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COMMENTARY

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SNOTEL, the Soil Climate Analysis Network, and water supply forecasting at the Natural Resources Conservation Service: Past, present, and future

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Abstract

The Snow Survey and Water Supply Forecasting (SSWSF) Program and the Soil Climate Analysis Network (SCAN) of the United States Department of Agriculture's Natural Resources Conservation Service (NRCS) generate key observational and predictive information for water managers. Examples include mountain climate and snow monitoring through manual snow surveys and the SNOw TELemetry (SNOTEL) and SNOtel LITE networks, in situ soil moisture data acquisition through the SCAN and SNOTEL networks, and water supply forecasting using river runoff prediction models. The SSWSF Program has advanced continuously over the decades and is a major source of valuable water management information across the western United States, and the SCAN network supports agricultural and other water users nationwide. Product users and their management goals are diverse, and use-cases range from guiding crop selection to seasonal flood risk assessment, drought monitoring and prediction, avalanche and fire prediction, hydropower optimization, tracking climate variability and change, environmental management, satisfying international treaty and domestic legal requirements, and more. Priorities going forward are to continue innovating to enhance the accuracy and completeness of the observational and model-generated data products these programs deliver, including expanded synergies with the remote sensing community and uptake of artificial intelligence while maintaining long-term operational reliability and consistency at scale.

Abbreviations: AI, artificial intelligence; ASO, Airborne Snow Observatory; CSO, Citizen Snow Observations; DCO, data collection office; ESP, ensemble (or extended; usage varies, but meaning is the same) streamflow prediction; iSNOBAL, Image SNOwcover energy and mass BALance model; JPL, Jet Propulsion Laboratory; M^4, Multi-Model Machine-learning Metasystem; MAYA, Most Advanced Yet Acceptable; MODIS, MODerate resolution Imaging Spectroradiometer; NASA, National Aeronautics and Space Administration; NOAA, National Oceanic and Atmospheric Administration; NRCS, Natural Resources Conservation Service; NWCC, National Water and Climate Center; PCR, principal component regression; PRMS, Precipitation Runoff Modeling System; QC, quality control; S2S, seasonal to subseasonal; SCAN, Soil Climate Analysis Network; SCS, Soil Conservation Service; SDO, Service Delivery Organization; SNODAS, SNOw Data Assimilation System; SNOTEL, SNOw TELemetry; SRAM, snow remote sensing, assimilation, and modeling; SSWSF, Snow Survey and Water Supply Forecasting; SUMMA, Structure for Unifying Multiple Modeling Alternatives; SWANN, Snow Water Artificial Neural Network; SWE, snow water equivalent; SWESARR, Snow Water Equivalent Synthetic Aperture Radar and Radiometer; USDA, United States Department of Agriculture; VHF, very high frequency; VIPER, Visual Interactive Prediction and Estimation Routines; WRF-Hydro, Weather Research and Forecast-Hydrological model; WSF, water supply forecast.

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KEYWORDS
water resources, snow, climate, mountain weather, forecasting, remote sensing, modeling

1 | INTRODUCTION: HISTORICAL CONTEXT AND PROGRAM STRUCTURE

The systematic use of snow survey data to quantitatively forecast spring–summer river runoff volumes originated with Dr. James Church, a classics professor at the University of Nevada-Reno, who worked in the Sierra Nevada beginning in the early 1900s. Following on this pioneering work, the United States Department of Agriculture's Natural Resources Conservation Service (NRCS) has continuously maintained expansive operational programs for mountain snow measurement and river runoff prediction in the American West since the 1930s.

The NRCS was created during the Great Depression as the Soil Erosion Service to provide scientific solutions to address the Dust Bowl and the agricultural practices that contributed in part to this social, economic, and ecological catastrophe, which had been predicted by the NRCS's founder, H.H. Bennett, decades beforehand. It was soon renamed the Soil Conservation Service (SCS) and then NRCS.

The agency has a long and wide-ranging history of socially impactful innovation in snow science, environmental science, and water resource science and engineering, among other areas. The SCS curve number method, for example, remains a widely used scoping-level hydrologic model. The SNOw TELemetry (SNOTEL) observation network is the primary source of winter mountain snowpack and associated meteorological information in the western United States (U.S.). It also provides the direct observational data required to create or ground-truth spatially distributed snowpack estimates such as those from the National Weather Service's SNOw Data Assimilation System (SNODAS), the NASA Airborne Snow Observatory (ASO) remotely sensed snow product, and various other high-resolution snow datasets. NRCS additionally pioneered the use of principal component regression (PCR) for probabilistic water supply forecasts (WSFs) using high-dimensional multicollinear predictors (Garen, 1992). WSFs are predictions of upcoming spring–summer river runoff volumes, issued once or twice per month with more frequent updates, beginning the previous winter. WSFs are largely predicated on measurements, mainly from SNOTEL, of the mountain snowpacks that are the primary source of river runoff across most of the western U.S. (Li et al., 2017). PCR remains a community benchmark, being widely adopted for operational WSF by several other organizations within and beyond the western U.S. and for water resource and hydroclimatology research (e.g., Eldaw et al., 2003; Fleming & Goodbody, 2019; Glabau et al., 2020; Gobena et al., 2013; Harpold et al., 2016; Hsieh et al., 2003; Kennedy et al., 2009; Lehner et al., 2017; Moradkhani & Meier, 2010; Najafi & Moradkhani, 2016; Perkins et al., 2009; Regonda, Rajagopalan, & Clark, 2006; Regonda, Rajagopalan, Clark, & Zagon, 2006; Risley et al., 2005; Rosenberg et al., 2011). The NRCS also operates the Soil Climate Analysis Network (SCAN) of in situ soil moisture, soil temperature, and climatic sensors, which has a wider geographic scope than SNOTEL, spanning much of the continental U.S., Alaska, Hawaii, Puerto Rico, and the U.S. Virgin Islands (Table 1).

SNOw TELemetry and WSF are part of the NRCS Snow Survey and Water Supply Forecasting (SSWSF) Program. This program is administered by the National Water and Climate Center (NWCC) and state-level snow survey programs in 12 western states. Data collection offices (DCOs) in Alaska, Colorado, Idaho, Montana, Oregon, and Utah are primarily responsible for SNOTEL operations and data quality control (QC); coordinating and executing manual snow observations; collection and entry of streamflow and reservoir data; and dissemination of WSFs. Water Supply Specialists provide additional program support in Arizona, California, Nevada, New Mexico, Washington, and Wyoming. The NWCC, headquartered in Portland, Oregon, performs operational WSF modeling and research and development (R&D) around next-generation hydrologic models; provides technical support to DCO SNOTEL activities; manages program databases; and oversees collection

TABLE 1 Summary of current SSWSF and SCAN program monitoring and forecasting efforts.

