BUREAU OF RECLAMATION

Emerging Technologies in Snow Monitoring

Report to Congress

U.S. Department of the Interior November 2021

Mission Statements

The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated Island Communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

Cover Photo: Tennessee Creek near the confluence of the East Fork Arkansas River in winter with snow on the Continental Divide (Reclamation).

Emerging Technologies in Snow Monitoring
Report to Congress

Prepared by:

Research and Development Office

Kenneth Nowak, PhD, Research Coordinator

Technical Service Center

Lindsay Bearup, PhD, P.E., Civil Engineer – Hydrologic

Deena Larsen, Technical Writer

California Great Basin Region

Donna Garcia, Economist, Project Manager, Central Valley Operations

Chad Moore, Physical Scientist, San Joaquin River Restoration Program

Lower Colorado Basin

Sarah Baker, PhD, Civil Engineer – Hydrologic, Research and Modeling Group

Acknowledgements

We acknowledge the following agencies for their contributions and review of this report: National Oceanic and Atmospheric Administration, U.S. Army Corps of Engineers, U.S. Department of Agriculture – Natural Resources Conservation Service and Agricultural Research Service, National Aeronautics and Space Administration, U.S. Geological Survey, and California Department of Water Resources

We thank the following peer reviewers for their review of the report: Lineke Woelders, PhD, CU Boulder, CIRES, Western Water Assessment and Jeff Derry, Executive Director, Center for Snow and Avalanche Studies, Silverton, CO

Acronyms and Abbreviations

°F	degrees Fahrenheit
3D	three-dimensional
Act	Snow Water Supply Forecasting Program Authorization Act, 2020
ARS	Agriculture Research Service
ASO	Airborne Snow Observatory
CA-DWR	California Department of Water Resources
CCSS	California Cooperative Snow Surveys
CHL	Coastal and Hydraulics Laboratory
COOP	Cooperative Observer Program
CoReH2O	The Cold Regions Hydrology High-Resolution Observatory
CRREL	Cold Regions Research and Engineering Laboratory
CSAS	Center for Snow and Avalanche Studies
CSO	Community Snow Observations
CSSL	Central Sierra Snow Lab
CU-SWE	University of Colorado real-time spatial estimates of snow water equivalent
DOC	Department of Commerce
DOI	Department of the Interior
DSM	digital surface models
EO	Executive Order
ERDC	USACE's Engineer Research and Development Center
EROS	Earth Resources Observation and Science
fSCA	fractional Snow-Covered Area
GLISTIN-A	Glacier and Ice Surface Topography Interferometer
GPR	ground penetrating radar
HEC	Hydrologic Engineering Center
InSAR	Interferometric Synthetic Aperture Radar
JPL	Jet Propulsion Laboratory
kg/m3	kilograms per cubic meter
lidar	light detection and ranging
LIS	Land Information System
MODIS	Moderate Resolution Imaging Spectroradiometer
MODDRFS	MODIS Dust Radiative Forcing in Snow
MODSCAG	MODIS snow-covered area and grain size
NASA	National Aeronautics and Space Administration
NGWOS	Next Generation Water Observing System
NISAR	NASA-Indian Space Research Organization SAR
NOAA	National Oceanic and Atmospheric Administration

NRCS	Natural Resources Conservation Service
NSIDC	National Snow and Ice Data Center
NWC	National Water Center
NWM	National Water Model
NWP	numerical weather prediction
NWS	National Weather Service
O&M	operation and maintenance
PRISM	Parameter-elevation Regressions on Independent Slopes Model
PRMS	Precipitation Runoff Modeling System
QA/QC	quality assurance/quality control
Program	Snow Water Supply Forecasting Program
Reclamation	Bureau of Reclamation
RFC	River Forecast Center
SAC-SMA	Sacramento Soil Moisture Accounting
SAR	Synthetic Aperture Radar
SCA	snow-covered area
SNODAS	Snow Data Assimilation System
SNOLITE	SNOw telemetry LITE
SNOTEL	Snow Telemetry
sq km	square kilometer
SSWSF	Snow Survey and Water Supply Forecast
SWANN	Snow Water Artificial Neural Network
SWE	snow water equivalent
TLS	terrestrial laser scanning
TRL	technology readiness level
UAV	Unmanned Aerial Vehicle
UAVSAR	UAV Synthetic Aperture Radar
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
West	Western United States
WRF-Hydro	Weather Research and Forecasting Hydrologic model
WWAO	NASA’s Western Water Application Office

Contents

Page

Executive Summary **1**
1. Introduction and Background **4**
1.1. Snow Properties 5
1.1.1. Snow Depth 5
1.1.2. Snow Density 5
1.1.3. Snow Water Equivalent 5
1.1.4. Snow-Covered Area 5
1.1.5. Snow Temperature 6
1.1.6. Albedo 6
1.1.7. Grain Size 6
1.2. Measuring and Monitoring Snow Properties 6
1.3. Using Snow Monitoring Data in Water Supply Forecasts 7
1.3.1. Operational water supply forecasts 9
1.3.2. Water Supply Forecasting Benefits 10
1.3.2.1 Water Supply Reliability 10
1.3.2.2 Environmental Benefits 10
1.3.2.3 Flood Control 11
1.3.2.4 Hydropower Benefits 11
1.3.2.5 Groundwater Management 11
1.3.3. Other Benefits Associated with Better Snow Monitoring and Water Supply Forecasting 11
1.4. Federal Coordination and Partners 12
2. Ground-Based Technologies **15**
2.1. Description 15
2.1.1. Scope 15
2.1.2. Applications in Water Supply Forecasting 16
2.1.3. Challenges 16
2.2. Tech Summary 17
3. Aircraft and Satellite-Based Technologies **21**
3.1. Description 21
3.1.1. Scope 21
3.1.2. Applications in Water Supply Forecasting 22
3.1.3. Challenges 22
3.2. Tech Summary 24
4. Models **31**
4.1. Description 31
4.1.1. Scope 31

4.1.2. Applications in Water Supply Forecasting 32
4.1.3. Challenges 32
4.2. Tech Summary 33
5. Synthesis 37
5.1. Intro 37
5.2. Resolution and Range of Coverage 37
5.3. Reliability 38
5.4. Measurement Properties 39
5.5. Selected Emerging Snow Measurement Technologies 39
5.6. Technology Readiness Level and Cost 40
5.7. Conclusions 45
6. Implementation and Federal Coordination 47
6.1. Partner Agencies 47
6.1.1. Natural Resources Conservation Service 47
6.1.2. Agricultural Research Service 47
6.1.3. National Oceanographic and Atmospheric Administration 48
6.1.4. United States Geological Survey 48
6.1.5. National Aeronautics and Space Administration 48
6.1.6. United States Army Corps of Engineers 48
6.1.7. State and Other Agencies 48
6.2. Partner Agency Coordination Activities 49
6.3. Partner Agency Review of Emerging Technologies 49
6.4. Looking Forward—Program Coordination Process 51
7. References 53

Figures

Figure 1. Snow measurement properties and platforms 7
Figure 2. Role of current conditions in water supply forecasts and water management. 8
Figure 3. Partner agency logos. 13
Figure 4. Snow measurements across time and space. 38

Tables

Table 1. Ground-Based Technologies Summary 18
Table 2. Air and Space-Based Technologies Summary 25
Table 3. Model Technologies Summary 34
Table 4. Selected Emerging Snow Measurement Technologies 40
Table 5. Technology Readiness Levels Definitions 41
Table 6. Technology Readiness Levels and Cost 42

Attachment: Snow Water Supply Forecasting Program Authorization Act

Technical Appendix: Snow Measurement Technology Summaries

Executive Summary

As water supplies and demands change, improved snow monitoring technologies and water supply forecasts are increasingly important for water managers.

Snow plays an important role in water supplies in most Bureau of Reclamation (Reclamation) watersheds. Snow in mountain watersheds acts as a natural reservoir, holding the frozen water that gradually melts to release flows as the season progresses. Accurately estimating the water contained within the snow is critical for water supply forecasts that reservoir operations and broader water management in the seventeen Western United States (West) rely on. This, coupled with impact of climate change on historical precipitation and snow melt patterns, and increases on water demands due to regional population growth, underscores the critical importance of snow monitoring for water managers and water users alike.

The Snow Water Supply Forecasting Program Authorization Act, 2020 (Act), establishes the Snow Water Supply Forecasting Program (Program) within the Department of the Interior (DOI). Reclamation, acting on behalf of the Secretary of the Interior, is implementing the Program to advance emerging technologies to enhance snow monitoring and subsequent water supply forecasts. Program activities stand to build climate change resilience by enabling improved water management and will be implemented consistent with Executive Order (EO) 14008: *Tackling the Climate Crisis at Home and Abroad*.

Emerging snow measurement technologies stand to improve snow monitoring and water supply forecasts in the Western United States.

Snow surveys date back to the early 1900s. Today, activities to monitor snow have expanded to cover more areas, with technological advancements making these measurements more precise. Snow monitoring informs a host of forecasts ranging from short-term streamflow to seasonal water supply forecasts, and advancements in monitoring can lead to forecast benefits. However, uncertainty about snow conditions as well as timing and magnitude of snow melt runoff remains. These uncertainties reflect, in part, the challenges of monitoring snow in the West, which include a very diverse landscape with high peaks over 14,000 feet in elevation, expansive plains, high deserts, and heavily forested areas. Access for measuring snow can be challenging over private lands, wilderness areas, and physically inaccessible areas. The variable nature of snow itself and the extreme cold that often accompanies snow can pose challenges for effective, reliable snow monitoring. Snow measurement can be conducted from different platforms, ranging from ground-based to aircraft and satellite based, or estimated using modeling tools. Each platform and each specific snow monitoring technology has tradeoffs between cost, spatial coverage, temporal coverage, accuracy, precision, resolution, geographic suitability, and reliability.

Pursuant to the Act, this report evaluates emerging snow measurement technologies, discusses their benefits to forecasting, water supply reliability and the environment, and proposes a framework for coordinating with other agencies on Program implementation. To help identify emerging technologies, this report reviews snow measurement methods ranging from long-standing practices to approaches still in research or development phases. For this report, an "emerging" technology is mature enough to be usable in water supply forecasts within the next 5 years—but is not being widely used today. Further, for this report, technologies can include sensors, methods, and models. The report found that ten technologies meet these criteria and stand to improve operational water supply forecasts. These technologies are summarized in Table ES-1. In addition to identifying these "emerging" technologies, the report finds:

- Ground-based snow measurements are critical to developing and evaluating new snow monitoring technologies; maintaining and enhancing these networks is a high priority.
- No single snow monitoring technology provides complete snow condition information throughout the West with the desired frequency, precision, and efficiency. There is unlikely to be such a technology for some time. Accordingly, a "portfolio" approach to snow monitoring that uses a blend of complementary technologies is and will continue to be important.
- While snow characterization is critical for water supply forecasts, weather forecasting and other variables (e.g., soil moisture) play major roles in being able to predict runoff and overall water availability. Improving weather and seasonal climate forecasts for temperature and precipitation will provide the complementary information needed for a more complete picture of future water conditions.
- Several snow monitoring technologies were reviewed but did not meet the emerging technology criteria as they are not yet sufficiently mature. Many of these have the potential to produce substantial future benefits. Continued development of these promising technologies and research on new concepts is valuable.
- Emerging technologies would benefit from an efficient pipeline to integrate them into widespread water supply forecasting. This will require cooperation amongst agencies and a continuing commitment.
- Partner agencies are engaging in significant efforts related to emerging snow monitoring technologies and their use in water supply forecasts.

Reclamation worked with Federal and other partner agencies to review snow monitoring technologies and their use in water supply programs. There is strong consensus that existing technologies are under-used and could be used more effectively to enhance water supplies in the next 5 years.

> A Program Partner Agency Council will be established to coordinate activities and to facilitate the use of emerging technologies in operational water supply forecasts.

Reclamation's Program investments will target activities that improve water supply forecasts, expand snow monitoring in existing and into new river basins, and develop and use new snow measurement tools. Reclamation will collaborate with partner agencies to advance emerging technologies, to coordinate data use and collection for snow monitoring, and to improve water supply forecasting. In support of this, Reclamation will formalize and convene a Partner Agency Council to maximize Program impacts by leveraging investments and provide a forum for information exchange related to use of snow monitoring in water management and water supply forecasting.

Table ES-1. Emerging Technologies

Emerging Technologies Summary

Ground-Based Technologies

- Net radiometers measure energy from the sun and heat from the ground, which informs snow melt timing and can be used to improve snow science.
- Snow temperature sensors measure how cold the snow is at various depths in the snowpack, which can improve predictions of snow melt timing and informs snow science.

Air and Space-Based Technologies

- Aircraft lidar (e.g., Airborne Snow Observatory [ASO]) maps snow depth and when coupled with modeling, provides information on water held as snow.
- Snow Covered Area (SCA) / fractional Snow-Covered Area (fSCA) methods use satellite imagery to map the portion of the land covered by snow.
- Satellite albedo methods use satellite imagery to measure how clean/dirty the snow is, which has implications for how slowly/quickly snow melts.
- Satellite stereo imagery methods use high-resolution pictures from space captured from different perspectives to construct a three-dimensional (3D) model of the Earth’s surface providing information on snow depth.

Modeling Technologies

- Snow Data Assimilation System (SNODAS) is a National Oceanic and Atmospheric Administration (NOAA) system that blends observations and weather model output to estimate snow conditions across the United States.
- Snow Water Artificial Neural Network (SWANN) estimates snow conditions across the United States using a machine learning system that blends snow observations and estimated precipitation data.
- University of Colorado real-time spatial estimates of snow water equivalents (CU-SWE) uses statistical modeling that blends satellite information with historical snow patterns and landscape characteristics to estimate snow conditions.
- Advanced snow models (e.g., iSnobal) use physics to track finely detailed snow conditions and can produce high resolution maps of basins or regions and can more easily incorporate data from air and space-based technologies.

1. Introduction and Background

> To understand the time and space variation in the snow's energy and mass balances along with the extensive feedbacks with the Earth's climate, water cycle, and carbon cycle, it is critical to accurately measure snowpack. - NASA SnowEx Science Plan

For most of the watersheds where the Bureau of Reclamation (Reclamation) operates, snow plays an important role in water supply and thus, its characterization is the foundation for many forecasts regarding water availability. Snow in mountain watersheds acts as a natural reservoir, holding the frozen water that gradually melts to release flows as the season progresses. Snow surveys in the Sierra Nevada of California and Nevada date back to early 1900s. These surveys informed early forecasts, such as those pioneered by James Church at the University of Nevada Reno for the rise in Lake Tahoe from snowmelt. This information informed dam releases and helped to ease tensions among farmers over water availability. Today, snow and other basin condition monitoring is enhanced in spatial coverage and technical precision. These and other advancements have enabled a host of forecasts that span short-term streamflow to seasonal water supply forecasts and are relied on by water managers. Despite these improvements, uncertainty remains about the amount of water held as snow and the physical processes that affect the runoff volume and timing. This is attributable to the multi-faceted nature of snow monitoring and challenges of monitoring snow across the diverse western landscape—from high peaks over 14,000 feet elevation to expansive plains to high deserts to heavily forested areas. Access for snow monitoring can be challenging over private lands, wilderness areas, and rugged mountainous terrain. Emerging technologies for snow monitoring offer opportunities toward more spatially and temporally continuous, high fidelity snow monitoring for a variety of snow properties.

