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Assessing climate change impacts on water availability of snowmelt-dominated basins of the Upper Rio Grande basin

E.H. Elias[a,*], A. Rango[a], C.M. Steele[a], J.F. Mejia[b], R. Smith[a]

[a] *USDA-ARS Jornada Experimental Range, New Mexico State University, PO Box 3003, MSC 3JER, Las Cruces, NM 88003, USA*
[b] *Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512, USA*

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A B S T R A C T

Study region: Upper Rio Grande, Colorado and New Mexico, USA.
Study focus: Climate change is predicted to further limit the water availability of the arid southwestern U.S. We use the snowmelt runoff model to evaluate impacts of climate change on snow covered area (SCA), streamflow timing and runoff volume. Simulations investigate four future conditions using models downscaled to existing climate stations. Twenty-four subbasins of the Upper Rio Grande containing appreciable snowmelt and a long-term gauging station are simulated.
New hydrological insights for the region: Future annual volume is 193–204 million m^3 more to 448–476 million m^3 less than the pre-climate change value of 2688 million m^3. There is disparity between increased volume in wetter simulations (+7%) and decreased volume (−18%) in drier simulations. SCA on 1 April reduced by approximately 50% in all but the warmer/wetter climate. Peak flow is 14–24 days early in the future climates. Among the 24 subbasins there is considerable range in mean melt season SCA (−40% to −100%), total volume change (−30% to +57%) and runoff timing advancement indicating that climate change is best evaluated at the subbasin scale. Daily hydrographs show higher streamflow in March and April, but less from mid-May until the end of the water year. The large decrease in volume in May, June and July will compound water management challenges in the region.

* Corresponding author. Tel.: +1 575 646 4842.
E-mail addresses: eliaseh@nmsu.edu (E.H. Elias), alrango@nmsu.edu (A. Rango), caiti@nmsu.edu (C.M. Steele), John.Mejia@dri.edu (J.F. Mejia), rxsmith3@nmsu.edu (R. Smith).

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1. Introduction

Water resources of the arid southwest are primarily a result of winter snowpack accumulation and spring snowmelt runoff. Climate change is predicted to decrease snowpack accumulation and cause earlier snowmelt runoff in the Upper Rio Grande (URG) basin (Llewellyn and Vaddey, 2013). Climate change could further limit water availability in much of the southwestern United States, including the URG (Garfin et al., 2013).

The URG basin is located in the semi-arid southwestern United States and covers portions of southern Colorado and northern New Mexico. From its headwaters in the San Juan and Sangre de Cristo Mountains of southern Colorado, the Rio Grande flows southward to eventually form the international boundary between Texas and Mexico. Here we focus on the mountainous headwaters of the Rio Grande and the river mainstem north of the city of Albuquerque, New Mexico. The most important source of water in the Rio Grande drainage results from snowmelt in the mountains of the upper basin, as 50–75% of the flow in the Rio Grande is sustained by melting snow (Rango, 2006).

Rio Grande streamflow generally peaks in the late spring and early summer and diminishes rapidly by mid-summer. Local precipitation primarily occurs in the summertime and summer monsoons can provide additional peak flows in the river. Peak runoff is from April to June, but highest evapotranspiration and irrigation demands along the Rio Grande occur from June through mid-September (Llewellyn and Vaddey, 2013). Streamflow in the basin is historically highly variable as indicated by tree ring analysis and droughts, defined as a year or more with annual flows less than the long-term median, are common (Woodhouse et al., 2012). The URG basin is located on the boundary between the subtropical dry and temperate mid-latitude climate zones. This boundary is anticipated to shift northward and alter seasonal precipitation patterns in the region as a result of climate change (Llewellyn and Vaddey, 2013).

Temperature and precipitation vary by latitude and elevation in the URG (Kunkel et al., 2013). By the end of the century, temperatures in the URG are anticipated to increase by about 5 °C under high emissions global climate model scenarios (Cayan et al., 2013; NOAA, 2013). Temperature increases will be highest in summer and fall. While models are split between those showing declines in winter precipitation and those showing small increases, winter precipitation is expected to increasingly fall as rain rather than snow (Gutzler et al., 2006). Temperature driven increases in evaporation will change the components of the overall water budget, resulting in less available water even with potential small increases in precipitation (Nash and Gleick, 1993). Given the large percentage of Rio Grande streamflow derived from snowmelt, simulation of a snowmelt and streamflow response to anticipated increased temperatures of a changed climate is vital for developing adaptive management strategies. Water resources of this region are particularly vulnerable to the projected increased temperatures since supplies are presently limited. Increased temperatures and population growth in the Rio Grande basin will cause the gap between water supply and demand to continue to grow (Rango, 2006). The timing of water supply will shift to earlier in the year and water management flexibility for current water users may decrease because of the shift in runoff timing (Llewellyn and Vaddey, 2013). An analysis of Colorado River supplies under a changed climate suggests that water management flexibility will minimize climate change impacts (Rajagopalan et al., 2009). Additionally, the notion that groundwater supplies can be tapped to make up the deficit in future shortages ignores supply limitations as the groundwater reservoir is already heavily mined and depleted in the basin (Rango, 2006).

Previous URG modeling efforts have characterized streamflow response to a changed climate (Rango and Martinec, 1997, 2000). The Rio Grande near del Norte was simulated to represent an extremely wet year (1979), a dry year (1977) and a near average year (1976) with good results (Rango and Martinec, 1997). A projected climate change of +4 °C was simulated for this basin. In a dry year the proportion of total annual runoff occurring in the summer (76%) was less than a wet year (93%). Climate change increased winter runoff and decreased summer runoff in dry, moderate and wet simulations of the Rio Grande near del Norte. Rango and Martinec (2000) evaluate the impact of different climatic zones on climate change by simulating Illecillewaet (British Columbia, Canada, very humid), Kings River (California, USA, semi-humid) and Rio Grande at del Norte (Colorado, USA, semi arid). The smallest snowpack reduction occurred at Rio Grande near Del Norte and the decline in snow covered area was accelerated by about 1 month in all climates. Most of the Rio Grande runoff was shifted from June–July to April–May under a changed climate. While the Rio Grande near Del Norte supplies a large portion of the total annual runoff of the URG basin, many other, smaller watersheds supply water. This work simulates climate change on the Rio Grande at Del Norte along with the other major snowmelt contributing subbasins ($n = 24$) of the URG. We compare the spatial and temporal differences in snowmelt timing and water provision from these subbasins.

SRM was designed to simulate daily streamflow in mountain basins where snowmelt is a major contribution to runoff. SRM was developed by Martinec (1975) for simulation of small European basins. The model has since been applied in over 100 basins in at least 29 different countries. SRM successfully underwent tests by the World Meteorological Organization with regard to runoff simulations (WMO, 1986). The first evaluation of the effect of climate change using SRM dates back to 1980 (Martinec, 1980).

Downscaling of global climate model (GCM) temperature and precipitation data is an important step in hydrologic modeling because the spatial resolution of GCM simulated temperature and precipitation (~100–250 km) is too coarse for basin scale hydrologic modeling. In this study, GCM temperature and precipitation data were downscaled to the climate station using bias-corrected construction analogues (BCCA) and station-based bias correction in a method termed double statistical downscaling (Mejia et al., 2012). This method has improved hydrologic simulation in other western basins of the United States (Mejia et al., 2012).

The main objective of this paper is to examine the impact of four plausible future conditions on the runoff timing and total volume of subbasins supplying the URG. SRM is used to simulate streamflow under the changed climate for the subbasins of the URG containing both a long-term gauging station and appreciable snowmelt ($n = 24$ basins). Here we present the results of future temperature and precipitation, snow covered area, runoff volume and streamflow timing of four realistic cases near the end of the 21st century.

2. Methodology

The methodology is divided into four steps: SRM parameterization, GCM downscaling, future snowpack estimation and future runoff simulation.

2.1. SRM background and parameterization

SRM was used to simulate observed streamflow at the outlet of 24 subbasin tributaries to the URG (Table 1; Fig. 1) using daily observed precipitation and temperature data collected during a moderate runoff year (generally, Oct 1, 1998 to Sept 30, 1999) at climate stations throughout the basin.

SRM is a temperature-index model that has been used to simulate runoff from snowmelt basins since 1975. SRM operates on a daily time-step and simulates streamflow based upon changes in daily temperature, precipitation and a variety of parameters representing physical conditions. Data for each of the 24 simulated basins were derived or collected to populate 24 different SRM models. Basin characteristics, including basin area, gage locations, elevation zones and hypsometric mean elevations were collected or calculated. Gage locations and elevations are from the National Water Information Service (NWIS) website (USGS, 2001) and study basins are delimited using digital elevation data and ArcGIS hydrology tools (ESRI, 2011). We determine elevation zones of ~500 m for each basin and calculate hypsometric mean elevations for each zone.

We collect daily streamflow data from NWIS (USGS, 2001) or the Colorado Division of Water Resources (CDWR, 2008). Streamflow data are used as an initial input for the first day of simulation and later to compare with simulated flow to measure model performance. We collect air temperature and precipitation data from available daily time-step weather stations including the National Weather Service Cooperative Observer Program (COOP: NOAA, 2013), the Natural Resource Conservation Service Snow Telemetry (SNOTEL) system (NRCS, 2013) and the Remote Automatic Weather Station (RAWS) network (USFS, 2011). We extrapolate precipitation data to zonal hypsometric mean elevations of each zone by 3–4% per 100 m difference in elevation. Temperatures are lapsed to the hypsometric mean of each zone within SRM using a lapse rate of 0.65–0.8.

Table 1
Subbasin area, elevation range, weather stations, 1999 precipitation and April 1 snow covered area.

