Workshops Report

SNOWPACK MONITORING FOR STREAMFLOW FORECASTING AND DROUGHT PLANNING

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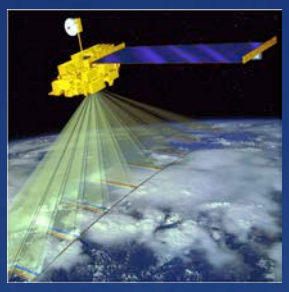

WESTERN WATER ASSESSMENT
A NOAA RISA TEAM
CIRES
University of Colorado Boulder

Workshops Report

Snowpack monitoring for streamflow forecasting and drought planning

Western Water Assessment
Cooperative Institute for Research in Environmental Sciences
University of Colorado Boulder

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Main cover photo:
The Senator Beck Basin in the San Juan Mountains, Colorado, in spring 2010, showing the spatial complexity of the spring snowpack, including the uneven emergence of the dust deposited in multiple events earlier in the spring. Photo credit: Jeff Deems.

First inset photo:
Schematic of the Terra satellite, which carries the MODIS instrument along with several others, capturing multi-spectral imagery of the earth's surface. Image credit: NASA/JPL.

Second inset photo:
Chad Pickett and Kevin Pantle from the Wyoming State Engineer's Office measure the water content of the snowpack at the Haskins Creek Snow Course in the Sierra Madre Mountains, Wyoming. Photo credit: Matt Hoobler.

Third inset photo:
Mt. Dana and the Dana Plateau in the Tuolumne River Basin within Yosemite National Park, California, as seen out the window of a Twin Otter aircraft carrying NASA's Airborne Snow Observatory (ASO) in April 2013. Photo credit: NASA/JPL-Caltech.

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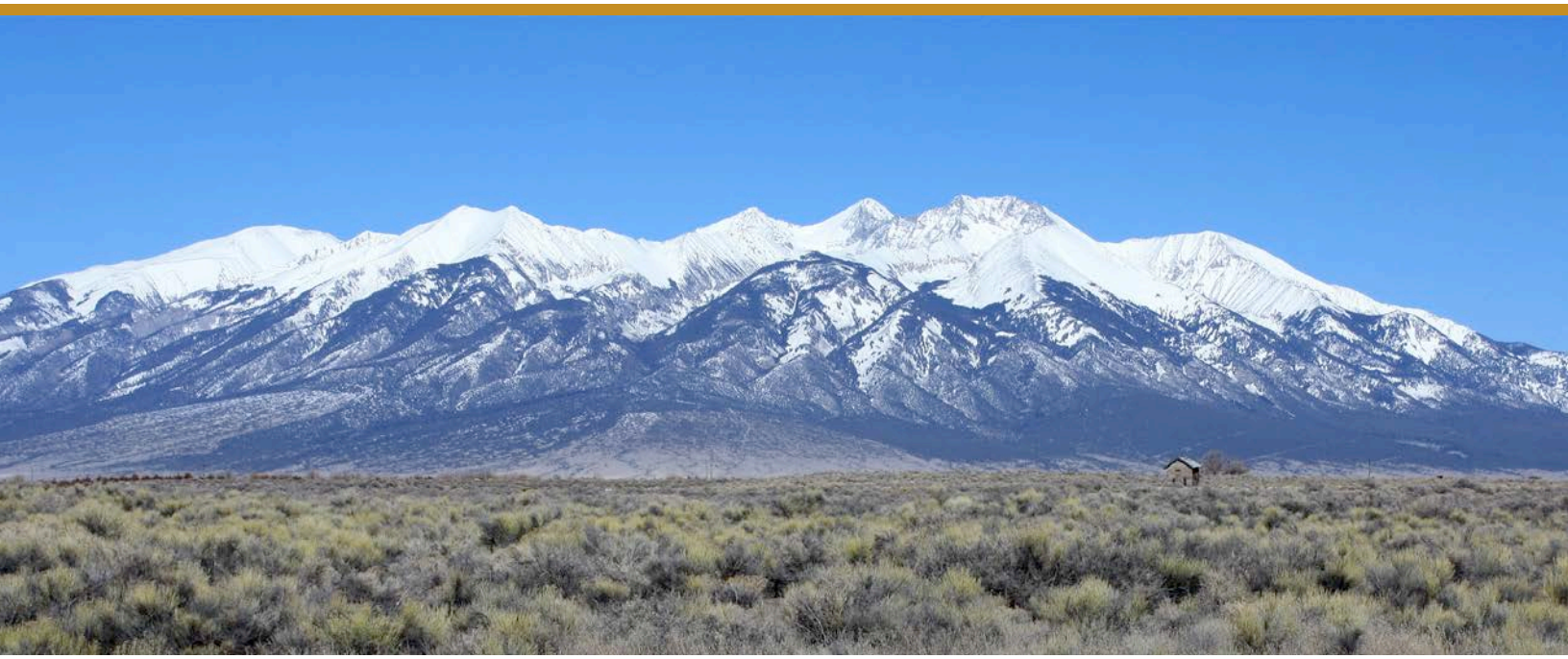
- National Integrated Drought Information System (NIDIS) - Alicia Marrs, Chad McNutt, Veva DeHeza
- Natural Resources Conservation Service (NRCS) Snow Survey – Randy Julander, Brian Domonkos, Lee Hackleman
- NOAA Colorado Basin River Forecast Center (CBRFC) – Stacie Bender, Michelle Stokes
- Colorado Climate Center, Colorado State University – Nolan Doesken, Zach Schwalbe
- Wyoming State Engineer's Office – Matt Hoobler

We also thank all of the other workshop presenters (see Table 1), and these organizations for assistance with outreach and logistics: Jordan Valley Water Conservancy District, Wyoming Water Association, and the Colorado Department of Agriculture.

Finally, Dominik Schneider and Leanne Lestak (WWA and INSTAAR, University of Colorado) helped to create the demonstration materials for the MODIS-based spatial SWE product, and assisted the development and presentation of the workshops.



Blanca Peak on the Sierra Blanca Massif in south-central Colorado. Photo: Wikimedia Commons, David Herrera.

EXECUTIVE SUMMARY

For water providers and others in the Rocky Mountain West who depend on the pulse of runoff from the melting snowpack from April through July, snowpack monitoring *is* drought monitoring. A well-below-average snowpack as measured by snow-water equivalent (SWE) is a harbinger of not only low water supply but also other drought impacts, such as increased fire risk and below-normal summer soil moisture. However, the snowpack is complex, varying tremendously over short distances and from year-to-year, and changing rapidly during the season, especially in the spring. The in-situ snow-monitoring network—from snow courses and SNOTEL sites—provides a robust snapshot of conditions in most years and most basins, but may not capture large deviations from more typical patterns of snow accumulation and melt.

In summer and early fall 2015, the Western Water Assessment (WWA) organized and delivered three all-day workshops intended to improve the usability of snowpack monitoring information in the Rocky Mountain West, with a particular view to enhancing that monitoring with new technologies. The workshops were in West Jordan, UT (August 11), Lander, WY (August 27), and Broomfield, CO (September 9). This effort was supported by "Coping with Drought" funding from the NOAA National Integrated Drought Information System (NIDIS). The workshops brought together a total of 180 participants, mainly representing a core user community of local, state, and federal water managers, along with other stakeholders, researchers, and operational information providers.

The main workshop objectives were to:

- Help improve the *usability* and *use* of snowpack monitoring information for runoff forecasting, drought early warning and planning, and other applications;
- Provide background information on snow hydrology and snow measurement;
- Describe operational snow-monitoring products and how they are used in runoff forecasts;
- Provide guidance for accessing and interpreting operational data;
- Introduce and demonstrate new snow-monitoring products using satellite and airborne sensors being developed by WWA researchers and others; and
- Facilitate interaction and further conversation between stakeholders, researchers, and operational data providers in NRCS and NOAA.

The key partners for all three workshops were NIDIS, the NRCS Snow Survey offices covering the three states, and the NOAA NWS Colorado Basin River Forecast Center (CBRFC). Presenters representing those entities described the current state of drought monitoring and early warning in the region, operational in-situ snowpack monitoring, and the operational seasonal runoff forecasts from both NRCS and NOAA. Presenters from local and state water entities provided a view of how operational snowpack and runoff information is currently being used. And a pre-workshop survey of participants rounded out the picture of current use of this information. A repeated theme was how critical the SNOTEL-based monitoring capacity is to managers, forecasters, and researchers.

NOAA CBRFC staff also described how CBRFC is piloting the use of satellite information to supplement their picture of the snowpack from SNOTEL sites. This served as a bridge to the afternoon portion of the workshops, which focused on emerging applications of remote-sensing technologies for snowpack monitoring. Snow hydrologists on WWA's research team (Jeff Deems and Noah Molotch) are involved with two such efforts: NASA's Airborne Snow Observatory (ASO) that measures snow depth at extremely high resolution (~1 m) using LIDAR (laser) altimetry; and a wide-area SWE reconstruction product based on 1-km satellite imagery from the NASA MODIS sensor. In both cases, the new products depend on and complement the in-situ snow-monitoring network, but are not intended to replace it. In both cases, there was high interest from participants in expansion of current pilot efforts in the western US, mainly California, to additional basins in Utah, Wyoming, and Colorado.

Overall, the workshops were highly successful in bringing water managers and other stakeholders in open dialogue with researchers and operational providers about snowpack monitoring. The participants showed great willingness to learn from each other and help each other. From these discussions, and our own observations, we synthesized these main findings from the workshops:

- The in-situ snowpack monitoring network (SNOTEL and snow course) is absolutely essential. Reductions in capacity should be avoided and targeted additions would be welcome.
- The use of data products from the in-situ network could still be made more effective with additional training and guidance.
- While the new remote-sensing products could bring substantial benefits to snowpack and drought monitoring, there is no single, clear path to expanding the operational reach of these products across the Rocky Mountain region.

The post-workshop evaluations indicate that participants consistently reported gains in knowledge of snow hydrology and monitoring, and improved awareness of existing and emerging products. We recognize that there will need to be many more conversations to work out the implementation of new capabilities in a cost-effective manner.

WORKSHOP HOMEPAGES

The homepages for three workshops, with links to the PowerPoint presentations (as PDF files), participant lists, and state-specific resources for snowpack monitoring and runoff forecasting:

Utah:
http://wwa.colorado.edu/events/workshops/UTsnow2015.html

Wyoming:
http://wwa.colorado.edu/events/workshops/WYsnow2015.html

Colorado:
http://wwa.colorado.edu/events/workshops/COsnow2015.html

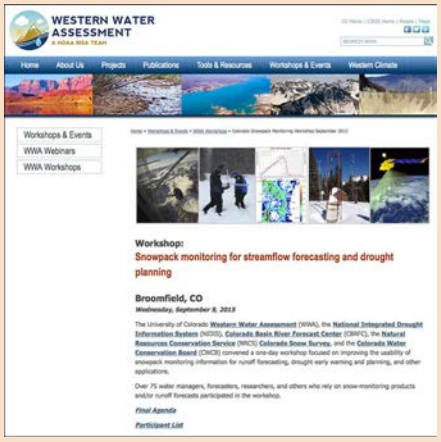


Figure 1. Participants at the Broomfield, Colorado snowpack workshop, September 9, 2015. Photo: Robin Strelow, CIRES.

1. WORKSHOP PARTICIPANTS

About 10 days prior to each workshop, we sent the registrants a link to a brief online survey with 12 questions. The objectives of the survey were to (1) ascertain the work responsibilities and basins of interest of the participants, (2) assess their familiarity with and use of current snow-monitoring and runoff-forecast products, (3) gage their self-reported knowledge of those products and the science behind them, and (4) capture their personal objectives for the workshop, including specific questions they wanted to see answered.

About 60% of the registrants completed the survey. Findings from the pre-surveys are integrated into the description of the workshop participants below.

Overall, the participants in the workshops covered the *range* of entities (local, state, federal, tribal), job responsibilities, and sectors that we had anticipated, though with less participation from agriculture and recreation interests, and private-sector consultants, than we had desired.

UTAH

Of the 50 non-WWA participants at the West Jordan, UT, virtually all were with public entities: 20 with Federal agencies (NOAA, NRCS, Reclamation, US Geological Survey, US Forest Service), 7 with state agencies (all Utah), 15 with local entities (cities, counties, and water districts), 6 with universities. Two participants were with private or non-profit entities. As expected, the Wasatch Front was strongly represented, with few participants from outside of the Wasatch Front.