The Snow Water Supply Forecasting Program Authorization Act (Act), 2020, establishes the Snow Water Supply Forecasting Program (Program) within the Department of the Interior (DOI). Reclamation, acting on behalf of the Secretary, is implementing this program. Pursuant to the Act, a report on Emerging (Snow Measurement) Technologies is to be submitted to Congress. This report focuses on snow measurement in the West. Specifically, this report:

- Describes the benefits derived from using technologies to increase water supply reliability and support the environment
- Summarizes the state of practice for snow monitoring and the opportunities presented by emerging technologies to enhance snow monitoring and subsequent forecasts: on-the-ground technologies in Section 2, air and space technologies in Section 3, and snow models in Section 4
- Synthesizes technologies across platforms and discusses how these methods can be used together to provide effective snow monitoring for water supply forecasts in Section 5
- Describes how Federal agencies will coordinate to implement emerging technologies in Section 6

Detailed snow monitoring technology summaries are available in the Technical Appendix of this report.

1.1. Snow Properties

A variety of snow properties play a role in water supply forecasts and subsequent water management and reservoir operations decisions. These can be grouped as measurements that inform how much snow there is and measurements that inform when snow will melt.

1.1.1. Snow Depth

From local weather forecasts to conditions at ski resorts, snow is foremost described by its depth. Across a basin or domain, snow depths can vary considerably as slope, vegetation, exposure, and other factors contribute to how and where snow has been deposited, redistributed, melted, and evaporated. Snow depth provides valuable information regarding water stored as snow, but alone, depth does not completely characterize snow's runoff potential.

1.1.2. Snow Density

Snow density describes the water content of the snow. Atmospheric and meteorological conditions that govern snow formation and deposition processes can produce snowfall with a wide range of densities (mass of liquid or frozen water per unit volume of snow)—from light powdery snow (i.e., 10 percent density or 10 kilograms per cubic meter [kg/m^3]) to heavy wet snow (i.e., 25 percent density or 250 kg/m^3). As such, characterizing the density of the snow is also an essential complement to snow depth in characterizing water volume stored in the snowpack (the accumulation of snow on the ground). A number of factors can impact snow and snowpack densities. For example, snow falling at lower elevations will have a different density than snow falling at higher elevations due to differing atmospheric conditions (e.g., temperature and humidity). Further, as snowpack evolves over time, it is possible for snow densities to vary based on local terrain, vegetation, and other properties.

1.1.3. Snow Water Equivalent

Snow water equivalent (SWE) refers to the depth of liquid water that would be obtained if a column of snow was completely melted. SWE reflects both snow depth and snow density. Total SWE across a watershed represents a measure of snowmelt volume potentially available for river runoff, subject to other geophysical, biophysical, and anthropogenic processes that affect basin water balance, including but not limited to evaporation losses, transpiration losses from forests and crops, interactions with natural storage mechanisms like soil moisture and groundwater, and human alterations to the landscape and its natural streamflow generation mechanisms, such as land use change. For many rivers in the West, SWE data are therefore the primary, but not sole, source of seasonal water supply forecast skill, and generally speaking, the better the SWE data, the better the forecasts.

1.1.4. Snow-Covered Area

Snow-covered area (SCA) refers to how much of the landscape is covered by snow. This allows forecasters, scientists, and water managers to understand what portion of their basin is covered in snow and guide water supply forecasts through empirical relationships. There are variety of methods for estimating this aspect of the snow, and many of these result in a gridded data product. Some gridded data products further refine these grids as fractional snow-covered area (fSCA) to specify what fraction of a grid cell is covered by snow.

1.1.5. Snow Temperature

Snow temperature can be useful for understanding how ready the snow is to melt. Snow at 32 degrees Fahrenheit (°F) is typically ready to melt (though other atmospheric parameters play a role in the 'readiness' of snow to melt), whereas snow that is colder has sufficient insulative capacity to resist melting. Temperature can be measured at the snow's surface or multiple measurements can be taken at different depths in the snowpack. Surface temperatures can be monitored by a variety of approaches, but the temperature profile along a vertical transect of the snowpack (at different depths) is primarily measured on site. While vertical snow temperature transect measurements are infrequently collected, this information is increasingly recognized as valuable for predicting snowmelt timing.

1.1.6. Albedo

Snow albedo refers to the fraction of incoming solar radiation, or sunlight, that the snow reflects. Clean, bright snow reflects a significant portion of incoming radiation; dirty or dusty snow will reflect less and absorb more incoming radiation. In some portions of the United States, dust and other impurities can significantly alter the snow's albedo, causing the snow to absorb more light and thus warm up faster. As such, dirty, dusty snow can melt faster than clean snow, which can significantly impact runoff timing.

Like snow temperature, albedo can be valuable in understanding the timing of snowmelt and subsequent runoff. The radiation/energy balance of the snow is often more significant for snowmelt timing than ambient air temperatures.

1.1.7. Grain Size

In freshly fallen snow, individual snowflakes are loosely and disorderly piled together. With time, the snowflakes merge together into larger ice particles or "snow grains." When snowpack temperatures are near the melting point, the grain size increases further. Larger grains absorb more sunlight than finer grained fresh snow. Subtle changes in the color and albedo of snow can be used to estimate grain size and further understand when snow will melt.

1.2. Measuring Snow Properties

Snow measurement can be conducted from different platforms, ranging from on the ground to in the air to satellites in space. Local, ground-based measurements tend to sample a particular site or very small area, whereas measurements taken remotely from higher altitudes cover larger areas. Ground-based measurements excel at a more exact characterization of the snow—but only at that one location. Aircraft-and-satellite-based measurements can reveal patterns and characteristics in the snow that cannot be seen from the ground—but are sometimes coarser in resolution and may have other limitations when relying on estimating snow properties from indirect signals.

Snow measurements can be manual or automated, with gradations in between. Manual measurements are tedious and infrequent—but allow human intervention for unusual situations and first-hand knowledge of the conditions on the ground. Automated measurements provide a wealth of data at finer time intervals, but equipment failures and measurement errors may go undetected or be difficult to resolve during winter. Figure 1 compares the types of measurement platforms with the snow properties they measure.

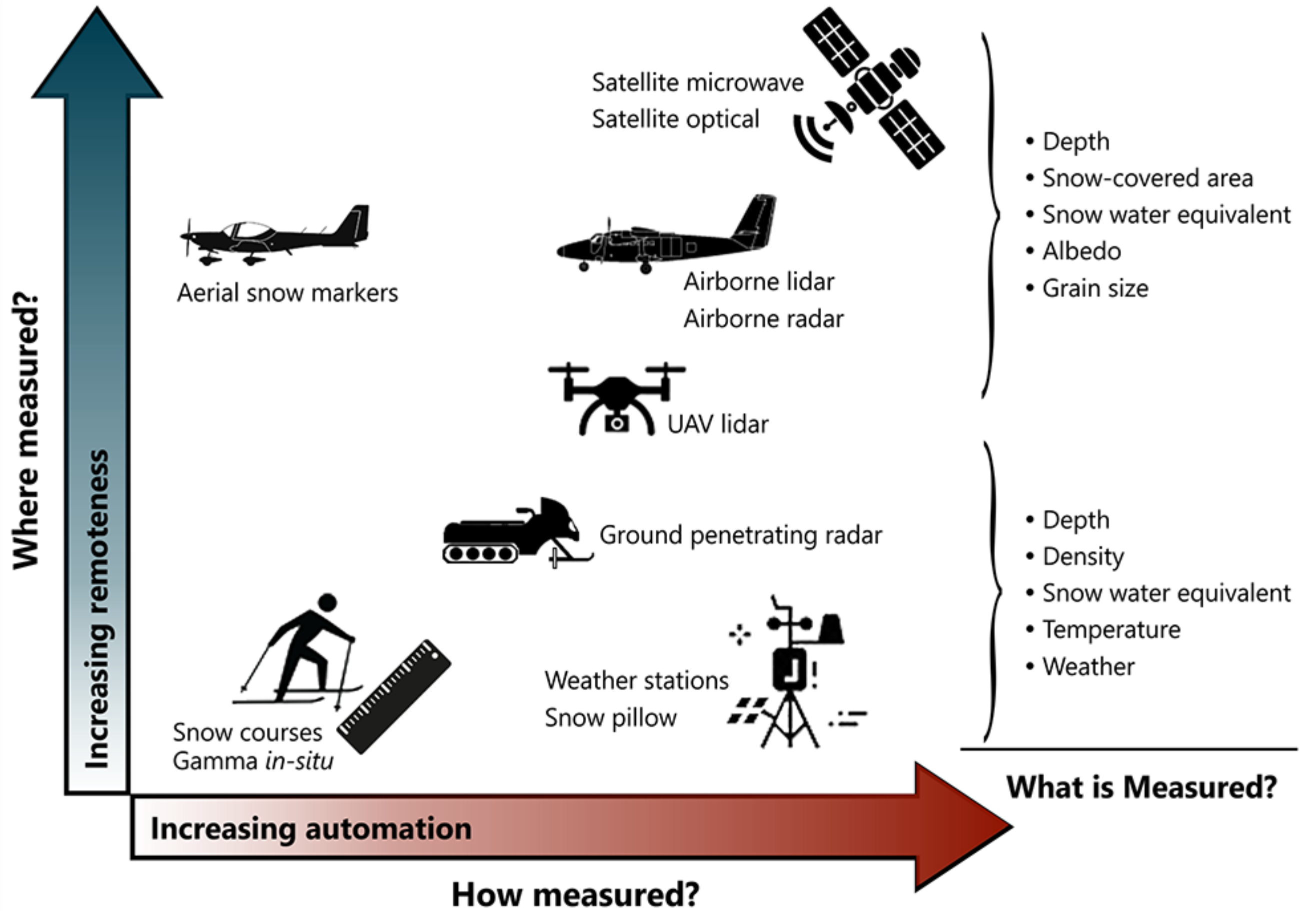

Figure 1. Snow measurement properties and platforms.

Finally, computer models can simulate snow conditions in space and time where/when observations are not available. These estimates provide a valuable complement to direct observations.

Snow models are flexible as they can derive nearly every type of measurement and work with a variety of data yet depend on high quality real measurements to be reliable. Real measurements can include measurements made manually or by automated instruments.

1.3. Using Snow Monitoring Data in Water Supply Forecasts

Water supply forecasts predict the volume of expected runoff over several months into the future. These forecasts inform water management across much of the West. In addition to water supply forecasts, other streamflow forecasts focus on how streamflow at a particular location will change in the near-term (i.e., sub-daily timestep flow forecasts typically on the order of a week into the future). Despite differences in these forecast types and the methods by which they are produced, they all rely in some way on data about current basin conditions (e.g., snowpack) and assumptions regarding future weather over the horizon of interest. Figure 2 shows a generalized process for developing water supply forecasts and their use in water management, including sources contributing to a forecast's uncertainty. Estimates of basin conditions (e.g., snow, soil moisture), future weather, and the model employed can all be sources of uncertainty. In the case of basin snow conditions, there can be uncertainty in the direct measure of snow (i.e., a sensor's accuracy), in the processing of sensor data (i.e., how does a sensor's measurement translate to a snow property), and in the extension/extrapolation of conditions to portions of the basin without direct measures of snow. Figure 2 includes a representation of how uncertainties can propagate into a forecast. Actual uncertainty propagation will vary situationally. In recognition of forecast uncertainty, many forecasts are issued probabilistically, reflecting a range of possible outcomes.

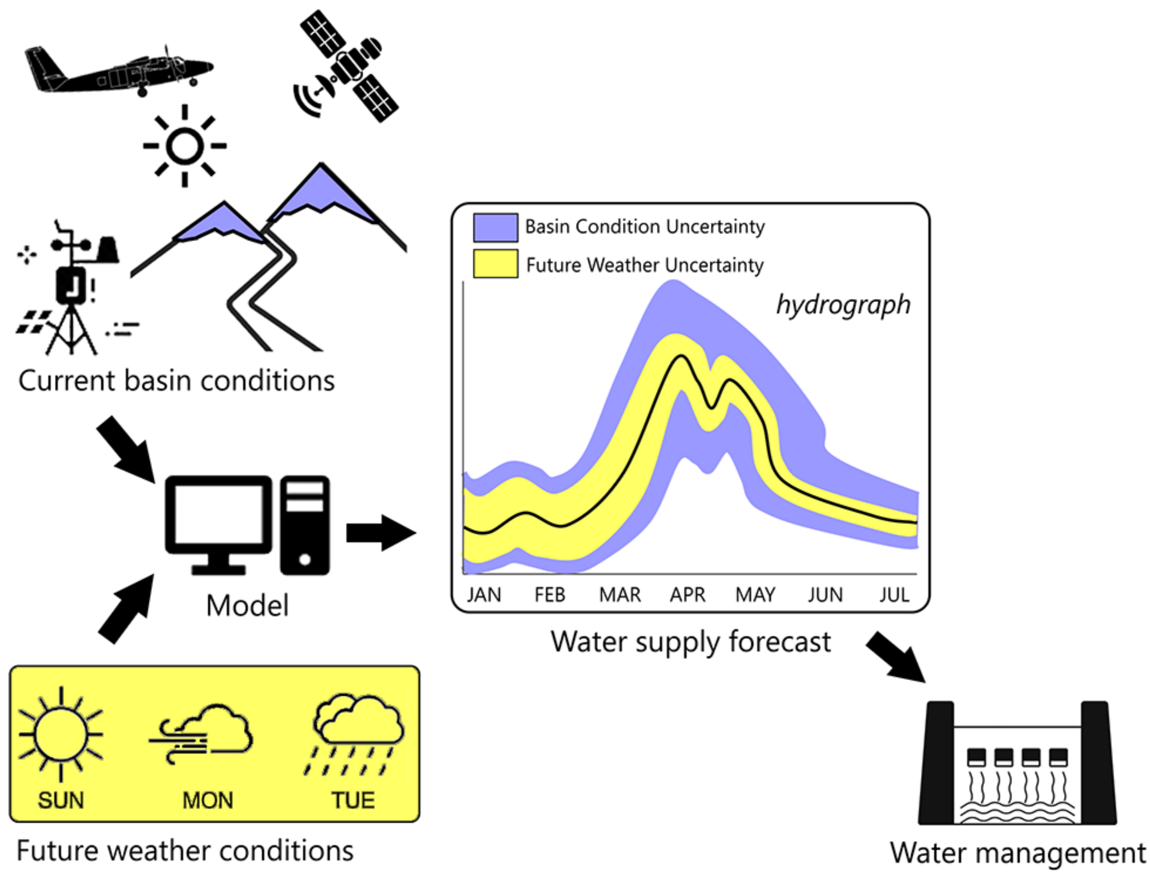

Figure 2. Role of current conditions in water supply forecasts and water management.

Snow monitoring is focused on characterizing current conditions, which are the legacy of past weather/storms. In river basins that rely predominantly on snowmelt runoff (i.e., where a high percentage of the streamflow is a result of melted snow), water supply forecasts derive much of their skill from knowledge about the snow that will eventually become runoff. As such, enhanced monitoring of basin conditions will improve most forecast types. Snowpack tends to peak in late winter and early spring, providing a strong indication of the runoff to come—generally, the more snowpack, the more runoff. However, even after peak snowpack accumulation is reached, future weather conditions (e.g., temperature and precipitation) play a significant role in seasonal runoff timing and volume, and in fact represent the largest remaining source of water supply forecast uncertainty. It is important to note that in addition to SWE, other snow properties can inform aspects of forecasting. For example, albedo (i.e., dust on snow) can have a notable impact on runoff timing. Further, it is possible to forecast changes in albedo if information on impurities in the snowpack have been collected.

