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

Prepared for: Colorado Water Conservation Board and the Conejos Water Conservancy District

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1. Project Motivation and Description [J. Busto and Gochis]

a. Overview

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

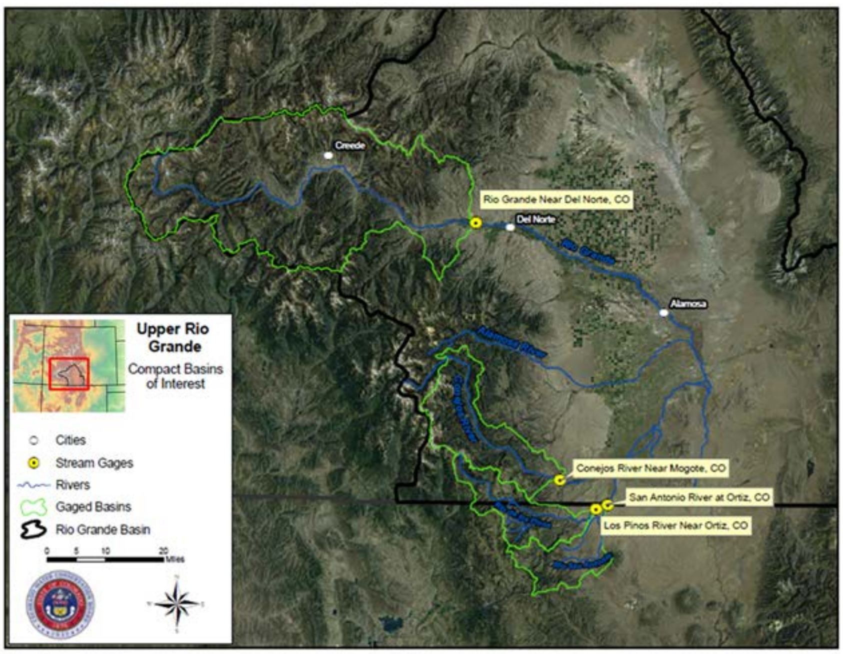


Figure 1. Colorado-New Mexico Water compact basins of the Upper Rio Grande River basin

<u>CWCB Involvement in Winter Science and Forecasting</u>

The Colorado Water Conservation Board is the water policy and planning organization within the Department of Natural Resources in the State of Colorado. Helping Colorado protect, conserve and develop water is in the mission. There are eight major river basins in Colorado and the voting board members are organized by watershed.

The CWCB has done several projects to assist with data and modeling for water supply forecasting. In partnership with local, state, and federal agencies 20 new SNOTEL were added for an 18% increase since 2004. Working with Riverside Technologies, Inc. three phases of NOAA Snow Data Assimilation System (SNODAS) investigations were completed by 2009 and data was tailored by watershed to provide maps of SWE above compact stream gauges in the Rio Grande. The CWCB also supports the Center for Snow and Avalanche Studies program Colorado Dust on Snow Program (CoDos). A new CWCB authorization will be called the Water Forecasting Partnership Project and it will be focused on making sustained improvements in ground and aerial data collection and hydrological modeling.

CWCB partnership with NOAA-NSSL and NCAR

In 2009 the CWCB partnered with NOAA-National Severe Storms Lab (NSSL) to conduct mobile radar meteorology projects that included ground validation measurements 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. Of relevance to this report a new radar-snow retrieval algorithm was developed in 2011. In spring 2012 NOAA-NSSL mapped snowpack and generated reasonable estimates of SWE in the Animas River and adjacent sub basins. In the spring of 2016 NOAA-NSSL will map snowpack in the Rio Grande for its eighth radar project in six years. The CWCB and its partners seek to build a business case for gap filling radars for Colorado to create continuous spatial coverage of radar data for a multitude of reasons.

Additionally, two recent radar campaigns were conducted by the Oklahoma University Advanced Radar Research Corporation to provide radar data used for flash flood forecasts in beam blocked parts of the Rio Grande where there is currently no useful radar coverage. 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 and provide funding for the CBRFC to host a long term forecasting workshop with universities.

The Rio Grande River

The Rio Grande total length 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, head lettuce and barley. The San Luis Valley Figure 2 is an extensive high-altitude depositional basin at an average elevation of 7,664 feet 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 are even flooded part of the year. Uncultivated land is often covered with "chico", low brush such as rabbitbrush, greasewood and other woody species. Cropland is typically irrigated with large (1/4-mile radius) center-pivot irrigation systems

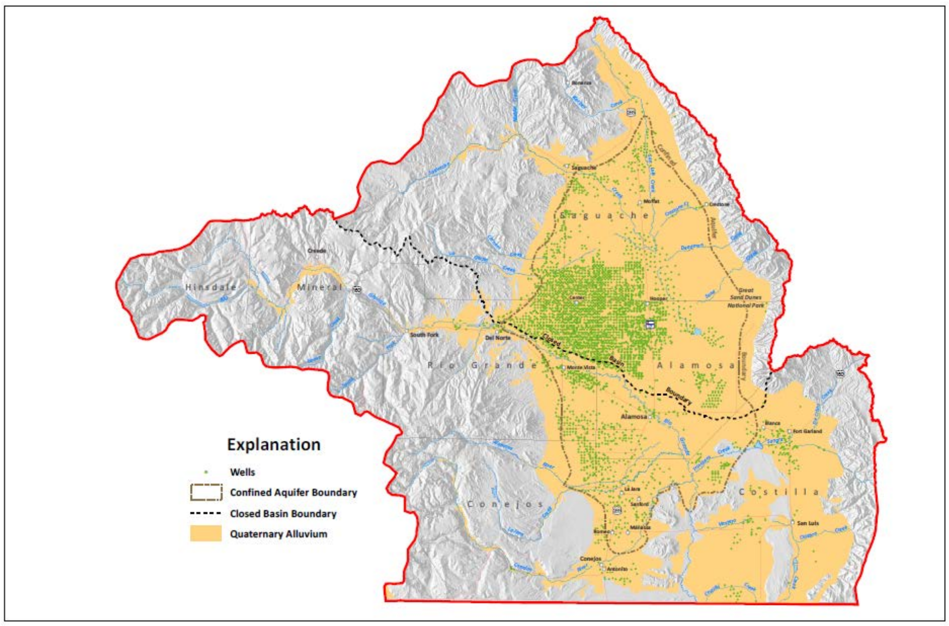
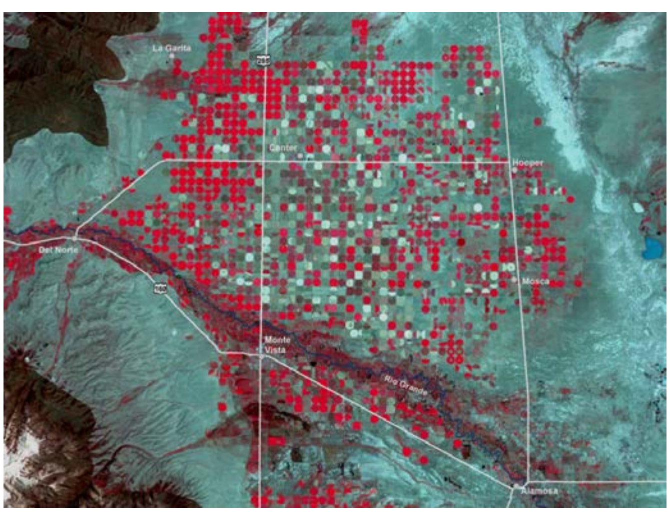


Figure 2. Map of the Upper Rio Grande basin and San Luis Valley



<u>Rio Grande Water</u>

Through a mixture of surface and groundwater rights, the Rio Grande River in Colorado is an over appropriated river. Beginning in 2015 groundwater well draft regulation went into effect that are the newest in the state. Other heavily used rivers such as the South Platte and Arkansas Rivers have had rules for decades. There is one functioning Sub district for monitoring groundwater use and it is operated by a board and general manager.

The Rio Grande Forecasting Project

In 2011 at the request of water users in the Rio Grande the CWCB convened a committee of the agency forecasters, researchers and consultants to develop different 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, Colorado Water Conservation Board, developed five project ideas. Project one was develop a compact compliance DSS tool for the DWR by Riverside, Technologies. Project two developed a set of modeled historical hydrologic forecasts to develop an archive of ensemble streamflow prediction (ESP) traces. Project three developed satellite and SNODAS data sets for the River Forecast Centers that make forecasts for Upper Rio Grande. Project four was gap filling snow data and hydrologic modeling by NCAR. Project five was develop remote sensing data sets through NASA Aerial Snow Observatory (NASA-ASO) and radar precipitation estimation data both for inputs into hydrologic modeling. Funding projects 1,4,5 cost a sum total of $745,000 and all are discussed in this final report. Funding from the CWCB, Rio Grande Basin and Statewide Round Table funds, and USBR Water Smart Funds were all leveraged to make this project possible. Project one 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.

Rio Grande River Compact

The Rio Grande River Compact is an interstate compact signed in 1938 in the United States between the states of Colorado, New Mexico, and Texas, and approved by the United States Congress, to equitably apportion the waters of the Rio Grande Basin. Strict Compact administration began in 1968. Since 1985 Colorado can accrue debits and credits based on its water use and delivery to New Mexico.

"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

"On a day to day basis we curtail pre-compact water rights every day in order to meet the obligation 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, "We have to deliver on two streams on a calendar year basis. It is about 650,000 acre-feet average annual flow on the Rio Grande and we have to deliver 28% of that. For the Conejos River we have to deliver 300,000 AF average annual flow and they have to deliver 38% every year. We deliver low on a low water year and more on a wetter year. In a good year we have to send 100% of the excess down to other states. The Conejos has a tight delivery schedule. We have to figure out how much water we have for the whole irrigation season. We need to know the total volume so we don't have debits or credits but deliver exactly what we are supposed to meet the compact obligations. We have endangered species issues with the southwestern willow fly catcher and silvery minnow. We have to have some water in New Mexico and keep the rivers wet to address habitat issues there as well. When Elephant Butte Reservoir is too low there is a 20 mile stretch of the River in New Mexico that is difficult to get water down into the Reservoir."

The main goal of the water forecast operations in the region are 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 is in the driver's seat 100% and has more past water information behind him than he has in front of him. Typically, by June 1st the river is beginning to recede from peak flow conditions and options for meeting interstate Compact delivery requirements become fewer. Also, the groundwater subdistrict has to turn in their annual replacement plan by April 1st so many decisions need to be made in the period from late March through late May. 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 what occurred during 2015.

Low snowpack and frozen rain and late fall and early winter events do make a differences and can provide some basic indications of seasonal runoff. For example, reservoir inflows into November in 2012 were 25 to 30 cfs where in 2015 they were 50 – 60 cfs which indicates that the contributing watershed is relatively wet.

