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Determining the importance of seasonality on groundwater recharge and streamflow in the Sangre de Cristo Mountains using stable isotopes

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DETERMINING THE IMPORTANCE OF SEASONALITY ON GROUNDWATER RECHARGE AND STREAMFLOW IN THE SANGRE DE CRISTO MOUNTAINS USING STABLE ISOTOPES

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ABSTRACT—In western states like New Mexico, where nearly all surface-water is derived from mountainous watersheds, it is becoming increasingly important to determine the sources that contribute to surface-water and provide recharge to groundwater, both spatially and temporally. The stable isotopes ^{18}O and ^{2}H were used to determine the influence of seasonal inputs of precipitation on groundwater recharge and streamflow in the Rio Hondo watershed, which is believed to be broadly representative of the Sangre de Cristo Mountains for similar climatic and orographic conditions. Precipitation collected during the winter and spring months showed δ^{18}O ranged from about -19 to -12‰, while summer and monsoon precipitation ranged from about -8 to -5‰. Surface-water, spring-water, and groundwater samples collected on a monthly to sub-monthly basis had mean δ^{18}O values of -14.3 ±0.7‰ (n=115), -13.9 ±1.2‰ (n=54), and -14.1 ±0.9‰ (n=56), respectively, which all fall within the winter and spring precipitation range. Using a simple two-component mixing model to determine the fractions of seasonal precipitation in samples, winter and spring precipitation account for about 68–88% of groundwater recharge and streamflow in the Rio Hondo while it only makes up about 45–55% of total annual precipitation. Therefore, reduction in the amount and duration of snowpack predicted by climate change will result in a disproportionate reduction of groundwater recharge and ultimately streamflow in the Rio Hondo watershed, and by extension similar watersheds in the Sangre de Cristo Mountains.

INTRODUCTION

With growing concerns about declining snowpack, warmer temperatures, and land use changes, it is becoming increasingly important to determine the sources that contribute to surface-water and provide recharge to groundwater. In semi-arid regions, such as New Mexico, nearly all surface-water is derived from mountainous watersheds where it is released from the snowpack in the spring and early summer when economic, environmental, and recreational demands are greatest (Winograd et al., 1998; Mote et al., 2005; Bales et al., 2006). Current climate models predict warmer temperatures, resulting in decreased snowpack and earlier snowmelt (Cayan et al., 2001; Mote et al., 2005; Barnett et al., 2005). While it is unclear whether climate change will affect total annual precipitation, it is almost certain that the proportion of precipitation that falls as snow will decrease (Barnett et al., 2005; Adam et al., 2009) with warming climate.

Precipitation in New Mexico generally falls either during the winter and early spring as snow or during the summer and fall monsoons as rain. This seasonality of precipitation is important because snowmelt generally results in a larger groundwater recharge fraction than its contribution to total annual precipitation would suggest (Wilson et al., 1980; Earman et al., 2006; Wahi et al., 2008). This is due to the low intensity and long duration of snowmelt, as opposed to the high intensity and short duration of monsoon storm events. A recent study in the Rio Hondo watershed in the Sangre de Cristo Mountains near Taos using end-member mixing analysis (EMMA) indicated that groundwater is a major contributor to surface water throughout the year, even during the snowmelt pulse (Tolley et al., unpubl. 2015). Therefore, understanding how groundwater recharge and streamflow are partitioned seasonally is an important step towards predicting how these mountain watersheds will behave under future climate change scenarios.

It is commonly assumed that recharge is a fraction of total annual precipitation (Schwartz and Zhang, 2003). This may be misleading because it assumes that all precipitation has an equal chance of making it past the root zone and contributing to groundwater recharge. In mountainous watersheds in the southeastern and midwestern U.S., recharge is likely not seasonally dependent because precipitation shows weaker trends with season. However, if recharge is seasonally dependent, then it may be more appropriate to express recharge as a percentage of the total annual SWE (snow water equivalent; water available for recharge) rather than total annual precipitation.

This study uses the stable isotopic composition of precipitation to explore how seasonality in precipitation influences groundwater, surface-water, spring-water, and soil-water isotopic compositions in the Rio Hondo watershed. Stable isotopes of water ^{18}O and ^{2}H were used as they provide information on the timing of recharge and physical processes such as evaporation. Our hypothesis is that groundwater recharge and streamflow are dominated by winter precipitation due to slow melting of the snowpack and deep percolation below the root zone when evapotranspiration (ET) demand is low. Although the isotopic data collected in this study are only from a single watershed, we believe that the process understanding gained from this work is broadly applicable to other catchments in the Sangre de Cristo Mountains under similar climatic and orographic conditions. We demonstrate this by comparing SNOTEL (short for snow telemetry) station data from the Rio Hondo with other stations in the area to show that the Rio Hondo has similar precipitation patterns and temperatures, both of which exert control on the isotopic composition of surface-water and groundwater.

STUDY AREA

The Rio Hondo watershed is located in northern New Mexico on the western side of the Sangre de Cristo Mountains about 50 km south of the Colorado border (Fig. 1). From its headwaters in the east, the perennial Rio Hondo flows approximately 32 km to the Rio Grande in the west. The watershed drainage area is approximately 190 km^2 and ranges from 1971–4013 m above mean sea level (m.a.s.l.).

Two distinct geologic landforms make up the watershed: the mountain block and the Taos Valley. The mountain block is comprised of Precambrian gneisses, schists, and mafic metavolcanics (Gruner, 1920; Clark and Read, 1972; Condie, 1979) with Tertiary granodiorite to granitic intrusions (Clark and Read, 1972; Johnson et al., 1989) and predominantly quartz monzonite, felsic gneiss, amphibolite, quartzite, and minor quartz mica schist. The Taos Valley is composed primarily of alluvial sediments and basalt flows (Rawling, 2005) and is part of the southern extent of the San Luis Valley. These two landforms are separated by the Sangre de Cristo fault, part of the Rio Grande rift zone that extends from central Colorado to Mexico (Rawling, 2005). Estimates of total displacement on the fault are up to 7 to 8 km (Lipman and Mehnert, 1979), although most of it is buried by young sediments and currently unexposed. Fault geometry ranges from essentially a single lineament in the north to several buried faults accommodating deformation in the south (Rawling, 2005). There are also several mapped faults within the mountain block itself including normal and thrust faults (Lipman and Mehnert, 1979), which together with the Sangre de Cristo fault have formed an extensive fractured zone.

Climate in the Rio Hondo watershed is semiarid with mild to moderate summers and cold winters. The topographic differences between the mountain block and the valley result in markedly different climates. Average annual precipitation ranges from 48.2–99.0 cm on the mountain range, while, in contrast, the average annual precipitation ranges from 28.0–45.7 cm in the valley (OSU, 2012; NRCS, 2015). Annual precipitation is nearly evenly split between the winter/spring and summer/monsoon precipitation seasons. However, only approximately 33% of the total annual precipitation on the mountain range falls as snow and only 13 to 18% falls as snow in the valley (Garrabrant, 1993).

