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Monitoring Effects of Wildfire Mitigation Treatments on Water Budget Components: A Paired Basin Study in the Sante Fe Watershed, New Mexico

Amy C. Lewis

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A division of New Mexico Institute of Mining and Technology

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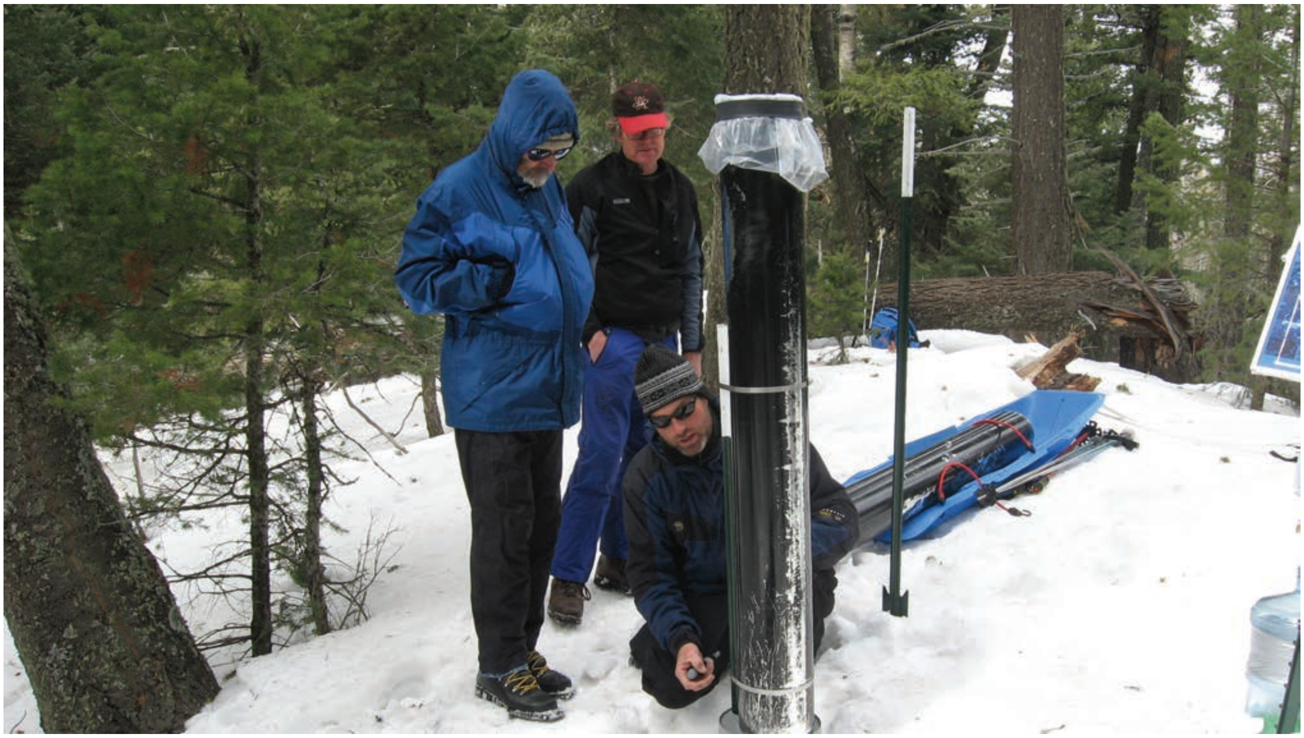
ABSTRACT

A paired basin study in the upper Santa Fe River watershed following forest restoration has successfully measured water budget components in a treated and an untreated (control) basin. The paired basin study was established to investigate questions that have arisen with regards to changes in water yield from forest treatments. If forest treatments, for instance, increase the water yield or increase the sustained flow in streams, this could have implications for sensitive ecosystems or downstream water users that require sustained flow. Precipitation, streamflow, soil moisture, and chloride concentrations in precipitation and streamflow were measured to quantify the water budget components. The results from nine years of data collection and analysis show a high degree of confidence with respect to measuring the water budget components based on the mass balance of water and chloride.

The cycle of chloride entering and exiting each basin is examined over five integration periods. The total inflow of chloride from precipitation is assumed to be equal to the outflow of chloride in streamflow and recharge over each integration period. Volume-weighted chloride concentration in precipitation ranges from 0.18 to 0.24 mg/L for the five integration periods. The volume-weighted chloride concentration in streamflow for the same periods ranges from 2.2 to 3.2 mg/L in the treated basin and 0.9 to 1.4 mg/L in the control basin. The difference in chloride concentrations between the two basins was observed prior to forest treatments. Based on the ratio of chloride concentration in precipitation to the chloride concentration in streamflow, outflow of water due to evapotranspiration (ET) is estimated to be about 90 to 94% of precipitation in the treated basin and 77 to 86% in the control basin, within the same range as observed prior to forest treatments. The higher ET in the treated basin both before and after forest treatments may be due to the much greater area of western slope in the treated basin that receives warm afternoon sun and the greater area of rock cover in the control basin. In this investigation, changes in the ratio of water budget components in the control as compared to the treated were the focus of this investigation. While the pre-treatment data before 2004 is limited, treatments will continue to occur in order to achieve a forest structure that is more resilient to wildfire.

Estimates of recharge, based on the chloride mass balance, range from 1.7 to 7.3% of precipitation in the treated basin and 1.1 to 13% in the control basin. While ET appears to decrease over time following forest treatments in the treated stream relative to the control basin (based on the chloride ratio), changes in streamflow and recharge are only observable during periods when winter precipitation represents a greater proportion of the annual precipitation. The relatively dry period of this nine-year investigation may have contributed to the lack of overall discernable differences in streamflow and recharge. Forest canopy reduction and increased ground cover appears to have reduced the peak hydrograph in response to intense storm events in the treated basin.



Installation of Upper Rain Gage Collector in January 2009. John Kay is kneeling; John Burkstaller is on the left; and Greg Lewis is on the right. *Photo by Amy C. Lewis.*

I. INTRODUCTION

A paired basin study located in the Santa Fe municipal watershed (Figure 1) was initiated to establish the impacts of forest treatments on evapotranspiration, streamflow and recharge. By monitoring the changes in the water budgets between treated and untreated basins of similar slope, aspect and area, the impact of the changing forest conditions can be tracked. This report documents the techniques and results of nine water years of investigating water budget components (water years 2009 through 2017).