Mountain snowpack and climate measurements	• SNOTEL (automated telemetered hourly measurements): 890 sites, up to 59 years of hourly and daily records • Manual snow courses (monthly snowpack measurements): 825 sites, up to 111 years of monthly records • SNOLITE (automated hourly or daily measurements): 41 sites, up to 11 years of hourly or daily records
Streamflow forecasts	• Volumetric water supply forecasts (issued at least once monthly with daily updates from January to June): 585 forecast points using statistics-, physics-, and artificial intelligence-based watershed hydrology models
Soil moisture monitoring	• SNOTEL (automated hourly or daily measurements): 469 measurement locations, up to 26 years of hourly or daily records • SCAN (automated hourly measurements): 210 measurement locations, up to 39 years of hourly and daily records

Abbreviations: SCAN, Soil Climate Analysis Network; SNOTEL: SNOwTELemetry; SNOLITE (SNOwtel LITE); SSWSF, Snow Survey and Water Supply Forecasting.

Research Impact Statement

This commentary summarizes the history, current state, and future of the U.S. Department of Agriculture's Snow Survey and Water Supply Forecasting Program and Soil Climate Analysis Network.

of telemetered datasets. SCAN is distinct from the SSWSF Program and is administered by the NWCC and the NRCS Soil and Plant Science Division (Figure 1).

A comprehensive technical review of SSWSF and SCAN techniques and products is far beyond the scope of this invited Water Commentary. Rather, we focus below on presenting short and accessible summaries of our core activities and datasets, identifying some connections to other areas, and describing current and future directions. Suggestions for further reading are also provided.

2 | MANUAL SNOW COURSE MEASUREMENTS

Manual snow surveys are a cooperative effort across multiple federal, state, and other partners. The goal is large-scale, long-term monitoring of mountain snowpack across a diverse range of snow climates. Observations are taken during the last week of every month from January through June by trained observers. Parameters recorded include snow water equivalent (SWE), snow depth, and snow density. Measurements are made along an established transect using the Federal Sampler, a modified version of the Mt. Rose Sampler first used by James Church (Figure 2). Manual snow surveys carried out by the SSWSF Program date back to the early 1900s in some locations, with some measurement sites now having a continuous record surpassing 100 years. Of special note is that, unlike automated and telemetered monitoring stations, the technique and equipment used for manual snow sampling has changed very little during the observation period, contributing to consistency and repeatability of these snow observations (Farnes et al., 1982; Jones, 1934).

Cooperative surveys carried out across the western U.S. provide some of the most spatially diverse and longest-running records of snowpack observations in the world. The NRCS coordinates measurements at 825 snow courses monthly, with the total number increasing to 1170 locations when surveys conducted by BC Hydro, Alberta Environment, and California Cooperative Snow Surveys are included; results from these additional programs are also stored in SSWSF Program databases. Monthly observations are quality controlled by DCOs, entered into public-facing databases, and made available by the first business day of each month. Uses of manual snow measurement data include WSFs and other hydrologic analysis and modeling tasks; habitat studies; supporting and ground-truthing snow remote sensing, snow modeling, and weather radar products; and long-term climate studies.

Readers interested in additional technical, logistical, and operational details of the NRCS manual snow course measurement program are referred to USDA (2012).

3 | SNOTEL AND SNOLITE AUTOMATED STATIONS

Extensive technical information around SNOTEL data collection sites, equipment, sensors, and procedures can be found in USDA (2012), and a history of the SSWSF Program is provided by USDA (2008). The following is a brief summary of the SNOTEL network, its rationale, its applications, and current and future directions.

SNOTEL is an automated, remote, telemetered, large-scale, long-term, and low-latency mountain snowpack and weather monitoring network, with 890 sites operated by NRCS across the western U.S. and Alaska (Perkins et al., 2009; Schaefer & Paetzold, 2000; Strobel et al., 2009). Standard SNOTEL stations measure several critical hydrometeorological variables, including SWE, snow depth, precipitation, and air temperature (Figure 3). SNOTEL has been augmented by the relatively new SNOtel LITE (SNOLITE) network, which has increased to over 40 automated stations and measures a subset (at least two) of these four core SNOTEL parameters. Conversely, enhanced SNOTEL sites are outfitted with additional sensors beyond the standard SNOTEL suite due to a specific local resource management concern, measuring soil moisture, relative humidity, solar radiation, wind speed/direction, or other important metrics (see also SCAN discussion below).

The SNOTEL network emerged in the late 1950s through the early 1960s to gather and telemeter information from existing snowpack measurement locations on a daily basis; in many cases, SNOTEL sites replaced manual snow courses (see previous section). Transmitters at the first sites used roll recorders to report SWE and radio/repeater arrays to telemeter data to state DCOs. As alternative radio technologies emerged during the Cold War, the network moved to innovative Meteorburst communications to relay data from remote weather stations to centralized databases. Meteorburst technology consists of very high-frequency radio signals that are reflected at a steep angle off a permanent band of ionized meteors approximately 50–75 miles above Earth's surface (Schaefer et al., 2007; Schaefer & Paetzold, 2000). The system

