Upper Rio Grande Basin Snowfall Measurement and Streamflow (RIO-SNO-FLOW) Forecasting Improvement Project

January 4, 2016

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EXECUTIVE SUMMARY:

This reports summarizes work and key findings to date from the Upper RIO Grande Basin SNOwfall Measurement and streamFLOW (RIO-SNO-FLOW) Forecasting Improvement Project conducted from Jan. 1, 2014 through Dec. 31, 2015. The project area was centered over the upper mainstem Rio Grande and Conejos River basins in southern Colorado. This report is organized into 7 chapters that detail the major elements of the project including; a Project Description, NOAA Gap-filling Radar, NASA Airborne Snow Observatory, *In-Situ* Ground Observations, Distributed Hydrologic Modeling, and Community Engagement. While several follow-on activities are still in progress, a number of conclusions and recommendations have emerged from the RIO-SNO-FLOW project. These major conclusions and recommendations are as follows:

- NOAA experimental gap-filling radar observations greatly improved the spatial and temporal distribution of precipitation over the Conejos River Basin in comparison to the existing operational National Weather Service (NWS) radar network
- Local radar adds value by reducing forcing-related biases in model-simulated runoff and providing more information in areas not currently monitored by SNOTEL stations
- More/better ground-based snowpack monitoring is needed at elevations above 11,000 ft. and in areas with greater/persistent snowpack
- Snowpack remote sensing platforms from the NASA Airborne Snow Observatory provide valuable sources of quantitative spatially distributed, high-resolution information on snow depth, snow water equivalent and snow albedo to uniquely constrain the modeling and assess WRF-Hydro and SNODAS simulations
- *In-situ* meteorological measurements identified significant biases in operational meteorological forcing datasets that need to be addressed through improved observation and/or assimilation and bias correction methodologies
- Physics-based, high-resolution (<1 km) hydrologic modeling with the soon-to-be operational community WRF-Hydro modeling system showed reasonable simulation skill in snowpack conditions and in seasonal runoff accumulation when compared against available data.
- Probabilistic streamflow forecasts from the National Weather Service synthesized within the Colorado Water Conservation Board (CWCB)-funded Rio Grande Decision Support Tool, developed by Riverside Technologies, Inc., provided useful, skillful probabilistic water supply forecast information compared with single value, regression-based forecasts.

A number of other findings and recommendations for future activities are provided in the individual chapters and in the Chapter 7.

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1. Project Motivation and Description

a. Overview

This project aims to improve seasonal water supply forecasts for the Upper Rio Grande basin in southern Colorado (Figure 1) and, in doing so, help minimize the costs associated with erroneous forecasts and related sub-optimal allocations of water for surface irrigation, groundwater recharge, and endangered species management.

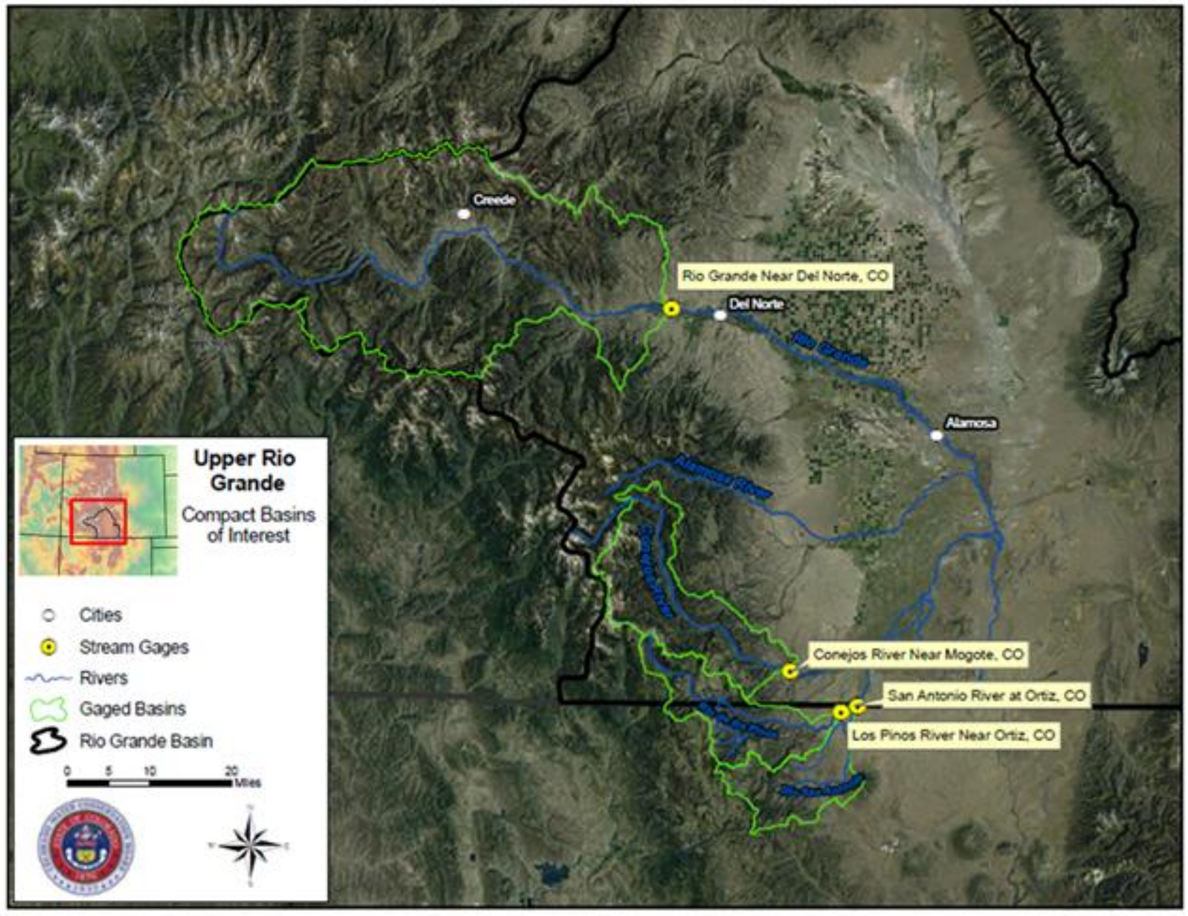


Figure 1. Colorado-New Mexico Water Compact basins of the Upper Rio Grande River basin

CWCB Involvement in Winter Science and Forecasting

The Colorado Water Conservation Board (CWCB) is the water policy and planning organization within the Department of Natural Resources for the State of Colorado. Its sister agency is the Division of Water Resources, which is charged with administering water in Colorado. Helping Colorado protect, conserve, and develop water supply is the CWCB mission. There are eight major river basins in Colorado and the voting CWCB members are organized by these watersheds.

In the past, the CWCB in partnership with local, state, and federal agencies partnered to install 20 new SNOTEL sites (an 18% increase) within the state. Working with Riverside Technologies, Inc., three phases of NOAA Snow Data Assimilation System (SNODAS) investigations were completed by 2009. The SNODAS dataset was tailored by watershed to provide maps of Snow Water Equivalent (SWE) above compact stream gauges in the Upper Rio Grande River basin. At the conclusion of the CWCB SNODAS investigations, a recommendation was made to seek better forcing data. The CWCB also supports the Center for Snow and Avalanche Studies and their Colorado Dust on Snow Program (CoDos). As an outgrowth of these projects, a new CWCB authorization through the Water Projects Bill initiated the Water Forecasting Partnership Project. The new funding will focus on partnerships where there are known administration and forecasting issues needing improved ground and aerial data and hydrological modeling.

Dick Wolfe, the Colorado State Engineer, said, "There is a general need for better forecasting statewide. Better forecasts help the DWR and municipal, agriculture, environmental (including ESA issues), recreation, and other interests. Good forecasts are needed by well owners that rely on streamflow forecasts for replacement of water through the augmentation plans and support [conjunctive use] rules in the Rio Grande."

CWCB partnership with NOAA-NSSL and NCAR

Since 2009 the CWCB has partnered with NOAA-National Severe Storms Lab (NSSL) to conduct mobile radar meteorology projects with ground validation conducted by the National Center for Atmospheric Research. Mobile radar campaigns were completed in the Gunnison, Durango, and Rio Grande basins for both summer and winter radar projects. In spring 2011, NOAA-NSSL mapped snowpack and generated reasonable estimates of SWE in the Animas River for a single event. In the spring of 2016, NOAA-NSSL will map precipitation in the Rio Grande to track mixed-phased precipitation after the peak NASA flight. This is the eighth CWCB-sponsored radar project in the last six years.

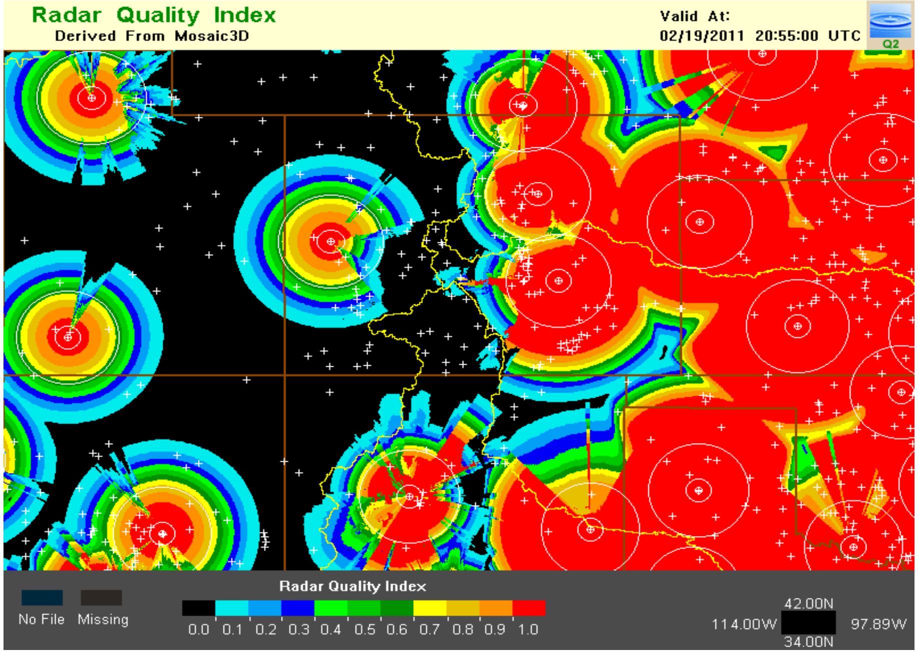


Figure 2. The RQI shows red as good radar coverage and black as no or poor radar coverage. 80% of Colorado's snowpack and water comes from the mountains that are poorly covered by existing NWS radars.

The CWCB and its partners seek to build a business case for gap filling watershed based radars for Colorado to create continuous spatial coverage for a multitude of reasons.

Figure 2. The OU ARRC PX1000 was rented and operated on Wolf Creek Pass to give the NWS eyes on the area for flash flood forecasts below the fire burn areas

Additionally, two recent radar campaigns were conducted by the Oklahoma University Advanced Radar Research Corporation to provide radar data for the Pueblo NWS Weather Forecast Office to use for flash flood forecasts in radar beam-blocked parts of the Rio Grande where there is currently no useful radar coverage (See Fig. 2). The CWCB has also partnered with NRCS Western Regional Climate Center and the Colorado Basin River Forecast Center to provide satellite and SNODAS data to all RFCs that cover Colorado. The CWCB has also provided funding for the Colorado Basin River Forecast Center to host a long term forecasting workshop with universities.

The Rio Grande

The total length of the Rio Grande is about 1,900 miles long and is the fifth-longest river system in North America. The San Luis Valley is approximately 122 miles long and 74 miles wide, extending from the Continental Divide on the northwest rim into New Mexico on the south. Agriculture in the San Luis Valley is generally concentrated around the Colorado towns of Monte Vista and Center. Principal crops include potatoes, alfalfa, and small grains. The San Luis Valley (Figs. 3a, b, and c) is an extensive high-altitude depositional basin at an average elevation of 7,664 ft above sea level. The valley is a section of the Rio Grande Rift and is drained to the south by the Rio Grande. The river rises in the San Juan Mountains to the west of the valley and is bordered on the east by the Sangre de Cristo Mountain range. Broad areas, especially in Saguache County, Colorado have a high water table or even having standing water part of the year. Uncultivated land is covered with "chico," low brush such as rabbitbrush, greasewood, and other woody species. Cropland is irrigated with (1/4-mile radius) center-pivot irrigation systems, sideroll irrigation systems and some furrow irrigation.

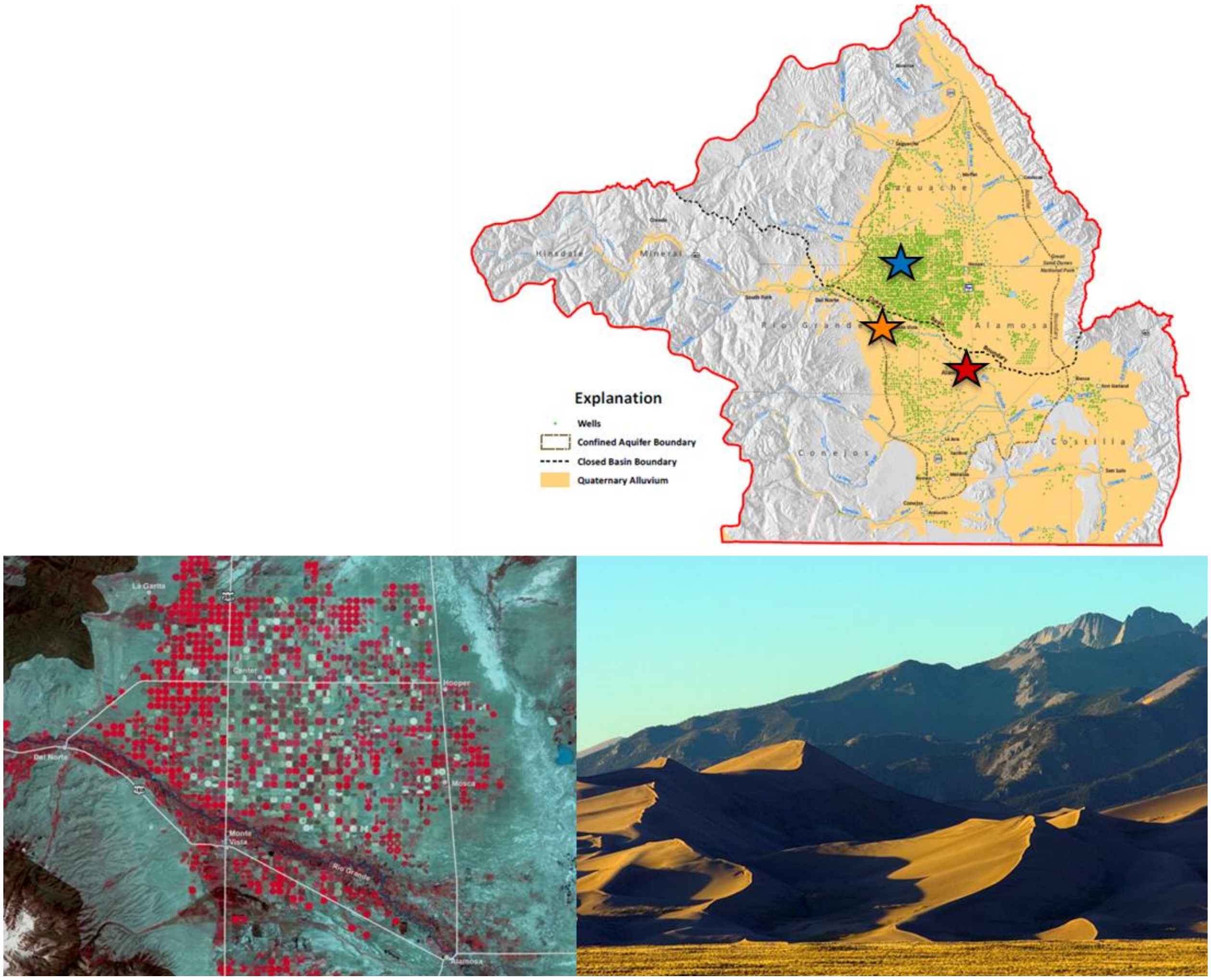


Fig. 3a (upper right) San Luis valley. Groundwater irrigated areas shaded in green. Blue, orange and red stars designate Center, Monte Vista and Alamosa, Colorado, respectively. (lower left) Thermal imagery of center pivot irrigation in the San Luis valley. (lower right) Great Sand Dunes National Monument.

Rio Grande Water

Through a mixture of surface and groundwater rights, the Rio Grande Basin in Colorado is extremely over-appropriated. In late 2015, groundwater well regulations were submitted to the Division 3 Water Court. These regulations require the replacement of injurious stream depletions caused by groundwater use and also require that the underground aquifers be brought back to a sustainable condition. It is hoped that these regulations will be approved by the court and will go into effect in the near future. Other heavily used rivers, such as the South Platte and Arkansas Rivers, have had rules in place for decades. One of the tools that will be used by well owners to meet the requirements of the regulations will be the implementation of groundwater management sub-districts. There is currently one sub-district in operation, replacing depletions due to groundwater use in a portion of the San Luis Valley and ensuring sustainability of the aquifer. However, six other sub districts are in various stages of formation. It is anticipated that these sub-districts will be able to replace the depletions of the vast majority of the wells in Division 3, and will ensure the long term sustainability of the aquifer systems.

The Rio Grande Forecasting Project

In 2011, at the request of water users, the CWCB convened a committee of agency forecasters, research and development agencies, and consultants to develop projects to address the water supply forecast process. The NRCS Portland Basin River Forecast Center, West Gulf Basin River Forecast Center, National Center for Atmospheric Research, Division of Water Resources, Conejos Water Conservancy District, NOAA-National Severe Storms Lab, and Colorado Water Conservation Board developed five project ideas. Project 1 aimed to develop a compact compliance Decision Support System (DSS) tool for the DWR by Riverside Technologies and was funded and completed. Project 2 was tasked to develop a set of modeled historical hydrologic forecasts to build an archive of ensemble streamflow prediction (ESP) traces. Project 3 developed satellite and SNODAS datasets for the RFCs. Project 4 filled gaps in ground-based snow data and hydrologic modeling by NCAR. Project 5 developed remote sensing data sets through NASA Airborne Snow Observatory (NASA-ASO) and NOAA radar quantitative precipitation estimation as inputs into hydrologic modeling. Funding projects 1, 4, 5 cost a sum total of $745,000 and are discussed in this report. Funding from the CWCB, Rio Grande Basin and Statewide Round Table funds, and U.S. Bureau of Reclamation (USBR) Water Smart Funds were all leveraged to make this project possible. Project 1 was funded as the immediate need and top priority project by the West Gulf RFC and projects 4 and 5 were funded as they were research and development projects with a goal of making improvements to the forecast process. Results from project 1 are summarized in Section 6 while results from projects 4 and 5 are collectively summarized in Sections 2, 3, 4 and 5 of this report.

Rio Grande Compact

The Rio Grande Compact is an interstate compact signed in 1938 between the states of Colorado, New Mexico, and Texas, and approved by the United States Congress in 1939, to equitably apportion the waters of the Upper Rio Grande Basin. Due to a lawsuit brought by the States of New Mexico and Texas in the mid 1960's, strict Compact administration by Colorado began in 1968.