Infrastructure on the mainstem Rio Grande

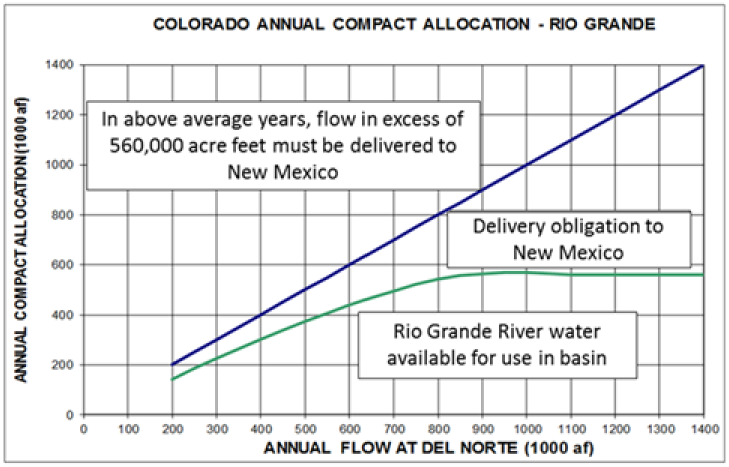
Rio Grande Dam was built between 1910 and 1914 by the San Luis Valley Irrigation District to store water for agriculture with a capacity of 52,000 acre·ft at an elevation of 9,449 ft about 20 mi (32 km) southwest of Creede below the headwaters of the Rio Grande. Once on the San Luis valley floor there 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 Dam

Platoro Dam was constructed between 1949 and 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 dam is owned by the Bureau, and operated by the local Conejos Water Conservancy District. It holds 53,506 acre feet 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) northeast 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 Conejos and joins the Rio Grande from the west approximately 15 mi (24 km) southeast of Alamosa.

b. Water Supply and Compact Issues – Detailed Administration

The water delivery obligations from Colorado to New Mexico on the Rio Grande River, as specified in Rio Grande River Compact (or 'the Compact') provide stringent constraints on water management decision makers in the Upper Rio Grande basin. Principally, 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 New Mexico during low flow years. Figure XX illustrates the terms of the water obligations from Colorado to New Mexico in the Upper Rio Grande basin from the mainstem Rio Grande River and the Conjeos River. Flow from the Conejos River constitutes nearly 40% of the delivery obligation to New Mexico with the remainder largely coming from the mainstem Rio Grande River. In a given year the maximum amount of water that can be stored or diverted for use in Colorado is 560,000 acre-feet for the mainstem Rio Grande and of that amount, 224,000 acre-feet is available for use in the Conejos basin. Any flows in excess of those levels must be delivered to New Mexico through the mainstem Rio Grande River. In any given year, the projected seasonal flow sets the delivery target for that year according to the consumption curves (green lines) shown in Fig. 3. The Colorado Supreme Court also has ruled that 1 April streamflow forecasts are to be used for conjunctive-use management of groundwater pumping operations. (Col. Supreme Court, 1994)



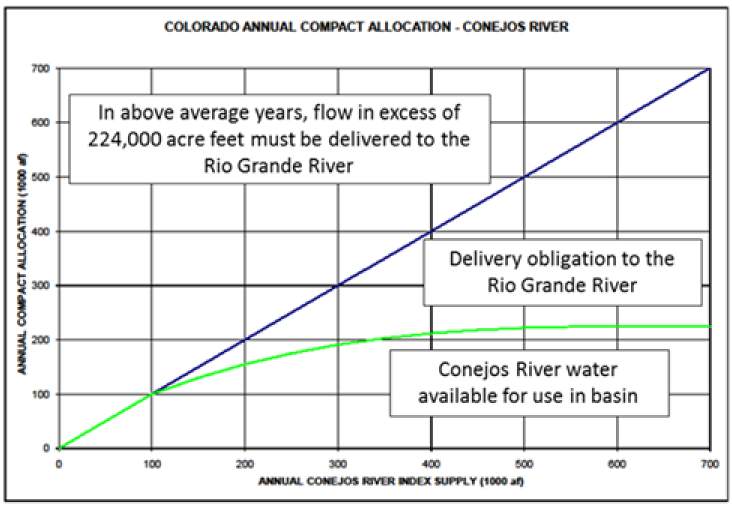
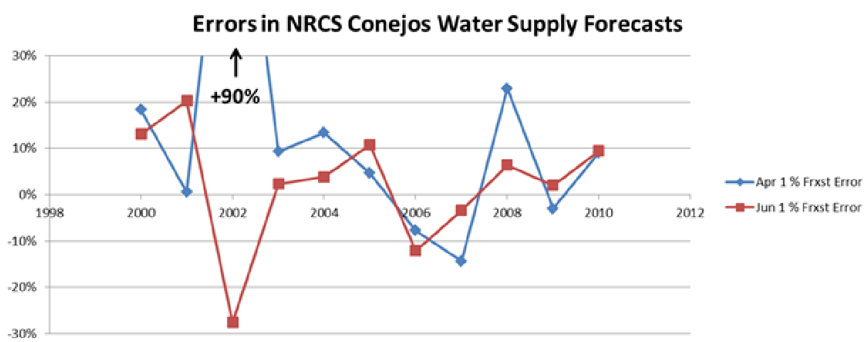


Figure 3. Structure of Rio Grande River Compact delivery requirements from Colorado to New Mexico for the mainstem Rio Grande River and tributary Conejos River. Data source: Craig Cotton, State of Colorado, Division Engineer

<u>Case Study on the Cost of Erroneous Forecasts</u>

Uncertainty in seasonal water supply forecasts in the Upper Rio Grande River basin can have a significant impact on water management, agricultural production and economic vitality. A recent analysis by the Colorado Water Conservation Board (CWCB) and Colorado Division of Water Resources (CDWR) illustrated that seasonal water supply forecasts based primarily on Natural Resources Conservation Service (NRCS) 'SNOw TELemetry' (SNOTEL) data has struggled with accuracy particularly in wet and dry years in the last several years. As shown in the Figure 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. The higher error rate in the Apr. 1 forecasts translates into millions of dollars lost annually due to reduced agricultural productivity on irrigated lands. According to Col. State Division Water Engineer Craig Cotten, "Inaccurate streamflow forecasts can cause unnecessary curtailment of ditches, over- or under-delivery of Colorado's compact obligations, and a disruption of the priority system." 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 acre-feet less than actual. In 2007, the June 1 forecasts were 143,000 acre-feet 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, and 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 demonstrate the cost-effective utilization of state-of-the-art observational and modeling techniques in improving streamflow predictions in the Upper Rio Grande basin and to help advance the optimal management of water.

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, snowpack observations and physics-based hydrological modeling. An underlying premise of this work is that improved characterization of peak snowpack conditions through Snow Water Equivalent (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. 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 this overall project were to:

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

Goal 2: Improve 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

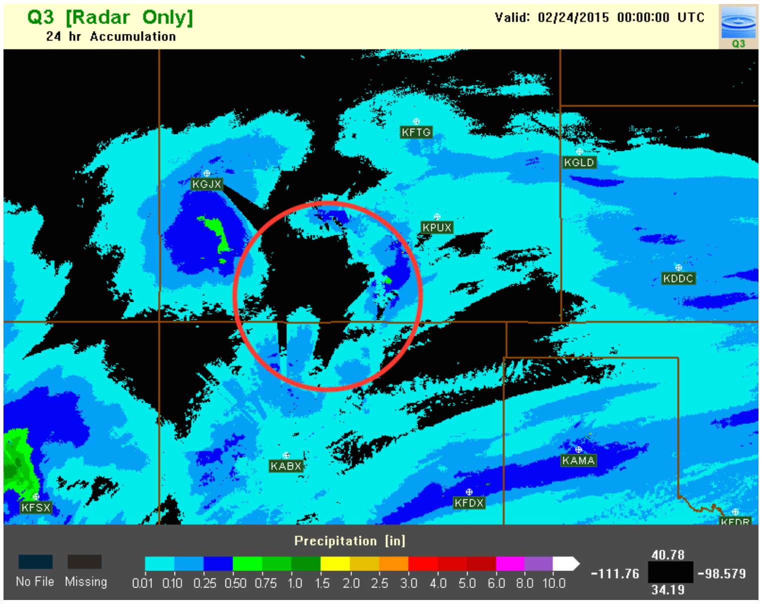
Goal 4: Demonstrate operational snowpack and streamflow forecasting impacts through disseminate observational and model-based monitoring and prediction products to, and coordination with, local, state and federal water prediction and water management partners

2. Gap-filling Radar Estimation of Snowfall in Complex Terrain [K. Howard, L. Tang]

a. Background

A contiguous observation of precipitation across the intermountain west poses a significant challenge for National Weather Service (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 10 years, several field campaigns have been conducted between the State of Colorado, local water districts and the National Severe Storms Laboratory (NSSL) to highlight the challenges and deficiencies with the current NWS operational radar network towards building a business and scientific case for the deploying 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.

Figure 4 provides illustration of the coverage gap of the NWS WSR-88D over the Rio Grande basin. The locations and surrounding terrain render both the Grand Junction (KGJX) and the Pueblo (KPUX) WSR-88Ds lower scans unusable for determining phase and rate (snow and snow water equivalent) 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.



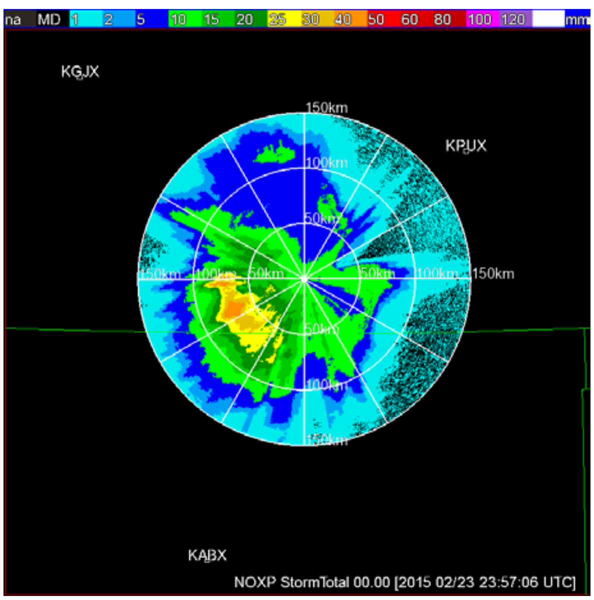


Figure 4a(top). Radar based 24-hr accumulated QPE derived by the WRS-88D radar network in MRMS system; 4b(bottom). 24-hr accumulated QPE estimated by radar NOXP. The QPE accumulation ends at UTC 00:00:00 on Feb. 24th, 2015.

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 (NXOP), gap-filling radar was deployed in Alamosa, CO at the municipal airport grounds during the winter of 2014-2015. The NXOP 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 NXOP. Figure 5 provides a tilt-by-tilt depiction of the beam blockage (by percentage) experience by the NXOP 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 improved hydro meteorological surveillance of the basin.