Subbasin	Basin area (km^2)	Elevation range (m.a.s.l)	Weather stations	USGS gauge number	1999 precip. (cm)	1999 snow covered area (km^2)
Alamosa River	274	2624–4036	Del Norte[1], Lily Pond[3]	08236000	66.3	214
Carnero Creek	273	2486–3794	Del Norte[1], Saguache[1], Lujan[2], Blue Park[2]	08230500	41.1	125
Conejos	729	2524–4005	Big Horn[2], Lily Pond[3]	08246500	67.9	543
Costilla	566	2409–3941	San Luis[1], North Costilla[3]	08255500	68.4	278
Culebra (1994)	649	2428–4265	Culebra[3]	08250000	70.4	357
Del Norte (1987)	3396	2436–4222	Del Norte[1], Wolf Creek Summit[3]	08220000	79.3	3234
El Rito	131	2264–3246	El Rito[1], Hopewell[3]	08288000	71.2	78
La Jara	266	2464–3632	Big Horn[2], Lily Pond[3]	08238000	67.9	149
Los Pinos	395	2454–3716	Big Horn[2], Cumbres Trestle[3]	08248000	73.3	250
Lucero	43	2472–3976	Red River[1], Tolby[3]	08271000	67.9	35
Ojo Caliente	1066	1939–3302	El Rito[1], Hopewell[3]	08289000	71.2	244
Red River	290	2276–3988	Red River[1], Red River Pass[3]	08265000	66.7	169
Rio Chama (2001)	1222	2159–3886	Chamita[3], Cumbres Trestle[3]	08284100	73.9	1028
Rio Grande del Rancho	208	2201–3643	Taos[1], Gallegos Peak[3], Tolby[3]	08275500	75.4	124
Rio Hondo	96	2349–3992	Red River[1]	08267500	55.9	70
Rio Pueblo near Penasco	258	2624–4036	Taos[1], Gallegos Peak[3]	08277470	79.0	149
Rio Pueblo de Taos	150	2262–3892	Cerro[1], Red River Pass[3]	08269000	60.2	98
Saguache Creek	1340	2448–4229	Saguache[1], Lujan[2]	08227000	39.9	765
San Antonio	298	2437–3327	Big Horn[2], Hopewell[3]	08247500	63.4	124
Santa Barbara	102	2596–3953	Gallegos Peak[3]	08278500	80.4	75
Santa Cruz (1994)	239	1974–3972	Santa Fe[1], Gallegos Peak[3]	08291000	63.2	176
Santa Fe	47	2368–3757	Santa Fe[1], Santa Fe[3]	08316000	99.1	11
Trinchera	137	2601–4113	Blanca[1], Trinchera[3]	08240500	69.6	78
Ute Creek	104	2459–4351	Blanca[1], Trinchera[3]	08242500	37.7	21

[1] Coop station.
[2] RAWS station.
[3] denotes SNOTEL station.

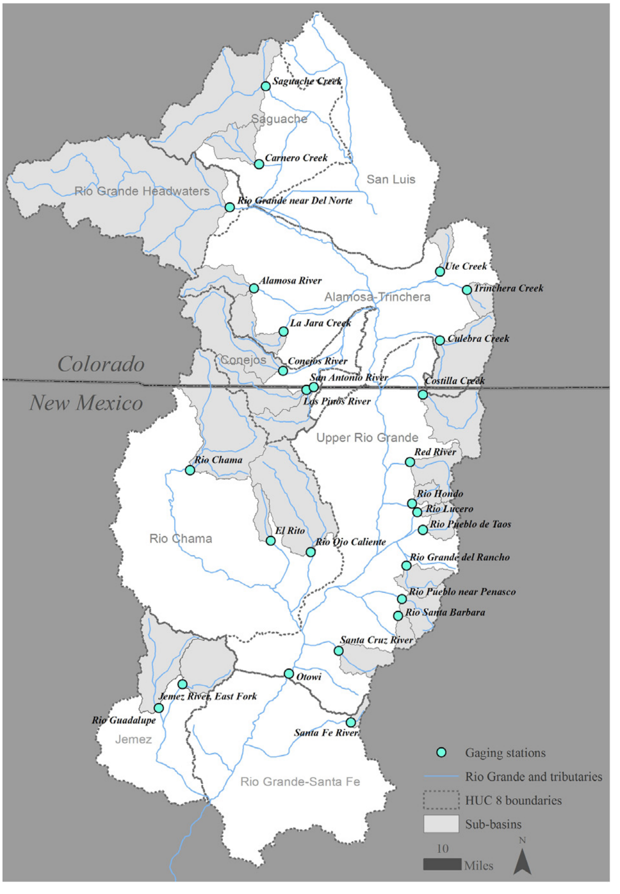

Fig. 1. Subbasins and gauging stations of the Upper Rio Grande study area located in Colorado and New Mexico, USA.

Following an evaluation of MODIS and Landsat Thematic Mapper (TM) imagery to estimate snow covered area, we elected to use Landsat TM (30 m spatial resolution) to generate estimates of snow cover for each zone and basin. We used between four and seven satellite images to generate snow covered area. Zonal analysis was used to estimate snow cover in each basin and zone for each date of available Landsat TM imagery. Snow cover estimates between February and August along with Sigmaplot software were used to fit decay curves to the data, termed conventional depletion curves in SRM.

SRM parameters include recession coefficient, degree day factor and runoff coefficients for snow and rainfall. In SRM, parameters can change throughout the simulation and by zone. Parameters were selected for each basin within a range of acceptable values. SRM parameters alter runoff simulation and influence model performance (Panday et al., 2013). SRM parameterization occurred in a basin-by-basin manner and adjustments to parameters were made until measured and simulated runoff reached an acceptable agreement (Appendix I). The 24 simulated subbasins range in size from 43 to 3396 km^2 with measured annual runoff volume ranging from 6 to 1323 million m^3. For the parameterized basins, the average difference in volume between measured and SRM computed runoff was 9.4% and average Nash-Sutcliffe coefficient was 0.82.

For the 24 simulated basins, the parameters used in present climate simulations did not change in the simulations of future climate.

2.2. GCM downscaling

Climate data from general circulation models (GCM) from the coupled model intercomparison project CMIP3-A2 and CMIP5-RCM8.5 dataset are downscaled to weather stations used to force the SRM. GCM temperature and precipitation data were downscaled to 25 climate stations for use in SRM simulation of climate change using Bias-Correction Constructed Analogues (BCCA) (Maurer et al., 2010) along with station-based bias correction (double statistical downscaling; Mejia et al., 2012). Period change analysis from 1990–1999 to 2090–2099 produces estimated changes in temperature and precipitation near the end of the 21st century. Here we use four climate models to simulate future conditions. We statistically select the four models that represent a warmer/wetter, warmer/drier, hotter/wetter and hotter/drier future condition.

Limitations in computing resources require an efficient and unbiased subsample strategy, which also allows characterizing the GCMs/downscaled inherited range of uncertainty in the weather data. For these purposes, we adopted a modified approach, consisting of selection of the four intersecting points defined by the nearest GCMs intersection of 10th to 90th percentile changes in temperature and 10th to 90th percentile changes in precipitation and combining all the scenarios available (Reclamation, 2008). We selected the 10th and 90th percentile changes of the temperature–precipitation parameter space representing warmer/wetter, warmer/drier, hotter/wetter and hotter/drier mean future projections. Of note is that this approach is robust and covers the envelope of weather possibilities, minimizes information loss, and assumes that any combination of precipitation–temperature states within this envelope creates a hydrologic response that falls within the range of hydrologic solutions produced by the four ensemble members. One marked difference between our approach and that of Reclamation is that we opted to use the warmest climate scenario (A2 for CMIP3 and RCP 8.5 for CMIP5).

2.3. Future snow covered area

SRM was used to evaluate the impact of future temperature on snow covered area by basin. SRM uses basin snow cover estimated in the present climate from snow cover maps or remotely sensed data over the snowmelt period in order to produce snow cover in a changed climate.

Two options are available to estimate the snow cover of a changed climate with SRM. The modeler could elect to estimate future snow cover outside the SRM framework and then use the projected future snow cover within SRM or the modeler could allow SRM to adjust snow cover based upon daily time step modifications of the depletion curve using temperature, precipitation and other factors in internal calculations. Other researchers have used a combination of multiple linear regression of monthly climatic factors to estimate the change in snow cover (Khadka et al., 2014). The obvious drawback of this approach is the monthly timescale. SRM internal snowcover modification occurs on a daily timestep, hence the depletion curve for each simulated zone is modified for each day. Monthly changes in snowcover based upon projected temperatures may miss important runoff events. The benefit of using multiple linear regression over decadal time frame to estimate snow cover is that it reduces the uncertainty associated with interannual variability inherent in calibrating to a single year. This can be somewhat reduced by selecting a year of moderate precipitation, temperature and streamflow. Both approaches assume that past relationships between temperature and snow cover will persist in the future, which may not be the case.

SRM requires the following data to predict snow covered area in a changed climate: Number of elevation zones for each basin, current snow covered area, snow cover values (S, daily), average maximum and minimum temperatures (T, daily); precipitation, daily; degree-day factor (a); temperature lapse rate and critical temperature.

The critical temperature is used to decide if a precipitation event will be treated as rain or new snow. Precipitation is stored by SRM and then subsequently melted. Using snow coverage as a model input, the climate-affected runoff during the entire hydrologic year is computed within SRM. The climate affected conventional depletion curves (CDC_{CLIM}) are derived to generate a depletion curve that accounts for new summer snow and the decrease in snow water equivalent due to increased winter snowmelt (winter deficit).

The difference between present and future area water equivalent of snow cover (ΔH_w) is determined by calculating how precipitation falling as snow in winter (1 October–31 March) under cooler historical conditions may be converted to rain in a warmer climate. In SRM this is formulated:

$$\Delta H_W = \sum_{n=1}^{182} [a_n \cdot T_n \cdot S_n + a_n \cdot T_n (1 - S_n) + P_{Rn}] - \sum_{n=1}^{182} \left[a_n \cdot T_n^{'} \cdot S_n^{'} + a_n \cdot T_n^{'} \left(1 - S_n^{'}\right) + P_{Rn}^{'}\right] \quad (1)$$

For a given day (n) this formula expresses the inputs to runoff from seasonal snow cover, melting of temporary snow cover from the snow-free area ($1 - S$) and input from rain (P_R). The prime denotes variable values in the warmer climate (Eq. (1)).

Accumulated zonal melt (AZM) is calculated from the product of snow cover and computed snowmelt depths for the historical summer (1 April–30 September).

$$\text{AZM} = \sum_{n=1}^{183} [a_n \cdot T_n \cdot S_n] - [a_n \cdot T_n (1 - S_n)] \quad (2)$$

By comparing ΔH_w with AZM we can identify the day on which ΔH_w exceeds AZM. The value for snow cover on this day is then shifted to 1 April and snowmelt for the changed climate then follows the original depletion curve. An example given by Martinec et al. (2008) shows ΔH_w exceeding AZM on 27 April. The melt depths and associated snow cover values for 27 April are shifted to 1 April, thus adjusting the conventional depletion curve for a warming climate.