> *"The benefits of better observations and forecasts are tremendous. Our compact operations are based exclusively on streamflow forecasts. Inaccurate streamflow forecasts can cause unnecessary curtailment of ditches, over- or under-delivery of compact obligations, and a disruption of the priority system."* Craig Cotten, Division Engineer, CDWR, Division 3

Rio Grande Water Administration – Practitioner's Perspective

Figure 4. Dave Gochis of NCAR and Nathan Coombs of the Conejos WCD downloading data west of Platoro Reservoir

"*On a day to day basis we curtail pre-compact water rights in order to meet the obligations of the compact*," Steve Vandiver, Rio Grande Water Conservation District. Water rights are administered by the Colorado Division of Water Resources. According to the Division Engineer Craig Cotten, "*Under the provision of the Compact Colorado must deliver a percentage of the flow of the mainstem of the Rio Grande and from its biggest tributary in Colorado, the Conejos River. This water can be delivered at any time of the year, but with Colorado having so little water storage capacity in the Rio Grande Basin, realistically this water must be delivered on a daily basis as it shows up in the system. Additionally, the percentage of water that Colorado is obligated to deliver changes based on the total yearly flow in the system. For instance, 650,000 acre-feet (AF) is the average annual flow on the Rio Grande and Colorado would be obligated to deliver 28% of that amount in an average year. However, if the yearly total flow is 1,000,000 acre- feet, the obligation jumps to 43% of the total. For the Conejos River, the average annual flow is approximately 315,000 AF and Colorado would need to deliver 38% of that amount, but would be required to deliver 63% of a 600,000 acre-foot annual amount. Similarly, if the annual amount is less than average, the percentage decreases. Colorado would only be obligated to deliver 13% on a 150,000 acre-feet annual flow year for the Conejos River system.*

Because of the lack of storage, we rely very heavily on the streamflow forecasts to tell us at the beginning of the irrigation season just how much water we will need to deliver to the downstream states. Since the Rio Grande and Conejos systems are so over-appropriated, the only way to ensure that Colorado's compact obligation is met is to curtail, or shut off, some Colorado water users. Obviously the less ditches we have to shut off, the better for Colorado's water users.

Colorado does have the ability to either over or under deliver on its compact obligations in a certain year. However, my goal is to meet our obligations as closely as possible every year without going into a debit status. This ensures that there will be no accusations from downstream entities that Colorado is not delivering its fair share of water, and no need to greatly increase the curtailment in the future to cover past debts."

The main goals of water forecast operations in the region are to meet the compact obligations, minimize curtailments of ditches to meet those obligations, and to maximize the limited storage capacity on the Rio Grande system. Early in the spring, water release considerations are made based on expectations of high (flood) versus low flow conditions. The division engineer holds primary responsibility for the delivery and curtailment decisions and nearly always has more past water knowledge behind him than he has in front of him. Typically, by June 15th the river is beginning to recede from peak flow conditions and options for meeting interstate Compact delivery requirements become fewer. Also, the groundwater sub-district has to turn in their annual replacement plan by April 1st. *So, many key decisions need to be made in the period from late March through early June.* However, forecasting total seasonal runoff from the early part of the melt season is notoriously difficult and water supply can be heavily influenced by late spring storms in April and May, like those occurring during 2015.

Low snowpack and frozen rain and late fall and early winter events do make differences and can provide some basic indications of seasonal runoff. For example, reservoir inflows into Rio Grande reservoir November in 2012 were 25 to 30 cfs, where in 2015 they were 50 to 60 cfs, which indicates that the contributing watershed is relatively wet. One of the key RIO-SNO-FLOW project proponents was Travis Smith of the San Luis Valley Irrigation District and also a Colorado Water Conservation Board member representing the Rio Grande Basin. Travis Smith said early on, "*If we can all put our heads together and make improvements to the forecast process we need to do it.*"

Infrastructure on the main stem Rio Grande

Rio Grande Reservoir was built from 1910 to 1914 by the San Luis Valley Irrigation District to store water for agriculture with a capacity of 52,000 AF at an elevation of 9,449 ft about 20 miles (32 km) southwest of Creede, near the headwaters of the Rio Grande. On the San Luis valley floor there is significant modification of natural flow conditions by a large number of irrigation ditches, groundwater pumping and irrigation return flows.

The Conejos River and Platoro Reservoir

Platoro Reservoir was constructed from 1949 to 1951 by the U.S. Bureau of Reclamation to impound the Conejos River, a tributary of the Rio Grande, for irrigation water storage as part of the larger San Luis Valley Project. The reservoir and dam are owned by the Bureau, and operated by the local Conejos Water Conservancy District. It holds 53,506 AF of water when full. The Conejos River is approximately 92.5 miles long and rises from snowmelt along the continental divide west of Conejos Peak in western Conejos County, approximately 15 miles (24 km) east of Pagosa Springs. It flows briefly northeast, through Platoro Reservoir, then southeast through the Rio Grande National Forest, then east along the New Mexico border through a scenic canyon. It enters the southwestern corner of the San Luis Valley from the west near Antonito and joins the Rio Grande from the west approximately 15 miles (24 km) southeast of Alamosa.

b. Water Supply and Compact Issues – Detailed Administration

The water delivery obligations from Colorado to the downstream states on the Rio Grande, as specified in Rio Grande Compact (hereafter, “the Compact”) provide stringent constraints on water management decision makers in the Upper Rio Grande basin. Because of limited storage capabilities within the Upper Rio Grande and because of the terms of the interstate compact, Colorado has a limited capability to store water during high flow years for eventual delivery to downstream states during low flow years. Figure 5 illustrates the terms of the Colorado’s water obligations from the mainstem Rio Grande and the Conjeos River. In an average year, flow from the Conejos River constitutes nearly 40% of the delivery obligation with the remainder largely coming from the mainstem Rio Grande. In a given year, the maximum amount of water that can be stored or diverted for use in Colorado is 560,000 AF on the mainstem Rio Grande, and 224,000 AF on the Conejos. Any flows in excess of those levels must be delivered to the Colorado-New Mexico stateline through the mainstem Rio Grande. In any given year, the projected annual flow sets the delivery target for that year, according to the consumption curves (green lines) shown in Fig. 5. The Colorado Supreme Court also has ruled that April 1 streamflow forecasts are to be used for management of groundwater pumping operations through the sub-district’s annual replacement plans.

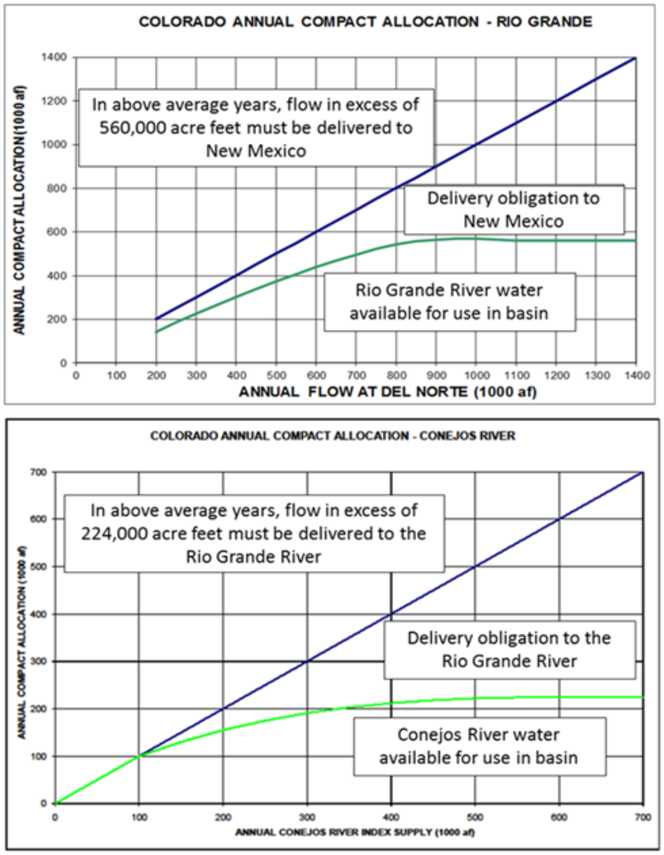


Figure 5. Obligations for the Conejos and Rio Grande.

Case Study on the Cost of Forecast Errors

Uncertainty in seasonal water-supply forecasts in the Upper Rio Grande basin can have a significant impact on water management, agricultural production, and economic vitality. A recent analysis by the CWCB and Colorado Division of Water Resources (CDWR) illustrated that seasonal water-supply forecasts based primarily on Natural Resources Conservation Service

(NRCS) SNOTEL data have struggled with accuracy, particularly in wet and dry years in the last several years.

As shown in the Figure 6 below, the average error in seasonal water-supply forecasts for the Upper Rio Grande River basin from the NRCS since 2000 are approximately +/- 15% with more extreme wet or dry years, for example 2002, exhibiting even larger forecast errors. There are also substantial differences, usually improvements, between the Apr. 1 and Jun. 1 water-supply forecasts. However, numerous state and federal statutes require many water management decisions be based on the Apr. 1 forecast.

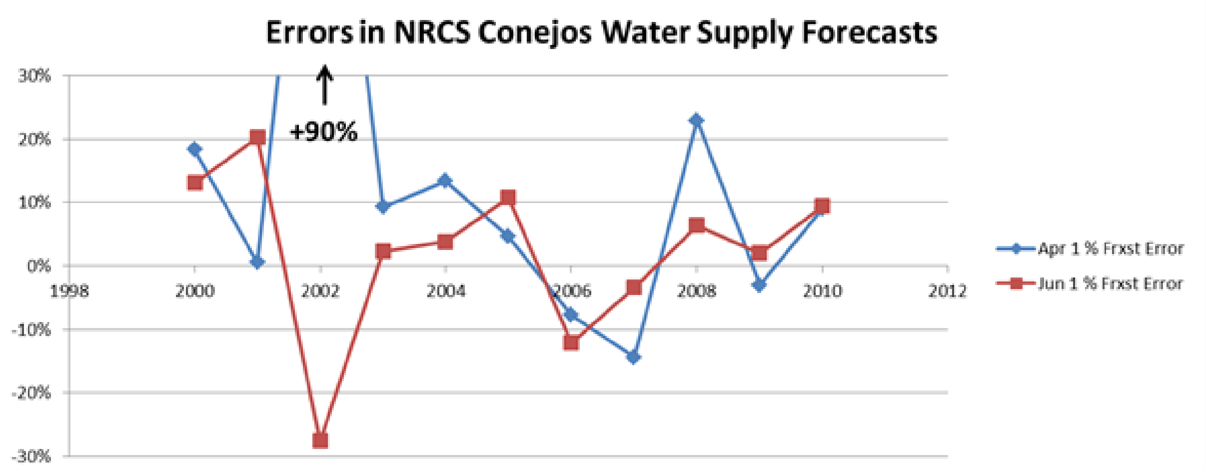


Figure 6. Conejos Basin water supply forecast errors from April 1 and June 1 forecasts.

The higher error rate in the Apr. 1 forecasts translates into millions of dollars lost annually due to reduced agricultural productivity on irrigated lands.

Using the CDWR forecasted to actual streamflow information and the 2012 rate of $230/AF of water for lease in the Rio Grande basin the CWCB determined that the potential benefit or impact to agricultural water rights holders along the Rio Grande can number in the millions of dollars depending on the accuracy of forecasts in a given year. For example, in 2005, the June 1 forecasts were 112,000 AF less than actual. In 2007, the June 1 forecasts were 143,000 AF higher than actual. Using the 2012 price per acre foot of water the potential impact or benefit of forecast errors is in the -$25.8M to +$32.9M range in terms of the leased value of water. Through administration, the Colorado Division of Water Resources seeks to minimize these impacts on a basin-wide level. However the first step to minimizing these economic losses is to minimize seasonal water-supply forecast errors. To achieve that goal, investment in improved observational, data assimilation and modeling methodologies is needed. The work carried out under this project aimed to address this need.

c. Project Goals

This joint observational-modeling study was designed to demonstrate the cost-effective utilization of state-of-the-art observational and modeling techniques in improving streamflow predictions in the Upper Rio Grande basin. We believe this will help advance optimal water management.

Figure 7. John Mickey of NCAR downloading data at the town of Platoro

The project addressed shortcomings in seasonal streamflow prediction through the utilization and evaluation of state-of-the-art methods in radar-based wintertime precipitation estimation (see Fig. 8), snowpack observations, and physics-based hydrological modeling. An underlying premise of this work is that improved characterization of peak snowpack conditions through SWE surveys (via point observations, field surveys, or airborne/satellite platforms), while necessary, are individually insufficient to optimizing snowmelt-driven streamflow predictions. This is because copious precipitation can and does occur during melt season, freezing levels and rain-versus-snow elevations fluctuate rapidly during melt-out, melt out processes (i.e. spatial and temporal patterns) vary widely from year to year as functions of local meteorology, and antecedent (i.e. previous-season) hydrologic conditions in the basin impart slow-memory impacts on springtime flows.

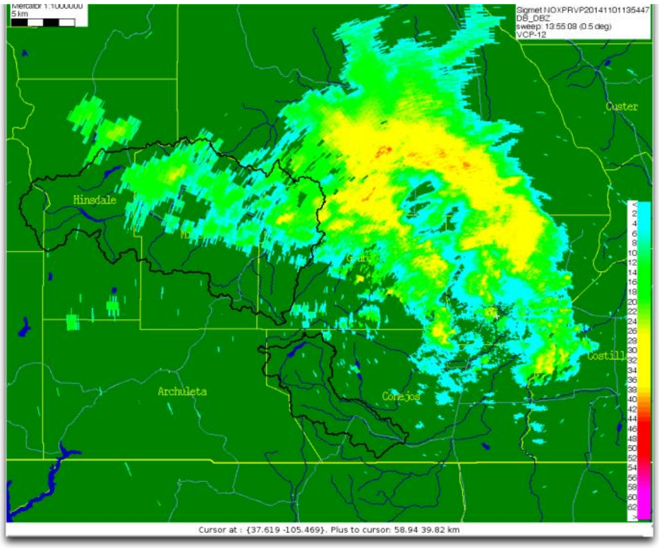


Figure 8. NOAA NOXP radar data. Reflectivity is correlated to precipitation rate. Yellow and red are the snow falling in the Rio Grande.

Thus, the full hydrometeorological cycle of the snow accumulation and melt seasons must be better observed and modeled if seasonal streamflow predictions used in water resource management decision making are to be improved. Improved hydrometeorological process description through the integration of ground-validated experimental, gap-filling radar precipitation estimates, remotely sensed snow depth and snow area extent observations, improved sampling of *In-situ* snowpack (snow depth, density and SWE conditions) across elevation gradients, and improved estimates of meteorological conditions are required to constrain uncertainty in hydrologic forecasts. To address these critical needs, the specific goals of the RIO-SNOW-FLOW overall project were to:

Goal 1: Develop state-of-the-art precipitation and snowpack monitoring products through the use of experimental radar, airborne LIDAR/spectrometer snow-depth, SWE and albedo estimates, surface observations, and land data assimilation systems

Goal 2: Improve the representation of the spatial and elevational distribution of snowfall, snowpack, and meteorological forcing terms used in hydrological prediction models

Goal 3: Conduct streamflow prediction experiments using current operational and state-of-the-art physics-based hydrological models

Goal 4: Demonstrate operational snowpack and streamflow impacts forecasting capabilities through dissemination of observational and model-based monitoring and prediction products and coordinate with, local, state, and federal water prediction and water management partners

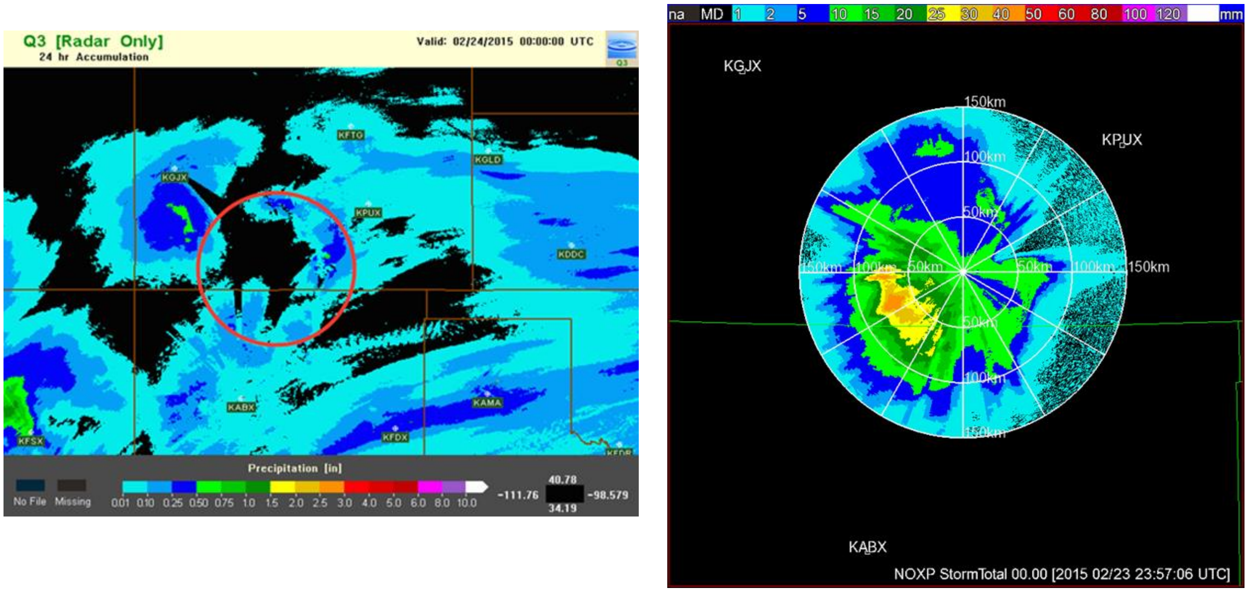
2. Gap-filling Radar Estimation of Snowfall in Complex Terrain

a. Background

A contiguous observation of precipitation across the intermountain west poses a significant challenge for NWS operations and hydrological forecasts and warnings. Current operational weather radars located in Colorado do not provide adequate coverage over key basins for use towards accurate water resources accounting. This is especially true for winter precipitation in the high-elevation headwaters of major compact river basins such as the Rio Grande.

During the last seven years, several field campaigns have been conducted between the CWCB, local water districts, Division of Emergency Management, and the National Severe Storms Laboratory (NSSL) to highlight the challenges and deficiencies with the current NWS operational radar network. This was meant to build a business and scientific case for the deployment of new operational weather radars in the state. The additional radars, or "gap-filling" radars, if strategically placed, would provide a more comprehensive depiction of cool and warm-season precipitation occurring over the intermountain regions of Colorado potentially leading to improved snowfall estimates for use in modeling to more accurately quantify runoff from mountain snowpack.

Figures 9 and 10 provide an illustration of the coverage gap of the NWS WSR-88D over the Rio Grande basin for winter precipitation. The locations and surrounding terrain render both the Grand Junction (KGJX) and the Pueblo (KPUX) WSR-88Ds lower scans useless for determining phase and rate (snow and SWE) during the winter storm events. Winter precipitation processes are relatively shallow and stratiform, in comparison to deep upright thunderstorms during the summer. While these two radars can observe the upper portions of thunderstorms over the Rio Grande basin, they do not fully observe important precipitation processes during winter storm events especially over the Conejos River basin.



Figures 9 & 10. 9 (Left): Currently-operational radar-based 24-hr accumulated QPE derived by the WRS-88D radar network in MRMS system. Red circle encompasses Upper Rio Grande River basin which has little radar coverage; 10 (Right): 24-hr accumulated QPE estimated by the NOXP mobile radar. The QPE accumulation ends at UTC 00:00:00 on Feb. 24th, 2015. The red circle on the left approximately corresponds with the NOXP radar coverage shown on the right.