Ultimately the deployment of the NXOP at Alamosa was found to significantly improve coverage across the base as depicted in Figure 4b compared to the existing, currently operational radar network coverage shown in Figure 4a.

The NOXP radar is a mobile Doppler radar that operates on a 3cm 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	3cm/X-Band/9415MHz
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

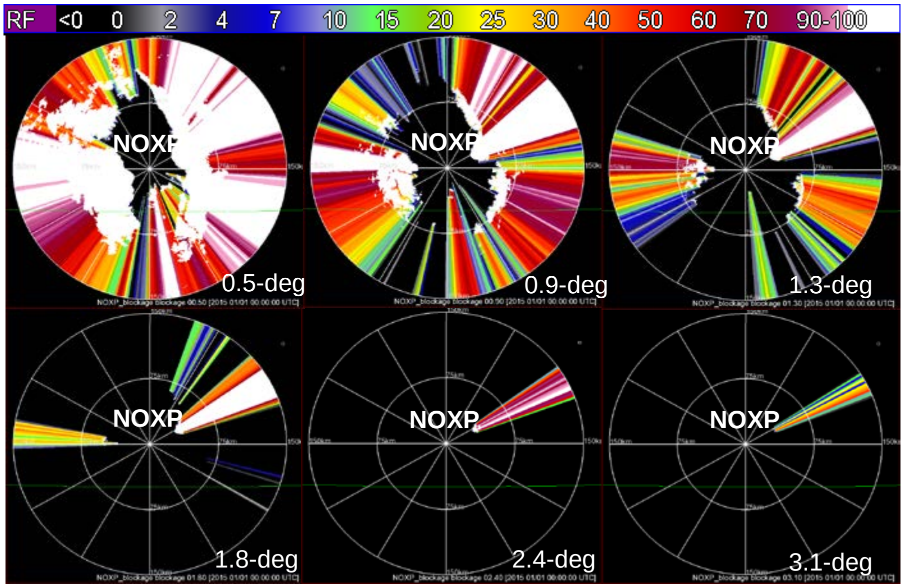


Figure 5: NOXP terrain blockage at the elevation tilts of 0.5-deg, 0.9-deg, 1.3-deg, 1.8-deg, 2.4-deg and 3.1-deg, respectively.

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 NXOP radar was staffed and closely monitored on site to ensure timely backup of the radar data and to 'trouble shoot' 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 guides 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 errors in forecasts and staffing delays as a result of travel logistics. Nevertheless, nearly 700 hours of radar data was 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 which is first corrected for beam attenuation which 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.

Figure 6: NOXP was operated at Alamosa, CO during the winter of 2014-2015.

c. Initial Project Findings

There are many challenges with using radar observations to obtain estimates of snowfall and associate snow water equivalent and this is an active area of scientific research. This difficulty is exacerbated by the presence of complex terrain as is present within Conejos and Upper Rio Grande River Basins. Remote sensing in complex terrain requires a host of assumptions such that whatever 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 is 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.

The initial pass through the NXOP data to produce a data collection period precipitation estimate used a simple approach where all the radar vertical scanning angles, or 'tilts', were combined into single composite field. The composite was constructed by using the highest reflectivity value observed for each individual tilt and using this value, no matter where it occurred in the volume, to develop a reflectivity and snow water relationship or Z-S. The snowfall rate was converted and accumulated into hourly snow water equivalent and compared with two heated weighing precipitation gauges at stations Platoro Cabin and Base (37.35167^o, -106.52815^o) and Rocky Mtn Lodge (37.18738^o, -106.44628^o). Examining the results (Figure 7), 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 relying solely on the previous derived Z-S failing to capture snowfall intensities observed in the Conejos River Basin.

d. Recommendations

The preliminary results from the 2014-2015 winter deployment were promising but require further analysis and refinement. The NOXP observations greatly improved the spatial and temporal distribution of precipitation over the Conejos River Basin in comparison to the existing operational NWS radar network. However, there remain challenges in which to bring snowfall estimates and associated water equivalent as derived from radar 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 2-D video disdrometers. Additionally, there needs to be a new approach to using dual pol moments to identify the 3D structure of winter storms and how the 3-D structure correspondence to precipitation type and snow water equivalent received at the ground surface.

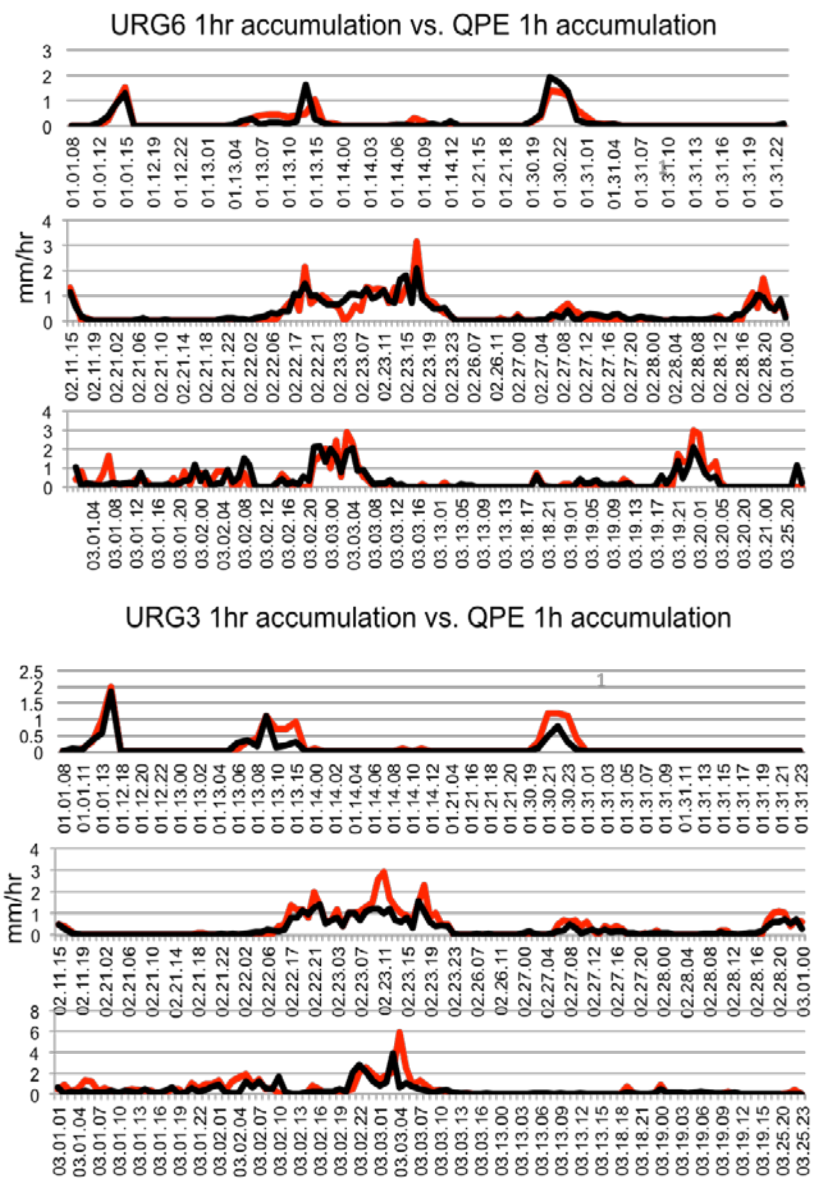


Figure 7: The results from the radar estimation and gauge measurement, where the red line is measurement from the ground gauge and the black line the accumulated hourly QPE derived by radar NOXP. The x-axis is the time series of the data comparison and y-axis is the snow water equivalent with the unit of millimeter per hour.

3. Airborne LIDAR Snowdepth and Albedo Observations [J. Deems and M. Richardson, M. Skyles, T. Painter]

a. Basic Overview of NASA ASO Platform

The NASA JPL Airborne Snow Observatory (ASO) combines lidar and spectrometer instruments on a single airborne platform with the objective of mapping snow depth, snow water equivalent, 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.

ASO uses an itres CASI 1500 imaging spectrometer and a Riegl Q1560 airborne laser scanner (ALS-See Fig. 8). The spectrometer retrieves spectral albedo and spectrally-integrated 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 data sets.

Figure 8. ASO King Air platform (top) and lidar and spectrometer instruments (bottom).

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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 50m resolution maps of snow depth, SWE, and snow albedo (e.g. Figure 9). Additionally, aggregated tabular or map products are generated according to stakeholder/partner requirements (e.g. Table 2).

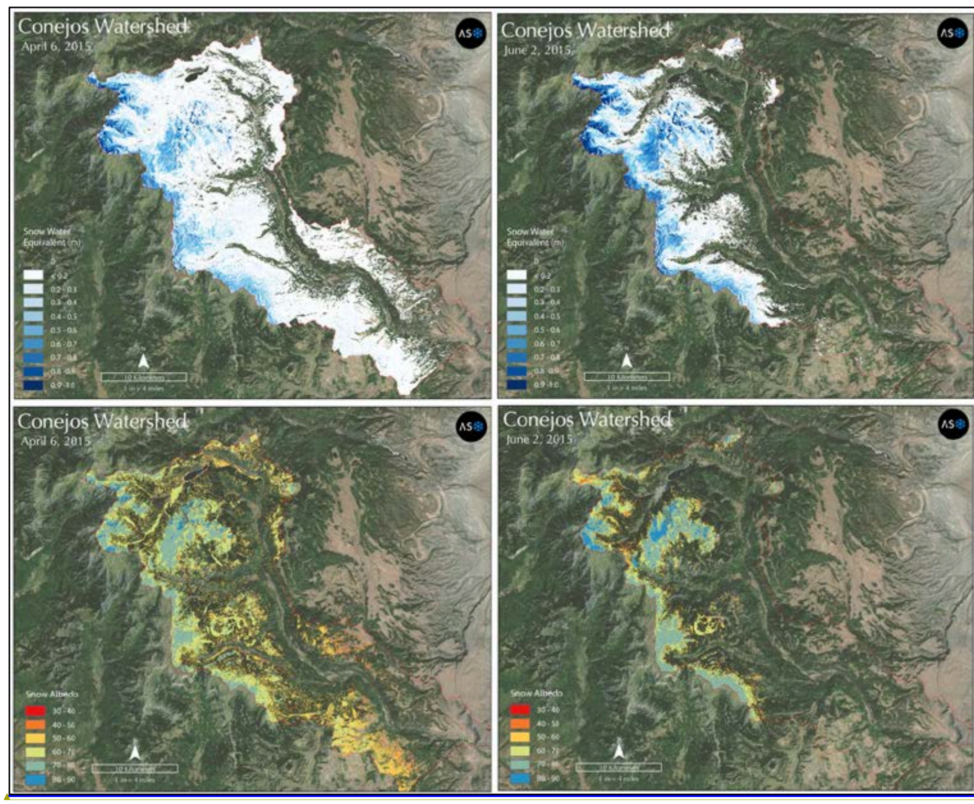

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Figure 9. Maps of Conejos Basin SWE (top row) and snow albedo (bottom row) from 6 April (left column) and 2 June (right column), 2015.