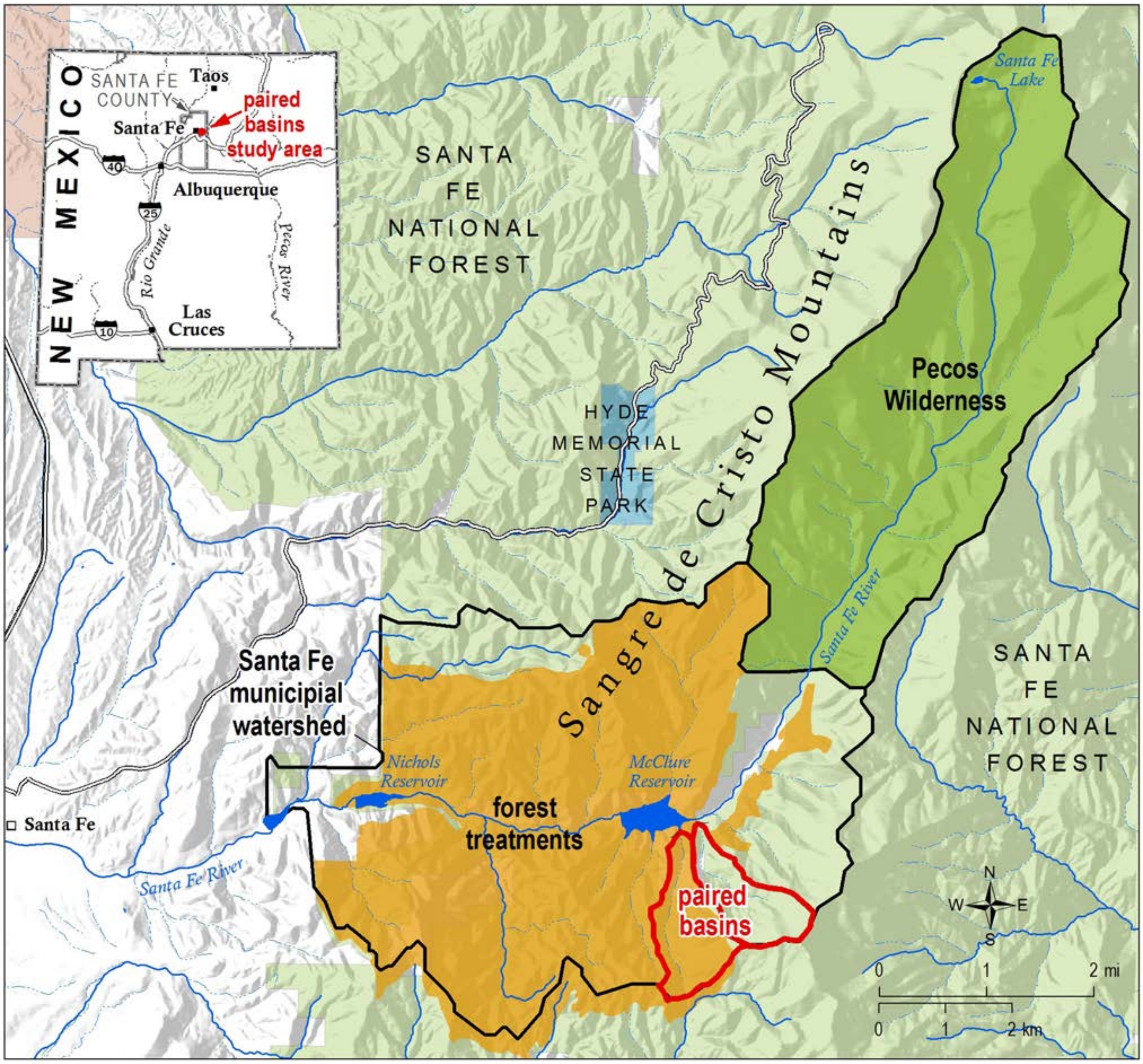


Figure 1. Forest treatments and paired basins within the Santa Fe municipal watershed.

Background

In 2001, the City of Santa Fe and the Santa Fe National Forest began thinning and using prescribed fire on 2,942 hectares (ha) of dense ponderosa pine forest surrounding two water supply reservoirs in the Santa Fe River watershed to reduce the risk of a catastrophic wildfire. The dense condition of the forest developed after heavy livestock grazing and logging in the 1800s followed by closure of the forest and wildfire suppression. By 1996, tree densities averaged 1,200–2,500 trees/ha, whereas ponderosa pine forests were historically 50–200 trees/ha (USFS, 2001). Forest restoration activities aimed at reducing the fuel load and the potential for catastrophic fire have been widely implemented in the Western United States, yet questions remain about the response of the water budget to changes in vegetation. Anecdotal evidence has reported that restoring forests to pre-development conditions with reduced tree density resulted in dry creeks flowing again (Scarlett, 2002).

Impacts to the water budget from vegetation changes can occur at various time scales, including annual yield, seasonal runoff and response to storms. To investigate these potential effects, a paired watershed study was implemented in 2008 under a Joint Powers Agreement between the New Mexico Interstate Stream Commission, the City of Santa Fe and the Santa Fe National Forest to evaluate differences between the treated and untreated basins. The paired basins were initially established in 2001 and the first phase of treatment occurred in 2004, followed by prescribed burns in 2010 and 2011.

Purpose and Scope

The thinning and prescribed fire treatments are designed to initially remove or decrease canopy to reduce the risk of catastrophic wildfire. The forest treatments have four important impacts that theoretically alter the hydrologic regime. One is that the reduction in the overstory canopy reduces sublimation (of snow that was intercepted by trees), which reduces evaporation, thereby increasing runoff. Secondly, the reduction in forest canopy allows more sunlight on the forest floor, which may increase the subsequent growth of understory (shrubs, grasses and forbs) and increase soil temperatures, resulting in higher evapotranspiration. A third possible modification to the hydrologic system following forest restoration is the potential increase in recharge due to the increase in understory vegetation and subsequent development of soils, enhancing infiltration. And finally, surface runoff following intense rainfall events may be reduced in intensity and prolonged in duration because of increases in understory vegetation, which increases hillslope surface roughness. Thus, this investigation aims to measure not only the volumetric changes in total surface runoff volume, evapotranspiration and the other components of the water budget (recharge, and soil moisture storage) as the forest structure changes, but also any changes in the intensity of surface runoff.

In this report, the time periods for evaluating water budget components are presented as integration periods over single or multiple water years. A water year includes the period between October 1 of any given year and September 30, of the following year. The integration periods were selected to best represent the cycle of chloride entering and exiting the watersheds. Selection of the appropriate beginning and end to each integration period is based on water years and water years were combined to reflect the periods when flow diminished. The first integration period includes a relatively wetter period when the streams flowed throughout 2009 until September of 2010, thus the water from the previous wet winter was continuing to produce runoff. The second integration period was very dry and thus the chloride was accumulating in the soils until September 2013 when heavy rains resulted in continuous streamflow into the following winter snow melt. The last three integration periods represent the water year, beginning with dry streams in October and flow beginning with spring snow melt, supplemented with summer thunderstorms, with flows diminishing in September. Thus, the water budget components are estimated here for five integration periods:

1) October 2008 through September 2010

2) October 2010 through September 2014

3) October 2014 through September 2015

4) October 2015 through September 2016

5) October 2016 through September 2017

To investigate the changes in the water budget, methods are presented to measure or estimate the following components of the water budget in each basin (treated and control):

1. Streamflow (runoff out of each basin) through direct measurement.
2. Precipitation (including snow) through direct measurement.
3. Soil moisture changes through direct measurement and the National Weather Service (NWS) monthly soil moisture estimates for the northern mountains of New Mexico.
4. Evapotranspiration estimated by comparing chloride concentrations in precipitation to concentrations in streamflow.
5. The amount of water lost to (recharge) or gained from groundwater, measured indirectly by quantifying the chloride mass balance of each watershed (which is also equal to the remainder of the water balance).

Previous Work

Paired basin studies of vegetation changes

Many paired basin experiments, which examine adjacent treated and untreated watershed basins, have investigated changes in yield (Bosch and Hewlett, 1982, Brown et al., 2005, Andréassian et al., 2003, and Troendle et al., 2010 provide summaries of the experiments) but these have primarily focused on the impacts following clear cutting and the regrowth of forest cover. These studies, such as the first one conducted at Wagon Wheel Gap, Colorado in 1910 (Bates and Henry, 1928), found an initial increase in water yield following clear cutting, and an eventual return to pre-logging conditions following the regrowth of the forest. The Santa Fe paired basin study differs in that the forest treatments are intended to restore the forest to a pre-development condition when the tree density was much lower and the understory vegetation (grass and shrubs) was greater.

Veatch et al. (2009) quantified the effects of mixed conifer forest canopy cover on net snow accumulation in northern New Mexico and found that the maximum snow accumulation occurred with forest canopy density between 25 and 40%, resulting in 25 percent deeper snow than either large open areas or densely forested areas. Gustafson et al. (2010) estimated snow sublimation for five locations in northern New Mexico to quantify the impacts of aspect and vegetation on sublimation and snow melt. They found that sublimation was higher from tree canopy than from open areas.

Biederman et al. (2015) investigated impacts of tree die-off on streamflow in western North America and found little impact to streamflow. Biederman et al. (2015) provide an excellent overview of historical and current research on the investigations into influences of vegetation on water yield. As explained by Biederman et al. (2015), many of the studies involve modeling and assumptions about changes in evapotranspiration and input from precipitation, without physical measurement of water budget components. Livneh et al. (2015) modeled forests in the Colorado Rocky Mountains and concluded that greater snow accumulation would occur due to less interception from the reduced tree canopy, resulting in 8 to 13% increase in streamflow. The opposite conclusion was found by Guardiola-Claramonte et al. (2011), who documented a decrease in streamflow following drought-induced tree die-off.

Previous work in the Santa Fe watershed paired basins

The Santa Fe watershed paired basin study expands on an earlier investigation into the potential impacts of forest treatments on water quality. Streamflow and turbidity and rainfall were monitored in the paired basins beginning in 2001 by a contractor to the City of Santa Fe (Watershed West, 2008). However, the flumes were too large to accurately measure streamflow during low flows and only summer precipitation and streamflow were monitored, limiting the use of the pre-treatment data to calculate water budgets. Watershed West found that turbidity did not increase due to forest thinning, the primary purpose of their investigation. Dr. Carl White collected a stream sample from the treated basin in 1995 before the treatments began and several samples in 2006 and 2007 for chloride analysis (White, 2007) and concluded, based on no change in the chloride ratios, that no initial effect from the forest treatments could be detected.

The U.S. Forest Service surveyed the soils and vegetative cover of the Santa Fe National Forest in 1992–93 (USDA Forest Service, 2009). Vegetation, bird communities, and small mammal surveys were conducted by the Rocky Mountain Research Station (RMRS) in 2001, 2005, and 2010 (Bagne & Finch, 2008, Bagne, 2011).

