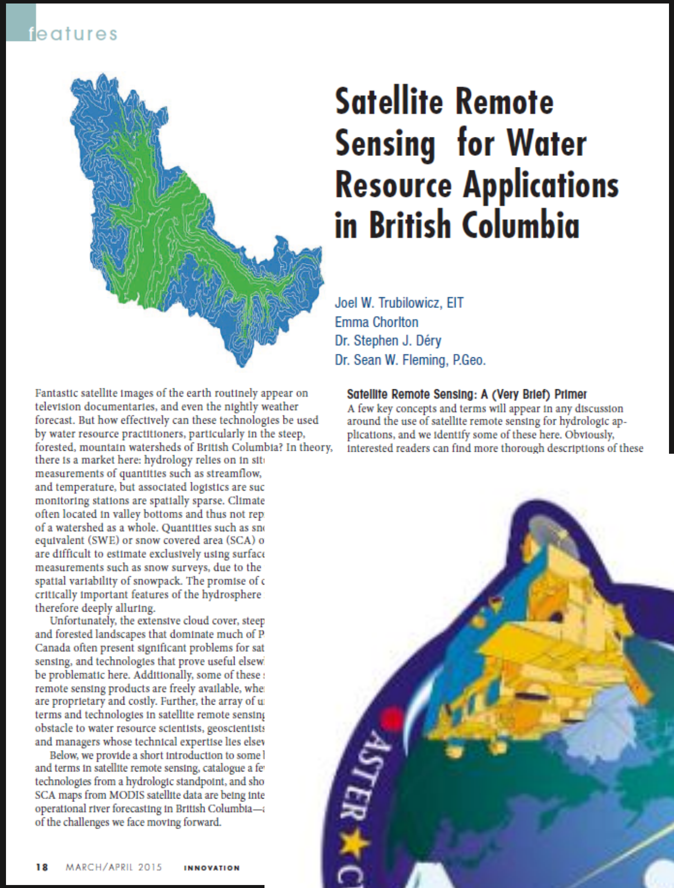
A Machine Learning Metasystem for Robust Probabilistic Nonlinear Regression-Based Forecasting of Seasonal Water Availability in the US West

SEAN W. FLEMING[1] AND ANGUS G. GOODBODY[2]

- New core WSF model at NRCS: Multi Model Machine-learning Metasystem (M^4)
- Built from scratch, in a user needs-driven framework, to meet key NRCS design criteria for an operational WSF model
- Metasystem of 6 data-driven forecast systems
- MAYA design philosophy: hot-rodded the old & trusted PCR system with glass-box AutoML, genetic algorithm feature optimization, multi-model ensembles, heteroscedatic & non-Gaussian prediction uncertainty estimates, etc.

MODIS-based snow data


features

Satellite Remote Sensing for Water Resource Applications in British Columbia

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Dr. Sean W. Fleming, P.Geo.

Fantastic satellite images of the earth routinely appear on television documentaries, and even the nightly weather forecast. But how effectively can these technologies be used by water resource practitioners, particularly in the steep, forested, mountain watersheds of British Columbia? In theory, there is a market here: hydrology relies on in sit[u] measurements of quantities such as streamflow, and temperature, but associated logistics are suc[h] monitoring stations are spatially sparse. Climate often located in valley bottoms and thus not rep[resentative] of a watershed as a whole. Quantities such as sn[ow water] equivalent (SWE) or snow covered area (SCA) o[r] are difficult to estimate exclusively using surfac[e] measurements such as snow surveys, due to the spatial variability of snowpack. The promise of critically important features of the hydrosphere therefore deeply alluring.

Unfortunately, the extensive cloud cover, steep and forested landscapes that dominate much of P[acific] Canada often present significant problems for sat[ellite remote] sensing, and technologies that prove useful elsew[here] be problematic here. Additionally, some of these remote sensing products are freely available, whe[reas others] are proprietary and costly. Further, the array of terms and technologies in satellite remote sensing obstacle to water resource scientists, geoscientists and managers whose technical expertise lies elsew[here].