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 data set. The flights covered the entire Conejos River and the mainstem Rio Grande river basins for areas above the San Luis valley floor. (See Fig. 10) 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.

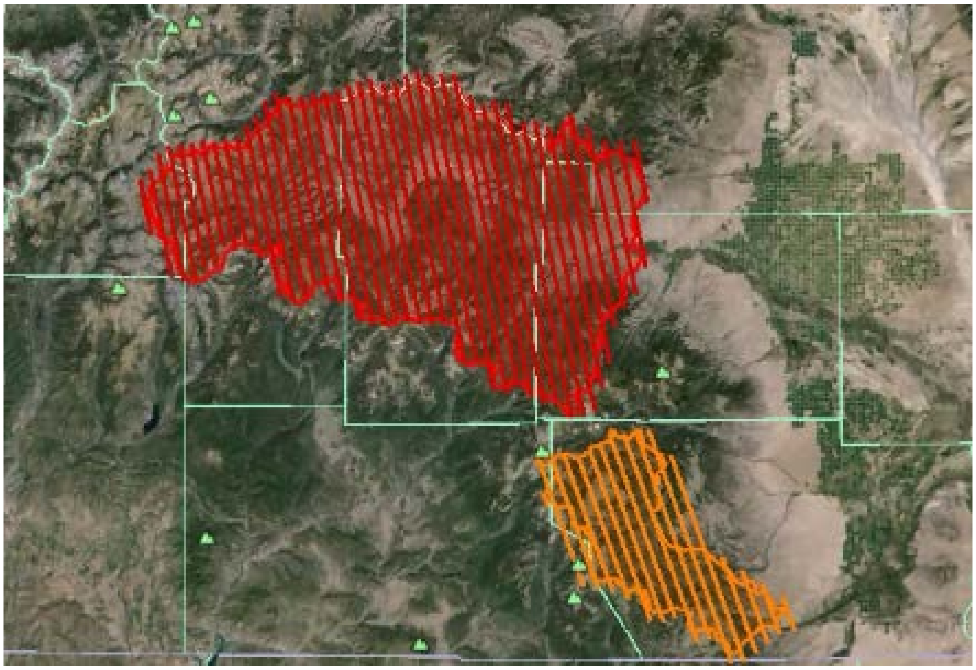


Figure 10. Google Earth image displaying ASO planned flight lines over the Upper Rio Grande (red) and Conejos (orange) basins.

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.

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 snow water equivalent (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 9 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 feet. 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 data set, 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 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.

d. Recommendations

Work on quantifying the value of the ASO snowpack volume and albedo estimates in modeled seasonal water supply forecasts is currently ongoing. However, the initial results strongly suggest that remotely sensed snowpack conditions from ASO and/or similar platforms provides critical information on high-elevation snowpack dynamics, particularly, in late spring and during melt out which are not currently properly observed. 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 data set 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 [D. Gochis, J. Mickey, A. Dugger, L. Karsten]

a. Basic Overview of Ground Validation Strategy

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 11 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 which do not possess restrictions against such installations (e.g. not in 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 in order to measure river stage. The device used was a pressure measurement device 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 and 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 12.

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.

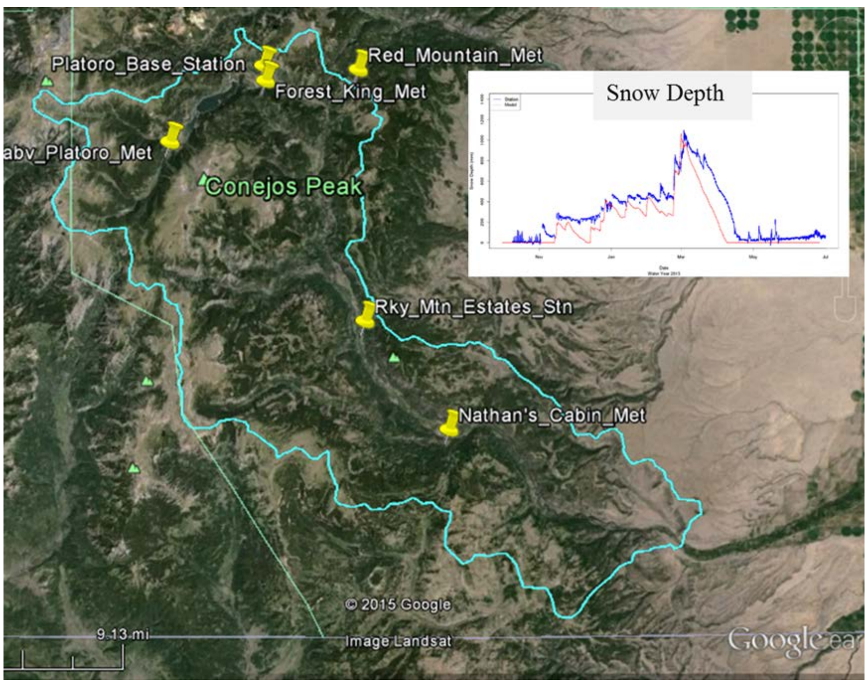


Fig. 11. Map of new in-situ 'SNO-LITE' station locations within the Conejos River Basin that were deployed during the summer of 2014 and continue in operation. Inset graph shows an example modeled (red) versus observed (blue) snow depth from one of the stations in the basin. Modeling system is described in the next section.

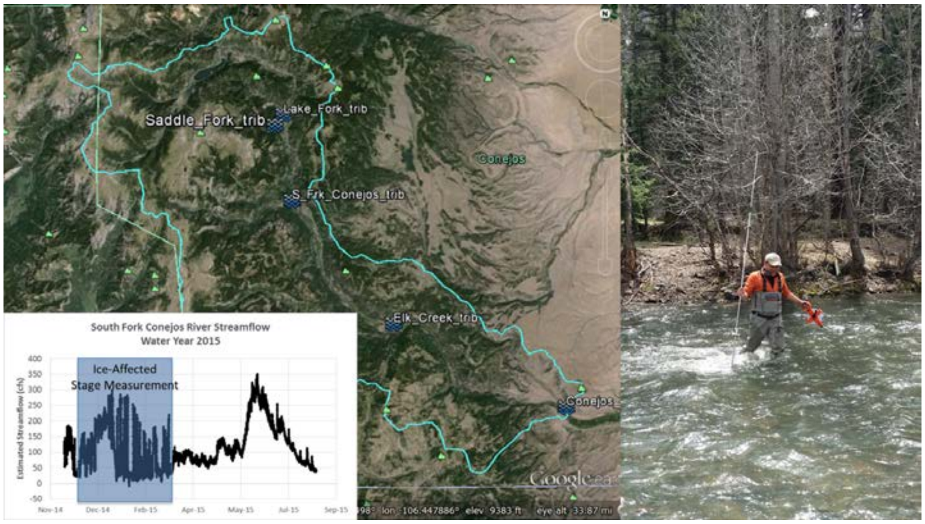


Fig. 12. Map of Water Year 2015 supplemental river stage monitoring locations (blue wave icons-station at basin outlet is the Col. Division of Water Resources operated station at Mogote). Inset graph shows an example of the estimated from the South Fork Conejos tributary site. Inset photo shows CWCB Scientist Joe Busto making manual streamflow measurements at same site.

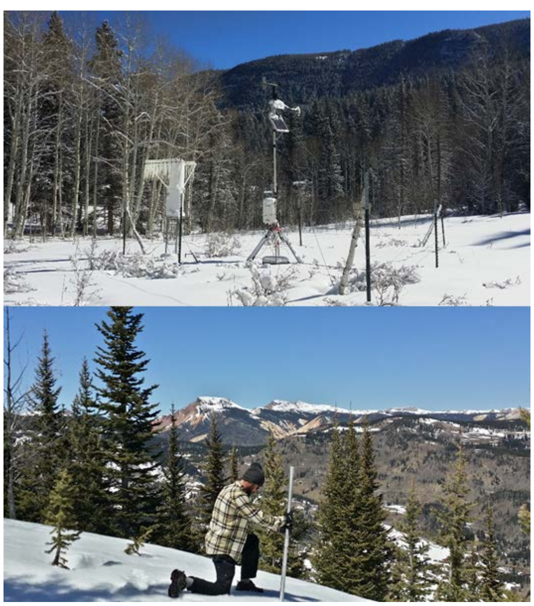


Figure 13. From top, photos of SNO-LITE and river stage monitoring stations. Photo of NCAR technician making manual snow core sample for snow density estimation.

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:

i. 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.
ii. 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.]
iii. Significant errors in other, non-precipitation operational meteorological forcing variables exist which, when un-corrected result in excessive energy inputs into hydrologic model depictions of snowpack, snowmelt and runoff dynamics
iv. Over 40% of the streamflow measured at the Mogote gauging station on the Conejos River originate from previously un-gauged tributaries to the Conejos.

v. The timing of peak streamflow from basin tributaries appears to be fairly well synchronized to within one-week of each other.

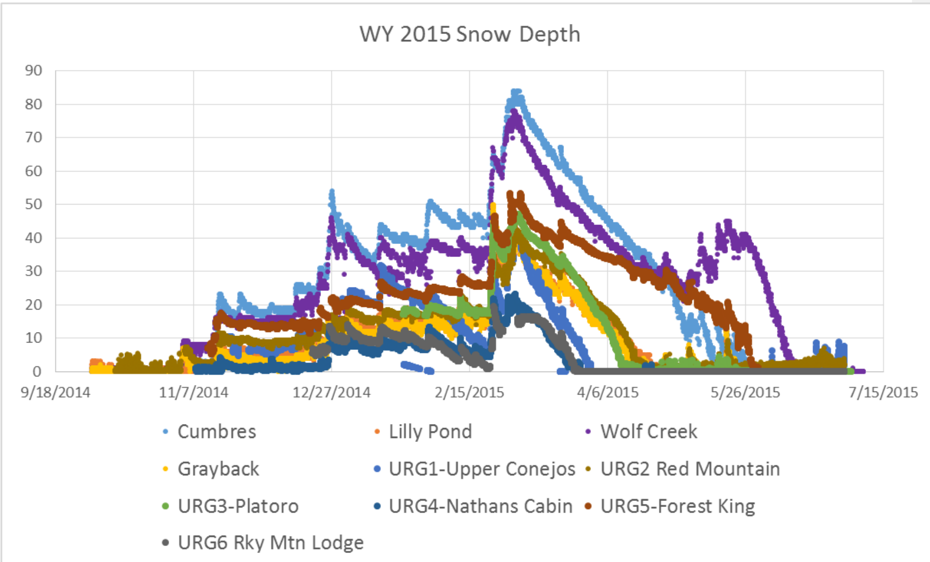


Figure 14. Time series of snow depth as measured by regional SNOTEL stations and project in situ observations. SNOTEL stations 'Wolf Creek' and 'Greyback' are not within or near the Conejos river basin. SNOTEL stations Lilly Pond and Cumbres Trestle are very near the Conejos basin and all project 'URGX' 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 14 shows 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 foot 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 ac-ft of snowpack SWE still on the watershed. 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 feet 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 a lot of variability in the agreement between local observations and national analyses a few consistent features can be summarized. Figure 15 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 largely comes from an over-estimation of daytime maximum temperatures as compared with observations (not shown). Additional biases in NLDAS2 analyzed shortwave radiation (Fig. 16) and relative humidity (not shown) also imply greater energy forcing in the national analysis compared to local in situ observations. Fig. 16 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.