To understand the uncertainties associated with current coverage and to assist in developing and prototyping a state-of-the-science snowpack monitoring capability, an experimental mobile X-band radar (NOXP), gap-filling radar was deployed in Alamosa, Colorado at the municipal airport property during the winter of 2014-2015. The NOXP was deployed at latitude 37.435^o and longitude -105.857^o near the Alamosa airport. The deployment location was chosen based upon obtaining the least obstructed view the Conejos River basin and other portions of Rio Grande basin while scanning as close to the terrain as possible starting with the lowest tilt mechanically feasible on the NOXP. Figure 11 provides a tilt-by-tilt depiction of the beam blockage (by percentage) experienced by the NOXP at the Alamosa airport location. Not until tilt 3 is the radar mostly unimpaired by terrain. However, the Conejos River basin was observable starting in the lower tilts with all tilts being ultimately used in deriving snowfall rates for the basin. Further, if an operational gap-filling radar was to be purchased and deployed in the Rio Grande basin, the Alamosa airport would likely be the most cost-effective location for a radar serving the local communities, aviation interests as well as improved hydrometeorological surveillance of the basin. *Ultimately the deployment of the NOXP at Alamosa demonstrated significantly improved coverage across the base as depicted in Figures 9 and 10.*

The NOXP radar is a mobile Doppler radar that operates on a 3-cm wavelength (X-band), with dual-polarization capabilities. Table 1 shows the specifications of radar NOXP. The available polarimetric variables include the horizontal polarization reflectivity (Z), spectrum width (SPW), aliased velocity (V), correlation coefficient (RhoHV), differential reflectivity (Zdr), differential phase (PhiDP) and specific differential phase (Kdp). The contamination from ground clutter is eliminated using an embedded SIGMET “GMAP” notch filter.

Table1: Specifications of NOXP.

Wavelength/Frequency	3 cm/X-Band/9415 MHz
Horizontal and vertical beam width	0.9 degree
Scanning VCP	0.5, 0.9 1.3, 1.8, 2.4, 3.1, 4.0, 5.1, 6.4, 8.0, 10.0
Volume scan time	5 min
Peak power	250 kw
Operational range	130 km
Ground clutter cancellation	SIGMET “GMAP” notch filter
Polarization	Simultaneous horizontal and vertical transmission

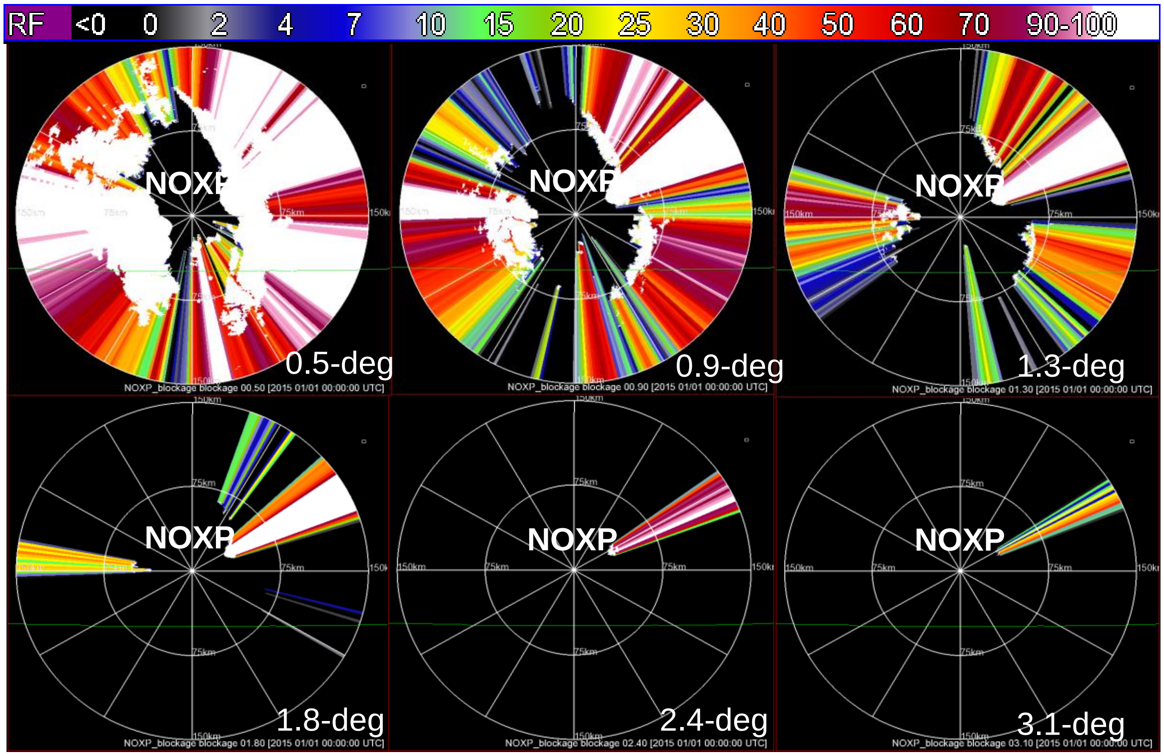


Figure 11: NOXP terrain blockage at the elevation tilts of 0.5-deg, 0.9-deg, 1.3-deg, 1.8-deg, 2.4-deg and 3.1-deg, respectively.

b. Project Operations

During the project, the radar was operated on a storm event base where the operational High-Resolution Rapid Refresh (HRRR) model was used to forecast winter storm events potentially impacting the Conejos River basin. The NOXP radar was staffed and closely monitored on site to ensure timely backup of the radar data and to “troubleshoot” issues during operations. Given the severe cold during some events, extra precautions were required. For example, to keep the waveguide free of condensed water or ice, nitrogen was continuously pumped into the wave guide assemblies. While every attempt was made to collect radar data when precipitation was occurring the Conejos Basin, the onset of precipitation was missed on several occasions due to errors in forecasts and staffing delays resulting from travel logistics. Nevertheless, nearly 700 hours of radar data were collected during the 2014-2015 winter campaign and these data were used to calculate snowfall over the basin.

The basic precipitation estimation, or retrieval, process consists of an initial pass of the reflectivity (Z) field, first corrected for beam attenuation which, if left uncorrected, results in signal strength loss. A composite reflectivity field is then constructed and is ultimately used in the snowfall rate estimation using a reflectivity-snow, or “Z-S” relationship derived from previous studies in the Durango, Colorado area.

The experimental Z-S relationship used for the initial precipitation estimate product was:

$$S(Z) = 0.0365*Z^{0.6875}$$

where, S(Z) is the liquid water equivalent snowfall rate in units of mm/hr, and Z is the attenuation-corrected composite reflectivity value. It is important to note that this experimental Z-S relationship is not definitive and is subject to change based on additional analysis of the project data.

Initial Project Findings

Figure 12: NOXP at Alamosa airport winter of 2014-2015.

There exist many challenges using radar observations to obtain estimates of snowfall and associated SWE, and this is an active area of scientific research. This difficulty is exacerbated by the presence of complex terrain inherent to the Conejos and Upper Rio Grande River Basins. Remote sensing in complex terrain requires a host of assumptions. Whichever sensor is used, there will be inherent limitations in sampling key precipitation microphysics that influence estimates of snow-water content as precipitation falls to the surface. Radar observations are not exempt from these limitations and in complex terrain regions radar will typically under sample key microphysics occurring below mountaintops. Because of this limitation, physics-based assumptions are made to relate information from where the radar is sampling above mountaintops in the atmosphere and what is actually falling on the ground as precipitation, both in terms of rain versus snow and precipitation intensity.

For initial, quantitative evaluation, the NOXP-estimated snowfall rate described above was converted and accumulated into hourly SWE and compared with two heated weighing precipitation gauges at stations Platoro Cabin and Base (37.35167°, -106.52815°) and Rocky Mountain Lodge (37.18738 °, -106.44628°). Examining the results (Figure 13), a good agreement between the radar estimation and gauge measurement was found, despite small spatial and temporal offsets. However, during major snowfall events, the radar-derived estimates show a very distinct underestimation, which is likely a result of sole reliance on the previously derived Z-S relationship failing to capture snowfall intensities for all events observed in the Conejos River Basin.

c. Recommendations

The preliminary results from the 2014-2015 winter deployment were promising, but require further analysis and refinement. The NOXP observations greatly improved knowledge of the spatial and temporal distributions of precipitation over the Conejos River Basin in comparison to the existing operational NWS radar network. However, there remain challenges in bringing snowfall estimates, and associated water equivalent as derived from radar, up to the accuracy required by snowpack evolution and runoff models. Future work and refinement include, but are not limited to, 1) improving the radar data quality to address terrain partial blockage using dual polarization data (so-called "moments") and 2) refine the preliminary Z-S relationship for the Rio Grande Basin. This would include an in-depth analysis of Z-S using standard gauges as well as 2D video disdrometers. Additionally, a new approach is required to use dual polarization moments to identify the 3D structure of winter storms and how the 3-D structure correspondence to precipitation type and SWE received at the ground surface. Finally, an assessment of the radar snowfall retrievals by the ASO snowfall retrievals from pre- and post-storm acquisitions would tightly constrain our understanding of the efficacy of the radar data.

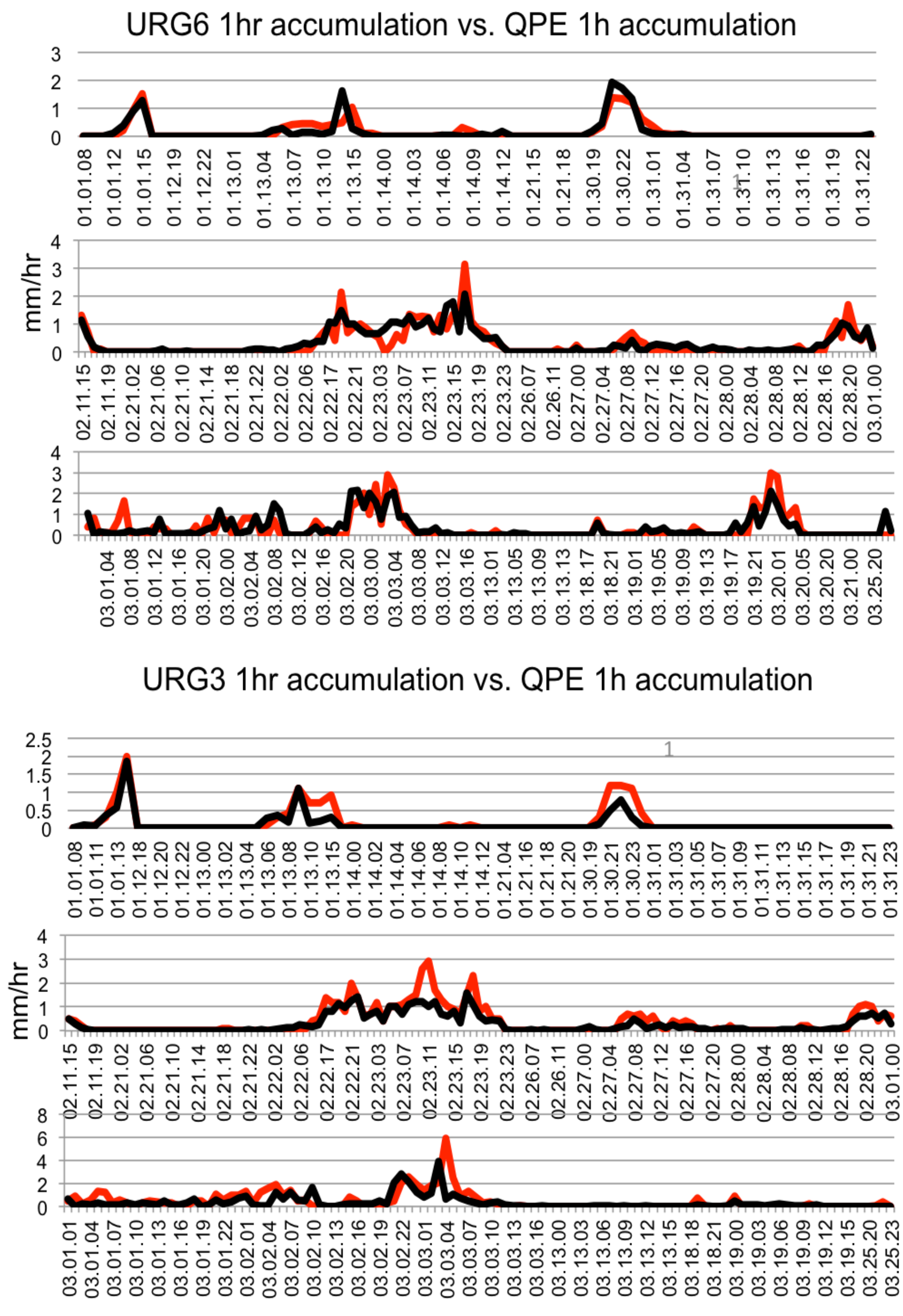


Figure 13: The results from the radar estimation and gauge measurement, where the red line is the measurement from the ground gauge and the black line is the accumulated hourly QPE derived by radar NOXP. The x-axis is the time series of the data comparison and y-axis is the SWE with the unit of millimeter per hour.

3. Airborne LIDAR Snow Water Equivalent and Albedo Observations

a. Basic Overview of NASA ASO Platform

Figure 14. NASA King Air ASO

The NASA JPL Airborne Snow Observatory (ASO) combines lidar and spectrometer instruments on a single airborne platform with the objective of mapping snow depth, SWE, and snow albedo across entire mountain watersheds. The ASO is the first such system designed specifically for snow and water resources monitoring and research. The time-critical nature of the snow data coupled with the relatively large and complicated mountain areas that need to be measured, drive the system to high altitude flight, wide swaths, and optimized processing. The resulting ASO system is unique in two aspects: (a) the joint inversion of the active lidar and passive imaging spectrometer data coupled to an energy balance snow model for full SWE and snow albedo retrievals and (b) the sub-24-hour latency for full product generation and delivery to water managers.

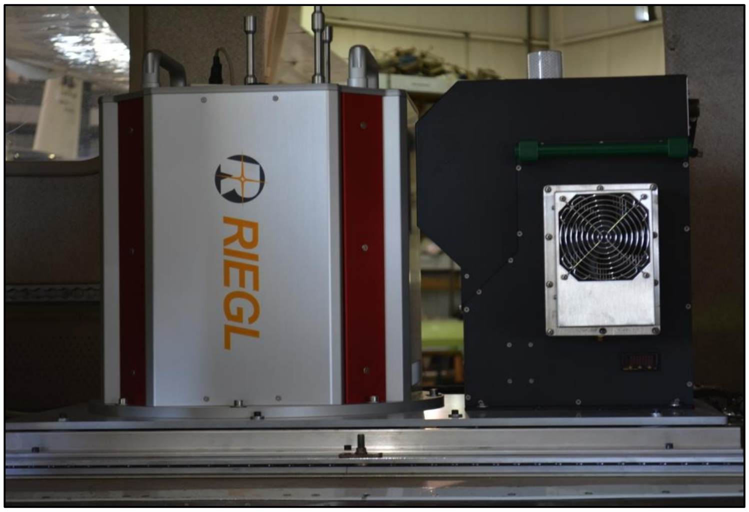


Figure 15. LIDAR and Spectrometer aboard NASA ASO

ASO uses an itres CASI 1500 imaging spectrometer and a Riegl Q1560 airborne laser scanner (ALS-See Fig. 15). The spectrometer retrieves spectral albedo and broadband albedo across the majority of the significant solar irradiance spectrum at Earth’s surface, allowing discrimination of the impacts on these albedos of changes in snow grain size and radiative forcing by dust and black carbon. The ALS system maps surface and forest canopy elevations from which snow depths are calculated by subtracting snow-free from snow-covered datasets.

ASO uses *In-situ* and field-observed snow density information to convert the measured snow depths to SWE estimates. Density data were retrieved from NRCS SNOTEL and snow course observations, and from field measurements conducted as a part of this study.

ASO primary data products are 50-m resolution maps of snow depth, SWE, and snow albedo (e.g. Figure 16). Additionally, aggregated tabular or map products are generated according to stakeholder/partner requirements (e.g. Table 2).

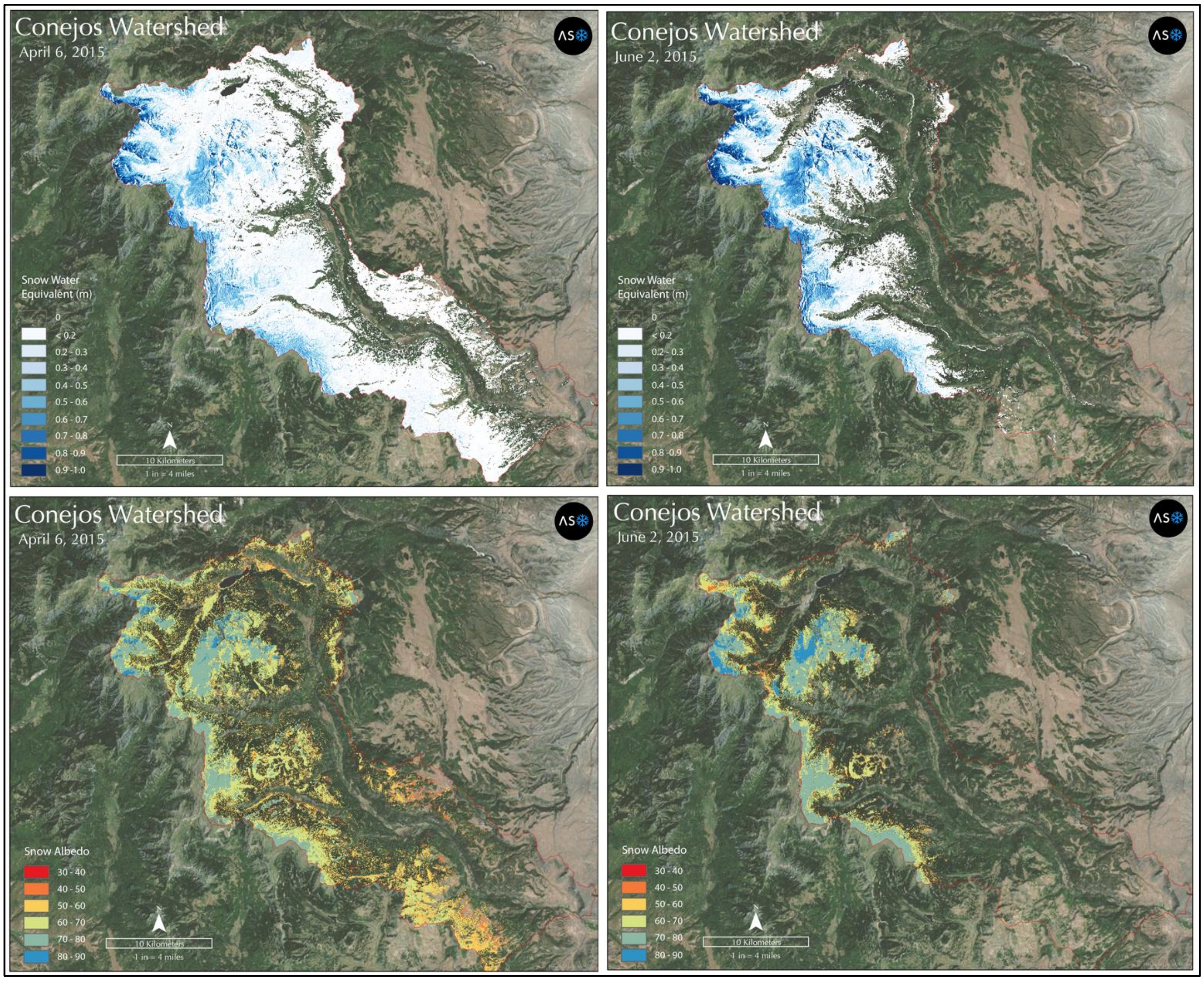


Figure 16. Maps of Conejos Basin SWE (top row) and snow albedo (bottom row) from 6 April (left column) and 2 June (right column), 2015.