Below, we provide a short introduction to some and terms in satellite remote sensing, catalogue a fe[w] technologies from a hydrologic standpoint, and sho[w] SCA maps from MODIS satellite data are being inte[grated] operational river forecasting in British Columbia—a[nd] of the challenges we face moving forward.

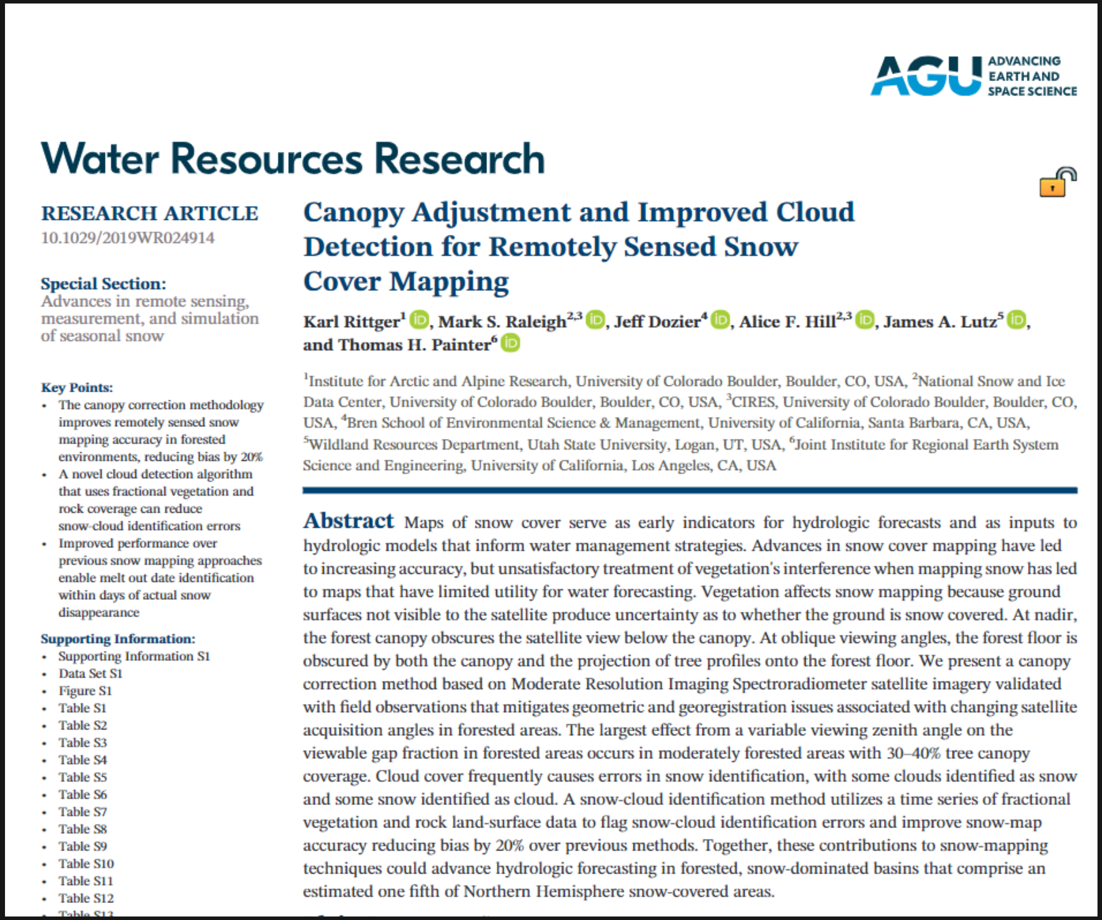
Satellite Remote Sensing: A (Very Brief) Primer

A few key concepts and terms will appear in any discussion around the use of satellite remote sensing for hydrologic applications, and we identify some of these here. Obviously, interested readers can find more thorough descriptions of these

18 MARCH/APRIL 2015 INNOVATION

- MODerate resolution Imaging Spectroradiometer (MODIS) instrument aboard NASA's Aqua and Terra satellites
- Provides basis for measuring fractional snow-covered area (fSCA) from space
- Long history of use in river forecasting research & operations, domestically & internationally