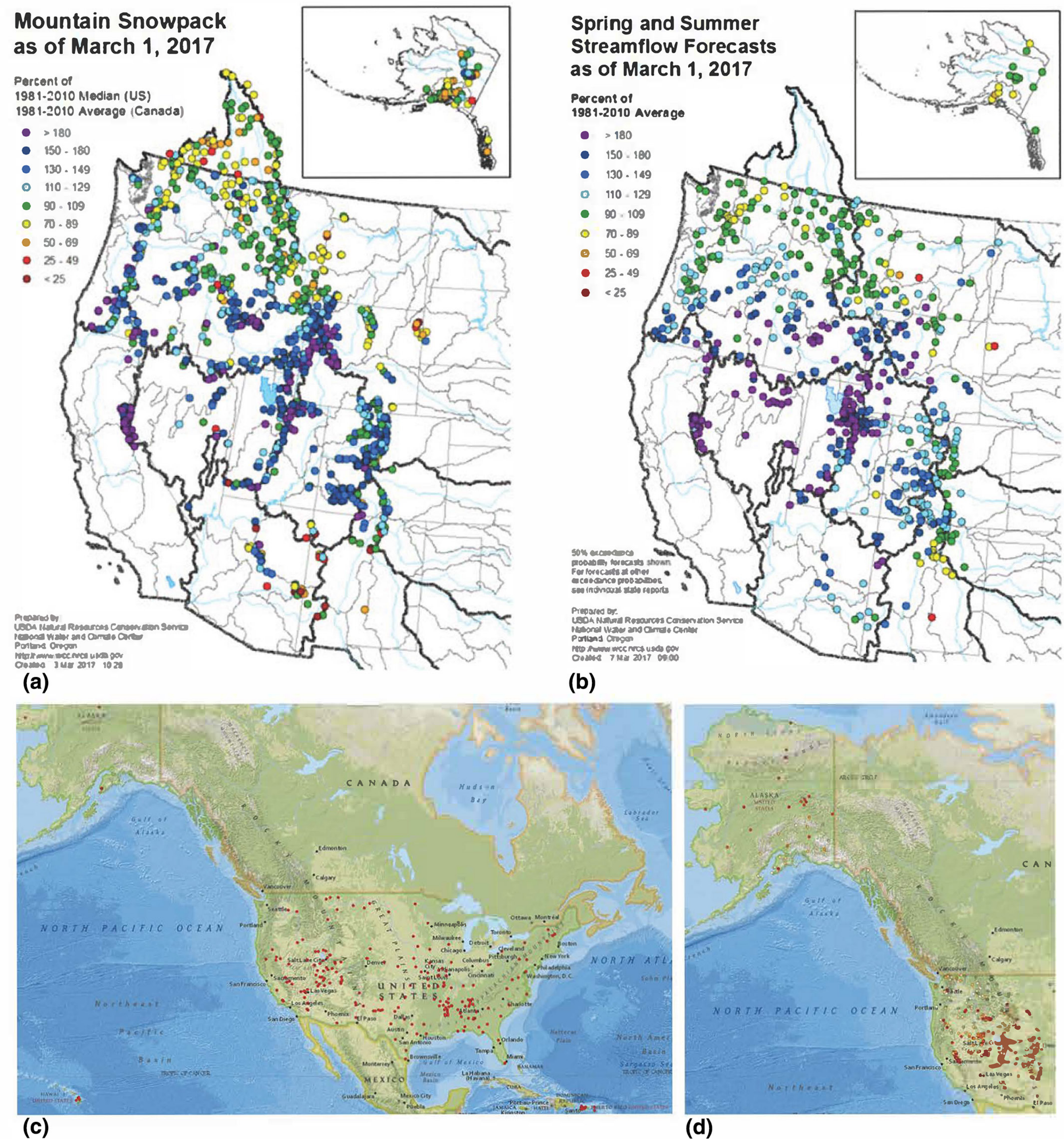

FIGURE 1 Spatial coverages of Natural Resources Conservation Service (NRCS) monitoring programs discussed in this article. The (a) SNOTEL monitoring network and (b) NRCS water supply forecast system span the western United States (U.S.) and Alaska. The (c) SCAN soil moisture monitoring network and (d) the subset of SNOTEL network sites monitoring soil moisture collectively span the conterminous U.S., Alaska, Hawaii, Puerto Rico and the U.S. Virgin Islands.

is unique in that NRCS has total control over the data stream and is the sole owner/operator of the Boise and Dugway Master Stations, which collect information from remote stations. Data are then transferred to centralized databases managed by the NWCC. As this technology became more widely available, the largest historical expansion in the SNOTEL network occurred, growing from 76 stations in 1975 to 512 stations in 1985. Today, the SNOTEL network is undergoing a major transformation in the way data are collected and telemetered. Though a tremendous advance in its day, Meteorburst technology is growing dated and more difficult and costly to support. Consequently, newer technologies, specifically cellular and satellite communications, are being deployed across the network to replace the legacy Meteorburst system.

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FIGURE 2 Example of the Federal Sampler in the field (left) and individuals performing snow course measurements in Nevada in the 1940s (James E. Church Collection UNRS-P2004-18, Special Collections and University Archives Department, University of Nevada, Reno) (right).

FIGURE 3 SNOTEL station configuration during summer (left) and SNOTEL station in Nevada during winter (right).

In addition, new datalogger technology is allowing for increased measurement accuracy and the ability to deploy a wider array of sensors. These technologies will provide the backbone for the SNOTEL network and guide network design for the coming years.

Snow water equivalent observations are made with a snow pillow, which uses a pressure transducer to measure displacement in a fluid-filled bladder due to the weight of accumulated overlying snowpack. The development of this technology began in the late 1950s and was operationalized by the SSWSF at snow measurement locations in the early 1960s (Beaumont, 1965). While current technology may use different materials like Hypalon and Polypropylene for the construction of the snow pillow, the measurement principle remains largely unchanged. SNOTEL precipitation data are collected using an all-season storage gauge recharged annually with an anti-freeze solution. Like the snow pillow, the precipitation gauge is connected to a pressure transducer and uses the weight of the column of water in the gauge to report inches of precipitation. The height and capacity of these gauges varies by the amount of anticipated maximum annual precipitation and snow depth, generally ranging from 8′ to 30′ in height. An Alter shield is fitted to the top of each gauge to reduce under-catch due to wind (Alter, 1937). Snow depth is found using an acoustic sensor mounted on a tower, measuring the distance to the snow surface relative to the height of the sensor. Air temperature measurements are made using a thermistor fitted inside a multi-vane radiation shield mounted at a fixed height above the ground surface.

Quality control of daily SWE and precipitation data is performed daily to weekly by the state DCO responsible for the sites in their region. Automated processes flag the data for editors to review, and suspect values are reviewed for accuracy, with correction steps taken where required. Readers interested in details of QC procedures for other data elements and sampling intervals are encouraged to contact SSWSF Program staff. It has occasionally been suggested that a select subset of long-term SNOTEL sites, accompanied by exhaustive data homogenization, might in principle be used to create carefully curated reference datasets for climate and other analyses akin, for instance, to the U.S. Historical Climatology Network (e.g., Menne et al., 2009). To our knowledge, however, this is rarely if ever done for long-term automated mountain snow datasets. Applicability of conventional climate data homogenization procedures using more prodigious valley-bottom meteorological station networks as a basis for comparison and correction may be limited by the elevation dependence of weather and climate variability (see below) and by the lack of SWE measurements at many meteorological stations. We identify this as a potentially important research question for the snow-science community. It also bears emphasizing that the methodological consistency of manual snow surveys (refer to previous section) provides a long-term record that is inherently relatively homogeneous. Moreover, current operational procedures include documenting changes in site instrumentation or surrounding land cover characteristics, such as those due to wildfires, and periodically undertaking homogenization procedures, like double mass-curve analysis and corresponding corrections. Consequently, SNOTEL data are routinely used successfully for climate change and other studies (again see below). In some cases, reflecting various issues including, for example, avoidance of theft and vandalism, publicly available SNOTEL site location metadata may be less precise than ideal for certain science and engineering applications. A network-wide solution is under development. In the interim, science-community data users requiring more precise coordinates are encouraged to reach out to the NWCC or their local DCO, who will provide those metadata on request.