SRM conducts winter and summer present and climate change simulations in a series of six steps. In the first four steps (computed within the SRM climate change module) zonal melt totals are computed which are used by the model to calculate climate modified snow depletion curves. The winter adjusted depletion curves under climate change are computed in step five. Depletion curves are derived by the following steps:

1. Compute winter change (ΔH_w)
2. Develop a zonal melt curve (AZM) for each zone for the normal climate and find the date where ΔH_w is equaled or exceeded.
3. Create the modified depletion curve for each zone by adjusting for winter deficits or surpluses.
4. Modify the depletion curve to account for the daily melt depths of the new snow in the future climate.
5. For each daily value of the new depletion curve adjust the percent snow cover based upon future climate temperature
6. Compute the climate change CDC by infilling any missing daily values with the earlier days' percent snow cover value. This new depletion curve is used in the climate change simulations. See the SRM manual (page 104) for further details (Martinec et al., 2008).

2.4. *Climate change runoff simulation*

SRM contains a climate change scenario definition table that allows for the input of starting and ending date of climate change, the variable to change, an edit action and an edit factor (such as °C). Many past applications of SRM have employed an average increase of a specified amount for the entire year, generally +4 °C (Rango and Martinec, 1997, 2000). In this simulation, statistically subsampled climate data are used to derive a range of expected temperature and precipitation changes for each basin (see Section 2.2). For each of the 24 subbasins, four climate change scenarios are simulated. A parameter shift, as recommended by van Katwijk et al. (1993) of 30 days is used for the degree day factor and the snowmelt runoff coefficient to better represent the changed climate.

2.4.1. Snow covered area

Basin snow covered area (SCA) is evaluated for each subbasin and zone. The effects of climate change on snow cover depletion curves (CDC) are reported as the change in mean SCA for the April-September period for each basin (hereafter, melt season SCA). Initial snow cover at the onset of snowmelt (usually 1 April) is reported for each basin and mountain range.

2.4.2. Total runoff volume by subbasin and mountain range

The change in annual runoff volume for each subbasin and mountain range are reported to evaluate how climate change impacts total water availability throughout the URG and which basins may be particularly vulnerable. This analysis allows for estimation of the range of responses in a variety of basins within the same region.

Results are presented for each basin, mountain range and the URG. The basins within the San Juan Mountain range for the purposes of this analysis are Del Norte, Saguache, Rio Chama, Ojo Caliente, Conejos River, Los Pinos, San Antonio, Alamosa, Carnero Creek, La Jara Creek, and El Rito. Saguache and Carnero Creeks are geographically located in the La Garita and Cochetopa Hills, but are included within the San Juan Mountains for this analysis. The basins within the Sangre de Cristo Mountain Range include Culebra Creek, Costilla Creek, Red River, Rio Pueblo near Penasco, Santa Cruz, Rio Grande del Rancho, Pueblo de Taos, Trinchera Creek, Ute Creek, Santa Barbara, Rio Hondo, Santa Fe and Lucero.

2.4.3. Streamflow timing

The shift in runoff timing is calculated using the 7-day peak flow for all simulations. It is calculated by determining the time period with the highest 7-day average flow during the year. Difference in number of days between the pre-climate change and the warmer/wetter, warmer/drier, hotter/wetter and hotter/drier simulations is used to represent the shift in runoff timing.

3. Results and discussion

3.1. Downscaled temperature and precipitation

The base simulation year representing the present climate (1999 for most basins) was a moderate year in terms of both precipitation and measured streamflow. Historic data (1961–2000) from 25 weather stations supplying SRM values were analyzed for average temperature and annual precipitation. Average annual temperatures (1961–2000) from the 25 weather stations used in SRM simulation ranged from 3.4 to 5.7 °C. In comparison with the 1961–2000 record, 1999 average temperature (5.2 °C) was warm, with only 5 years of the 40-year record having higher average temperatures. Annual precipitation of the historic record (1961–2000) ranged from 39.4 to 85.4 cm. 1999 precipitation was the median value of the historic period with 57.6 cm. Period change analysis from 1990–1999 to 2090–2099 and subsampling results to characterize uncertainty produces four temperature and four precipitation values to represent future conditions for each subbasin (Table 2; Appendix II). For 'hotter' scenarios, which represent the higher projected temperature changes, temperature increase ranges from 5.7 to 6.7 °C with a mean of 6.1 °C. For 'warmer' scenarios, which represent the lower predicted temperature change, temperature increase ranges from 3.0 to 4.8 °C with a mean of 3.4 °C (warmer/wetter) to 4.4 °C (warmer/drier). Future precipitation values portend both wetter and drier conditions. Across the subbasins precipitation ranges from a decrease of −24% to an increase of +41%. For the drier scenarios, precipitation decrease ranges from a decrease of −12% to −24% with a mean decline of −16%. For the wetter scenarios, precipitation increase ranges from +14% to +41% with a mean increase of +23%. Fig. 2 depicts selection of future temperature and precipitation values for selected weather stations.

3.2. Snow reserves in a warmer climate

3.2.1. Effects of climate change on snow cover depletion curves

In SRM, the modified depletion curves of the present climate are deprived of the amount of water which would be missing from the snowpack of a warmer future climate. The mean melt season SCA, as

Table 2
Temperature and precipitation changes representing subsampled period change from 1990–1999 vs. 2090–2099 for four future conditions in subbasins of the Upper Rio Grande.

Basin	Temperature change (°C)				Precipitation change (%)			
Scenario	HD	HW	WW	WD	HD	HW	WW	WD
Rio Grande del Norte	6.5	5.9	3.2	4.4	−15.7	18.5	17.0	−14.6
Saguache Creek near Saguache	6.5	6.6	4.8	4.5	−16.7	41.3	41.1	−12.6
Rio Chama near La Puente	6.2	6.4	3.0	4.4	−12.4	15.8	14.1	−15.1
Rio Ojo Caliente at La Madera	6.1	5.8	3.1	4.3	−17.1	17.0	16.6	−16.6
Conejos River near Mogote	6.1	6.0	3.1	4.5	−15.4	23.6	25.7	−13.5
Los Pinos River near Ortiz	6.1	6.7	3.1	4.5	−14.7	21.8	23.5	−17.3
San Antonio River at Ortiz	6.0	6.0	3.1	4.4	−17.1	22.0	25.9	−16.5
Alamosa River above Terrace	6.0	6.0	3.1	4.4	−17.1	22.0	25.9	−16.5
Carnero Creek near La Garita	6.4	6.3	4.0	4.3	−18.7	37.8	37.3	−16.7
La Jara Creek at Gallegos Ranch	6.1	6.0	3.1	4.5	−15.4	23.6	25.7	−13.5
El Rito near El Rito	6.1	5.8	3.1	4.3	−17.1	17.0	16.6	−16.6
Culebra Creek at San Luis	6.1	6.0	3.9	4.6	−15.6	19.6	14.2	−13.9
Costilla Creek near Costilla	6.3	6.2	3.1	4.3	−16.1	20.1	21.5	−14.1
Red River near Questa	6.2	6.3	3.6	4.3	−15.4	17.9	18.4	−14.4
Rio Pueblo near Penasco	6.1	6.0	3.5	4.5	−18.7	24.6	22.3	−19.1
Santa Cruz River near Cundiyo	6.1	6.0	3.6	4.3	−24.0	33.2	33.3	−21.6
Rio Grande del Rancho	5.8	5.8	3.5	4.3	−17.5	23.4	22.4	−16.9
Rio Pueblo de Taos near Taos	6.2	6.4	3.8	4.4	−17.5	28.1	28.4	−15.9
Trinchera Creek	6.1	6.3	3.6	4.4	−14.9	18.0	16.7	−11.8
Ute Creek near Fort Garland	6.1	6.3	3.6	4.4	−14.9	18.0	16.7	−11.8
Rio Hondo near Valdez	6.2	6.4	3.1	4.3	−16.0	17.3	19.6	−15.8
Santa Barbara near Penasco	6.0	5.7	4.0	4.3	−19.1	18.2	19.0	−21.0
Santa fe River near Santa Fe	6.1	6.2	3.1	4.5	−22.8	32.4	32.0	−18.2
Rio Lucero near Arroyo Seco	5.7	5.9	3.3	4.1	−15.4	19.2	21.0	−14.1

represented by the model adjusted, winter adjusted depletion curve [$CDC_{CLIM\ WA,\ MA}$], was lower than base simulation SCA in all simulations of all 24 basins due to the influence of increased temperatures. In general, the basins with the highest mean pre-climate change SCA had the highest mean melt season SCA in the climate change simulations. In order of subbasin area they are Del Norte, Rio Chama, Conejos and Culebra. These four basins, along with Los Pinos, retain the largest mean melt season SCA in climate change simulations. These five basins are also among the eight largest in terms of total subbasin area. It is not possible, however, to attribute snow retention to watershed size alone in the URG. Saguache, Ojo Caliente and Costilla Creeks are among the largest by watershed area, but retain a low mean melt season SCA (zero to 7 km^2). The initial snow depletion curves for the large basins influence the amount of SCA retained during climate change. In the pre-climate change simulations, the five basins with the highest mean SCA also retained the most basin snow cover (>90 km^2 by 30 May) under climate change. The three basins with small remaining climate change mean melt season SCA in pre-climate change simulations lost SCA early in the base simulations (<40 km^2 by 30 May). This highlights the importance of initial accounting of SCA prior to climate change simulations.

Generally the most mean melt season SCA is retained in the warmer/wetter climate and the least in the hotter/drier climate (Fig. 3). The reduced SCA was unique to each basin, ranging from a 40% reduction at the Trinchera Basin in the northern Sangre de Cristo Mountains to a 100% reduction in several basins. Four of the 24 basins simulated have effectively no mean melt season SCA (<0.5 km^2) for all climate change scenarios (Carnero Creek, El Rito, Ojo Caliente, and Rio Grande del Rancho). These subbasins lie in both the San Juan and the Sangre de Cristo mountain ranges. Three regions of the URG depict a decline in mean melt season SCA of between 90% and 100% (Table 3). The northern San Juan mountains (Carnero and Saguache Creeks); the southern San Juan mountains (El Rito and Ojo Caliente) and the central Sangre de Cristo mountains including Costilla Creek, Red River, Rio Hondo, Rio Grande del Rancho and Rio Pueblo near Penasco. The basins of these three regions retain relatively little mean melt season SCA (km^2) and have a large (>90%) decline in mean melt season SCA.