STC-MODSCAG fSCA



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Water Resources Research

RESEARCH ARTICLE
10.1029/2019WR024914

Special Section:
Advances in remote sensing, measurement, and simulation of seasonal snow

Key Points:
- The canopy correction methodology improves remotely sensed snow mapping accuracy in forested environments, reducing bias by 20%
- A novel cloud detection algorithm that uses fractional vegetation and rock coverage can reduce snow-cloud identification errors
- Improved performance over previous snow mapping approaches enable melt out date identification within days of actual snow disappearance

Supporting Information:
- Supporting Information S1
- Data Set S1
- Figure S1
- Table S1
- Table S2
- Table S3
- Table S4
- Table S5
- Table S6
- Table S7
- Table S8
- Table S9
- Table S10
- Table S11
- Table S12

Canopy Adjustment and Improved Cloud Detection for Remotely Sensed Snow Cover Mapping

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Abstract Maps of snow cover serve as early indicators for hydrologic forecasts and as inputs to hydrologic models that inform water management strategies. Advances in snow cover mapping have led to increasing accuracy, but unsatisfactory treatment of vegetation's interference when mapping snow has led to maps that have limited utility for water forecasting. Vegetation affects snow mapping because ground surfaces not visible to the satellite produce uncertainty as to whether the ground is snow covered. At nadir, the forest canopy obscures the satellite view below the canopy. At oblique viewing angles, the forest floor is obscured by both the canopy and the projection of tree profiles onto the forest floor. We present a canopy correction method based on Moderate Resolution Imaging Spectroradiometer satellite imagery validated with field observations that mitigates geometric and georegistration issues associated with changing satellite acquisition angles in forested areas. The largest effect from a variable viewing zenith angle on the viewable gap fraction in forested areas occurs in moderately forested areas with 30–40% tree canopy coverage. Cloud cover frequently causes errors in snow identification, with some clouds identified as snow and some snow identified as cloud. A snow-cloud identification method utilizes a time series of fractional vegetation and rock land-surface data to flag snow-cloud identification errors and improve snow-map accuracy reducing bias by 20% over previous methods. Together, these contributions to snow-mapping techniques could advance hydrologic forecasting in forested, snow-dominated basins that comprise an estimated one fifth of Northern Hemisphere snow-covered areas.

- Here, use spatially and temporally complete (STC) MODSCAG fSCA
- NRCS WSF criteria for RS products:
  - Long record (>20 years)
  - Fast cadence, short latency (data within couple days of the start of the month)
  - Continuity (via VIIRS)
  - No spatial or temporal gaps

Experimental design

- Developed 220 models in a relatively exhaustive set of experiments drawn from existing operational NRCS forecast system
- Interpreted results from a NRCS operational perspective, with an eye to when, where, and why satellite data improve WSF skill

Location	Lead time	Hydrologic model	Driving data
• Walker River, Sierra Nevada (Great Basin) • Wind River, Northern Rockies (Missouri) • Gila River, Gila Mountains (Lower Colorado) • Piedra River, Southern Rockies (Upper Colorado)	Every month from start of forecast season (January) to end (typically June)	• PCR with genetic algorithm predictor selection • M^4	• SNOTEL SWE & P • MODSCAG fSCA (basin average) • MODSCAG fSCA (elevation bands) • SNOTEL & average MODSCAG • SNOTEL & elevation-band MODSCAG

