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Observed Changes in Climate and Streamflow in the Upper Rio Grande Basin

Shaleene Chavarria
University of New Mexico

Shaleene Chavarria
Candidate

Earth and Planetary Sciences
Department

This thesis is approved, and it is acceptable in quality and form for publication:

Approved by the Thesis Committee:

Dr. David Gutzler , Chairperson

Dr. Grant Meyer

Dr. Peter Fawcett

Dagmar Llewellyn, M.S.

**OBSERVED CHANGES IN CLIMATE AND STREAMFLOW
IN THE UPPER RIO GRANDE BASIN**

by

SHALEENE CHAVARRIA

**B.S., ENVIRONMENTAL SCIENCE
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ABSTRACT

Observed streamflow and climate data are used to test the hypothesis that climate change is already affecting the streamflow volume derived from snow accumulation in ways consistent with climate model-based projections of 21st century streamflow. Annual and monthly changes in streamflow volume and surface climate variables on the upper Rio Grande (URG) near its headwaters in southern Colorado are assessed for water years 1958-2015. Trends in discharge are examined together with variations in snow water equivalent and surface climate variables. Results indicate that temperatures in the basin have increased significantly primarily in the winter and spring seasons, April 1 snow water equivalent has decreased by approximately 25%, and streamflow has declined in the runoff season, but small increases in precipitation have reduced the impact of declining snowpack on streamflow. Changes in the snowpack-runoff relationship are noticeable in hydrographs of mean monthly streamflow, but most apparent in the changing ratio of precipitation (rain+snow, and snow water equivalent) to streamflow and in regression statistics. The observed changes impact our ability to predict streamflow on a seasonal basis and affect long-term water management of the Rio Grande.

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1. INTRODUCTION

Climate in southwestern North America (SWNA) is changing in ways that are projected to have significant impacts on water availability and water management in the Rio Grande basin. Streamflow is primarily driven by spring snowmelt that results from snow accumulation in the southern mountains of Colorado, and is a vital surface water supply in three southwestern states and northern Mexico (Rango, 2006). A decreasing trend in spring snow extent and snow depth in the western U.S. has been linked to warmer temperatures (Mote et al., 2005), with shifts toward earlier spring streamflow (Cayan et al., 2001; Stewart, 2009), and more precipitation falling as rain rather than snow (Knowles, 2006; Barnett et al. 2008). Hydrologic model projections of 21st century streamflow suggest that the southwestern U.S. will see an overall decrease in water availability, changes in the timing of snowmelt runoff, and increased variability in flows mainly due to increased temperatures (Hurd and Coonrod, 2012; Llewellyn and Vaddey, 2013; Elias et al., 2015). The projected changes have serious social, economic, and ecological implications for users reliant on Rio Grande water.

Although springtime temperatures in SWNA have been increasing, the impact that warming has had on snowmelt runoff in the headwaters region of the Rio Grande is not readily apparent. Furthermore, characterizing changes in climate and streamflow is essential for short-term seasonal streamflow forecasting, and is relevant for validating or improving model projections of streamflow in the Rio Grande basin for long-term water management.

This study examines the snowpack-runoff relationship in the upper Rio Grande basin (URG), testing the hypothesis that climate change is already affecting the streamflow volume derived from snow accumulation in ways consistent with climate model projections of 21st century streamflow. We assess annual and monthly changes in climate variables and streamflow volume on the upper Rio Grande near its headwaters in southern Colorado for water years 1958-2015. Trends and interannual variability in streamflow are examined together with variations in snow water equivalent and surface climate variables to determine if the relationship among variables is changing.

The goal of this study is to determine if observed climate change is impacting spring runoff that is primarily derived from winter snow accumulation. The results of two studies on the effects of climate change on streamflow in the Rio Grande basin were used to determine whether results in this study were consistent with model projections of streamflow.

In the first study, Hurd and Coonrod (2012) developed a hydro-economic model to investigate changes in water supply and demand that may result from climate change in the Rio Grande basin. Projected monthly temperature and precipitation (not statistically downscaled) from three selected global circulation models (GCM) in the suite of Coupled Model Intercomparison Project Phase 3 (CMIP3) models (Meehl et al., 2007) were used to drive the WATBAL rainfall runoff model and generate monthly streamflow projections for two future time periods (2020-2039 & 2070-2089) and three future scenarios (‘warm and wet’, ‘middle of the pack’, and ‘hot and dry’). In all scenarios temperature increases, especially in the runoff season. Precipitation increases in the summer season in the warm and wet scenario. Average monthly streamflow projections show decreasing runoff season flow as early as 2030, and shifts toward earlier runoff season flow by 2080 under all scenarios. Notably, discharge in the 'warm and wet' scenario decreases despite increasing precipitation.

The second study is part of the Bureau of Reclamation's West-Wide Climate Risk Assessment (WWCRA), where an evaluation of the risk posed by climate change to water supplies in river basins of the western U.S. has been undertaken since 2011 (Reclamation, 2011). Streamflow projections in the 2013 Upper Rio Grande Impact Assessment, part of the WWCRA, were based on CMIP3 model projections of temperature and precipitation (Llewellyn and Vaddey, 2013). The most recent set of WWCRA hydroclimate projections for the URG are based on CMIP5 model projections (Reclamation, 2016). The results in this study are primarily compared to streamflow and snow water equivalent projections based on the most recent 2016 set of projections.

The 2016 WWCRA uses an ensemble median of statistically downscaled daily temperature and precipitation projections, from GCMs in the CMIP5 model ensemble (Taylor et al., 2012), to drive the Variable Infiltration Capacity (VIC) hydrologic model, and produce monthly hydroclimate projections for the URG through the 21st century. Results from two future time periods, the 2020s decade (WY 2020-2029) and 2050s decade (WY 2050-2059), show small increases in median precipitation in both periods in the high elevations of the basin relative to the 1990 baseline median (WY 1990-1999), and large continued increases in temperature. In the 2020s decade, the greatest projected percentage decrease in April snow water equivalent (SWE) occurs at mid-elevations; results show a 20-40% decrease in SWE at elevations lower than 2700 m and up to a 20 % decrease in SWE at elevations between 2700-3048 m. By the end of the 2050s decade, elevations below 3353 m may see a 10-70% decrease in median SWE relative to the

1990s median baseline, with the greatest decrease in SWE at the loweer elevations. Streamflow projections for Rio Grande near Lobatos (Fig. 1) show an increase in April-June median runoff season flow in the 2020s decade with very little change in July-September flow. By the end of the 2050s decade April-July flow has decreased, the runoff season peak has flattened out, and a visible shift toward earlier peak flow has occurred relative to 1990s median baseline.

Despite the differences in methods used to produce streamflow projections, the results from both Hurd and Coonrod (2012) and the Reclamation assessments imply that even if precipitation in the basin increases, it will likely not be enough to offset streamflow losses that will result from diminished snowpack and increased evapotranspiration rates. This conclusion is similar to those reached by studies of other southwestern river basins such as the Colorado (Vano et al., 2014). The changing relationship between snowpack and streamflow also has implications for water management in the current climate. Because snowpack provides a major source of seasonal streamflow predictability (Garen, 1992), short-term water management decisions based on seasonal streamflow forecasts will be impacted by modifications to the snowpack-runoff relationship, if climate change in SWNA continues as projected.

The next section provides an overview of the URG and hydroclimatic variability of the southwestern U.S. This is followed by a presentation of data sources and methods used to assess the snowpack-runoff relationship in the URG. Notable findings of changes in surface climate variables and streamflow are summarized and discussed in relation to previous studies and streamflow projections, followed by implications for short-term and long-term Rio Grande water management.

2. BACKGROUND

a. URG basin

The Rio Grande (henceforth RG) originates in the San Juan Mountains of southern Colorado and flows south through New Mexico, along the Texas border with Mexico, and ultimately to the Gulf of Mexico. The Upper Rio Grande basin, as defined here and shown in Figure 1, is located in southern Colorado. The area of interest extends from the headwaters to the USGS stream gage RG near Lobatos, encompassing approximately 19,800 km^2.