While the potential for enhanced snow monitoring to improve water supply forecasts is widely recognized, how readily these advancements can be integrated into forecast processes and ultimately improve skill must be considered. Examples include ensuring the new monitoring data and monitoring period of record is in a format that current forecasting systems can ingest. In some cases, modest forecast model adjustments may be able to address compatibility issues. In other cases, completely different models and paradigms may be needed. Additionally, forecast models all involve some form of calibration whereby the model's response to inputs is tuned. Sufficient historical data are important for this process to be effective. Thus, while most forecasts can and will improve with better basin condition monitoring, use and compatibility considerations must be addressed for maximum impact. Weather forecast improvement is complementary to better basin condition monitoring in improving overall water supply forecast skill. Accordingly, it is important to appreciate how enhanced monitoring of current conditions can improve forecasts compared to other sources of error in a water supply forecast.

1.3.1. Operational Water Supply Forecasts

The Natural Resources Conservation Service (NRCS) and National Weather Service (NWS) River Forecast Centers (RFC) are the main Federal agencies that produce water supply forecasts, though other Federal and State agencies also produce their own water supply forecasts. For some areas and actions, legal decisions or international treaties mandate the use of specific forecasts.

The NRCS maintains a large network of ground-based snow monitoring (i.e., Snow Telemetry [SNOTEL], SNOw telemetry LITE [SNOLITE], and manual snow surveys) stations across the West, which provide valuable real-time and historical snow data. The NRCS uses their extensive network of snowpack observations along with other variables to produce water supply forecasts using various statistical regression methods (e.g., Principal Component and Z-score Regressions), along with physically based models. NRCS forecasts are typically issued at the beginning of each month from January through June.

The RFCs produce short-term streamflow nationwide and seasonal water supply forecasts in the West using hydrology and weather models. RFCs use snow monitoring data (mostly from the NRCS's network), and data from other hydrometeorological networks, to tune hydrology models that produce sub-daily streamflow forecasts at numerous locations throughout a watershed. The RFC hydrology models use equations that estimate physical processes over subdivisions of a watershed based on elevation. Physical models like those used by the RFCs can be more data intensive than statistical models, though they also allow for streamflow forecasts at different spatial and temporal scales. Some RFCs also use statistical water supply models to inform their official water supply forecast.

Several other agencies across the West conduct their own water supply forecasting. The California Department of Water Resources (CA-DWR) maintains ground-based snow monitoring and produces water supply forecasts using statistical methods. CA-DWR's ground-based snow monitoring is coordinated among Federal and State agencies, public utilities, and other cooperators. The CA-DWR uses ground-based monitoring measurements to inform water supply forecasts uses statistical regression methods to produce their Water Supply Index and Bulletin 120. CA-DWR's forecasts, issued December through May, are widely referenced in the state and are the basis for water contracts and joint Federal-State water operations. In addition to CA-DWR, other agencies actively engage in their own water supply forecasting for internal uses.

1.3.2. Water Supply Forecasting Benefits

Improved snow monitoring data offered by emerging technologies has potential to improve water supply forecasts and water management outcomes by improving the timeliness, accuracy, and completeness of our understanding of snow. Improved snow monitoring data offered by emerging technologies can improve water supply forecasts and water management outcomes.

Water managers can use snow data directly in their daily operations, with greater benefit realized when snow data can be fully integrated into water supply forecasts. Reservoir operations and water management often balance competing objectives (e.g., water supply, flood risk management, hydropower, environment, and recreation). Improved information about future hydrology, in precision and lead time, can support a more optimal operational balance for those objectives. The sections below highlight benefits of improved snow monitoring and water supply forecasting to a range of water management and other related sectors.

1.3.2.1 Water Supply Reliability

Water supplies are typically allocated to users based on a runoff forecast, also called a water supply forecast, or a model simulation of reservoir conditions based on such a forecast. Water supply forecasts can be highly uncertain, especially forecasts made early in the winter for snow dominated basins where most of the snowpack has yet to accumulate. Enhancements to water supply forecasts associated with improved snow monitoring can have benefits to water supply reliability and accuracy. With increased forecast confidence, it is possible to align allocations more closely to the forecast, which may provide the ability for managers to allocate more water. The timing of allocations is also important; decisions regarding crops to plant, the need to pursue alternate water supplies, and other considerations benefit from greater confidence in earlier allocations. Further, for reservoirs with carry-over capacity (i.e., there is potential for a significant amount of water to remain in storage from one year to the next), improved water supply forecasts can support maximal fill during the runoff season, which could increase water carried over from one year to the next. Additional carryover can mitigate conditions if the following year has below average runoff to benefit water supply reliability.

1.3.2.2 Environmental Benefits

Reservoir operations and river flows are often regulated to meet the needs of the environment. Sometimes those environmental needs are static, such as releasing a constant flow rate; but usually environmental regulatory flows are proportional to the runoff. Accurate and timely runoff forecasts informed by snow monitoring help assure that such regulatory flows have the most benefit for the environment, as defined by water project's operating criteria or other considerations. It is common for these environmental flows to be released early in the season to aid in life cycles (e.g., cottonwood germination, silvery minnow spawning, or salmon returning from the ocean). Delays in runoff forecasts or runoff underestimates can result in poor timing for these flows that can miss the species' window of opportunity—compounding the conflict between the environment and various other needs and further threatening species.

Water supplies generated from snow are often crucial for maintaining suitably cold-water temperatures. On many rivers, water releases to maintain a certain water temperature for fish habitat are closely tied with water volume available for other uses. Since snowmelt is the primary source of cold water in many Western watersheds, snow monitoring is paramount for managing water temperatures for fish.

As water managers learn to deal with climate extremes and shifting climate averages, critical decision processes hinge upon the volume and timing of snowmelt runoff. Better water supply forecasts, water temperature forecasts, and the timing of runoff are essential for raising the sustainability of water operations, helping ecosystems cope with climate change through managed water releases and flood flows, and generally improving the resilience of reservoir and river operations and infrastructure.

1.3.2.3 Flood Risk Management

By impounding spring runoff for release through the summer, many reservoirs not only provide reliable water supply but also provide flood risk reduction. However, managing for flood risk can at times be competing with water supply objectives. Maintaining significant reservoir storage capacity for flood risk management can reduce the likelihood of a reservoir filling. Conversely, maintaining higher storage volumes for water supply can lessen its capacity to provide flood risk management. Improved knowledge of snow conditions can narrow the range of forecast uncertainty, allowing reservoirs to operate more efficiently and better balance objectives such as flood risk management and water supply.

1.3.2.4 Hydropower Benefits

Improvements in water supply forecasting equates to improvements in fuel supply forecasting for hydropower generation—and, more broadly, a better understanding of potential hydropower generation, flexibility, and value. Depending on the power facility and forecasting timesteps, improved forecasting could deliver a number of benefits—including optimized generation scheduling and dispatch; refined rate-setting, outage and investment planning, power purchasing; and reduced spills. In summary, improvements in water supply forecasting allows better management and increase value from hydropower facilities.

1.3.2.5 Groundwater Management

Groundwater has been used for many centuries if not millennia to supplement rainfall and surface water supplies. Groundwater pumping has allowed agriculture to survive through periods of drought or persistent aridity. The sustainability of groundwater resources is closely tied to accurate and timely runoff forecasts, which in turn benefits substantially from advances in snow monitoring. With sharply increasing interests in managing groundwater sustainably, water managers now need to find ways to recharge aquifers during wet times so that groundwater remains available through future dry times. Thus, water managers today are keenly interested in knowing when more water is available than can be stored or diverted under normal operations. Any forecasted available water could be stored using groundwater recharge if a water right for groundwater storage and reuse is established.

1.3.3. Other Benefits Associated with Better Snow Monitoring and Water Supply Forecasting

Advances in snow measurement and/or water supply forecasting have benefits to a variety of sectors beyond water management. Sectors that benefit from improved snow monitoring and improved water supply forecasts include:

- **Food production.** Food production in the West contributes significantly to regional and national economies and food security. This high productivity depends largely on irrigation and water supply. Improved snow monitoring and water supply forecasts can help growers and producers plan earlier and with greater confidence, informing decisions such as what to plant and how many acres to put into production—or if they need to purchase feed, reduce herd size, or seek alternate water supplies.
- **Forestry.** Snow cover is a component of understanding water availability in forest ecosystems as well, which allows for better management of timber harvesting, forest health, and wildfires. Additionally, data sometimes used to measure snow, such as lidar, multispectral imagery, and weather stations, are directly useful for forest and ecosystem management.
- **Tourism and recreation.** Snow measurement has value to recreation planning, including the ski industry, recreational skiers, and snow motorsports as well as hikers, horseback riders, and other backcountry activities. Snow measurement also informs avalanche risk information, which supports safe wintertime recreation. Runoff forecasts inform a range of river recreation activities such as kayaking, rafting, and fishing.
- **Transportation.** Roadways and rail lines through mountainous areas are costly to maintain, particularly due to snow and related hazards such as rockfalls and avalanches. Measuring snow in and around transportation corridors helps maintenance planning and improves public safety. Improved water supply forecasting would also benefit navigation on waterways that rely on knowledge of water supply to regulate water levels.
- **Infrastructure planning**. Aspects of infrastructure operation and maintenance are informed by runoff forecasts and flood frequency analyses, both of which benefit from improved snow monitoring. Examples include scheduling maintenance and construction or assessing risk.
- **Wastewater treatment.** Influent flow rate is an important parameter to help plan wastewater treatment operations to achieve stable effluent quality, identify capacity risks, and develop alternatives to upgrade existing infrastructure. In some regions, snowmelt contributes to wastewater treatment influent flows; and thus, better snow monitoring and water supply forecasts may benefit determining the influent inflow rate.

Other secondary effects, such as rural area employment, often depend on tourism, food production, and transportation—all areas that benefit from improved forecasts. Conversely, inaccuracy or latency in water supply forecasts can have far-reaching and seldom quantified costs.

1.4. Federal Coordination and Partners

Monitoring snow and using snow data in forecasting applications span a range of Federal and State agencies. Consistent with Section 4.3.c of the Act, Reclamation coordinated with a range of agencies involved in snow monitoring and / or forecasting to develop this report and will continue to do so through Program implementation. Agencies include:

- United States Department of Agriculture (USDA) – Natural Resources Conservation Service (NRCS) and Agricultural Research Service (ARS)

- Department of the Interior (DOI) – United States Geological Survey (USGS)
- National Aeronautics and Space Administration (NASA)
- Department of Commerce (DOC) – National Oceanic and Atmospheric Administration (NOAA)
- United States Army Corps of Engineers (USACE)
- California Department of Water Resources (CA-DWR)

In addition to Federal and State snow monitoring efforts, a number centers and institutes conduct important snow monitoring activities. These entities often focus on a specific region and encompass research and operational monitoring aspects of snow science. Examples include the Center for Snow and Avalanche Studies (CSAS) and the Central Sierra Snow Lab (CSSL).

Figure 3. Partner agency logos.

2. Ground-Based Technologies

2.1. Description

2.1.1. Scope

Ground-based technologies measure snow on the ground, usually at a single location or in a small area. Measurements are typically made at predefined locations where measurements have been made historically, such as at automated snow and weather stations (e.g., SNOTEL and SNOLITE sites). These stationary measurements (e.g., snow pillows/load cells, snow cams, or other measurements such as snow courses) measure snow depth and SWE. At monitoring sites such as SNOTELs, typical measurements include SWE, snow depth, precipitation, and air temperature, as well as other variables that are measured concurrently, including wind speed, solar radiation, humidity, and soil moisture. Mobile measurement technologies (e.g., ground penetrating radar [GPR] or terrestrial laser scanning [TLS]) cover a slightly larger area but are not widely used. Specific technologies are described in Appendix A.

Over the past century, ground-based technologies have improved. The first snow measurements were made by manually measuring snow depth and SWE using snow tubes at permanent snow course locations. Snow courses were typically visited monthly throughout the winter and remain important as they provide information about historical trends in snowpack. Newer developments and applications for ground-based technologies build upon these basic ideas to measure a slightly larger area and provide more effective maintenance—thus improving the accuracy and range of previous measurements. As technologies improved through the 20th century, permanent automated weather stations with snow-specific sensors were installed in remote locations to continuously measure SWE, snow depth, and other snow properties. These automated weather stations, many co-located with snow courses, have operated for decades. This rich history of snow data is important to provide a long historical record, which is widely used in operational water supply forecasts. Both manual and automated ground measurements must contend with extreme cold temperatures, rugged terrain, and other access limitations such as land ownership or wilderness designations.

Ground-based technologies vary widely. Some technologies measure continuously while other measurements are made a few times during the winter, as they require a person to manually measure snow variables. Though manual measurements can only be made a few times each winter, there is generally high confidence in these measurements since a person can validate these data. Remotely installed technologies that measure continuously, such as those at weather stations, may have errors that cannot be easily validated or corrected. For instance, snow pillows could produce bad readings due to sensor malfunctions or snow bridging, which may be difficult to diagnose remotely. Snow bridging refers to a condition that can result in artificially low snow measurements. Sensors placed under the snow can estimate snow water content based on its weight upon the sensor. Occasionally, snow or ice may form a "bridge" over the sensor to the adjacent ground, preventing an accurate measure of weight. Though these automated weather stations may require careful quality control to identify and address such issues in a timely manner, they are very useful as they help track the snow accumulation through the winter and melt through the runoff season. Continuous measurement capabilities are critical in water supply forecasting as they provide useful information on the timing of runoff—rather than just the runoff volume. Ground-based measurements are also vital for verification and validation of other products that model or remotely measure snow properties.

In addition to differences in each technology's measurement frequency, technologies also differ in their complexity. Technology ranges from simple (e.g., snow markers that are photographed for manual measurements) to complicated (e.g., snow pillows installed below grade level that transmit hourly data). New ground-based technologies stand to improve upon existing technologies or apply existing instrumentation that is used in other fields to snow measurement applications (e.g., TLS and GPR), though these emerging technologies are not widely used in operational water supply forecasting.

2.1.2. Applications in Water Supply Forecasting

Forecasting agencies rely on ground-based snow measurement locations with a long historical record to inform their predictions of water supply. The NRCS and other agencies, such as the CA-DWR, collect manual snow measurements and installs and maintains automated weather stations across the West. Various Federal and State agencies use automated and manual snow measurements (along with air and space-based measurements discussed in the following section) to inform the statistical methods that NRCS and CA-DWR typically use. RFCs use automated weather station data to develop forcings for hydrology models that produce sub-daily streamflow forecasts at numerous locations throughout a watershed. Reclamation uses water supply forecasts produced by the RFCs and NRCS to inform water management throughout basins in the West.