On the pre-workshop survey, about two-thirds of the participants identified their sector as “Water”, with “Public Lands Management” a distant second, and “Ag or Ranching”, “Recreation”, and “Energy” receiving a few responses each. On the pre-workshop survey, participants identified their roles as “Operations”, “Research”, and “Management” most frequently, with “Planning”, “Policy” and “Education” also seeing at least 9 responses. The basins for which participants said they had responsibility included all of the drainages in northern and central Utah, including the Provo, Weber, Bear, Duschesne, and Six Creeks, as well as the Green and Colorado basins; southern Utah’s basins were less well represented.

Participants reported themselves to be frequent users of snowpack monitoring and runoff forecasts, with most of them consulting key products from NRCS and NOAA at least monthly, especially SWE data from the NRCS Utah Snow Survey. Participants used the runoff forecasts from NRCS and NOAA RFCs in roughly equal numbers. Least-used were the WWA Intermountain West Climate Dashboard, the NIDIS Upper Colorado Basin drought webinars, and the NOAA SNODAS snow analyses.

The vast majority of participants self-reported their working understanding of snow hydrology, and the production, access, and use of snowpack information to be either "average" or "above-average". To the question, "How do you use snowpack information?", the top three responses selected were the same as in Wyoming and Colorado, though in a different order:

- To get a better sense of how the snowpack is evolving
- To anticipate likely runoff anomalies
- To anticipate other impacts to my resources of interest

WYOMING

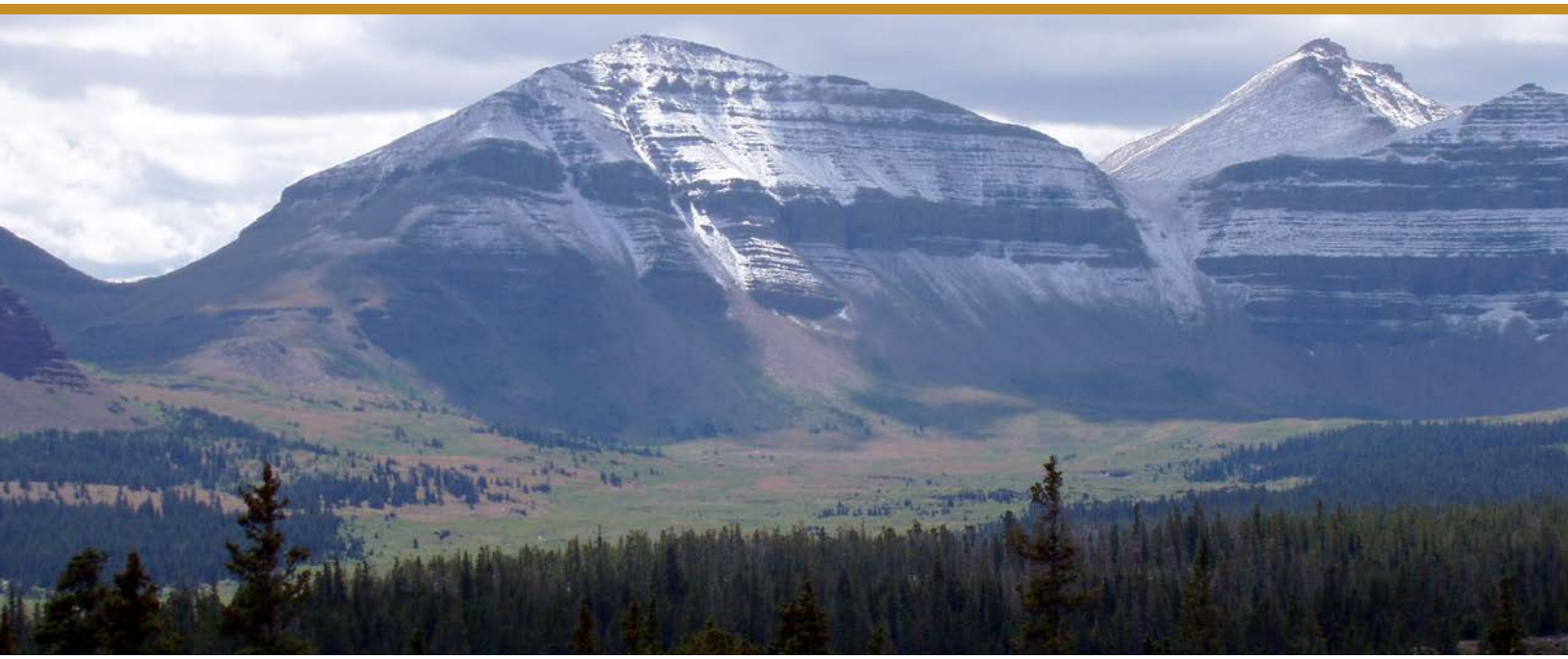
The mix of participants at the Lander, WY workshop was similar to the Utah workshop. Nearly all of the 53 non-WWA participants were public employees: 15 with Federal agencies (NOAA, NRCS, Reclamation, US Geological Survey, BLM, US Forest Service, US Fish & Wildlife Service), 8 with state agencies (all Wyoming), 13 with local entities (cities, counties, and water districts), 8 with universities, and 5 with tribal entities (all the Office of Tribal Water Engineer, Wind River Indian Reservation). Four participants were with private or non-profit entities. An important difference from the other two workshops is that the non-federal participants tended to represent much smaller entities than in Colorado and Utah, which may speak to capacity to use new information. Wyoming is a much smaller state than the other two, population-wise, and the workshop was held in a rural part of Wyoming.

On the pre-workshop survey, about half of the participants identified their sector as "Water", with "Ag or Ranching" and "Public Lands Management" the next two most frequent responses. Participants identified their roles as "Operations", "Planning", "Management", and "Education" most frequently, with "Research" and "Policy" also seeing multiple responses. The basins for which participants said they had responsibility had a local orientation, with the Bighorn and Wind being the most frequent responses, and all other major Wyoming basins receiving at least a few responses.

Participants reported themselves to be frequent users of snowpack monitoring information, with most of them consulting key products from SWE data from the NRCS Wyoming Snow Survey at least monthly. Seasonal runoff forecasts from the NRCS were consulted much more often than those from the NOAA RFCs, in contrast with the Utah participants. Seldom-used products included the CBRFC monthly webinars, the WWA Intermountain West Climate Dashboard, the NIDIS Upper Colorado Basin drought webinars, and the NOAA SNODAS snow analyses.

Most of the participants self-reported their working understanding of snow hydrology, and the production, access, and use of snowpack information to be "average," with many fewer indicating "above-average" understanding than in the Utah or Colorado workshops. To the question, How do you use snowpack information, the top three responses chosen were:

- To anticipate other impacts to my resources of interest
- To get a better sense of how the snowpack is evolving
- To anticipate likely runoff anomalies



Close-up shot of Kings Peak, Utah. Kings Peak is on the right, and Gunsight Pass is on the far left. Photo: Creative Commons, Hyrum K. Wright.

COLORADO

The mix of participants at the Broomfield, CO workshop was similar to the other two workshops, though slightly more diverse in that "only" 59 of the 67 non-WWA participants were public employees: 17 with Federal agencies (NOAA, NRCS, Reclamation, US Geological Survey, BLM), 5 with state agencies (Colorado & Wyoming), 24 with local entities (cities, counties, and water districts), 12 with universities, and 1 with a tribal entity (White Mountain Apache Tribe, AZ). Five participants were with private-sector entities, and three with non-profits.

On the pre-workshop survey, about 75% of the participants identified their sector as "Water", with "Public Lands Management", "Ag or Ranching", and "Recreation" the next most frequent responses. Participants identified their roles as "Operations", "Planning", and "Management", most frequently, with "Research" and "Education" just behind. The basins for which participants said they had responsibility were tipped to those in the northern half of the state, with the South Platte and Colorado basins having the most responses, though all major Colorado basins received multiple responses.

Participants reported themselves to be very frequent users of snowpack monitoring information, more so than in Utah and Wyoming, with most of them consulting SWE data from the NRCS Colorado Snow Survey at least weekly. Seasonal runoff forecasts from the NRCS and the NOAA RFCs were consulted with roughly equal frequency, as in Utah. Among the lesser-used products, the NIDIS Upper Colorado Basin drought webinars and the WWA Intermountain West Climate Dashboard were more frequently consulted than by the Utah or Wyoming participants. CBRFC monthly webinars were used less than in Utah, but more than in Wyoming, and the NOAA SNODAS snow analyses were used more than in the other two states.

The self-reporting of participants' working understanding of snow hydrology, and the production, access, and use of snowpack information was very similar to Utah, with "average", and "above-average" responses predominating. To the question, "How do you use snowpack information?", the top three responses selected were the same as in Wyoming:

- To anticipate other impacts to my resources of interest
- To get a better sense of how the snowpack is evolving
- To anticipate likely runoff anomalies

2. WORKSHOP PRESENTERS AND MAIN CONTENT

The sequence of the presentations and the content at all three workshops was very similar. The presentations are summarized below, noting any elements unique to one of the workshops.

Each workshop began with the WWA moderator reviewing of the workshop objectives (listed in Overview, above) and an overview of the day's proceedings. This was followed by Elizabeth McNie presenting the the results of the pre-workshop surveys, as described in the previous section on workshop participants.

NATIONAL INTEGRATED DROUGHT INFORMATION SYSTEM (NIDIS)

A NIDIS staffer gave an overview of the National Integrated Drought Information System, covering the history, objectives, and implementation of NIDIS, emphasizing the Regional Drought Early Warning Systems (RDEWS) and how they work with existing networks to build capacity for drought early warning. In Wyoming, Chad McNutt (NIDIS) also gave an overview of the new Missouri Basin Regional Drought Early Warning System.

UPPER COLORADO RIVER BASIN REGIONAL DROUGHT EARLY WARNING SYSTEM

A Colorado Climate Center staffer presented an overview of the Upper Colorado River Basin Regional Drought Early Warning System (UCRB RDEWS) drought webinars and website, focusing on the snow-monitoring information. Most of the information provided through the UCRB RDEWS covers all of Utah, Wyoming, and Colorado, not just the portions of those states within the Upper Colorado River Basin.

MEASURING AND MODELING OUR SNOW-WATER RESOURCE

The core of the workshop's technical content began with a presentation by WWA researchers Noah Molotch and Jeff Deems called "Measuring and modeling our snow-water resource." This first covered the importance of snow hydrology in our region, and the processes of snow accumulation and snowmelt. One misconception that was addressed is that warming temperatures melts snow in the spring, when it is actually the increased solar radiation from higher sun angles and longer days that is the primary driver of melt, with temperature playing a secondary role.

The presentation then covered operational snow monitoring, different approaches to snowmelt and runoff modeling and forecasting, and runoff forecast error sources. It was explained that there are several approaches to runoff modeling and forecasting, distinguished by the degree to which they explicitly represent the underlying physical processes. The simpler statistical models (e.g., as used by NRCS) may produce reasonably accurate forecasts in most years, but are more vulnerable to errors when there are unusual weather and snowpack conditions.

The core presentation finished with an introduction to new spatially-explicit approaches to snowpack monitoring using remote sensing. A key message was that remote sensing will not replace the in-situ network; in fact, we may need more in-situ monitoring to help calibrate and cross-check with the remotely-sensed monitoring products.