The SCA decline is smallest for Del Norte, Chama and Trinchera in the warmer/wetter climate (Fig. 3). However, Del Norte has a 79% decline in mean melt season SCA in the hotter/drier simulation.

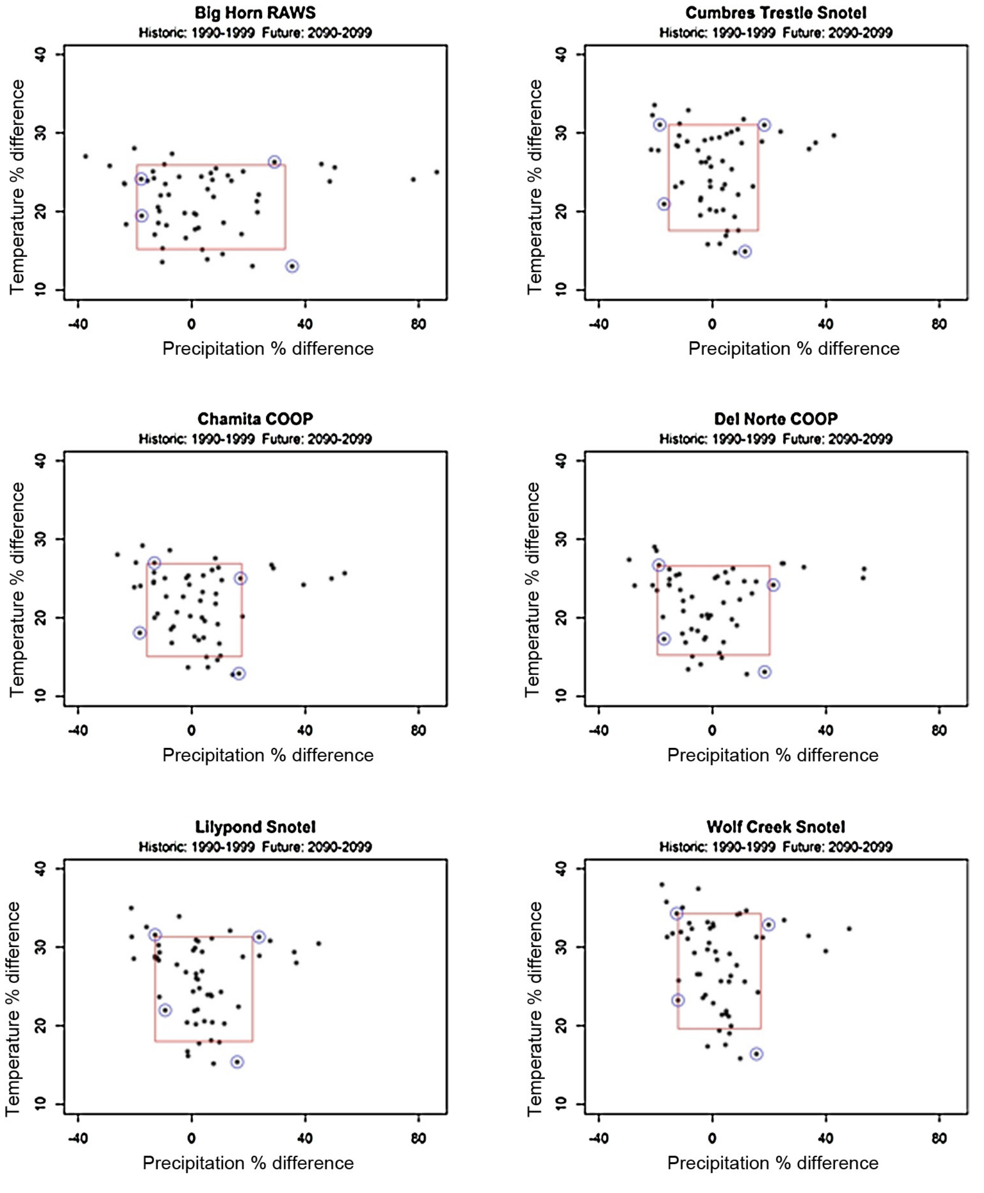

Fig. 2. Selected period change weather station simulations showing subsampling to select four future conditions to represent a warmer-wetter, warmer-drier, hotter-wetter and hotter-drier future condition.

Since this watershed provides a large proportion of the URG streamflow, the amount of mean melt season SCA retained under climate change is particularly important to regional water supplies.

Snow reserves in terms of basin snow cover on 1 April in the present and future climate

The summation of snow cover for all snowmelt basins ($n = 24$) in the base simulation representing present climate on 1 April is 7818 km^2 (Table 4). Under the temperatures of the 'hotter' climate change simulations, this area decreased by approximately 50% (3460 hotter/drier; 3986 hotter/wetter). In order of total 1 April SCA, the climate change scenarios progress from warmer/wetter (5166 km^2) > hotter/wetter (3986 km^2) > warmer/drier (3777 km^2) > hotter/drier (3460 km^2).

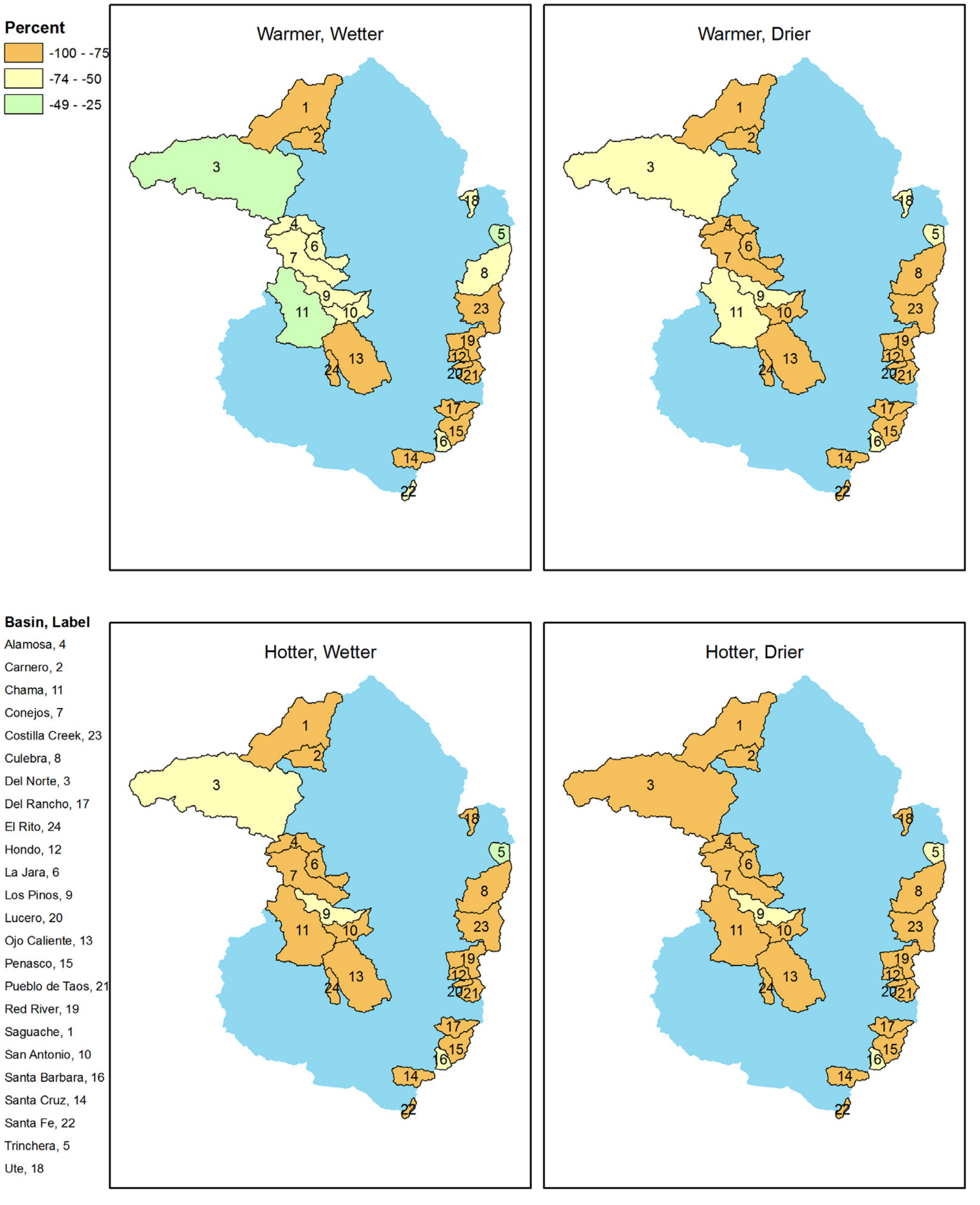

Fig. 3. Percent change in mean April–September proportion snow covered area for subbasins of the Upper Rio Grande study area.

3.2.2. Snow cover by mountain range

In the base simulation representing present climate, the San Juan Mountains provide 81% of the total URG SCA at the onset of the melt season. The proportion of total URG SCA supplied by the San Juan mountains increases in all future climates (84% (hotter/drier) to 88% (warmer/wetter)). Under future climatic conditions, the San Juan mountain range will hold a larger proportion of the total URG

Table 3
Average Snow Covered Area (SCA) from April to September and percent change in Snow Covered Area between calibrated and climate change scenario values.