2.1.3. Challenges

- **Maintenance and reliability:** Many automated ground-based snow measurements are in remote areas that are difficult to access during the winter. If ground equipment is disturbed or stops working, measurements won't be recorded until the next service visit. There are potential issues with reliability due to bad measurements (e.g., snow bridging or sensor malfunction) or extreme cold that may be difficult to verify and can decrease confidence in the sensors. As with any automated measurement devices, a strategy to verify and to ensure quality control is important. As such, agencies that maintain these automated monitoring stations review datasets daily using automated flags that typically catch erroneous readings and through manual quality control techniques. The ability to repair a malfunctioning sensor in a timely manner can depend on access, safety, and environmental conditions at the location.
- **Access and safety:** Manual snow measurements are often conducted in remote locations and under the demanding conditions of short days, steep terrain, avalanche danger, high altitude, cold temperatures, towering winds, heavy precipitation, low visibility, and deep snow. Maintaining automated stations faces many of these same difficulties. Despite these considerations, manual measurements are still regularly conducted. Similarly, it is possible to access automated stations in winter—but is more resource, labor, and time intensive as compared to summer.
- **Cost:** Cost to set up a manual snow courses is modest, with cost to collect the data being substantially higher over time. Often, cooperators (land management agencies, private reservoir operators, or other Federal agencies) bear the cost of snow course data collection. Automated stations may cost over $100,000 to establish a new site in a remote location, with

annual maintenance depending largely on accessibility. For both manual and automated stations, challenges include the continued cost of data collection and operation and maintenance (O&M), which often requires snowmobile or helicopter access and landowner permission.

- **Spatial coverage:** Measurement sites only provide data for an individual location. Because of this, assumptions are often made on how a site represents a wider area. This can cause errors in water supply forecasts as there is high variability in snow over a watershed.

2.2. Tech Summary

Table 1 summarizes important ground-based snow measurement technologies, and Appendix A provides more detail for these technologies. It is noteworthy that many sensors have been developed or tested for monitoring snow or snow related parameters. This table offers a subset that are focused on characterization of the snow itself, with applications for water supply estimation and forecasting. Examples of snow technologies not included are blowing snow sensors and snow detection sensors. Further, it is acknowledged that monitoring hydro-metrological variables related to snow (e.g., wind, ambient temperature, soil heat flux, and soil moisture) is important for improved snow science and modeling but are beyond the scope of this report. Last, there have been many demonstrations of how an existing sensor or technology might be repurposed for snow monitoring; these concepts are also beyond the scope of this report.

Ground-based snow technologies are invaluable for snow water supply forecasting. Snow measurements at prescribed sites that have a rich history of data are routinely used for operational water supply forecasting (e.g., the RFCs, NRCS, and CA-DWR). Many ground-based snow measurement sites are in remote locations that either have automated technologies transmitting data or require manual measurements. The remoteness of sites causes challenges with accessibility, safety, and reliability of the measurements. A continuation of these records, both from manual and automated measurements, along with strategically adding new monitoring, is necessary for accurate water supply forecasts. Additionally, these data are critical for ground-truthing other snow measurements from other technologies (e.g., satellite and model-based products).

New technologies stand to provide more complete measurements of snow parameters. They can provide new insights into the snowpack, including new ways to measure albedo, snow temperature, and grain size, which are important for understanding the energy balance of the snowpack. With continued research, these technologies will add to our knowledge and effectiveness at forecasting water supply.

Table 1. Ground-Based Technologies Summary

Technology Name	Property	Description	Strengths	Limitations
Snow Courses and Snow Tubes	Snow Depth, SWE	Snow courses are locations where manual snow measurements are taken during the winter using a snow tube. Snow tubes or samplers are specially designed tubes that allow a snow core or profile to be extracted from the snowpack, from which snow depth and SWE can be ascertained.	Many measurement locations have a long history of snowpack information, which is vital to water supply forecasting. There is high confidence in measurements as they are verified in-person.	Measurements require a person to physically visit a location, many of which are remote and may be difficult to access safely. They also provide data at individual points in time, as measurements are only made a few times each winter.
Snow Pits	Snow Depth, Albedo, SWE, Snow Temperature, Grain Size	A snow pit involves digging a trench in the snow, exposing a vertical profile of the snowpack for inspection and various measurements.	Allows for direct interaction and observation of the snowpack, and layers. A variety of snow properties can be measured / documented, including dust/impurity layers.	Digging a snow pit and making measurements of snow properties is a labor-intensive process. Data from snow pits are generally limited to a few point locations, with variable data temporal frequency and latency. These factors contribute to snow pit measurements being largely used opportunistically and qualitatively in forecasting.
Citizen Snow Measurements	Snow Depth	Community Snow Observations (CSO) is a citizen science project that provides a platform for the larger community to upload snow depth measurements via smartphone apps that provide a time and location of the observation.	CSO and similar efforts provide more spatial coverage and possibly data in challenging terrain, making these observations complementary to established monitoring sites.	Community data vary in regularity and are often measurements of opportunity. Data collected may not necessarily be used for water management purposes but more so for recreational uses, such as avalanche conditions. Further, it is difficult to know the quality of community measurements as there can be variability in practices from individual to individual.
Aerial Snow Marker	Snow Depth	Tall vertical posts with horizontal cross-pieces that can be read by aircraft passing at low altitudes.	Inexpensive and minimal maintenance. Effective at capturing snow depth at high elevations and inaccessible sites.	Snow drifts can form around the post. Post can cause melting. Difficult to install in Wilderness Areas. Readings require aircraft passes, which have substantial safety and cost considerations.

Technology Name	**Property**	**Description**	**Strengths**	**Limitations**
Snow Pillow	SWE	Common technology used at automated weather stations (e.g., SNOTEL sites), which uses a flexible bladder filled with antifreeze to convert fluid pressure into weight, which is then converted to SWE.	Useful in providing continuous knowledge of SWE throughout the accumulation and runoff season, which is important for water supply forecasting, especially during the runoff season.	Operations and maintenance issues can occur and may be difficult to remediate during the winter. There is a potential for bad readings (e.g., due to snow bridging or sensor malfunction), which are difficult to verify and decrease confidence in sensor.
Snow Depth Sensor	Snow Depth	Sensor uses ultrasonic pulses to measure the distance from the sensor to the snow. This combined with the sensor's height above the ground provides snow depth.	Technology is low cost, extensively used, and provides quality non-contact measurements.	Measurements can be impacted during and shortly after snowfall.
Load Cell / Fluidless Snow Pillow	SWE	A series of flat panels assembled on a rigid frame, which uses force transducer sensors to measure the weight of snow, which is then converted to SWE.	Avoids using anti-freeze in bladder. May reduce O&M compared to snow pillows. Panels are relatively small sections, making for reasonable portability.	Cost to install is higher than snow pillows. May present issues with snow bridging across the primary measurement load cells. Technology is not widely used operationally.
Gamma *In-situ*	SWE	An instrument placed on a framed structure facing downward that measures energy penetrating the snowpack.	Avoids using anti-freeze in bladder and is not affected by snow bridging. May have less O&M than snow pillows. Sensor is relatively small with a larger area measured than snow pillows.	Calibration may be challenging to keep operating in remote environment. Technology is not widely used operationally.
GPR	Snow Depth, Snow Density	Ground penetrating radar is an instrument pulled behind a skier or snowmobile that uses two-way travel time of electromagnetic waves in the microwave band to identify boundaries in the snowpack.	High spatial resolution; intermediate spatial coverage may be beneficial for specific local applications.	Limited spatial and temporal coverage for basin-scale water supply forecasting. Accessibility may be a challenge. 'Wet' snow adds additional complexity and introduces error in depth and SWE estimates.

Emerging Technologies in Snow Monitoring

Technology Name	Property	Description	Strengths	Limitations
TLS	Snow Depth, Snow Covered Area	Terrestrial laser scanning uses an instrument placed on a tripod that uses lidar to measure an area without snow, then with snow, to calculate snow depth.	High spatial resolution. Intermediate spatial coverage. Portable and easy to operate.	Limited spatial and temporal coverage for basin-scale water supply forecasting. Snow compaction during scans can cause errors in measurement; expensive instrumentation.
Net Radiometer	Solar Radiation, Albedo	A sensor that measures the energy in the form of incoming and outgoing short-wave and long-wave radiation from sky reaching the Earth's surface.	A relatively simple technology. Useful for energy budget modeling. New applications for use in measuring albedo. Estimation of albedo can support dust on snow monitoring.	Limited spatial coverage. Can be affected by site specific considerations (e.g., trees). Dust and/or snow can obstruct the sensor causing erroneous measurements. Independent calibrations for each deployed instrument can be difficult.
Snow Temperature Sensor	Snow Temperature	An arrangement of temperature sensors measuring snow temperature at distinct elevations within a snowpack.	Continuously measured. Simple technology. Impactful variable for snow energy balance modeling, especially during the runoff season.	Not a robust network and relatively unknown variable. Current forecasting methods do not have an easy way to ingest information. *In-situ* sensor can introduce bias to the measurement variable.
GPS Receiver	Snow Depth	A ground-based receiver records GPS satellite signal reflected off the ground to measure the change in ground elevation compared to a no snow measurement.	Measure a fairly large sensing area. Robust sensors require minimal maintenance.	Higher measurement errors than other devices. High initial cost. Difficulties when measuring at sites surrounded by trees.
Digital Snow Probes	Snow Density, Snow Depth, other snow properties	Snow probes estimate snow properties by measuring the force required to push the probe through the snowpack (e.g., snow penetrometers) or the capacitance of the snow.	Relatively portable. Quick measurements allow for more samples across an area. Adequate or high vertical resolution in the snowpack.	Indirect density measurements lead to larger errors, requires calibration. Individual measurement covers a very small area.
Cosmic Ray Neutron Sensor	SWE	A sensor measures the loss of energy undergone by naturally occurring neutron as they collide with water molecules in the snowpack; this loss is then used to estimate SWE.	Larger measurement footprint than snow pillows. Easy to install. No antifreeze. Continuous measurements.	Measurements require corrections to produce accurate estimates. Less accurate in deep snow.

3. Air and Space-Based Technologies

3.1. Description

3.1.1. Scope

Air and space-based technologies use sensors that can detect different characteristics and frequencies of energy (e.g., visible light, microwave, and other bands of electromagnetic energy) to estimate different properties of snow (e.g., SWE, snow depth, snow coverage, and grain size).

Air and space-based technologies for observing snow properties range from sensors mounted on Uninhabited Aerial Vehicles (UAV), to piloted airplanes, to satellites. Generally, as the distance of the platform from the ground increases, so does the area that can be observed. However, the tradeoff is often coarser resolution and sometimes reduced accuracy.

Small UAV, referred to colloquially as "drones," fly close to the ground and capture relatively small areas (tens to hundreds of hectares per flight) with good spatial detail. High-resolution photographic imagery and lidar instruments aboard UAV are used to determine snow depth. Similar sensors can be mounted on airplanes to provide broader spatial coverage at slightly coarser resolution. The Airborne Snow Observatory (ASO) methodology, first developed at NASA's Jet Propulsion Laboratory (JPL) and now commercially available (ASO, Inc.), combines lidar-derived snow depth with albedo estimates from an imaging spectrometer to model SWE using the iSnobal model described in Section 4.

Radar instruments can also be mounted on planes or large UAV, such as UAV Synthetic Aperture Radar (UAVSAR). UAVSAR is flown on a jet with a sophisticated autopilot system to estimate changes in SWE, while Glacier and Ice Surface Topography Interferometer (GLISTIN-A), its counterpart that uses a different radar band, provides snow depth. One disadvantage to airborne instruments is that data are only available when these platforms are flown, and these platforms are not yet flown fully operationally or regularly. Efforts to operationalize air-based snow monitoring technology face challenges, including ongoing costs and flight planning that is limited to times and places with suitable weather.

Despite decades of international effort, quantifying SWE from space continues to pose significant challenges. Although sensor and processing advancements have improved over the last 40 years, currently only passive microwave based SWE data are regularly produced—and these estimates are limited to specific snow and site conditions and are at a resolution that is generally too coarse for water supply forecasting in mountainous terrain. Ongoing research looks at combining different bands of radar to overcome the limitations of individual sensors for space-based applications, with much attention given to the upcoming NASA-Indian Space Research Organization SAR (NISAR) mission. NISAR includes L-Band and S-Band radar instruments and is set to launch later this decade. Other international missions are also under development. The Cold Regions Hydrology High-Resolution Observatory (CoReH2O; Rott et al., 2010) SAR mission from the European Space Agency did not receive authorization due to the reliability of retrieval algorithms for SWE in forest cover and need for snow grain size estimates, which are not available globally. The Canadian Space

Agency is exploring the use of a dual frequency Ku-band radar mission and the China-sponsored Water Cycle Observation mission could include a suite of radar instruments suitable for snow measurements.

Multiple satellite missions do support the operational production of other snow datasets, most notably fSCA and albedo. Unlike airborne approaches that are only flown on demand, satellite platforms orbit the Earth and revisit a location on regular timescales of days to weeks—creating a more continuous record.

3.1.2. Applications in Water Supply Forecasting

The most reliably produced satellite snow product, fSCA, indicates the presence or absence of snow and does not quantify snow depth or SWE independent of additional analyses such as the University of Colorado real time spatial estimates of SWE product (CU-SWE) described in the Technical Appendix. Operators can use fSCA to identify what areas of the watershed have melted out—providing a check on remaining snowpack that can be used to adjust model snow states. For example, water supply forecasts such as those from NOAA's RFCs, do not directly use remotely sensed information as input in a typical model forecast (see the discussion of this model, SNOW-17, in Section 4.1.2 and Appendix A). Forecasters use remote sensing information, notably the Moderate Resolution Imaging Spectroradiometer (MODIS)-derived fSCA and albedo products, to adjust forecasts when they begin to deviate from real-time conditions. Research applications using sophisticated snow models also use fSCA to constrain models when no other observations are available, reinforcing the strength of satellite products for remote areas.

Airborne platforms such as ASO collect remotely sensed information (aerial lidar-measured snow depth and spectrometer-measured albedo) and have a workflow in place to provide SWE with turn-around times that are reasonable for operational use. An informal working group led by CA-DWR guides ASO deployment in California, providing SWE data to water managers in important water supply basins, including the Tuolumne, Merced, San Joaquin, Kings, and Kaweah River basins. A similar group recently formed to develop a plan for funding ASO flights in Colorado. Operators indicate that this information has improved decision making and the ability to balance competing water demands, including power supply and environmental flows, as well as minimizing flood risks. Several groups have expressed interest in this technology based on its ability to fill gaps in traditional snow measurement. Using ASO data in operational water supply forecasts, such as RFC forecasts, is still an active area of development.

3.1.3. Challenges

Different airborne and space-based technologies have different challenges (see Table 2 for more information about each technology's specific strengths and limitations). Challenges may include:

- **Accuracy**: The accuracy of remotely sensed data can be influenced by many factors, depending on the sensor, including:
    - Cloud cover: some sensors cannot penetrate cloud cover—resulting in frequent data gaps, particularly in cloudy regions.
    - Vegetation: some sensors cannot take measurements below the canopy at all, while others may have reduced accuracy in areas with dense vegetation due to sparser measurements or challenges in distinguishing vegetation from the ground surface (for surface differencing techniques).

  - Snowpack properties (moisture content, grain structure, and shallow or deep depths): Approaches that rely on interpreting the response of electromagnetic signals after interacting with the snowpack must account for how the properties of the snowpack influence the signal response.
  - Topography (shading, resolution): sensors that rely on the passive sensing of sunlight (i.e., optical sensors) are limited in shaded areas.
  - Repeat imagery: many processing techniques rely on multiple collections over the same location. Ensuring the observations are correctly and accurately located relative to each other is critical for accurate measurements.