NRCS SNOW SURVEY: THE SNOTEL NETWORK AND RUNOFF FORECASTING

This was followed by staff from the NRCS Snow Survey offices describing in greater detail the primary operational snowpack monitoring network, based on SNOTEL sites (Figure 2) and snow courses. In the Utah workshop, Randy Julander, Utah Snow Survey Supervisor, walked through many of the snow and water supply data products provided by the Utah Snow Survey. He described the Snow Survey's role as collecting data, and synthesizing the data into products, so they can then lead to a decision or action by

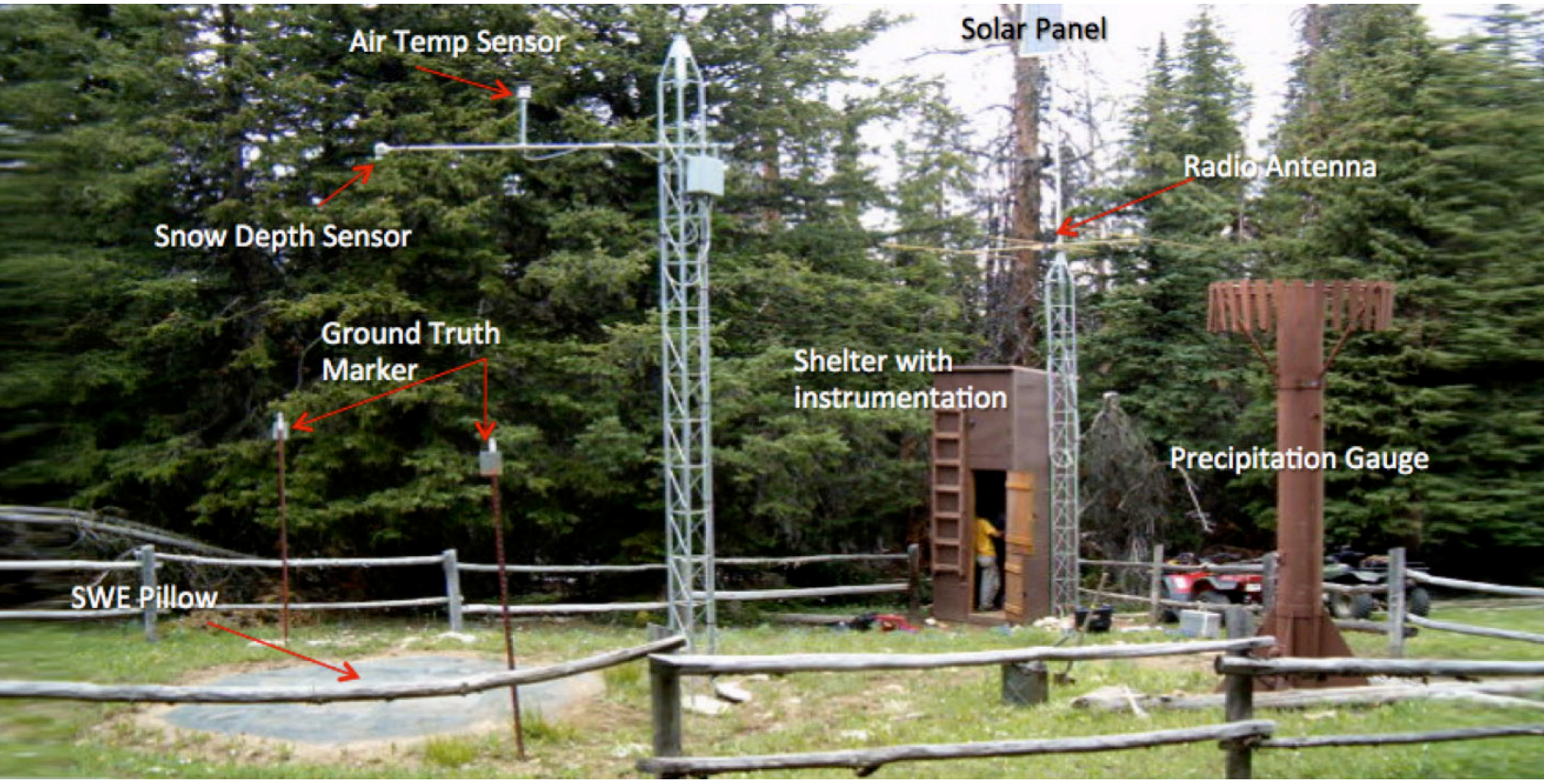


Figure 2. The basic instrumentation at a SNOTEL (SNOwpack TELemetry) site. The 300+ SNOTEL sites across Utah, Wyoming, and Colorado form the backbone of the in-situ snowpack monitoring capacity in the region. Image: Brian Domonkos, NRCS.

a user, minimizing risk and maximizing benefit. They try, through their suite of products, to ensure that users can relate the information on current and forecasted conditions to their past operational decisions. Julander concluded with "a short course" on the role of observations in runoff forecast accuracy and uncertainty, pointing out that the uncertainty in streamflow observations is the ultimate constraint on runoff forecast accuracy: "you cannot forecast any better than you can gage."

In Wyoming and Colorado, Brian Domonkos, Colorado Snow Survey Supervisor, emphasized the new national map-based tool for accessing NRCS snow data (Interactive Map v. 2.0; Figure 3), as well as the state-specific products. He also covered several data-handling procedures, including quality assurance and quality control (QA/QC) and the calculation of long-term medians, and the NRCS runoff forecasting procedures.

USING SNOWPACK INFORMATION IN NOAA CBRFC'S RUNOFF FORECASTING

Next up, Stacie Bender from NOAA CBRFC described how snow-related data is incorporated into their seasonal runoff and peak-flow forecasts, detailing the increasing use of remotely-sensed snow data to complement observations from the NRCS network. She described CBRFC's forecasting platform and approach, how data is used from the SNOTEL observations, and the more recent use of NASA/Jet Propulsion Lab (JPL)-provided MODIS (satellite) snow-covered-area product (MODSCAG) and a dust-forcing product (MODDFRS) to make adjustments to the forecasts, resulting in improved accuracy in most, but not all, cases. CBRFC is moving to more sophisticated and automated approaches to use these new data sources, laying the groundwork for the use of other spatial snow products such as the ones described in the workshops. She emphasized that even with the increasing use of remotely-sensed data, their forecasts will remain reliant on the in-situ SNOTEL network.

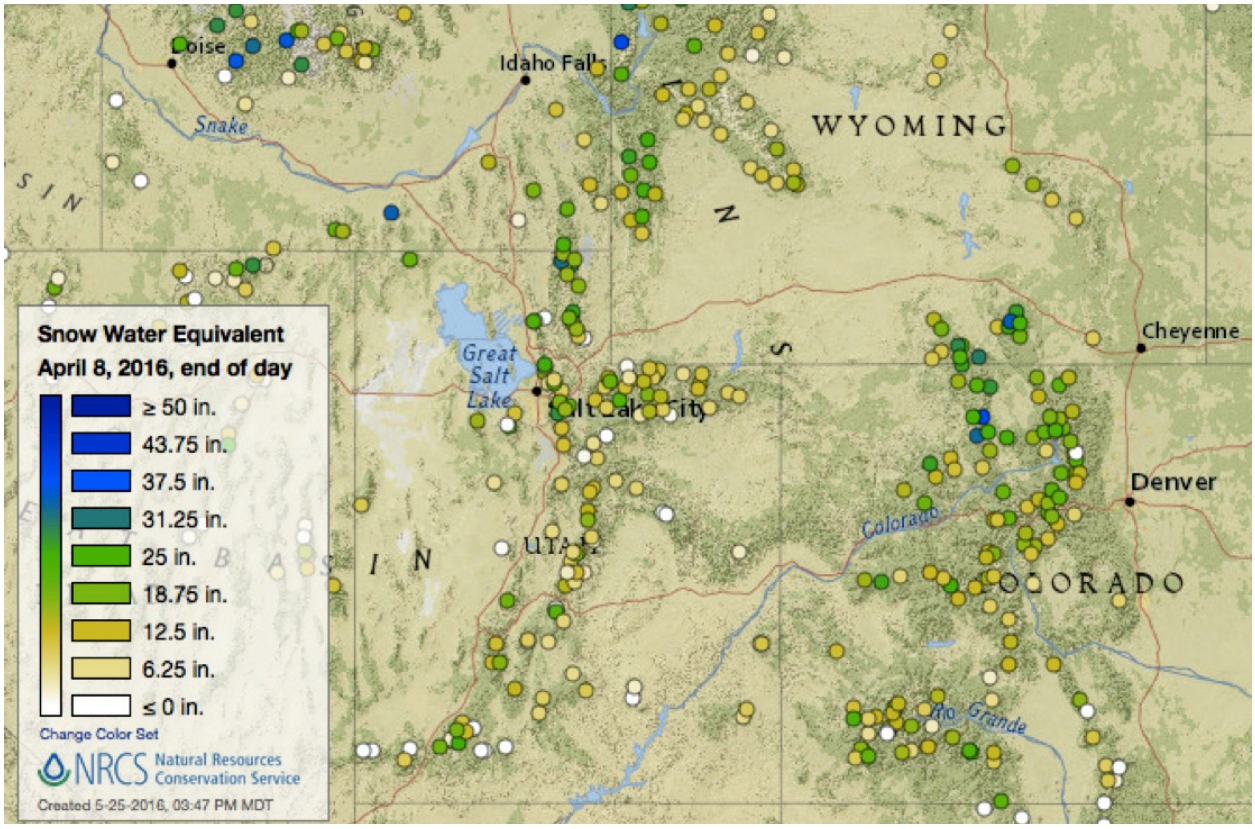


Figure 3. Screenshot of the NRCS Interactive Map v. 2.0 (http://www.wcc.nrcs.usda.gov/webmap), showing the extent of the SNOTEL site network in Utah, Wyoming, and Colorado (all colored dots) and the SWE values at those sites as of April 8, 2016.

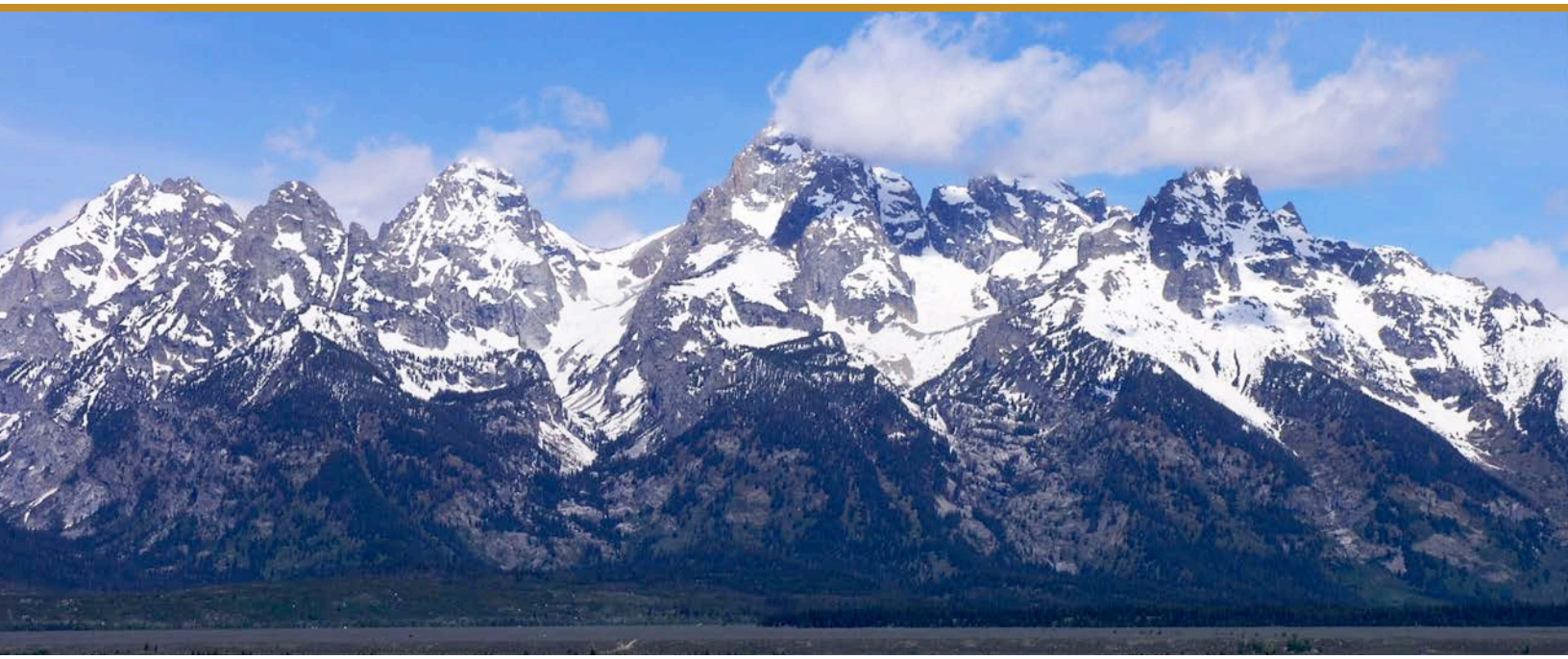
WATER MANAGERS ON THEIR USE OF SNOW-MONITORING INFORMATION

Before moving onto those new products, at two of the three workshops we had water managers describe their current use of operational snow-monitoring products such as the SNOTEL data and the NRCS and NOAA RFC runoff forecasts. We felt that these 'peer-to-peer' presentations would help stimulate and ground the later discussions of snow-monitoring products and their use.