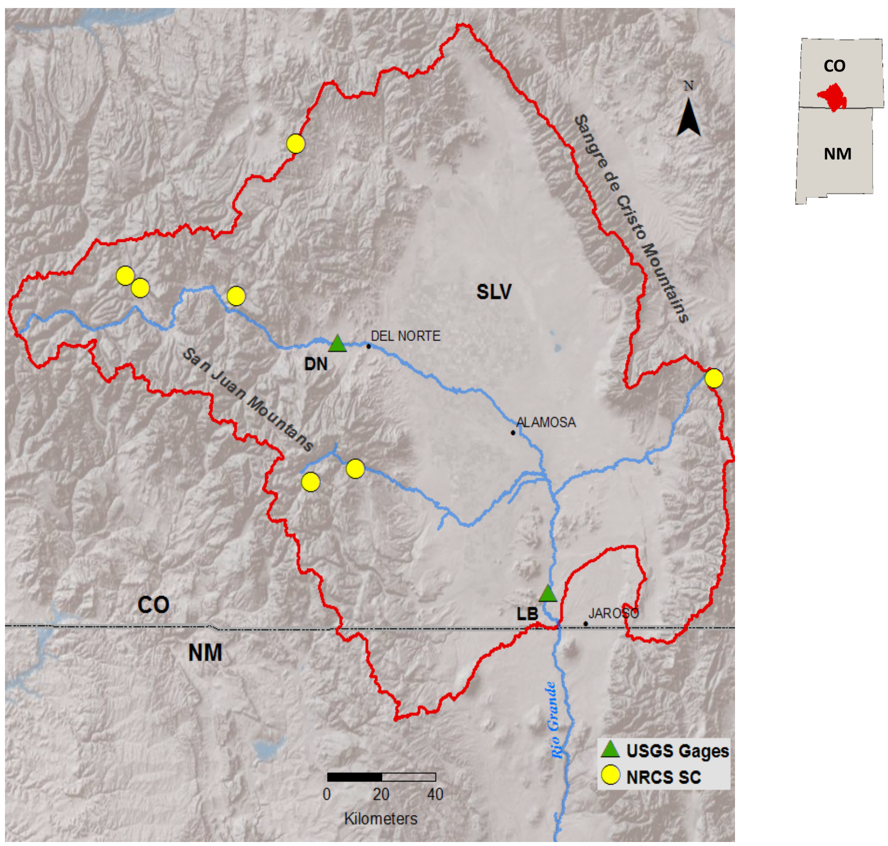


Figure 1. Upper Rio Grande basin defined in this study is shown by the red boundary line, which spans the headwaters west of the Rio Grande near the Del Norte stream gage (DN), to the Rio Grande near Lobatos gaging station (LB). Green triangles show locations of stream gages and yellow circles denote the seven snow course sites used to generate SWE indices.

A major portion of runoff originates as snow in the San Juan Mountains west of the San Luis Valley (SLV in Fig. 1), and in the Sangre de Cristo Mountains to the east. The SLV receives less than 26 cm of precipitation per year and the San Juan Mountains receive between 100-152 cm of precipitation per year; mean annual temperatures range between 5 and 7 °C with a very pronounced seasonal cycle, and nearly sixty-five percent of the native flow to the RG is generated in the headwaters region (Mix et al., 2012; Llewellyn and Vaddey, 2013).

Water diverted from the river in the SLV is primarily used for agricultural irrigation, with approximately 2,400 km^2 of land being cultivated (Mix et al., 2012). The RG Compact constrains interstate water distribution among the states of Colorado, New Mexico, and Texas, and a 1906 treaty allocates a portion of RG water to Mexico (Mix et al., 2012). Several anthropogenic factors, including compact regulation, agricultural diversions, land use changes and groundwater pumping in the SLV complicate climate and streamflow-related studies, and anthropogenic effects on RG streamflow become greater downstream.

b. Hydroclimatic variability

In the southwestern U.S., interannual and longterm natural climate variability strongly influence water availability (Gutzler, 2012). Climate reconstructions of the western U.S. (Cook et al., 2004) and portions of the southwest, including the Rio Grande Basin (Woodhouse et al., 2010, 2013) show pronounced multidecadal fluctuations in precipitation and streamflow for several time periods as far back as AD 900. Extended periods of drought between AD 900 and 1300, and in the 20th century (1930's and 1950's) coincide with warm temperatures and decreased precipitation (Woodhouse et al., 2010). Less arid conditions after 1300 to about the early 20th century indicate times of increased precipitation (Cook et al., 2004).

Drought and pluvial periods are further influenced by interannual climate fluctuations linked to atmospheric teleconnections. Natural variability in precipitation occurring in winter and early spring is highly influenced by the El Niño Southern Oscillation (ENSO) (Molles and Dahm, 1990; Seager et al, 2005 a,b). ENSO refers to the coupled phenomenon that includes fluctuations in sea surface temperatures (El Niño/La Niña) and sea level barometric pressure (Southern Oscillation) in the equatorial Pacific (NOAA, 2016). El Niño, the warm phase of the ENSO cycle, is characterized by increased sea surface temperatures and decreased barometric pressure in the central Pacific that force (via teleconnections) shifting storm tracks and increased storm generation in southwestern North America; La Niña, the cool phase, can create conditions opposite to El Niño which shift the jet stream northward changing the trajectory of winter storms away from the southwest (Molles and Dahm, 1990). Studies indicate that El Niño is associated with increased winter-spring precipitation and streamflow across the southwest, and that La Niña can escalate drought conditions (Molles and Dahm, 1990; Clark et al., 2001).

In addition to ENSO influences, longer-term natural variability in the Pacific Ocean can affect drought and wet periods on decadal timescales. The Pacific Decadal Oscillation (PDO) is known to exhibit two extreme phases, the cool (-) phase and the warm (+) phase, which are identified by SST anomalies in the northeast and tropical Pacific Ocean (Mantua et al., 1997). Drought and SST reconstruction using climate proxies indicate that decadal variability of Pacific SST played a role in prehistoric megadroughts that affected western North America (Seager et al., 2005b; Cook et al., 2007). Additional evidence suggests that wintertime ENSO impact is significantly enhanced when the positive phase of the PDO and warm ENSO phase coincide, and when the negative phase of the PDO coincides with the cool ENSO phase; predictability diminishes when the ENSO and PDO phases are not synchronized (i.e. (-) PDO and warm ENSO, (+) PDO and cool ENSO) (Gershunov and Barnett, 1998; Gutzler et al., 2002).

Anthropogenic climate change is now superimposed on the natural variability described above. Natural variability is most pronounced in precipitation patterns produced by shifting storm tracks tied to oceanic-atmospheric interactions (ENSO, PDO). The biggest signal in ongoing and projected climate change in SWNA is observable in the continued increase in temperatures (Gutzler and Robbins, 2010).

3. DATA SOURCES AND METHODS

a. Streamflow

Daily mean discharge data from gages on the RG near Del Norte (08220000) and RG near Lobatos (08251500) (see Fig. 1) were taken from the U.S. Geological Survey's National Water Information System (https://waterdata.usgs.gov/nwis). The Water Data Report (2013) for RG near Del Norte indicates that in general discharge measurements are good, meaning that recorded discharge values fall within 10 percent of the true value. Discharge values recorded between November and early December are fair or within 15 percent of true value, and estimated discharge values are poor or less than 15 percent accuracy. Discharge records for RG near Lobatos are good, except for estimated measurements, which are poor. Of the 21,184 daily mean discharge values used to compute monthly values for water years (WY) 1958-2015 for each site, fewer than 10 percent of the measurements were estimated (2086 for RG Del Norte, 1867 for RG Lobatos).

Monthly naturalized or "adjusted" streamflow values for the RG near Del Norte were obtained from the U.S Natural Resources Conservation Service (NRCS) National Water and Climate Center report generator (https://wcc.sc.egov.usda.gov/reportGenerator/) for months included in WY 1958-2015. Naturalized flows represent the volume of streamflow that would occur in the absence of diversions or reservoirs upstream of a discharge point (NRCS, 2016). Adjustments to streamflow are made by removing anthropogenic effects from recorded historical flows (Nowak et al., 2012). The NRCS computes naturalized flow for some streamflow forecast points including RG near Del Norte, and sites with adjusted streamflow volumes are denoted in basin data reports. Naturalized flows were primarily used to determine the extent of anthropogenic influence on observed flows at the RG near Del Norte and Lobatos gages.

b. Temperature and Precipitation

Monthly mean temperature and monthly total precipitation (combination of both rain and snow) for Colorado climate division 5 (CO5) were used in the analysis. Climate divisional data from the National Ocean and Atmospheric Administration (NCDC-National Climatic Data Center), for CO5 which delineates the URG, were obtained from the Western Regional Climate Center database (http://www.wrcc.dri.edu/spi/divplot1map.html). Climate divisional values were recently revised using area-weighted averages, based on 5 km grid resolution estimates, interpolated from station data (Vose et al., 2014).

c. Snowpack

Snowpack data were obtained from the NRCS (https://www.wcc.nrcs.usda-.gov/snow/) for the years 1951 through 2015. Monthly snow course measurements of snow water equivalent (SWE) for seven sites within the NRCS-defined URG (see Fig. 1), were used to create indices representative of March, April, and May basin wide SWE. The seven sites were selected based on the length and continuity of records for each month, with measurements made on or close to the first day of each month for selected sites (Serreze, 1999). Four of the seven sites are in watersheds that drain into the RG above the Del Norte stream gage; the other three sites are in watersheds that drain into the RG above the Lobatos gage (Table 1; Fig. 1).