- **Ground verification:** As with any measurement, and particularly with non-manual measurements, verifying remote sensing data is important to ensure quality control. With remote sensing, ground verification may also be needed to adjust for physical properties that effect accuracy, such as snow structure, vegetation, and terrain. Further, some retrieval processes require ground-based measurements to correlate sensor signals to snow properties.
- **Resolution**: There is often a tradeoff between the spatial and temporal resolution of remotely sensed data products. Aerial (UAV/aircraft) observations tend to have very high spatial resolution, on the order of meters, but temporal resolution is limited to when flights can be made. In contrast, satellite products have higher temporal frequency, on the order of days to weeks, but a range of spatial resolution from tens to thousands of meters.
- **Spatial coverage**: Aerial based products are limited in spatial coverage to the areas that can be flown, which are often centered around an aircraft's base of operations.
- **Temporal coverage (period of record)**: Many aircraft-and-satellite-based products are new, relative to ground-based measurements. Currently used water supply forecast models often require calibration/training or assessment of longer datasets to ensure correct assimilation before a product can be used operationally.
- **Complexity of retrieval algorithms**: Remotely sensed datasets require a range of processing methods to convert the sensed signal to information about that snowpack. These retrieval algorithms represent a range of complexities, from screening out vegetation appropriately in lidar point clouds to combining multiple bands or repeat passes of SAR instruments in a meaningful way.
- **Cost**: Costs for air and satellite-based technologies are a combination of equipment/capital costs, operation and maintenance costs, data collection costs, and research costs to develop data processing methods. While similar types of costs exist in ground-based technologies, the complexity of air and space platforms often come with significantly higher up-front costs before any benefits are realized. However, these costs are often shared, or technologies may take advantage of existing assets, thereby reducing or eliminating costs to end users. Many satellite products are used for applications other than snow and water sector, limiting the costs to processing the existing data for snow products. Aircraft-based products, such as ASO, are considerably less expensive to deploy relative to a new satellite, but the cost is ongoing and often not shared across sectors. Small UAV-based observations are relatively inexpensive and can be integrated into existing UAV programs that likely have lidar and imaging sensors, but large survey areas are not realistic and would take many days to cover, thereby increasing costs.

Thus, a least cost analysis or cost effectiveness analysis would be required for each technology considered to determine the benefits gained for the particular use of an aircraft or satellite to gather data.

3.2. Tech Summary

The great diversity in snowpack characteristics (e.g., depth and liquid water content) and cold regions environments (e.g., forests, complex terrain, and barren tundra) pose a great challenge for measuring global SWE. The international snow remote sensing community has been active in responding to this challenge and has developed a number of snow remote sensing technologies. – NASA SnowEx Science Plan

Table 2 summarizes the air and space-based technologies most suitable for snow measurement to support water supply forecasting. Appendix A provides more detail for these technologies.

Snowpack conditions vary within watersheds and larger regions, and sensors may be more effective in certain environments (e.g., microwave sensors require similar, flat landscapes and are not as accurate in areas with differing vegetation or uneven terrain, where a lidar sensor would be more appropriate). While there is not currently a single sensor that can accurately measure SWE across the diverse snow-covered areas of the world, thoughtful use of air and space-borne sensors can provide critical information to observe snow and support water supply forecasting.

Further coordination to include emerging snow measurements from remote sensing programs and leveraging advances in snow modeling and data assimilation could provide significant opportunities for understanding SWE and other snow properties. For this snow information to be readily useful to water managers, water supply forecasting workflows must also evolve to use the spatially distributed information. In addition, ongoing support for these emerging observational platforms is needed so that they may develop long enough records to enable incorporation in forecast models.

Table 2. Air and Space-Based Technologies Summary

Technology Name	**Property**	**Platform/ Product**	**Description**	**Strengths**	**Limitations**
Interferometric Synthetic Aperture Radar	Snow Depth; SWE	NISAR (satellite-based L-Band) UAVSAR (UAV based L-Band) GLISTIN-A (UAV based Ka-Band)	An active remote sensing technology emitting energy that interacts with the earth surface before being reflected back to the sensor. Processing SAR data using interferometry relies on correlating a shift in the phase of the signal between repeat passes to determine a property of the ground or snow cover. Ka-Band InSAR uses repeat InSAR passes to estimate changes in snow depth by differencing the resulting surfaces and can be combined with snow density modeling to estimate SWE. L-Band InSAR differences repeat passes but directly estimates SWE from interferometry.	Radar methods do not require sunlight and can penetrate cloud cover. Spatial resolution (e.g., NISAR at 30 meters [m]) is good for snow observations. Ka-band can be used in wet snow conditions and in complex terrain. Ka-Band is on board the GLISTIN-A aircraft, part of the UAVSAR program, and specific flights can be requested making it near operational.	Retrieval of snow property data requires extensive processing and often corrections including other observations to ensure reasonable accuracy, particularly in areas of deep snowpack and vegetation. Products are largely experimental, and snow products are not yet produced operationally. Even after deployment, satellites will require testing and validation (e.g., NISAR). L-Band only provides estimates of SWE in dry or nearly dry snow conditions (little to no liquid water in the snowpack). Temporal resolution of airborne products (e.g., UAVSAR) is limited to flight time while satellite products (e.g., NISAR) may only be available every 6 to 12 days. InSAR retrieval techniques require repeat passes of the same location, thus orbital positioning control and precise geo-location data are needed for accurate measurements.

Technology Name	Property	Platform/ Product	Description	Strengths	Limitations
Synthetic Aperture Radar-Backscatter	Snow Depth; SWE	Sentinel-1 (satellite-based C-Band), SnowSAR, SWESARR, TerraSAR-X	An active remote sensing approach that estimates snow properties from the backscattering response of radar. Using different retrieval approaches, snow depth and SWE can be estimated from the scattering response of radar through the snowpack. SWE estimates have been made using multiple bands, or combinations of bands of radar, such as K, X, and Ku, while snow depth has been estimated from Sentinel-1 C-Band backscatter signatures. Backscatter-based approaches are also well suited for the detection of the onset of snowmelt.	Temporal (6 day) and processed spatial (1 kilometer [km]) resolution of Sentinel-1 data are reasonable for some snow applications. Radar methods do not require sunlight and can penetrate cloud cover. Sentinel-1 data processed for snow depth are available through the C-SNOW project. https://ees.kuleuven.be/project/c-snow.	With most bands, the approach is only accurate in dry snow and may require additional corrections or verification in shallow snowpack, forested areas, or complex terrain.

Technology Name	Property	Platform/ Product	Description	Strengths	Limitations
Lidar	Snow Depth	ASO (aircraft -based) ICESat-2 (satellite-based)	An active remote sensing technology that uses laser response times to generate very high-resolution maps of altimetry. Snow depth is calculated by differencing snow-covered and snow-free surfaces. This method can be combined with snow density measurements or models to estimate SWE. Lidar instruments are also mounted on satellites (such as ICESat-2) but snow depth products are not currently available at the spatial resolution needed for water supply forecasting.	The ASO program provides flights and processing to generate SWE estimations with minimal additional processing needed by the customer. With airborne deployment, estimates can be made in rough terrain and in vegetated areas, if processed correctly.	Currently, no operational program is in place to ensure flight timing or availability. Cost for flights is passed directly to the consumer, creating higher costs than technologies supported by other entities. Instruments cannot penetrate cloud cover and are limited to suitable flight days. Satellite deployment is not currently practical for snow applications.
Passive Microwave	SWE, Snow Depth	GlobSnow, AMSR	Compares two frequencies of microwave energy passively emitted by the Earth's soils and their change through the snowpack to determine water content of snow. The time of response through the snowpack provides snow depth, while the scattering response to snow provides SWE.	The period of record (40 years) is long enough to support model calibration and statistical approaches. This approach is insensitive to atmospheric and lighting conditions.	Satellite based sensors provide a coarse spatial resolution (e.g., a 25-km grid). The inversion approach does not work in mountainous areas due to uneven terrain and the presence of deep snowpack. The approach is also sensitive to snow properties such as grain size.

Emerging Technologies in Snow Monitoring

Technology Name	Property	Platform/ Product	Description	Strengths	Limitations
Signals of Opportunity	SWE, Snow Depth	SNoOPI / CubeSat	The signals of opportunity approach use two sensors to detect P-Band signals from telecommunications satellites. One sensor measures the signal directly emitted from the satellite and the other detects the reflected signal from the Earth's surface. The phase change can be used to determine SWE, for dry or mostly dry snow or snow depth for wet snow.	Satellite leverages existing, high-TRL components, reducing the cost of hardware development. Technique relies on signals emitted by other satellites, reducing need to include a transmitter. P-Band can penetrate vegetation and cloud cover to sense SWE across weather conditions and land cover types.	This technology has not yet been proven from space and requires extensive testing and validation before operational snow products could be available. SWE is only available directly in dry, or nearly dry, snow.
Optical Sensors / Spectroradiometers	fSCA	MODIS, Landsat, Sentinel-2 (satellites with suitable imagery)	Optical sensors measure visible, near infrared, and short-wave infrared energy to determine the amount of snow-covered area.	These satellites are part of established programs with broad support. Most satellites have either good temporal (e.g., daily) or spatial (e.g., 30 m) resolution.	Only data from a clear day without clouds can be used. Vegetation also obscures the imaging and must be accounted for in processing workflow.

Technology Name	Property	Platform/ Product	Description	Strengths	Limitations
Imaging Spectrometers (continued)	Albedo	ASO (plane-based imaging spectrometer) MODIS Dust Radiative Forcing in Snow (MODDRFS)	ASO measures snow reflectance across visible and near infrared bands using an imaging spectrograph (or "hyperspectral" camera). Subtle difference in reflectance between discrete bands in the infrared can determine snow grain size, albedo that are used to constrain SWE modeling. Hyperspectral, or measurements of reflected light with a high resolution of bands detected, provide better estimates of albedo and grain size due to the subtle changes in reflectance. This type of imagery can also measure SCA and support energy balance modeling. Similar approaches are used to provide radiative forcing from dust based on satellite-based spectroradiometer data (MODDRFS), although not currently using hyper-spectral sensors.	Approach is suitable in wet or dry snow.	Same as optical sensors, above.

Emerging Technologies in Snow Monitoring

Technology Name	Property	Platform/ Product	Description	Strengths	Limitations
Aircraft Gamma Radiation Surveys	SWE	NOAA	Natural gamma radiation is emitted from the potassium, uranium, and thorium radioisotopes in the upper soil layer. This radiation can be measured from a low-flying aircraft (500 feet above the ground). Each flight line is approximately 10 miles long and 1,000 feet wide. Water mass (regardless of phase) in the snow cover blocks a portion of the terrestrial radiation signal. The difference between radiation measurements made over bare ground and snow-covered ground can be used to calculate a mean areal SWE estimate.	Data from these flights are assimilated into NOAA's SNODAS, which provides daily, gridded snow data. For some flight lines, there can be long data collection records, in some cases going back to the 1980s.	It can be challenging to collect data in complex topography that limits ability to fly at the required low elevation. Natural radiation levels vary over time and must be continuously monitored, requiring snow-off and snow-on flights each year. Sensitivity is reduced in deep snowpack. In areas with high SWE, nearly all gamma radiation is blocked, thereby limiting the ability to differentiate between SWE conditions greater than that threshold. Spatial coverage is limited to flight lines. Most flight lines flown regularly are outside the West. NOAA's aviation program capacity can be limited by other priorities, such as hurricanes.
Stereo Photogrammetry	Snow Depth	Pleiades, WorldView, Planet (satellites with suitable imagery)	Photogrammetric imagery can be used to develop digital surface models (DSM) by UAV, plane, or satellite. Differencing these DSMs between times with and without snow cover produces snow depth maps at reasonably high resolution, depending on the how the imagery is collected.	This approach relies on broadly used imaging satellites producing both publicly and commercially available imagery. Able to be collected nearly on demand due to simplicity and prevalence of sensors needed.	Snow depth derived from stereo satellite imagery, the focus of this summary, has a higher error than lidar estimates, but relatively low overall bias. Correctly referencing the images to the same location is critical for accuracy of this approach.

4. Modeling Technologies

4.1. Description

4.1.1. Scope

Modeling snow conditions is a valuable complement to snow measurements. Snow models can often integrate data from multiple sources (e.g., manual measurements, automated measurements, and remotely sensed snow data) into a single platform and fill in the gaps between available data. The results produced by models are not direct (real) measurements—they are simulated conditions, and therefore models must be carefully applied and verified.

Models range in approach. Physically based models aim to represent the dynamics of snow accumulation and melt throughout the winter based on known scientific principles of energy and mass fluxes. Statistical approaches rely on historical relationships between observed snow conditions and various inputs. Regardless of approach, models depend on observed data to calibrate and validate the method.

Both physical and statistical models range in complexity. Factors related to complexity include the model resolution (space and time) and model sophistication. Increasing model sophistication and employing finer spatial resolutions can enhance representation of snow properties and spatial distribution. This may improve the ability to model snow in the context of runoff timing and volume, particularly under changing future conditions. However, more sophisticated models may have input requirements that may not be readily available for the area of interest at the needed resolution or for a sufficiently long period of record. Furthermore, more complex models typically have higher computational needs, which is an important consideration when viewed as part of an operational forecasting workflow. Accordingly, there may be practical limits to how much modeling advancements can improve forecasting.

Inputs to snow models range considerably, but typically include meteorological data (e.g., temperature, precipitation, and radiation) and traits of the land surface (e.g., elevation, orientation, and vegetation). In some models, snow observations are a direct input; in other cases, they are used to calibrate/train the model based on other inputs. The practice of adjusting a model based on recent observations is often referred to as "data assimilation," and ranges in complexity based on the type of model and the data to potentially be assimilated. While assimilating observations into a model may represent snow conditions more realistically, it must be done thoughtfully with consideration for impacts to subsequent use of model output. For example, assimilating new snow observations can cause a step change in the model's conditions (e.g., new data will correct an erroneous or biased condition in the model), even though the actual conditions did not suddenly change. In that case, if the model's snow information was being used to make a water supply forecast, the forecast is likely to see a similar step change. This begs the question of "did the water supply forecast improve"? Although the model's previous snow information may have been biased from the observations, if the water supply forecast was calibrated to account for the bias, the "correction" associated with data assimilation could degrade forecast skill rather than improve it.

Water supply forecasters must understand the workings of underlying snow models to take full advantage of the technology.

Snow models are typically calibrated based on various inputs (e.g., snow depth and temperature). This process benefits from measurements that have a sufficiently long period of record and consistent methodologies. Although new observed snow (and other input) data sets may be of high fidelity, incorporating these datasets into a model can present challenges if data of the same quality cannot be extrapolated back in time. Accordingly, using new snow observations in snow models (and water supply forecast models) is an area of active and necessary research.

4.1.2. Applications in Water Supply Forecasting

Modeled snow data can be used directly (i.e., as a water supply forecast model input), to provide situational contexts for forecast adjustments, or to inform end users about the overall snowpack situation as a complement to water supply forecasts.

The most widely used snow model in operational flood and water supply forecasting in the United States is the SNOW-17 model used as part of the RFC hydrologic modeling process. This is a relatively simple, physically based snow model. The model is initially calibrated using snow observations and models snow conditions throughout the season using temperature and precipitation inputs; it does not directly assimilate snow observations during the winter. The RFCs' hydrology model, the Sacramento Soil Moisture Accounting (SAC-SMA) model is calibrated to forecast flow based, in part, on the snow conditions of SNOW-17. Accordingly, assimilation or insertion of observed snow information into SNOW-17 may disrupt the calibration between SAC-SMA and SNOW-17 and reduce forecast performance without further calibrations.