Table 2. Conejos River Basin SWE (acre-feet) from ASO observations, aggregated by elevation band and total basin.

SWE Totals	6 April, 2015	2 June, 2015
Elevation Band 1 1158 – 2073m	0.0	0.0
Elevation Band 2 2073 – 2987m	405.2	14.6
Elevation Band 3 2988 – 4200m	60346.2	54236.5
Basin Total	60751.4	54251.1

b. Project Operations

Three flight periods were planned and executed during water year 2015, two during the spring melt season and one during the snow-free summer season to provide the reference dataset. The flights covered the entire Conejos River and the mainstem Rio Grande river basins for areas above the San Luis valley floor (See Fig. 17). For the Conejos basin, this included areas above the Conejos River at Mogote CDWR stream gauging station. For the mainstem Rio Grande, this included areas above the Rio Grande River at Del Norte gauging station. Timing of flights was dictated in part by existing ASO obligations in other regions, but was also coordinated with field experiments conducted by collaborators on this project. Flight lines were planned for efficiency of data collection, and to ensure full coverage of the watersheds by both instruments. Actual flight lines were adjusted in-flight to accommodate clouds and snow-free areas.

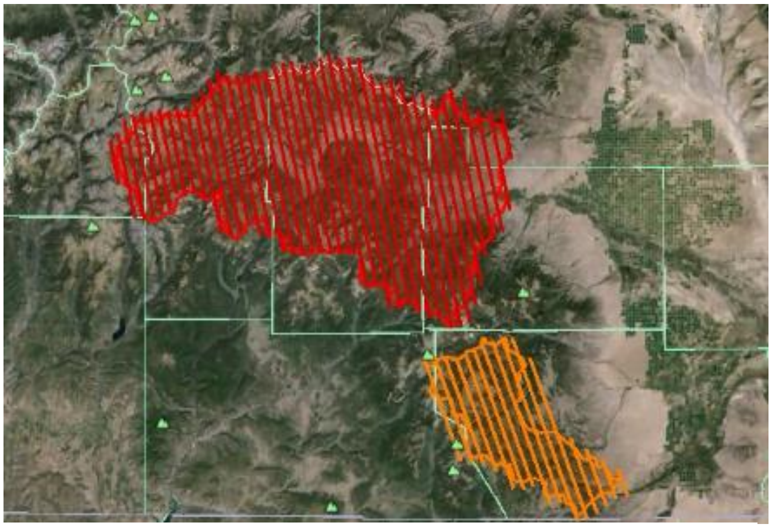


Figure 17. Google Earth image displaying ASO planned flight lines over the Upper Rio Grande (red) and Conejos (orange) basins.

c. Project Findings

Initial project results are being developed and delivered by the ASO team at the time of this report. However, initial maps of SWE and snow albedo as well as SWE volumes aggregated by elevation band and full basin area illustrate the capabilities of the ASO measurement techniques to quantify the amount, location, and reflectivity of the mountain snow water resource. The Conejos River Basin maps in Figure 16 highlight the strong terrain control on SWE accumulation patterns. Additionally, while the total basin SWE volume is similar on the two flight dates (Table 2), the vastly differing spatial SWE patterns reveal that the unusual snowfall totals accumulated during May 2015 occurred under relatively warm air temperatures, with a relatively high snow/rain transition elevation, primarily above 10,500 ft. This feature was also confirmed in the analysis of *in-situ* snow-depth monitoring stations described below in Section 4. These conditions produced the ASO-observed increase in high-elevation SWE in the June dataset, with basin totals remaining relatively consistent, despite the loss of low-elevation snow cover. This high-resolution, spatially explicit snow cover information is extremely valuable to this study for evaluation and development of forecast improvements, and on its own to support runoff estimation and physical process studies. Specifically, the high-elevation areas (e.g. above the average treeline in southern Colorado), have the ability to hold and accumulate appreciable volumes of snowpack during the springtime. Currently operational observing systems, such as SNOTEL, do not have sufficient spatial density or sufficient elevation sampling to account for snowpack changes in these areas, which leads to significant uncertainty in late-season snowpack status. ASO markedly reduces this uncertainty.

Figure 18. Megan Richardson of NASA JPL offering a tour of the NASA ASO airplane

Dust in snow has been shown to play an important role in hydrologic forcing in this region, advancing snowmelt by a month on average and up to 2 months in extreme dust years. In addition to snow albedo and snow grain size, radiative forcing by light absorbing impurities in snow is retrieved from the ASO imaging spectrometer data. At time of overflight impurity radiative forcing in the Conejos was ~65 W/m^2 on April 6th and ~60 W/m^2 on June 2nd. The lower June radiative forcing lower is likely due to the above average May snowfall, which would have buried the dust deposited by three episodic dust events observed in April (1st, 8th, 15th).

How WY2015 compares to other years in terms of dust loading and impacts can be inferred from the data record at Senator Beck Basin Study Area (SBBSA) in the San Juan Mountains, west of Rio Grande and Conejos basins, where the hydrologic impacts of dust in snow have been studied since 2005. Relative to the last 10 years at SBBSA, WY 2015 was one of the lowest dust years. Total end of season dust loading was ~ 2 g/m^2 in 2015, approximately a tenth of what was deposited in 2014 (18 g/m^2), a lesser dust loading year, and a minor fraction of what was deposited in 2013 (53 g/m^2), an extreme dust loading year. SBBSA is located in the Upper Uncompahgre Watershed, which has been flown by ASO monthly in the spring since 2013. In

May 2013 basin average radiative forcing over the Uncompahgre was over ~250 W/m^2 at time of overflight, significantly higher than what was measured in 2015.

d. Recommendations

Work on quantifying the value of the ASO snowpack volume and albedo estimates in modeled seasonal water-supply forecasts is currently in progress, and additional results and comparisons against model-simulated snowpack are provided in Sections 4 and 5 below. However, the initial results strongly suggest that remotely sensed snowpack conditions from ASO and/or similar platforms provide critical information on high-elevation snowpack dynamics, particularly, in late spring and during melt out, which are not accurately observed currently. As such, ASO snowpack products provide a very useful piece of information for forecasters and water managers to understand how much snow remains on the landscape. Because these initial results were only for one season, plans for a single snow-on flight for Rio Grande and Conejos basins are in place for spring 2016. As the snow-free dataset will be available, the potential exists for ASO observations to be used in parallel with operational forecasting efforts. It is likely that additional acquisitions would benefit this project and related water management decision making. Furthermore, it is expected that assimilation of ASO snowpack information into the hydrological modeling system described below in Section 5 will have a significant beneficial impact on seasonal water-supply forecasts.

4. Ground Validation Measurements

a. Basic Overview of Ground Validation Strategy

Figure 19. Dave Gochis making streamflow measurements on the Conejos River.

The principle task and goal of the In-situ ground observation effort were to design, install and operate a network of snowpack and hydrometeorological monitoring stations that significantly improve the sampling of snowfall, snowpack, hydrological and meteorological conditions across elevation bands. Key measurements of snow depth, temperature, humidity, shortwave radiation and precipitation were augmented with soil moisture and streamflow conditions at several additional sites. Figure 20 shows a map of the installed network of surface, *In-situ* hydrometeorological stations, referred to as "SNO-LITE" stations, distributed within the Conejos (south) basin. For this design, all stations were placed on currently accessible private or U.S. Forest Service federal lands without restrictions against such installations (e.g. not in federally designated Wilderness or other ecologically or culturally sensitive areas).

A second goal of the *In-situ* measurement effort was to evaluate both experimental and currently operational snowfall, snowpack estimation and meteorological forcing products (e.g. temperature, humidity, wind radiation) that would become inputs into the hydrological modeling system described in Section 5**.** Specifically, we compared measurements from our topographically distributed network against existing NRCS basin-scale snowpack and water-supply products, the NWS/NOHRSC SNODAS product and the NASA NLDAS2 land-surface modeling system. Near peak SWE conditions in late March/early April we also conducted field surveys of SWE conditions across our sites. Some of these surveys were performed in conjunction with NASA Airborne Snow Observatory (ASO) overflights described above. This joint automated-manual survey approach is common in snowpack assessment and was recently used to verify the operational NWS/NOHRSC SNODAS product by Clow et al. (2012-though it is noted that Clow's verification study did not include most of southern Colorado, in particular the Upper Rio Grande basin).

Several, previously un-monitored tributary streams into the Conejos River basin were outfitted with water-level sensors for the 2015 Water Year to measure river stage. The device used was a pressure measurement device (HOBO Water Level Sensor by Onset Computing Corp.) that measures the pressure for the overlying water in the stream. With repeated manual measurements of streamflow (aka "stream surveys") an empirical relationship can be developed between the measured river stage and the streamflow. Manual surveys were conducted during field excursions starting in Nov. 2014 on through September 2015, except for periods when ice covered the streams. Stage-discharge relationships ("rating curves") are still under development. A map of locations where river stage was monitored during the 2015 Water Year is shown in Figure 21.

Project leveraging for supplemental In-situ observations:

Instrumentation for the *In-situ* monitoring sites was co-sponsored by a U.S. Bureau of Reclamation WaterSmart project. That project was approved in the early winter of 2013 and provided initial support for instrumentation purchase and construction in preparation for field deployment during the summer and autumn of 2014, prior to the 2015 Water Year.

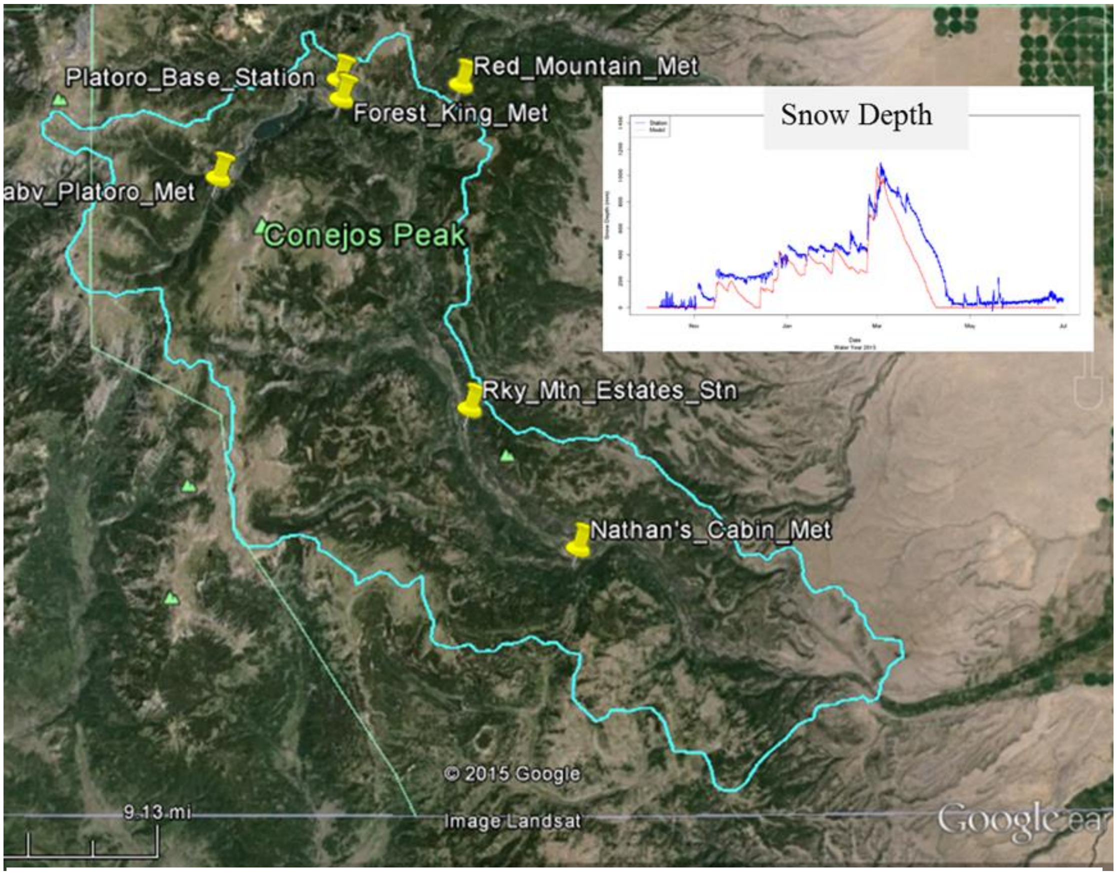


Figure 20. Map of new In-situ "SNO-LITE" station in the Conejos deployed summer of 2014 and continue in operation. Inset graph shows modeled (red) versus observed (blue) snow depth from one of the stations.

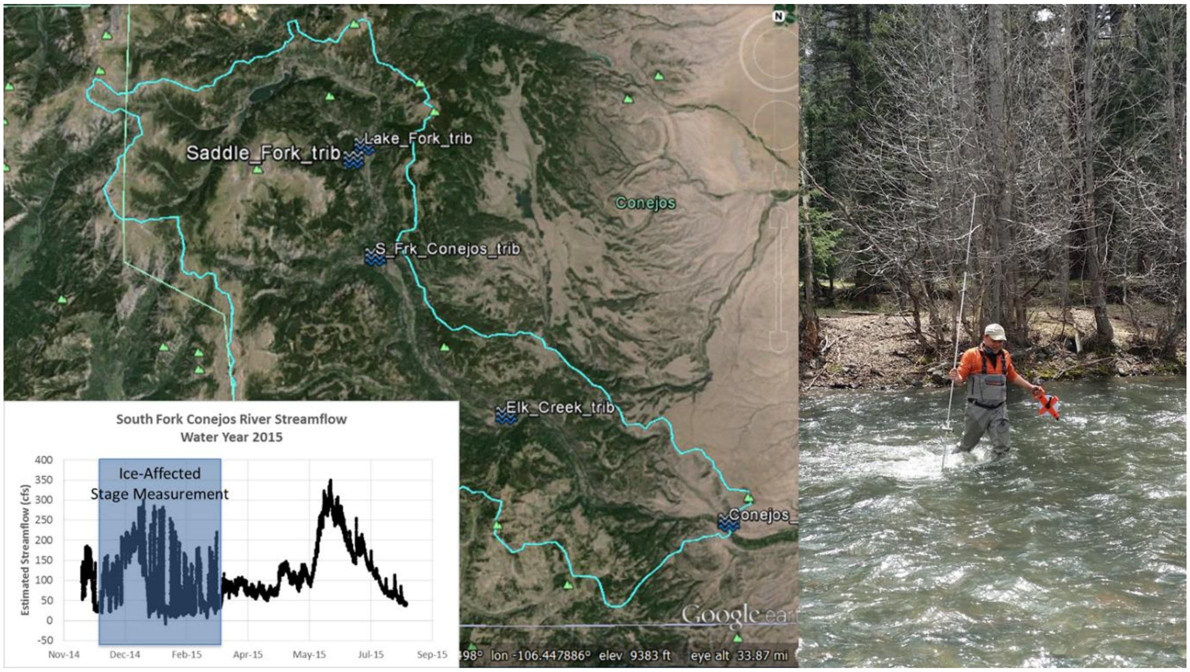


Figure 21. Map of Water Year 2015 supplemental river stage monitoring locations (blue wave icons-station at basin outlet is the DWR operated station at Mogote). Inset graph shows the estimate from the South Fork Conejos tributary site. Inset photo shows CWCB Scientist Joe Busto making manual streamflow measurements at same site.

Figure 22. From top, left photo of SNO-LITE and right is river stage monitoring station. Bottom is a NCAR technician making manual snow density estimate

b. Project Operations

The instrument sites were visited approximately once per month following installation and continue through the present. Additional manual measurements of snow depth and snow water equivalent were made to validate and calibrate automated snow depth measurements and to provide snow density estimates for converting automated, ultrasonic snow depth measurements into continuous SWE measurements.

Supplemental streamflow measurements at ungauged tributaries were made approximately every month from May through September when streams were free of ice and flow was not too low to make river current measurements. Current measurements were made with a standard Price AA current meter and wading rod where possible. In one stream, the Saddle Fork tributary, the cascading nature of the stream prohibited current measurement with the Price AA current meter so a floating object technique was used to estimate streamflow velocity. From survey measurements of flow depth and velocity taken across the channel, full channel discharge was estimated.

c. Project Findings

The primary findings from the supplemental *In-situ* measurement task are summarized as follows:

1. Timing and magnitude of peak SWE and of timing snowmelt in the Conejos River basin is not particularly well captured by surrounding operational SNOTEL sites.
2. Radar-estimated snowfall agrees well against *In-situ* station measurements of snowfall in both timing and in relative amount (Comparison of radar-estimated and station-observed precipitation for several events is shown above in Section 2.).
3. Significant errors in other, non-precipitation operational meteorological forcing variables exist which, when uncorrected, result in excessive energy inputs into hydrologic model depictions of snowpack, snowmelt, and runoff dynamics
4. Over 40% of the Conejos River streamflow measured at the Mogote gauging station on the Conejos River originate from previously un-gauged tributaries to the Conejos.
5. The timing of peak streamflow from basin tributaries appears to be fairly well synchronized to within one week of each other.

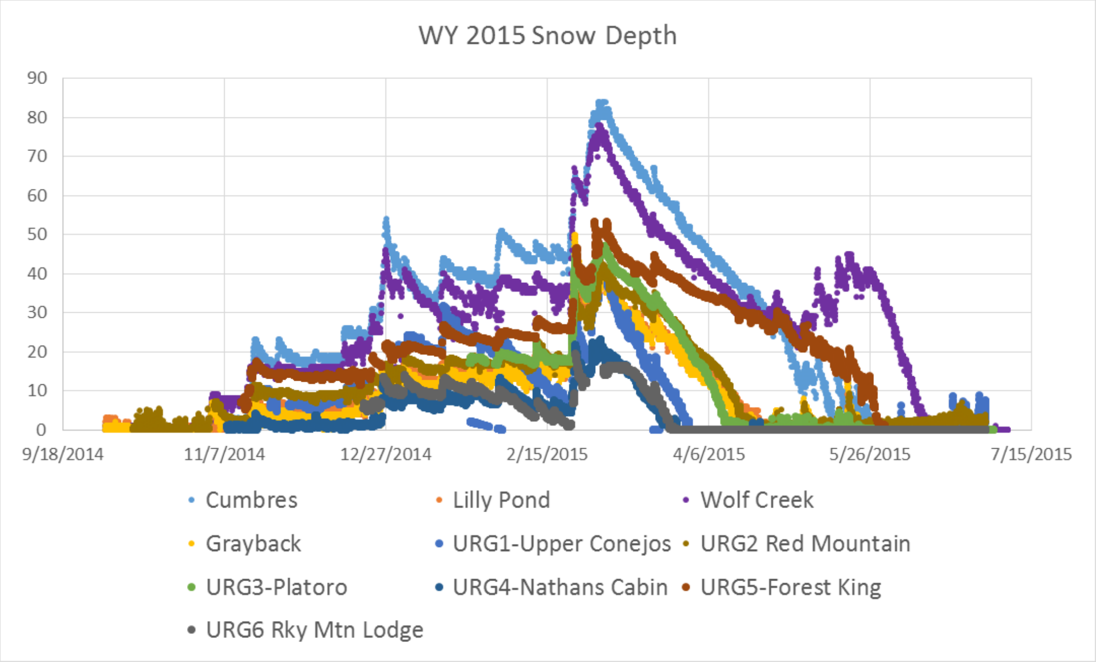


Figure 23. Time series of snow depth as measured by regional SNOTEL stations and project *in-situ* observations. SNOTEL stations "Wolf Creek" and "Greyback'"are not within or near the Conejos river basin. SNOTEL stations .Lilly Pond and Cumbres Trestle are very near the Conejos basin and all project 'URGX' stations are within the Conejos basin.