SNOTEL network design and operation is not, and for all practical purposes cannot be, simultaneously optimized for every conceivable snow data application. Granted, as summarized below, SNOTEL datasets are indeed useful for a rich diversity of physical, life, and engineering science applications, and the SSWSF Program is working with a variety of user communities to reach site placement and instrumentation decisions that make SNOTEL data even more broadly valuable. Nevertheless, it is important for SNOTEL data users to understand that selection of sites and instrumentation is driven by the primary purpose of the SNOTEL network: reliable, accurate, long-term mountain snow and climate data collection as a primary basis for seasonal water supply assessment and forecasting in the western U.S., reflecting the operational mission of the SSWSF Program and NWCC. In practice, this means SNOTEL and snow course station placement is guided by nearly a century of institutional experience identifying locations that serve as useful index sites for representing total mountain snowpack available for spring–summer runoff generation within a given watershed of interest (USDA, 2008, 2012). Site placement and instrumentation are also subject to a multitude of logistical considerations associated with establishing almost 900 snow monitoring stations spanning the U.S. West and Alaska, with consistent measurement (e.g., instrumentation) protocols across sites, and then reliably and continuously operating these stations for decades or, indeed, generations. Such considerations include land ownership; safety, speed, and cost of site access; and feasibility, cost, and overall sustainability of maintenance and operation.

The SNOTEL network is constantly reassessed and adjusted by the SSWSF Program on the basis of ongoing operational experience; moreover, changing snow lines and other crysopheric and hydrologic shifts under climate change (e.g., Nolin et al., 2021) may influence site selection going forward. However, it also bears emphasizing that maintaining fixed SNOTEL monitoring locations over very long timeframes provides a crucial sentinel function. Such long-term SNOTEL monitoring at permanent sites has enabled clear and direct observational detection and analysis of long-term changes in mountain snow and climate attributable to global anthropogenic climate change (e.g., Mote et al., 2018; Surfleet & Tullos, 2013; Wagner et al., 2021) or other environmental shifts, like worsening wildfire threats (Giovando & Niemann, 2022; Smoot & Gleason, 2021) reflecting historical fire suppression and fuel-load buildup, climate change, and growing human intrusions into forest lands. The need for that sentinel function will only increase going forward. A particular asset of the SNOTEL climate and snow monitoring network, and similar operational networks in western North America like those operated by the British Columbia River Forecast Center and California Cooperative Snow Surveys Program, is that they provide long-term measurements specifically at mountain sites typically not sampled by networks of weather stations, which are generally located in or near valley bottoms. Over the short term, for example in flood-forecast model development, testing, and operation (e.g., Cunderlik et al., 2013), such relatively high-elevation data are crucial for tracking current mountain weather and snow conditions, which in general cannot be easily and reliably extrapolated from low-elevation weather station data due to basic meteorological dynamics like temperature inversions and complex orographic effects such as nonlinear and spatially heterogeneous precipitation lapse rates. Over longer time scales, climate change impacts are known to differ substantially between mountain and valley locations. Some examples include elevation-dependent climate warming (e.g., Mountain Research Initiative EDW Working Group, 2015), elevation-dependent snowpack sensitivity to climate change (e.g., Shea et al., 2021), and elevation-dependent climatic trends in rain-on-snow events, which are a key driver of extreme flood events in the western U.S. (e.g., McCabe et al., 2007). Modeled and remotely sensed estimates of climate, snow, and other environmental parameters provide valuable insights into these high-elevation phenomena but are fundamentally reliant on ground-based monitoring for rigorous product development and verification, as discussed further below. For objectively identifying, tracking, and understanding climate and other environmental change impacts in western U.S. mountain environments, there is no surrogate for the observational data of the SNOTEL and similar long-term, fixed-location, ground-based station networks.

Some additional uses of SNOTEL data include other water resource science and management applications beyond operational forecasting; water quality studies; ecology and habitat studies; supporting and ground-truthing snow remote sensing, snow modeling, and weather radar products; testing climate models; avalanche hazard assessment and prediction studies; and recreation-industry (e.g., skiing, snowmobiling, rafting, fishing) planning (e.g., Corn, 2003; Painter et al., 2016; Pierce, 2010; Rasmussen et al., 2014; Todd et al., 2012; USDA, 2012). An instructive, if highly approximate, metric of the overall science and engineering impact of SNOTEL data is that a Boolean search in Google Scholar on ' "SNOTEL" and "climate change" ' returns over 4,000 hits. A similar search solely on "SNOTEL" leads to almost 8000 publications. These numbers are minimum estimates of the impact of SNOTEL data, as Google Scholar omits non-documented data uses and does not consistently include many public and private documents generated by government and industry in association with day-to-day activities across the U.S. West, such as environmental and engineering consultant reports, WSF reports routinely issued by practical service-delivery organizations (SDOs; Serafin et al., 2021) like the NRCS and National Weather Service River Forecast Centers (RFCs), and so forth.

4 | SCAN

SCAN is a comprehensive, nationwide, soil moisture and climate information system designed to provide data to support natural resource assessments and conservation activities (Schaefer et al., 2007; Schaefer & Paetzold, 2000). Administered by the NRCS through the NWCC in cooperation with the NRCS National Soil Survey Center, the system focuses on agricultural areas of the U.S. SCAN began as the soil moisture/soil temperature pilot project in 1991. Significant knowledge and experience have been gained regarding network operation, QC, product analysis, and dissemination of information to users. Sites operate in cooperation with federal, state, local, and tribal entities. There currently are more than 200 stations in 40 states, as well as Puerto Rico and the U.S. Virgin Islands, with a growing list of requests for new sites across the nation. SCAN plays a critical role in assessing the impacts of climate and drought on agriculture by providing real-time soil moisture, soil temperature, and atmospheric information necessary to (1) support county-, state-, regional- and national-level drought risk assessments, (2) assist in production agriculture assessments and crop management, (3) provide improved WSFs for water managers, (4) detect and manage the impacts of climate extremes, (5) support conservation planning, and (6) support global climate change research. In addition to the present SCAN network, over 468 SNOTEL stations and two SNOLITE stations in the western U.S. have soil moisture/soil temperature sensors and add to the data used in SCAN. SNOTEL/SNOLITE is funded and operated through the SSWSF Program under a separate authority from SCAN.

Previously, the ability of NRCS and its partners to make sound resource assessments and watershed decisions has been limited by the lack of quality, historic, and real-time soil climate information. Other network data tended to be application-specific, short-term, incomplete, limited in the area of coverage, and often were non-standard. SCAN is providing a long-term national network of standardized data, allowing NRCS and other groups to build, operate, maintain, and develop models and products that facilitate sound resource management decisions.

In particular, the use of SCAN data is increasing with global climate modelers, soil scientists, ecologists, drought managers, and farmers to support various activities including soil surveys, water management and irrigation schedules, crop production models, and planting schedules. Additional natural resource management issues informed by SCAN data include monitoring drought development and developing plans and policies for mitigation, investigating climate change scenarios, predicting the long-term sustainability of cropping systems as well as watershed health, monitoring and predicting changes in crop, range, and woodland productivity relative to soil moisture-temperature changes, predicting regional shifts in irrigation water requirements, predicting shifts in wetlands, developing new soil moisture accounting and risk assessments, and predicting changes in runoff that affect flooding and flood control structures (Figure 4). In addition to operational and practical planning applications, some examples of research uses of SCAN data include Cosh et al. (2021), Ford et al. (2020), Zhao et al. (2020), Leeper et al. (2019), and Xia et al. (2015).