Nonetheless, incorporating observed and/or other modeled snow data products could enhance performance. For example, precipitation estimations in mountainous areas can have considerable uncertainty, and poor precipitation data can adversely affect the model's snow information. Observations or models that simulate conditions based on observations can help to reconcile disparities. Several efforts are currently underway to examine how assimilation of advanced snow observations or output from other snow models into SNOW-17 could enhance forecast skill.

In addition to SNOW-17, there are other hydrology models used in the United States and globally that contain snow sub-models. Examples include the Precipitation Runoff Modeling System (PRMS) developed by the USGS, and the Weather Research and Forecasting Hydrologic model (WRF-Hydro), which is the basis for NOAA's National Water Model (NWM).

4.1.3. Challenges

Modeled data products have a variety of challenges associated with them, including:

- **Verification**. Modeled data can be verified against observations. However, modeled data products are used to provide information in places or at times where observations aren't available. Accordingly, it can be difficult to know how a model is performing in remote or high-elevation areas where observational data are difficult to acquire.
- **Period of record.** Modeled snow data products have widely differing periods of record for their simulated conditions. Short periods of record, or longer periods of record that include step changes associated with the underlying input data (e.g., satellite) can make using these datasets difficult in water supply forecasting.

- **Operational readiness.** As data science methods, access to computing resources, and data catalogs (e.g., satellite data) improve and grow, it is expected that modeled snow products will continue to expand. Using these data in operational water supply forecasting continues to be explored, but hinges on a variety of factors. Operational readiness and reliability are crucial as forecasters and water managers need to be able to depend on the inputs to their forecast and decision processes.
- **Access**. Related to operational readiness, with the proliferation of snow models, access to modeled snow data and understanding nuances of each snow model can be a barrier to use. Users of modeled snow data need to carefully consider the limitations and inherent assumptions associated with those data. A consolidated resource for snow information documentation, comparison, and download could facilitate use of these products more readily.
- **Input requirements**. Advances in snow modeling often result in more sophisticated models with more complex input data requirements. Finding suitable data to meet those requirements in an operational application may not be trivial. For example, some new models can simulate snow redistribution due to wind. This may be an important process for improving the distribution of snow, but access to suitable wind data of sufficient spatial resolution may be difficult.
- **Accuracy.** Snow models can vary in performance based on the model's construct and how well suited it is to the geography and weather of a particular location at a particular time.

4.2. Tech Summary

Models can produce a wide variety of simulated snow conditions at spatial scales and temporal frequencies far better than direct snow measurements. They complement both on-the-ground measurements and are an ideal platform for incorporating the range of emerging snow measurement technologies. Models need sufficient calibration, ongoing validation, and frequent assimilation to provide trustworthy data. More complex models tend to be able to integrate more types of snow measurements, and can be more accurate, but require substantially more resources to operate. Key limiting factors include computational power, the availability of weather data inputs, and the time necessary for skilled model operators to maintain and distribute model results. Water supply forecasts which have relied upon long data sets, typically using automated SNOTEL stations, manual snow courses, or models such as SNOW-17, need to be revised to take full advantage of the new generation of snow models and snow measurement technologies as they become available.

Snow measurements, snow models, and water supply forecasts are each links in a chain. The evolution of these tools should be conducted in coordination with one another—snow models should co-evolve with both monitoring technologies and water supply forecast technologies. There is also a growing need for software tools that make acquiring weather data for model input and data assimilation more efficient. Table 3 summarizes models most suitable for snow measurement to support water supply forecasting.

Table 3. Model Technologies Summary

Technology Name	Property	Description	Strengths	Limitations
GlobSnow	SCA, SWE	Uses a data-assimilation based approach combining space-borne passive radiometer data with data from ground-based synoptic weather stations.	Available simulated conditions extend back to 1979.	At a 25-km resolution, data are coarse compared to many other spatially distributed snow products. Data are limited to non-mountainous regions and GlobSnow has difficulty in areas with wet snow or a thin snow.
SWANN	SCA, SWE, Snow Depth	SWANN (Snow Water Artificial Neural Network) is a real-time, west wide, 4 km snow product. It assimilates *in-situ* snow data from the NRCS SNOTEL network and the NWS Cooperative Observer Program (COOP) network with modeled, gridded temperature and precipitation data from Parameter-elevation Regressions on Independent Slopes Model (PRISM).	This method leverages existing data and advances in data science. It has been used to assimilate other data sources (e.g., lidar) in the Salt River Project domain to enhance the product.	Performance varies regionally; spatial resolution limits ability to represent complex topography and sub-grid processes / snow distributions. Input weather data vary in accuracy based on interpolation assumptions.
SNODAS	SCA, SWE, Snow Depth	SNODAS (Snow Data Assimilation System) is a 1 km spatial resolution daily national product from NOAA. It uses a physically based, spatially distributed, energy- and mass-balance snow model to integrate snow data from satellite, airborne platforms, and ground stations with output from the numerical weather prediction (NWP) models.	SNODAS is an operationally supported product, blends variety of data sources, and provides range of snow properties.	Performance varies regionally. Has challenges in alpine/high elevation regions.
Modern Snow Models	SCA, SWE, Snow Depth	Modern snow models are physically based, and spatially distributed, which enables representation of complex topography and mass/energy fluxes. These models can include advanced processes such as wind re-distribution of snow. iSnobal is an example of such a model, developed by USDA ARS that characterizes snowpack conditions for each grid cell across a basin. iSnobal runs at an hourly time step using input from weather models and/or *in-situ* data with ability to assimilate observations and ASO data. It has been run from 2.5 m to 1 km resolution, typically ~50 m.	iSnobal provides high resolution characterization of a range of snowpack properties with ability to effectively assimilate remote sensing observations. It has good performance when forcing inputs are properly calibrated.	Requires intensive set-up and calibration for new areas, computational requirements can be significant for larger domains/higher resolution. iSnobal is not yet operational outside of a few watersheds.

Technology Name	Property	Description	Strengths	Limitations
CU-SWE	SCA, SWE, Snow Depth	This 500 m spatial resolution product is typically generated bi-weekly. It involves a statistical model that blends data such as MODIS snow covered area and grain size (MODSCAG), physiography, SNOTEL, analog historical SWE patterns.	This data product comes with summary report. It leverages a variety of data sources and has flexibility to integrate other data sources.	Latency is about 1 week from satellite data acquisition. Quality/availability of satellite data can be impacted by cloud cover and satellite angle. Error can be higher in situations with significant low elevation snow or when only very high elevation snow remains.
SNOW-17	SWE	SNOW-17 is a spatially lumped temperature index model that estimates SWE using observed precipitation and temperature. It is used by NOAA RFCs in conjunction with the SAC-SMA model to produce their forecasts.	SNOW-17 only requires two variables (temperature and precipitation), which are readily available.	Results can have biases associated with a temperature index snow model. In some cases, manual intervention may be needed to maintain realistic snow states. The lumped nature can make representing complex topography challenging.

5. Synthesis

5.1. Intro

By taking advantage of recent advances in snow monitoring, better understanding of seasonal snowpack characteristics is possible. With a range of tools and techniques available, the challenge before water managers and forecasters is less on developing new technologies, and more towards selecting and applying the most promising technologies. There is no single snow monitoring solution to meet all needs. Each existing and emerging snow monitoring technology has their own strengths and weaknesses; through strategic maintenance or adoption of multiple technologies these traits can be made to complement one another. When selecting a portfolio of snow monitoring technologies to invest in, consideration must be given to the degree to which they improve near-term and long-term water supply forecasts. In particular, technology resolution (temporal /frequency of measurement and spatial), coverage (temporal and spatial), data reliability, the variable measured, the cost, and finally the technology readiness level (TRL) must be considered. There are additional technical considerations in determining the best way for snow information to be efficiently integrated into water supply forecasts that are beyond the scope of this report.

5.2. Resolution and Range of Coverage

The temporal aspect of various snow monitoring technology is a key consideration. This includes how often the technology can produce data (e.g., hourly, daily, monthly) and the timespan that data are available. Snow characteristics that change quickly and weather influences are important to capture on finer timescales (high temporal resolution such as hourly to daily), while characteristics that change more slowly may be measured at greater intervals. Further, the desired frequency of a measurement may vary over the course of a season. As an example, during spring, when conditions may be changing quickly, more frequent data may be desirable. Automated weather stations and snow models are the types of snow monitoring technology most suited to generating frequent data. Methods that require manual measurement, such as snow courses, or where human piloting is necessary are better suited for generating less frequent data (Figure 4). A strategic solution would have sufficient technologies measuring at finer timescales to complement those technologies that are deployed less frequently as well as considering the period of record of the technology (i.e., temporal coverage). Data have been collected at manual snow courses in some locations for decades or nearly a century. Some satellite records of SCA are available going back over 20 years, so long-term records are not exclusive to low-tech tools. Long-term records are particularly important for calibrating water supply models and can serve to “tie” different technologies together through a common historical record.

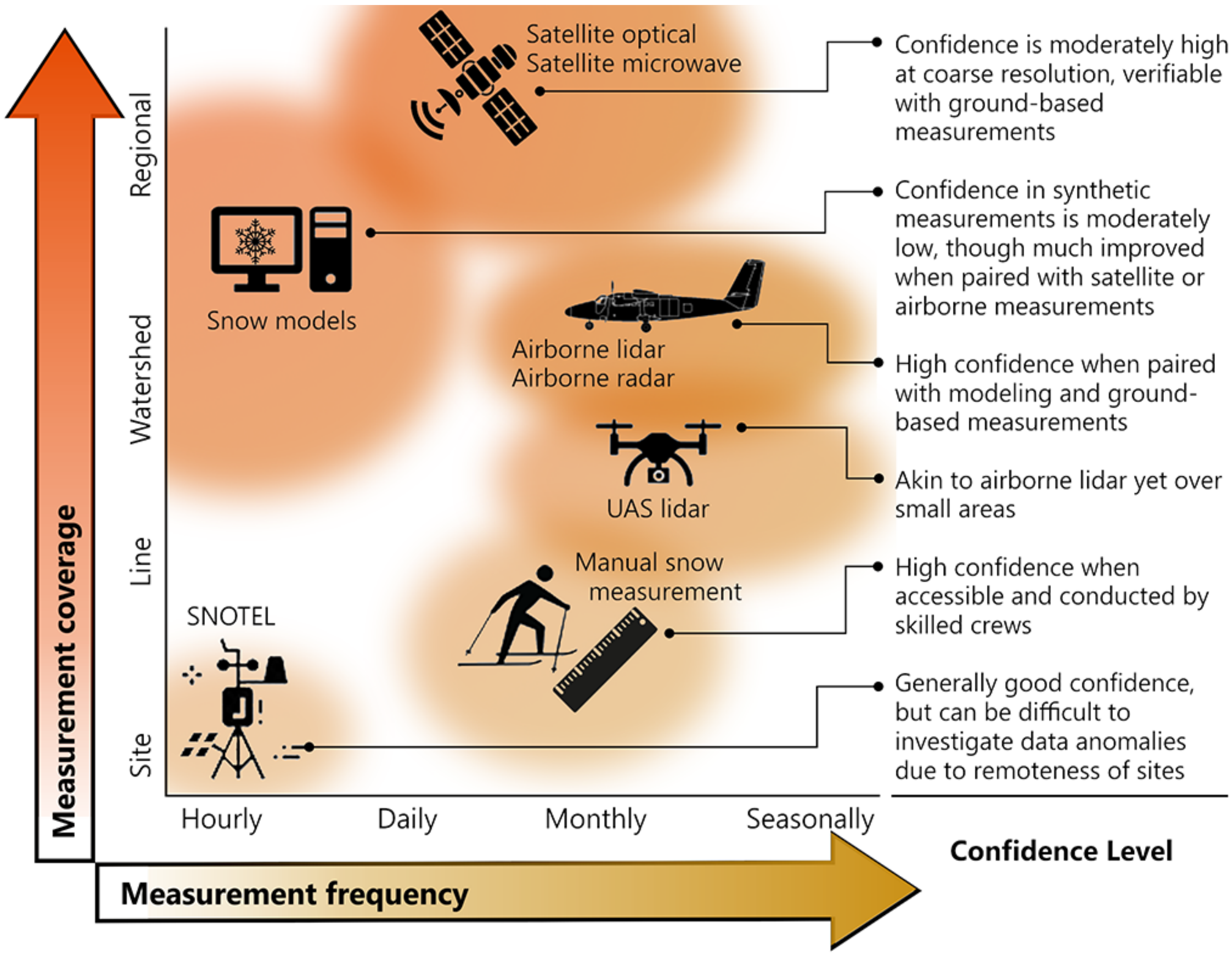

Figure 4. Snow measurement across time and space.

Recent advances in snow monitoring technologies have most strikingly improved snow measurement's spatial resolution and coverage. Whereas snow monitoring once relied upon measurements at a few spot locations to characterize an entire watershed or mountain range, aerial and satellite snow monitoring technologies can characterize snowpack over large areas. Continued incremental improvements in technology are producing those wide coverages at finer and finer spatial resolution. Most snow monitoring technologies can be deployed throughout the West, although visual and lidar technologies are more constrained in areas with frequent cloud cover such at the Pacific Northwest.

5.3. Reliability

The reliability of information produced is another key factor in creating snow monitoring networks which are both robust and efficient. Snow information which is simulated by models is generally (but not always) inferior to remote measurements of the snowpack; and remote measurements are generally (but not always) inferior to direct measurements taken on the ground.

Any snow measurement method which is highly automated and without validation has the potential to produce information with lower reliability. Often, snow measurement technologies with the greatest spatial coverage and spatial resolution require extensive validation with ground-based measurements to be reliable enough for water supply forecasting. Snow measurement technologies which retain high reliability should be sought out or retained to verify technologies which may be high resolution and efficient but are otherwise lacking in reliability.

5.4. Measurement Properties

SWE is the single most useful snow property to measure as it describes the water volume that is in the snow. SWE can be measured directly by weighing the snow or can be calculated using the product of snow depth and snow density. Snow depth varies considerably across the landscape, while snow density varies less and can be quantified by fewer measurements. Snow covered area, indicating only presence or absence of snow across the landscape, is sometimes used as a coarse substitute for snow depth, SWE, and its constituents of depth and density. However, SCA only describes the extent of snowpack—to understand how the snow may persist or melt requires additional information about the snow and weather. Snow temperature, snow reflectance (albedo), grain size, and solar radiation provide additional information and validation of snow models, allowing them to simulate current and future snow condition and thus better inform runoff forecasts. There are many other potential measurement variables, but snow models and subsequent runoff forecasts are most likely to use the above variables.

5.5. Selected Emerging Snow Measurement Technologies

Through analysis and consultation with other Federal and State agencies, Reclamation has identified ten emerging snow measurement technologies or technology products which are most likely to improve operational water supply forecasting and yield improved water management at Reclamation's reservoirs, hydropower facilities, and water delivery systems (Table 4). These selected technologies are currently not yet in widespread use and are at a mature stage of research and development. Each is deployable across Reclamation's regions, though the ideal mix of technologies may vary regionally or locally. These emerging technologies do not replace existing snow measurement technologies such as snow courses and snow pillows, though their adoption could result in existing methods being deployed more efficiently. It is important to note that these emerging technologies rely heavily upon the on-site measurements and long historic records produced by older snow measurement technologies.

Table 4. Selected Emerging Snow Measurement Technologies

Emerging Technologies Summary
Ground-Based Technologies

- Net radiometers measure energy from the sun and heat from the ground, which informs snow melt timing and can be used to improve snow science.
- Snow temperature sensors measure how cold the snow is at various depths in the snowpack, which can improve predictions of snow melt timing and informs snow science.