Description of Study Area

The study area lies at the southern end of the Sangre de Cristo Mountains, south of the Santa Fe River, a tributary to the Rio Grande. The Santa Fe Watershed paired basins are located east of the City of Santa Fe on two tributaries to the Santa Fe River that discharge into McClure Reservoir (Figure 1). The control basin area is approximately 1.53 km^2 ranging in elevation from 2,400 m to 3,200 m above mean sea level (amsl) at the top of Thompson Peak. The treated basin is approximately 1.79 km^2 and ranges in elevation from 2,400 m to 3,020 m. Each basin drains to the north and is populated with limber pine (*Pinus flexilis*), Gambel oak,

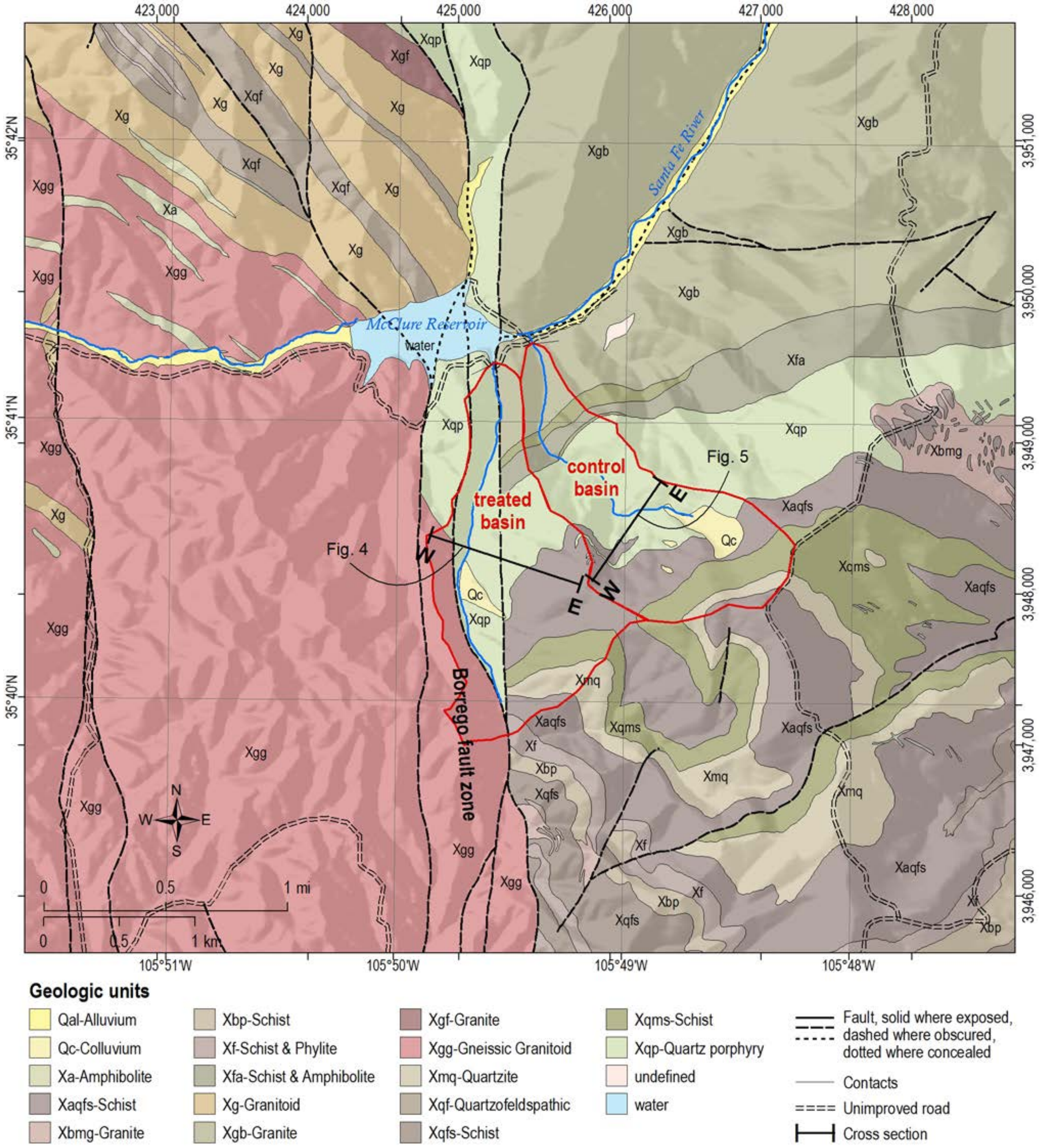


Figure 2. Geologic map of the paired basins (after Bauer et al., 1996).

(*Quercus gambelii*), white fir (*Abies concolor*), Douglas fir (*Pseudotsuga menziesii*), ponderosa pine (*Pinus ponderosa*), and quaking aspen (*Populus tremuloides*) (Bagne & Finch, 2008).

The mountains in this temperate steppe regime receive precipitation primarily in the form of snow in the winter and rainfall from summer thunderstorms. Proterozoic plutonic rocks and supracrustal rocks composed of quartzites and schists, called the Thompson Peak metamorphic suite, (Bauer et al., 1996) crop out in the basins. Two inferred north-south trending faults occur in the treated basin, which may impact groundwater flow (Figure 2). The stream in the treated basin follows the inferred fault splays in the upper and lower reaches but flows parallel to and between two fault splays in the central reach of the stream. The faults in the treated stream are part of the Borrego fault zone, which consists of highly fractured and brecciated granitoids that are poorly cemented in other parts of the watershed where the exposure allows for assessment (Bauer, 1997). Thus, it is not known how the fault affects the aquifer characteristics of basement rocks along the Borrego fault within the treated basin. While no wells are present in the study area or vicinity, it is presumed that the topography is the dominant control of groundwater flow, flowing towards each stream and north towards the Santa Fe River. Regionally, the Sangre de Cristo Mountains provide a source of recharge to the aquifers to the west, thus the regional flow direction follows the larger topographic gradient (Wasiolek, 1995), which is perpendicular to the local topography (and local groundwater flow) within the paired basins (Figure 3).

The soil and vegetation classification types within the two basins had many of the same characteristics prior to treatments. For example, the overstory cover was 75 to 80%, rock fragment cover is 60 to 65% and the gradient is 50 to 55% (USDA FS, 2009). The soils of the upper third of the control basin are characterized as an Inceptisols (initial stages of a soil formation), whereas the remainder of the control and all the soils within the treated basin are characterized as Entisols (distinct pedogenic horizon is absent). The entire area is characterized as GW under the Unified Soil Textural Classification, which is defined as a coarse-grained soil that is well graded, with less than 5% passing the Number 200 sieve, and with permeability greater than 0.01 cm/s.

The paired basins differ from each other in that the west-facing area in the treated basin is larger than that of the control basin (Figure 4 and Figure 5), allowing for more warm afternoon sun exposure. The control basin reaches a higher elevation, which can have an impact on the amount of snow remaining on the ground due to the cooler temperatures at higher

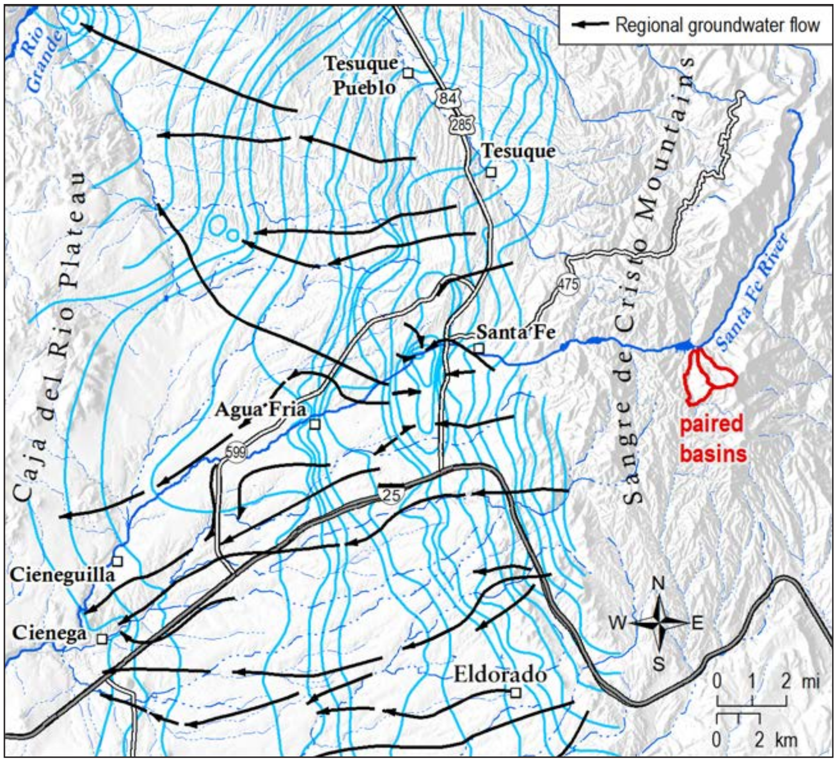


Figure 3. Location of paired basins showing the Sangre de Cristo Mountains and the direction of groundwater flow (Johnson, 2009).