Table 1. Snow course sites in the URG used in EOF analysis to create SWE indices.

Station	Cochetopa Pass †	Porcupine †	Pool Table Mountain †	Santa Maria†	Silver Lakes*	Platoro*	La Veta Pass*
Elevation (m)	3048	3133	2999	2926	2896	3011	2877
Latitude (deg)	38.2	37.9	37.8	37.8	37.4	37.4	37.6
Longitude (deg)	-106.6	-107.2	-106.8	-107.1	-106.4	-106.6	-105.2
Missing data	2015 (Mar)	1963 (Mar)	none	none	1965 (Mar)	1952, 1960 1961,1963 (Mar)	1978 (May)

† Drain into the Rio Grande above the Del Norte gage
* Drain into the Rio Grande above the Lobatos gage

We chose to use snow course measurements rather than SNOTEL data due to the longer length of the snow course records. SNOTEL data for the URG begins in the mid-1980s or later for most sites. The variability in a 1997-2015 SNOTEL sample set was compared to the variability in monthly indices created from snow course data (Fig. 2). The comparison shows that the variability in snow course data and SNOTEL data is similar, but SWE values recorded at SNOTEL sites are larger than snow course values in any given month. Greater SWE values at SNOTEL sites are expected because SNOTEL sites are typically located at higher elevations than snow course sites.

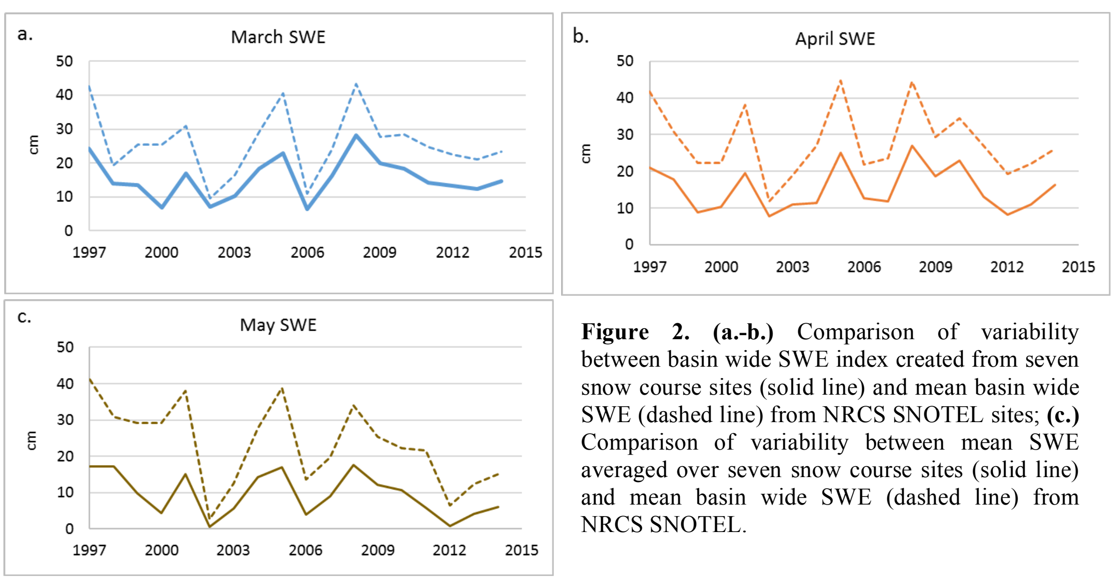


Figure 2. (a.-b.) Comparison of variability between basin wide SWE index created from seven snow course sites (solid line) and mean basin wide SWE (dashed line) from NRCS SNOTEL sites; **(c.)** Comparison of variability between mean SWE averaged over seven snow course sites (solid line) and mean basin wide SWE (dashed line) from NRCS SNOTEL.

d. Methods

Historical hydrologic and climate parameters were examined on a water year (1958-2015) and monthly basis, focusing on the snow accumulation and runoff seasons. The water year referred to throughout this report begins October 1 of any given calendar year and ends September 30 of the next year. For example, WY 1980 begins October 1, 1979 and ends September 30,1980. Spring runoff and spring precipitation are defined respectively as the sum of monthly April-July streamflow volume, and the sum of monthly April-July precipitation. Winter precipitation is defined as the sum of monthly December-March precipitation, and winter temperature is the mean December-March monthly temperature. SWE indices for a specific month represent the integrated snow accumulation and ablation processes from preceding months of the snow season, with April 1 considered to represent the climatological peak of snow accumulation season (Stewart, 2009).

Mean daily discharge values, in cubic feet per second (cfs), were combined into monthly values and converted into volumetric units of millions of cubic meters (Mm^3). Monthly streamflow values for the RG near Del Norte were compared to monthly naturalized flow values at the same site. Since gaged flow and naturalized flow were nearly identical (Fig. 3), the analysis of streamflow primarily focused on gaged flows at the Del Norte during the runoff season. This study only briefly addresses flows at RG near Lobatos because naturalized flow data are not readily available for the gage, and the river reach downstream from RG near Del Norte is significantly affected by agricultural diversions and flows reaching the RG near Lobatos gage are subject to RG Compact regulation (Mix et al., 2012).

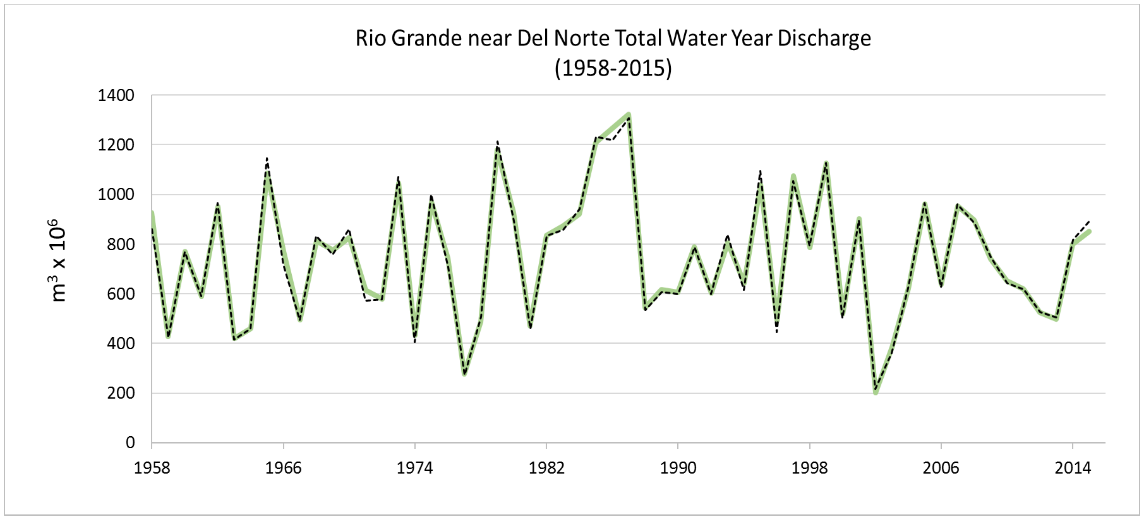


Figure 3. Gaged water year flow from the USGS (green) and naturalized flow from the NRCS (dashed) for the Rio Grande at Del Norte, for WY 1958-2015.

Empirical orthogonal function (EOF) analysis was used to produce a single basin-wide index of URG SWE interannual variability for March 1 and April 1. Eigenvectors and eigenvalues were computed from the interannual covariance matrix of SWE anomalies at the seven sites for each calendar month. A square root transformation was applied to SWE values to reduce the skewness of the data. For sites that contained a missing SWE value in a particular month (Table 1), the entire year for all seven sites was removed before the anomaly matrix was computed. The month of March contained six years of missing SWE observations, April had all years of data observations, and May was missing one year of data. The first eigenvalues computed for 1 March [E1M] and 1 April [E1A] account for 76.8% and 77.3% of the interannual SWE variability, respectively, indicating that interannual fluctuations in SWE are highly correlated across the watershed.

The eigenvectors corresponding to E1M and E1A were used to create a linear combination of snow course SWE values for each year. First, missing SWE anomalies for a specific site and year were computed by multiplying the average normalized anomaly by the standard deviation for that site. The anomalies for the seven sites for each year were then multiplied by the coefficients corresponding to the first eigenvalue for a specific month. The mean was added to each value in the previous step and each of the values was squared to reverse the square root transform performed in the initial steps. With the values obtained, a variance-normalized SWE index for 1 March and 1 April was generated for each year from 1958-2015.

A straightforward arithmetic mean of SWE at the seven sites was used as the annual index for May 1 SWE because the data were highly skewed toward low values and could not be rectified by the square root transformation used for March and April SWE indices. Analysis of variance (ANOVA) was used to test the significance of trends in SWE for March, April, and May against the null hypothesis of zero trend in SWE values.