At the Utah workshop, first Heather Patno from the Bureau of Reclamation's Upper Colorado Regional Office in Salt Lake City focused on the three BuRec operational models that ingest snowpack data and how they are used in operational decisionmaking. She raised the need for better SNOTEL data from the Wind River Range in Wyoming—a concern that re-emerged in the Wyoming workshop—and also raised the important question of how resources should be allocated between expansion of the SNOTEL network, versus supporting remotely-sensed snow products.

Tom Bruton of the Central Utah Water Conservancy walked through the snow and runoff products that they use operationally, mainly from the NRCS Utah Snow Survey, to manage the complex Central Utah Project. Through the winter and spring, they use a system model to project whether key reservoirs will fill, based on current contents and the snowpack conditions.

At the Colorado Workshop, Bob Steger of Denver Water described how they analyze key data sources. First, they make custom groupings of selected SNOTEL sites in their watersheds, to monitor SWE. Then, they use the NRCS seasonal runoff forecasts as the basis for three probabilistic runoff projections: one assuming climatological average weather from that point forward through the runoff season, one assuming dry weather, and one assuming wet weather. Finally, they use the CBRFC ensemble runoff forecasts in combination with historical analogs to get a better sense of when a given basin is likely to have peak daily runoff, and also to manage Dillon Reservoir in high-flow years.



Grand Teton National Park, Wyoming. Photo: Creative Commons, Daniel Mayer.

The afternoon of all three workshops was focused on describing the emerging remote-sensing-based products for snow monitoring, and discussing how their use could be most efficiently and effectively scaled up from current pilot programs.

Workshop	Utah	Wyoming	Colorado
Location	West Jordan (Salt Lake City metro area)	Lander	Broomfield (Denver metro area)
Date	August 11	August 27	September 9
Total Participants	53	48	77
WWA Moderator	Tim Bardsley	Jeff Lukas	Jeff Lukas
WWA Presenters	Noah Molotch (MODIS product), Jeff Deems (ASO)	Noah Molotch (MODIS product), Jeff Deems (ASO)	Noah Molotch (MODIS product), Jeff Deems (ASO)
NIDIS Presenter	Alicia Marrs	Chad McNutt	Alicia Marrs
UCRB DEWS Presenter (Colorado Climate Center)	Zach Schwalbe	Nolan Doesken	Nolan Doesken
NRCS Snow Survey Presenter(s)	Randy Julander (UT)	Brian Domonkos (CO) Lee Hackleman (WY)	Brian Domonkos (CO)
CBRFC presenter	Stacie Bender	Stacie Bender	Stacie Bender
Water Agency Presenter(s)	Tom Bruton (Central Utah WCD) Heather Patno (Reclamation)	Matt Hoobler (WY State Engineer's Office)	Bob Steger (Denver Water) Joe Busto (CWCB) Craig Cotten (CO DWR)
Other Researcher Presenter			David Gochis (NCAR)
Primary MODIS-product demo area	Weber Basin	Upper Green Basin	Colorado Headwaters

Table 1. Summary of the three workshops and the workshop presentations.

MODIS-BASED GRIDDED SWE PRODUCT

First, Noah Molotch (WWA; also affiliated with INSTAAR, C-WEST, and NASA/JPL) gave an overview of his gridded SWE product based on MODIS satellite data (Figure 4). Since the MODIS instrument doesn't directly capture snow depth or water equivalent, the product ingeniously combines real-time MODIS observations of snow-covered area, real-time SNOTEL observations, and gridded historical SWE patterns (since 2000) that are reconstructed from MODIS snow-covered-area data, using an energy-balance model to determine how much snow was present in a given gridcell through the melt season, given the date it became snow-free. MODIS imagery is available daily, though the need for a cloud-free image means that the gridded SWE product is most reliably offered at a weekly time-step. The main advantages of this product are that it can cover a very large area, at 1-km resolution, at relatively low cost, and performs better than unguided interpolation between SNOTEL sites, and performs much better than extrapolation above and below the elevational band of SNOTEL sites. It can not, however, match the accuracy of the ASO product.

Molotch described how the MODIS-based gridded SWE product has been validated through comparisons with manual high-resolution SWE sampling in both the Sierra Nevada and in the Colorado Front Range, and also with ASO (below) in the Tuolumne basin in California. He then walked through demo products, emulating a real-time operational product, that his team produced specifically for each workshop, highlighting local basins of interest (see Table 1) and the snowpack anomalies as they would have been reported in real-time for April 2011 (a very wet winter) and April 2012 (a very dry winter). These demo products were based on reports that have been produced weekly for the Sierra Nevada for the California Department of Water Resources and its cooperators. The information in the Sierra Nevada reports is used to adjust streamflow forecasts, providing valuable information for augmenting SNOTEL data.

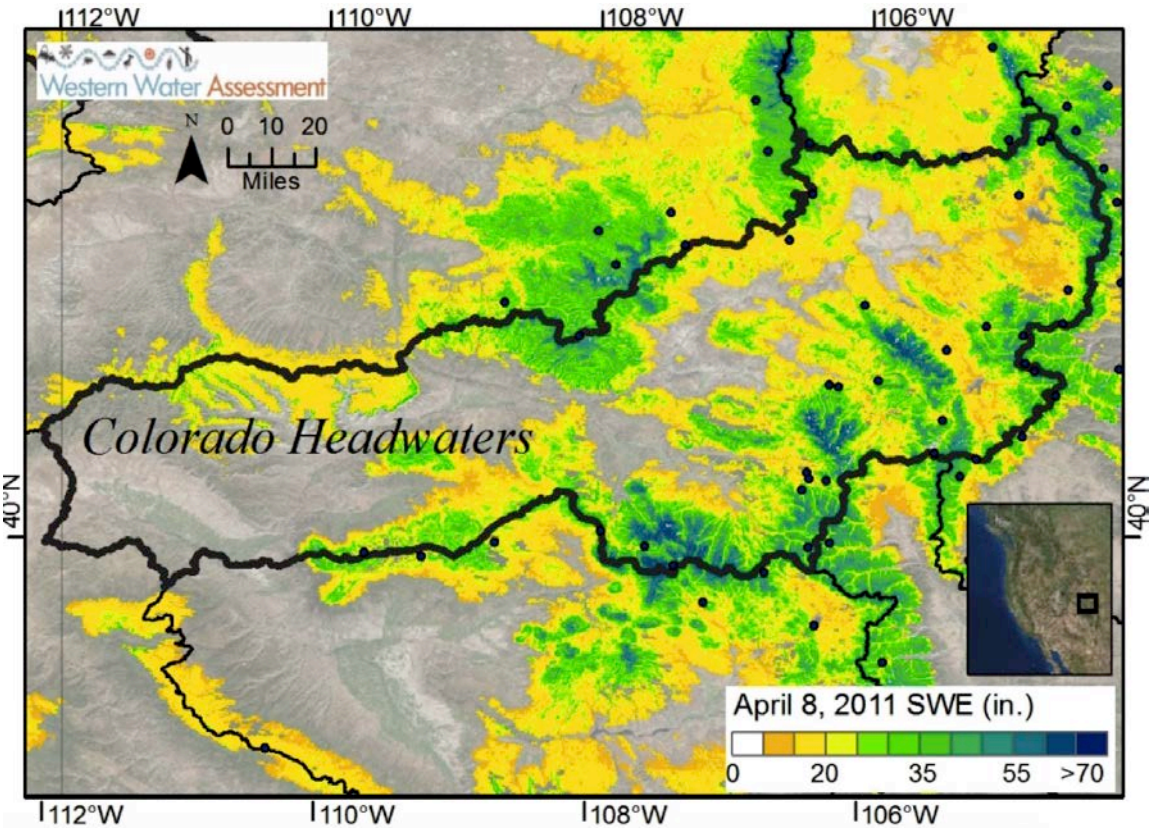


Figure 4. Example of MODIS-based Gridded SWE product, showing SWE in west-central Colorado for April 8, 2011, retrospectively produced from the SNOTEL data and MODIS imagery available for that date. Credit: Leanne Lestak, Dominik Schneider, and Noah Molotch.

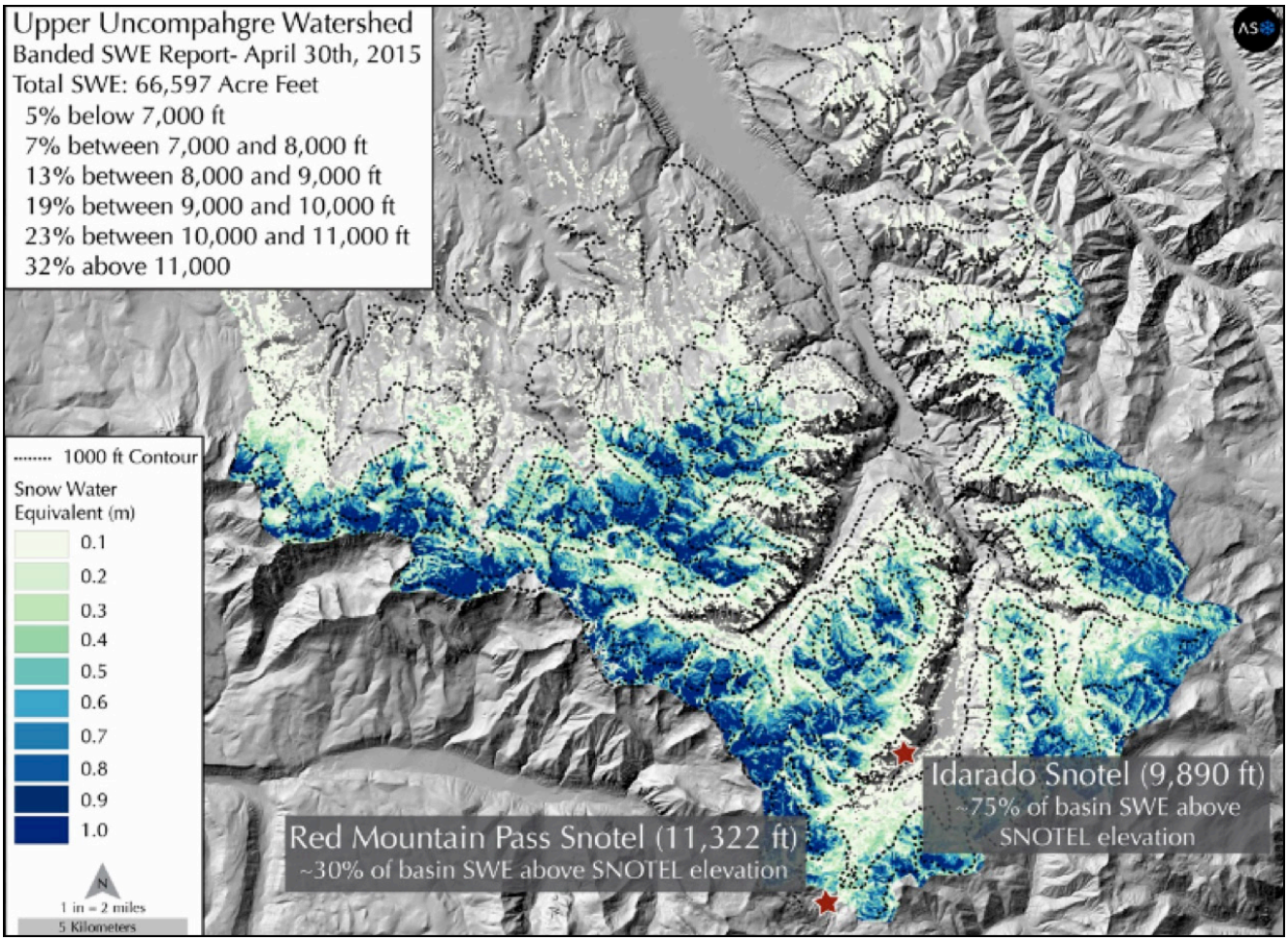


Figure 5. Example of SWE data from the Airborne Snow Observatory (ASO) plotted as a map for the Upper Uncompahgre Basin in western Colorado, for April 30, 2015. The annotations at top indicate what percentage of the total SWE lies within different elevation bands, and the annotations at bottom show that a large fraction of the total basin SWE lies above the highest SNOTEL site (Red Mountain Pass). Credit: Jeff Deems, ASO, NASA/JPL.