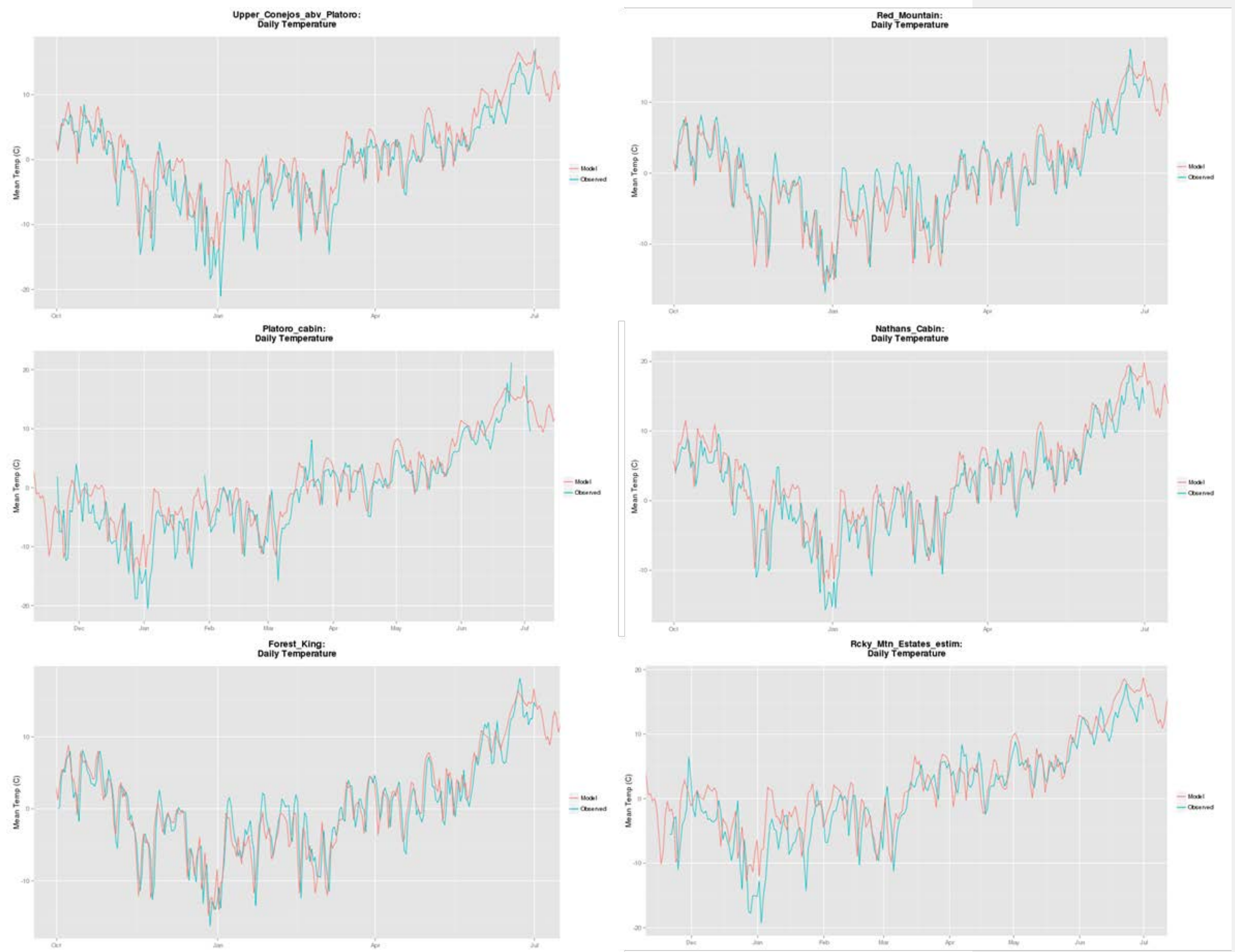


Figure 15. In situ observed (blue) versus NLDAS2 analyzed mean daily temperature (deg C).

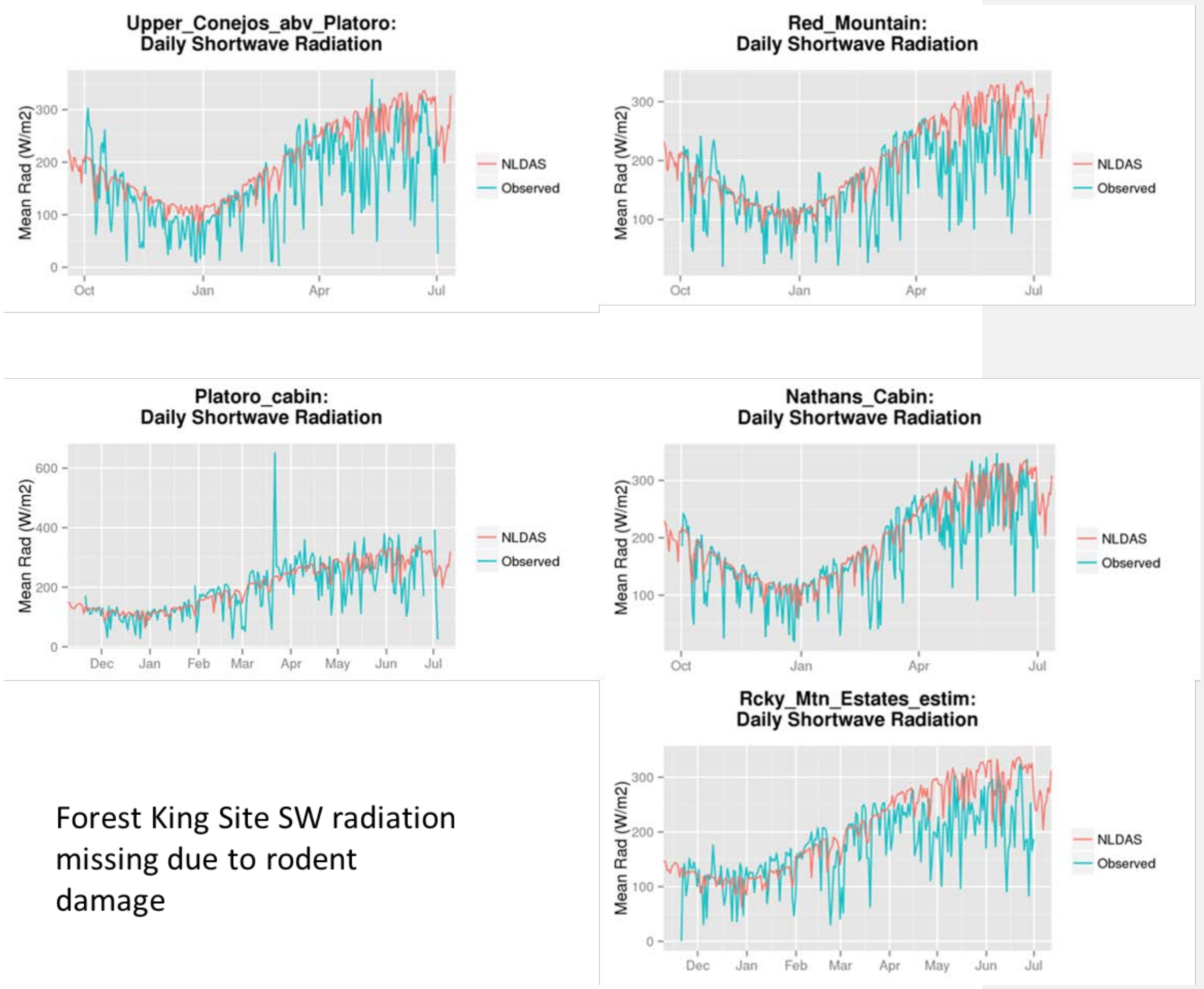


Figure 16. In situ observed (blue) versus NLDAS2 analyzed mean incoming shortwave radiation (W/m^2).

Additional in situ observations of river channel stage were made beginning in the summer of 2014 and 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 17 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 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. Diagnosis of the relationship between observed snowpack and precipitation conditions and river flow in these tributary catchments is ongoing.

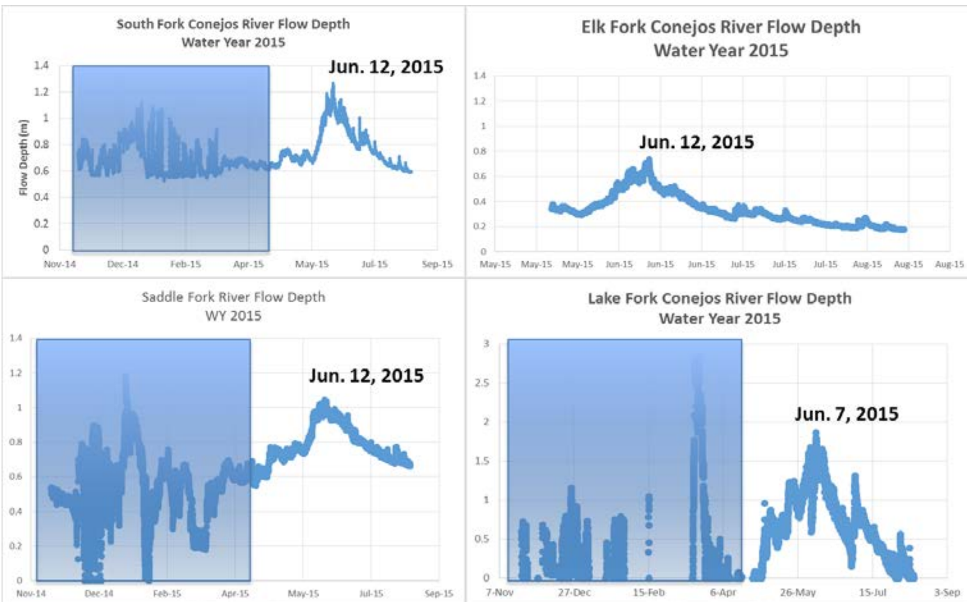


Figure 17. In situ observed river flow depth from previously ungauged tributaries in the Conejos River basin. Shaded blue squares indicate periods of river ice influencing flow depth estimates. Inset date annotations indicate the date of observed peak flow. Rating curves for continuous flow estimation 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 feet). 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 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 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 [D. Gochis, A. Dugger, M. Barlage and L. Karsten]

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 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 has incorporated the use of a new finely resolved hydrological modeling system called 'WRF-Hydro' as its experimental modeling tool. Ongoing work is going to compare results from this model against results from existing operational models which use more traditional modeling approaches. In this section we describe the basic structure of the WRF-Hydro modeling system and then show results from hydrologic simulation experiments which 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 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 get 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 1km snowpack and plant canopy grid and a 100m overland, subsurface and channel routing 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. 18.