5 | WSF

Water scarcity has guided the development of the western U.S. and continues to be one of its most complex and pressing public issues (Reisner, 1986). Quantitative operational WSFs provide the means for anticipating water shortage or abundance in a given year, and for planning accordingly (e.g., Glantz, 1982; Grantz et al., 2005; Hoekema & Ryu, 2013; Kalra et al., 2013; NMFS, 2019; Regonda, Rajagopalan, Clark, & Zagon, 2006). For example, WSFs are required under international treaties such as those governing transboundary management of the Columbia, Colorado, and Rio Grande basins. WSFs are also specified in some legal decisions, such as Biological Opinions issued in the Klamath Basin, following a series of lawsuits, to guide water management under Endangered Species Act Section 7 consultations. WSFs are the central input to engineering models and decision support systems used in optimal reservoir management for meeting and balancing needs around flood control, agricultural and urban water supply, navigation, hydroelectric power generation, and ecological instream flows. Forecasts also influence multi-year facility construction plans for reservoir systems, and they can be the deciding factor in choices around annual crop selection and amount of land left fallow, rental of water rights, and negotiation of forward contracts for hydroelectric power in deregulated western electricity markets.

The rewards of forecast quality improvements can be tremendous, as the value of the water managed using such forecasts rises well into the billions (Pierce, 2010) or trillions (James et al., 2014) of dollars each year. For example, Hamlet et al. (2002) and Yao and Georgakakos (2001) demonstrated that even incremental WSF improvements could increase the value of hydroelectric power generation by over $100 M per year in a single basin, and Hoekema and Ryu (2013) similarly documented the economic value of WSFs to the agricultural sector.

Watershed-scale hydrologic prediction models provide the basis for generating operational WSFs. These models capture and predict the complex interactions between meteorological forcing and terrestrial hydrologic processes that combine to generate river flows. Introductions and overviews around streamflow prediction modeling are provided by Fleming and Gupta (2020) and Bourdin et al. (2012). Gelfan and Motovilov (2009) provide a useful summary of general WSF principles and procedures in mountain and northern environments. Broader perspectives can be found in Leopold (1994) and Fleming (2017). To summarize, river runoff prediction models include both process-simulation models that aim to explicitly represent the physics of runoff generation and streamflow dynamics, and data-driven models that capture geophysical processes implicitly by mapping inputs to outputs through transfer functions. Months-ahead streamflow volume forecasts can

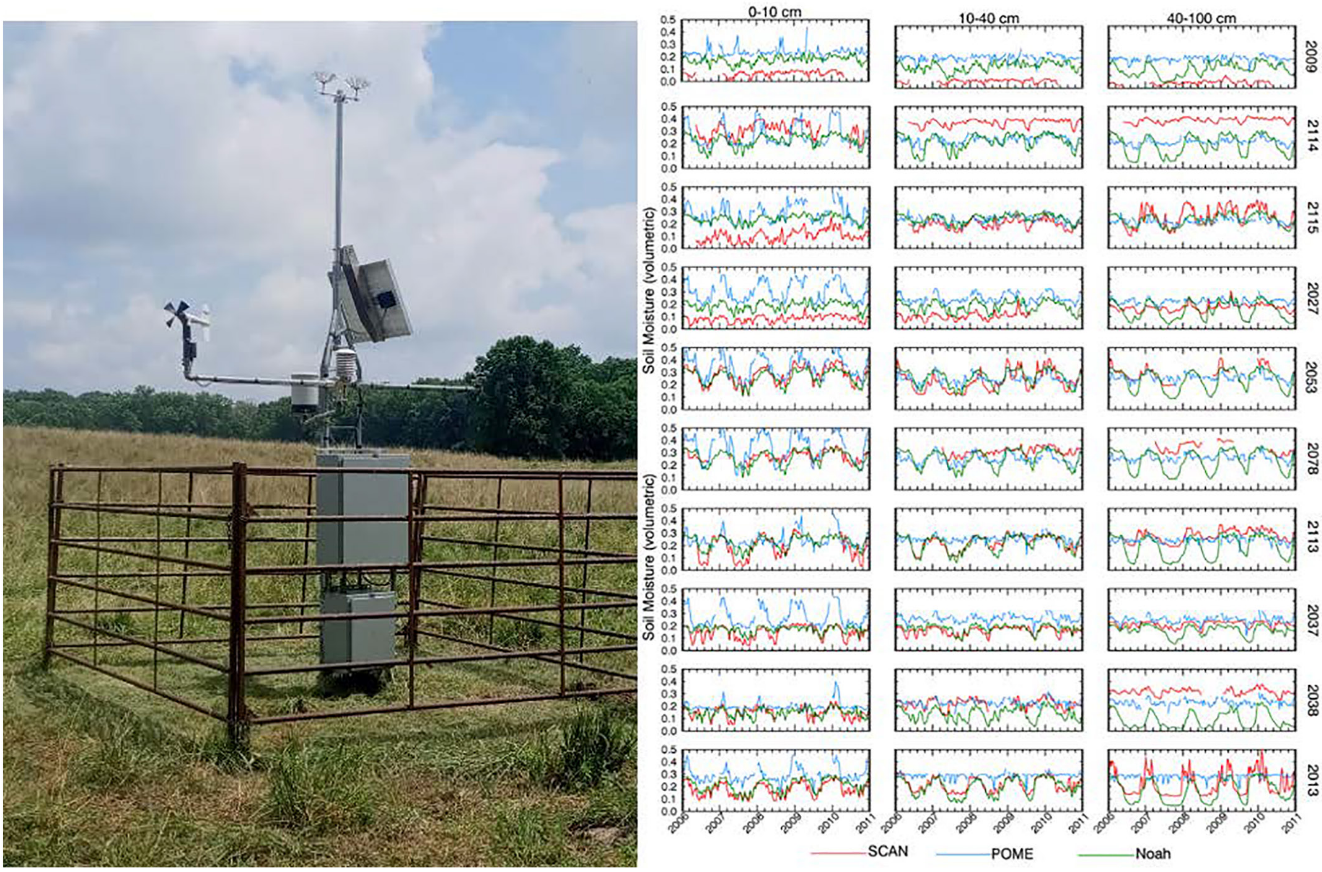

FIGURE 4 SCAN station (left) and time series of soil moisture condition at 10 SCAN sites from the POME model (Blue), Noah LSM (green) and in situ SCAN observations (red) at three-layer depths (2006–2010) (Mishra et al., 2018) (right).

be made with surprisingly good accuracy using these models despite poor seasonal-scale climate forecast skill, because much of the spring–summer river runoff volume in many western U.S. rivers is derived from melting of snowpack accumulated the previous winter. Observational winter–spring SWE data are therefore the primary predictor variates in data-driven models and provide a means for internal state updating through data assimilation procedures for process-simulation models, though many other environmental processes must additionally be taken into account in a watershed model to successfully predict downstream river flow dynamics and volumes.