Analysis of additional *in-situ* snow depth observations along with analysis of modeled and ASO-observed snow depth revealed that snow melt out in the Conejos basin is highly variable in space and time. Figure 23 gives a time series of snow depth as measured by regional SNOTEL stations and project *in-situ* observations. *In-situ* observations at the Forest King measurement site along with ASO LIDAR snowpack estimates on June 2 revealed that appreciable snowpack remained in the watershed above the 11,000-ft elevation level. The Forest King observation site still held several inches of snow depth until the end of May and the ASO survey estimated 54,000 AF of snowpack SWE still on the watershed. [It is interesting to reiterate here that the capacity of Platoro Reservoir is 56,000 ac ft.] However, lower elevation *in-situ* observations and operational SNOTEL observations at the Lilly Pond and Cumbres Trestle sites had largely melted out weeks prior to this date (April 21 for Lilly Pond and May 14 for Cumbres Trestle). *For water managers to have a reliable accounting of snowpack remaining on the watershed, additional in-situ monitoring sites at elevations above 11,000 ft of elevation are recommended.*

In addition to precipitation and snowpack, additional meteorological variables including temperature, humidity, wind speed and direction, incoming solar radiation and surface wetness were also measured. Comparison plots of *in-situ* observed values and values extracted from national meteorological analyses are shown in the figures below. While there is significant variability in the agreement between local observations and national analyses, a few consistent features can be summarized. Figure 24 shows that on average, the NLDAS2 national analysis is somewhat warmer than local observations indicate, which will artificially accelerate snowpack ablation (sublimation and melt out) in hydrological models as compared to reality. The warm bias in the NLDAS2 national analysis is likely caused by an over-estimation of daytime maximum temperatures when compared with observations (not shown). Additional biases in NLDAS2 analyzed shortwave radiation (Fig. 25) and relative humidity (not shown) also imply greater energy forcing in the national analysis compared to local *in-situ* observations. Figure 25 shows that for most of the *in-situ* sites and in the spring and early summer, incoming shortwave radiation from the NLDAS2 analysis is greater than what is observed from *in-situ* observations. Similarly, relative humidity from the NLDAS2 analysis is consistently less than (i.e. drier) than what local observations indicate. Combined these errors in meteorological forcing conditions will result in increased sublimation, earlier melt out and increased evapotranspiration in models using the NLDAS2 national analysis compared to what should be occurring in nature. It is recommended that additional years of meteorological monitoring be maintained so that a retrospective bias correction can be developed and applied to the historical NLDAS2 national analysis. Also, it is recommended that *in-situ* observations of temperature, humidity, wind speed, and incoming solar radiation also be enhanced to have real-time reporting capabilities so that these *in-situ* measurements can be assimilated into national meteorological analysis products like NLDAS2.

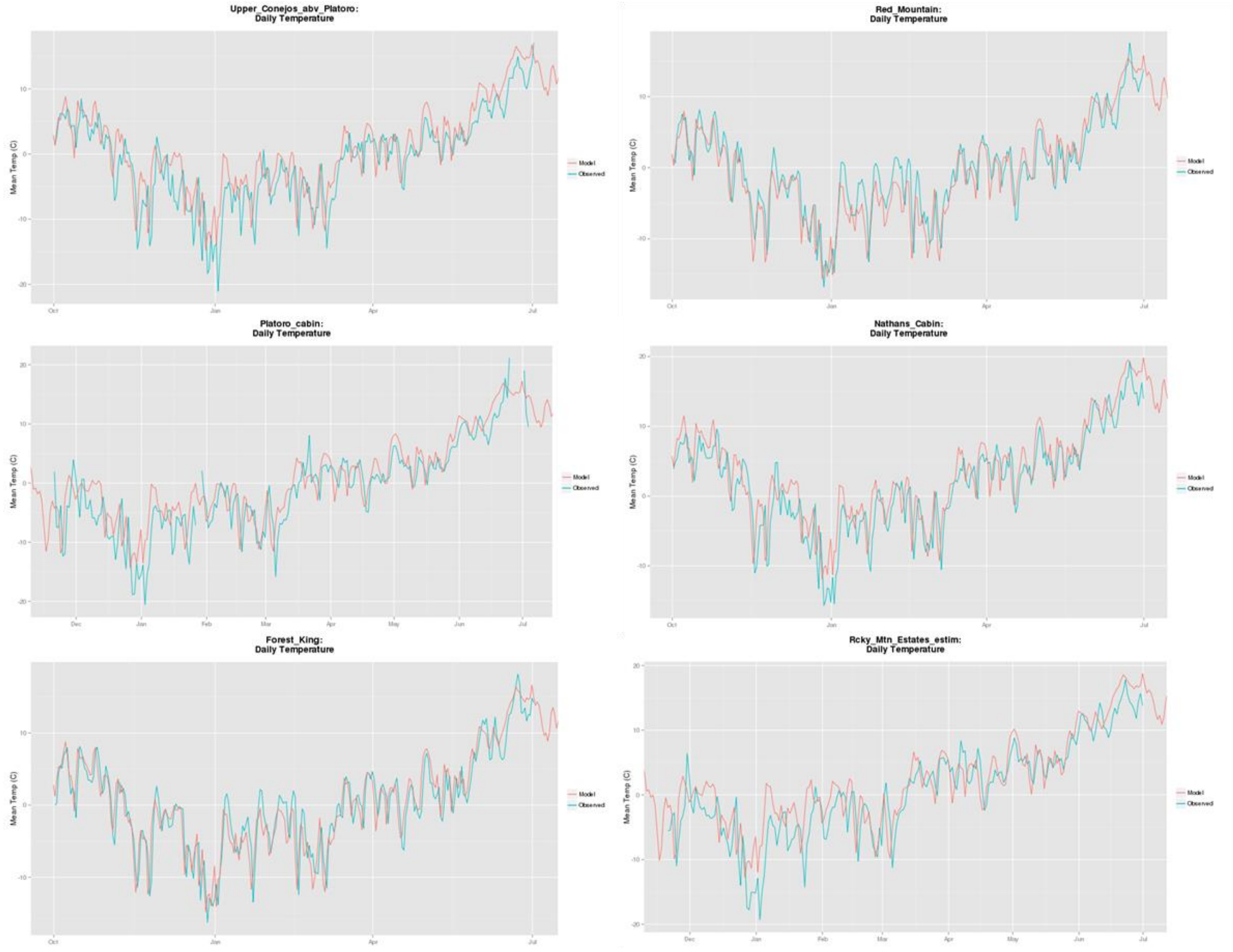
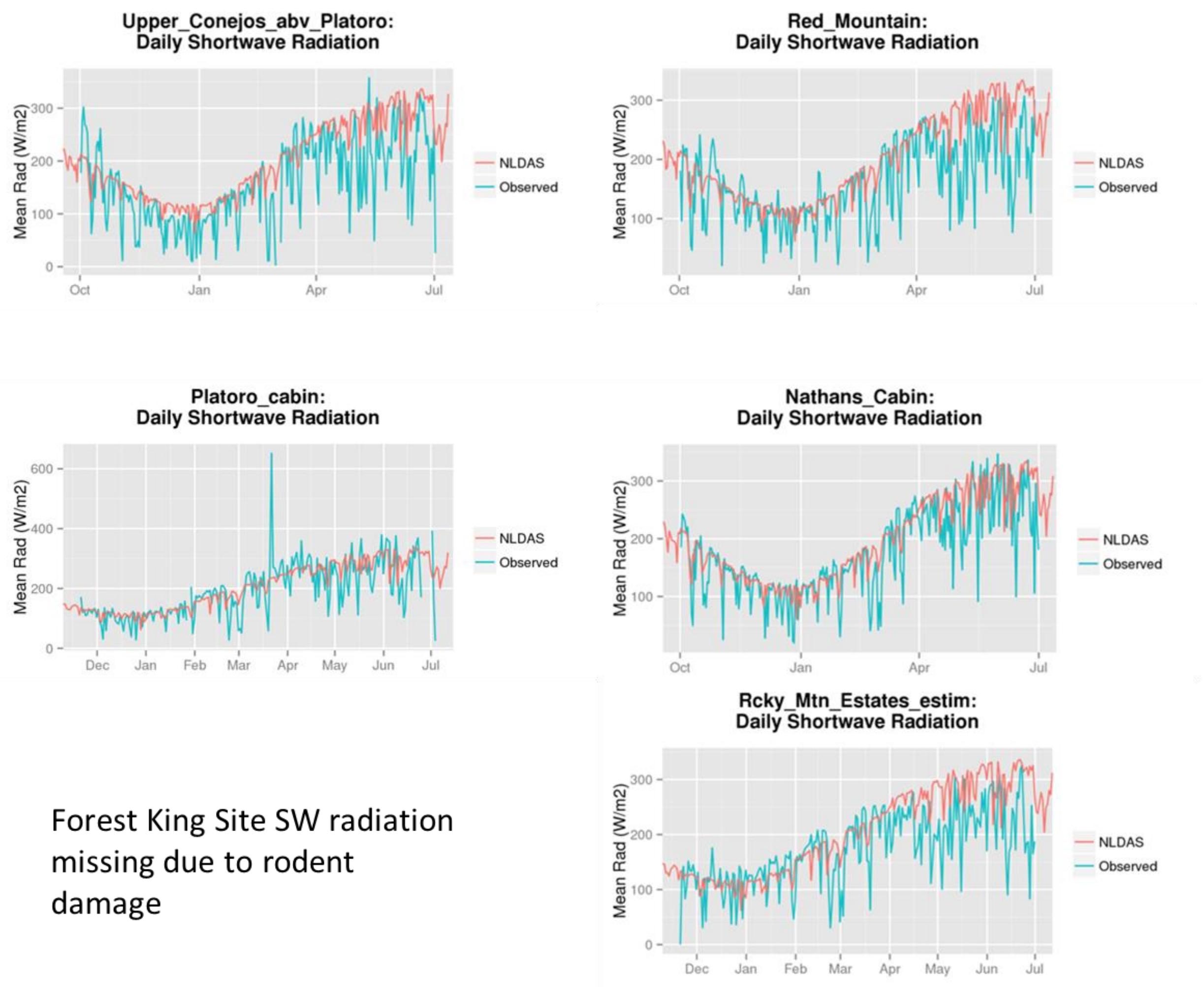


Figure 24. In-situ observed (blue) versus NLDAS2 analyzed mean daily temperature (deg C).



Forest King Site SW radiation missing due to rodent damage

Figure 25. In-situ observed (blue) versus NLDAS2 analyzed mean incoming shortwave radiation (W/m^2).

Additional *in-situ* observations of river channel stages were made beginning in the summer of 2014 on though the 2015 Water Year. These measurements provided estimates of streamflow on previously ungauged tributaries to the Conejos River. Plots of river levels from each of the manual stations observed are shown in Figure 26 below. Periods when river ice were clearly influencing river stage estimates are shaded out. It is clear from these plots that there is reasonably good synchronicity in the timing of peak runoff responses from the tributary systems. After estimating river discharge at times when manual streamflow measurements were made, it was estimated that approximately 40% of the total Conejos River streamflow at the Colorado Division of Water Resources (CODWR) gauging station at Mogote comes from these previously ungauged tributaries. In descending order, the fractional contributions appear to come from the South Fork, the Elk Fork, Saddle Fork, and Lake Fork tributaries. Analysis of the relationship between observed snowpack and precipitation conditions and river flow in these tributary catchments is ongoing.

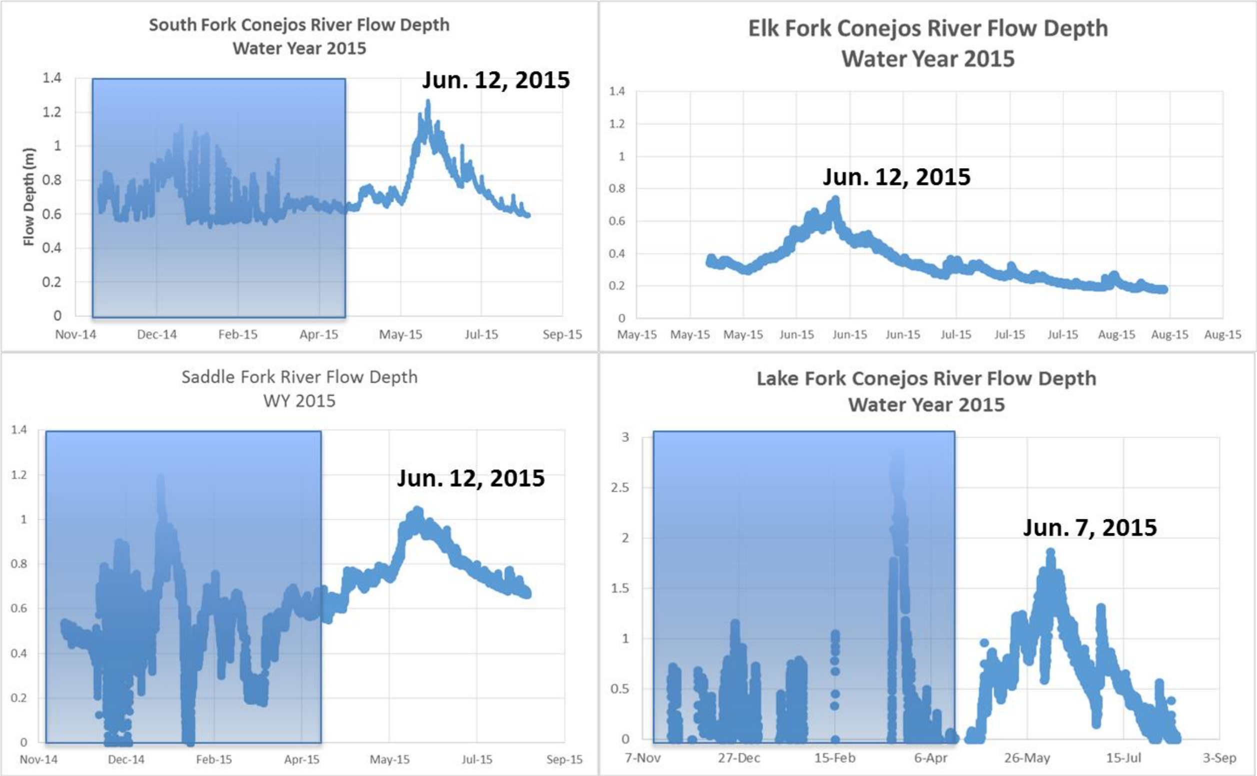


Figure 26. In-situ observed river flow depth from previously ungauged tributaries in the Conejos River basin. Shaded blue squares indicate periods of river ice influencing flow depth estimates. Inset date annotations indicate the date of observed peak flow. Rating curves for continuous flow estimation are still being constructed.

d. Recommendations

Based on these findings, the following set of recommendations is made with respect to improving ongoing *in-situ* precipitation, snowpack, other meteorological variables, and streamflow monitoring activities for water resources management:

1. Improve the monitoring of high-elevation snowpack (e.g. above 11,000 ft). This will help water managers better quantify late-season snowpack conditions.
2. Maintain a network of reliable, operational, real-time reporting surface meteorological stations and ensure these measurements are ingested into the national operational analysis system. Doing so should improve the fidelity of the operational national meteorological analyses in the study region.
3. Maintain tributary streamflow measurements on the Conejos system for a few additional years to: a) develop statistically reliable relationships between tributary streamflow contribution and total streamflow on the Conejos system, and b) sustain a streamflow monitoring capability to track potential impacts of land cover change due to fire and insect-driven forest mortality on tributary streamflow.

4. Explore the potential for improving *in-situ* monitoring on other Rio Grande River Compact tributaries including tributaries on the mainstem Upper Rio Grande, the Los Pinos and the San Antonio rivers.

Once established, the annual maintenance of a modest network of real-time reporting, *in-situ* meteorological, snowpack and hydrological observations should not be onerous from a labor or cost perspective. Based on experience during this project, site visits on the timescale of every three months, or less frequently in winter, were sufficient for maintaining instrument operations. The addition of real-time communications will also help improve site monitoring operations.

5. Modeling of Snowpack and Streamflow

a. Basic Overview of Hydrological Modeling System

Hydrologic processes in the mountains of southern Colorado are strongly influenced by the interactions of climate and terrain. Land-surface elevation, slope and azimuth (direction) and their relationship with temperature, humidity, incoming solar radiation, and precipitation help determine how precipitation partitions into evaporation or runoff, can influence how snowpack evolves throughout the year and can be a primary determinant of whether or not precipitation falls as snow or rain. Historically, operational hydrological models have attempted to predict river flow by lumping watersheds together as one homogenous unit and then averaging meteorological and hydrological conditions across a watershed in order to predict streamflow at a single point coinciding with the watershed outlet. Snowpack and hydrological model research findings over the past 2 decades have begun to show benefit in representing the detailed interactions between finely resolved meteorological conditions and terrain features, particularly in mountainous regions. As such, this project incorporated the use of a new finely resolved hydrological modeling system called “WRF-Hydro” as an experimental modeling tool. The WRF-Hydro modeling system is also undergoing transition as a national hydrologic prediction model within the National Weather Service so this project serves as an important pilot testing project for that national effort. Ongoing work aims to compare results from this model against results from existing operational models that use more traditional modeling approaches. Such efforts are discussed in Section 6 below. In this section we describe the basic structure of the WRF-Hydro modeling system and then show results from hydrologic simulation experiments that utilized the experimental observations from radar, airborne LIDAR, and *in-situ* observing stations.

The WRF-Hydro modeling system is a modern multi-scale, multi-physics hydrologic modeling system designed for use in conjunction with high-performance computers. The “multi-scale” characteristic of WRF-Hydro means that the model has the ability to represent different physical processes like precipitation, infiltration, snowmelt, hillslope overland flow, and channel flow on different grid structures. The “multi-physics” characteristic means that there are typically multiple options for the way in which certain hydrologic processes may be represented in the model, recognizing that different model formulations can work better or worse in different regions. For this study, in the Upper Rio Grande basin we configured the WRF-Hydro modeling system to have a 1-km snowpack and plant canopy modeling grid and a 100-m overland, subsurface and channel routing model grid. We use a finer resolution grid for the routing processes so we can better represent the effects of steep terrain slope in the region on runoff and streamflow processes. A general schematic illustrating the physics processes represented in WRF-Hydro is shown in Fig. 27.