Sampled springs were perennial and primarily located in the upper portions of the watershed, although one large spring emerged just outside of the mountain block. Flow rates at springs were not measured but appeared to be consistent throughout the year at each site, ranging from approximately half a liter per minute up to about one hundred (or more) liters per minute at the overflow for the developed Village of Taos Ski Valley spring (RHS-04). Nearly half of the wells sampled were located within the mountain block, although screened depth information was not available.

METHODS

Precipitation was collected seasonally in two to three month intervals between September 2011 and March 2013 from six bulk collectors located from 3643 m.a.s.l. (ISO-01) to 2057 m.a.s.l (ISO-06) with roughly equal elevation spacing. Collectors were 4 in diameter acrylonitrile butadiene styrene (ABS) or polyvinyl chloride (PVC) tubes sealed on one end with a cemented cap with no internal barriers or constrictions (see Earman et al., 2006, fig. 1). Mineral oil was placed in the collectors with a sufficient thickness to prevent evaporation (Friedman et al., 1992). The low density of the oil (about 0.8 gcm^{-3}) allows snow or rain to sink below the oil quickly, minimizing postfall fractionation (Earman et al., 2006).

Sample volumes were measured to provide a weighted seasonal average, with ^{18}O and ^{2}H analyzed using a Picarro L1102-*i* Isotopic Water Liquid Analyzer cavity ringdown spectrometer at the New Mexico Tech Stable Isotope Laboratory. Samples were analyzed a total of six times sequentially with the first three runs excluded to eliminate possible system memory effects, and the sample result being an average of the last three runs. Corrections were applied using internal standards and results are reported in per mil (‰) notation relative to Vienna Standard Mean Ocean Water (VSMOW). Typical permil precision for δ^{18}O and δ^{2}H was less than 0.1‰ and 0.5‰, respectively. When duplicate samples were collected, the mean of the two samples was used to prevent statistical bias of those samples.

Samples of surface-water, groundwater, and spring-water, denoted with sample prefixes of RHR, RHW, and RHS, respectively, were collected throughout the watershed from March 2012 to March 2013 (Fig. 2). The majority of these samples were collected on a monthly or sub-monthly time interval. The stable isotopic composition of these samples was determined using the methods described above.

Grab samples of soil were collected at the two highest precipitation collector sites (ISO-01 and ISO-02) and vacuum distilled to obtain the pore water according to the procedures described by Knowlton (1990). Modified passive capillary samplers (PCAPS) were installed at these two locations from October 20th, 2012 to June 29th, 2013 according to the methods described by Frisbee et al. (2009) in order to obtain a time-integrated snowmelt signature in the soil. Wick samplers were sheathed with polyvinyl chloride (PVC) tubing, except for the portion in contact with the soil, and emptied into separate one gallon containers housed in a 48 quart ice chest. Holes were drilled into the top of the ice chest to pass the PVC sheath and wick through to the sample containers. These holes were subsequently sealed with silicon to prevent any snowmelt from leaking in. Sample containers within the ice chest were filled with approximately 250 mL of mineral oil to prevent evaporation. Each PCAPS installation contained four wick samplers with the wicks placed into two specific soil horizons at each site. Opposite walls of the soil pit had a wick placed in both the upper and lower soil horizon. PCAPS-1 had two upper wicks placed in a clay loam at 15 and 18 cm below ground surface (bgs), and two lower wicks placed in a silty clay at 49 and 51 cm bgs. PCAPS-2 had two upper wicks placed in a silty clay at 25 cm and 29 cm bgs, and two lower wicks placed in a clay loam at 41 cm and 42 cm bgs. Stable isotopic ratios from samples obtained from the soil grab samples and PCAPS were measured using the methods described above.