A number of SDOs perform operational WSF in western North America, including the NRCS, California Department of Water Resources, various National Weather Service RFCs, Bonneville Power Administration, U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, BC Hydro, Alberta Environment, and others. Each uses different hydrologic models or different variants of the same model, and many organizations deploy more than one model. Typically, these operational WSF systems are underlain by decades-old but proven and continuously refined hydrologic models (for a review and synthesis, see, e.g., Weber et al., 2012). However, research on new hydrological prediction methods in support of improved operational WSF is also continuous. For instance, the National Oceanic and Atmospheric Administration (NOAA) National Water Model is an operational prototype that does not yet perform seasonal-scale WSF (e.g., Lhotak, 2022), but the underlying hydrologic prediction model, the Weather Research and Forecasting-Hydrologic model (WRF-Hydro), has seen research applications relevant to improving WSF (e.g., Lahmers et al., 2022). Examples of hydrologic model development focusing specifically on SDO-oriented operational river forecasting applications include emerging practical frameworks for flexible process-based modeling like the Structure for Unifying Multiple Modeling Alternatives (SUMMA), which is being tested for WSF in the western U.S. (e.g., Sturtevant et al., 2021), and Raven, which has been adopted by several operational groups in Canada (e.g., Craig et al., 2020). Innovation in WSF also includes R&D on a wide range of statistical and machine learning approaches (e.g., Bathulla & Miller, 2020; Hsieh et al., 2003; Najafi & Moradkhani, 2016; Upstream Tech, 2022), reflecting the emergence of data science as the fourth paradigm of science and the fourth industrial revolution (Hey et al., 2009; Schwab, 2017).

NRCS operates the largest stand-alone WSF system in the western U.S., and possibly the largest statistically based WSF system globally, with nearly 600 forecast points across 13 western states including Alaska (USDA, 2012). For each of these locations, multiple forecast issue dates and target horizons are considered. The system's primary model is an application, Visual Interactive Prediction and Estimation Routines (VIPER), that implements PCR (Garen, 1992) along with supporting techniques. *Z*-score regression (Pagano, 2005), and an ensemble streamflow prediction (ESP) system based on the U.S. Geological Survey's Precipitation Runoff Modeling System (PRMS) process-simulation model (Leavesley et al., 2010), which is also the basis of the U.S. Geological Survey's National Hydrologic Model (not to be confused with the NOAA National Water Model mentioned above), also see use at NRCS.

A new primary WSF method, the multi-method machine learning metasystem (M^4), has been developed and is now semi-operational at NRCS with imminent transition into full production systems. Details are provided in Fleming and Goodbody (2019), Fleming, Garen, et al. (2021), and Fleming and Garen (2022). In summary, M^4 meets pragmatic criteria for NRCS WSF by combining several elements, including an ensemble of diverse artificial intelligence (AI) and advanced statistical prediction models to improve accuracy, address model equifinality, and solve specific known technical issues with existing systems; statistical pattern recognition for dimensionality reduction and feature extraction; a genetic algorithm for optimal feature selection; parallel processing for reduced training times; a modular framework that can be readily updated and expanded to integrate emerging new prediction methods; deployment of autonomous machine learning (AutoML) concepts to improve process efficiency, reproducibility, and ease of use; amenability to incorporation of outside forecasts, such as those from the NRCS PRMS system or from other forecast SDOs (see above), into its multi-model ensemble; and pragmatic application of physics-aware AI, which spans theory-guided and geophysically explainable machine learning (see Fleming, Watson, et al. (2021) for a synthesis, and implications of physics-aware AI in the Earth and environmental sciences). Some practical advantages of M^4 include improved forecast skill relative to existing operational WSF systems at SDOs in western North America; maintaining the capacity to generate easily relatable explanatory climate and hydrology 'storylines' around the forecast, as in existing operational WSF systems; and amenability to relatively easy and effective integration of emerging new types of predictor variates into an operational environment, ranging from remote sensing data to climate model outputs, some of which the NWCC is currently exploring with partner organizations (see below).

To our knowledge, M^4 represents the first large-scale migration of machine learning from research into a genuine operational river forecast setting at a governmental SDO. This migration is enabled by adopting a Most Advanced Yet Acceptable (MAYA) design principle (e.g., Hekkert et al., 2003; Thompson, 2017) which, in essence, involves maintaining the proven, widely adopted, and well-accepted techniques and implementation protocols of PCR for western U.S. operational WSF, while augmenting its performance, flexibility, and efficiency using a range of carefully chosen modern geophysical modeling concepts and data-science technologies (Fleming, Garen, et al., 2021). Current efforts are focused on development of a user-friendly Software-as-a-Service (SaaS) prototype solution on a private cloud to facilitate operationalization of the R-based M^4 scientific computing engine into a full production environment (David et al., 2014; Figure 5).

6 | CONNECTIONS TO SNOW MODELING AND REMOTE SENSING

Snow remote sensing, assimilation, and modeling (hereafter SRAM) systems, spanning a continuum of output products ranging from derived to synthetic data, have been an important additional source of snow information for decades. Well-established examples in the western U.S. include snow-covered area data from space-based MODerate resolution Imaging Spectroradiometer (MODIS) and Landsat platforms, operational SWE maps from SNODAS, and SWE transects from NOAA gamma flights, all of which have been used operationally to varying degrees by different SDOs. The importance of such technologies is only growing stronger with recent advances in the field, including widely acknowledged, and in some cases semi-operational or fully operational, SRAM systems like ASO, SWESARR, iSNOBAL, SWANN, CSO, and the University of Colorado Boulder model, which use technologies spanning lidar, synthetic aperture radar, AI, multivariate regression, micrometeorological models, citizen-science snow observations, and physics-based snow modeling, among others (e.g., Broxton et al., 2019; Crumley et al., 2021; Hedrick et al., 2019; Painter et al., 2016; Rincon et al., 2019; Schneider & Molotch, 2016; Snauffer et al., 2018).

What does this mean for the SSWSF Program? The development, verification, or day-to-day operation of all SRAM products, which are heavily processed or modeled datasets, depend on the ground-truth provided by direct in situ observational data obtained via SNOTEL and other site-based monitoring programs. As such, the accelerating pace of development in SRAM is only increasing the requirement for high-quality SNOTEL data collection—a rising tide floats all boats, so to speak.

The SSWSF Program has long tracked progress in snow remote sensing and modeling, with periodic experimentation to test potential synergies. That effort is being redoubled today, including engagement in partnerships with the NASA/JPL Western Water Applications Office and the U.S. Bureau of Reclamation, for example, in collaborative projects testing the value of space-based and airborne snow remote sensing for the program. Broadly speaking, our current efforts focus on two general themes: what can SRAM products do for the SSWSF Program, and what can the SSWSF Program do for the SRAM community?