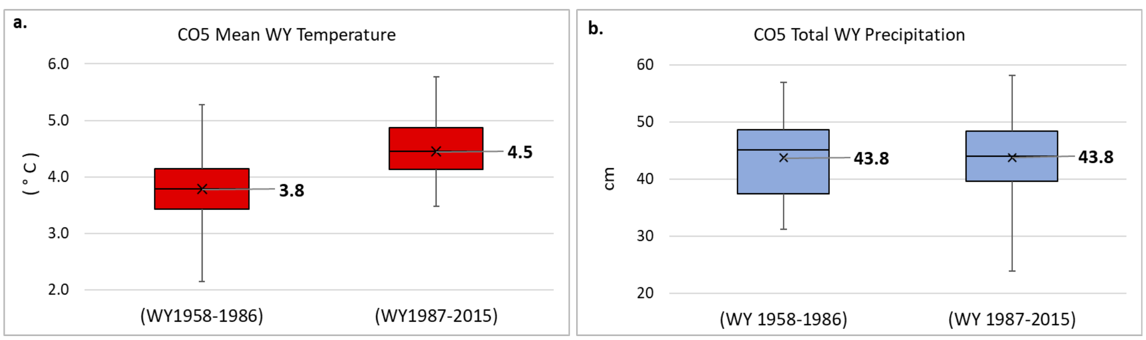
Streamflow and climate data sets (SWE, precipitation, temperature) were split into two 29-year time periods. The first time period corresponds to WY 1958-1986 and the second corresponds to WY 1987-2015.The distribution of total WY streamflow (Q), mean WY temperature (T), and total WY precipitation (P) were evaluated between the two time periods. The same variables (Q,T,P) along with SWE were also evaluated for the winter snow accumulation and runoff seasons. Statistical significance tests were conducted on mean change in each variable against a null hypothesis of zero change in mean values between the two time periods. All significance tests were evaluated at an alpha level (α) of 0.05 and p-values are reported in the results section.

Regression analysis was used to examine the relationships between April 1 snowpack and runoff season (Apr-Jul) streamflow, and precipitation during the winter accumulation season and runoff season streamflow between the selected time 29-year time periods. Lastly, the ratios of April 1 SWE to winter season precipitation (SWE/P_{winter}), snowmelt runoff to April 1 SWE (Q_{sp}/SWE), and snowmelt runoff to winter season (Q_{sp}/P_{winter}) precipitation were evaluated and compared to seasonal evaluations and regression results.

4. RESULTS

a. WY evaluation

Evaluation of differences in annual temperature, precipitation, and streamflow between the first and second halves of the data record shows that mean temperature in the URG has sharply increased, mean WY precipitation totals have not changed, and mean WY streamflow volume has decreased (Fig. 4). The difference in mean WY temperature was 0.67 °C with the second half of the study period being significantly warmer than the first half ($p < 0.005$). A 4% decrease in mean WY flows of approximately 32 Mm^3 was not statistically significant ($p = 0.63$, two-tailed).



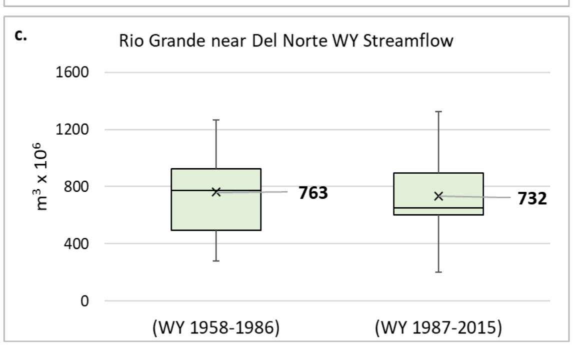


Figure 4. Distribution of (a.) mean annual (Water Year) temperature; (b.) total water year precipitation for Colorado climate division 5; (c.) total water year flow at Rio Grande near Del Norte, for the first and second halves of the data record. The whiskers on each box and whiskers plot represent the absolute maximum and minimum annual value in each data set, the top and bottom of each box represent the 25th and 75th quartile respectively, and the line splitting each box is the median value of each data set. Labeled values on each graph are mean values for each 29-year period.

The entire distribution of annual temperature values shifts upward from the first half to the second half of the record (Fig. 4a) with little change in interannual variability. In contrast, the precipitation distribution shifts toward fewer near-average years and more extreme years (smaller boxes but longer whiskers in recent years in Fig. 4b), with a corresponding increase in interannual variance. Shifts in streamflow (Fig. 8c) are intermediate between the changes of temperature and precipitation: a modest change downward in average flow in recent years, and a modest widening of extreme values of annual flows that does not appear as an increase in total interannual variance in the second half of the record.

b. Winter-Spring evaluation

A monthly assessment of hydrologic and climate variables through the winter accumulation and spring runoff season offers a closer look at variables exhibiting the greatest change over the study period. Streamflow projections for the URG suggest that climate change will have the greatest impact on streamflow during the runoff season resulting from higher temperatures and decreased snowpack (Hurd and Coonrod, 2012; Llewellyn and Vaddey, 2013; Elias et al., 2015).

Since the late 1970s, mean temperatures in the winter and spring seasons have increased in comparison to the 100-year mean (1901-2000) (Fig. 5a). Pronounced increases in temperature have occurred late in the winter season (March) and through the months of the runoff season (Apr-Jul) where successive years of above-mean temperatures have been prevalent in the second half of the study period. Figure 5b shows an increased frequency in anomalously warm months in the second half of the study period where mean monthly temperature was 1.7°C or greater than the 100-year mean, and a decreased frequency in anomalously cold months where mean temperature was - 1.7°C or less than the 100-year mean. The 1.7°C (3°F) anomaly was arbitrarily chosen in the frequency evaluation. A change in mean winter temperature of 0.8°C, and a change of 0.7°C for mean spring time temperature (Fig. 6 a-b) has occurred between the early and later time periods evaluated ($p < 0.005$).

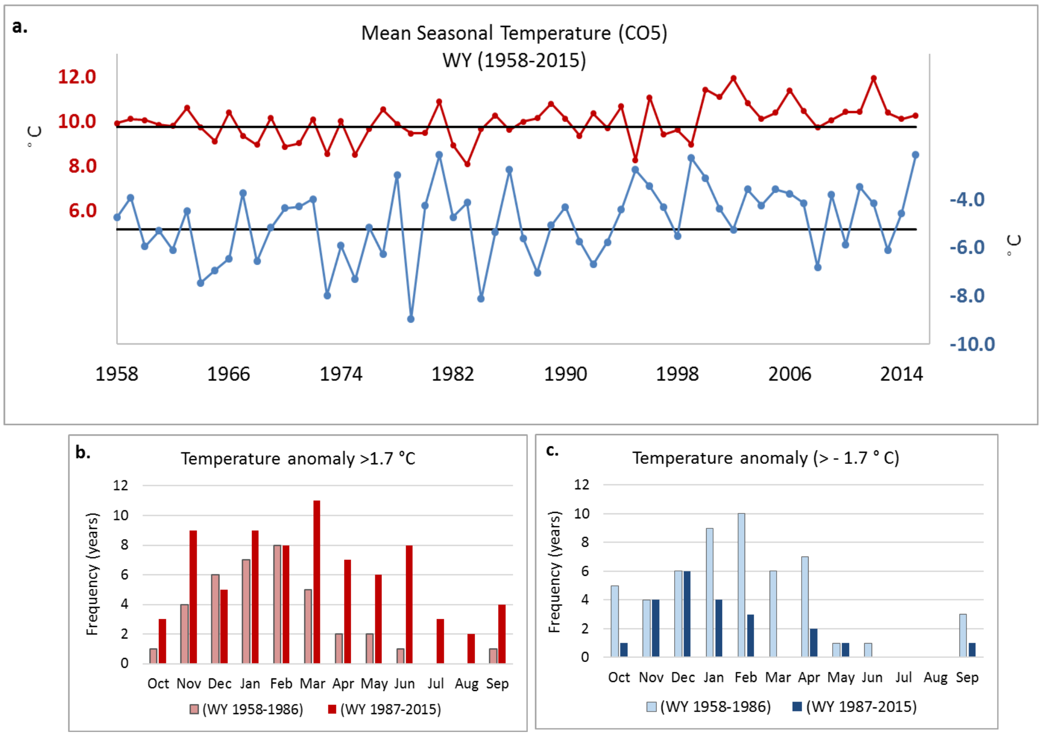


Figure 5. (a) Time series of mean spring (Apr-Jul; red) and a winter (Dec-Mar; blue) temperatures (°C) for Colorado climate division 5, and the 100 year average for each season (black). **(b.-c.)** Frequency of monthly temperature anomalies, 1.7 degrees Celsius or greater than 100 year average (left), and - 1.7 degrees or less than the 100 year average (right).