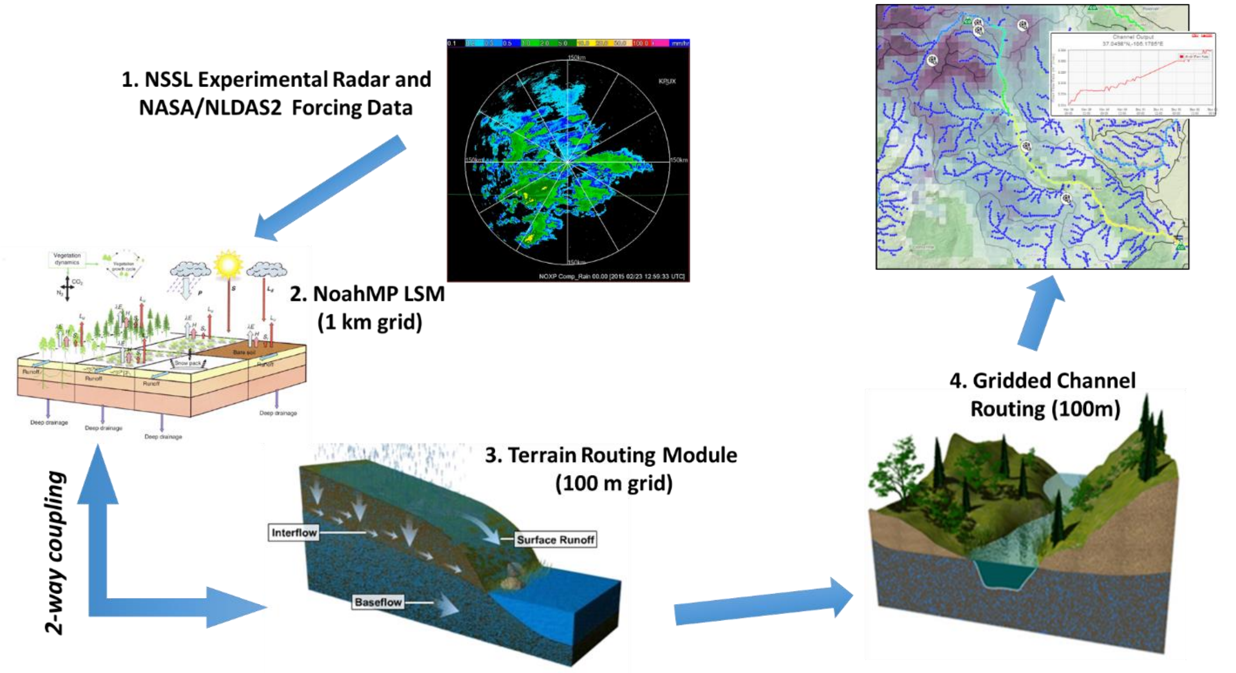


Figure 27. Schematic showing the hydrological process components of the WRF-Hydro modeling system leading to the final production of streamflow simulations (upper right).

The output from this configuration of the WRF-Hydro system includes grids of snowpack (snow depth and SWE), soil moisture, evapotranspiration, standing/ponded water, and shallow groundwater levels, as well as flow across the river channel network of the Upper Rio Grande region. A map of the domain over southwestern Colorado and northern New Mexico being modeled is shown in Figure 28.

The WRF-Hydro model was driven by meteorological analyses provided by the operational NASA/NOAA NLDAS2 set of meteorological analyses for 2013, 2014 and 2015. The NLDAS2 dataset provides hourly gridded analyses of temperature, humidity, wind, shortwave and longwave radiation, surface pressure, and precipitation. These data were processed onto the 1-km WRF-Hydro grid using a topographic downscaling algorithm which accounts for elevation and slope-dependent changes in temperature, humidity, and solar radiation. For the Water Year 2014-2015 when the NSSL NOXP radar was operated, radar precipitation estimates were substituted onto our NLDAS2 forcing data analyses and the WRF-Hydro model was then run using either the NLDAS2 precipitation estimate or the NSSL NOXP radar precipitation estimate. For times when radar data were not available the NLDAS2 data were used.

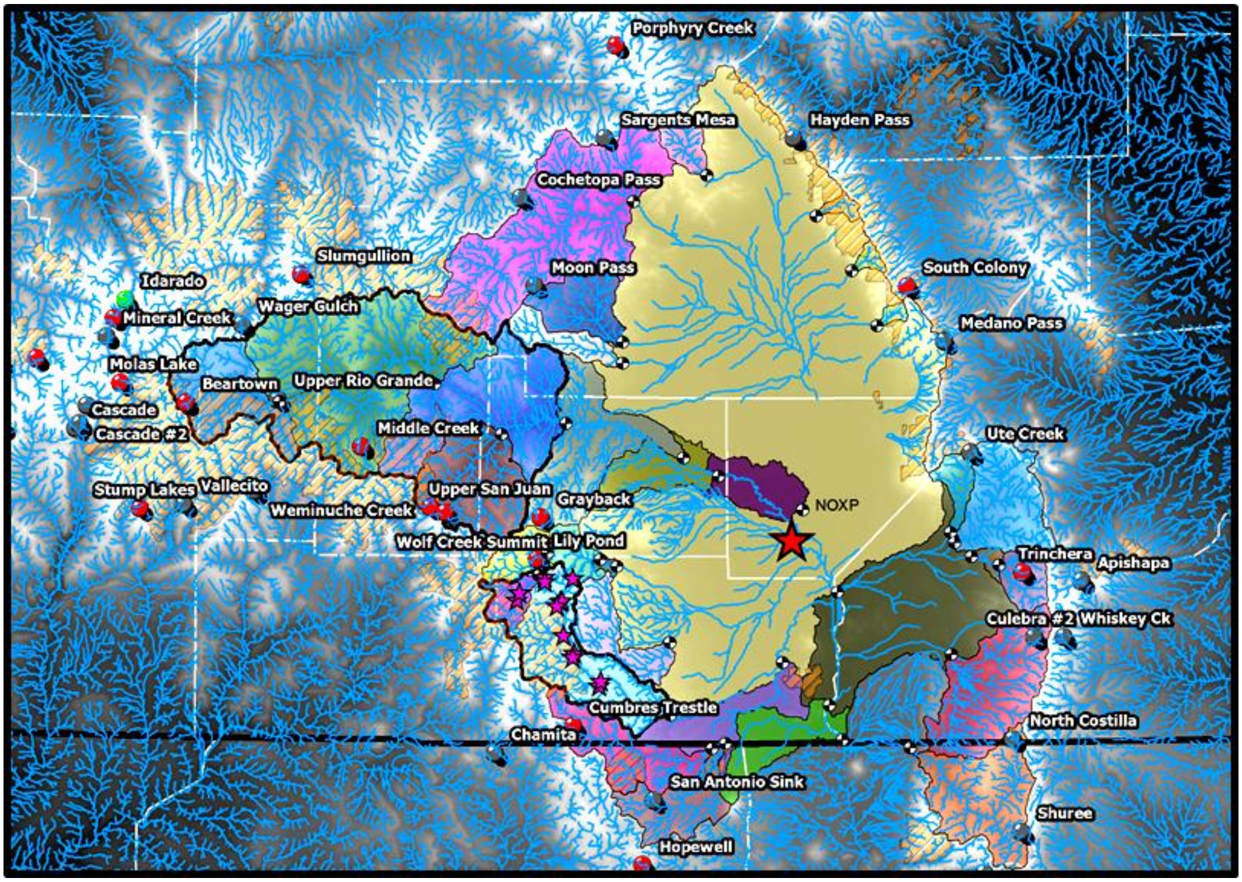


Figure 28. Map of the modeled channel network from the Upper Rio Grande river basin. Location of NSSL-NOXP radar shown with red star. In-situ ground validation stations within the Conejos basin shown with pink stars. Un-labeled black-white markers denote CODWR streamflow gauging stations. Labeled red, blue, and green station sites are NRCS-SNOTEL locations.

b. Hydrological Modeling Operations

The primary goals of the hydrological modeling activities in this project were as follows:

i. Demonstrate the applicability of a physics-based hydrologic modeling system as a reliable source of information for snowpack, soil moisture, evapotranspiration, and streamflow estimates and forecasts.

ii. Assess the impact of using gap-filling research radar estimates of wintertime precipitation as compared to currently operational coarse resolution surface station precipitation analysis products on hydrologic model performance.

iii. Assess the impact of using initial snowpack conditions provided by the operational SNODAS systems and the NASA Airborne Snow Observatory on simulated seasonal water supplies.

As described above, the WRF-Hydro system was executed from Jan. 1, 2013 through Oct. 1, 2015 using downscaled meteorological data from the operational NLDAS2 analyses and the NSSL NOXP radar. *It is important to note here that no specific model calibration was performed to any of the model simulations shown. Effectively, all WRF-Hydro results are presented in their uncalibrated form.*

Output from these model runs were compared against a variety of observational products including the following:

1. CDWR measured streamflow
2. *In-situ* measurements of snow depth and meteorological conditions collected as part of this project
3. NOAA SNODAS daily snow depth and SWE analyses
4. NASA ASO LIDAR estimated snow depth and SWE analyses observed on Apr. 6 and June 2, 2015
5. NRCS SNOTEL station estimates of snow depth and SWE
6. NASA/MODIS remotely-sensed snow covered area analyses

c. Project Findings

NLDAS2 vs. NSSL NOXP Estimated Precipitation

Comparisons of NLDAS2 versus NSSL NOXP precipitation estimates from Dec. 2014 through April 2015 are shown in Fig. 29 while time series plots of basin average precipitation from these two products are provided in Fig. 30. In general, these figures illustrate that over most of the domain, the NSSL NOXP radar estimate is less than that from the operational NLDAS2 analysis. There are a couple of regions within the domain where the NSSL NOXP estimates are equal to or slightly greater than the NLDAS2 that include a small region over the Conejos River basin and the area on the San Luis Valley floor immediately southwest of the radar location (center of the circle). In a basin-average sense though the small area where NOXP precipitation exceeds that of NLDAS2 in the Conejos basin does not fully change the sign of the difference in total accumulated precipitation over the Conejos basin leaving that basin. In other major basins in this region the NLDAS2 estimate is greater than that NSSL NOXP estimate. Preliminary analyses of precipitation accumulation at the two *in-situ* research sites in the Conejos basin (see Section 2 above) suggest that the NOXP product is close to gauge-observed precipitation in that area. Additional analysis documenting the relative performance of these two precipitation products is ongoing.

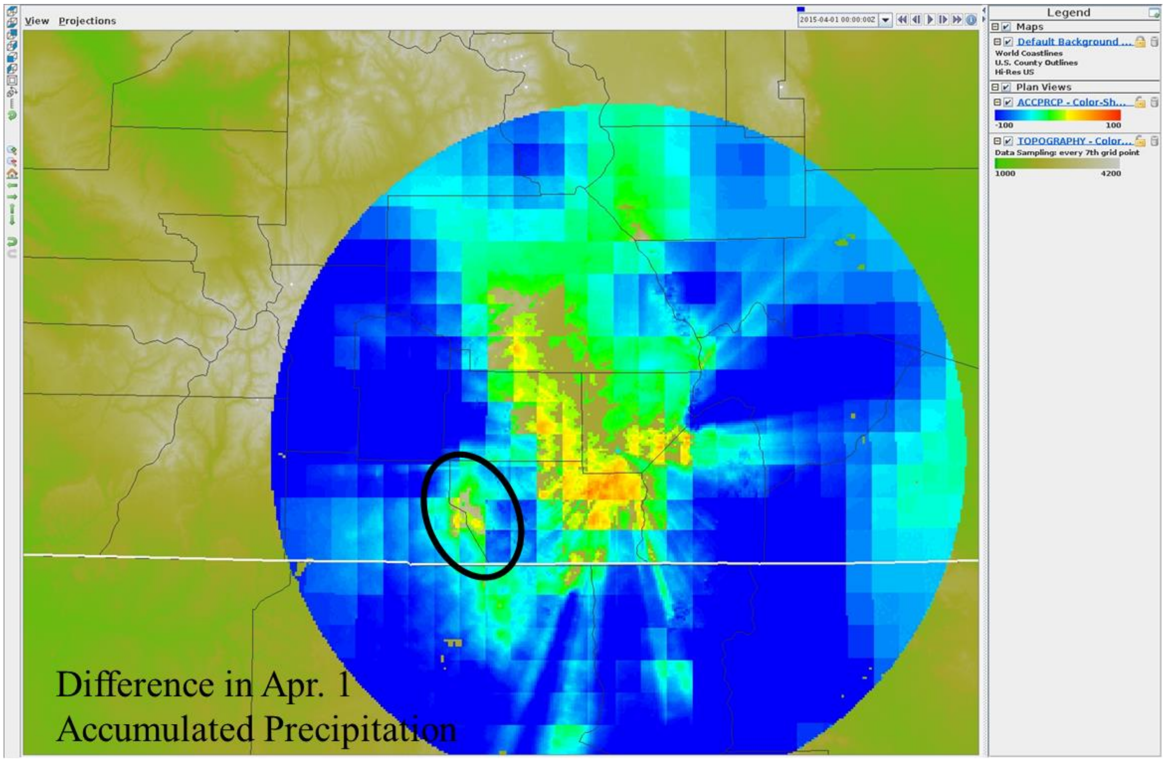


Figure 29. Map NSSL-NOXP accumulated precipitation minus NLDAS2 precipitation from Dec. 2014 through Apr. 1, 2015. The difference color scale ranges from -100 (blue) to +100 (red) mm. The range distance of the NSSL NOXP radar precipitation estimate is indicated by the edge of the shaded circle.

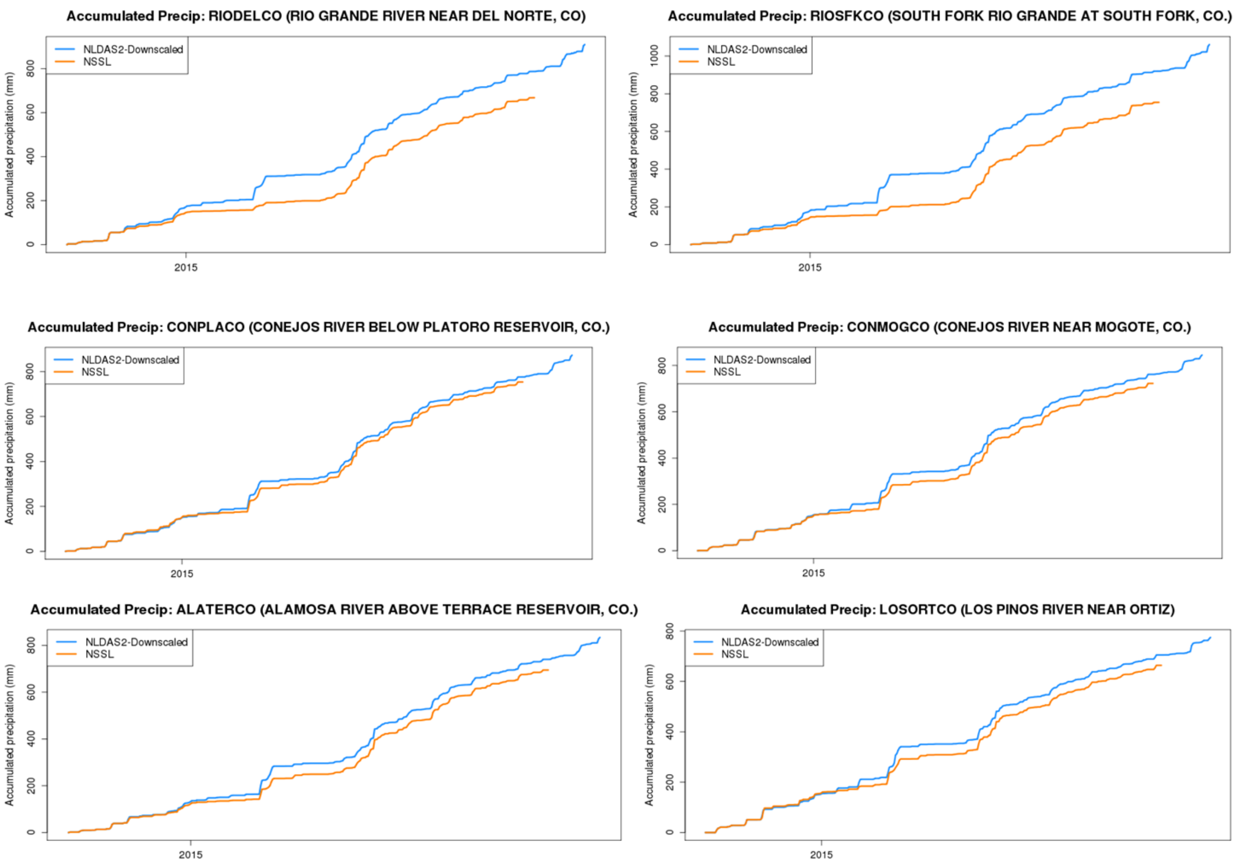


Figure 30. Time-series plots of basin averaged accumulated precipitation from the NLDAS2 (blue) and NSSL-NOXP (orange) precipitation products for selected basins.

ASO, SNODAS, WRF-Hydro Snowpack Comparison

Snowpack simulated from the WRF-Hydro system was compared against both the experimental NASA ASO products (described above) and the operational NOAA SNODAS product. Results of these comparisons for the two NASA ASO sampling days of Apr. 6 and June 2, 2015 are tabulated from the Conejos River basin in Table 3 and maps of SWE estimates from these products are shown in Figures 31 and 32. Results for the Upper Rio Grande basin are under preparation. On each sampling day, more of the statistics between the WRF-Hydro-simulated snowpack agree more closely with the statistics from the NASA ASO product than do those from SNODAS. These differences are more pronounced and consistent on the June 2 sampling day when compared to the April 6 sampling day. When combined, the statistics suggest that the WRF-Hydro modeling system, with either the NLDAS2 or NOXP forcing, can produce reasonable representations of snow area extent, elevation distribution, and total water volume. In general, the WRF-Hydro system significantly underestimates the absolute peak snow depth when compared with the NASA ASO estimate, which begins at spatial resolution of 1.5 m. This latter fact is not surprising since the model does not account for local wind scour and deposition that occurs in nature. The differences between the NLDAS2 versus the NSSL-NOXP-driven WRF-Hydro simulation are somewhat less pronounced. Consistent with the magnitudes of the precipitation differences, snowpack amount and areal extent are somewhat greater with the NLDAS2 driven run.

Conejos Basin Snowpack						
Apr. 6, 2015	**Snow Covered**	**Snow Covered**	**Mean Snow Line**			
	Area	**Area Fraction**	**Elevation**	**SWE Volumne**	**Mean SWE**	**Max. Snow Depth**
Product	**(km^2)**	**(km^2)**	**(meters)**	**(ac-feet)**	**(mm)**	**(mm)**
ASO	516	0.71	3219	60,751	150	569
WRF-Hydro (NLDAS)	663	0.91	2784	112,319	207	759
WRF-Hydro (NSSL)	620	0.85	2908	88,337	175	741
SNODAS	633	0.87	2819	60,940	118	682

Conejos Basin Snowpack						
Jun. 2, 2015	**Snow Covered**	**Snow Covered**	**Mean Snow Line**			
	Area	**Area Fraction**	**Elevation**	**SWE Volumne**	**Mean SWE**	**Max. Snow Depth**
Product	**(km^2)**	**(km^2)**	**(meters)**	**(ac-feet)**	**(mm)**	**(mm)**
ASO	261	0.36	3430	54,251	260	610
WRF-Hydro (NLDAS)	239	0.33	3045	36,044	184	474
WRF-Hydro (NSSL)	220	0.30	2805	31,244	175	455
SNODAS	428	0.59	3034	22,129	62	188

Table 3. Snowpack statistics comparisons between the NASA ASO product (regridded to 1 km), the WRF-Hydro model driven by NLDAS2 precipitation, the WRF-Hydro model driven by the NSSL radar, and the operational NOAA-SNODAS product.