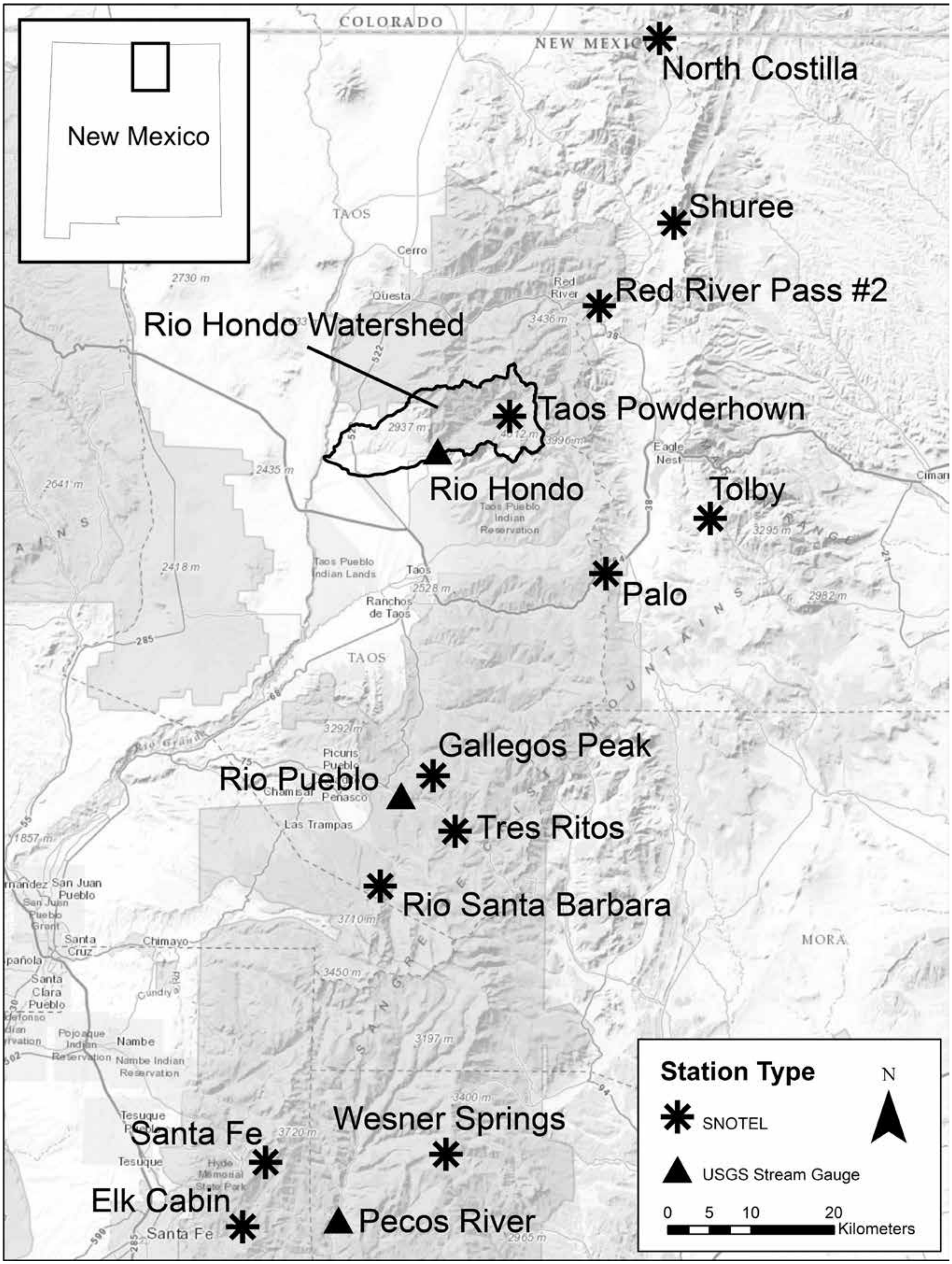

FIGURE 1. Location of the Rio Hondo watershed (shown in Fig. 2), Sangre de Cristo SNOTEL (short for snow telemetry) stations, and USGS stream gauging sites used for hydrograph comparisons.

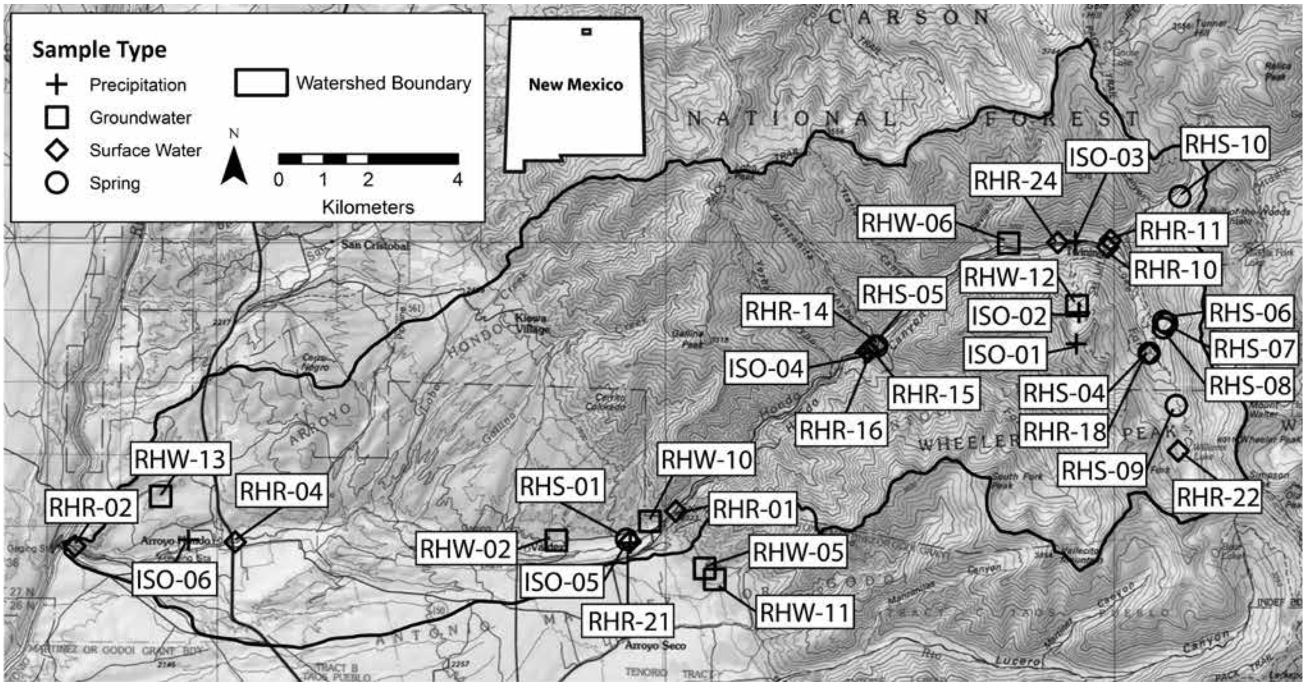

FIGURE 2. Map of the Rio Hondo watershed showing sampling locations. PCAPS -01 and PCAPS-02 are co-located with ISO-01 and ISO-02, respectively.

Precipitation and temperature data were obtained from the 12 New Mexico SNOTEL stations located in the Sangre de Cristo Mountains (Fig. 1) to compare how representative conditions in the Rio Hondo watershed are for the rest of the Sangre de Cristo Mountains. SNOTEL stations are generally located in remote, high-elevation mountain watersheds where access is difficult or restricted. Data are collected every 15 minutes and reported as daily values of snow water equivalent (SWE, in.), water year accumulated precipitation (in.), maximum air temperature (°F), minimum air temperature (°F), average air temperature (°F), and precipitation (in.) in near real-time using meteor burst communications technology. Conditions at each station are monitored daily to check for serious problems or deteriorating performance.

Seasonal precipitation amounts were determined for the winter and spring seasons, defined here as lasting from October 1st to March 31st, and for the summer and fall seasons, defined as lasting from April 1st to September 30th. For the purpose of convenience we will hereafter refer to the winter and spring seasons generally as the winter season, and the summer and monsoon seasons generally as the monsoon season to reflect the bimodal distribution of precipitation in the watershed. Mean seasonal temperatures were calculated by averaging mean daily temperatures recorded by the SNOTEL stations.

Streamflow data were obtained from the U.S. Geological Survey (USGS) Rio Hondo gauging station (08267500) near Valdez, NM for the period of record (1935–2014). The mean of the average daily streamflow for each day of the year (excluding leap days) was calculated and then normalized to the maximum average daily mean for the same dataset. The same was done for the Pecos River (1930–2014) near Pecos, NM and the Rio Pueblo (1992–2014) near Peñasco, NM. This allowed comparison of hydrographs for several streams located in the Sangre de Cristo Mountains (see Fig. 1 for stream gauge locations), even though absolute flows between streams were not of the same magnitude. The maximum average daily streamflow used to normalize the average daily streamflow was 3.5 m^3s^{-1}, 11.4 m^3s^{-1}, and 7.4 m^3s^{-1} for the Rio Hondo, Pecos River, and Rio Pueblo, respectively.

Since stable isotopes mix conservatively, the seasonal contributions to annual groundwater recharge and streamflow can be estimated using a simple two-component mixing model defined by

$$\delta^{18}O_{sample} = F_{wp}\delta^{18}O_{wp} + (1 - F_{wp})\delta^{18}O_{sp}$$

where F_{wp} is the percentage of winter precipitation in a given sample and $\delta^{18}O_{wp}$ and $\delta^{18}O_{sp}$ are the average isotopic compositions of winter and monsoon precipitation, respectively. Rearranging Equation 1 to solve for the fraction of winter precipitation that contributes to groundwater recharge yields

$$F_{wp} = (\delta^{18}O_{sample} - \delta^{18}O_{sp}) / (\delta^{18}O_{wp} - \delta^{18}O_{sp})$$

Therefore, if the long-term average values of winter and spring precipitation are known, then the mean annual fraction of winter precipitation that contributes to groundwater recharge and streamflow can be determined.