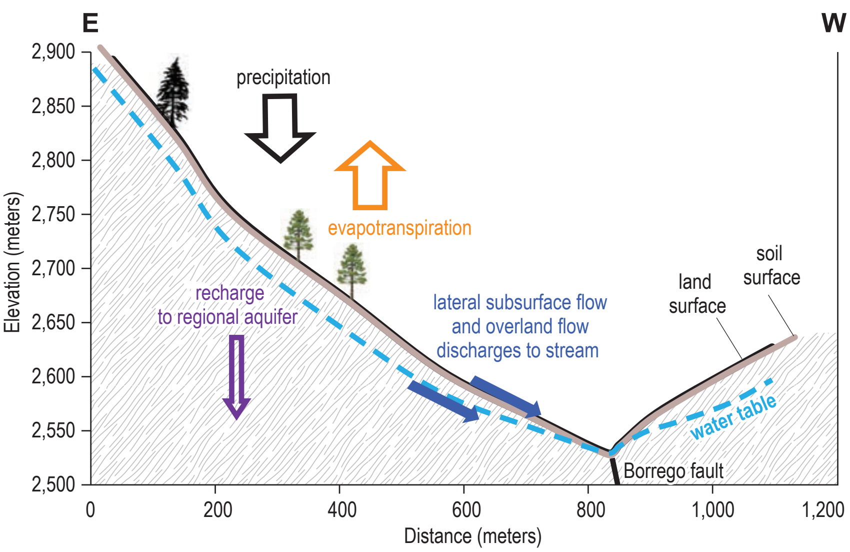


Figure 4. Schematic east-west cross section of the treated basin (4X exaggeration) showing the components of the water balance calculation. See location on Figure 2.

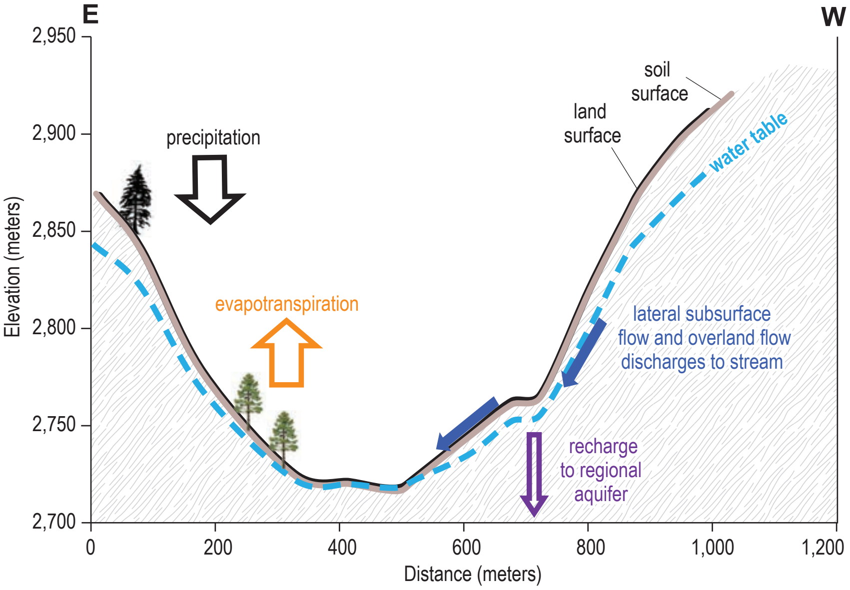


Figure 5. Schematic east-west cross section of the control basin (4X exaggeration) showing the components of the water balance calculation. See location on Figure 2.

elevations. The control basin has more abiotic cover than the treated basin (38% in the control compared to 22% in the treated). These intrinsic differences may impact the rate of evapotranspiration occurring in each basin.

During March and April of 2004, 1.2 km^2 (70%) of the treated basin was thinned using chainsaws and, in the fall of 2004, the piles of slash were burned. Following the initial mechanical treatments and pile burns in 2004, prescribed fires were conducted in 2010 and 2011. The U.S. Forest Service has conducted the forest treatments in the treated basin and other areas within the Santa Fe watershed. Long-term maintenance plans for the watershed include repeated prescribed burns every 5 to 7 years (Margolis et al., 2009).

The time for the forest to reach a new equilibrium state following the forest treatments is expected to take years. Brown et al. (2005) state that it takes longer than 5 years for this process and recovery could take over 100 years. In the paired basins, the new equilibrium will be reached when the ground cover (grasses and forbs) have developed to a point where they can carry surface fires. The periodic prescribed burns should help the forest maintain the new equilibrium. The time it takes for the ground cover to reestablish will be impacted by the amount of precipitation and the slope and aspect. On some areas where the ground is less steep, the grass cover has developed, but on steeper slopes this process may take much longer. Slopes in the treated basin are as high as 75% and average 40%.

II. METHODS

The goals of the study are to estimate and examine changes in the water budget components and flow response following storm events for the two basins over multiple years within the treated basin as the ground cover reestablishes. Ideally, the paired basins have similar characteristics in terms of slope, aspect, soils, area, vegetation and climate and are monitored for a period of years to assess any differences. While the pretreatment data collected is not complete in terms of assessing the annual water budget components, some information about the pretreatment chemistry and streamflow is available from Carl White (2007) and Watershed West (2008).

The water budgets for each of the basins were calculated assuming the standard water balance equation:

$$P=RO+ET+R+\Delta S \qquad (1)$$

where P is precipitation, RO is runoff, ET is evapotranspiration, R is recharge, and ΔS = change in storage (soil moisture).

Conceptual Model

Figure 4 and Figure 5 show a schematic of the cross section in the treated and control basins, respectively and the water budget components estimated for this investigation. Because the basins are relatively small (<2 km^2) and very steep, the run-off processes are relatively fast and the flow mechanisms relatively simple. Observations of the runoff processes over the nine years of this investigation suggest that overland flow only occurs following intense summer thunderstorms after soils are nearly saturated and field capacity is reached, and the rainfall intensity exceeds the infiltration rate. Overland flow was evident only once during the nine years of this investigation after the September 2013 storm event, as indicated by soil deposition and bent grass in the areas near the stream.

With both rain and snowfall events, moisture enters the soil profile, and when nearly saturated, seeps into the fractured bedrock, or on rare occasions, produces overland flow if the rainfall intensity exceeds the infiltration rate. Water in the soil is available for evaporation from direct sunlight or evapotranspiration from vegetation. If sufficient moisture is available, water in the fractured bedrock will drain relatively quickly to a water table. The surface of the water table is assumed to reflect the steep terrain where a significant portion discharges to the streams (shown as lateral subsurface flow on Figures 4 and 5) and is the primary source of water in the streams. The groundwater that does not appear at the stream gages may flow towards the Santa Fe River to the north or recharge the regional aquifer to the west.

Frisbee et al. (2011) discuss the impacts of watershed scale on predicting streamflow, a process that becomes more complex as scale increases, particularly above 100 km^2. With minimal soil thickness in each of the basins (<1 m), the method applied here assumes that the flow processes are not complex as reported by Harmen (2014) or Gierke et al. (2016). Harmen (2014) describes the storage-dependent transport of chloride in a watershed and the potential for a “long memory” of past inputs when water moves through multiple pathways. In the paired basins, the conceptual model used in this study assumes that past inputs of chloride from dry (eolian) deposition and wet precipitation will stay in the soil profile until flushed from the system following sufficient precipitation events (primarily spring snow melt). If the integration periods are chosen well, the age distribution should be uniform and reflect a well-mixed system. Gierke et al. (2016) found multiple travel-times and pathways (bulk soil water and passive-wick soil water) in their study of soil-water dynamics in the Sacramento Mountains in New Mexico, suggesting that preferential flow is active. The thicker soil profile and underlying karst bedrock in the Sacramento Mountain study may have created a more variable and complex flow system.

Modeling Stations

Table 1 provides a description of the monitoring equipment deployed in the basins and Figure 6 shows the monitoring locations. Monitoring of

Table 1. Descriptions of monitoring stations in the paired basins.