AIRBORNE SNOW OBSERVATORY (ASO)

The second presentation on remote-sensing based products was by Jeff Deems (WWA; also affiliated with NSIDC and NASA/JPL), described the NASA/JPL-funded Airborne Snow Observatory, known as ASO. The ASO is a twin-turboprop aircraft carrying two primary instruments: (1) a scanning LiDAR instrument that uses lasers to measure the height of the land or snow surface at 5-10-cm accuracy, at a 1.5-3-m resolution, and (2) an imaging spectrometer that measures the spectral characteristics of the snow surface, specifically to retrieve snow albedo and grain size.

The LiDAR does not measure SWE directly, but by making a snow-free scan of the basin of interest in late summer, and then differencing it from a winter-time scan, the snow depth can be measured to 5-cm accuracy (at 3-m resolution). Then snow density is estimated across the landscape from SWE and snow depth measurements at SNOTEL sites and snow courses, fed into a snow-density model, with depth times density equaling SWE (Figure 5). The spectrometer measurements of snow albedo can then inform snowmelt and runoff rates that spring.

The advantage of ASO products is very high accuracy and resolution. The chief disadvantage is relatively high cost per unit area, mainly reflecting the operating expense of the aircraft and also the intensive processing needed given the huge data stream from the instruments. The data from each flight is commonly processed within 24 hours. Deems described the current operational use of ASO in the Sierra Nevada, showing multiple maps of the Tuolumne Basin through the late winters of 2014 and 2015, and then how the ASO information was used to improve the inflow forecasts for San Francisco's reservoirs.

WYOMING: ASO AND GROUND-PENETRATING RADAR

At the Wyoming workshop, the final presentation was by co-convenor Matt Hoobler from the Wyoming State Engineer's Office (WY SEO). Hoobler first outlined WY SEO's aspiration to deploy ASO in four Wyoming mountain ranges. SEO has a draft agreement with NASA/JPL that if and when state funding becomes available ($850K), five ASO flights would be conducted in the initial year: one snow-free to establish ground elevations, and four during the snow season. Hoobler also described a successful collaboration with NRCS and the University of Wyoming, using ground-penetrating radar (GPR) dragged alongside manual snowcourses to measure snow density and SWE over long transects, supplementing the point measurements from SNOTEL and snowcourses. Finally, Hoobler outlined an ongoing research project by NCAR that has been using the new NCAR supercomputer near Cheyenne to assess the ability of six different land-surface models to simulate the seasonal snowpack evolution in Wyoming, compared with SNOTEL observations, and in the future, with ASO and GPR data. (As of late spring 2016, the State had been unable to secure funding for ASO flights, but was pursuing a contract with CU-Boulder (Noah Molotch) to provide the MODIS-based SWE estimates for the North Platte River Basin for the late winter of 2016-2017.)

RIO GRANDE BASIN FORECASTING PROJECT

At the Colorado Workshop, the final presentation also described a successful collaboration of state water-planning agencies and snow/hydrology researchers—in this case, the Colorado Water Conservation Board (CWCB) and the Colorado Division of Water Resources (DWR), with NCAR, NASA, and NOAA. Craig Cotten (DWR), Joe Busto (CWCB), and Dave Gochis (NCAR) laid out the complicated water management considerations in the upper Rio Grande Basin, and the compelling need to improve water supply forecasts. The Rio Grande Basin Forecasting Project deployed temporary weather stations, a weather radar, and ASO flights to supplement the existing snowpack monitoring. The high-resolution, physics-based WRF-Hydro model was used to capitalize on these new data inputs to produce runoff forecasts to compare with the operational runoff forecasts. This effort has identified limitations of the SNOTEL network for the upper Rio Grande, in which the critical high-elevation (>11,000') snowpack is not well represented, reducing the accuracy of runoff forecasts.

3. WORKSHOP DISCUSSIONS AND Q&A

One key objective of the workshops was to provide a space for users of snowpack information to talk with each other and with the operational information providers and snow researchers—about the data, how they use it, and what needs for decision support are still unmet. In addition to Q&A time during and immediately following each presentation, there were specific blocks set aside for group questions and discussion in the morning and afternoon. The gist of the dialogue during these discussions is captured in Appendix B, with the exclusion of questions about minor technical issues. In general, the content of the discussions spoke to the participants' keen interest in understanding the operational and emerging snow-monitoring products, and improving their use of the products.

4. POST-WORKSHOP EVALUATIONS

At the conclusion of the workshops, the participants were given an evaluation form to fill out on site, to capture what they had learned, and what worked and didn't work for them in the workshops. Because of attrition in the groups as people left the workshop early, especially in Utah, and some participants did not complete the evaluation, the response rate ranged from ~25% (Utah) to ~50% (Wyoming). Thus, the evaluations may not reflect a fully representative sample of the participants. Complete summaries of the post-workshop evaluations are found in Appendix C.

Dallas Divide, Colorado. Photo: iStock, kjschoen.

WHAT WAS THE MOST HELPFUL THING YOU LEARNED TODAY?

Over half of the respondents cited the new spatial products, ASO and/or the MODIS product. Other frequent responses were: awareness of the availability of operational snow-monitoring or runoff forecast products; the limitations of the SNOTEL network and the various monitoring approaches; the impacts of dust-on-snow; the descriptions of the NRCS and CBRFC runoff forecasting methods; and who to contact to get more information on snowpack monitoring.

WHAT WORKED BEST ABOUT THE WORKSHOP?

Respondents frequently cited the organization and time management, the breadth of presenters, the quality and usability of the information provided, the open discussions, the networking, and having the operational agencies (NOAA, NRCS) available for questions.

WHAT WOULD YOU SUGGEST WE DO DIFFERENTLY NEXT TIME?

Respondents cited a desire for more discussion time, more presenters who use snow data in operations, more focus on how the new monitoring products might get implemented and applied, and overall content that was less technical. In the Wyoming workshop, several respondents asked for more Wyoming-specific examples in the core presentation and the presentations on the new data approaches.

SELF-ASSESSMENT

For the Wyoming and Colorado workshops, we also included a self-assessment of knowledge outcomes from the workshop. We asked if participants' understanding had been unchanged, improved a little, or improved a lot after the workshop, in these four areas: Snowmelt hydrology, how snowpack information is produced, how to access snowpack information, and how to use snowpack information. For all four areas, the vast majority of participants indicated that their understanding had improved, with the most "improved a lot" responses for "how snowpack information is produced."

5. SYNTHESIS FINDINGS

The workshops brought together snow and drought researchers, operational snow and monitoring data providers, streamflow forecasters, and users of monitoring data, including users from a wide variety of tribal, local, state, and Federal entities. While it was not the objective of the workshops to bring this diverse group to consensus and identify future monitoring strategies, we believe that we can synthesize from the presentations and group discussions, and our own perspectives, some key 'take-home' messages:

The in-situ snowpack monitoring network (SNOTEL and snow course) is absolutely essential. Reductions in capacity should be avoided and targeted additions would be welcome.

A consistent theme from the workshop discussions was the widespread and fundamental reliance on the in-situ (SNOTEL and snowcourse) network, both direct use of the data for snowpack, water supply, and drought monitoring, and indirect use, as the basis for both the NRCS and NOAA RFC seasonal runoff forecasts. In addition, the development and deployment of the new remote-sensing-based spatial snow products still depends on a robust in-situ network for calibration and/or production of the data.

Participants were concerned about the potential erosion of the capacity of the in-situ network, especially removal of snowcourses without the installation of a co-located SNOTEL site to take over its function. NRCS has been under longstanding budgetary and other challenges in maintaining staffing and services for the Snow Survey Program. Only a handful of new SNOTEL sites (i.e., not at preexisting snowcourse locations) added to the network in the Rocky Mountain states in the past five years.

Workshop participants identified "underserved" areas that would benefit from additional SNOTEL sites, specifically the Wind River Range in Wyoming. The recently-developed "SNOTEL-Lite", an augmented aerial survey marker, can serve many of the functions of a full SNOTEL site at much lower installed cost, a smaller footprint, and lower maintenance. These "Lite" sites could be helpful in fleshing out the in-situ network, especially in very remote areas.

The use of data products from the in-situ snowpack monitoring network could be made more effective with additional training and guidance.

Data products from the SNOTEL/snowcourse network have been used extensively and effectively for water supply and drought monitoring for several decades. Yet, discussion during the workshop, comments on the pre- and post-workshop surveys, and self-evaluation after the workshops indicate that use of these data could still be improved. Several specific issues emerged during the workshops:

- The main approach for spatial aggregation and reporting of SNOTEL data, basin-wide averages and/or medians, may provide a distorted view of the snowpack when its elevational or spatial distribution departs from typical conditions. Users may not be aware of when these anomalies are occurring.

- Users may not know how to aggregate or otherwise analyze SNOTEL data themselves to fit their specific needs, or select from among the many existing data products.

- The availability of NRCS Snow Survey data products varies from state to state; users in Wyoming have fewer products available to them than those in Utah and Colorado.

- New data visualization tools, such as the NRCS NWCC Interactive Map v. 2.0, have the potential to improve usability—if users can effectively match the new features to their needs.

Overall, many of the participants might benefit from additional training or other guidance on the use of SNOTEL products. The recommendations to NIDIS below include specific suggestions on what this might look like.

While the new remote-sensing-based spatial snow products could bring substantial benefits to snowpack and drought monitoring, there is no single, clear path to expanding the operational reach of these products across the Rocky Mountain region.

The group discussions and post-workshop surveys indicated keen interest in the ASO and MODIS-based snow products, and appreciation for the potential benefits of expanding their use. But with respect to funding such an expansion in the Rocky Mountain Region, there is no "cavalry" out there. The experience so far in the West suggests that new deployments, especially of ASO, will need to be funded by coalitions of users leveraging targeted Federal and State funding.

6. RECOMMENDATIONS FOR NIDIS

Since the workshops were funded by NIDIS, we want to conclude this report with recommendations for how NIDIS might move forward given the lessons learned from the workshops. Currently, in the Rocky Mountain region, NIDIS supports snowpack monitoring mainly through the dissemination of snowpack information via the Upper Colorado River Basin Regional Drought Early Warning System (UCRB RDEWS) drought web resource and webinars.

Our suggestions to promote more effective use of snowpack monitoring information in the region, within the constraints of NIDIS's mission, funding, and staffing:

- In general, NIDIS should use its coordination, connecting, and convening capacities to keep conversations about snow data going among stakeholders, researchers, and operational providers.

- NIDIS could co-sponsor user workshops, with the NRCS Snow Survey programs and the NOAA RFCs, to provide hands-on training on the use of SNOTEL/snowcourse data products and tools.

- NIDIS could co-produce with NRCS and other partners a print and/or online handbook of 10-20 pages on using snowpack data for drought monitoring, providing information and guidance similar to that presented at the workshop.

- The upcoming revision of the UCRB RDEWS strategic plan should consider that, although there are many regular users of the RDEWS drought webinars and web resource, the workshop participants indicated that they obtain snowpack information more frequently from other resources, primarily the NRCS Snow Survey program webpages. Thus, any effort to enhance the snow-monitoring component of drought early warning in our region would be more effective if it integrated these other resources.