Measuring the WSF value of satellite data

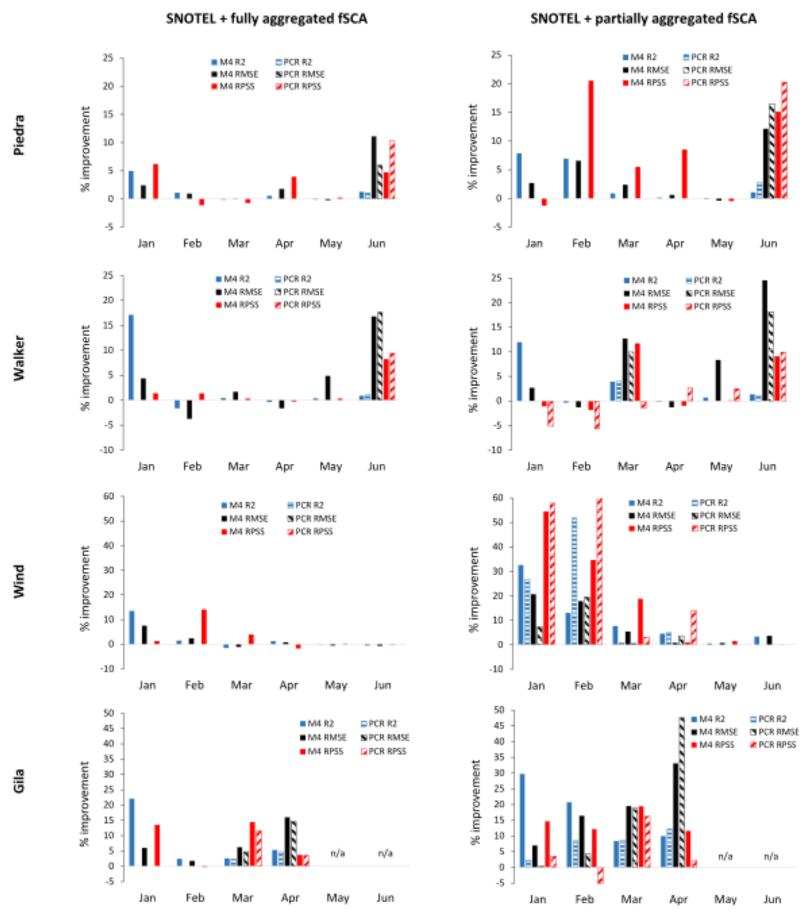


Figure 3. Percent improvements in R^2 (blue), root mean square error (black), and ranked probability skill score (red) resulting from using both SNOTEL and STC-MODSCAG fractional snow-covered area (fSCA) data, relative to using SNOTEL data alone. Solid shaded bars: M^4; patterned bars: principal component regression. Each row corresponds to a different watershed. Left and right columns correspond, respectively, to spatial aggregation of fSCA data to a single watershed-wide mean value, or to seven mean values, one for each of seven equally spaced elevation bands.

% improvement in deterministic & probabilistic forecast accuracy metrics

Degree to which genetic algorithm-based candidate predictor optimization retained MODSCAG