RESULTS AND DISCUSSION

Winter precipitation accounted for about 54% of the annual total in the Rio Hondo, compared to an average of 46% at the other SNOTEL stations (Fig. 3A). Some fraction of the greater winter proportion in the Rio Hondo may result from snowmaking operations in the Taos Ski Valley where the station is located. Streamflow is used as the water source for this artificial snow (Harding, 2012), which is unlikely to significantly alter the isotopic composition of the bulk snowpack due to the similar composition of winter precipitation and surface-water (see below) and the relatively small area of the snowmaking operations. Mean daily temperature distributions for the 12 SNOTEL stations are shown in Figure 3B and are similar for all sites.

Normalized mean daily flow hydrographs from the Rio Hondo, Pecos River, and Rio Pueblo are shown in Figure 4. The timing of snowmelt for the Rio Hondo and Pecos River are similar, with steady rise and recession of flow during the snowmelt period, though the Rio Hondo appears to have a more sustained snowmelt peak. The Rio Pueblo is somewhat flashier compared to the Rio Hondo and Pecos River, although this may be due to the shorter period of record. Baseflow is present for all three streams, at approximately 4 to 10% of the peak flow or greater using straight-line analysis. This suggests there is significant storage and release from storage in these three watersheds despite the predominance of crystalline bedrock in the mountain block, although it is less pronounced for the Rio Pueblo. The rises in the hydrographs after the second half of the year for the Pecos River and Rio Pueblo are attributable to monsoonal storms, but only appear to make up a small proportion of the total annual flow. The similarity in streamflow behavior, temperature, and precipitation suggests related processes are operating in each drainage, and therefore streamflow generation processes active within the Rio Hondo watershed are likely broadly applicable to other watersheds within the Sangre de Cristo Mountains.

Stable isotopes of precipitation showed a strong seasonal signature of lighter compositions during the winter season and heavier compositions during the monsoon season, consistent with published trends (Clark and Fritz, 1997; Anderholm, 1994). Volume-weighted averages of δ^{18}O for winter precipitation fell between approximately -19‰ and -12‰, while volume-weighted monsoon precipitation values ranged from -8‰ to -5‰ (Fig. 5). The local meteoric water line (LMWL) showed a δ^{2}H excess of 8.6‰ compared to the global meteoric water line (GMWL), similar to other published LMWLs from the Sagauche Creek watershed to the north (Frisbee et al., 2009) and the Sacramento Mountains to the south (Newton et al., 2012). Winter precipitation did not show a trend with elevation, with the average slope for δ^{2}H from each seasonal collection being 1.2E-4 and R^2 values ranging from 0.08–0.63. Summer precipitation showed a strong correlation with elevation, with δ^{2}H decreasing by 0.01‰ per m on average and R^2 values ranging from 0.86–0.96. The seasonal correlations of isotopic composition with elevation can be explained by the precipitation patterns of New Mexico. Summer precipitation falls largely due to localized orographic lifting of water vapor originating from the Gulf of California, Gulf of Mexico, and local recycling due to evapotranspiration (ET), whereas winter precipitation comes from more regional storm fronts that originate from the Pacific Ocean (Tuan et al., 1973).

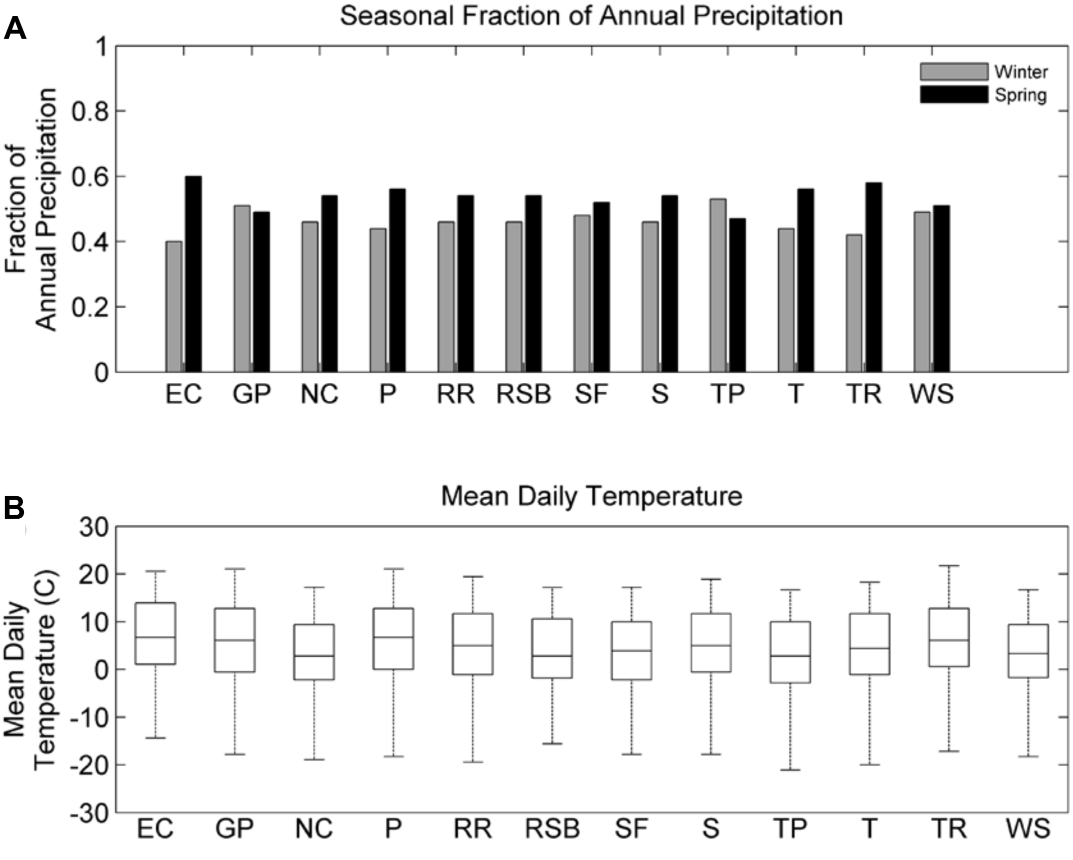

FIGURE 3. A. The seasonal fraction of annual precipitation and B. Mean daily temperature for all 12 SNOTEL sites in the southern Sangre de Cristo Mountains. EC = Elk Cabin, GP = Gallegos Peak, NC = North Costilla, P = Palo, RR = Red River, RSB = Rio Santa Barbara, SF = Santa Fe, S = Shuree, TP = Taos Powderhorn, T = Tolby, TR = Tres Ritos, WS = Wesner Springs. Station locations shown in Figure 1.