Air and Space-Based Technologies

- Aircraft lidar (e.g., Airborne Snow Observatory [ASO]) maps snow depth and when coupled with modeling, provides information on water held as snow.
- Snow Covered Area (SCA) / fractional Snow-Covered Area (fSCA) methods use satellite imagery to map the portion of the land covered by snow.
- Satellite albedo methods use satellite imagery to measure how clean/dirty the snow is, which has implications for how slowly/quickly snow melts.
- Satellite stereo imagery methods use high-resolution pictures from space captured from different perspectives to construct a three-dimensional (3D) model of the Earth's surface providing information on snow depth.

Modeling Technologies

- Snow Data Assimilation System (SNODAS) is a National Oceanic and Atmospheric Administration (NOAA) system that blends observations and weather model output to estimate snow conditions across the United States.
- Snow Water Artificial Neural Network (SWANN) estimates snow conditions across the United States using a machine learning system that blends snow observations and estimated precipitation data.
- University of Colorado real-time spatial estimates of snow water equivalent (CU-SWE) uses statistical modeling that blends satellite information with historical snow patterns and landscape characteristics to estimate snow conditions.
- Advanced snow models (e.g., iSnobal) use physics to track finely detailed snow conditions and can produce high resolution maps of basins or regions and can more easily incorporate data from air and space-based technologies.

5.6. Technology Readiness Level and Cost

The maturity of a snow monitoring technology can be classified by its technology readiness level (Table 5). Reclamation reviewed a wide range of technologies and incrementally narrowed suitable technologies to ones which could be deployed throughout the West where Reclamation operates within a 5-year time span. This objective limited selected technologies to a TRL of 6 or higher. The TRL indicates the readiness to deploy in snow monitoring. Use of the snow information in water supply forecasts is not captured in this TRL assessment. Less mature technologies bear watching as they may become worthy of investment.

Table 5. Technology Readiness Levels Definitions

TRL	Definition
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof of concept
4	Component and/or system validation in laboratory environment
5	Laboratory scale, similar system validation in relevant environment
6	Pilot-scale system validation in relevant environment
7	Full-scale system demonstrated in relevant environment
8	Actual system completed and qualified through test and demonstration.
9	Actual system operated over the full range of expected conditions.

TRL definitions are adapted from U.S. Department of Energy's Technology Readiness Assessment Guide, 2009.

Costs vary considerably across technologies, based on a variety of factors including, but not limited to: how the data are collected, their spatial/temporal extent, and the level of processing complexity. It is often the case that operationally, technologies are deployed in bundles. The table below provides cost information regarding both individual technologies and common technology bundles. It is important to note that cost comparisons between technologies and or technology bundles can be challenging due to the differences in spatial and temporal coverage (e.g., some costs are for a single measurement, others are for a station that reports measurements hourly). In some cases, snow products leverage government investments in methods (e.g., research) and data (e.g., satellites). As a result, these products themselves may be free or lower cost to users, as compared to the full cost of development and deployment. In particular, developing emerging snow monitoring technologies often depends on data from existing snow monitoring networks, which have their own cost. In Table 6, costs are estimated as "user costs", and do not attempt to quantify underlying investments that may be leveraged.

Table 6. Technology Readiness Levels and Cost
$ = 0 - $5k, $$ = $5k - $25k, $$$ = $25k - $100k, $$$$ = $100 - $250k, $$$$$ = $250k+

Technology	TRL	Initial Implementation Cost[1]	Annual Operating Cost[1]	Notes
Net Radiometer	9	$$	$	Cost is to add sensors to 6 existing monitoring stations with telemetered data, reporting hourly. Initial cost is for sensor purchase and installation, and the annual operating cost is for additional site maintenance, quality assurance/quality control (QA/QC), etc. 6 stations is a median estimate of the number of SNOTEL stations in a 1,000 – 1,500 square kilometer (sq km) basin. Actual numbers will vary from basin to basin. This also assumes that existing stations/sites are suitable for a radiometer; additional costs may be incurred if new stations/sites are needed.
Snow Temperature	7	$$	$	Cost is to add sensors to 6 existing monitoring stations with telemetered data, reporting hourly. Initial cost is for sensor purchase and installation, and annual operating cost is for additional site maintenance, QA/QC, etc. 6 stations is a median estimate of the number of SNOTEL stations in a 1,000 – 1,500 sq km basin. Actual numbers vary from basin to basin.
Aircraft Lidar	8	$$$$	$$$$$	Cost is for aircraft based lidar survey of a 1,000 – 1,500 sq km basin, coupled with snow modeling to provide 3-meter spatially distributed SWE data. Initial cost is for the required bare ground survey and annual operating cost is for three surveys with snow and associated data processing. The assumption of three data collections per year per basin is based on anecdotal evidence that it can be beneficial to survey early, peak, and late snow conditions.
SCA/fSCA	8	$ to $$$$$	$ to $$$	Cost is to acquire or produce SCA/fSCA data for a 1,000 – 1,500 sq km basin. Currently, several SCA/fSCA datasets are operationally produced and available to end users at no cost. Costs associated with producing these data are born by various agencies/programs. For example, MODSCAG is freely available for the West on an approximately 8-day repeat cycle (subject to image acquisition) at 500-meter resolution. Operationalizing promising new SCA/fSCA datasets (improved resolution, sensors, and processing methods) would likely have additional initial costs and may have higher annual operating costs if imagery must be purchased. Note that initial costs associated with operationalizing a new dataset would likely facilitate broad geographic application of this technology (i.e., additional locations would incur a significantly lower initial cost). Alternatively, there may be opportunities to acquire SCA/fSCA via the private sector. Such costs are beyond the scope of these estimates.

[1] Costs are best estimates based on information available. Actual costs may vary based on a number of factors including but not limited to: location, scale, and changes in technology.

Technology	TRL	Initial Implementation Cost[1]	Annual Operating Cost[1]	Notes
Satellite Albedo	8	$ to $$$$$	$ to $$$	Cost is to acquire or produce satellite snow albedo data for a 1,000 – 1,500 sq km basin. Currently, operationally produced satellite snow albedo data are available to end users at no cost. Costs associated with producing these data are borne by various agencies/programs. For example, MODDRFS is freely available for the West on an approximately 8-day repeat cycle (subject to image acquisition) at 500-meter resolution. To operationalize promising new satellite albedo datasets (improved resolution, sensor, and processing methods) would likely have additional initial costs and may have higher annual operating costs if imagery must be purchased. Note that initial costs associated with operationalizing a new dataset would likely facilitate broad geographic application of this technology (i.e., additional locations would incur a significantly lower initial cost). Alternatively, there may be opportunities to acquire satellite snow albedo via the private sector. Such costs are beyond the scope of these estimates.
Satellite Stereo Imagery	7	$ to $$$$$	$ to $$$	Cost is for producing snow depth across a 1,000 – 1,500 sq km basin using stereo imagery techniques. At this time, satellite stereo imagery methods are not operationally used to estimate snow depth. Workflows exist that could be leveraged but would require refinement and support for an operational snow product. These costs are reflected by the higher end of the initial cost range. Note that such an investment would likely facilitate broad geographic application of this technology (i.e., additional locations would incur a significantly lower initial cost). Annual operating cost reflects acquiring and processing data. The range of operating costs acknowledges that in some cases freely available data may be suitable, but in other cases, commercial data may need to be procured. Alternatively, there may be opportunities to acquire snow depth via the private sector as stereo imagery techniques used by commercial satellite companies could likely be adapted to this application. Such costs are beyond the scope of these estimates.
SNODAS	9	$	$	Cost is to acquire SNODAS SWE data for a 1,000 – 1,500 sq km basin. SNODAS data are produced daily for the United States and are freely available from NOAA NWS National Water Center (NWC). and via National Snow and Ice Data Center (NSIDC). NWC is supported by appropriations through the NWS.
SWANN	8	$ to $$$$	$ to $$$	Cost is to acquire SWANN SWE data for a 1,000 – 1,500 sq km basin SWANN data are produced daily for the contiguous United States by the University of Arizona, supported by a variety of projects/sponsors. In some regions, SWANN has been enhanced with additional data. The initial cost range reflects using the data as produced currently or investing in regional enhancements.

Emerging Technologies in Snow Monitoring

Technology	TRL	Initial Implementation Cost[1]	Annual Operating Cost[1]	Notes
CU-SWE	7	$ to $$$$	$$$	Cost is for operational production of CU-SWE at a regional scale (e.g., Upper Colorado River Basin) for an entire snow season. Data and reports are generated approximately twice a month over the snow season. Initial costs are low in basins where CU-SWE is already produced. Expansion to new basins may have additional initial costs.
Modern Snow Modeling	8	$ to $$$$$	$ to $$$	Cost is to implement a modern snow model in an operational forecasting workflow. A number of modern snow models have various TRLs. Many, such as the iSnobal model, are the result of government sponsored research and are freely available. Adopting any new model (even freely available) will come with initial costs to implement and train staff. Several factors will impact initial costs, reflected by the range. For example, the higher TRL and better supported the model is, the lower those costs tend to be. The scope of the deployment is also impactful; while some efficiencies may be gained in a multi-basin implementation, there is still likely significant work to establish the model in each new basin. Once implemented, these models may have additional annual operational costs as compared to legacy tools as they may require more advanced computing resources and additional data storage.

5.7. Conclusions

Snowpack volume and snowmelt timing are a major source of operational uncertainty at Reclamation facilities throughout the West. Technologies and products to measure snowpack variables more accurately, at higher resolutions, and with greater coverage have recently emerged. Several of these are underused and could improve water supply forecasts. As the major Federal agency charged with managing water supply reservoirs, hydropower facilities, and water distribution systems, Reclamation has a clear role in bringing mature snow monitoring technologies to bear for broader use in forecasts across the West. Through analysis and coordination, Reclamation has identified ten well-researched snow monitoring technologies worthy of consideration for deployment over the next 5 years.

Deployment of emerging technologies should be in cooperation with existing ground-based snow monitoring efforts, which are of critical value for verification and calibration of new tools. Through consultation and experience, these emerging snow monitoring technologies can be strategically deployed to produce a robust and efficient snow monitoring network. The earlier these technologies are deployed, the longer the period of record produced, increasing the value to forecasting. The data produced by these technologies are also foundational for the advancement of snow modeling, which has so far been limited by relatively sparse snow information. The precise mix of emergent technology will vary geographically and in response to the parallel development of operational water supply forecasts.

Many snow monitoring technologies that are not discussed in Section 5 still have potential to advance water supply management once they mature. Tracking and/or nurturing these nascent technologies is important even if those benefits may not be realized in the next 5 years. In addition, the adoption of emergent technologies does not reduce the continued need for on-the-ground snow measurements. Such legacy measurements provide a long-term record which are foundational to snow science and serve as verification and calibration of many emerging snow monitoring technology.

Advancements in snow monitoring can meet multiple purposes, whether being directly usable by water managers, spurring further research and development, or being integrated into water supply forecasts. Continued advancements in weather forecasts and seasonal climate forecasts are necessary to fully realize improvements in water supply forecasts. There are remaining challenges in integrating new types of snow data into water supply forecasts. Most efficient use of snow monitoring information into water supply forecasts will required the creation of coordinated pipelines where data can flow and be readily integrated. This synchronization will require enhanced coordination between agencies and Federal leadership to guide efforts.

6. Implementation and Federal Coordination

Consistent with the Act, Reclamation's development of this report has been conducted in coordination with Federal and other partner agencies. Topics of coordination included review of snow monitoring technologies, the use of those technologies in water supply forecasts, and program implementation. Among the seven agencies engaged, there is strong consensus that the emerging technologies identified in Section 5 are currently under-used in water supply forecasts and that with support from the Program, have strong potential to enhance water supply forecasts in the next 5 years. Furthermore, there is optimism for other new snow monitoring technologies that are likely to mature over the next decade. There is also a recognition that the Program is timely; it stands to provide multiple benefits: support for implementing emerging technologies, coordination on agency activities related to snow monitoring and forecasting and overcoming structural barriers to using new technologies in forecasting workflows. As such, a Partner Agency Council will be formalized as part of Program implementation. The Council will initially be comprised of representatives from Reclamation and the seven agencies engaged for the drafting of this report to provide a forum for coordinating snow activities and building a pipeline for moving emerging technologies into operational water supply forecasts.

6.1. Partner Agencies

As discussed in Section 1, many agencies have a role in snow monitoring technology development, deployment, and use in water supply forecasting, which points to the importance of robust partnerships for the Program to have the maximum impact. The following summarizes agencies that have been engaged through development of this report and describes their role(s) in snow monitoring, forecasting, and water management.

6.1.1. Natural Resources Conservation Service

The USDA's NRCS operates the Snow Survey and Water Supply Forecast (SSWSF) Program, which is jointly administered by 12 Western NRCS state offices and the NRCS National Water and Climate Center. Its snow survey component is the primary snow data network in the West with over 1,700 measurement sites including SNOTEL and SNOLITE stations, manual snow courses, and aerial markers. Its forecasting component is the largest stand-alone operational system in the West, issuing water supply forecasts at over 600 locations, primarily using statistical methods, locally complemented by physics-based models, with a forthcoming migration to an artificial intelligence-based system.

6.1.2. Agricultural Research Service

The USDA ARS conducts and transfers research to address high priority issues for national food supply and the environment. Within ARS, a number of Watershed Research Centers investigate biophysical topics, including a substantial line of research on snow measurement and modeling. ARS develops the iSnobal model as well as various methods of snow water supply forecasting, with a focus in mountainous areas.

6.1.3. National Oceanographic and Atmospheric Administration

NOAA is home of the NWS, which operates 13 RFCs across the United States that produce operational streamflow forecasts which focus on river flow and water supply forecasts for their specific region. RFC predictions are based on tightly coupled models of snowpack, soil moisture, hydrology, and future weather to inform water supply management, flood management, and hydropower operation. RFCs frequently collaborate with their data users, including many Federal partners such as Reclamation.

6.1.4. United States Geological Survey

The USGS has a history of monitoring, modeling, and studying snow properties and is well known for their long-term network of stream gauges that are critical for water supply forecasting. The USGS operates the Earth Resources Observation and Science (EROS) Center, which maintains a large collection of satellite-based imagery products. Together with NASA, the USGS operates the Landsat satellite program, which generates fractional snow-covered area products.

6.1.5. National Aeronautics and Space Administration

NASA is the United States' civil space program that conducts research and develops technologies, both for space exploration and for earth observation. Operational snow products include snow-covered area maps and radiative forcing products. NASA sponsors the SnowEx program to advance the capabilities of snow remote sensing by testing airborne and on the ground sensing techniques with a goal of mapping global SWE as part of a future snow satellite mission. NASA's Western Water Application Office (WWAO) works to identify decision making needs of water managers and builds partnerships to address those needs.

6.1.6. United States Army Corps of Engineers

USACE has a variety of missions across its civil and military business areas. The USACE has a civil works footprint that spans the United States, and it has a presence supporting military operations across the globe. The USACE operates the Engineer Research and Development Center (ERDC), a Department of Defense supported consortium of seven sister laboratories, to conduct research into ice, snow, and hydrology. Each laboratory focuses on a different aspect of civil and military infrastructure, and each provides unique insights into snow behavior. Those with a primary focus on snow include the Cold Regions Research and Engineering Laboratory (CRREL) and the Coastal and Hydraulics Laboratory (CHL). In addition to the ERDC, the USACE operates the Hydrologic Engineering Center (HEC), which produces modeling tools used broadly across the water management community.