APPENDIX A

LISTS OF WORKSHOP PARTICIPANTS

Utah Workshop
West Jordan – August 11, 2015

Brenda Alcorn, NOAA CBRFC
Cody Allred, PacifiCorp
Larry Alserda, Salt Lake City
Rodney Banks, Roy Water
Tim Bardsley, WWA
Stacie Bender, NOAA CBRFC
John Berggren, CU/WWA
Brent Bernard, NOAA CBRFC
Courtney Black, NIDIS
John Briem, UT Dept Water Rights
Tom Bruton, Central Utah Water Cons. Dist.
Jeff Budge, Provo River Water Users
Steve Burgon, Salt Lake County
Jordan Clayton, NRCS UT Snow Survey
David Clow, USGS
Charlie Condrat, USDA Forest Service
Jeff Deems, CU/WWA
Dave Eiriksson, University of Utah
Rich Giraud, UT Geologic Survey
Pete Gomben, USDA Forest Service
Melissa Haeffner, Utah State University
Chris Haight, Salt Lake County
Alex Hamilton, Salt Lake County
Jared Hansen, Central Utah Water Cons. Dist.
Candice Hasenyager, UT Dept Water Resources
Chris Hogge, Weber Basin Water
Jay Humphrey, Emery County Water
Randy Julander, NRCS UT Snow Survey
Tracie Kirkham, Salt Lake City Public Utilities
Jeff Lukas, WWA
Ryan Luke, Reclamation
John Mann, UT Dept Water Rights
Jared Manning, UT Dept Water Rights
Alicia Marrs, NIDIS
Elizabeth McNie, WWA
Craig Miller, UT Dept Water Resources
Paul Miller, NOAA CBRFC
Noah Molotch, CU/WWA/INSTAAR
Ryan Mower, USDA Forest Service
Stacie Olson, Riverton City (Water)
Heather Patno, Reclamation
John Rice, Southern Rockies LCC/Reclamation
Jason Scalzitti, University of Utah
Mike Schaffner, NOAA
Dominik Schneider, CU/WWA/INSTAAR
Todd Schultz, Jordan Valley Water
Zach Schwalbe, Colorado Climate Center
Graham Sexstone, USGS
Greg Smith, NOAA CBRFC
Everett Taylor, UT Dept Water Rights
Michaela Teich, Utah State University
Bob Thompson, Salt Lake County
Matt Tietje, Metro Water District
Lee Traynham, Reclamation
Josh Walston, Utah State University
Kevin Werner, NOAA Western Region
Tony Willardson, Western States Water Council

Wyoming Workshop
Lander – August 27, 2015

Loren Antelope, Ray Canal Water Users Assn
Stacie Bender, NOAA CBRFC
James Campbell, USGS
Al C'Bearing, Office of the Tribal Water Engineer
Dan Coughlin, Sheridan Area Water Supply
Simeon Coskey, USDA Forest Service - Shoshone NF
Mitch Cottenoir, Office of the Tribal Water Engineer
Jared Dalebout, BLM Worland
Rick Deuell, WY State Engineer's Office
Jeff Deems, CU/WWA
Nolan Doesken, Colorado Climate Center/CSU
Brian Domonkos, NRCS Colorado Snow Survey
Ralph Estell, NOAA National Weather Service
Jim Fahey, NOAA National Weather Service
Kenneth Ferris, Office of the Tribal Water Engineer
RaJean Fossen, City of Lander
Josh Fredrickson, WY State Engineer's Office
Bill Gordon, Hot Springs County Emergency Mgt
Lee Hackleman, NRCS WY Snow Survey
Mike Henn, Sublette Cty Conservation Dist
Dave Hill, City of Casper
Pat Hnilicka, US Fish & Wildlife Service
Lance Hopkin, City of Lander Public Works
Mark Hogan, US Fish & Wildlife Service
Matt Hoobler, WY State Engineer's Office
Windy Kelley, University of Wyoming Extension
Holly Kennedy, WY Farm Bureau
Matt Ley, Laramie County Cons. Dist.
Rod Liesinger, Sheridan County Public Works Director
Jeff Lukas, WWA
Shannon Mazzei, WY SEO & University of Wyoming
Brett McDonald, NOAA
Jalynda Mary Mckay, University of Wyoming/WRDS
Shannon McNeeley, North Central Climate Science Center/CSU
Chad McNutt, NOAA NIDIS
Elizabeth McNie, WWA
Brenna Mefford, WY State Engineer's Office

Ryan Mikesell, WY State Engineer's Office
Noah Molotch, CU/WWA/INSTAAR
Dave Myers, HDR Engineering
Dave Patterson, Basin Electric Power Cooperative
Ron Perry, Ray Canal Water Users Assn
James Pogue, Office of the Tribal Water Engineer
Kathy Raper, Sublette Cty Conservation Dist
Tina Russell, University of Wyoming Extension
Nick Scribner, Wyoming Game and Fish Dept
Craig Schwieger, Reclamation
Loren Smith, WY State Engineer's Office
Mae Smith, UW Extension
Herbert Stoughton, Geodetic Engineer
Fred Tammany, Ray Canal Water Users Assn
Elizabeth Traver, University of Wyoming
Cody Tusing, NRCS Area Engineer
Cal Van Zee, City of Laramie Utilities
Rollin Ware, Office of the Tribal Water Engineer
Jennifer Wellman, University of Wyoming EPSCoR
Natasha Wheeler, Wyoming Livestock Roundup
Jerrod Wheeler, USGS

Colorado Workshop
Broomfield – September 9, 2015

Jeremy Allen, Denver Water
Tony Anderson, NWS Pueblo WFO
Emily Baker, CU/INSTAAR
Tim Bardsley, WWA
Dave Barnard, CU/INSTAAR
Stacie Bender, NOAA CBRFC
Tony Bergantino, WY State Climate Office
Kathy Bogan, NIDIS
Bret Bruce, USGS
Joe Busto, Colorado Water Conservation Board
Don Campbell, USGS
John Carron, Hydros Consulting
Craig Cotten, Colorado DNR - Water Resources
Theresa Dawson, Reclamation - FryArk
Jay Day, Riverside Technology
Jeff Deems, CU/WWA
Jeff Derry, Center for Snow and Avalanche Studies
Candida Dewes, NC CSC
Swithin Dick, Highlands Ranch (Water)
Lisa Dilling, CU/WWA
Nolan Doesken, Colorado Climate Center
Brian Domonkos, NRCS CO Snow Survey
Nathan Elder, Denver Water
Dan Elliott, Associated Press
Mike Eytel, Colorado River District
Stephen Fassnacht, Colorado State University
Dave Gochis, NCAR
Clay Good, Denver Water
Mary Hull, City of Thornton (Water)
Treste Huse, NWS Denver-Boulder WFO
Kim Hutton, City of Boulder (Water)
Kevin Hyatt, BLM Colorado Office
Anne Janicki, Colorado Water Trust
Laurna Kaatz, Denver Water
Rick Kienitz, Aurora Water
Bob Kimbrough, USGS
Bobbie Klein, CU/CSTPR
Bob Krugmire, City of Westminster (Water)
Frank Kugel, Upper Gunnison River WCD
Lexi Landers, NRCS Colorado Snow Survey
Leanne Lestak, CU/INSTAAR
Sue Lowry, Wyoming State Engineer's Office
Jeff Lukas, WWA
Alicia Marrs, NIDIS
Elizabeth McNie, WWA
Katie Melander, Northern Water
Noah Molotch, CU/WWA/INSTAAR
Jeff Morisette, North Central Climate Science Center
Marta, Nelson, Radiometrics Inc.
Chris Nicholson, WY State Climate Office/WRDS
Cheryl Pailzote, White Mountain Apache Tribe (Water)
Danielle Perrot, City of Greeley (Water)
Andy Pineda, Northern Water
Steve Pope, Colorado DNR - Water Resources
Imtiaz Rangwala, WWA/NC CSC
Henry Reges, Colorado Climate Center
Ursula Rick, Western Water Assessment
Ana Ruiz, City of Thornton (Water)
Ed Rumbold, BLM Colorado Office
Russ Sands, City of Boulder (Water)
Dominik Schneider, CU/INSTAAR
Wayne Schwab, Trinchera Irrigation
Zach Schwalbe, Colorado Climate Center
Gabriel Senay, USGS/North Central Climate Science Ctr
Graham Sexstone, USGS Water Science Center
Sara Simonson, CSU/North Central Climate Science Ctr
Tim Skarupa, Salt River Project (Water)
Sarah Smith, Northern Water
Bob Steger, Denver Water
John, Thornhill, City of Greeley (Water)
Melissa Valentin, Colorado School of Mines
Todd Vandegrift, Reclamation
James Walter, Salt River Project
Natalie Ward, City of Boulder (Water)
Matt Welsh, ELEMENT Water Consulting
Karl Wetlaufer, NRCS Colorado Snow Survey
Troy Wineland, Colorado DNR - Water Resources
Jeanette Wolf, City of Westminster (Water)

APPENDIX B

SUMMARY OF Q&A AND DISCUSSION SESSIONS

Utah

Cloud seeding: After the core technical presentation on snowpack hydrology, Tom Bruton (CUWCD) asked Noah Molotch and Jeff Deems for their thoughts on cloud seeding, which many of the conservation districts in Utah fund. Another participant offered that they hear cloud seeding causes a +3-10% increase in precipitation, and they use a +5% figure. Molotch pointed out that it's "really hard" to demonstrate whether precipitation is enhanced, and by how much. The +5% figure seems reasonable. Deems added that the new remote-sensing snowpack monitoring tools may be helpful in pinning down the effects of cloud seeding. Tony Willardson (WGA) noted that the State of Wyoming just completed a cloud-seeding study which suggested a +10% increase in precipitation [under storm certain conditions].

Additional SNOTEL sites: Tom Bruton followed up on Molotch's statement that more in-situ (i.e., SNOTEL) sites might be required to maximize the utility of the new remote-sensing approaches. What is the best way for water managers to support the snow-monitoring network? Deems stated that we first need to "stop the bleeding" and keep sites from closing. Tony Willardson added that it helps WGA if snow data users contact their own Congressional representatives, and convey the importance of SNOTEL sites, why they're useful, and how much they cost.

ASO data: Dave Erickson (Univ. of Utah) asked if the SWE data from ASO LiDAR were publicly available, and if those data are unique to California. The answer to the first was yes and no, and to the second, that that ASO is also doing flights in Colorado, Oregon, Washington, and Idaho.

SNOTEL technology: After Randy Julander's presentation, Kevin Werner (NOAA) asked if there will be changes in the technology of the SNOTEL instrumentation. Julander responded that there's no "paradigm shift" planned, and that he'd be reluctant to replace the current instrumentation, that consistency is more important than new sensors. Adding more sensors might add too much complexity to the site and the data stream.

Paying for new SNOTEL sites: Tony Willardson noted that some states or water districts might have the ability to pay for new sites, but the limitation is the lack of NRCS personnel to install and maintain sites. Julander agreed that NRCS staffing is a real limitation, and that getting additional NRCS staff will be difficult or impossible. Willardson added that USGS writes numerous contracts for operating and maintaining stream gages—could this work for snow sites? Julander said that it might, and could be considered.

Runoff forecast errors: After Tom Bruton's presentation, Noah Molotch asked if he had notable examples of when forecast errors were particularly high, similar to Denver Water flagging under-forecast peak flows in June 2010. Bruton answered that he keeps track the NOAA, NRCS, and Reclamation forecasts, and is appreciative of the overall accuracy. He has not seen years when forecasts have been far off the mark. Heather Patno (Reclamation) pointed out that in May 2015, the Reclamation forecast for inflows to Lake Powell was 3 MAF, but the observed inflows were 6.9 MAF. She said they're also noticing changes from snow to rain, and that it's hard to know under those conditions how much will end up in reservoirs.

Cross-agency access to information by basin: Tom Bruton (CUWCD) said that he likes how the Utah Snow Survey organizes their information by drainage basin. It would be even better if there were one place on the web to get snowpack, forecast, weather, and reservoir data all in one place, drainage basin by drainage basin, through a single interface that crosses the multiple agencies (NRCS, NOAA, USGS, etc.). He noted that there is so much information out there that it is hard to find the specific product you're looking for. Tracie Kirkham (SLCDPU) agreed that if we could put the "pieces of the puzzle" together with all this information in one place, that would be helpful. This topic came up again in the open discussion, and Jeff Lukas (WWA) asked the group who found it difficult to pull information from multiple websites, with

about half the participants raising their hands. But when he asked who would like to see a movement towards a single provider or portal, only a couple of people raised their hands.

Who uses whose runoff forecasts? In Tom Bruton's presentation, he said that CUWCD uses both NRCS and NOAA (CBRFC) runoff forecasts, but noted that the forecasted values are no longer coordinated between the two offices, so there are two different forecast values to consider now, in most cases. Later, during the open discussion, Jeff Lukas asked for thoughts on having two different sets of forecasts from NRCS and NOAA, and added that while in some ways this is functional redundancy, some users have long-standing relationships with one or both forecast providers. Stacie Bender (CBRFC) agreed that the established relationships are important. But users without that personal connection to the agencies need to be able to find clear information on how the models work. She noted that accessible documentation on what goes into the respective agencies' models is lacking. Randy Julander (NRCS) said that NRCS is heavily invested in small agricultural and water operations as users of their forecasts. CBRFC has a specific customer base as well, including Reclamation. The two customer bases overlap in part, but are also different.