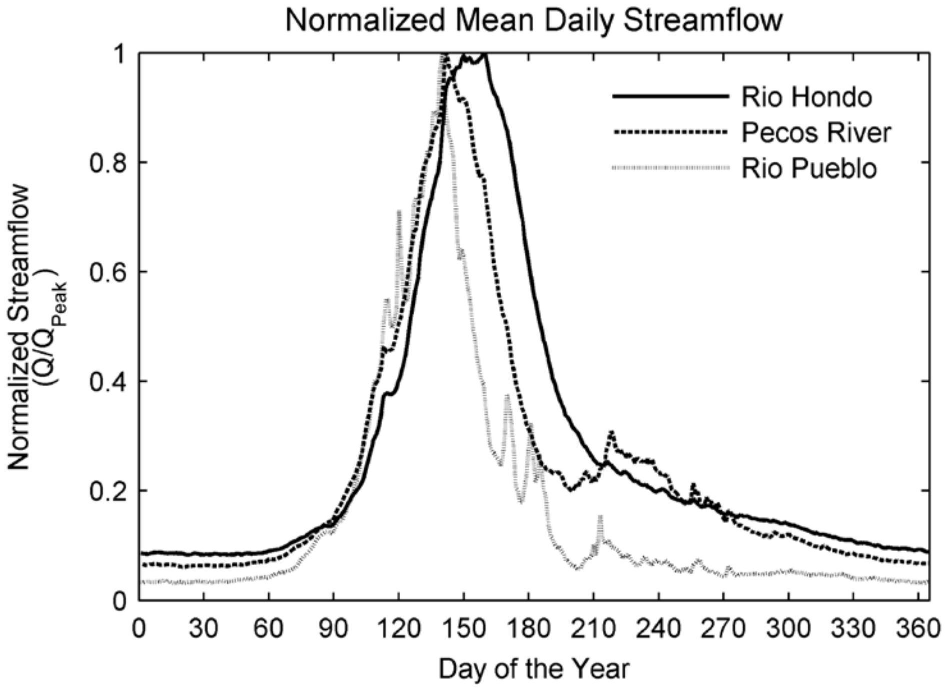

FIGURE 4. Normalized average daily streamflow for Rio Hondo, Pecos River, and Rio Pueblo. The similar shape and timing of the Rio Hondo and Pecos River hydrographs suggests similar streamflow generation processes may be operative in those two watersheds. The Rio Pueblo hydrograph is similar for the first half of the year but indicates groundwater is a smaller contributor to surface-water later in the year.

Despite the relatively large fluctuations in isotopic composition of seasonal precipitation, measured values of $\delta^{18}O$ and $\delta^{2}H$ are remarkably similar and consistent for surface water, groundwater, and spring water samples (Table 1) The mean $\delta^{18}O$ for surface-water was -14.3 ±0.7‰ (n=115). Groundwater samples had a mean $\delta^{18}O$ of -13.9 ±1.2‰ (n=54). Mean $\delta^{18}O$ in spring-water was -14.1 ±0.9‰ (n=56). The measured values all fall within the winter precipitation range (Fig. 6), despite about only half of annual precipitation having a similar isotopic composition.

One possible explanation for the isotopic composition of the samples is mixing between very light winter and heavy monsoon precipitation. However, equal mixing of seasonal precipitation is unlikely as monsoon precipitation appears to be routed out of the watershed very quickly. In comparison to winter precipitation and gradual snowmelt processes, monsoon storms are very intense and short duration events. Therefore, it is very possible that the precipitation rate during monsoon storms exceeds the soil infiltration rate. For example, in September 2012, a 2.5 cm monsoon storm event took place that increased flow in the Rio Hondo by approximately 0.1 m^3s^{-1} (Fig. 7). Sampling was performed three days later and the mean $\delta^{18}O$ of surface water only increased by about 1‰, indicating that monsoon precipitation is quickly flushed from the system, consistent with fast runoff process with short residence times on the order of days for monsoon precipitation. In addition, since potential ET is greatest during the summer (Stewart et al., 1999) a large portion of monsoon precipitation is lost to canopy interception, bare soil evaporation, and uptake by vegetation. As a result, very little of the precipitation that falls during monsoon storms, if any, makes

TABLE 1. Mean isotopic compositions ± one standard deviation of surface-water, spring-water, and groundwater samples collected in the Rio Hondo watershed.

	Sample ID	**$\delta^{18}O$ (‰)**	**$\delta^{2}H$ (‰)**	**n[1]**
Surface-Water	RHR-01	-14.26 (± 0.61)	-93.21 (± 1.20)	10
	RHR-02	-14.02 (± 1.11)	-92.97 (± 1.11)	10
	RHR-04	-14.06 (± 0.73)	-92.36 (± 1.13)	10
	RHR-10	-14.39 (± 0.72)	-92.62 (± 1.59)	10
	RHR-11	-14.92 (± 0.77)	-97.85 (± 0.85)	10
	RHR-14	-14.46 (± 0.75)	-93.93 (± 1.15)	10
	RHR-15	-14.43 (± 0.76)	-94.40 (± 0.89)	10
	RHR-16	-14.15 (± 0.77)	-90.54 (± 2.01)	10
	RHR-18	-14.12 (± 0.54)	-92.08 (± 2.69)	9
	RHR-21	-14.41 (± 0.73)	-92.92 (± 1.23)	9
	RHR-22	-13.86 (± 0.91)	-89.43 (± 0.91)	7
	RHR-24	-14.40 (± 0.67)	-93.69 (± 1.64)	8
Spring-Water	RHS-01	-14.40 (± 0.70)	-93.11 (± 1.17)	10
	RHS-04	-14.18 (± 0.73)	-91.26 (± 3.49)	10
	RHS-05	-14.41 (± 0.75)	-94.45 (± 1.12)	9
	RHS-06	-14.29 (± 0.58	-93.50 (± 1.04)	7
	RHS-07	-13.86 (± 0.82)	-88.07 (± 0.72)	4
	RHS-08	-13.99 (± 0.58)	-88.07 (± 0.77)	5
	RHS-09	-14.24 (± 0.51)	-91.87 (± 2.11)	4
Groundwater	RHW-02	-14.40 (± 0.54)	-95.98 (± 0.95)	9
	RHW-05	-14.00 (± 0.75)	-94.42 (± 1.34)	9
	RHW-06	-14.42 (± 0.57)	-96.21 (± 1.15)	9
	RHW-10	-12.99 (± 0.74)	-88.47 (± 1.50)	9
	RHW-11	-13.55 (± 0.56)	-90.98 (± 0.75)	7
	RHW-12	-14.76 (± 0.94)	-95.12 (± 1.88)	6
	RHW-13	-14.84 (± 0.81)	-96.50 (± 1.46)	7