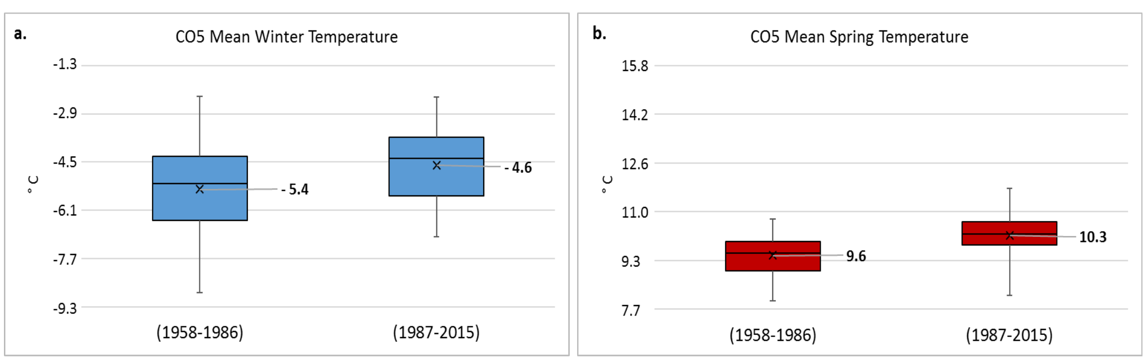


Figure 6. Distribution of (**a.**) mean winter and (**b.**) mean spring temperature for Colorado Division 5. Labeled values on each graph are mean values for each 29 year period.

Snowpack in the URG for the three months evaluated has diminished. March, April, and May SWE indices all show decreasing trends. Only the trend in April 1 SWE was statistically significant (p= 0.05), given large interannual variability. A linear trend fit to the time series shows an approximate 25% decrease in 1 April SWE from 1958-2015 (Fig. 7). This is a substantial finding given the fact that snowpack is one of the largest and most important water reservoirs in the URG.

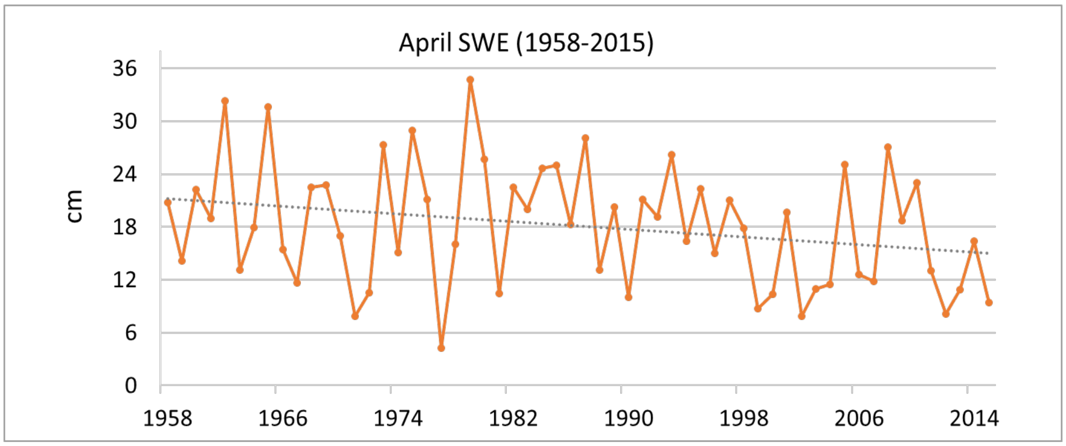


Figure 7. Time series of an eigenvector-based index of April 1 snow water equivalent (SWE) created from NRCS snow course data using seven sites in the URG (Fig. 1). 1 April is the peak of the climatological snow accumulation season in the URG and the graph shows approximately 25% decline in April 1 SWE over the study period ($F_{1,56} = 4.16$); p=0.05).

Seasonal precipitation was variable between the time periods examined (Fig. 8a-b) as expected from previous studies (Regonda et al.,2005; Barnett et al., 2008, Melillo et al., 2014). A modest increase in winter and spring precipitation (rain + snow) occurred during the second half of the study period. The winter months of January-March showed the greatest increase in precipitation in the second half of the study period (Fig. 8c) with an approximate 7% increase (0.68cm) in mean precipitation. A 4% increase (0.35 cm) in mean spring precipitation occurred primarily in the months of April and May, with increased variability in the same months (Fig. 8b).

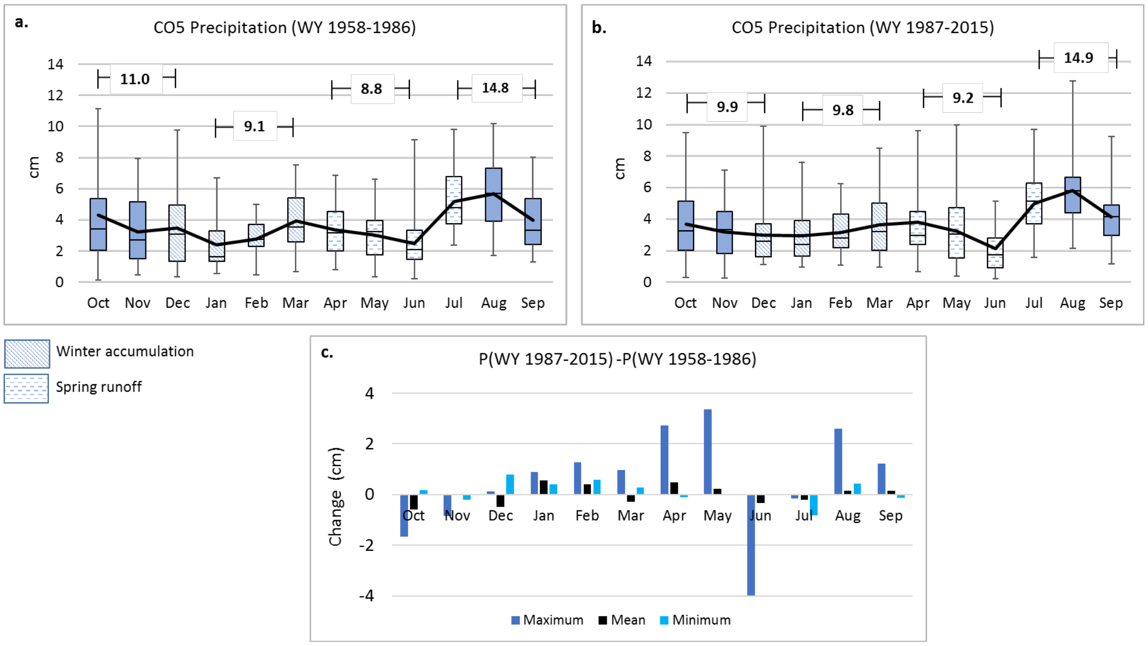


Figure 8. Monthly distribution of precipitation for CO5 in the **(a.)** first and **(b.)** second halves of the data record. The values above each three month period show the sum of monthly mean precipitation (cm) for the three months. The black line shows mean monthly precipitation. **(c.)** Difference in maximum (blue), mean (red), and minimum (green) monthly distribution values (shown in top figure). A negative change means that precipitation in the first 29 year period (1958-1986) was higher than the later 29 year period (1987-2015).

A change in the fraction of winter precipitation occurring as snow is reflected in the ratio of 1 April SWE to winter precipitation (SWE/P_{winter}), which is an indicator of temperature effects on precipitation (Serreze et al., 1999; Knowles et al., 2006). A decreasing trend in SWE/P_{winter} throughout the study period is evident with the smaller ratios mainly due to the decrease in SWE (Fig. 9). Normally, the SWE/P ratio is a number less than or equal to 1, but the location and number of collection sites used in this analysis for precipitation and SWE vary and the ratio reflects elevational differences and the amount of precipitation received. Ratio values are greater than 1 because a greater amount of precipitation falls at mid-elevations where SWE samples are taken than at lower elevations where most precipitation gages are located. Therefore, the change in SWE/P over time is more meaningful than absolute values in Figure 9.