6.1.7. State and Other Agencies

Partnering efforts between Federal, State, and private agencies have established the successful use of snow measurements through various technologies for runoff forecasts over the last century. These cooperating agencies not only share a pool of expert staff but share in funding programs which collect, analyze, and disseminate snow data throughout the West. An example of the Federal/State/local cooperation is the California Cooperative Snow Surveys (CCSS) program which is a statewide program of more than 50 Federal, State, and private agencies and was established in 1929 by the California State Legislature. The CA-DWR is the lead agency in coordinating the CCSS program and produces the Bulletin 120: Water Conditions in California Forecasts, which both State and Federal water managers rely upon for coordinated operations. California is the only Western state to perform this function on its own. In the other Western states, the NRCS conducts snow measurements and snow surveys—a program that began in the mid-1930s. The CCSS and the NRCS programs have a high degree of cooperation between the two entities.

6.2. Partner Agency Coordination Activities

Throughout the development of this report, coordination has occurred with the agencies listed in Section 6.1, including internally at Reclamation, and with other institutions involved in advancing and using snow measurement technology. Specifically, coordination activities have included:

- Held internal Reclamation orientation to the new Program and established a Reclamation Advisory Panel for this report in March 2021
- Conducted partner agency Program orientation meetings in March 2021
- Engaged partner agencies to assist in reviewing new internal Reclamation snow projects in March 2021
- Provided update to Reclamation Advisory Panel in June 2021
- Provided individual partner agency update and feedback meetings in June 2021
- Solicited input from partner agencies on specific snow monitoring technologies in July 2021
- Held a multi-agency meeting in July 2021 to solicit feedback on technologies and to discuss process for next steps
- Engaged partner agencies to review a draft of this report in September 2021

6.3. Partner Agency Review of Emerging Technologies

Through meetings and written feedback, partner agencies provided input on the ten emerging technologies identified in Section 5, their potential use in water supply forecasts, and synergistic efforts underway related to those technologies. A summary of this feedback is listed below.

- No red flags or fatal flaws were raised for the ten emerging technologies identified in Section 5.
- Under this report's definition of emerging technologies (limited use in operational water supply forecasting and sufficiently mature with potential to improve water supply forecasts in the 5-year program horizon), no additional technologies were recommended for inclusion.
- Considerable activities related to technologies identified in Section 5 are underway at partner agencies. Examples include:
    - NOAA's Colorado Basin RFC has and is exploring the potential for the following technologies to enhance their forecasts:
        - MODSCAG
        - MODDRFS
        - SNODAS
        - iSnobal

  - Aircraft lidar snow surveys and derived SWE products
  - CU-SWE
  - SWANN

- USDA NRCS is deploying additional snow monitoring sensors at existing *in-situ* locations. This effort is in collaboration with Reclamation and USACE, and includes the following emerging technologies identified by this report:
  - Snow Temperature Profile
  - Net Radiometer
- USDA NRCS is collaborating with both NASA and Reclamation to test the use of satellite-based and airborne data as predictive inputs for improved machine learning-based water supply forecasts.
- USDA ARS is continuing development of the iSnobal model, including coordination with to NOAA's Colorado Basin RFC's efforts related to iSnobal and supporting an iSnobal pilot at CA-DWR.
- CA-DWR is investigating how aircraft lidar snow surveys and derived SWE products can best inform their statistical Bulletin 120 Water Supply Forecasts and iSnobal model pilot project.
- USGS has planned new *in-situ* snow monitoring for the Colorado Headwaters pilot location of their Next Generation Water Observing System (NGWOS). These monitoring stations may include:
  - Snow Temperature Profile
  - Net Radiometer
- NASA continues the development of air and space-based snow remote sensing technologies through a variety of campaigns, including SnowEx, which leverages:
  - MODSCAG
  - MODDRFS
  - Aircraft lidar surveys and derived SWE products
- NASA's Land Information System (LIS) is a software framework that enables users to drive multiple, land surface models with a variety of different meteorological forcing inputs and other configuration options. The system has the capacity to assimilate a variety of satellite and other observations. Thus, it may serve as testbed for evaluation of new information in snow modeling.

Considering these numerous relevant activities at partner agencies, there is an opportunity for the Program to serve as a coordination forum broadly amongst agencies pursuing improved snow monitoring and water supply forecasting. Regular agency coordination can facilitate leveraging other agencies' activities and investments, which can enhance program impacts. Agency coordination can also support mechanisms and standards for awareness and access to snow data. Sharing experiences and practices and can help streamline operationalization of emerging technologies. Discussion between snow monitoring efforts, water supply forecasters, and water managers can foster opportunities for integrating emerging technologies into operational forecasts.

6.4. Looking Forward—Program Coordination Process

The Program's objective of improving snow monitoring and water supply forecasts is clearly of considerable interest to many agencies and entities. Implementing emerging technologies requires thoughtful planning to effectively use the data collected in models and water forecasts.

To this end, coordination will be formalized via the creation of a Program Partner Agency Council to initially include the partner agencies listed in Section 6.2, with flexibility to expand as needed. The Council will meet regularly and be designed to facilitate coordination of Program implementation, which will include:

- Providing an awareness of agency activities
- Facilitating partnerships on projects and topics of mutual interest—leveraging current and future investments
- Developing mutual understandings for potential uses for traditional and emerging technologies
- Identifying needs, gaps in monitoring and understanding, and barriers to using technologies
- Establishing effective pipelines for integrating emerging technologies into operational forecasts

7. References

Anderson, E.A., 2006. Snow Accumulation and Ablation Model – SNOW-17, Nat. Weather Serv., 44 pp.

Blair, J.B., D.L. Rabine, and M.A. Hofton, 1999. The Laser Vegetation Imaging Sensor: a medium-altitude, digitisation-only, airborne laser altimeter for mapping vegetation and topography. ISPRS Journal of Photogrammetry and Remote Sensing 54(2-3), 115-122.

Broxton, P., X. Zeng, and N. Dawson, 2019. Daily 4 km Gridded SWE and Snow Depth from Assimilated In-Situ and Modeled Data over the Conterminous US, Version 1. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center.

Carroll, T 2001. Airborne Gamma Radiation Snow Survey Program. NOAA, National Operational Hydrologic Remote Sensing Center. https://www.nohrsc.noaa.gov/special/tom/gamma50.pdf.

Clow, D.W., L. Nanus, K.L. Verdin, and J. Schmidt, 2012. Evaluation of SNODAS snow depth and snow water equivalent estimates for the Colorado Rocky Mountains, USA. Hydrol. Process., 26: 2583-2591. https://doi.org/10.1002/hyp.9385.

Chang, S., J. Shi, L. Jiang, L., Zhang, and H. Yang, 2009. Improved snow depth retrieval algorithm in China area using passive microwave remote sensing data. In: Proceedings of IEEE International Geoscience and Remote Sensing Symposium, 2. IGARSS, pp. II614eII617, 2009 IEEE International.

Crumley, R.L., D.F. Hill, K. Wikstrom Jones, G.J. Wolken, A.A. Arendt, et al., 2020. Assimilation of citizen science data in snowpack modeling using a new snow dataset: Community Snow Observations. Hydrology and Earth System Sciences Discussions, 1-39.

Deschamps-Berger, C. et al., 2020. Snow depth mapping from stereo satellite imagery in mountainous terrain: evaluation using airborne laser-scanning data. The Cryosphere, 14(9), 2925-2940.

Marks, D., J. Domingo, D. Susong, T. Link, and D. Garen, 1999. A spatially distributed energy balance snowmelt model for application in mountain basins. Hydrological Processes, 13(12-13), 1935-1959.

McGrath, D., R. Webb, D. Shean, R. Bonnell, H. P. Marshall, T.H. Painter, and L. Brucker, 2019. Spatially extensive ground-penetrating radar snow depth observations during NASA's 2017 SnowEx campaign: Comparison with *in situ*, airborne, and satellite observations. Water Resources Research, 55(11), 10026-10036.

NASA, NASA SnowEx Science Plan: Assessing Approaches for Measuring Water in Earth's Seasonal Snow. https://snow.nasa.gov/sites/default/files/SnowEx_Science_Plan_v1.6.pdf.

Painter, T.H. et al., 2009. Retrieval of Subpixel Snow Covered Area, Grain Size, and Albedo from MODIS. Remote Sensing of Environment 113, 868–879.

Painter, T.H. et al., 2016. The Airborne Snow Observatory: Fusion of scanning lidar, imaging spectrometer, and physically-based modeling for mapping snow water equivalent and snow albedo. Remote Sensing of Environment 184, 139-152.

Rittger, K., T.H. Painter, and J. Dozier, 2013. Assessment of methods for mapping snow cover from MODIS. *Advances in Water Resources*, *51*, 367-380.

Rott, H., S.H. Yueh, D.W. Cline, C. Duguay, R. Essery, et al., 2010. Cold regions hydrology high-resolution observatory for snow and cold land processes. Proceedings of the IEEE, 98(5), 752-765.

Schneebeli, M. and J.B. Johnson, 1998. A constant-speed penetrometer for high-resolution snow stratigraphy. Annals of Glaciology, 26, pp.107-111.

Schneider, D. and N. Molotch, 2016. Real-Time Estimation of Snow Water Equivalent in the Upper Colorado River Basin Using MODIS-Based SWE Reconstructions and SNOTEL Data. Water Resources Research 52, 7892–7910.

The Resources Agency of California, 2018. Snow Survey Procedure Manual. Department of Water Resources, California Cooperative Snow Surveys. https://cawaterlibrary.net/wp-content/uploads/2017/12/SnowSurveyProcedureManualv20141027.pdf.

U.S. Department of Agriculture (USDA), 2010. A Measure of Snow: Case Studies of the Snow Survey and Water Supply Forecasting Program. Natural Resources Conservation Service. https://www.nrcs.usda.gov/wps/wcm/connect/wcc/e2323413-1532-457c-bdc3-2e76eafbdd47/MeasureofSnowFullReport.pdf?MOD=AJPERES&CVID=nHe-XYF&CVID=nHe-XYF.

USDA, 2016. Manual Snowpack Measurement: Snow Courses & Aerial Markers. National Water and Climate Center and Natural Resources Conservation Service. https://www.wcc.nrcs.usda.gov/snotel/snowcourse_brochure.pdf.

USDA, 2016. Snow Telemetry (SNOTEL) Data Collection Network. National Water and Climate Center and Natural Resources Conservation Service. https://www.wcc.nrcs.usda.gov/snotel/snotel_brochure.pdf.

USDA, Technical Note: Statistical Techniques Used in the VIPER Water Supply Forecasting Software. National Water and Climate Center and Natural Resources Conservation Service.

U.S. Department of Energy, 2009. Technology Readiness Assessment Guide. https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04/.

Woelders, L., J. Lukas, E. Payton, and B. Duncan, 2020. Snowpack Monitoring in the Rocky Mountain West: A User Guide. Western Water Assessment.

Zhang, Q., L. Zhong, S. Snowling, A. Siam, and W. El-Dakhakhni, 2019. Predictive models for wastewater flow forecasting based on time series analysis and artificial neural network. Water Sci Technol 15 July 2019; 80 (2): 243–253.

Attachment: Snow Water Supply Forecasting Program Authorization Act (Public Law 116-260 Section 1111)

1. Short title

This Act may be cited as the Snow Water Supply Forecasting Program Authorization Act.

2. Definitions

In this Act:

(1) Program. The term *program* means the Snow Water Supply Forecasting Program established by section 3.
(2) Reclamation State. The term *Reclamation State* means a State or territory described in the first section of the Act of June 17, 1902 (32 Stat. 388, chapter 1093; 43 U.S.C. 391).
(3) Secretary. The term *Secretary* means the Secretary of the Interior.

3. Snow water supply forecasting program

(a) Program establishment. The Snow Water Supply Forecasting Program is hereby established within the Department of the Interior.

(b) Program implementation. To implement the program, the Secretary shall—

(1) develop the program framework in coordination with other Federal agencies pursuant to section 4, culminating in the report required under section 4(c); and

(2) after submitting the report required by section 4(c), implement activities to improve snowpack measurement in particular watersheds pursuant to section 5.

4. Development of program framework in coordination with other Federal agencies

(a) Snowpack measurement data

When determining water supply forecasts or allocations to Federal water contractors, the Secretary, acting through the Commissioner of the Bureau of Reclamation, shall incorporate, to the greatest extent practicable, information from emerging technologies for snowpack measurement, such as—

(1) synthetic aperture radar;

(2) laser altimetry; and

(3) other emerging technologies that the Secretary determines are likely to provide more accurate or timely snowpack measurement data.

(b) Coordination

In carrying out subsection (a), the Secretary shall coordinate data use and collection efforts with other Federal agencies that use or may benefit from the use of emerging technologies for snowpack measurement.

(c) Emerging Technologies Report

Not later than October 1, 2021, the Secretary shall submit to Congress a report that—

(1) summarizes the use of emerging technologies pursuant to this section;

(2) describes benefits derived from the use of technologies summarized under paragraph (1) related to the environment and increased water supply reliability; and

(3) describes how Federal agencies will coordinate to implement emerging technologies.

5. Program implementation

(a) Activities implementing framework

After submitting the report required under section 4(c), the Secretary shall participate with program partners in implementing activities to improve snowpack measurement in particular watersheds.

(b) Focus

The program shall focus on activities that will maintain, establish, expand, or advance snowpack measurement consistent with the report required by section 4(c), with an emphasis on—

(1) enhancing activities in river basins to achieve improved snow and water supply forecasting results;

(2) activities in river basins where snow water supply forecasting related activities described in this section are not occurring on the of the date of the enactment of this Act; and

(3) demonstrating or testing new, or improving existing, snow and water supply forecasting technology.

(c) Information sharing

The Secretary may provide information collected and analyzed under this Act to program partners through appropriate mechanisms, including interagency agreements with Federal agencies, States, State agencies, or a combination thereof, leases, contracts, cooperative agreements, grants, loans, and memoranda of understanding.

(d) Program partners

Program partners with whom the Secretary enters into cooperative agreements pursuant to subsection (e) may include water districts, irrigation districts, water associations, universities, State agencies, other Federal agencies, private sector entities, nongovernmental organizations, and other entities, as determined by the Secretary.

(e) Cooperative agreements

The Secretary may—

(1) enter into cooperative agreements with program partners to allow the program to be administered efficiently and cost effectively through cost sharing or by providing additional in-kind resources necessary for program implementation; and

(2) provide nonreimbursable matching funding for programmatic and operational activities under this section in consultation with program partners.

(f) Environmental laws

Nothing in this Act shall modify any obligation of the Secretary to comply with applicable Federal and State environmental laws in carrying out this Act.

6. Program implementation report

Not later than 4 years after the date of the enactment of this Act, the Secretary shall submit a report to the Committee on Natural Resources and the Committee on Appropriations of the House of

Representatives and the Committee on Energy and Natural Resources and the Committee on Appropriations of the Senate, that includes—

(1) a list of basins and sub-basins for which snowpack measurement technologies are being used under the program, including a description of each technology used; and

(2) a list of Federal agencies and program partners participating in each basin or sub-basin listed in paragraph (1).

7. Authorization of appropriations

There is authorized to be appropriated to the Secretary to carry out this Act $15,000,000, in the aggregate, for fiscal years 2022 through 2026.