Station name	Latitude	Longitude	Elevation (meters)	Parameters	Equipment	Measurement interval
Control basin stream	35.68806	105.82352	2,418	Streamflow, temperature and chloride concentration	0.23-meter (9-inch) and 0.76-meter (30-inch) Parshall flumes INW AquiStar PT2X transducer	15 minutes
					Stream samples collected for chloride analysis	Twice monthly
Treated basin stream	35.68688	-105.82631	2,415	Streamflow, temperature and chloride concentration	0.23-meter (9-inch) and 0.76-meter (30-inch) Parshall flumes INW AquiStar PT2X transducer	15 minutes
					Stream samples collected for chloride analysis	Twice monthly
Lower rain	35.6878	-105.8241	2,458	Precipitation volume and chloride concentration	Campbell Scientific TE-525 tipping bucket rain gage with snowfall adapter	Hourly
Middle rain	35.6777	-105.8212	2,767			
Upper rain	35.6716	-105.8149	3,021		1.5-meter precipitation collector, 0.3-meter diameter	Monthly
Lower rain	35.6878	-105.8241	2,458	Soil moisture content	12 cm water content reflectometer (CS655-L50DS)	Hourly

precipitation and streamflow near the paired basins was also conducted by the Natural Resources Conservation Service (NRCS), U.S. Forest Service (USFS), City of Santa Fe, NWS, and U.S. Geologic Survey (USGS) (Table 2) and was used for comparison of the data collected in the paired basins (Figure 7).

Vegetation Monitoring

Prior to this paired-basin investigation, vegetation surveys were conducted at eight plots in the treated basin by the USFS in 2003, 2004, and 2005 as part of a larger study by the Rocky Mountain Research Station. Follow-up surveys were conducted at two of the plots in 2006, at three of the plots in 2007, and at one plot in 2009. No vegetation surveys were conducted in the control basin as part of the RMRS study (Bagne & Finch, 2008). The USFS monitored for tree density, shrub cover, and understory cover (grass, forbs, litter, and abiotic) on each 11.3 m radius plot (Figure 8).

Characterization of vegetation in both basins was conducted in 2010 for this study. Melissa Savage was retained to characterize the differences between the treated basin and the control basin. Vegetation surveys were conducted using the Daubenmire (1959) method for estimating understory and canopy-cover density; the amount of skylight that is intercepted before reaching the forest floor was estimated using the Cottam and Curtis (1956) method for phytosociological sampling, which involves a point center quarter method to sample for density and tree size (Savage, 2010).

The indicators sampled were 1) tree density, 2) tree size, 3) overstory canopy cover, and 4) understory plant cover. Sampling was done along transects at points 30 m apart. In both the treated and untreated

Table 2. Regional precipitation and streamflow monitoring stations.

Station name	Latitude	Longitude	Elevation (meters amsl)	Responsible party	Equipment
Santa Fe SNOTEL	35.77	-105.79	3,488	NRCS	Snow pillow-snow water equivalent
Elk Cabin SNOTEL	35.71	-105.81	2,502	NRCS	Snow pillow-snow water equivalent
Above McClure	35.69	-105.82	2,414	City of Santa Fe	Heated tipping bucket
SFWN5	35.68	-105.86	2,339	USFS	20.3 cm (8-in) Tipping bucket
Santa Fe Seton 29-8088-02	35.60	-105.93	2,134	NWS Observer	20.3 cm (8-inch) cylinder
Santa Fe River Above McClure	35.69	-105.82	2,415	USGS	Streamflow replogle flume

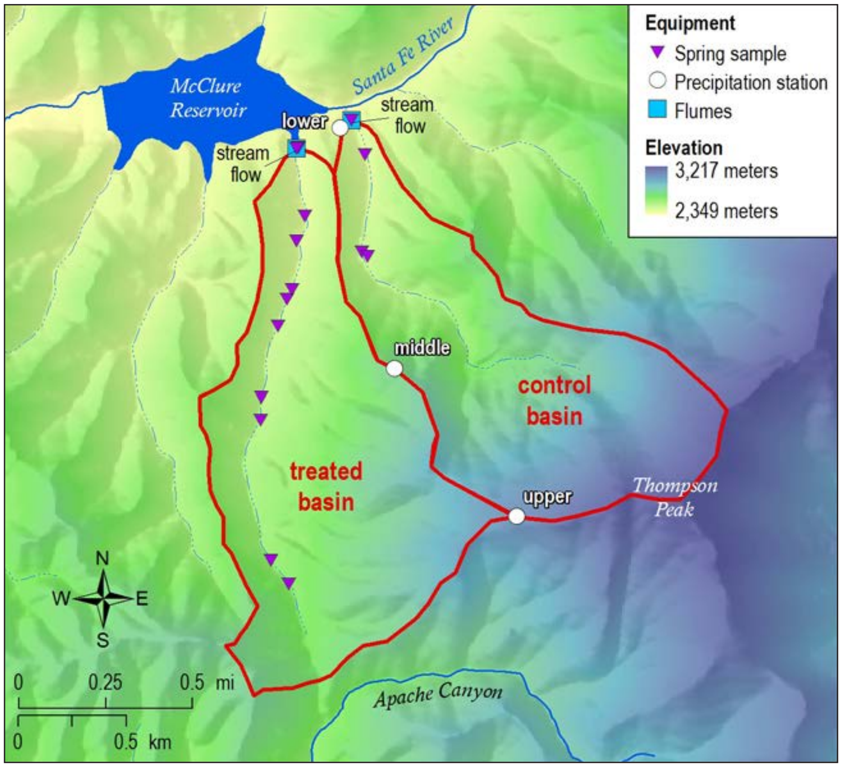


Figure 6. Location of monitoring stations in the paired basins.

basin, four 300-m long transects were placed in each of four cardinal directions located approximately 400 m from the bottom of the basins.

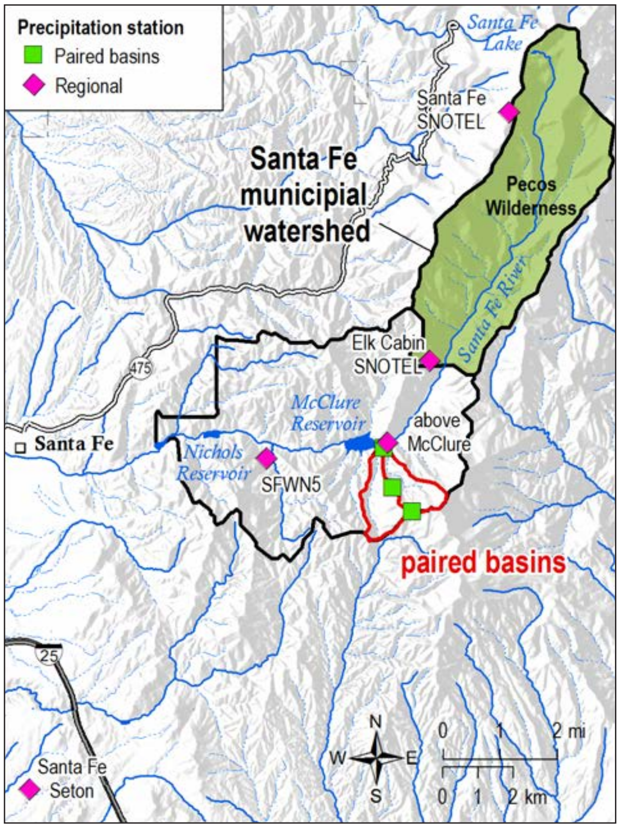


Figure 7. Location of regional precipitation monitoring.

Measurement of Precipitation

Precipitation was measured at three precipitation stations (lower, middle and upper) at elevations of 2,440 m, 2,743 m, and 3,048 m (amsl), on the ridge that forms the boundary between the control and treated basins (Figure 6). The ridge is heavily wooded, except at the middle gage, which is slightly more exposed. The most desirable location for a rain gage is in a location with no obstructions in a 45° angle from the gage. The most open area in the forest was selected at each location, but some obstruction may occur if the precipitation falls during high winds. Wind shields were not used at the sites. Each precipitation station consisted of a tipping-bucket rain gage with a snow adapter (Campbell Scientific TE-525) to measure precipitation volumes and rates. The snow adapter (not used in summer months) is anti-freeze-based system, which has delays (hours) in recording snow fall, but was adequate for the purposes of this investigation.