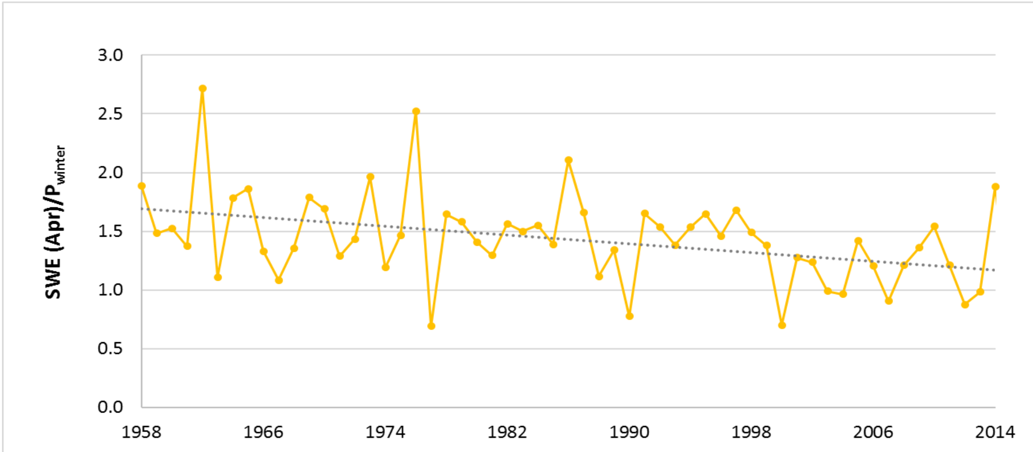


Figure 9. Ratio of April 1 SWE to winter (Dec-Mar) precipitation. The ratio shows a decreasing trend indicating the fraction of winter precipitation occurring as snow is decreasing over the study period (1958-2015).

Spring runoff at RG near Del Norte gage contributed approximately 72% of the total WY flow over the study period. The distribution of monthly streamflow at RG near Del Norte shows that a major portion of streamflow occurs in the months of May, June, and July (Fig. 10a-b). Despite the small increase in winter and spring precipitation (Fig. 8), an 8% decrease in mean spring runoff of 41 Mm^3 occurred in the second half of the evaluation period ($p > 0.05$). The greatest increases in mean spring runoff occurred in March-May, and the greatest decreases were in June-August (Fig. 10c). The hydrograph of mean monthly streamflow shows a notable decrease in mean June-August flow, and an increase in mean March-May flow indicative of earlier snow melt in the latter half of the study (Fig. 10d), both consistent features of streamflow projections.

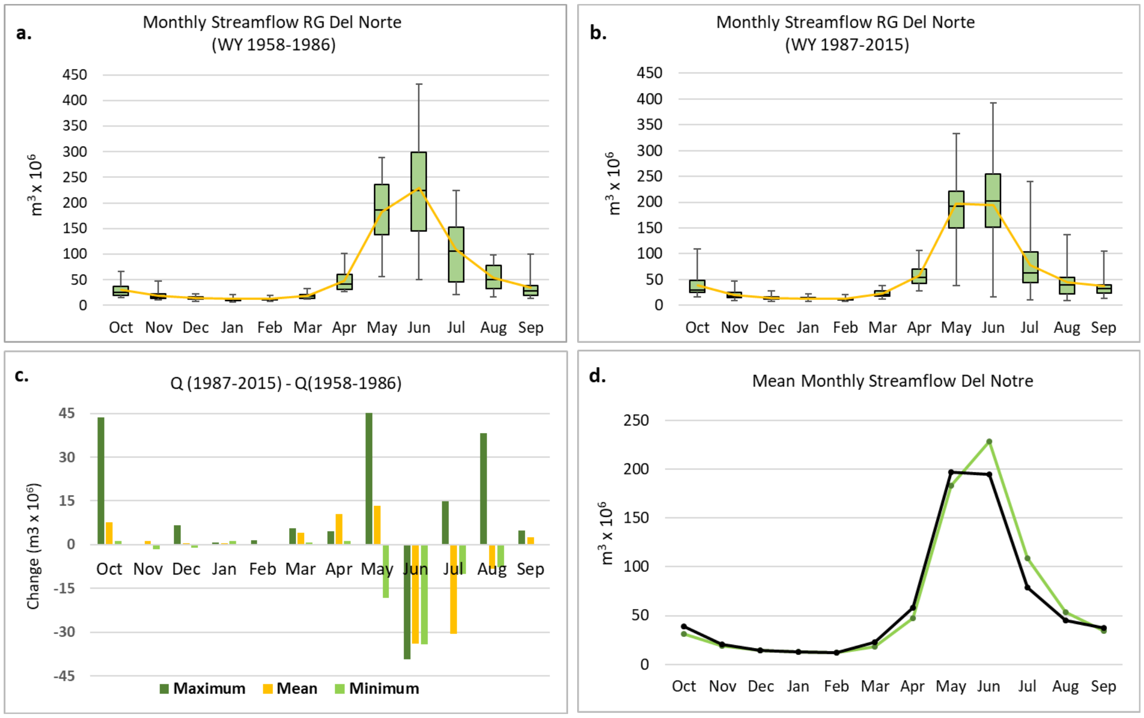


Figure 10. (a.-b.) Distribution of monthly streamflow at Rio Grande near Del Norte stream gage. Orange line indicates mean flow. **(c.)** Difference in maximum (green), mean(orange), and minimum distribution values from top graph values (light green). A negative change indicates that a specific value from the first 29 year period (1958-2015) was greater than the second 29 year evaluation period (1987-2015). **(d.)** Hydrograph of mean monthly streamflow at Rio Grande near Del Norte for the first (green) and second (black) halves of the study period

The ratios of spring runoff to April SWE (Q_{sp}/SWE), and spring runoff to winter precipitation (Q_{sp}/P_{winter}), were used to determine if the amount of precipitation contributing to spring runoff (McCabe and Wolock, 2016) has changed over time. Winter precipitation and April 1 SWE values were first integrated over the entire study area in order to compute ratios. The Q_{sp}/SWE ratio shows an increasing trend over the study period (Fig. 11a). An increasing ratio over time could indicate that a greater amount of winter precipitation (SWE) is contributing to spring flow, but in this case the ratio increases because SWE decreases. This differs from the Q_{sp}/P_{winter} ratio which shows no significant trend in the ratio over time (Fig. 11b), meaning that the contribution of winter precipitation to spring runoff has remained consistent. Thus, the runoff ratios defined using precipitation vs using SWE show quite different temporal changes in this basin.

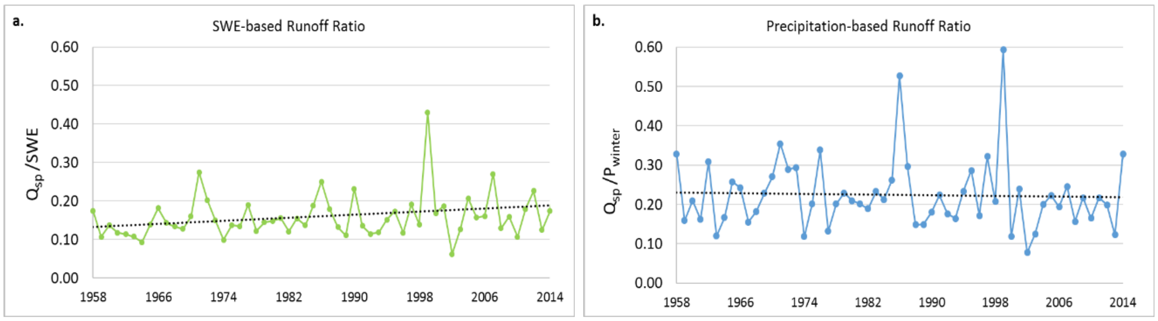


Figure 11. Runoff ratio at Rio Grande near Del Norte defined as **(a.)** total spring streamflow to April 1 SWE. **(b.)** Runoff ratio defined as total spring streamflow to winter precipitation (Dec-Mar).

Similarities and differences can be seen in streamflow at the RG near Lobatos vs. flow at RG near Del Norte (locations in Fig. 1). April- July runoff season flow at RG near Lobatos contributed to approximately 50% of the total runoff season flow, and the distribution of flow shows a dampened runoff season peak for both evaluated time periods (Fig. 12a-b). The difference in mean flow between the first time period and the second shows that monthly streamflow volume has decreased from April-September and increased in the late winter months (Fig. 12c). Changes in mean streamflow are more prominent in the hydrograph of monthly flow (Fig. 12d), but determining if these changes are due to climate change or anthropogenic influence is difficult. This is because the Bureau of Reclamation (BOR) and the Rio Grande Conservation District divert water from the closed basin north of the RG in the San Luis Valley (Fig. 1), called the Closed Basin Project, and discharge some to the RG above Lobatos to meet water delivery requirements set forth by the Rio Grande Compact (Reclamation, 2015). Water contributions from the Closed Basin Project are important to consider because additions could manifest in increased outflows at gages immediately downstream of the project (Mix et al., 2012).