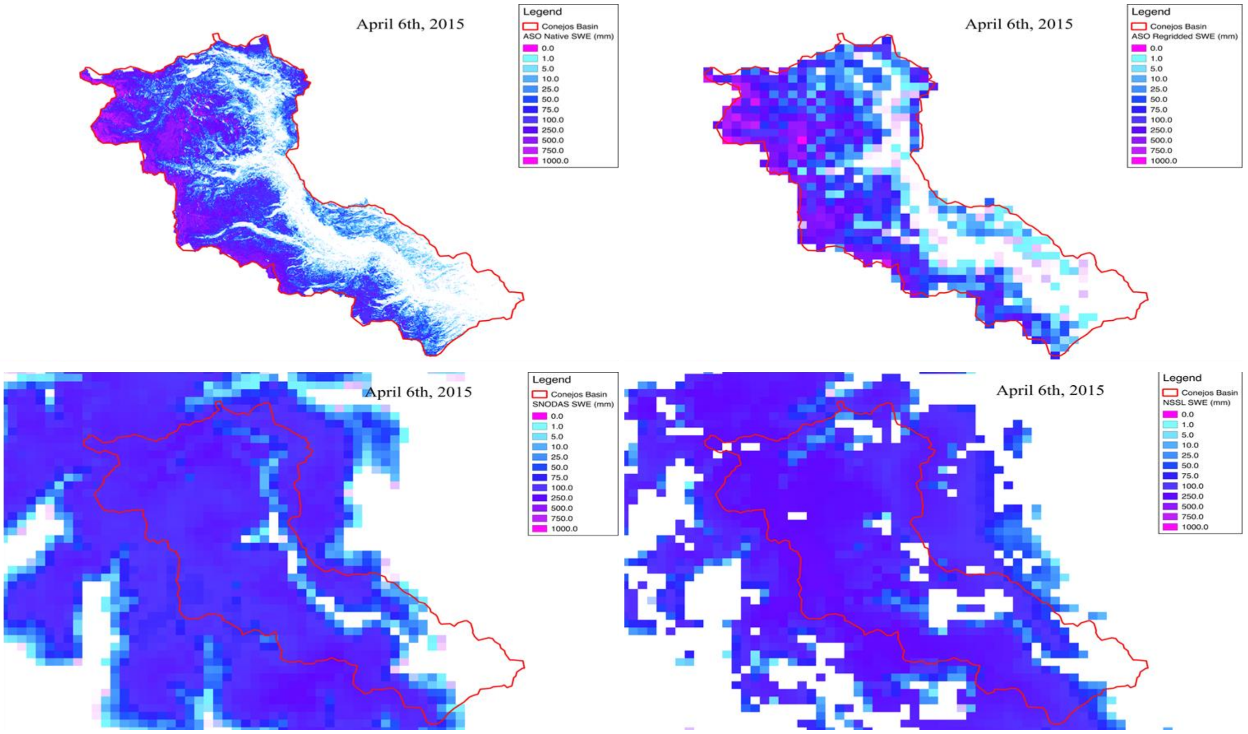


Figure 31. Comparison of April 6, 2015 SWE estimates from ASO 50 m (top left), ASO regridded to 1 km (top right), 1-km operational SNODAS (lower left), 1-km WRF-Hydro driven by NSSL radar precipitation (lower right).

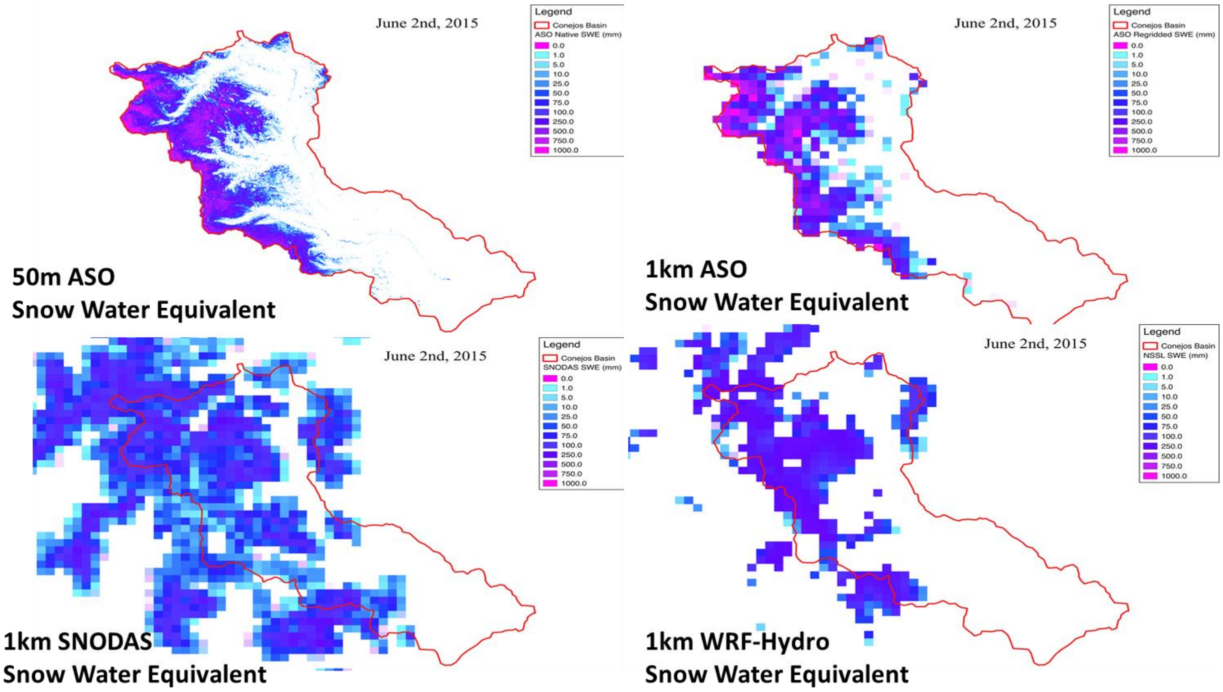


Figure 32. Comparison of June 2, 2015 SWE from ASO 50m (top left), ASO regridded to 1 km (top right), 1km operational SNODAS (lower left), 1-km WRF-Hydro driven by NSSL radar precipitation (lower right).

WRF-Hydro-Simulated Streamflow and Total Seasonal Runoff

Simulated daily streamflow values from WRF-Hydro reflect the differences in precipitation forcing between NLDAS2 and NOXP described above. In each of the four basins plotted in Fig. 33, streamflow from the NOXP-driven simulation is less than that from the NLDAS2-driven run and generally speaking, the NOXP-driven run better matches with CDWR-observed streamflow. Also, consistent with the accumulated precipitation plots above, the difference for the Conejos basin is modest, but the difference is larger in other basins where the difference in precipitation is greater.

WRF-Hydro-simulated streamflow correlation and bias values for model simulations driven by the NSSL-NOXP radar are provided in Figs. 34 and 35. In general, streamflow correlation values between modeled and CODWR-observed values are good for most areas, except the San Luis Valley floor and the northern portion of the Sangre de Cristo Mountains. Streamflows on the valley floor are heavily influenced by water management and irrigation diversion practices so "natural flow" simulated results would not be expected to perform well there. The diminished performance in the drainages of the Sangre de Cristo Mountains is still under investigation, but it is hypothesized to be related to large losses of streamflow to groundwater. The model performance for streamflow bias is very similar to that of streamflow correlation in that most areas have fairly small biases (small, white circles), except for those areas on the San Luis Valley floor. Combined, these results demonstrate that, driven by the NSSL-NOXP radar data and the NLDAS2 non-precipitation meteorological forcings, the WRF-Hydro model is able to produce daily streamflow values with relatively high correlation and low bias when compared against observations. Assessment of these model results against operational streamflow analyses and forecasts from the National Weather Service and the NRCS is still ongoing.

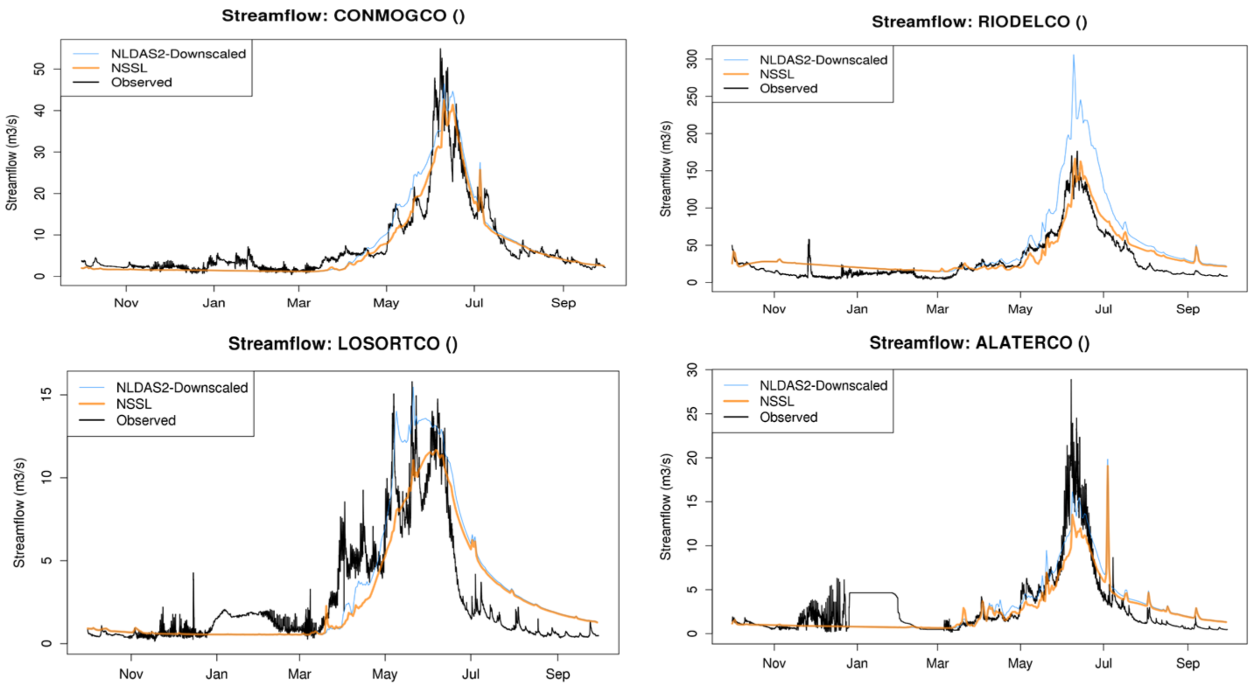


Figure 33. Modeled and observed (black) daily streamflow hydrographs from the NLDAS2 (blue) and NSSL-NOXP (orange) forced WRF-Hydro model.

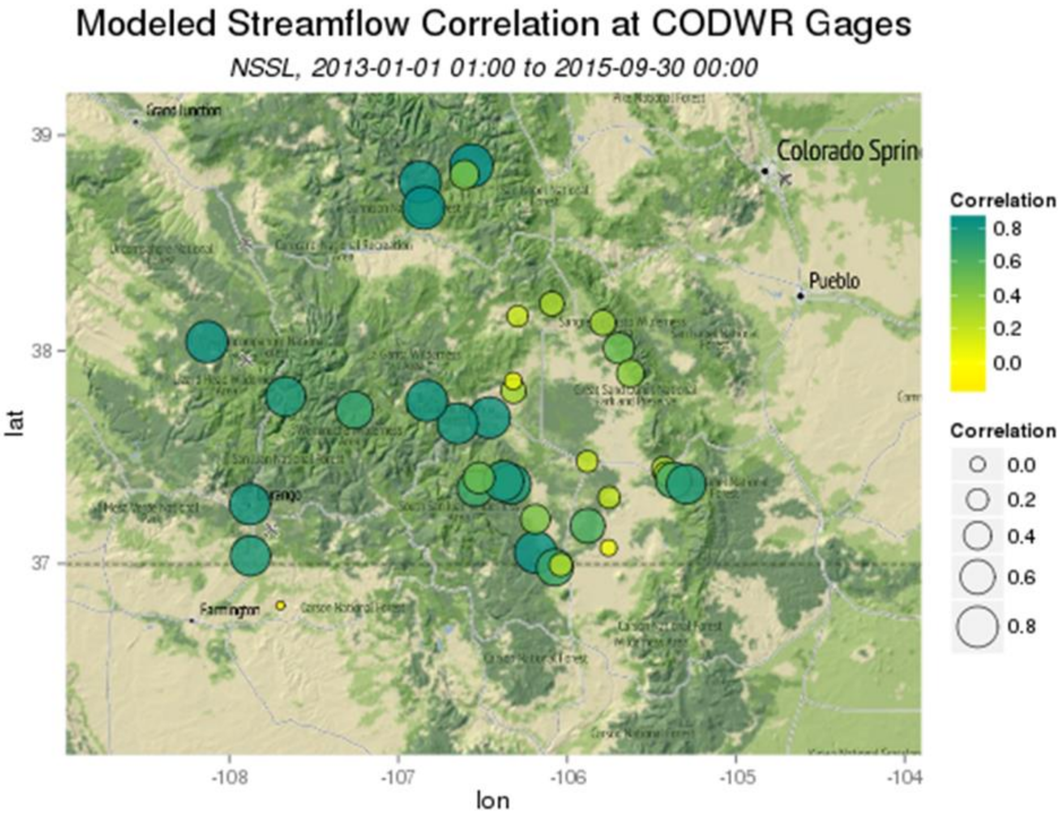


Figure 34. Mapped values of the correlation between daily streamflow values between the WRF-Hydro model and CODWR streamflow observations. Low correlation values on the San Luis Valley floor are due to water management operations.

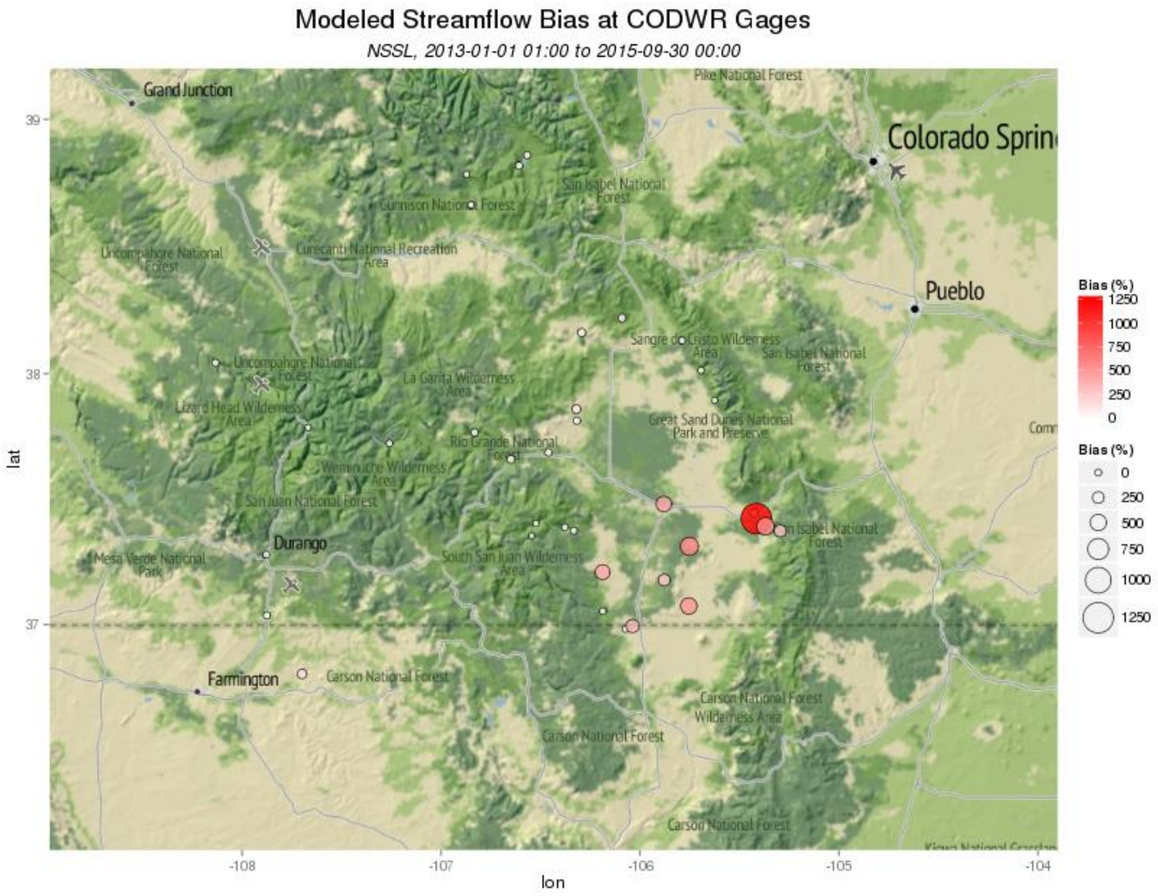


Figure 35. Mapped values of WRF-Hydro-modeled streamflow bias at CODWR stream gauging stations. Large bias values on the San Luis Valley floor are due to water management operations.

Of greater interest to water managers than daily correlation is the skill of simulated total seasonal runoff, as that value is most directly related to the quantity of water that must be delivered as part of Colorado’s compliance with the Rio Grande Interstate River Compact Agreement. Figure 36 shows plots of accumulated streamflow. Consistent with the above statistics on streamflow behavior, the NOXP-driven WRF-Hydro simulation tends to show better agreement in total seasonal streamflow accumulation than the NLDAS2 driven run.

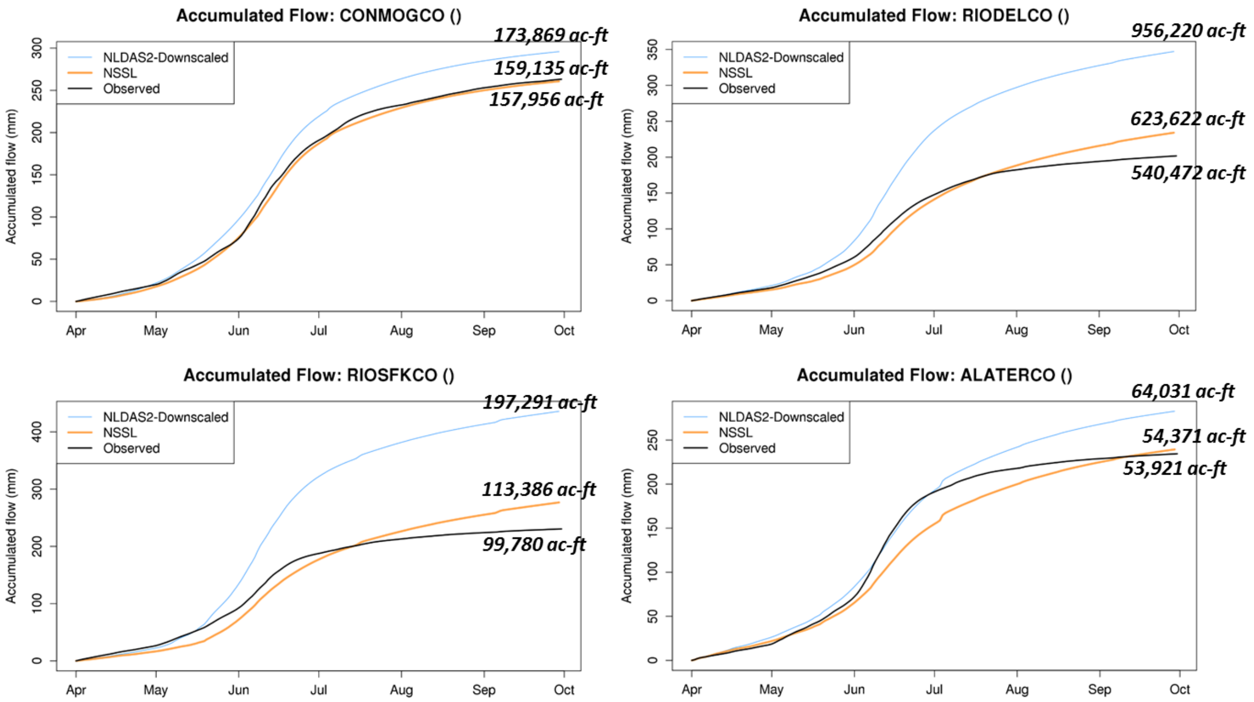


Figure 36. Modeled and observed (black) daily accumulated streamflow hydrographs from the NLDAS2 (blue) and NSSL-NOXP (orange) forced WRF-Hydro model. Inset numbers provide Apr. 1 – Oct. 1 accumulated runoff in ac-ft.

d. Recommendations

The results presented above suggest that spatially distributed, physics-based modeling of snowpack, runoff, and streamflow using models like WRF-Hydro appear feasible for operational work. In general, WRF-Hydro-simulated streamflow, when driven by the NSSL-NOXP radar precipitation estimate, was improved when compared to simulations using the NLDAS2 precipitation. When compared against snowpack observations from the operational SNODAS product and the NASA ASO platform and against CODWR streamflow data, the WRF-Hydro system appears to reasonably capture snowpack accumulation and ablation processes, as well as runoff and streamflow processes reasonably well. This preliminary analysis suggests that when driven by high-quality forcing data, such as the NSSL-NOXP radar, the quality of the snowpack analyses from WRF-Hydro are comparable to or, at times, better than the operational SNODAS analysis. Analysis of these results though is still ongoing and further exploration of these initial findings is warranted. Nevertheless, the analysis of the model results presented above yield the following recommendations:

1. Bias correction of operational meteorological datasets using additional *in-situ* meteorological observations needs to be further researched.