	Mean Apr–Sep SCA (km^2)					Percent change in Apr–Sep SCA (%)			
Subbasin	Calibration year	WW	WD	HW	HD	WW	WD	HW	HD
Alamosa River	68	21	13	10	10	−70	−81	−85	−85
Carnero Creek	12	0	0	0	0	−100	−100	−100	−100
Conejos	170	74	43	18	17	−57	−75	−90	−90
Costilla	41	1	0	0	0	−98	−100	−100	−100
Culebra (1994)	91	33	21	18	16	−63	−77	−80	−82
Del Norte (1987)	874	483	289	271	187	−45	−67	−69	−79
El Rito	7	0	0	0	0	−100	−100	−100	−100
La Jara	26	9	4	6	4	−65	−86	−78	−84
Los Pinos	62	25	21	17	18	−59	−65	−73	−71
Lucero	8	2	1	1	1	−77	−85	−88	−88
Ojo Caliente	35	0	0	0	0	−100	−100	−100	−100
Red River	36	2	2	2	2	−95	−95	−95	−95
Rio Chama (2001)	225	115	60	46	47	−49	−73	−79	−79
Rio Grande del Rancho	18	0	0	0	0	−100	−100	−100	−100
Rio Hondo	13	1	0	0	0	−95	−98	−98	−98
Rio Pueblo de Penasco	19	2	1	0	1	−91	−94	−98	−96
Rio Pueblo de Taos	14	3	2	1	1	−81	−84	−94	−90
Saguache Creek	76	6	7	2	3	−92	−91	−97	−96
San Antonio	20	6	4	3	3	−69	−78	−85	−85
Santa Barbara	18	7	6	6	5	−62	−64	−68	−70
Santa Cruz (1994)	35	9	8	8	7	−75	−77	−78	−80
Santa Fe	2	1	0	0	0	−71	−85	−86	−87
Trinchera	17	9	7	10	7	−45	−61	−40	−57
Ute Creek	3	1	1	0	0	−70	−74	−94	−95

SCA at the beginning of the snowmelt season as compared with the present SCA. Presently the Sangre de Cristo range has 19% of the URG SCA on 1 April as compared with 12–16% in a changed climate.

In SRM, the decline in mean melt season and 1 April SCA are in response to the increased future temperatures. The initial snow cover from satellite imagery supplies the pre-climate change snow cover. Daily temperature changes of a future climate modify the observed snow cover to approximate future snow cover. Many factors influence initial snow cover, such as basin slope, aspect and elevation. While the large and productive basins of the URG continue to retain the largest future snow cover, basin size and mountain range are not consistently responsible for differences in snow cover. For example, several large basins of the San Juan Range have little mean melt season SCA. Our results are consistent with recent observed trends of lower spring snowpack across much of the United States (Mote et al., 2005; Knowles et al., 2006; Pierce et al., 2008). Results of variable infiltration capacity (VIC) model simulation also indicate a marked reduction in spring snow accumulation in mountainous basins across the southwestern United States (Cayan et al., 2013). The SRM future snow pack results corroborate the predictions of others that snowpack in the southwestern U.S. will continue to decrease (Garfin et al., 2013).

3.3. *Future runoff*

3.3.1. *Total annual runoff volume*

Total annual volume for all basins is 7% (warmer/wetter) to 8% (hotter/wetter) higher than present climate (computed) total annual volume in the wetter simulations. Total annual volume is 17–18% lower in drier simulations. In the base simulations representing the present climate, the simulated total annual volume delivered by the snowmelt basins of the URG is 2688 million m^3. With the future conditions of a changing climate, the total annual volume delivered is predicted to be 193–204 million m^3 more (wetter) to 448–476 million m^3 less (drier) than pre-climate change values. The drier simulations have more than twice the impact on total runoff volume as compared with wetter simulations indicating that it may take longer to recover from periods of sequential dry years. The implications of

Table 4
April first snow covered area and percent decrease in snow covered area in the Upper Rio Grande subbasins during base and climate change simulations (km^2).

Basin	Base	Hotter-drier		Hotter-wetter		Warmer-wetter		Warmer-drier	
	km^2	km^2	% Change	km^2	% Change	km^2	% Change	km^2	% Change
Alamosa	214	63	−71	63	−71	84	−61	63	−71
Carnero	81	5	−94	5	−94	8	−90	8	−90
Rio Chama	1070	771	−28	775	−28	1017	−5	779	−27
Conejos	545	139	−74	139	−74	316	−42	244	−55
Costilla	227	6	−97	6	−97	6	−97	6	−97
Culebra	340	159	−53	168	−51	218	−36	123	−64
DelNorte	3235	1611	−50	2124	−34	2682	−17	1845	−43
ElRito	38	14	−63	14	−63	18	−53	15	−61
Hondo	70	9	−87	9	−87	9	−87	9	−87
La Jara	149	81	−46	81	−46	81	−46	40	−73
LosPinos	250	128	−49	128	−49	128	−49	128	−49
Lucero	35	9	−74	9	−74	11	−69	9	−74
Ojo	178	0	−100	1	−99	45	−75	19	−89
Penasco	119	6	−95	7	−94	10	−92	9	−92
Taos	78	12	−85	12	−85	18	−77	16	−79
Red River	161	18	−89	18	−89	28	−83	3	−98
Rio Grande del Rancho	99	15	−85	15	−85	23	−77	17	−83
Saguache	458	61	−87	60	−87	82	−82	83	−82
San Antonio	117	42	−64	42	−64	66	−44	50	−57
Santa Barbara	75	54	−28	54	−28	54	−28	54	−28
Santa Cruz 1994	176	172	−2	172	−2	173	−2	172	−2
Santa Fe	11	10	−9	10	−9	10	−9	10	−9
Trinchera	78	73	−6	73	−6	73	−6	73	−6
Ute	14	1	−93	1	−93	5	−64	5	−64
Total	7818	3460	−56	3986	−49	5166	−34	3777	−52
San Juan	6335	2915	−54	3432	−46	4528	−29	3274	−48
Sangre de Cristo	1483	544	−63	554	−63	638	−57	504	−66

this on the overall water budget and sequential years must be included in management planning for future water resources. Del Norte, the basin with the highest streamflow, also showed a large decline in both of the drier simulations, but only a slight increase in the wetter simulations (Fig. 4).

3.3.2. *Runoff volume by subbasin*

Simulated total runoff by basin was lower than simulated pre-climate change runoff for most basins in the drier climate (Fig. 5). Typically, total annual runoff by basin reduced by 1% to 25% in drier conditions. Only Alamosa River showed a decline larger than 25%. Two basins (El Rito and Santa Cruz) showed a small increase in runoff during the warmer/drier climate (0.34–0.46 million m^3). The hydrographs of these subbasins show a large increase in April runoff. In the warmer/drier climate, percent change in total annual runoff by basin ranged from +2% to −29%. In the hotter/drier climate, percent change in total annual runoff by basin ranged from −4% to −30%.

In the wetter climate, the total annual runoff was generally 1–25% more than pre-climate change runoff (Fig. 4). Several basins had an increase higher than 25%, with the largest increase at Trinchera Creek (57%) in the hotter/wetter simulation. Several adjacent basins had a small decline in total runoff in the 'wetter' climate change simulations (Alamosa, Conejos and Los Pinos) up to a decline of 9%. The pre-climate change June hydrograph peak of these basins is shifted earlier and diminished for both Alamosa and Conejos subbasins (Appendix II). In the warmer/wetter climate, percent change in total annual runoff by basin ranged from −9% to +29%. In the hotter/wetter climate, percent change in total annual runoff by basin ranged from −7% to +57%.

3.3.3. *Shift in runoff timing*

3.3.3.1. Monthly. With simulation of climate change, 58–66% of the total annual volume is predicted to occur between April and July, as compared with 77% in the base simulation representing the present

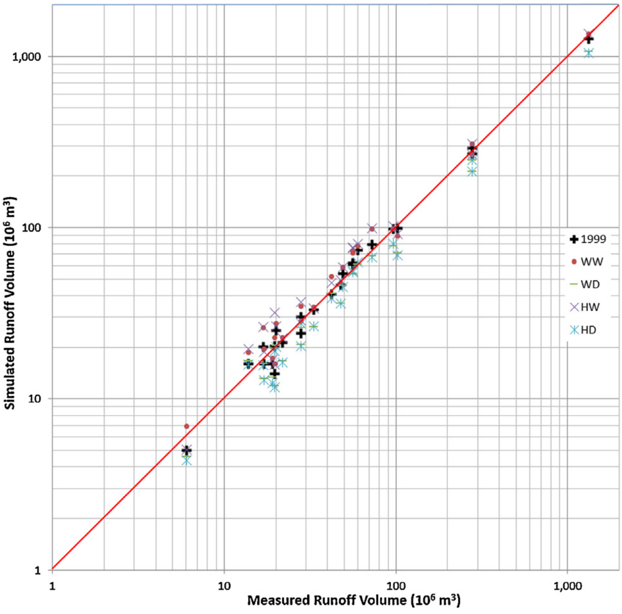

Fig. 4. Simulated vs. observed runoff volume for the pre-climate change and warmer/wetter, warmer/drier, hotter/wetter and hotter/drier simulations.

climate. This is partially attributable to a shift towards earlier springtime runoff. Runoff volume in March before climate change was 2% of the total annual volume whereas runoff volume in March of future climates was 6% (warmer/wetter) to 12% (hotter/drier) of the total annual volume. A similar shift in volume occurs in April, which represents 10% of the total pre-climate change volume and 22% (warmer/wetter) to 26% (hotter/drier) under climate change. An opposing shift in volume occurred in May, June and July wherein present climate simulations had a larger fraction of the total annual volume than future simulations. The increase in March streamflow volume was also documented in an analysis of measured streamflow in snowmelt-dominated rivers of the western United States (Regonda et al., 2005).

In the individual snowmelt basins of the URG, the percent of total annual volume occurring in between April and July in base simulations is between 47% and 86%. A shift to higher March volume is apparent in 94 of the 96 simulations reflecting the expected earlier runoff. Each basin shows a reduction in mean April to July volume. The mean pre-climate change April to July volume is 77% of the total annual volume, whereas the post-climate change April to July volume ranges from 66% (warmer/wetter) to 57% (hotter/drier).

3.3.3.2. Peak flow. Annual peak runoff occurs earlier due to the increased temperatures of a changed climate. The largest mean advance in 7-day maximum streamflow occurs for the hotter/drier scenario (25 days) and the smallest for the warmer/wetter scenario (14 days). The advance in streamflow timing by basin is fairly similar for the warmer/wetter, warmer/drier and hotter/wetter scenarios.