NRCS and CBRFC still get along: Greg Smith (CBRFC) addressed the misconception, which he heard earlier, that there was a "divorce" between NRCS and CBRFC with the end of explicitly coordinated runoff forecasts about three years ago. He said that the two forecaster groups still communicate regularly and look at each other's numbers. He said the end of coordination had more to do with wanting to take full advantage of each group's modeling capabilities. He conceded that the agencies could do a better job communicating the differences in the forecasts. In response to a comment, he also noted that in the extreme years, the forecasts tend to have larger errors than in near-average years.

Communication: Elizabeth McNie (WWA) asked the group who has gone to either agency to talk about specific information needs. Tom Bruton said that both NRCS and NOAA have been very responsive to questions and needs for information, including custom products.

MODIS-based gridded SWE product: After Noah Molotch's presentation, Rich Giraud (UTGS) asked how quickly the information can be produced, and the accuracy. Molotch reiterated that clouds represent a challenge in obtaining usable MODIS imagery, but in California, they've always been able to find one cloud-free image per week, which is why they do weekly reports. Regarding accuracy, they haven't done a rigorous analysis that considers differences between slope aspects. Another participant asked where the MODIS SWE products are available. Molotch said the California reports are being delivered on-demand through a CU-Boulder FTP site. He encouraged anyone in the room who is interested in having reports for their basin, to let him know.

Funding ASO flights and SWE products: After Jeff Deems' presentation, Tom Bruton (CUWCD) asked, what about Utah? Deems responded, "Let's talk!" It can be a challenge to get funds to NASA because of the contract mechanisms in the Space Act Agreement, making multi-agency partnerships an attractive option. In Colorado and Wyoming, contracts are being run through state agencies, which are also acting on behalf of smaller entities like water districts that want the ASO data. To Deems' knowledge, no one from the State of Utah has looked into ASO data yet.

Using new spatial snow products for flood risk: In the open discussion, Elizabeth McNie asked what opportunities participants would see in using the new tools. Rich Giraud (UTGS) asked, if we were back in 2011, a very wet year, could you use these tools to assess flood risk? Noah Molotch responded, absolutely, yes, though he hasn't been involved with a specific project applied to flood risk. Jeff Deems added that in California they are using ASO data to manage reservoirs "much tighter," accounting closely for runoff at high elevations after the SNOTEL sites have melted out so they don't release any more water than is necessary.

Do the new spatial SWE products play well with hydrology models: Another participant asked, are there obstacles to using the spatial SWE estimates in hydrology models? Jeff Deems said that this has worked fairly well in California, and is also showing its merit in the Rio Grande Basin in Colorado with one or two

flights per melt season. Some hydrology models run on a grid and can ingest the gridded SWE data as-is. Other models need a single volumetric number, but that can be extracted from the gridded SWE data and plugged into the model.

Which entities can use the new products: Tracie Kirkham (SLCDPU) said that she appreciated the technology, but wondered if their department were too small to request and use it. Noah answered that no user is too small, and that he is interested in all partnerships. Tim Bardsley (WWA) added that the watersheds of many of the users in the room are in close enough proximity, mainly in the Wasatch Range, that multiple entities could be served by one deployment of a product.

More on who will use the new products: Jeff Lukas asked in the closing discussion, of the participants who work in planning and operations, who would like to use more spatial products in the future, several people raised their hand. Lukas noted that there are real costs involved in integrating a new product into decision-making, even if you don't pay for the product itself. But as the new products get integrated into runoff forecasts (e.g., CBRFC), it is likely that everyone in the room will at least become indirect users of the new spatial products. Tim Bardsley added that even if smaller entities don't have the technical capacity to use the new products, they can still benefit from larger entities (e.g., Reclamation, state agencies) adopting them.

The unusual years, system resilience, and new tools: Jeff Lukas noted that when we have large snowpack and hydrologic anomalies, like the high runoff in June 2010, that is fertile ground for investigating new tools, since the large anomalies tend not to be captured well in the traditional forecast models. Jeff Deems added that if conditions were consistently near-average every year, we wouldn't be here because a simple statistical forecasting approach would work well. The unusual events are the ones that test the resilience of our systems. As we see more years that fall under "unusual" due to climate change, that's even more motivation to bring new tools to bear on our decision-making. Heather Patno (Reclamation) added that CBRFC has been really good about looking closely at these anomalous events, to decrease the forecast errors during the extremes.

Wyoming

Identifying and funding new SNOTEL sites: After the NRCS presentation, Shannon McNeeley and Jennifer Wellman asked how NRCS decides which manual snowcourses to automate. Brian Domonkos and Lee Hackleman answered that in the past it was driven by cooperators who wanted to automate those sites for their use, and that beyond the availability of funding, accessibility was also considered: remote snowcourses would be more likely to be transitioned to a SNOTEL site. But no Wyoming SNOTEL sites are currently in designated Wilderness areas; there used to be one, but it is more difficult to work in a Wilderness due to the regulations.

Dust-on-snow sources: After Stacie Bender's presentation, a participant asked whether analysis has been done on where the dust that falls on snow in the CBRFC forecast region (mainly western Colorado) comes from. Bender and Jeff Deems answered that the big source areas are to the southwest, in the Colorado Plateau: northeastern Arizona, northern New Mexico, southern Utah. For dust deposition in the central Wyoming and the Lander area, the source area is usually the Great Basin, and sometimes the Snake River Plain. Satellite imagery of dust plumes and back-trajectory analysis of air parcels are used to determine source regions. In a follow-up on dust-on-snow, Deems added that, in the source area of the Colorado Plateau, most of the surface is covered with a biogenic crust that is impervious to wind but is easily crushed by disturbances such as grazing, energy exploration and development, and off-road vehicle use.

Creating a custom subset of SNOTEL sites: In the first group discussion, on using operational snow data, a participant who is in the Bighorn Basin notes that sometimes the basinwide % of median SWE reported by NRCS doesn't always reflect his local conditions on the southwest side of the basin, and he wondered if it would be appropriate to take the data from a subset of the SNOTEL sites in the basin and calculate SWE statistics for his local area. Jeff Lukas responded that this was a very reasonable thing to do, and a

show of hands indicated that many other participants create their own "basins" by custom-aggregating SNOTEL data. Stacie Bender and Brian Domonkos added that it is helpful to look at historical SNOTEL data and run correlation analyses to confirm which sites are most connected with the streamflow gage(s) of interest; both CBRFC and NRCS can help users with this.

Who paid for ASO: Jeff Deems answered that for the California (Tuolumne) ASO work, the initial funding was from NASA and the California Department of Water Resources. The cost per year, with weekly flights in late winter and spring, was $300K, but that goes down over time. For the Colorado work, only NASA funding, and the cost was about $60K for one snow-free flight and three snow flights.

UAV for ASO? A participant asked if drones (unmanned aerial vehicles; UAVs) could be used for the ASO flights. Jeff Deems responded that they've looked at using small piloted UAVs for some snow-monitoring work, but using larger automated UAVs that could carry the ASO instrumentation is a long ways off due primarily to FAA UAV use restrictions.

Forecast uncertainty: Noah Molotch pointed out that in some years like 2015, precipitation after April 1 may make up a significant portion of the runoff; i.e., the snow that is on the ground in April may not reflect the how the water supply turns out. Jeff Lukas added that there are two main types of uncertainty in runoff forecasts: (1) The accuracy of the measurements of water volume in the snowpack, and (2) How the weather will play out during April, May, and June with respect to new snow accumulations and the drivers of runoff efficiency. Jeff Deems added that we have particular trouble predicting extremes like the very high May 2015 precipitation in the region. This puts a greater priority on building resiliency into our systems so we can cope with extremes when they do come.

Future changes: A participant, after the above discussion, speculated that May 2015 was not so much an anomaly as a reflection of overall changes to the climate. Jeff Lukas noted that May 2015, despite being much wetter than average, was also warmer than average, which is indicative of the regional warming trend. That warming is linked to lower recent April 1 SWE in many parts of the Rocky Mountain West. We need to watch for our traditional snowpack metrics like April 1 SWE being less reliable in a warming climate, as more precipitation comes as rain, versus snow.

Predictability at different timescales: A participant (water manager of a smaller entity) asked about snowpack changes and climate change and what the impacts might be over the next ~10 years. They're concerned with what might happen to their water supplies in the medium-long term. Lukas responded that weather and climate forecasts out to a several months have skill, and we also have confidence in the broad aspects of projections of anthropogenic climate change 30-100 years out. But there's a "hole" in predictability at the intermediate time scales, from a year to 10-15 years out, because unpredictable (as of yet) natural climate variability dominates what will happen over that interval. So we can't provide much insight into how the climate will behave over the next decade, except the likelihood of warming.

Colorado

NRCS adjustments to flows: After Brian Domonkos's talk, he was asked if NRCS makes adjustments to the observed and forecasted flows for diversions and depletions. Brian answered that while some small diversions are not accounted for, most are accounted for, and so the flows are near-natural.

Future of NRCS snow courses: Brian was also asked if the snow course network was "safe"—will sites be removed in the future? And was there any chance for the restoration of snow courses that have been discontinued? He answered that no removals are foreseen, but you never know when funding cuts might necessitate that. Restoration of discontinued sites is not on the table right now.

Accuracy of SNOTEL vs. snow courses: In a group discussion, a participant asked about differences in accuracy between SNOTEL and manual snow courses. The answer, with several people contributing, was that they are both good indicators of SWE, but conditions can change (i.e., to the surrounding forest) that affect the measurements at both types of site. So the question of whether one is better than the

other depends on the location. The snow courses are not always measured on the same date from month to month and year to year, and may be measured by different observers from one year to the next. So SNOTEL measurements may be more consistent in that sense. For both, we have to recognize they are point measurements and extrapolating them to the broader landscape is challenging.

Using forecasts in the Rio Grande basin: Craig Cotten (DWR) was asked how they deal with having two operational forecasts (from NRCS and NOAA) for the Rio Grande, and whether they have seen specific trends or issues with the forecasts. Cotten answered that when the two forecasts are different, as they were in 2015, they split the difference. In the last 4-5 years, the forecasts have consistently underestimated the observed streamflows, and they speculated that the extensive wildfires and beetle kill may have had an impact on streamflow.

Use of the new spatial snow products: In the final discussion, Jeff Lukas asked how many of the participants involved with operations or planning would use the spatial snow products. Few raised their hands regarding the MODIS product, and a few raised their hands about ASO. It was pointed out that ASO is much more expensive per unit area than the MODIS product, and that we might need to understand the economic benefits of better information on water supply before deciding which products to use. Different basins would have different cost:benefit profiles. On the cost side, agencies need to identify which outcomes they're most trying to avoid, and how much they would cost if they occurred. Jeff Deems added that if you can manage your existing storage to a tighter margin with more accurate information, it's like adding storage—and dams are not cheap.

Long-term support for monitoring: How do we fund long-term monitoring infrastructure and data management at the state level? What entity or entities in Colorado would have the capacity for long-term support. In California, CADWR has been deeply involved with ASO. It was pointed out that NOAA's new National Water Center is looking for ways to support application of hydroclimate tools, and maybe they could be asked to make the new spatial products operational.

APPENDIX C

WORKSHOP EVALUATION RESPONSES

Utah

14 responses out of 48 participants

What was the most helpful thing you learned today?

- LIDAR MODIS information
- There are a number of new tools that can be used to refine SWE-to-streamflow projections.
- There are a lot of individual agencies and groups that should be working together to develop additional tools.
- New products that were presented. Very interesting.
- Networking, open discussions.
- Learning about additional snow products ASO MODIS.
- MODIS reconstructed SWE.
- Deems/Molotch talks on new snow survey methods.
- Great to have so many varied users in one room.
- Newest available information such as soil, temp.
- I think I got a better understanding of how the remotely-sensed snow is derived and developed. It was good to see how the different efforts work together.
- Updates on the projects and research.
- MODIS and LIDAR research.
- That the SWE reconstructions are available over CO, in addition to CA, through ~2013. I knew they were working on expanding the dataset but the expansion of the datasets to near present will be useful.
- The utility of products from both CBRFC and NRCS. Status of science of spatially distributed SWE data.
- Real-time SWE simulation presentation from Noah.

What worked best about this workshop?