1. Number of samples collected

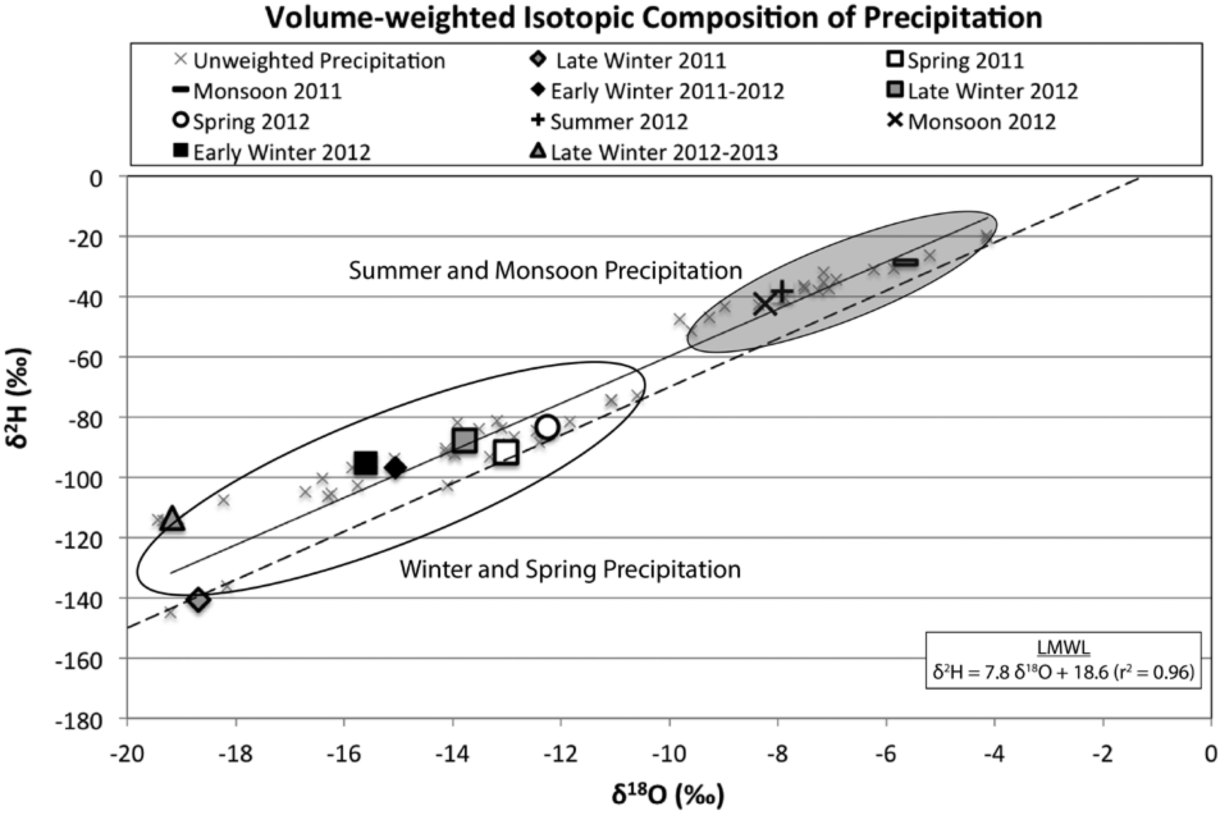

FIGURE 5. Volume-weighted isotopic composition of precipitation. Ovals show approximate seasonal precipitation range. Dashed line represents the global meteoric water line (GMWL) and the solid line represents the local meteoric water line (LMWL).

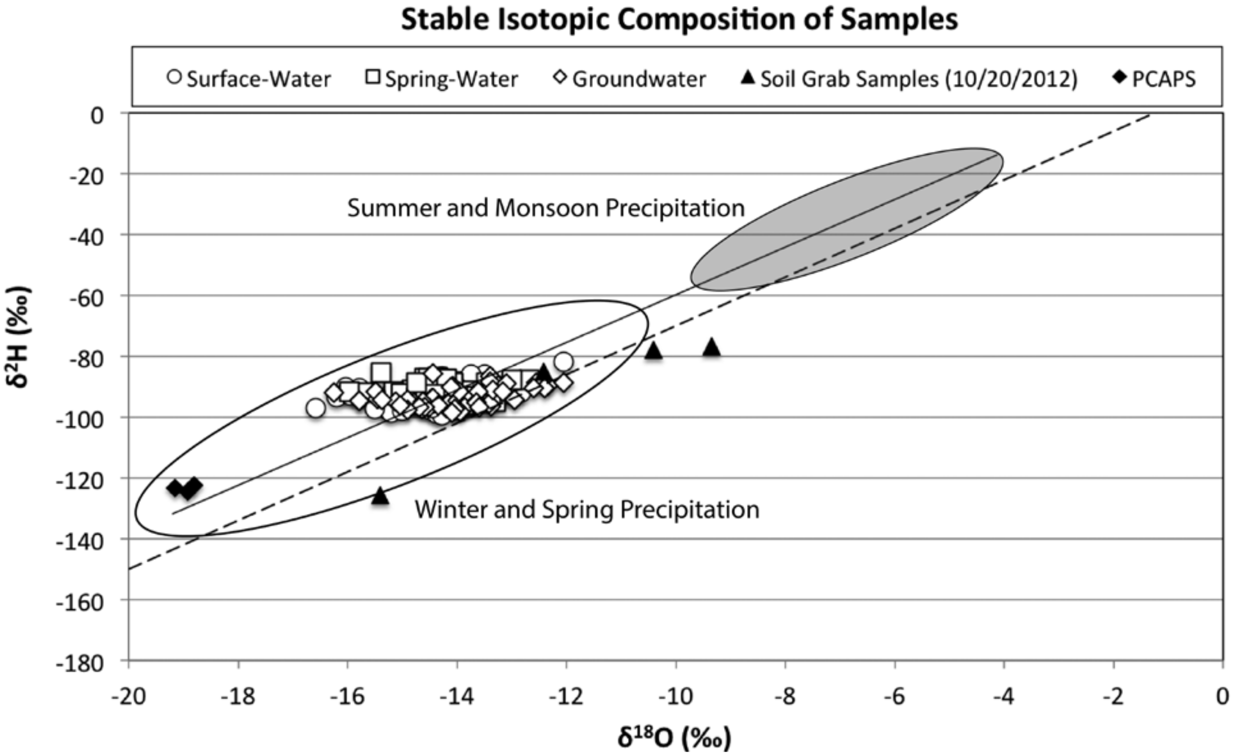

FIGURE 6. Isotopic composition of all surface-water, spring-water, and groundwater samples collected in the Rio Hondo watershed plot similarly. Three of the four soil grab samples (black triangles) collected at the end of the monsoon season in 2012 showed an evaporative signature with a slope of about 4–5 and indicates winter precipitation as the source. Ovals show approximate seasonal precipitation range. Dashed line represents the global meteoric water line (GMWL) and the solid line represents the local meteoric water line (LMWL).