Most (11 of 13) basins of the Sangre de Cristo Range had an advance in the 7-day peak flow in all future climates. There is a region of the mid-Sangre de Cristo Range from Costilla Creek to Rio Grande del Rancho that has a 1–25 day advance in peak streamflow in all future climate scenarios. Culebra and Trinchera in the northern Sangre de Cristo range had a >1 month earlier peak flow in all but the warmer/wetter simulation. Rio Grande at Del Norte supplies nearly half the URG streamflow and peak streamflow advances 18–28 days for this basin. The five most productive basins (Del Norte, Rio Chama, Conejos, Alamosa and Los Pinos), producing 75% of the total streamflow in pre-climate change simulations, had an advance in mean 7-day peak streamflow between 31 (warmer/wetter)

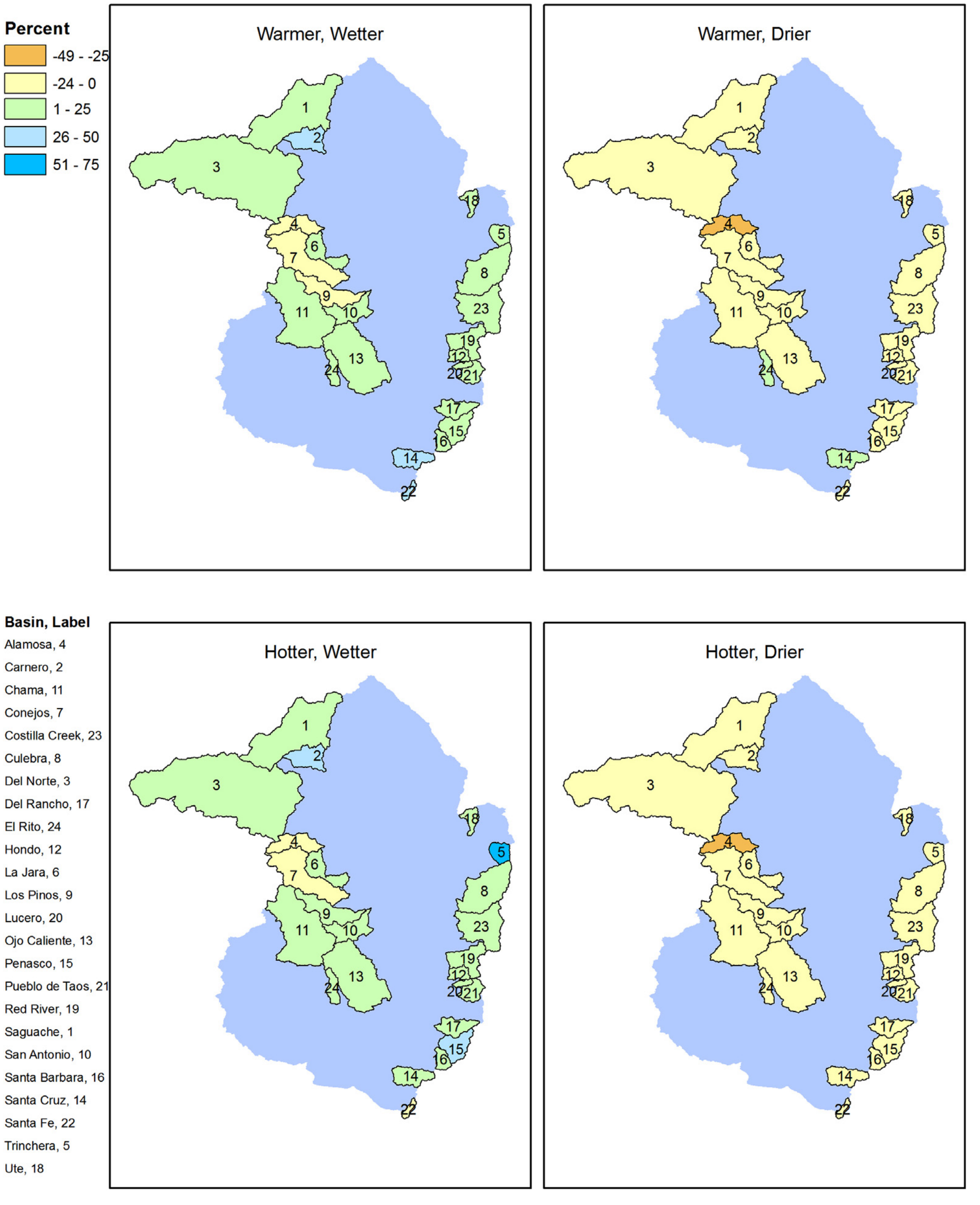

Fig. 5. Percent reduction in total annual runoff volume for subbasins of the Upper Rio Grande study area.

and 41 (hotter/drier) days. Several basins had no change or a slightly earlier 7-day peak runoff in at least three simulations (Saguache, El Rito and Ojo Caliente). While all three basins exhibit earlier runoff not captured in the 7-day peak analyses, the original peaks are retained in all but the most aggressive future climate scenario (hotter/drier). The hotter/drier simulation shows a much earlier peak for Saguache, Conejos and Ojo Caliente (Fig. 6). Conejos and Saguache Creeks have the largest advance in 7-day peak flow, which occurs 79 days earlier than in the pre-climate change simulation.

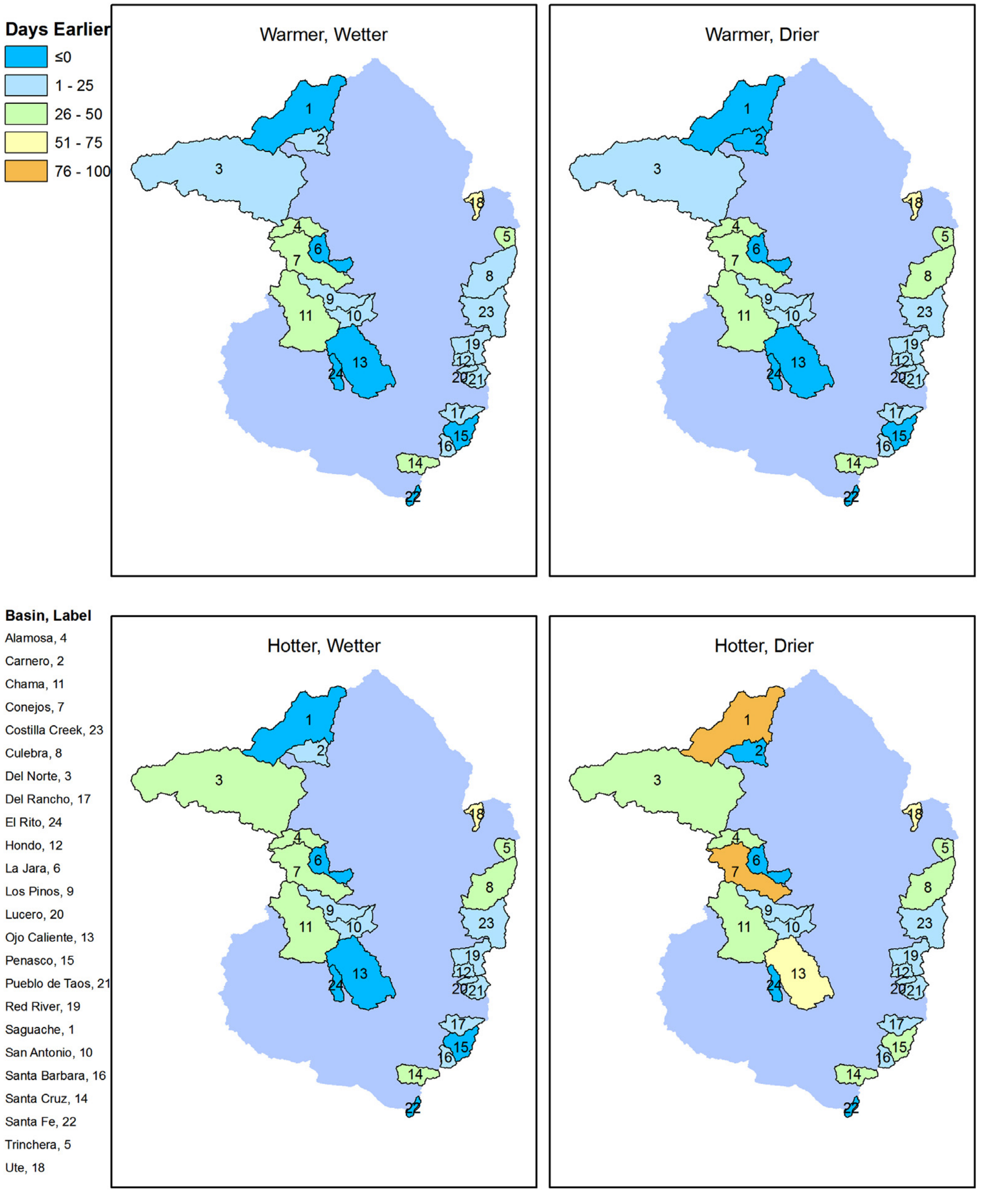

Fig. 6. Shift in runoff timing for basins of the Upper Rio Grande watershed.

Santa Fe is the only basin with much later peak flow, with the August peak becoming the largest peak in all climate change simulations.

The advance in 7-day peak flow appears the same for San Juan and Sangre de Cristo watersheds in all but the most aggressive climate change scenario. Both mountain ranges show an average advancement of 14 days (warmer/wetter), 15 days (warmer/drier), 16 days (hotter/wetter). The hotter/drier simulation shows the mean 7-day peak flow from the San Juan Mountains 31 days early while the

Table 5
Total runoff volume (millions of m^3) during 1999 and four future conditions to represent the warmer, wetter; warmer, drier, hotter, wetter and hotter, drier in future condition.

Basin	Base	Warmer, wetter	Warmer, drier	Hotter, wetter	Hotter, drier
Alamosa	103	90	70	92	69
Carnero	20	26	16	26	16
Chama	290	309	248	308	247
Conejos	270	268	212	267	211
Costilla Creek	62	73	54	76	55
Culebra	54	59	46	59	45
Del Rancho	30	35	26	37	27
Del Norte	1269	1363	1066	1352	1042
El Rito	16	19	17	20	16
Hondo	24	28	21	28	20
La Jara	16	20	13	19	13
Los Pinos	98	98	78	102	81
Lucero	14	16	12	16	12
Ojo Caliente	74	78	60	80	62
Penasco	61	71	53	77	56
Pueblo de Taos	21	23	17	23	16
Red River	46	47	36	49	36
Saguache	80	98	69	98	67
San Antonio	25	28	21	27	20
Santa Barbara	33	34	26	34	27
Santa Cruz	41	52	41	48	38
Santa Fe	5	7	5	5	4
Trinchera	20	23	20	32	19
Ute	16	17	13	17	12
Total	2688	2881	2240	2892	2212
San Juan	2262	2396	1870	2392	1844
Sangre de Cristo	426	485	369	500	368

mean 7-day peak flow from the Sangre de Cristo Mountains is 19 days early. In the hottest and driest simulated future condition, the San Juan peak was about 1 month early. There has also been a documented advance in the timing of peak spring season flows over the past 50 years (Regonda et al., 2005). Snow-fed streamflow arrived 5–20 days earlier in the recent decade compared to twentieth century averages (Stewart et al., 2005).