Snow remote sensing, assimilation, and modeling data can play three general roles in support of the SSWSF mission. Each is immensely promising but comes with significant challenges. The first is to support routine day-to-day SNOTEL data QC by providing additional information and spatial context. The main complication in this case is that, because SRAM product generation and verification necessarily uses snow data from SNOTEL or other ground-based monitoring networks, SRAM products do not in general constitute a fully independent check on SNOTEL measurements.

Snow remote sensing, assimilation, and modeling products can also provide additional contextual information to guide location selection for establishing new SNOTEL sites. A potential complication is that—broadly speaking, and there are exceptions—new sites are often placed

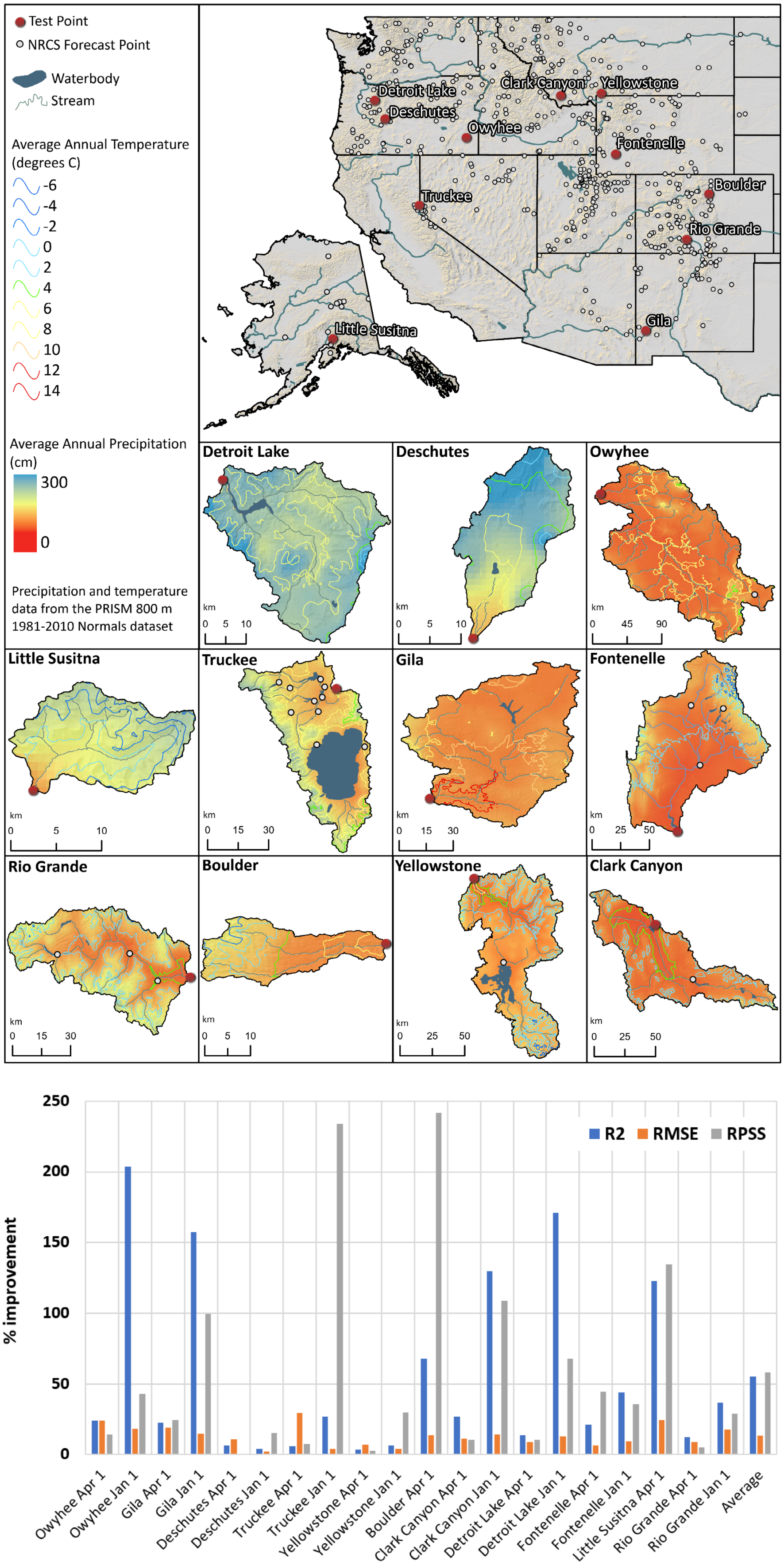

FIGURE 5 Testing locations, and out-of-sample accuracy improvements of AI-based M^4 water supply forecast metasystem compared to an existing benchmark (see Fleming, Garen, et al., 2021). R2, coefficient of determination; RMSE, root mean square error; and RPSS, ranked probability skill score.

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far from current sites to improve snowpack knowledge where little exists. Because the generation or validation of SRAM products depends on such ground-based monitoring data, however, these are also the sites where a SRAM product is, in general, least reliable. Whether this is in practice a significant issue for any particular site-selection process seems likely to depend strongly on location-specific characteristics and the specific SRAM product. An additional complication is that site selection is heavily constrained by logistical issues like site access, as discussed above.

The third, and perhaps most ambitious, role is to provide more spatially complete snow data as improved predictive input for WSF models. A complication is that the water resource science and engineering community, including in particular SDOs performing operational WSF modeling, normally considers long data records, typically 15–30 years spanning a wide variety of hydrometeorological events and hydroclimatic conditions, as necessary for rigorous incorporation of snow, water, and climate datasets into any class of predictive river hydrology model that is used for real-world water management purposes, and perhaps in particular, for the thorough verification procedures that such high-impact applications require (e.g., Cunderlik et al., 2013). Such long records are not available for many SRAM products. Another caveat is that while SRAM products undoubtedly have potential to improve WSF skill, those improvements will in general be incremental. For many rivers in the western U.S., existing ground-based monitoring networks provide a reasonable index of total basin SWE—this has been a primary criterion of site placement since the origins of snow monitoring in the region a century ago and has led to specific NRCS site selection protocols (see above). Today, it is well understood by operational hydrologic forecasters at SDOs that, normally, the largest single source of WSF error is, instead, uncertainty in seasonal to subseasonal (S2S) climate between the forecast issue date and the end of the forecast target period (e.g., Lhotak, 2022). Other components in the WSF process, including the accuracy of hydrologic modeling techniques, also play a significant role in WSF skill. Overall, SRAM data currently seem most likely to enable significant WSF model accuracy improvements in certain specific contexts, like late-season forecasts after the snow line has retreated above the highest-elevation ground station in the watershed; hydroclimatic environments where annual precipitation occurs largely in late autumn through early spring and as alpine snowfall; sparsely instrumented remote basins; and basins where other geophysical processes controlling river runoff dynamics, like surface water–groundwater interactions and evapotranspiration losses, are comparatively subdued. Progress in SRAM is fast-paced, however, and additional applied research may lead quickly to new ways to effectively capitalize on SRAM products as inputs to WSF models (e.g., Bearup, 2021; Bormann, 2020).