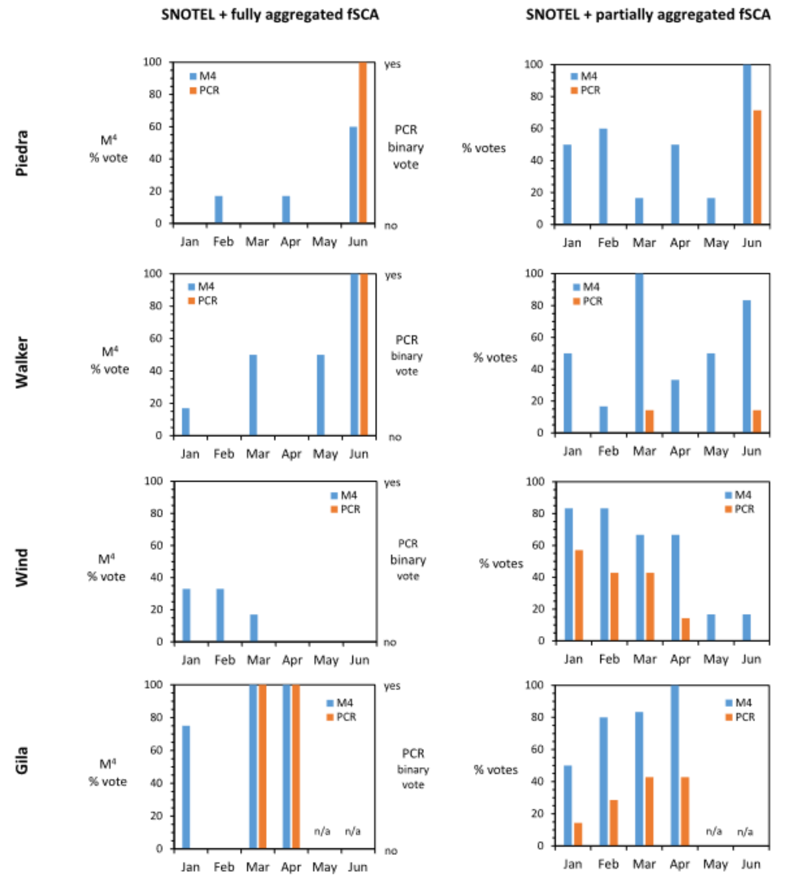


Figure 4. Metrics of how "popular" STC-MODSCAG fractional snow-covered area (fSCA) data were with the hydrologic models, via genetic algorithm-based predictor selection. Each row corresponds to a different watershed. Left and right columns correspond, respectively, to spatial aggregation of fSCA data to a single watershed-wide mean or to seven mean values, one for each of seven equally spaced elevation bands in the watershed. The popularity metrics differ, and therefore are not directly comparable, between the left and right columns and between the multi-model ensemble of M^4 and the single-model principal component regression approach (see text for details). In all cases, however, higher values indicate greater levels of fSCA retention in the optimal water supply forecast model.

Punch lines

- As expected, accuracy decreases with increasing lead time
- Also as expected, for cases where any reasonable prediction skill exists, M^4 generally meets or beats PCR accuracy considering multiple performance metrics
- Also kind of as expected but not quite… MODSCAG + SNOTEL often beats SNOTEL alone, but only in specific (though widely relevant) circumstances – and those circumstances are interesting, naturally parsing into 3 seasonal timeframes

Overall conclusion: integration of STC-MODSCAG fSCA into day-to-day production systems for water supply forecast modeling across much of the western US is advisable

Punch lines

1. **Short-lead/late-season forecasts**
   - Providing MODSCAG data alongside SNOTEL increases accuracy for 3 of the 4 rivers
   - Improvement roughly proportional to
     (i) how snowmelt-dominated spring-summer river flows are (e.g., versus spring-summer rain inputs)
     (ii) how poorly the local existing SNOTEL network samples late-season mountain snowpack (e.g., as snowpack becomes patchy and/or snowline moves above network)
   - % improvements in M^4 are no better than those in PCR

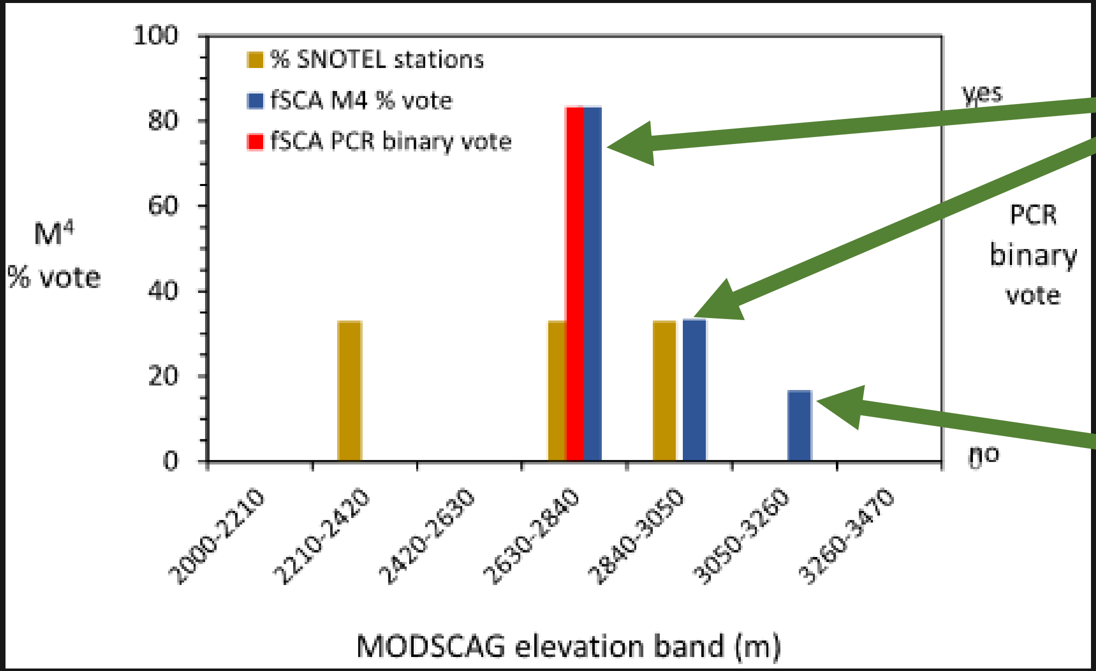
2. **Medium-lead/mid-season (peak snow period) forecasts**
   - Neither M^4 nor PCR benefit from MODSCAG: SNOTEL does reasonable job of indexing mountain snowpack available for spring-summer melt runoff generation