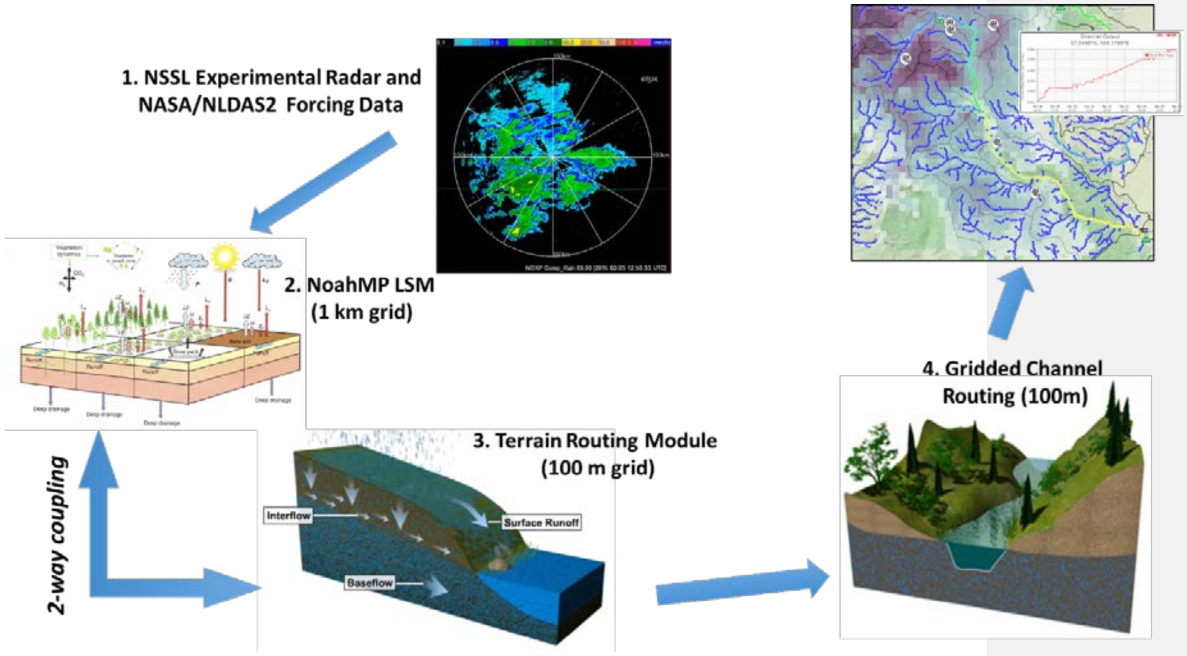


Fig 18. Schematic showing the hydrological process components of the WRF-Hydro modeling system leading to the final production of streamflow simulations (upper right).

The output from this configuration of the WRF-Hydro system includes grids of snowpack (snow depth and snow water equivalent), 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 19.

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 1km WRF-Hydro grid using a topographic downscaling algorithm which accounts for elevation dependent changes in temperature and humidity. 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 was not available the NLDAS2 data was used.

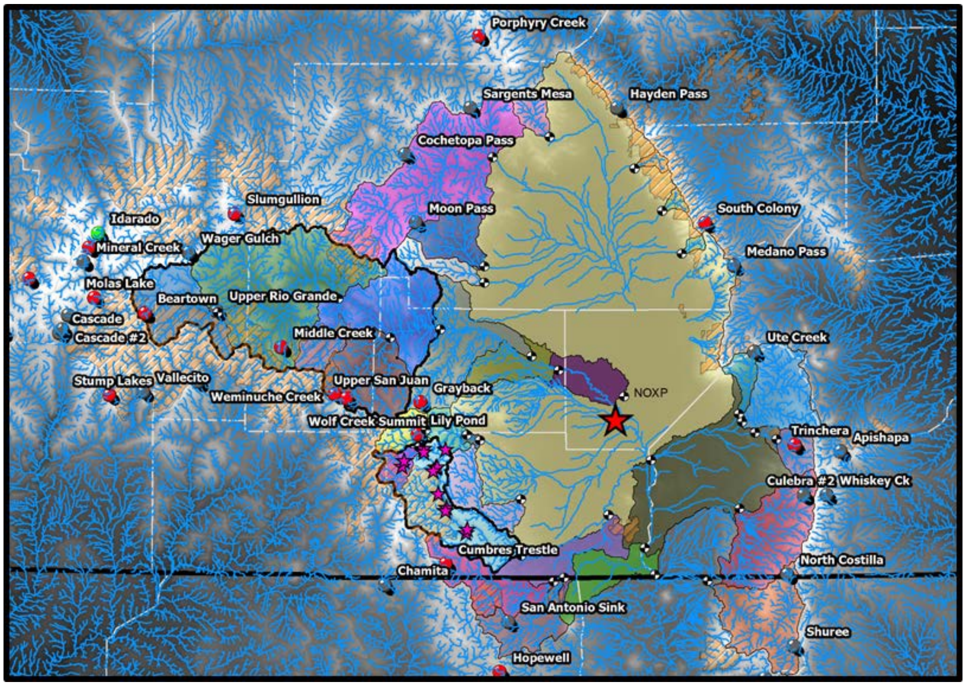


Fig. 19. Map of the modeled channel network from the Upper Rio Grande river basin. Location of NSSL-NOXP radar shown with red star. In-situ ground validation stations within the Conejos basin shown with pink stars. Un-labelled black-white markers denote CODWR streamflow gauging stations. Labelled red, blue and green station sites are NRCS-SNOTEL locations.

b. Hydrological Modeling Operations

The primary goal 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 National Weather Service SNOw Data ASsimilation (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. Colorado Division of Water Resources (CODWR) 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 snow water equivalent analyses
4. NASA ASO LIDAR estimated snow depth and snow water equivalent analyses observed on Apr. 6 and June 2, 2015
5. NRCS SNOTEL station estimates of snow depth and snow water equivalent
6. NASA/MODIS remotely-sensed snow covered area analyses

c. Project Findings

NLDAS2 vs. NSSL NOXP Estimated Precipitation

Comparison of NLDAS2 versus NSSL NOXP precipitation estimates from Dec. 2014 through April 2015 is shown in Fig. 20 while time series plots of basin average precipitation from these two products is provided in Fig. 21. 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 is a couple of region 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 then 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, like the other major basins in this region each showing that 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 suggest that the NOXP product is closer to gauge-observed precipitation in that area. Additional analyses documenting the relative performance of these two precipitation products is ongoing.

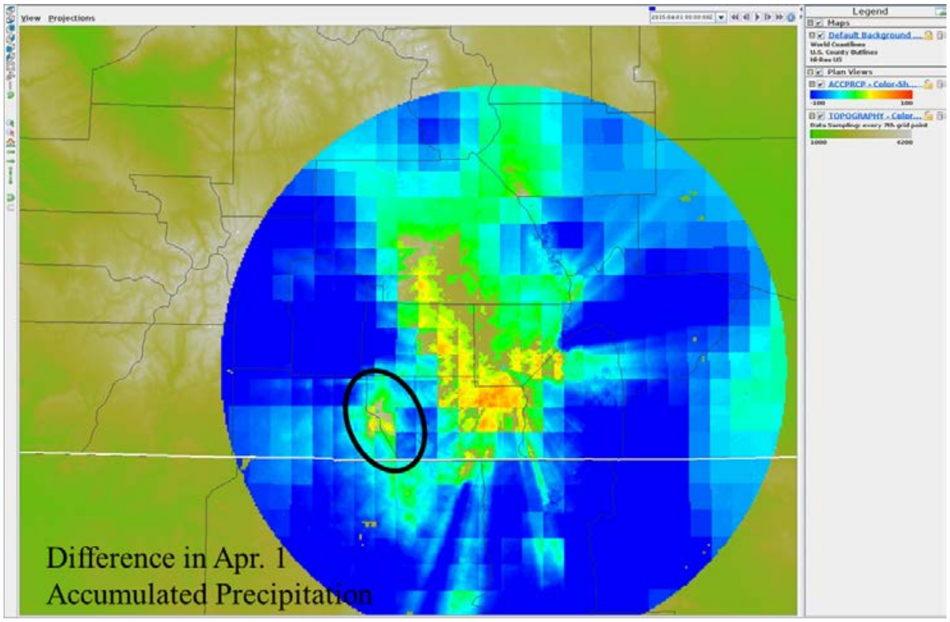


Fig. 20. Map NSSL-NOXP accumulated precipitation minus NLDAS2 precipitation from Dec., 2014 through Apr. 1, 2015. The difference colorscale ranges from -100 (blue) to +100 (red) mm. The range distance of the NSSL NOXP radar precipitation estimate is indicated by the edge of the shaded circle.