- It worked well. Discussions went well.
- So many products available right now. Exciting!
- These are amazing tools that can be used for several land management issues…fires, snow/SWE, etc.
- Breaks, lunch, meeting people.
- Loved the networking opportunities. Chance to talk to people whose data I used.
- Great spread of talks.
- Open discussions mixed with 'lectures'.
- WWA's moderation. Loved the Q and A time.
- Good banter between presenters and attendees.
- I enjoyed the open discussion portion of the workshop. I think some great questions were asked and answered.
- Great chance for people to articulate needs/wants/abilities.
- Format and open discussion.
- Sufficient opportunities for questions.

- Hearing from different agencies providing snow data, and who and how it is used.
- Learning about the latest research for creating spatially distributed SWE.
- It ran on time! Almost exactly!
- The variety of speakers and topics was excellent. The organizers did well to arrange the lineup.
- I also liked the presentation of survey results at the beginning so we knew who was in attendance.

What would you do differently?

- A bit shorter may be better.
- More one-on-one time.
- Maybe have a note card or place to list questions to help start off discussion session.
- Nothing really. This was an excellent meeting.
- Perhaps invite a few people who are not professionals.
- I think there is some misinformation out there regarding the CBRFC/NRCS relationship. It would be good to have a few members to address that.
- Perhaps have lunch 30-60 minutes earlier. People seemed a bit restless around noon.
- I might add a panel session in place of one of the 'open discussion' sessions. That would allow attendees to ask questions to reps from the various agencies and institutions.
- Get all the presenters together for a call to discuss progression of workshop, correlation of data and overall purpose and audience. Was this research or operations?

Wyoming

26 responses out of 48 participants

What was the most helpful thing you learned today?

- Albedo matters.
- ASO and satellite imagery application for monitoring snowpack.
- Dust on snow monitoring.
- Meet with Tribes.
- The limitations of SNOTEL and the satellite imagery (MODIS) that's improving the accuracy and predictive capabilities of it.
- The effects of dust.
- Additional websites for snowfall SWE/Streamflow forecasts.
- Updated products for developing better data/models.
- SNOTEL data is limited to mid-elevations. Doesn't capture the highs and lows.
- Learning more about the available tools, how to access them.
- A better understanding (overview) of how the data are collected.
- Networking – connecting faces to names.
- Websites and resources to access reports and forecasts.
- Available technology.
- Everything was useful.
- Newer technology overview.
- Getting contact information to get monthly Wyoming outlook report.
- The large number of products that are available.

- That the products all have limitations and strengths.
- That I probably don't have the expertise or time to determine what products are best for my water system management needs.
- Learned about more places to access snow information.
- Learned about new technologies to monitor snowpack.
- All the agencies working on snowpack/droughts.
- The different ways to detect runoff.
- Where to get information on snow pack in an area that affects our jurisdiction.
- Contacts for data recovery. How to get to existing data.
- Distributions of SNOTEL sites in Wyoming and Colorado.
- The ASO projects currently running and the potential for more applications.
- Application of ASO and its future use. Hopefully in Wyoming for water availability and forecasting.
- How the info is harvested and the interpretation of that info. In particular the subject of ASO.
- ASO information.
- CBRFC access.
- How important integrating dust into models.
- The dust on snow program was very interesting.
- MODIS technology is very interesting.
- How ASO and LIDAR works.

What worked best about the workshop?

- Lunch and networking
- Well run with excellent speakers and topics.
- Impacts on Wyoming.
- Networking.
- Presentations good. Shorter than typical. Weren't difficult to understand
- Information about new tools available and about forecasting models.
- Overall this was a good workshop.
- Keeping on the schedule.
- Great balance of technical and layman's explanations for my level of understanding.
- Networking.
- Hearing and being able to ask questions to the experts in each tool.
- Networking to improve water management.
- Informality.
- Brought together some experts from the area with those who use the data.
- Tight timeline kept it moving.
- Wyoming efforts to increase data collection and integration with other data sets.
- GPR use of super computer.
- Always good to connect with others that share the same interest as myself and to reconnect with previous contacts.
- Great facility.
- Good cross sector of presenters.

- Everything: like the format.
- Great speakers and varied subjects.
- The different speakers.
- Q & A and discussions.
- Glad to see that it was timed and organized.
- Logistically, having the workshop at the hotel.
- Having a variety of speakers – NRCS, weather service, university researchers.
- The diverse group of people and programs.
- Short segments: technical enough but good overview of products and where its headed.
- How to access all of the different websites.
- Thought it went pretty smoothly.

What would you suggest we do differently if we were to hold another workshop like this one?

- Less information, less technical, more Wyoming, less Colorado focus.
- Nothing.
- Early run-off drivers. What are the triggers?
- PowerPoint handouts for all presentations.
- Talk more about the weather modification project in Wyoming.
- It was fun to learn about new technology. However, would have been nice to spend more time understanding how to use the available data for Wyoming. I think all presenters used Wyoming examples when available. If not, I would encourage this for the future to be location specific.
- Would have been more useful for me to see/use the tools more than how the models are created.
- Provide contact information related to the organizations and material used in presentations. This could be in the form of links, emails, websites, etc.
- Need a comprehensive bibliography.
- More in depth look at how data is brought forward.
- For those of us who use this data it would be good to spend a bit more time on basic usage of the data.
- Some of the detailed information covered related to modeling got a little over my head.
- Less detailed data presentations.
- More generalized information aimed at what products are best tools to answer specific water management questions.
- Spend a little more time on the data and quality of from SNOTELS (for use in operations, daily).
- Maybe more local organizations and products (USGS/NWS/BOR).
- Have people bring laptops and walk them through the use of technology vs. telling them about it.
- Include information about where dust comes from with respect to dust-on-snow.
- Maybe include a presentation by a water manager about how they are currently using snow info and what they might do in the future.
- Limited and pertinent info for water managers. No information overload.

My understanding of snow hydrology:

- Is the same as before the workshop: 1 (4%)
- Has improved a little: 14 (56%)
- Has improved a lot: 10 (40%)

My understanding of how snowpack information is produced:

- Is the same as before the workshop: 1 (4%)
- Has improved a little: 12 (48%)
- Has improved a lot: 12 (48%)

My understanding of how to access snowpack information:

- Is the same as before the workshop: 3 (13%)
- Has improved a little: 14 (58%)
- Has improved a lot: 7 (29%)

My understanding of how to use snowpack information:

- Is the same as before the workshop: 2 (8%)
- Has improved a little: 16 (67%)
- Has improved a lot: 6 (25%)

Colorado

28 responses out of 77 participants

What was the most helpful thing you learned today?

- New methods of streamflow modeling.
- Forecasting models, how snow data is obtained, and the different tools available to complement on the ground measurements (i.e. radar technology).
- More details on all of the research based forecast and snow monitoring product that people want to put into operation.
- The promise of remote sensing products for improving streamflow forecasts.
- New snowpack measuring methods.
- New techniques and products.
- Dust cover.
- ASO.
- The increased focus on the integrated use of in situ and satellite data.
- Snow hydrology.
- LIDAR based SWE!
- Learned a lot about MODIS snow estimation, and its advantages and disadvantages.
- The ASO project and predicting inflow with ASO.
- MODIS and remote sensing components and contributions to snow modeling.
- The ASO work is freaking amazing!
- Aerial and spatial measurement methods.
- All of the resources and tools available for forecasting streamflow and snowpack.
- Snowpack data is spatially limited but new products are available (e.g. MODIS SWE) that can potentially fill the gap for research purposes at least.
- The impact of dust on snow/runoff.
- Really found the discussion about LIDAR and other aerial mapping techniques that can be used to improve and augment the more traditional SNOTEL station data.

- The application of the MODIS, LIDAR technologies into determining SWE on a volumetric basis.
- Well done today, thanks!
- Advances in remote sensing and how it could be integrated in our models.
- New technology to supplement NRCS snow survey, MODIS, ASO.
- Rio Grande Basin research.
- A better understanding of projects within the state as well as other areas of the US.
- CBRFC talk (Stacie Bender) – learning how they are adjusting forecasts to account for dust on snow (relevant to my research).
- New technologies and who is doing what.
- All the modeling and on-going efforts to improve the reliability of streamflow forecasts.
- Overview of traditional forecasting from NRCS, CBRFC along with intro to newer technology MODIS and ASO.
- Better sense of the different remote sensing products and issues related to them.
- Developed understanding of current and emerging methods for evaluating SWE and streamflow relationships.
- How water managers are using water supply forecasts.
- RS data is difficult to use. Trust in RS data is low.
- There is a decent possibility to transition research projects to operational tools.
- What new research is ongoing amongst various groups.
- How those on managing side of forecasting currently use snow products and challenges of implementing research to managing use.

What worked best about the workshop?

- The presentations stayed on time and moved smoothly.
- In depth presentations and ample time for questions (for the most part!).
- Good mix of presentations and breaks for networking.
- Variety of presenters and attendees.
- Great facility, great A.V., great coordination and diversity of speakers, especially integrating the actual operations utilizing these tools – Denver Water, California, Rio Grande.
- Group discussions.
- Nice facility.
- Great cast of presenters.
- Kept on time and good breadth of presentations.
- Presentations that included application.
- Great presentations.
- Good discussions.
- Lunch and refreshments were good.
- Presentations were well organized and ordered.
- The classroom setting.
- Having experts present state of the art information and developments.
- Organization and time management.
- Thought the flow went very well, going from standard measurement/forecast techniques through to new methods of ASO/LIDAR etc.
- I liked the basic primer on snowpack, streamflow at the beginning, then leading into the more detailed

topics, papers, etc.

- Good balance between research and real life use.
- There was a lot of information on where data is located and then how it can be used.
- Most presentations were at a level and could be understood.
- Great background on snowmelt monitoring.
- Interesting pre-workshop survey results.
- Great job moderating.
- Diverse group therefore diverse perspectives.
- Great subject matter.
- Great informative workshop. Thanks!
- Great lineup of knowledgeable speakers.
- Overall a great conference with great value (can't beat free!), so thank you very much.
- The tremendous diversity of attendees. It was great to have so many different agencies and partners.
- Meet people and have discussions.
- There are more opportunities for new ideas.
- Ability to time for group discussion and questions to continue conversations after presentations.
- Thanks for the workshop!

What would you suggest we do differently if we were to hold another workshop like this one?

- Pose the question to water managers of what reasonable changes to data products they would like to see.
- Presentations as handouts for note taking even on-line to print ourselves.
- A bit more time on group discussions, less time on research, and more time on what it would look like (logistics, cost, etc.) if these new tools were adopted by water providers.
- More space (room), maybe.
- More integration with decision making tools and procedures.
- Economic benefit of improved methods.
- Consider more from user/applications including the fish and wildlife sector.
- An additional presentation or two on operational forecast use would be informative.
- Brown bag lunch/order a specific lunch.
- I would not change anything. I thought it went really well.
- I would like to hear more about how to transfer the research projects into operations. Perhaps an entire session on this question (It was discussed briefly at the end).
- Maybe more discussion periods throughout the day.
- It's fascinating to learn about the latest science and ongoing studies. But I'm still struggling to figure out how to use this knowledge in my work. We don't have $$ for developing a custom tool, so I need a plug and play, free resource that provides a reliable drought forecast. Are any of the new, localized study results available to the public on websites?
- Show me how to use the tools available on your website.
- Include a talk from USGS on snow research.
- Quick round of introductions from participants.
- For a topic such as this, it might be helpful to have more speakers that are water operators or managers. I am personally most interested in how entities can use these techniques in a cost-effective way.

- A faster distribution of lunch so more networking could take place.
- I think bringing social scientists in to help the scientists identify the needs and unanswered questions of the managers and partners.
- More discussion opportunities (slightly shorter presentations).
- Go around the room and have everyone introduce themselves.
- More on operations, emergent technologies and hardware, meteorological contributions, monitoring.

My understanding of snowmelt hydrology:

- Is the same as before the workshop: 4 (14%)
- Has improved a little: 16 (57%)
- Has improved a lot: 8 (29%)

My understanding of how snowpack information is produced:

- Is the same as before the workshop: 1 (4%)
- Has improved a little: 12 (43%)
- Has improved a lot: 15 (53%)

My understanding of how to access snowpack information:

- Is the same as before the workshop: 5 (18%)
- Has improved a little: 15 (53%)
- Has improved a lot: 8 (29%)

My understanding of how to use snowpack information:

- Is the same as before the workshop: 5 (18%)
- Has improved a little: 14 (50%)
- Has improved a lot: 9 (32%)

Western Water Assessment
http://wwa.colorado.edu