3. **Long-lead/early-season forecasts**
   - Similar result to short-lead/late-season forecasts, except improvements generally only substantial for M^4: implies strong nonlinearity and/or interactions

Other outcomes: supporting in-situ site selection

For experiments using SNOTEL & MODSCAG elevation-band data: which MODSCAG elevation bands are retained by genetic algorithm-based WSF predictor selection (i) can provide guidance on where to place a new SNOTEL site, (ii) based directly on its potential contributions to WSF accuracy, and (iii) conditional on the existing SNOTEL sites

- **Example: Walker River June forecast issue date**
- **Results vary between watersheds and lead times**

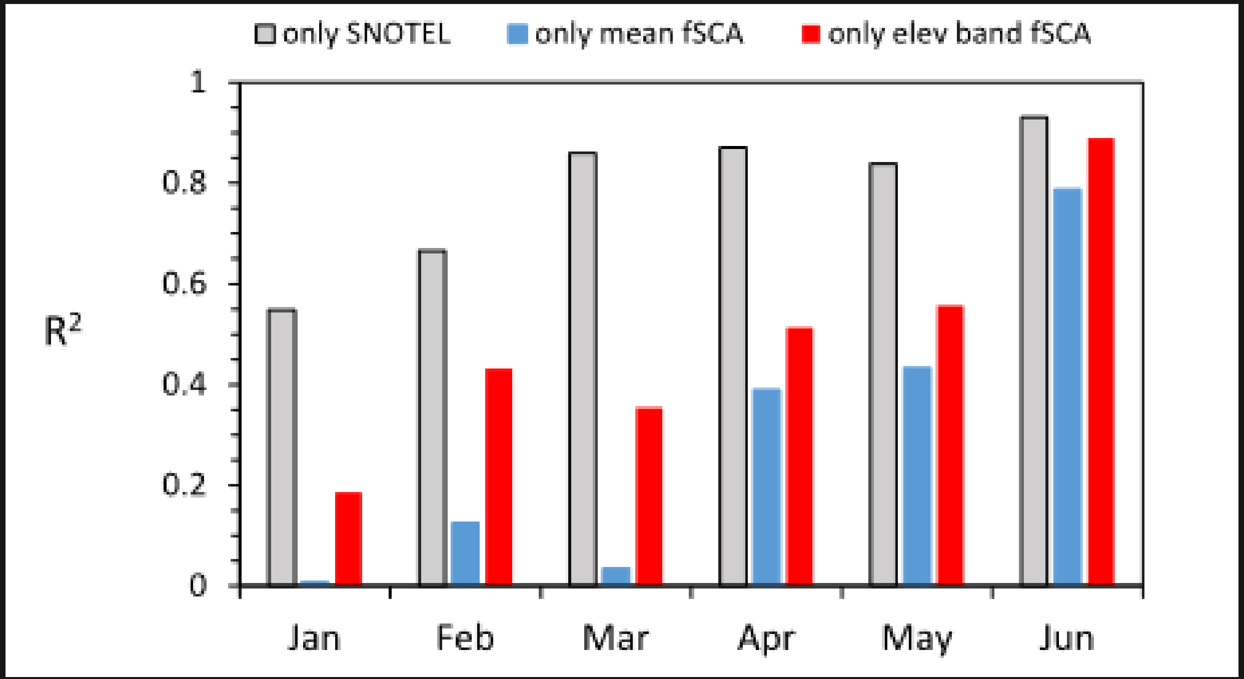


Suggests spatial gap-filling at mid-elevations

Suggests chasing the snowline uphill

Other outcomes: WSF using only satellite data

For basins where the spring-summer runoff is dominated by snowmelt, using MODSCAG with no in situ data may provide serviceable short- and medium-lead WSFs: potentially useful in sparsely monitored regions (e.g., international development applications?)



Example: Piedra River using M^4

Thank you for your interest

Please feel free to reach out to us with questions: fleminse@oregonstate.edu

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Water Resources Research

RESEARCH ARTICLE
10.1029/2023WR035785

Key Points:

- Improvements to operational water supply forecasts (WSFs), based heavily on mountain snow data, are critical to western US water management
- We test a new satellite remote sensing snow product, having no spatial or temporal coverage gaps, for ability to improve USDA WSF models
- Results argue for operational implementation and give practical guidance around when and where such data may provide the most benefit

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Formal analysis: Sean W. Fleming, Karl Rittger
Funding acquisition: Karl Rittger, Catalina M. Oaida Taglialatela, Indrani Graczyk

Leveraging Next-Generation Satellite Remote Sensing-Based Snow Data to Improve Seasonal Water Supply Predictions in a Practical Machine Learning-Driven River Forecast System