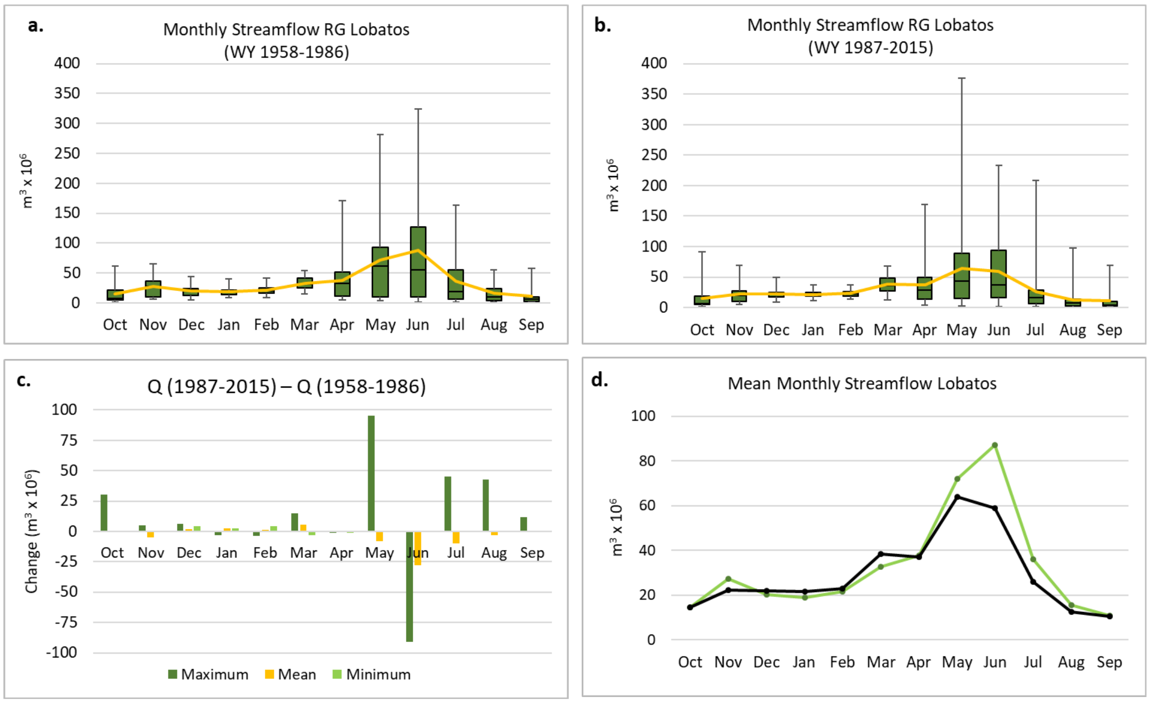


Figure 12. (a.-b.) Distribution of monthly streamflow at Rio Grande near Lobatos stream gage. Orange line indicates mean flow. **(c.)** Difference in maximum (green), mean(orange), and minimum distribution values from top graph values (light green). A negative change indicates that a specific value from the first 29 year period (1958-2015) was greater than the second 29 year evaluation period (1987-2015). **(d.)** Hydrograph of mean monthly streamflow at Rio Grande near Lobatos for the first (green) and second (black) halves of the study period.

c. Regression analysis

Regression analysis was used to explore the relationship between runoff season flow at RG near Del Norte and winter precipitation. The regression method used to predict spring runoff from winter precipitation is similar to the NRCS prediction algorithm (Garen, 1992), but the runoff season here is defined as April-June, whereas the NRCS defines the runoff season at RG near Del Norte as April-September.

We compared regressions of spring runoff (predictand) onto either April SWE or total winter precipitation (Dec-Mar) for the first and second halves of the data (Fig. 13 ad). A lower R^2 value in the regression of April SWE and spring runoff for the 1987-2015 time period indicates that the fraction of runoff season variability in flow accounted for by April SWE has decreased by approximately 40% versus the previous 29 years (Fig. 13a-b).

Additionally, the slope of the regression line between the two time periods decreases, suggesting that there is less predictable sensitivity of runoff to interannual changes in SWE. The runoff ratio defined by the slope of the regression line decreases, but the runoff ratio defined as Q_{sp}/SWE increases, demonstrating the importance of the way the runoff ratio is defined.

Similar results are seen in the regression of winter precipitation and runoff season flow where the R^2 value decreases by 47% in the second half of the study period (Fig. 13c-d), and the slope of the regression line decreases in the second half of the data period. The equation of the regression line indicates that in both cases streamflow volume increases in the second half of the data period despite the decrease in SWE and small increase in winter precipitation, implying that post-April 1 precipitation is contributing to the increase in streamflow.

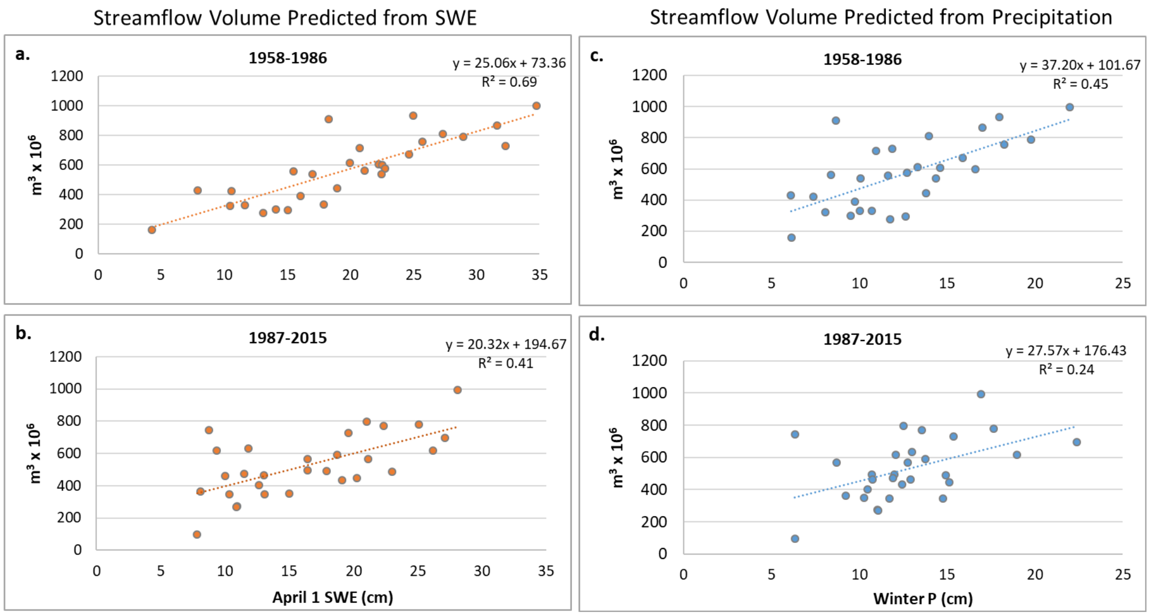


Figure 13. (a.-b.) Linear regressions of runoff season flow (Apr-Jul) to April 1 SWE for two 29 year time periods for the Rio Grande near Del Norte. Regression comparisons for the two time periods indicate a changing relationship between runoff season streamflow and April 1 SWE. **(c.-d.)** Linear regressions of runoff season flow (Apr-Jul) to total winter precipitation (Dec-Mar) for two 29 year time periods for the Rio Grande near Del Norte.

5. DISCUSSION

Our results indicate that climate change is impacting the snowpack-runoff relationship in the URG at Del Norte. This gage is far enough upstream that observed flows are approximately natural, unlike at downstream gages such as RG near Lobatos (Fig. 3). The results provide observational confirmation that long-term streamflow changes projected for the URG are underway, despite the absence of a significant trend in total streamflow.

Changes are apparent in mean runoff season climate and streamflow data, but most obvious in regression statistics and SWE-based runoff ratios. Winter and springtime temperatures in the URG have increased, peak snowpack has diminished significantly over the study period, and spring runoff has decreased at the RG near Del Norte stream gage. The significant decreasing trend in April 1 SWE is a major factor influencing SWE-based runoff ratios and the predictability of runoff season streamflow reflected in changing R^2 values. The decreasing trend in peak SWE over the study period has resulted in increasing Q_{sp}/SWE ratios, a trend that is not replicated using winter precipitation data. A recent study (Lehner et al., 2017) assessing the decline in WY runoff efficiency (or runoff ratio) in the URG for the last four centuries, using tree ring-based indices, suggests that the recent 30-year decline in the runoff ratio is "unprecedented" in the long-term context. Although the runoff ratio in the URG is primarily influenced by precipitation, the study showed that low precipitation in conjunction with increased temperatures increased the likelihood of very low runoff ratios (Lehner et al., 2017).

Results show both consistencies and differences with model projections. Specifically, a distinguishable decrease in mean streamflow volume during the runoff season is apparent despite the increase in winter and spring precipitation, and an increase in early runoff season flows is indicative of earlier snowmelt in the basin, both recurring features of climate change in model projections of URG streamflow. In addition, the decline in mid-elevation (~2870-3200 m) April 1 SWE is consistent with the projected percentage decrease in April SWE presented in the BOR Climate Risk Assessment. An important unresolved question is whether the increase in precipitation is due to natural variability or anthropogenic influences.