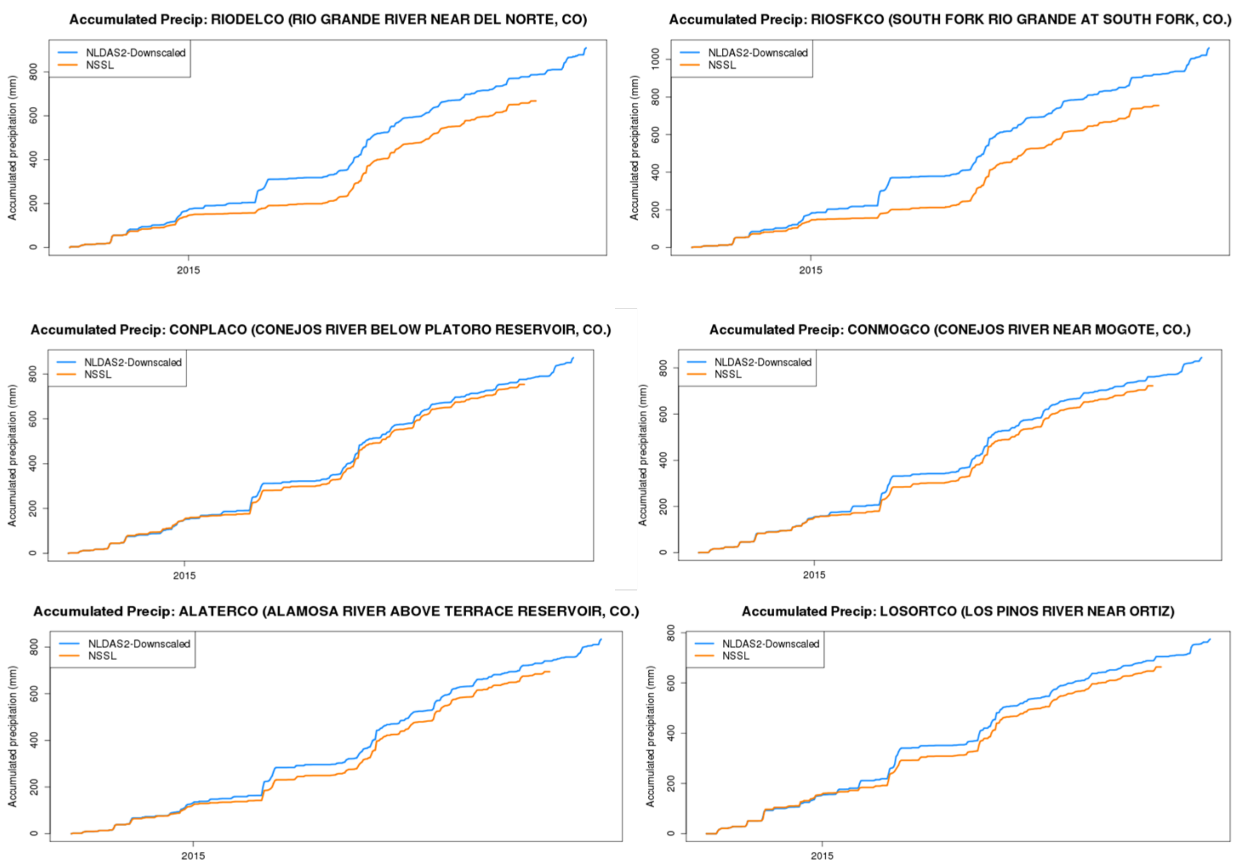


Fig. 21. Time-series plots of basin averaged accumulated precipitation from the NLDAS2 (blue) and NSSL-NOXP (orange) precipitation products for selected basins.

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 2 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 22 and 23. 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 to 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 compared to the April 6 sampling day. 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 compare with the NASA ASO estimate. This latter fact is not surprising since the model does not account for local wind scour and deposition as 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 Comparison - April 6, 2015

Product	Basin Area (sq km)	Snow Covered Area (sq km)	Fraction of Snow Covered Area	Snowpack Volume (ac-ft)	Mean SWE (mm)	Mean Snow Depth (mm)	Max Snow Depth (mm)
ASO	728	516	0.71	60751	150	440	569
WRF-Hydro (NLDAS)	727	663	0.91	112319	207	448	759
WRF-Hydro (NSSL)	727	620	0.85	88337	175	388	741
SNODAS	727	633	0.87	60940	118	369	682

Conejos Basin Comparison - June 2, 2015

Product	Basin Area (sq km)	Snow Covered Area (sq km)	Fraction of Snow Covered Area	Snowpack Volume (ac-ft)	Mean SWE (mm)	Mean Snow Depth (mm)	Max Snow Depth (mm)
ASO	728	261	0.36	66917800	260	610	5320
WRF-Hydro (NLDAS)	727	239	0.33	44459917	184	474	841
WRF-Hydro (NSSL)	727	220	0.30	38538424	175	455	821
SNODAS	727	428	0.59	27295280	62	188	706

Has to be decimal error in snowpack volume above in table for Conejos

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

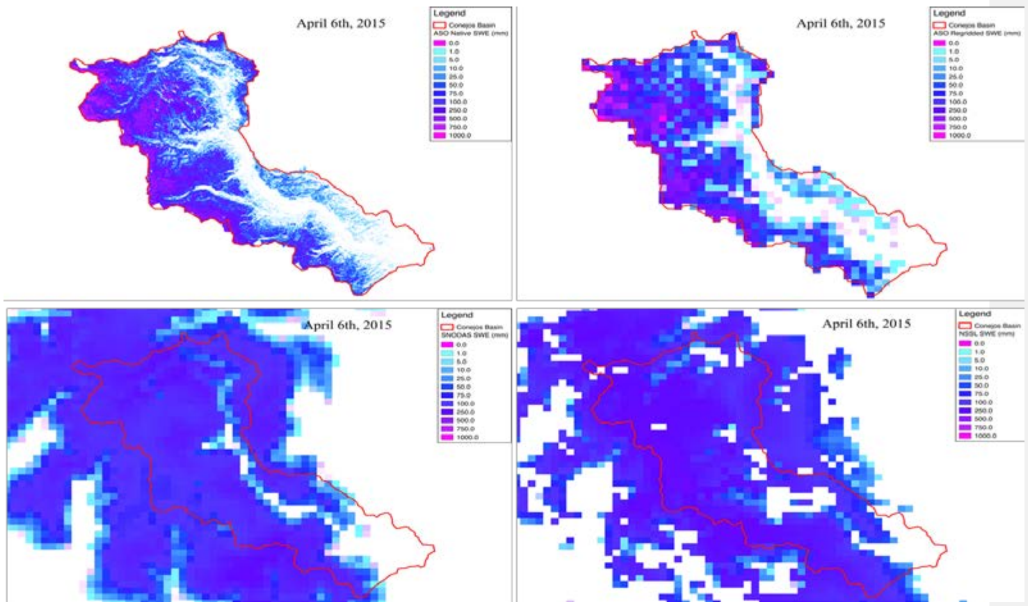


Fig. 22. Comparison of April 6, 2015 snow water equivalent estimates (SWE) from ASO 50m (top left), ASO regridded to 1km (top right), 1km operational SNODAS (lower left), 1km WRF-Hydro driven by NSSL radar precipitation (lower right).

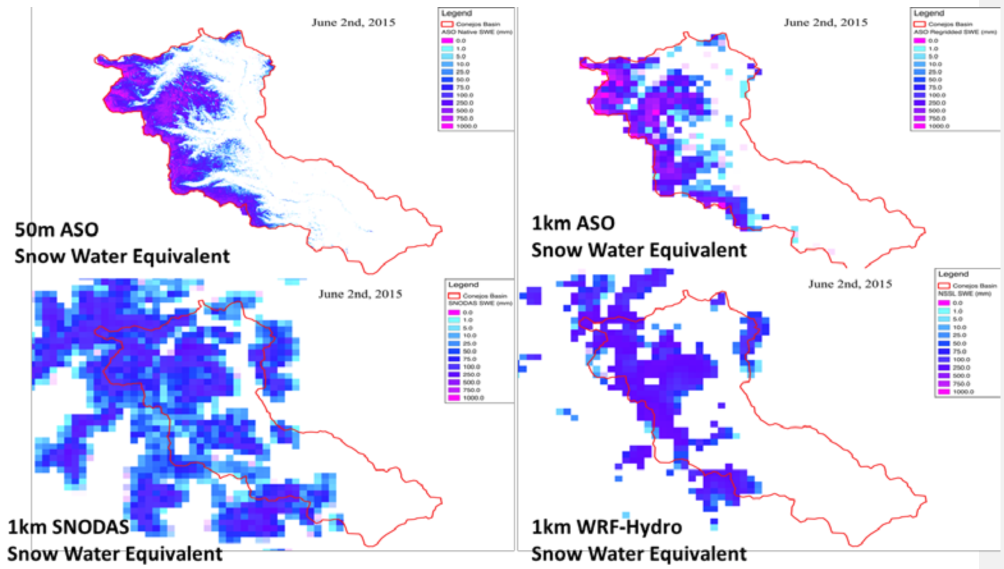


Fig. 23. Comparison of June 2, 2015 snow water equivalent estimates (SWE) from ASO 50m (top left), ASO regridded to 1km (top right), 1km operational SNODAS (lower left), 1km WRF-Hydro driven by NSSL radar precipitation (lower right).

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. 24, 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 CODWR 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. 25 and 26. In general, streamflow correlation values between modeled and CODWR observed values are good for most all areas except the San Luis Valley floor and the northern portion of the Sangre de Cristo Mountains. Streamflow 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 hypothesized to be related to large losses of streamflow to groundwater. The model performance for streamflow bias is very similar to that of 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 as 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.

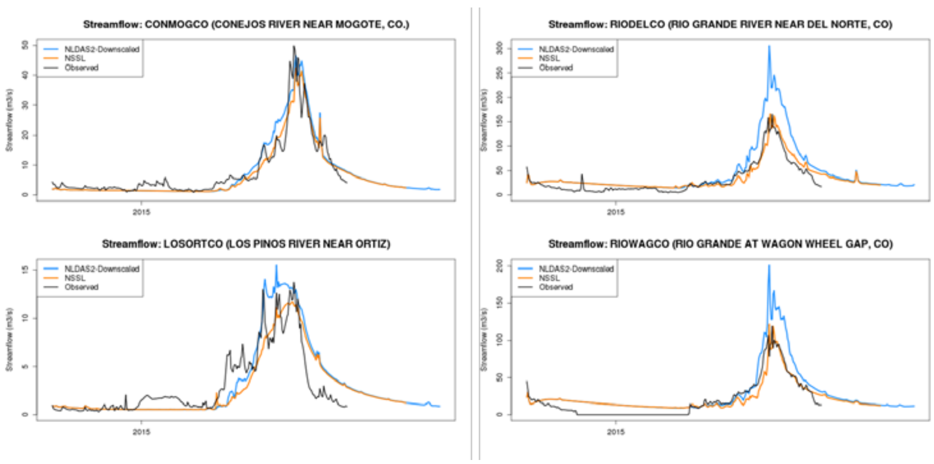


Fig. 24. Modeled and observed (black) daily streamflow hydrographs from the NLDAS2 (blue) and NSSL-NOXP (orange) forced WRF-Hydro model.

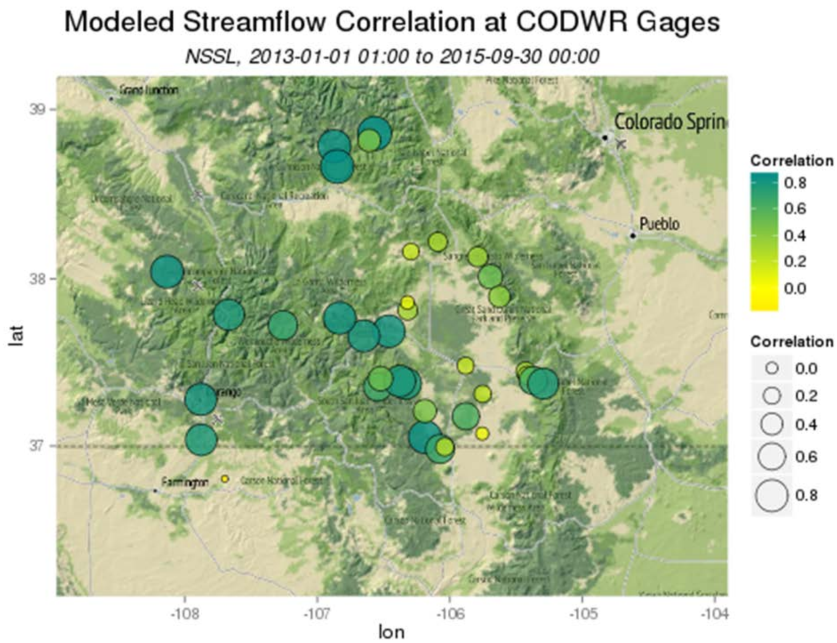


Fig. 25. Mapped values of the correlation between daily streamflow values between the WRF-Hydro model and CODWR streamflow observations. Low correlation values on the San Luis Valley floor are due to water management operations.