2. Gap-filling radar precipitation estimates in data-poor regions like the Upper Rio Grande River appear to provide significant benefit in the simulation of snowpack and streamflow and should be considered for continued use.

3. Snowpack and streamflow simulation from WRF-Hydro skill should be compared against actual “forecast” skill using downscaled numerical weather prediction forecasts to assess the real value of the modeling system and supporting observations on seasonal water-supply forecasts.

4. The NASA ASO platform provides invaluable information on spatially distributed snowpack states and should be considered for future snowpack monitoring, model verification, and model assimilation uses.

6. Collaborative Engagement in the Upper Rio Grande Region

a. a. Rio Grande Compact Decision Support Tool

Most of the streamflow in the Rio Grande and Conejos Rivers is generated by snowmelt runoff that occurs during the months of April through September. The irrigation season typically runs from April to November, when Colorado water users divert water for agricultural purposes. The Division 3 Engineer relies on seasonal water-supply forecasts issued by the NWS West Gulf River Forecast Center (WGRFC) and the Natural Resources Conservation Service (NRCS) to assess how much water will be available during the April-September period. The water-supply forecasts are issued on the first of the month from January through June, and predict how much natural runoff will occur during the April-September period. When the water-supply forecasts are issued each month, the Division Engineer refines the curtailments to ensure the Rio Grande Compact obligations are fulfilled.

Since 2009, the CWCB, Colorado Division of Water Resources DWR, NRCS, and WGRFC have worked to improve the snowpack and water-supply forecast information made available for the Upper Rio Grande Basin. One of the major successes of this collaboration has been the implementation of hydrologic models that include snow and rainfall-runoff modeling. The hydrologic models are now being used by the NWS WGRFC to provide additional data and products for their water-supply forecasts.

Prior to the development of hydrologic models, the official water-supply forecasts were developed solely based on regression models. The regression models produce forecasted seasonal water-supply volumes, with very limited information about the timing of the runoff. In balancing local water use for agriculture against delivery obligations under the Compact, timing of information is critical for the Division Engineer in administering the Compact.

The NWS WGRFC uses hydrologic models to produce ensemble streamflow prediction (ESP) products. The ESP program starts with the current conditions from the hydrologic models (i.e., soil moisture and snowpack) and generates potential runoff hydrographs assuming the upcoming weather is the same as has occurred in historical years. For the Upper Rio Grande Basin, the ESP program generates potential hydrographs using historical weather data for the period 1980-2007 (see Figure 37). The 28 potential runoff hydrographs are then analyzed using statistics to generate a variety of probabilistic products. The ESP products offer several potential advantages compared to the traditional regression models:

- The daily forecasted streamflow hydrographs contain valuable information about when the runoff is likely to occur that can support the Division Engineer in establishing curtailments.
- The daily hydrographs allow “what-if” scenario analyses if future weather conditions are forecasted to be similar to a historical year (i.e., analog years).

- The ESP products can be run more frequently than monthly (the time step on which the official water-supply forecasts are issued). This feature provides the Division Engineer with up-to-date information when making curtailment decisions mid-month.

- The ESP products can be run later in the calendar year, when the quality of the regression models breaks down.

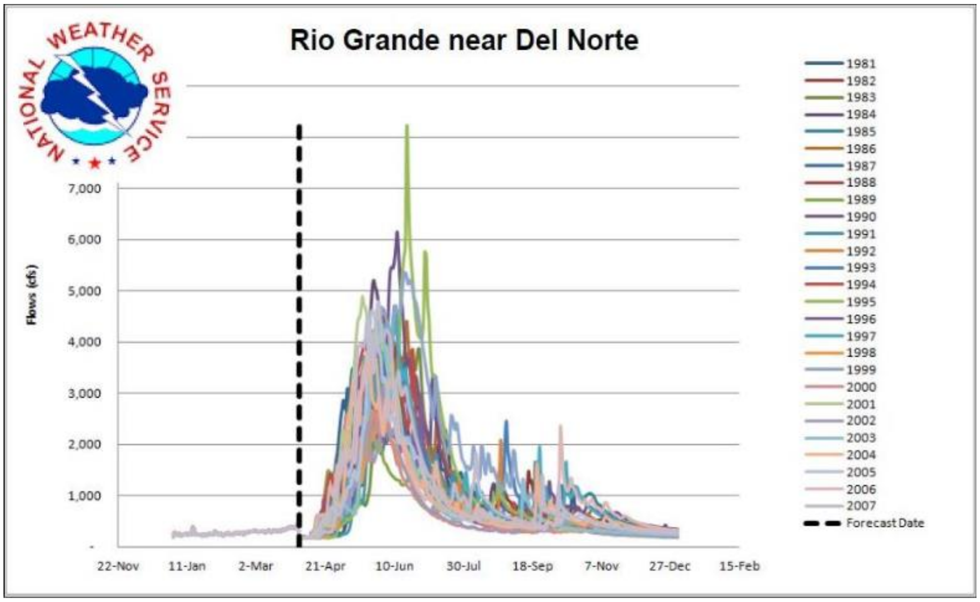


Figure 37. Example ensemble streamflow prediction (ESP) product in RGCDST

Since 2011, the CWCB has been working with the Conejos Water Conservancy District (CWCD) to identify additional projects that will improve the snowpack measurement and streamflow forecasting information available in the Upper Rio Grande Basin. For this project, the CWCB worked with the CWCD and Riverside Technology, Inc. (Riverside) to develop a decision-support tool that incorporates information from the ESP products and provides the Division Engineer with supplemental, probabilistic information when administering the Compact. The Rio Grande Compact Decision Support Tool (RGCDST) was developed and tested in 2014 and delivered in early 2015 to the Division 3 office for operational use.

Working with the DWR Division 3 office in Alamosa, Riverside identified and developed three major objectives of the RGCDST:

1. The tool makes use of ESP forecasts that the WGRFC is producing on a weekly basis. As a result, the DWR has the potential to make incremental changes to the curtailment values throughout the month, and avoid making large changes to the curtailment values at the beginning of each month when the official water-supply forecast is released.

2. The tool makes use of information from the newly available short-term deterministic (STD) forecasts to help DWR assess whether the ESP forecasts over the next 10 days are likely to be high or low and to incorporate that information into the selected curtailment values.

3. The tool computes the curtailment value for each member of the ESP forecast, resulting in a distribution of 26 curtailment values, rather than one curtailment value based on the 50% forecast. This analysis is potentially valuable because the distribution of curtailment values is not the same as the distribution of forecast values due to the delivery requirements specified in the Compact. This allows the DWR to review the distribution of curtailment values and to incorporate that information into the selected curtailment values.

An additional requirement was that the RGCDST was to be a desktop tool developed using only software that the DWR has licenses for or freeware. As a result, Riverside built the RGDST utilizing Microsoft Excel and Visual Basic to provide a user-friendly tool that could be supported. The RGCDST includes scripts to automatically access and import ESP and STD forecasts from a WGRFC ftp site; automatically connect to the DWR Satellite-Linked Water Resources Monitoring System (SMS) database for recently observed streamflow, reservoir storage, and diversions; and allows for input variables and results to be easily tabulated and plotted.

After the first year of use in 2015, the RGCDST demonstrated some initial benefits by offering DWR an alternative water-supply forecast to analyze with the monthly NRCS product. In reviewing that year, it is interesting to observe that generally the NWS ESP forecasts were consistently higher than the monthly NRCS (Figure 38a, left). For this year, this proved to be the more accurate of the two forecasts. It is also worth observing how the uncertainty in the ESP forecast decreases through the season as the runoff from snow subsides. Looking at the curtailment plot showing the range in delivery target as a percentage of flow (Figure 38b, right), the DWR tended to deliver less than the forecasted ESP would have projected throughout the season due to a greater reliance on the NRCS forecasts. A higher curtailment that matched the ESP early in the season (April-May) might have improved the necessary increase to 20% in late June and July, but the DWR was correct in setting the curtailment lower than the forecast throughout the summer months, since the ESP tended to be high during this period.

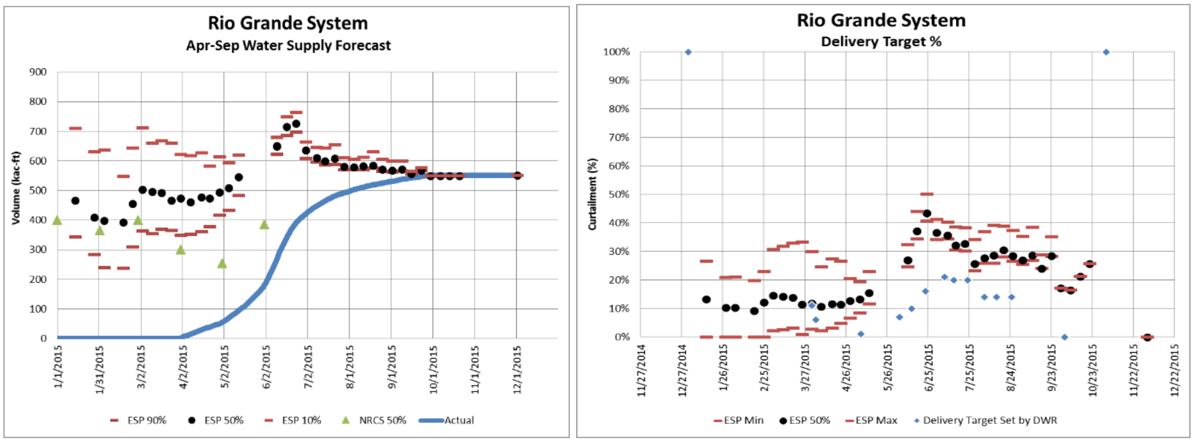


Figure 38. (left) Comparison of NWS ESP (black dots-mean values, red bars-ranges) versus monthly NRCS forecasts (green triangles) from RGDST, blue line represents actual water-supply forecast. b. (left) Projected (black dots/red bars) and actual (blue dots) deliveries to NM from the RGDST.

The RGCDST is currently being used by the DWR to enhance their decision making of Compact obligations for the Upper Rio Grande. Future developments that could build off the RGCDST tool could include:

- Enhance RGCDST to allow for individual ESP trace weights to account for climatological anomalies such as El Niño and La Niña for projected years.
- Integrate experimental snowpack and water-supply forecast products developed within the broader "RIO-SNO-FLOW" project to assess value of experimental products against currently operational products.
- Assess historical forecast performance through hindcasting (or re-forecasting).
- Perform comparative analysis of hindcasting curtailment results with historical curtailments.
- Explore risk tolerances through "what if" scenarios of decision variables and rules.

Additional enhancements to the quality of water-supply forecasts by WGRFC could include improvements in convective rainfall-runoff in the fall season and a move from ESP to the Hydrologic Ensemble Forecast System (HEFS) that includes Numerical Weather Prediction and climate forecast information.

b. Local Engagement

Members and participants of the monthly meetings of the Rio Grande Basin Roundtable comprise a diverse mix of water managers, municipalities, farmers, ranchers, agency directors, and State legislators. The Roundtable had been working hard with NRCS and with legislators, knowing that "something else" was needed -- additional SNOTELs or some other methods -- in order to improve the accuracy of the Division Engineer's predictions of annual flow at the Del Norte gauge. Water users in the Upper Rio Grande Basin, even very senior rights, are subject to Rio Grande Compact curtailments based upon these forecasts. For many years, the Roundtable community had endured significant economic losses and felt the negative impacts of inaccurate stream flow forecasts.

Figure 39. Nathan Coombs, Conejos Water Conservancy District was the local host an invaluable to the success of these projects

The boundaries of the Conejos Water Conservancy District (the District) include about 100,000 acres, of which 86,000 acres are irrigable. An additional 8,000 acres that are not within the boundaries of the District are also irrigated by the Conejos and its tributaries. Within this vast water management area, forecasting errors have historically been especially costly and hurtful. In an over-appropriated and drought-impacted basin, balancing surface and groundwater use and minimizing dependence on groundwater pumping by farmers and ranchers has always represented the State's last line of defense before letting the flows of the Rio Grande and Conejos River watersheds go south across the state line. With a high stake in the successful outcomes of this project, the District voted to take the supporting lead and was awarded $215,000 from the CWCB.

Figure 40. Katie Schulz at NOXP during an event.

The District joined with the Division of Water Resources, the Colorado Water Conservation Board, National Center for Atmospheric Research, the West Gulf RFC, NOAA-NSSL, NRCS and Riverside Technologies to conduct these projects. The goal was to accurately measure and predict snowfall and snowpack by assessing new experimental precipitation and snowpack estimation products and comparing them against currently operational products. Nathan Coombs said, "Working with the scientists and new technology has built confidence in the forecasts and has put more water at the head gates of our users."

Since the scientists of the various agencies were based in Denver, Boulder, and Norman, Oklahoma a local support crew was needed to help NOAA operate the NOXP. The Conejos Water Conservancy District fundraised on its own and from various reservoir and ditch companies to pay for the local help. Nicole Langley of Transforma Research & Design provided administrative and grant writing assistance and recruited the local "Radar Support Crew."

Figure 41. Local sponsor tour of the NASA ASO.

The District would like to acknowledge support provided by Adams State University's Dr. Robert Benson, Professor of Geology and Earth Sciences; Dr. Benita Brink, Professor and Chair of the Biology/Earth Sciences Department; and Dr. Jared Beeton, Assistant Professor of Earth Sciences. They helped promote the project and identify students that wanted to help with this high profile project. Those who were contracted (at $10/hour plus mileage) to provide this backup support at the NOXP were Stefan Armenta, Darrell Cordova, Katie Schultz. Over the course of the 2014-2015 winter season, despite demanding circumstances, long dark nights and cold conditions, the radar support crew demonstrated dedication to the project. Dr. Larry Sveum, retired professor of math, chemistry and physics at Adams State University and former Dean of the School of Science and Technology, made himself available 24/7 to work at the NOXP. Wayne Schwab, Manager of the Trinchera Irrigation Company, added NOXP duty to his work schedule, teaming up with Dr. Sveum to provide additional support.

Figure 42. NOXP radar at Alamosa airport taken by Jose Meitin

On April 7, 2015 the District welcomed the whole science team for dinner. The NASA's JPL Airborne Snow Observatory (ASO) team, provided a public tour of their airplane/observatory.

7. Conclusions and Recommendations

As a team that worked on this from all levels from water users, water administrators, water planners, research and development agencies, forecasters, and consultants, the following are our recommendations:

- Accurate determination of snowfall liquid water, snowpack and associated runoff remains a significant challenge in the local, state and federal water communities and only through collaborations and sponsorships, as fulfilled in the project, would fundamental progress be realized.

- Funding has been established to conduct one more year of NASA ASO flights, NOAA radar in the spring months, SNOTEL-lite hardening, and NCAR resources to continue to run a local version of WRF-Hydro in the Rio Grande. More local and grant funding will be needed to continue efforts in the Rio Grande beyond winter 2015-16 or Water Year 2016.

- Gap-filling, watershed-based radars would provide great benefit to Colorado for land, water, and weather management. Local, state, and federal coalitions should be built to purchase and maintain permanent and mobile radars to provide a more complete depiction of precipitation for use in hydrologic models such as WRF-Hydro and for flash flood prediction.

- A Colorado ‘Data Gaps’ strategic paper has been discussed with a draft currently being revised. A thorough analysis of radar data gaps has been completed and additional instrumentation to cover the gaps in the statewide observing network is being finalized by the CWCB, NOAA, and NCAR. The paper will be finalized by end February 2016 and distributed to Stakeholders and state and federal officials.

- Additional snowfall and snowpack data are valuable and partnerships with NRCS Snow Survey program should be developed to: a) add additional SNOTEL sites, b) create SNOTEL-lite sites, convert manual NRCS snowcourses to SNOTEL sites, c) upgrade the data collection platform to include more sensors on the physics of snowpack evolution processes and d) enable real-time data transmission from as many sites as possible.

- Additional snowfall and snowpack data are valuable, and when there are willing and capable local caretakers of watersheds, additional SNOTEL-lites can be developed, operated and maintained at the local level.

- NASA ASO data are invaluable and provide unprecedented details of snowpack distribution and totals. The data can be used for hydrologic modeling and analysis for where future ground snowpack data should go. More frequent ASO acquisitions will likely provide additional valuable constraint on runoff forecasting and allocation determinations.

- NASA was tasked by the State's All Hazard Mapping Program in partnership with FEMA to map LIDAR for several areas in the state. That effort should continue to collect LIDAR data to meet multiple needs. Water users should utilize the new mapping in San Miguel County, around Montrose, and in San Juan County for peak snowpack flight by NASA.

- Using data collected during the project new dual polarized radar applications are being developed and refined for use in National Weather Service and River Forecast Center operations. These new applications will benefit watersheds that are currently covered by the WSR-88D network and will serve as starting point for future 'gap' filling radar deployments.

- A national version of the WRF-Hydro modeling system will become operational in the summer of 2016, complementing existing forecasting tools. However, forecasts from WRF-Hydro system can benefit significantly and immediately from additional real-time snowpack, snowfall, soil moisture, and streamflow data. Also, short-term field projects to collect additional campaign-style snowpack and streamflow data can be used to improve the calibration of the model's snowpack, runoff, and streamflow physics, ultimately providing more reliable analyses and forecasts to the RFC and local water users.

- The report is a status and initial project outcomes for consideration to the sponsors. NASA, NCAR, and NOAA will continue to analyze the data and prepare the results for publication in peered reviewed scientific journals.

- The CWCB served as a valuable forum host for all interests to come together and work together on the issues. The CWCB is especially well suited to continue serving as a liaison between water stakeholders and administration and new science and data that will address monitoring and forecasting issues.

- The CWCB 2016 Water Projects Bill authorization (called Water Forecasting Partnerships Project) will have $300,000 available to partner on water monitoring and forecasting projects. Issues and ideas should be forwarded on to CWCB staff for consideration.