Our second general theme—identifying and acting upon potential directions for further improving the utility of the SNOTEL network for the SRAM community—is also seeing progress. The SSWSF Program has a long and continuous history of hands-on collaboration with snow science researchers and other interested communities in the instrumentation of SNOTEL sites. We are leaning further into this existing practice by instituting a Supersite initiative, which substantially augments instrumentation at a subset of SNOTEL sites to enable long-term, strategically located, and high-quality data collection for a wider-than-standard range of environmental variables. Selection of these additional sensors is guided in part by interest in further improving the utility of SNOTEL Program data to SRAM research. That said, further considerations include synergies with applied research in watershed hydrology modeling, paleoclimatology, fire weather, numerical weather and climate prediction, and other topics. As part of this initiative, we have assembled an external advisory panel sourced from outside organizations spanning government, academia, and the private sector. Some communities of practice currently represented on this informal panel, which is helping guide Supersite instrumentation suite selection and site design and operations choices, include space-based and airborne remote sensing, snow modeling and data assimilation, avalanche science and forecasting, weather radar, fire weather monitoring and forecasting, dendroclimatology, geospatial climatology, climate modeling, watershed hydrologic modeling, forest hydrology, and reservoir engineering and water management. The first wave of augmented sensor testing began in 2021, with trial installations at selected Supersites occurring in 2023. Beyond the Supersite initiative, additional SNOTEL development directions underway, or under consideration going forward, include network expansion, such as more complete spatial coverage and establishing even higher-elevation sites in alpine (above-treeline) zones; rigorously evaluating the implications of wildfires and climate change to site placement; exploring and assessing new methods to support site selection; continued refinement and evolution of SNOTEL site instrumentation and design; and continued improvement to existing data homogenization procedures. For example, it has been suggested that Supersites might, in principle, be augmented with a spatially distributed set of measurement nodes to capture finer-scale gradients of interest to snow scientists (e.g., Rice & Bales, 2010). That said, development paths like these are in addition to routinely performed ongoing upgrades to SNOTEL sites and their instrumentation—and of course are subject to the significant resource constraints and practical mission priorities of a water resource-focused operational SDO.

We also emphasize that linkages between remote sensing and the SSWSF Program extend beyond far beyond snow data. For instance, soil moisture is a crucial control on river runoff generation and could enable improved WSF models (e.g., Harpold et al., 2016); remotely sensed measurements promise to expand such capabilities. These considerations also dovetail with the NRCS SCAN network of station-based soil moisture monitoring sites, which provide valuable development and ground-truthing data for remotely sensed soil-moisture products; as noted above, some SNOTEL sites similarly monitor soil moisture as a function of depth.

7 | CONCLUSIONS: THE ROAD AHEAD

With increasing water demand under population growth, and potentially decreasing snowpack and manageable water supply under climate change, water scarcity in the western U.S. will only grow more intense, requiring water management and planning improvements that in turn hinge upon data and modeling advances. In fact, increased water management flexibility through more efficient use of available supplies and existing infrastructure is a leading goal in the U.S. Bureau of Reclamation's climate change adaptation strategy, and improved hydrometeorological forecasting—which necessitates improvements in both observation and prediction systems—is a central element of that plan (Bureau of Reclamation, 2016). The role of the NWCC and SSWSF Program is to support these improvements in water management by continuing to reliably provide, at an operational level and on an ongoing long-term basis, key geophysical data and predictions to other SDOs and to the general public, and to continue innovating to improve the quality, comprehensiveness, and accessibility of that technical information.

Such advances are not trivial, however. For instance, machine learning was first applied to hydrologic prediction research 25 years ago (Hsu et al., 1995; Minns & Hall, 1996). Nevertheless, applications to real-world river forecasting systems have been scarce because available techniques generally did not meet the theoretical and practical requirements of the operational hydrology community; similar experiences have occurred in other areas of Earth and environmental science (Fleming, Watson, et al., 2021). The aforementioned NRCS adoption of AI for improved WSF therefore required us to invent new, application-specific, integrative technologies built to meet the needs of NRCS and our clients, which included a delicate balance between leveraging new techniques while capitalizing on accepted principles and established successes.

The SSWSF Program and NWCC are forging ahead on such challenges. Some of these directions are briefly summarized above, while others we do not have space to cover in this Water Commentary. The paths of both scientific progress and societal priorities can be unpredictable, however, and the future may bring many other applied research achievements that will further improve NRCS ability to monitor and predict the natural environment and contribute to successful resource stewardship.

We are especially excited about identifying and assessing capabilities, gaps, and opportunities around expanding existing ties and building new relationships with other, complementary, communities of practice. Although a few of these partnerships were mentioned above, we have many others in place which we do not have room to discuss here. It also bears emphasizing that several SDOs beyond the SSWSF Program and the NWCC, including multiple semi-independent U.S. National Weather Service RFCs, the California Department of Water Resources, California Cooperative Snow Surveys, U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, Bonneville Power Administration, and others, each operate mountain snow monitoring programs, monitor soil moisture, and/or produce operational hydrologic forecasts, working in various parts of the western U.S., using overlapping but distinct processes and technologies. We are in regular contact to learn from each other's experiences and support each other's efforts; it is in some sense a deeply collaborative enterprise. Moreover, these partially overlapping responsibilities across agencies provide the functional redundancy that is a necessary engineering characteristic of critical operational systems (for a review, see, e.g., Jackson & Ferris, 2013) like the water management infrastructure of the largely dry, and increasingly heavily populated, western U.S. The net result is part of a diversified system for western water management that, relative to many other experiences globally in comparably water-stressed environments, has been demonstrated in social science studies to be reliable, effective, and robust in the face of tremendous challenges (e.g., Doyle, 2012).

AUTHOR CONTRIBUTIONS

Sean W. Fleming: Conceptualization; project administration; resources; supervision; visualization; writing – original draft; writing – review and editing. **Lucas Zukiewicz:** Conceptualization; writing – original draft; writing – review and editing. **Michael L. Strobel:** Conceptualization; writing – original draft; writing – review and editing. **Heather Hofman:** Conceptualization; visualization; writing – original draft; writing – review and editing. **Angus G. Goodbody:** Conceptualization; writing – original draft; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

No data were used in this Water Commentary article. However, readers interested in freely accessing the data, forecasts, maps, and other information resources briefly summarized in this paper may do so at www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/water/national-water-and-climate-center.

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