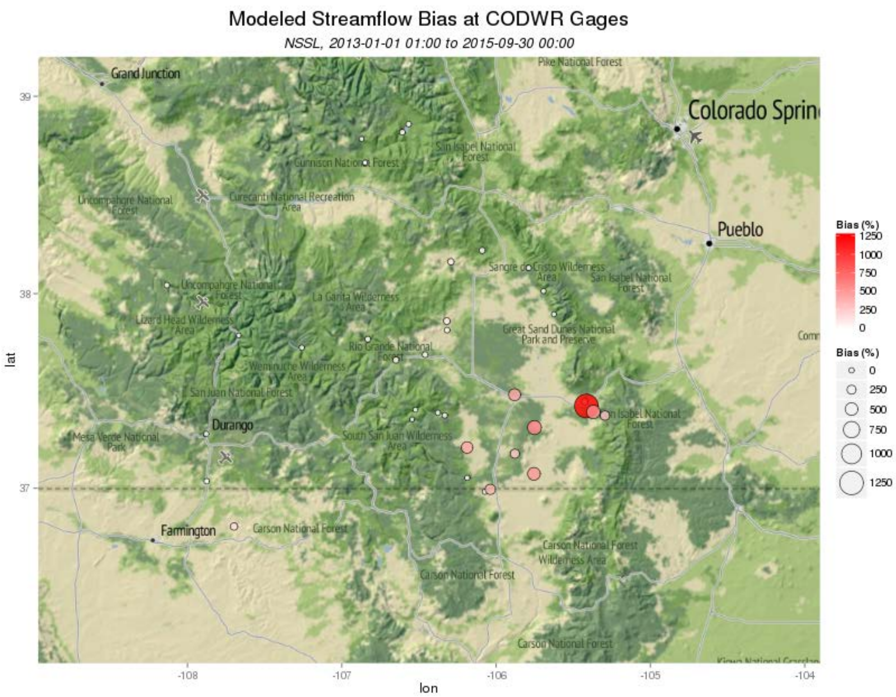


Fig. 26. Mapped values of WRF-Hydro modeled streamflow bias at CODWR stream gauging stations. Large bias values on the San Luis Valley floor are due to water management operations.

Of more 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 at part of Colorado's compliance with the Rio Grande Interstate River Compact Agreement. Fig. 27 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.

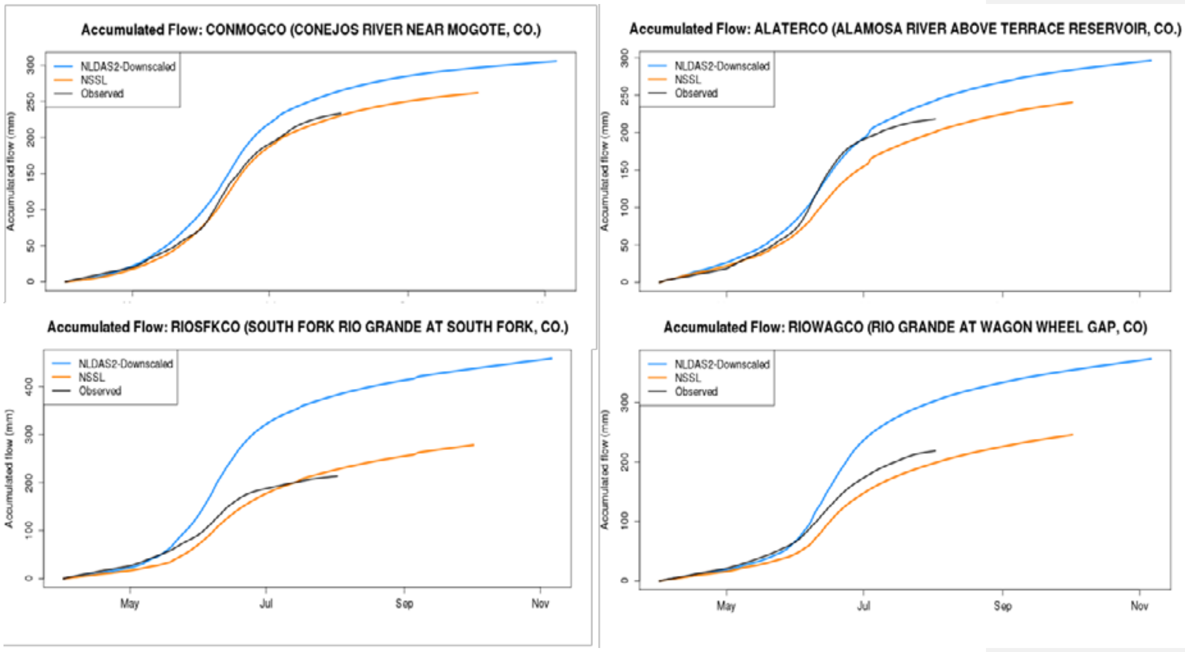


Fig. 27. Modeled and observed (black) daily accumulated streamflow hydrographs from the NLDAS2 (blue) and NSSL-NOXP (orange) forced WRF-Hydro model.

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 as compared to simulations using the NLDAS2 precipitation. As 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. The observation that SNODAS would benefit from radar observations is the same recommendation from the Phase III final report from the CWCB investigation into SNODAS ending in 2009. 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 need to 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. Community Engagement in the Upper Rio Grande Region

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 State 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.

The boundaries of the Conejos Water Conservancy District (the District) include about 100,000 acres, of which 86,000 acres are capable of being irrigated. 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 ground water use and minimizing dependence on ground water 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 $237,000 This numbers is about $237K not $215K remember there was a cherry on top for admin from the Colorado Water Conservation Board.

The District joined with the Division of Water Resources, the Colorado Water Conservation Board, the National Center for Atmospheric Research, the National Weather Service, NRCS and this project’s distinguished team of scientists to conduct a radar-based pilot project. 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. As District Manager Nathan Coombs explained regarding the Water Conservancy’s participation, “We’re the sherpas.”

The benefit for the whole Basin, in addition to improving the State Engineer’s ability to accurately forecast streamflows, was that upon completion of the project some important instruments and data would remain in place as a scientific legacy.

After considering other potential sites, Ken Howard advised deploying the NOXP at the Alamosa Airport, as this location provided the best line-of-sight and height above ground visibility for the Conejos basin and provided an excellent view of the Rio Grande.

Since the scientists of the various agencies were based in Boulder, Colorado; in Norman, Oklahoma; or in other remote locations, it was determined that a local support crew would be needed to operate the NOXP as backup to the project. Without any funds having been allocated for that purpose, the District conducted a fund-raising campaign, contributing

$18,000 of its own and raising donations of $8,250 from various reservoir and ditch companies. Nicole Langley of Transforma Research & Design provided administrative and funding assistance and recruited and coordinated a local "Radar Support Crew."

The District appreciates the 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 to promote the project to the academic community and helped identify those students who were interested in water and earth sciences and who were willing to be a part of such a high profile hydro-met test project. Those who were contracted (at $10/hour plus mileage) to provide this backup support at the NOXP were Stefan Armenta, Darrell Cordova, Kate Schultz, Wayne Schwab, Amanda Snow, and Larry Sveum.

Over the course of the 2014-2015 winter season, despite demanding circumstances, long dark nights and often bitterly cold conditions, the Radar Support Crew demonstrated a high level of 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, often covering for students if they were too busy 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 to the local Crew.

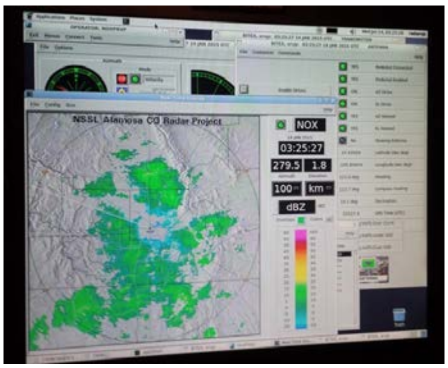
On April 7, 2015 the District welcomed NASA's JPL Airborne Snow Observatory (ASO) team, who provided a public tour of their airplane/observatory.

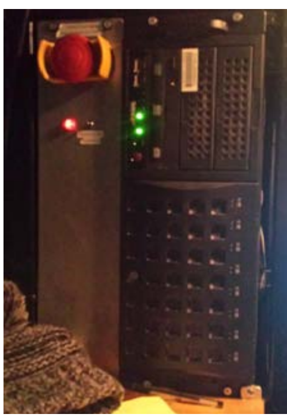
At that evening's dinner for those involved in the winter hydro-met study, Joe Busto presented a slide show by Dr. Thomas H. Painter explaining the methods and the objectives of the ASO team -- to accurately measure the water content of the Rio Grande Basin's mountain snowpack, thus improving snowmelt forecasts as the melt season progresses.

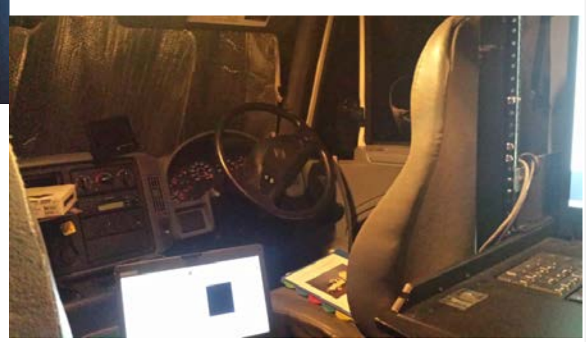
He explained how ASO's frequent flyover observations and LIDAR technology provide data which are otherwise impossible to obtain about the timing and changes in runoff, thus enabling the State Engineer to more accurately forecast stream flows in the Upper Rio Grande Basin.


(photo: Jose Meitin)

Amanda Snow sent some photos of the interior of the NOXP. The only interaction the Crew had with each other was when one relieved another's shift, so these are the only pics available.







Megan Richardson – JPL/ASO

Nathan Coombs, Manager,

Conejos Water Conservancy District