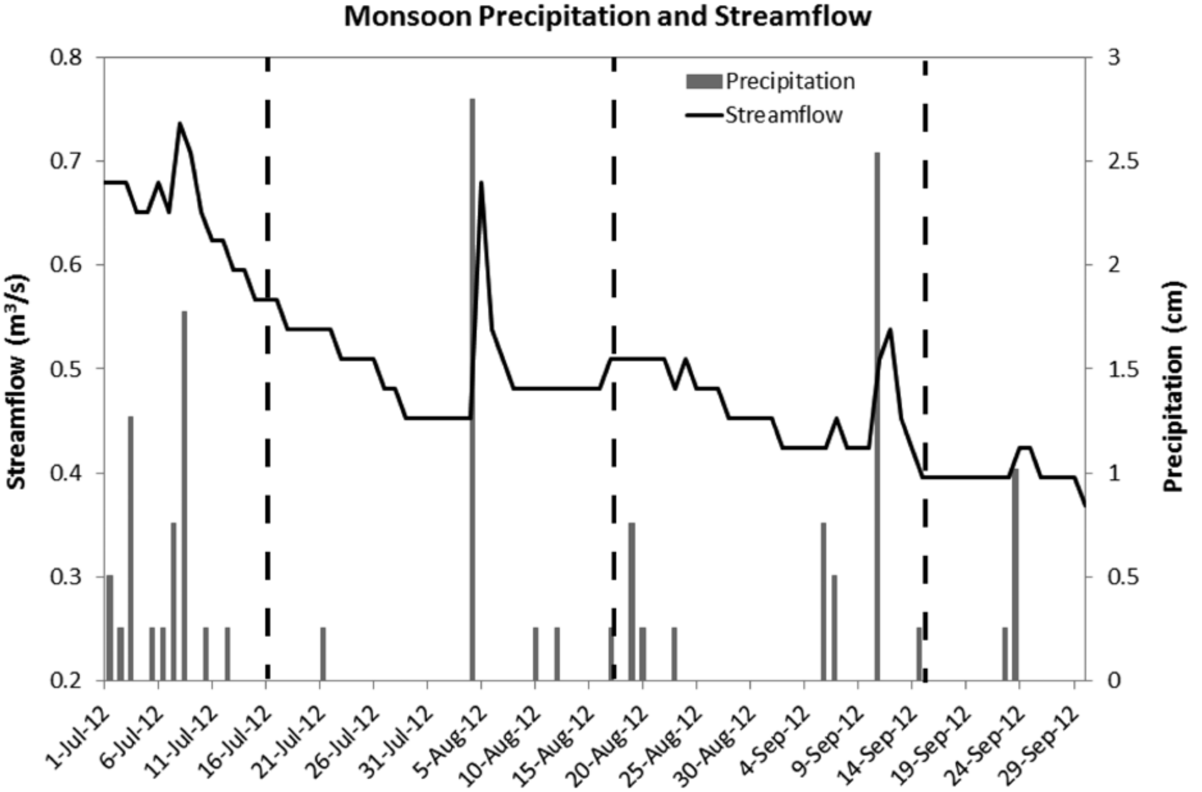

FIGURE 7. Rio Hondo hydrograph and daily precipitation from July-September 2012. Streamflow increases due to monsoon precipitation only persist for a few days. Vertical dashed lines indicate dates when samples were collected. Gauge location shown in Figure 1.

it past the root zone (Kurc & Small, 2004). A combination of fast runoff and ET processes is most likely responsible for the lack of a significant monsoon signature in surface-water.

A better explanation for the observed isotopic composition of groundwater, surface-water, and spring-water is that evolved snow and spring precipitation are the primary sources of surface and subsurface water. Three of the four discrete soil moisture grab samples collected when the PCAPS were installed in October 2012 show an evaporative signature with a slope of about 4–5 (Fig. 6, black triangles), which is expected for semi-arid regions (Clark and Fritz, 1997). Tracing this slope back to the LMWL yields an initial δ^{18}O value of about 14–15‰, similar to the recent winter's isotopic signature. The fourth sample plots well off both the LMWL and GMWL and is considered to be an outlier. These samples were collected after the entirety of the monsoon season yet they more closely resemble the isotopic composition of winter precipitation. This supports our assertion that monsoon precipitation does not make it very far into the subsurface and is quickly routed out of the watershed, while the slow melting of snow creates a vertical head gradient that is conducive for deep percolation of water past the root zone.

Samples collected from the PCAPS from October 2012 to June 2013 are shown in Figure 6. Not surprisingly, soil moisture collected from the PCAPS had an isotopic signature similar to the measured winter precipitation while they were deployed. Some of the 3.8 liter sample bottles appear to have overflowed due to the presence of mineral oil in the bottom of the ice chest. Approximately seven liters of water was found in the ice chest holding the bottles at PCAPS-1 and 30 L was found at PCAPS-2. Calculated capture volumes using the snow-water equivalent and the wick surface area are much smaller than these volumes and indicates that either the wicks are capturing an area much larger than their surface area, or, more likely, that our efforts to seal the ice chests failed. However, any water that leaked into the ice chest was from snowmelt and therefore has the same isotopic composition. Although snowmelt infiltration collected by the PCAPS was on the lighter end of the range of winter isotopic compositions, this is potentially due to annual variation as previous winter precipitation showed δ^{18}O values ranging from -18.7 to -12.3‰. This range is consistent with other studies showing that winter precipitation ranges from about -19 to -12‰ in the Rio Hondo watershed (Harding, 2012) and about -18 to -11‰ in the Sacramento Mountains to the south (Newton et al., 2012). The long-term mean of winter precipitation will therefore be somewhere within this range.

Using the mean and one standard deviation of all groundwater, surface-water, and spring-water samples collected (-14.2 ±0.8‰) as the $\delta^{18}O_{sample}$, and assuming long-term seasonal mean values of about -16‰ and -8‰ for $\delta^{18}O_{wp}$ and $\delta^{18}O_{sp}$, respectively, winter precipitation accounts for about 68 to 88% of groundwater recharge and streamflow in the Rio Hondo. Fractionation of the snowpack due to sublimation and differential melting, which we are not accounting for, would increase the isotopic ratio and move it closer to the mean ratio of the samples. Therefore, we are underestimating the proportion of winter precipitation in the samples. This indicates that while winter precipitation is only about half of total annual precipitation in the Sangre de Cristo Mountains, it is the source of two-thirds or more of groundwater recharge and streamflow annually.