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Abstract Seasonal predictions of spring-summer river flow volume (water supply forecasts, WSFs) are foundational to western US water management. We test a new space-based remote sensing product, spatially and temporally complete (STC) MODSCAG fractional snow-covered area (fSCA), as input for the Natural Resources Conservation Service (NRCS) operational US West-wide WSF system. fSCA data were considered alongside traditional SNOTEL predictors, in both statistical and AI-based NRCS operational hydrologic models, throughout the forecast season, in four test watersheds (Walker, Wind, Piedra, and Gila Rivers in California, Wyoming, Colorado, and New Mexico). Outcomes from over 200 WSF models suggest fSCA-enabled accuracy gains are most consistent and explainable for short-lead, late-season forecasts (roughly 10%–25% improvements, typically), which in operational practice can be challenging as snowlines rise above in situ measurement sites. Gains are roughly proportional to how thoroughly spring-summer runoff is dominated by snowmelt, and how poorly in situ networks monitor late-season snowpack. fSCA also improved accuracy for long-lead, early-season forecasts, which are similarly problematic in WSF practice, but not for WSFs issued around the time of peak snow accumulation, when in situ measurements reasonably characterize mountain snowpack available for upcoming spring-summer snowmelt. The AI-based hydrologic model generally outperformed the statistical model and, in some cases, better-capitalized on satellite remote sensing. Additionally, preliminary analyses suggest reasonable WSF skill in many cases using fSCA as the sole predictor, potentially useful in sparsely monitored regions; and that combining satellite and in situ products in data-driven hydrologic models using genetic algorithm-based predictor selection could help guide new SNOTEL site selection.

Plain Language Summary Western US operational water supply forecasts (WSFs) are predictions, typically issued at the start of every month from January through spring, of upcoming spring-summer flow volume for a given point on a river, performed by service-delivery organizations having strict accountabilities to end users around reliably delivering this information. WSFs use mathematical models of watershed hydrology that heavily leverage on-the-ground data on winter mountain snowpack, source of much of the spring-summer runoff. Past research shows that snow measurements from air and space can improve WSF accuracy, but