The tipping bucket rain gages had a 0.20 m orifice and detect rainfall in increments of 0.0254 cm. The number of tips is converted to rainfall (or melted

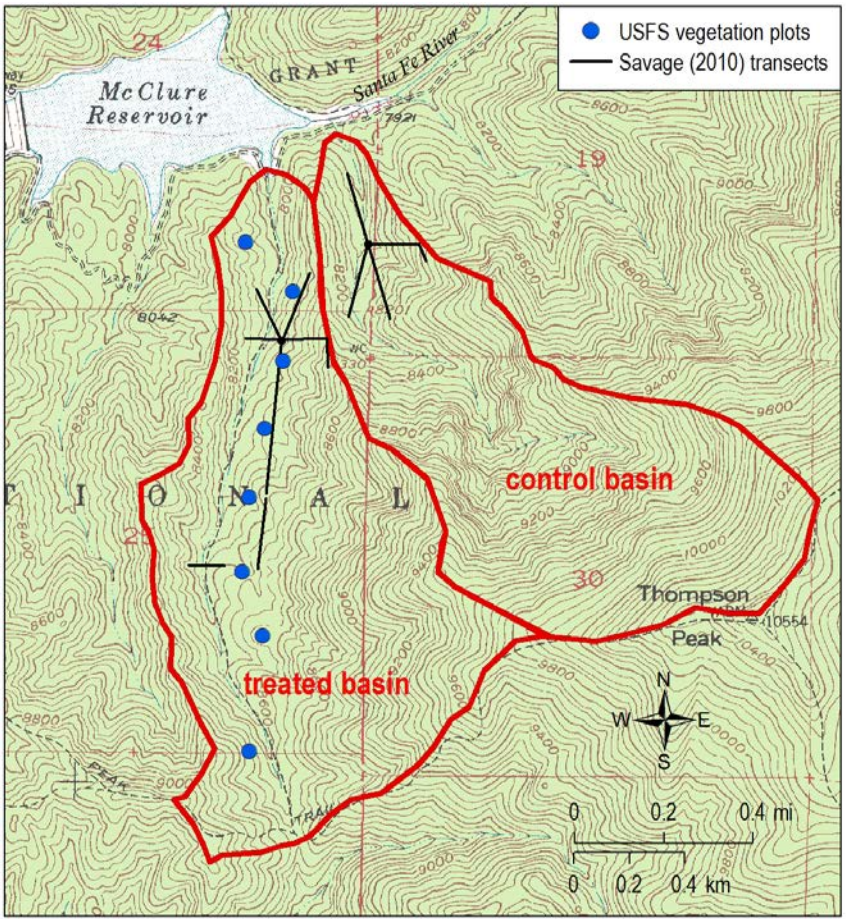


Figure 8. Location of vegetation transects in the paired basins.

snow), with the amount recorded every hour. Monitoring precipitation throughout the course of this investigation has been challenged by damage from wildlife, particularly bears (Figure 9). To protect the equipment, solar-powered electric fences were installed around the equipment, which is only effective when the ground is moist enough to conduct a current.

Measurement of Surface Water

Surface water flow was measured in each basin at the outlet using two flumes; a 0.23 m fiberglass Parshall flume (manufactured by Composite Structures, Inc.) downstream of a 0.76 m galvanized steel Parshall flume as depicted in Figure 10. The small flumes were used to monitor low flows (between 0.076 and 250 L/s) and the large flumes were used to monitor flows that exceed the capacity of the smaller flumes (accurate between 30 and 850 L/s). Both flumes are level and were serviced every two weeks to keep the flumes clear of debris. Stream gaging was performed by monitoring the stage with a pressure transducer (Instrumentation Northwest, Inc. AquaStar PT2X) in the Parshall flumes. A rating curve equation for each of the flumes was used to estimate the flow.

The pressure transducers are calibrated by plugging the hole in the stilling well with a stopper and attaching a tube connected to a small bucket. Water is added to the stilling well and the level in the bucket is compared to the depth recorded by the transducer. Calibration checks were performed twice a year and were observed to be accurate to 0.001 cm. Pressure transducers were replaced when observed to be out of calibration.

Chloride concentrations in streamflow were estimated from bi-monthly samples analyzed by Hall Environmental Analysis Laboratory (EPA Method 300.0). Blind duplicates were submitted approximately once per year to verify lab results. The total mass of chloride discharged from each basin through surface water was calculated by multiplying the daily chloride concentration by the mean daily flow. The daily chloride concentration was based on water quality samples collected in the streams approximately twice a month. If concentrations changed significantly (more than 0.3 mg/L) between sampling events, then the daily

Figure 9. Bear visitation to upper precipitation station.

Figure 10. Photograph of the large and small Parshall flumes in the treated basin.

concentration was averaged between the two samples for the intervening period. During dry periods when no flow was observed at the small flume, samples were collected when water was present a few meters upstream in a pool. On several occasions, when the stream was flowing over a longer reach, stream samples were collected upstream in pools where groundwater discharged to the stream.

Measurement of Evapotranspiration

ET was measured indirectly through a chloride mass balance method, whereby the concentration of chloride, which occurs naturally in precipitation, is increased through sublimation, transpiration and evaporation to yield the concentration observed in the outflow of surface water (Claassen et al., 1986).

To measure chloride in precipitation, a precipitation collector was installed at each of the precipitation gages using a method described by Claassen et al. (1986). Chloride collectors consist of 1.5 meter-long tubes with a diameter of 0.30 meters. The tubes were lined with 6-mil-thick plastic bags that are constricted near the middle of the tube to prevent evaporation while enabling snow and rain to drain into the bottom of the bag. The tubes were painted black to enhance the rate of melting of snow, thereby minimizing sublimation. Bags were placed in the tubes using surgical gloves to avoid contamination. Plastic bags were removed and, if frozen, samples were allowed to melt before filling sample bottles for laboratory analysis of chloride. All samples were analyzed by Hall Environmental Laboratory in Albuquerque, NM using EPA Method 300.0.

The amount of water collected over a sampling period was compared with the amount measured over the same period by the tipping bucket to estimate the amount of evaporation or sublimation of the sample after the precipitation was collected in the bag.

Evaporation of the sample can occur during light rainfall events when the precipitation evaporates prior to entering the lower part of the collection bag. Sublimation can also occur from snow fall that sits in the upper two thirds of the polyethylene bag before melting into the lower constricted area (Figure 11). Only a small amount of evaporation occurs once the precipitation enters the lower part of the bag. Claassen and Halm (1994) found that, at most, only 3% of the water was lost to evaporation within the collector over 1 to 3 months for a sample placed in the collector (with a cap to reduce introduction of precipitation). Collection of the samples was generally performed within a day or two after a significant precipitation event that could effectively “rinse” the chloride residue from the surface of the bags.

The reported chloride concentration, the percent of precipitation in the collector as compared to the tipping bucket, and the calculated adjusted chloride concentration are shown in Appendix D for each sampling event. The average daily precipitation from the three gages was multiplied by the average adjusted chloride for the time period over which the precipitation sample was collected and the basin area to estimate the mass of chloride entering each watershed. The average volume-weighted chloride concentration deposited (both wet and dry) on the basins was estimated using the total mass of chloride divided by the total volume of precipitation.

The chloride mass balance method assumes that the mass of total chloride input to the basin is from dry deposition and wet precipitation. The assumption that no other geologic source of chloride was present in the basins appears to be valid as the geology underlying each of the basins consists of early Proterozoic plutonic and metamorphic rocks (Bauer et al., 1996). The minerals within the quartz porphyry, interlayered felsic schist and amphibolite, gneissic granitoid, quartz-muscovite schist, interlayered amphibolite and quartz-feldspar schist, and muscovite quartzite do not contain chloride. Both basins remain uninhabited and undeveloped, with little human activity, other than the forest restoration efforts.

Figure 11. Snow on lower precipitation collector in November of 2015.

As an additional check on possible anthropomorphic sources entering the paired basins, bromide was tested in precipitation and stream samples. Mullaney et al. (2009) provide a summary of urban and agricultural impacts on chloride and bromide concentrations in surface and groundwater. Bromide in groundwater from forested lands showed concentrations between 0.015 and 0.02 mg/L. Stream and precipitation samples collected in April 2014 showed bromide concentrations of less than the detection limit of 0.021 mg/L, confirming that no anthropomorphic source of chloride is present in either basin.

Measurement of Soil Thickness

A soil survey was conducted in May 2013 to measure the depth of soil in each of the basins. A profile of the soil depth was measured in a cross-section near the downstream end of the basins and in three sections near the stream channel in each basin. A 1.5 meter section of rebar was driven into the ground in four locations about 2.4 meters apart at each site until bedrock was reached and then the rebar was removed using a high-lift jack and chain. The thickness of moist soil was noted.

Measurement of Soil Moisture

NOAA’s NWS Climate Prediction Center data was selected as the best estimate for changes in soil moisture for the beginning and end of the integration periods (NWS, 2017). The NWS estimates soil moisture using a one-layer hydrological model based on observed precipitation and temperature. A single onsite 12 cm soil moisture probe (CS655 Time Domain Reflectometry (TDR)), installed near the lower precipitation station in July 2013, compares favorably to the NWS model results for the northern mountains. Conversely, NASA’s North American Land Data Assimilation System (NASA, 2014) was compared to on-site data and determined to be less sensitive to observed changes in soil moisture within the paired basins.

III. MONITORING RESULTS

Daily, monthly, and annual summaries of the data collected in the paired basins is provided in Appendices A through J. The following sections describe the results of the data collected, and calculations performed with the data.