3.3.4. *Runoff volume by mountain range*

The San Juan Mountains supply roughly 84% of the total volume from the study basins in present and future scenarios (Table 5). With future temperature and precipitation, the Sangre de Cristo Mountains will continue to supply an important source (17%) of Rio Grande streamflow. In future, the Sangre de Cristo Mountains retain a snowmelt hydrograph that peaks in May (Fig. 7). All climate change simulations show a shift in the Sangre de Cristo Mountains from a moderate rising and falling limb of the hydrograph to a sharp peak in early May with less flow from mid-May to early July. The wetter scenarios for the Sangre de Cristo Mountains showed a higher peak than the base scenario. This increase in hydrograph peak was evident only in the warmer/wetter scenario of the San Juan Mountains, indicating that the impact of elevated temperature on streamflow of the hotter/wetter simulation outweighed the increase in precipitation of that scenario. The San Juan Mountains exhibit an earlier rising limb in all climate change scenarios than the base simulation, with the rising limb commencing in early March to a peak in April. The falling limb of the hydrograph shows a broad difference between the hotter/drier and the warmer/wetter climate, but all simulations depict less San Juan water available between May and August than the base simulation representing present climate. The implications of this are that in wetter years in basins of the URG, if temperature increase is between 3.1 and 4.5 °C, then there may be an opportunity to capture the elevated runoff from earlier snowmelt and the somewhat higher peak flow. Additionally in these warmer/wetter years, there may be more shallow groundwater infiltration and storage, making flow available to the stream later in the year. Both warmer/drier and hotter/drier

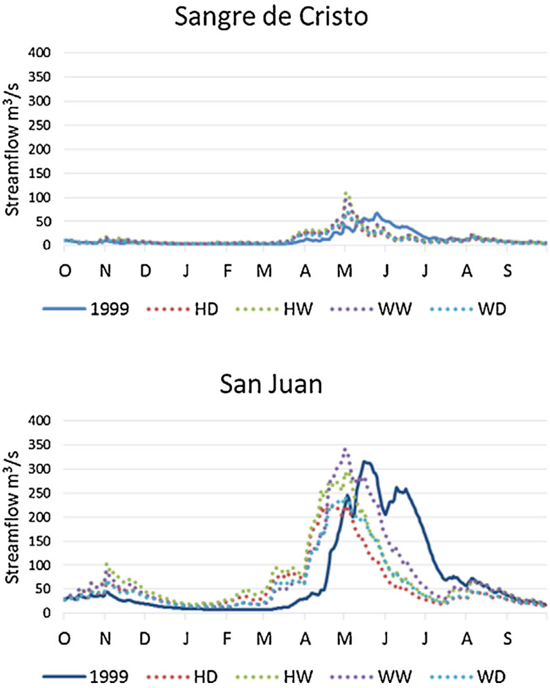

Fig. 7. Daily streamflow for base and climate change simulations by mountain range.

simulations show an earlier and lower peak for both mountain ranges with much less water available from May to August in the San Juan Mountains and May to July in the Sangre de Cristo Mountains.

In the subbasins of the Sangre de Cristo mountain range, total annual volume increases during wetter simulations by 13–17% and decreases during drier simulations by 13–14%. In the San Juan subbasins, total annual volume increases by 6% in wet climates, but decreases by 17–18% in the dry simulations. Thus, the basins of the San Juan Mountains, while they supply more than 80% of the total annual runoff, will not have as large an increase in runoff during the wet years of a future climate, possibly limiting subbasin recovery following dry years. The Sangre de Cristo basins appear more directly influenced by precipitation changes, with total annual volume increasing and decreasing by the same proportion in wetter and drier simulations. A study of observed runoff trends in Northern New Mexico showed that streams draining the Sangre de Cristo Mountain range have shifted from clearly snowmelt dominated to increasingly rain dominated from 1948 to 2008, but this trend was not observed in the San Juan Mountain Range (Fritze et al., 2011).

Many of the subbasin hydrographs show an exaggerated hydrograph peak following climate change (i.e. Costilla Creek, Rio Grande del Rancho, Rio Lucero, Rio Hondo, Pueblo de Taos, Red River, Santa Cruz, Santa Barbara and Ute Creek). This peak is especially evident in the basins of the Sangre de Cristo Mountains, implying possible future challenges in capturing the peak runoff of these basins for future use. Of the 13 Sangre de Cristo subbasins, only Culebra Creek and Santa Fe River do not have an increase in hydrograph peak during climate change simulations. Other basin hydrographs exhibit a more gradual shift in earlier runoff, but without a large increase in hydrograph peak (i.e., Del Norte, Conejos and Alamosa). This increase in hydrograph peak and the shift in earlier runoff will present water management challenges since there will be less available water between May and September, a time of elevated temperatures and high water demand.

Three areas of the URG had little or no SCA in future climates and appear to lose their characteristic snowmelt hydrographs (northern San Juans (Carnero and Saguache Creeks); southern San Juans (El Rito and Ojo Caliente); central Sangre de Cristos (Costilla Creek, Red River, Rio Hondo, Rio Grande del

Rancho and Rio Pueblo near Penasco). The basins of these areas had limited or no advancement in 7-day peak flow. Basins of the northern and southern San Juan mountains had rapid snowmelt in the pre-climate change simulations in most zones. This was further exacerbated by climate change. Low elevation and a relatively small elevation range may contribute to the low snow cover at the onset of snowmelt for the 4th largest subbasin (Ojo Caliente). The Sangre de Cristo Mountains have a west facing slope and temperature and solar radiation may be more direct during the warmest part of the day, leading to increased earlier snowmelt and the observed shift to rainfall dominance. Unlike other regions, the wetter and drier simulations of these basins generally have a similar increase or decrease in percent volume change. In future climates, precipitation in these basins may shift from snow to rain, changing the snow-melt dominated nature of these subregions of the greater URG.

3.3.5. Management implications

Results show wetter years with more total runoff and drier years with less, however the magnitude of the change varies by simulation, with wetter simulations having a 7% increase in total annual volume, but drier simulations having a 16–18% decrease in total annual volume. The climate change effects in the San Juan mountain range on total volume are driving the apparent larger decrease in total annual volume in dry years, leading to important information for management planning. In the subbasins of the Sangre de Cristo mountain range, total annual volume increases during wetter simulations by 13–17% and decreases during drier simulations by 13–14%. In the San Juan subbasins, total annual volume increases by 6% in the wet simulations, but decreases by 17–18% in the dry simulations. Thus, the basins of the San Juan Mountains, while they supply more than 80% of the total annual runoff, will recover less quickly from prolonged dry periods in a future climate. The Sangre de Cristo appear more directly influenced by precipitation changes, with total annual volume increasing and decreasing by the same proportion in wetter and drier simulations. Especially in the San Juan subbasins of the URG, sequential dry years could further impact the water deficit produced by climate change in dry years, extending the time required for recovery following drought.

Peak runoff for the five subbasins producing 75% of the total annual runoff was 31–41 days earlier than pre-climate change peak runoff. This advance in runoff timing may impact downstream agricultural and municipal water use.

The large increases in hydrograph peaks in many basins, especially Sangre de Cristo basins, may alter the ability of downstream users to capture and utilize peak runoff. It may also increase downstream flooding and change shallow groundwater infiltration, which has been shown as an important attribute of URG hydrology.

Before the water from many of the simulated basins reaches the Rio Grande mainstem, it is often used for irrigation or human consumption. Traditional irrigation communities, or acequias, apply water for irrigation, some of which becomes shallow groundwater and eventually returns to the river as return flow. The predicted early runoff may be somewhat offset by acequia irrigation within the URG if acequia communities are able to adjust planting and irrigation schedules to make use of early future snowmelt runoff. Fernald et al. (2010) instrumented an irrigated valley in the URG to measure the water balance. They report that of the river water diverted into the irrigation canal system, 32% of the water is returned to the river later in the year. Evaluation of the return flow function in conjunction with future runoff simulation will provide an estimation of the delayed river return flow for the benefit of acequia irrigation in a future climate.

Snowmelt is the main source for URG water. Four of the five basins that retain the largest mean melt season SCA in climate change simulations are located in the San Juan Mountains (Del Norte, Rio Chama, Conejos and Los Pinos). Presently the Sangre de Cristo range has 19% of the URG SCA on 1 April as compared with 12–16% in a changed climate. This indicates that under a changing climate, the San Juan Mountains will contain a large proportion of the snowpack vital to maintaining regional water supplies.

Results, however, also showed that reduction in snow covered area and precipitation varied by basin indicating that in future conditions, some subbasins will remain more resilient than others. In general, some large basins of the San Juan mountain range retained the most mean melt season snow covered area (Del Norte, Chama, Los Pinos and Conejos). The mean melt season SCA of the New Mexico Sangre de Cristo basins was 16% of the total SCA in pre-climate change simulations and 9–12%

of the total SCA following climate change. This decrease indicates these basins will be more rainfall dominated in the future. Measured data has already suggested this change is occurring (Fritze et al., 2011). The changes in total volume and runoff timing may necessitate adaptation, such as adjusting agricultural schedules, altering legislation to provide for more water sharing, or evaluating the existing water sharing mechanisms of the traditional acequia communities.

4. Conclusions and future directions

Here we describe the impact of four statistically selected future climate scenarios at the end of the 21st century on water resources of the water-limited URG basin. SRM simulation shows that total annual post-climate change volume for all basins was between 7% higher to 18% lower than pre-climate change computed total annual volume. The mean melt season total snow covered area in the simulated basins decreased by 57–82%. Before climate change the New Mexico Sangre de Cristo Mountains retain 17% mean melt season SCA. Post-climate change, the proportion is 9–13%. Our results are consistent with recent observed trends of lower spring snowpack across much of the United States.

Annual peak runoff occurs earlier due to the increased temperatures of a changed climate. Some of the largest and most productive basins of the San Juan Mountains produce the earliest 7-day maximum flow, predicted to be a month earlier or more. Since these basins collectively supply 75% of the total URG volume in 1999, the shift to earlier runoff may pose management challenges for URG water managers. More challenging from a water management perspective will be the decreased streamflow in May, June and July, months with high water demand. The 2002 hydrologic drought caused measured streamflow conditions more severe than those reported in this climate change simulation indicating that the SRM predicted changes are within previously observed values.