In addition to providing information about the seasonal source of groundwater recharge and streamflow, stable isotopes can also help us infer streamflow processes at the watershed scale. Since the Rio Hondo is a perennial stream and surface water appears to be primarily sourced from winter and spring precipitation, a significantly large subsurface reservoir of winter and spring precipitation would be required to sustain streamflow after the snowpack has melted out, which typically happens in early- to mid-June. Soil development in the Rio Hondo mountain block is fairly limited due to steep slopes, and therefore the soil zone is unlikely to be large enough to sustain streamflow through the second half of the year. Recent studies by Frisbee et al. (2011) in the Saguache Creek watershed in southern Colorado and Tolley et al. (unpubl. 2015) in the Rio Hondo watershed indicate that deep groundwater contributions can be a significant source of streamflow in high-elevation mountain watersheds due to increased subsurface permeability from fracture networks within the mountain block created by extensional and compressional tectonic events. The authors attributed the positive correlation between watershed drainage area and surface-water solute concentrations to increases in both groundwater age and contribution. Evaporative concentration is not a sufficient explanation for the surface-water solute concentration trends observed by Tolley et al. (unpubl. 2015) in the Rio Hondo, as the stable isotopic composition of surface water does not show an apparent correlation with drainage area (Fig. 8). The long residence times suggested by the authors could explain why the isotopic composition of groundwater, surface-water, and spring-water samples is so consistent despite a somewhat large range of winter precipitation, as mixing and dispersion/diffusion processes would be operating longer and smooth out annual variations.

CONCLUSIONS

Precipitation in the Sangre de Cristo Mountains shows a strong seasonal influence. Winter and spring precipitation has a significantly lighter isotopic composition compared to summer and monsoon precipitation. This difference in seasonal isotopic signatures allows for the determination of the relative importance of seasonal precipitation to groundwater recharge and streamflow. Due to the similar climate, precipitation patterns, and geologic history of the Rio Hondo compared with the southern Sangre de Cristo Mountains, physical processes active in the Rio Hondo are likely active in many other watersheds in the mountain range.

Samples of groundwater, surface-water, and spring-water collected within the Rio Hondo watershed at relatively high spatial and temporal resolution show similar and consistent isotopic ratios and indicate 68 to 88% of groundwater recharge and streamflow are sourced from winter and spring precipitation, which only accounts for 45 to 55% of total annual precipitation. This supports our hypothesis that groundwater recharge and streamflow are dominated by winter precipitation due to slow melting of the snowpack and deep percolation below the

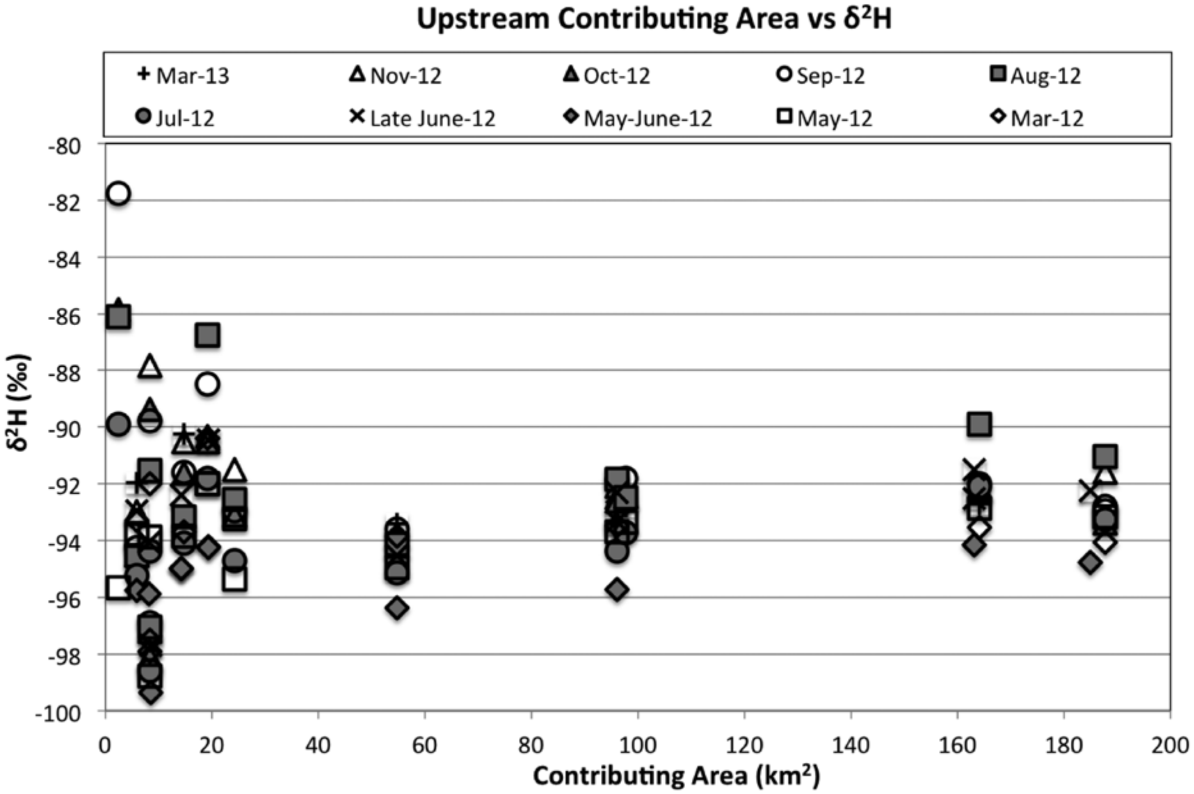

FIGURE 8. Upstream contributing area vs δ²H for surface water samples. Isotopic ratios do not change significantly downstream, indicating evaporation does not have a significant effect on surface-water samples.

root zone when evapotranspiration demand is low. Therefore, seasonality appears to be very important as winter and early precipitation is a disproportionate source of groundwater recharge and streamflow in the Sangre de Cristo Mountains relative to its annual contribution.

Using groundwater as a proxy for winter precipitation after the snowpack has melted indicates that the majority of surfacewater in the Rio Hondo is sourced from groundwater. This result is consistent with previous studies in the Saguache Creek watershed and the Rio Hondo watershed that have used geochemistry, age-dating, and end-member mixing analysis techniques in fractured bedrock mountain watersheds. Streamflow, and especially baseflow in this type of watershed, appear to be significantly controlled by groundwater contributions which in turn are heavily influenced by snowmelt-driven groundwater recharge processes. Therefore, reduction in the amount and duration of snowpack predicted by climate change will result in a disproportionate reduction of groundwater recharge and ultimately streamflow in these types of mountain watersheds.

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