Vegetation Surveys

The vegetation survey results show a significant change in the tree density before and after treatment and between the two basins (Table 3 and Figure 12). Prior to treatment (thinning in the spring of 2004 and prescribed burns in fall of 2004, 2010 and 2011), tree density was estimated to be about 1,000 trees/ha in the treated basin in 2003 (Bagne & Finch, 2008). By 2005, tree density was reduced to about 406 trees/ha through thinning, representing a reduction of 60%. Tree density sampled in 2010 was 675 trees/ha in the control basin, compared to 243 trees/ha in the treated basin, reflecting

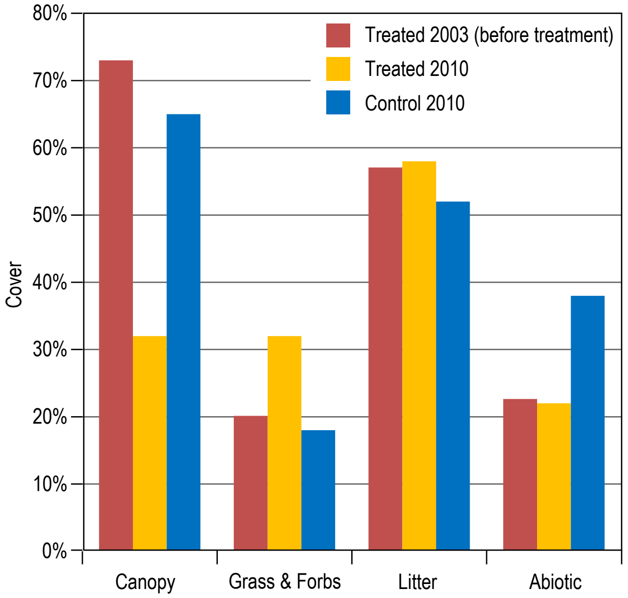


Figure 12. Percent cover for the control and treated basins based on vegetation surveys.

Table 3. Summary of vegetation surveys for the treated and control basins.

BASIN	**TREATED BASIN**				**CONTROL BASIN**
Treatment Condition	**Pre-treatment**	**Post-treatment**		**Percent change after treatment**	**Untreated**
Year surveyed	2003	2005	2010		2010
Density					
trees/ha	1,019	406	243	-60%	675
shrubs/ha	7,528	7,894	NA	5%	NA
Overstory					
Canopy	73%	56%	32%	-24%	65%
Understory					
Grass & Forbs	20%	28%	32%	38%	18%
Litter	57%	35%	58%	-38%	52%
Abiotic (incl. bare ground)	23%	15%	22%	-34%	38%
Source	Average of 8–11.3 m radius plots (Bagne & Finch, unpublished data)	Average of 7–11.3 m radius plots (Bagne & Finch, unpublished data)	Average of 7 transects (Approx. 10 Points each) Savage, 2010	2003 data/ 2005 data	Average of 4 Transects (10 Points each) Savage, 2010

64% fewer trees per acre from the control to the treated basins. The canopy cover in the control basin was about 65% in 2010, similar to the treated basin estimated canopy cover (73%) prior to treatment. Savage (2010) estimated tree canopy cover to be about 32% in the treated basin in 2010.

The density of grass and forbs increased in the treated basin after treatments, from 20% of ground cover in 2003 to 28% in 2005. In 2010, the grass and forb cover was measured at 35% in the treated basin, indicating continued increase in ground cover, a desired and expected change following thinning. The measured grass and forb cover in the control basin was 18% in 2010, very similar to the pre-treated condition of the treated basin. The abiotic cover is significantly greater in the control basin (38%) compared to the treated basin (22%). The greater area of abiotic (e.g. talus and outcrops) may be a contributing factor to the lower ET in the control basin. Similarities between the percent cover in the treated basin prior to treatment and the control basin provide confidence that the control basin is representative of pre-treatment conditions.

Precipitation Monitoring Results

Precipitation samples collected approximately once a month from the precipitation collectors for laboratory analyses of the chloride concentration are shown in Appendix D. Daily and monthly precipitation data are provided in Appendices E through G. The monthly precipitation measured at the three stations and other precipitation stations in the Santa Fe area are shown in Appendix H. Because periodic problems have resulted in some lost data at each station throughout this investigation (such as a clogged tipping bucket or damage by wildlife) the daily precipitation from each station is averaged to calculate the monthly and annual precipitation. For 80% of the 3,194 days, all three stations were used to estimate the daily precipitation and 13% utilized two gages.

The expected orographic effect on precipitation from the lowest to highest paired-basin precipitation stations did not occur over the 9 years of this investigation (Figure 13). The lower gage recorded about 11% more than the upper gage for months with complete daily data (2009–2017). In contrast, orographic precipitation is observed from southwest to northeast (Figure 14) (by comparing the same months totaled for Figure 13 for Santa Fe Seton (2,134 m) to Elk Cabin SNOTEL (2,502 m) and the Santa Fe SNOTEL (3,488 m)) due to the upward deflection of large-scale horizontal flow of air. Because the relief of the terrain within the basins is from north to south (perpendicular to the large-scale relief of the Sangre de Cristo Mountains), the orographic effect on precipitation may not manifest.

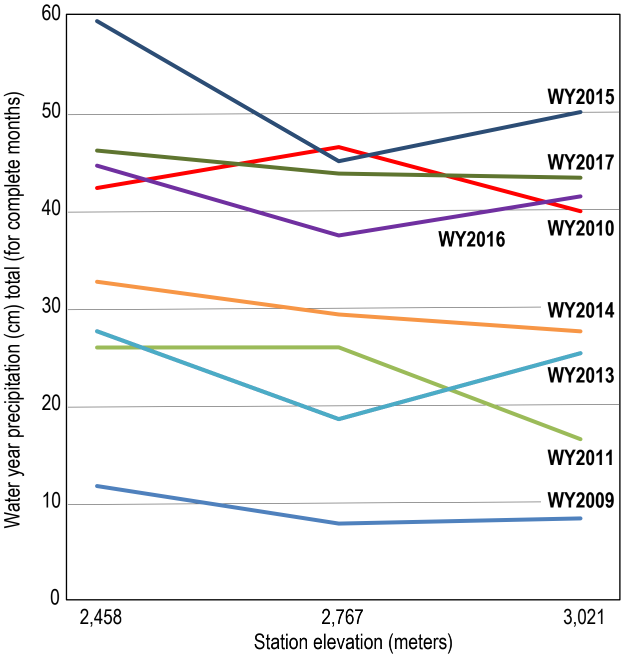


Figure 13. Precipitation by water year (WY) and elevation within the paired basins (from north to south).

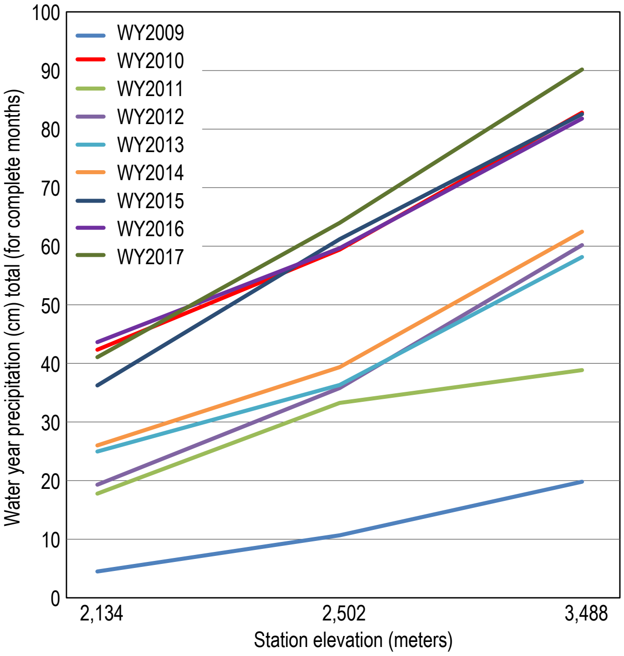


Figure 14. Precipitation by water year (WY) and elevation from regional precipitation collectors. The lowest elevation station (Seton) is located toward the southwest and the highest elevation station (Santa Fe) is located toward the northeast.

The annual precipitation over the period of study ranges from 31 cm in WY 2011 to 56 cm in WY 2015 (Figure 15). Precipitation at Elk Cabin SNOTEL for several years preceding this investigation is included to illustrate the variability of precipitation beginning in 2001 when the paired basins were first established. The correlation between the average monthly values of Elk Cabin and SFWN5 (see Figure 3) with the paired basin precipitation Figure 16), show an r^2 value of 0.86 and the standard deviation of about 1 cm difference between the monthly estimates.