Although the basins are situated within a relatively small area of the mountainous western United States, there is a wide range in snow covered area and annual volume reduction, as well as earlier peak flow. Future temperature unique to the weather station and specific basin characteristics influence this variation even among adjacent basins. This indicates the importance of planning for a changed climate at a subbasin scale, especially in mountainous regions where large elevation gradients have an influence on temperature and precipitation. Climate change analysis at the subbasin scale also affords a more informed planning of regional water management.

Daily hydrographs for the snowmelt basins show higher streamflow in March and April, but less from mid-May until the end of the water year. Annual precipitation variability, especially in the southwestern United states, is a source of uncertainty and a challenge to future planning. While there is considerable agreement regarding predicted future temperature, future precipitation results exhibit a larger range of variability and considerably less certainty (Cayan et al., 2013).

SRM proved to be a fairly rapid and effective model for climate change simulations on 24 URG subbasins. Several recommendations evolved from this effort. First, because of the differences in measured and computed volume of the initial basin simulations, evaluating the impacts of climate change should be conducted by comparing results with initial SRM simulations rather than measured values. Second, we recommend criteria for initial SRM measured vs. computed volume of <10% prior to conducting climate change simulations. Third, researchers often use the April–July timeframe to represent spring snowmelt runoff. There is a documented shift towards an earlier onset of snowmelt, often in March. Representing climate change with an April–July timeframe may be misleading since it combines the increase in April flow with the decrease in June and July streamflow. Changes in March to August monthly flow volume better represent the impact of climate change on snowmelt basins.

This study confirms the work of others on the impacts of climate change on snowmelt basins. Results show that total volume will decrease or increase in accordance with future climate scenario. Regardless of scenario, streamflow will be earlier due to the influence of warming temperatures. The study adds to previous work by showing the wide range of climate change impacts on snowpack, streamflow and runoff timing even on adjacent basins within a relatively small region. It also provides an assessment to allow for a range of results associated with future drier and wetter precipitation projections. Finally, it provides an evaluation of the least affected basins under a changed climate for planning and management purposes and a methodology to perform similar assessments elsewhere.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ejrh.2015.04.004.

References

Cayan, D.R., Tyree, M., Kunkel, K.E., Castro, C., Gershunov, A., Barsugli, J., Ray, A.J., Overpeck, J.T., Anderson, M., Russell, J., Rajagopalan, B., Rangwala, I., Duffy, D., 2013. The southwest climate of the future – projections of mean climate. In: Garfin, G. (Ed.), Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment. NCA Regional Input Reports. Island Press, Washington, DC, p. 509.

Colorado Division of Water Resources. 2008. Daily Streamflow Data. http://cdss.state.co.us/onlineTools/Pages/StreamflowStations.aspx

Environmental Systems Resource Institute. 2011. ArcGIS. Redlands, California: ESRI. http://www.esri.com

Fernald, A.G., Cevik, Y., Ochoa, C.G., Tidwell, V.C., King, P., Guldan, S.J., 2010. River hydrograph retransmission functions of irrigated valley surface water–groundwater interactions. J. Irrigation Drainage Eng. 136 (12), 823–835, http://dx.doi.org/10.1061/_ASCE_IR.1943-4774.0000265.

Fritze, H., Stewart, I.T., Pebesma, E., 2011. Shifts in Western North American snowmelt runoff regimes for the recent warm decades. J. Hydrometerol. 12, 989–1006.

Garfin, G., Jardine, A., Merideth, R., Black, M., LeRoy, S. (Eds.), 2013. Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment. A report by the Southwest Climate Alliance. Island Press, Washington, DC.

Gutzler, D.S., Garfin, G., Zak, B., 2006. Observed and predicted impacts of climate change on New Mexico's Water supplies. In: Watkins, A. (Ed.), The Impact of Climate Change on New Mexico's Water Supply and Ability to Manage Water Resources. New Mexico Office of the State Engineer/Interstate Stream Commission. Santa Fe, New Mexico, pp. 4–32.

Khadka, D., Babel, M., Shrestha, S., Tripathi, N., 2014. Climate change impact on glacier and snow melt and runoff in Tamakoshi basin in the Hindu Kush Himalayan (HKH) region. J. Hydrol. 511 (2014), 49–60.

Knowles, N., Dettinger, M.D., Cayan, D.R., 2006. Trends in snowfall versus rainfall in the western United States. Journal of Climate 19, 4545–4559.

Kunkel, K.E., Stevens, L.E., Stevens, S.E., Sun, L., Janssen, E., Wuebbles, D., Redmond, K.T., Dobson, J.G., 2013. Regional Climate Trends and Scenarios for the U.S. National Climate Assessment. NOAA Technical Report NESDIS 142-5.

Llewellyn, D., Vaddey, S., 2013. West-Wide Climate Risk Assessment: Upper Rio Grande Impact Assessment. US Department of the Interior. Bureau of Reclamation. Albuquerque Area Office, Upper Colorado Region, http://www.usbr.gov/WaterSMART/wcra/docs/urgia/URGIAMainReport.pdf

Maurer, E.P., Hidalgo, H.G., Das, T., Dettinger, M.D., Cayan, D.R., 2010. The utility of daily large-scale climate data in the assessment of climate change impacts on daily streamflow in California. Hydrol. Earth Syst. Sci. 14, 1125–1138, http://dx.doi.org/10.5194/hess-14-1125-2010.

Martinec, J., 1975. Snowmelt-Runoff Model for Streamflow Forecasts. Nordic Hydrology 6 (3), 145–154.

Martinec, J., 1980. Snowmelt Runoff Forecasts Based on Automatic Temperature Measurements. IAHS Symposium, Oxford, pp. 239–246, IAHS Publ. No. 129.

Martinec, J., Rango, A., Roberts, R., 2008. Snowmelt Runoff Model (SRM) User's Manual. New Mexico State University, Las Cruces, New Mexico, http://aces.nmsu.edu/pubs/research/weather_climate/SRMSpecRep100.pdf.

Mejia, J.F., Huntington, J., Hatchett, B., Koracin, D., Niswonger, R.G., 2012. Linking global climate models to an integrated hydrologic model: using an individual station downscaling approach. J. Contemp. Water Res. Educ. 147, 17–27, http://dx.doi.org/10.1111/j.1936-704X. 2012.03100.x.

Mote, P.W., Hamlet, A.F., Clark, M.P., Lettenmaier, D.P., 2005. Declining mountain snowpack in western North America. BAMS., 39–49.

Natural Resources Conservation Service. 2013. SNOTEL Data and Products. http://www.wcc.nrcs.usda.gov/snow/

Nash, L.L., Gleick, P.H., 1993. The Colorado River Basin and Climatic Change: the Sensitivity of Streamflow and Water Supply to Variations in Temperature and Precipitation. U.S Environmental Protection Agency, EPA230-R-93-009.

NOAA National Climate Data Center, 2013. NCDC Announces Warmest Year on Record for Contiguous U.S. Online, Available from: <http://www.ncdc.noaa.gov/neas/ncdc-announces-warmest-year-record-contiguous-us> (accessed 12.01.13).

Panday, P.K., Williams, C.A., Frey, K.E., Brown, M.E., 2013. Application and evaluation of a snowmelt runoff model in the Tamor River basin in the eastern Himalaya using Markov Chain Monte Carlo (MCMC) data assimilation approach. Hydrol. Process., http://dx.doi.org/10.1002/hyp.10005.

Pierce, D.W., Barnett, T.P., Hidalgo, H.G., Das, T., Bonfils, C., Santer, B.D., Bala, G., Dettinger, M.D., Cayan, D.R., Mirin, A., Wood, A.W., Nozawa, T., 2008. Attribution of declining western U.S. snowpack to human effects. J. Climate 21, 6425–6444, http://dx.doi.org/10.1175/2008JCLI2405.1.

Rajagopalan, B., Nowak, K., Prairie, J., Hoerling, M., Harding, B., Barsugli, J., Ray, A., Udall, B., 2009. Water supply risk on the Colorado River: can management mitigate? Water Resour. Res. 45, W08201.

Rango, A., 2006. Snow: the real water supply for the Rio Grande basin. N. M. J. Sci., volume 44.

Rango, A., Martinec, J., 1997. Water storage in mountain basins from satellite snow cover monitoring, Remote sensing and geographic information systems for design and operation of water resources systems (Proceedings of Rabat Symposium S3 April 1997) , IAHS Publ. no. 242.

Rango, A., Martinec, J., 2000. Hydrological effects of a changed climate in humid and arid mountain regions. World resource review 12 (3), 493–508.

Reclamation, 2008. "Sensitivity of Future CVP/SWP Operations to Potential Climate Change and Associated Sea Level Rise," Appendix R in Biological Assessment on the Continued Long-term Operations of the Central Valley Project and the State Water Project, prepared by Bureau of Reclamation, U.S. Department of the Interior, August 2008, 134 pp.

Regonda, S.K., Rajagopalan, B., Clark, M., Pitlick, J., 2005. Seasonal cycle shifts in hydroclimatology over the Western United States. J. Clim. 18, 372–384.

Stewart, I.T., Cayan, D.R., Dettinger, M.D., 2005. Changes toward earlier streamflow timing across western North America. J. Climate 18, 1136–1155, http://dx.doi.org/10.1175/JCLI3321.1.

U.S. Forest Service, 2011: Remote Automated Weather Stations Data. http://www.raws.dri.edu/

U.S. Geological Survey. 2001. National Water Information System Data. http://waterdata.usgs.gov/nwis/

Woodhouse, C.A., Stahle, D.W., Villanueva-Díaz, J., 2012. Rio Grande and Rio Conchos Water Supply Variability from Instrumental and Paleoclimatic Records. Clim. Res. 51, 147–158.

van Katwijk, V.F., Rango, A., Childress, A.E., 1993. Effects of Simulated Climate Change on Snowmelt Runoff Modeling in Selected Basins. Water Resour. Bull. 29 (5), 755–766.

WMO (World Meteorological Organization), 1986. Intercomparison of Models of Snowmelt Runoff. Operational Hydrology. WMO, Geneva, Switzerland, Report 23.