Seasonal streamflow forecasts, issued in the late winter and early spring by the NRCS, are an important tool for water management in the URG. The goal of a streamflow forecast (water supply outlook) is to predict the volume of water that will flow pass a selected stream gage during the runoff season, months in advance. Multiple regression techniques that rely primarily on the historic relationship between snowpack and streamflow, with additional variables including precipitation and antecedent streamflow, provide the basis for streamflow predictions (Garen, 1992).

Recent studies assessing NRCS streamflow forecasts in the western U.S. (Pagano and Garen, 2004) and in the Rio Grande and Pecos River basins (NM Working Group, 2015), found that prediction skill has not improved over the years, and in some western basins forecast skill has declined. Increased climate variability and changes in observation systems contributed to the decline in forecast skill in the western U.S. (Wood and Lettenmaier, 2006). Systematic overprediction of flows for recent drought years (2010-2016) for sites on the Rio Grande and Pecos rivers was linked to multiple years of anomalously hot and dry spring seasons (NM Working Group, 2015). The results of previous studies along with results presented here suggest that the use of regression-based forecasts have declining value for hydrologic prediction in a climate where the relationship between snowpack, the major predictor, and streamflow is changing (Wood and Lettenmaier, 2006). Various techniques have been employed to improve streamflow forecasts in the URG including the use of partial least-squares regression (Abudu et al., 2010) and stochastic hybrid models (Abudu et al., 2011), and improving forecast predictions in this and other basins is an active area of research.

Regression results in this study indicate that the volume of streamflow attributable to SWE is diminishing, and that the predictable sensitivity of snowmelt runoff to changes in SWE is declining. Here we used total April-July streamflow at RG near Del Norte as the predictand in the linear regression, whereas the NRCS predicts runoff season flow at this site for the period April-September. Defining the runoff season as total April-September streamflow in the regression of runoff season flow vs. April 1 SWE results in lower predictability (R^2 decreases by 50%) than defining the runoff season as total April-July flow, both because the Q_{sp}/ SWE relationship is changing, and because of summer precipitation late in the season. Although the correlation coefficient between Q_{sp} and April SWE remained high between the earlier (R=0.83) and later (R=0.64) time periods at RG near Del Norte, the compounding impacts of changes to the Q/SWE relationship, higher temperatures farther south in the basin, and human influences such as ground water pumping (not accounted for in naturalized flows; Lehner et al., 2017) may result in further degradation to streamflow forecasts at points downstream from RG near Del Norte.

It is important to note some of the limitations to our snow course based SWE index. Our SWE data may be biased toward the lower elevations of snowpack. High-elevation SWE may not be affected as much by increasing temperatures as our snow course-based index (Fig. 2), and we may only be seeing the initial effects of declining snowpack in streamflow data. Better estimates of snowpack at both high and mid-elevations may help to determine elevations most affected by warming. Previous studies (Regonda et al., 2005; Mote et al., 2006; Pierce et al., 2008) using NRCS snow course data have suggested that mid-high elevation snow course sites, such as those located in the interior west, may be less sensitive to temperature change. Tree ring-based April 1 SWE reconstructions for the past millennium, for three western river basins (Colorado, Columbia, and Missouri basins), have shown that high elevation snowpack has been impacted by increased temperatures less than low elevation snowpack (Pederson et al., 2011). Additionally, anthropogenic warming superimposed on decadal shifts in Pacific Ocean temperatures have likely masked or enhanced effects of warming on snowpack in different regions of the west (Pederson et al., 2011; Fyfe et al., 2017). Furthermore, SWE trends are sensitive to starting and ending years, and slope aspect may influence snow accumulation and melt rates at snow course sites. Other limitations to using snow course data are documented in the previously mentioned studies and in Clark et al. (2001).

Changes in total streamflow at Rio Grande near Del Norte were not statistically significant. Several more years of data may be required to see a significant change if we have documented just the initial effects of climate change on streamflow. In addition, trends in streamflow data and change in mean runoff season flow are sensitive to start and ending dates. The 58 year period of streamflow data was arbitrarily split in half in this analysis, but splitting the data at an earlier or later time period would affect trends and mean values because the mid-1980s was a period of increased precipitation and several years in the 21st century were drought years.

This study attributes streamflow decline to changes in temperature and precipitation (SWE, P), but other climate and non-climate related factors can also affect snowpack and streamflow in the URG. For example, forest disturbance due to insect outbreaks, wildfire, forest management, and logging can impact canopy interception, melt rates, and evapotranspiration rates. Changes in forest canopy can impact melt rates through changes in sheltering of snow from turbulent heat flux and solar radiation (Harpold et al., 2015). Wildfire can also affect soil properties with temporal effects often dependent on the severity of the fire. Reduced infiltration and increased runoff may result from severe wildfires (Certini, 2005; Doerr et al., 2006), but would likely have the greatest impact during the late spring when moderate to high intensity rainfall occurs in the URG. In June 2013 the West Fork Complex of fires generated a large burned area near Wolf Creek pass, on both sides of the Continental Divide in the San Juan Mountains. Rio Grande streamflows at Del Norte following these fires in Water Years 2014 and 2015, at the end of our analysis period, were above the long term mean after several years of declining flow (Fig.1). This short-term increase in runoff is what would be expected following an extensive fire, but more detailed analysis would be required to determine the quantitative effect of wildfire on Del Norte discharge.

Alterations to vegetation and soil properties can impact water yield that could be interpreted as or mask climate change effects (Jones, 2011). Studies examining the effect of dust on snow have also shown that dust from disturbed soils in SWNA can impact the duration of snow cover through changes in snow albedo (Painter et al., 2007; Livneh et al., 2015). Increasing temperatures in the basin could exacerbate the effects of forest disturbance leaving forests more susceptible to wildfire, insect outbreaks, and greater dust fluxes. Even with these influences, we see coherent changes in SWE and streamflow, suggesting that temperature and precipitation variability is the primary influence.

The results presented here may be applicable to other snow-fed river basins in the western U.S. River basins such as the Colorado are much larger than the URG but face many of the same stressors such as long-term drought compounded by increasing temperatures, increasing water demands, and interstate compact obligations (Barnett and Pierce, 2009; Udall and Overpeck, 2017). The headwaters of the RG basin is one of the southernmost snowmelt-dominated river sources, therefore we might expect the changing relationship between SWE and precipitation and the effects of climate change to be more pronounced than in colder, high-elevation basins north of the URG.

6. CONCLUSIONS

The principal goal of this study was to determine if climate change is impacting the snowpack-runoff relationship in the upper Rio Grande basin in ways consistent with climate model-based streamflow projections for the Rio Grande. Annual and monthly changes in streamflow and climate variables in the URG were examined for water years 1958-2015.

In observed data, we see that temperature in the basin has gone up significantly in the winter and spring season resulting in a significant decline in 1 April SWE, and non-significant decrease in spring runoff at RG near Del Norte, regardless of increasing precipitation in the same seasons. Results of this study indicate that climate change is beginning to impact the streamflow volume derived from snowpack in the upper Rio Grande basin, but recent increases in precipitation are masking the effects of declining snowpack. Increased winter and spring temperatures since the late 1970's have had a large impact on snowpack and streamflow through several possible processes including more precipitation falling as rain rather than snow, through sublimation of the snowpack, and through increased evapotranspitation rates. Earlier melting of seasonal snowpack is apparent in hydrographs of mean streamflow, where spring flows have increased in the late winter and early spring and decreased late in the runoff season, with both features consistent with streamflow projections through mid-century (Hurd and Coonrod, 2012; Llewellyn and Vaddey, 2013; Elias et al., 2015).

More importantly, regression results show that the relationship between streamflow and snowpack is weakening. Winter snow accumulation is one of the primary reasons that we can predict streamflow months in advance. Changes in the snowpack-runoff relationship and increased precipitation variability in the URG impact our ability to predict streamflow on a seasonal basis, and will lead to even greater streamflow prediction challenges if climate continues to change as projected. Climate change and streamflow projections through the mid-21^{st} century and beyond suggest temperature will continue to rise, and snowpack and streamflow will decline even further, even if precipitation increases as suggested in CMIP5 based projections (Vano et al., 2014; Reclamation, 2016). Further changes in southwestern hydroclimate will impact life in the region. For example, warmer temperatures and diminished streamflow in the growing season will increase reliance on groundwater resources, further depleting aquifers and altering surface water groundwater interactions (NM Working Group, 2015). In addition to greater water demands by agriculture and vegetation, demands for water to meet energy needs could increase. The ability to meet obligations set forth by the Rio Grande compact and instream flows for aquatic species would also be affected (Llewellyn and Vaddey, 2013). Knowing that changes are occurring should motivate those reliant on Rio Grande water to plan for less water in the years ahead, and to support more sustainable and efficient use of water.

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