Seasonal precipitation in the paired basins varies from year to year (Figure 17). For the years of this investigation, winter precipitation (October through March) has averaged about 41% of the yearly precipitation and has varied from 23% (WY 2013; skewed by the big September rain) to 58% (WY 2010). Comparing the percentage of precipitation that occurs in the winter (as snow fall) to the ratio of streamflow in the treated basin to the control basin (Figure 18) shows a strong correlation. In years with a greater percentage of precipitation in the winter, runoff in the treated basin increases relative to the

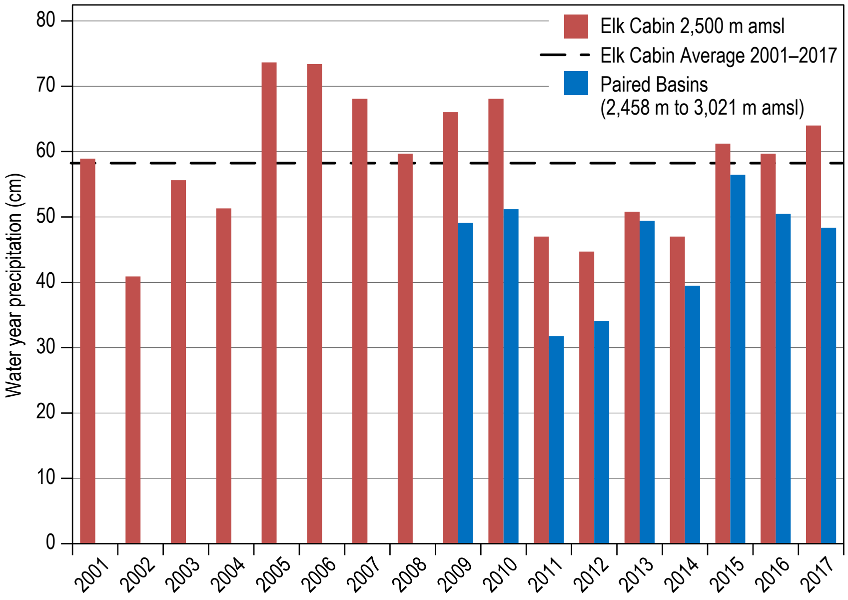


Figure 15. Precipitation by water year for Elk Cabin SNOTEL and the average of stations in the paired basins.

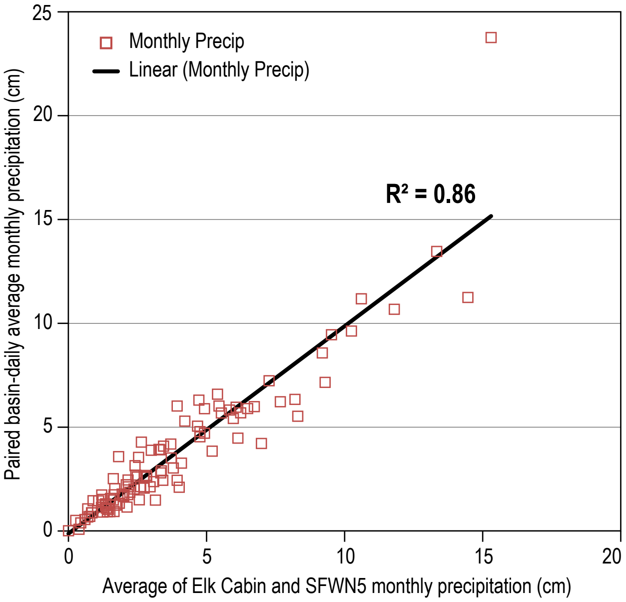


Figure 16. Cross plot of average monthly precipitation at the paired basins and the average between Elk Cabin and SFWN5.

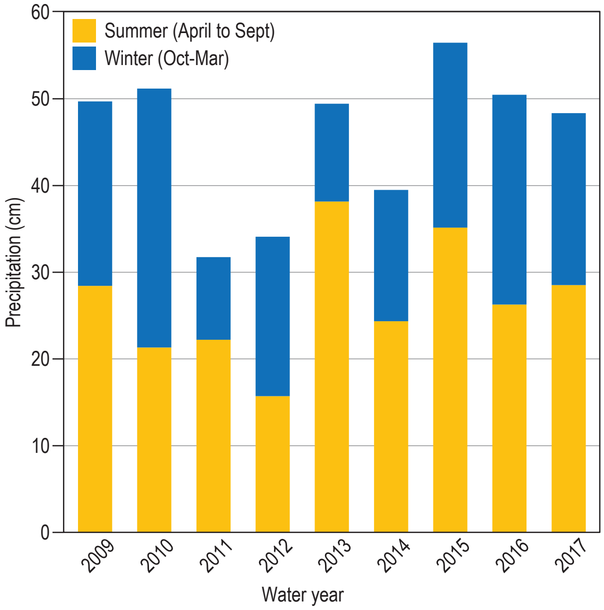


Figure 17. Distribution of winter (October-March) and summer (April–September) average paired basin precipitation.

control basin. Water year 2014 was preceded by nearly 24 cm of rainfall in September of 2013, which continued to produce significant runoff into October and November.

The upper gage periodically showed higher concentrations of chloride in samples (Appendix D). The reason for this occasional increase is not known. The overstory canopy at the upper site is similar to the lower site, thus interception by tree canopy is not suspected. Furthermore, the higher concentrations generally occur in the summer months, thus increased sublimation from snow (at the higher colder location) does not appear to explain the differences. Choularton et al. (1988) showed no influence of altitude on wet deposition of chloride. One possibility is that dry deposition of chloride is greater at the upper gage due to the greater exposure to west winds than the other sites that are more protected.

Assuming that each basin received the same rate of precipitation (because no orographic effect has been observed) and same concentration of chloride, the estimated total chloride deposited through precipitation (and dry deposition) onto the 153-hectare control basin and the 179-hectare treated basin was calculated for each integration period (Appendix J). The chloride concentrations and deposition rates shown in Table 4 are within the values published for New Mexico (NADP, 2017). Average chloride concentrations by integration period range from 0.18 to 0.24 mg/L as shown in Table 4 with an overall average of 0.21 mg/L.

Surface Water Monitoring Results

Streamflow in the treated basin is generally less than the flow in the control basin and water temperature is significantly less in the fall and winter, resulting in freezing conditions within the channel by the flume from December through February, a condition that is rare in the control basin.

Mean daily streamflow for the period of record is shown in Figure 19. Annual streamflow in 2010 exceeded streamflow in all other years during this study, although the highest instantaneous peak flow occurred in September 2013. Appendix A and B provide mean daily flow, and the maximum and minimum instantaneous flow measured each month for 2009 through September 2017 for the treated and control streams, respectively. Concentrations of chloride in stream samples are provided in Appendix C.

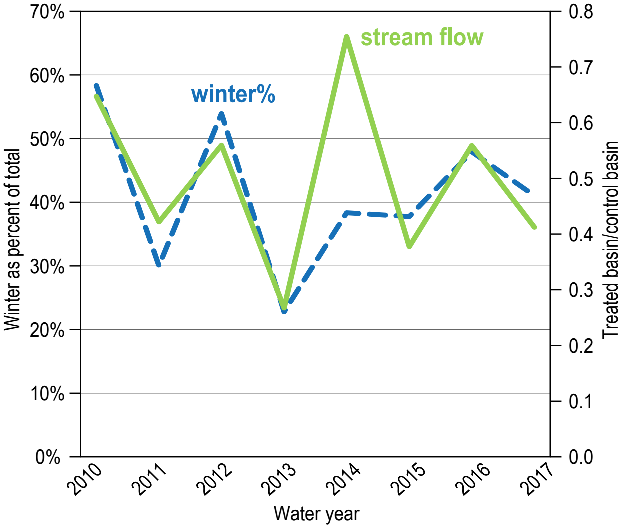


Figure 18. Percent winter precipitation to ratio of runoff in the treated stream to the control stream by water year.

Table 4. Summary of chloride concentrations in precipitation and deposition rate by integration period.

Integration period	Average volume weighted chloride concentration in precipitation (mg/L)	Chloride annual deposition rate (kg/ha/yr)
10/2008–9/2010	0.21	1.06
10/2010–9/2014	0.21	0.81
10/2014–9/2015	0.18	0.99
10/2015–9/2016	0.23	1.14
10/2016–9/2017	0.24	1.18

The total yield from the control basin continues to be greater than the treated basin for all water years 2009 through 2017. Figure 20 includes the flow at the Santa Fe River above McClure Reservoir for eight years preceding this investigation. Total yield in the control basin varies from 1.3 to 5.4 times the total yield in the treated basin by water year.

A cross-plot (Figure 21) compares the monthly flow in the treated and control basins before and after forest treatments to look for trends or a shift in the runoff between the two basins. If streamflow yield is increasing in the treated basin relative to the control basin, the linear fit would shift towards treated basin (y-axis) (an increase in slope). Instead, after forest treatment the streamflow in the treated basin appears to decrease slightly relative to the control stream. However, any decrease in treated basin streamflow is small and generally within the range of measurement error; thus, no quantifiable shift in the monthly flow between the two basins can be determined. The scatter in the mean monthly

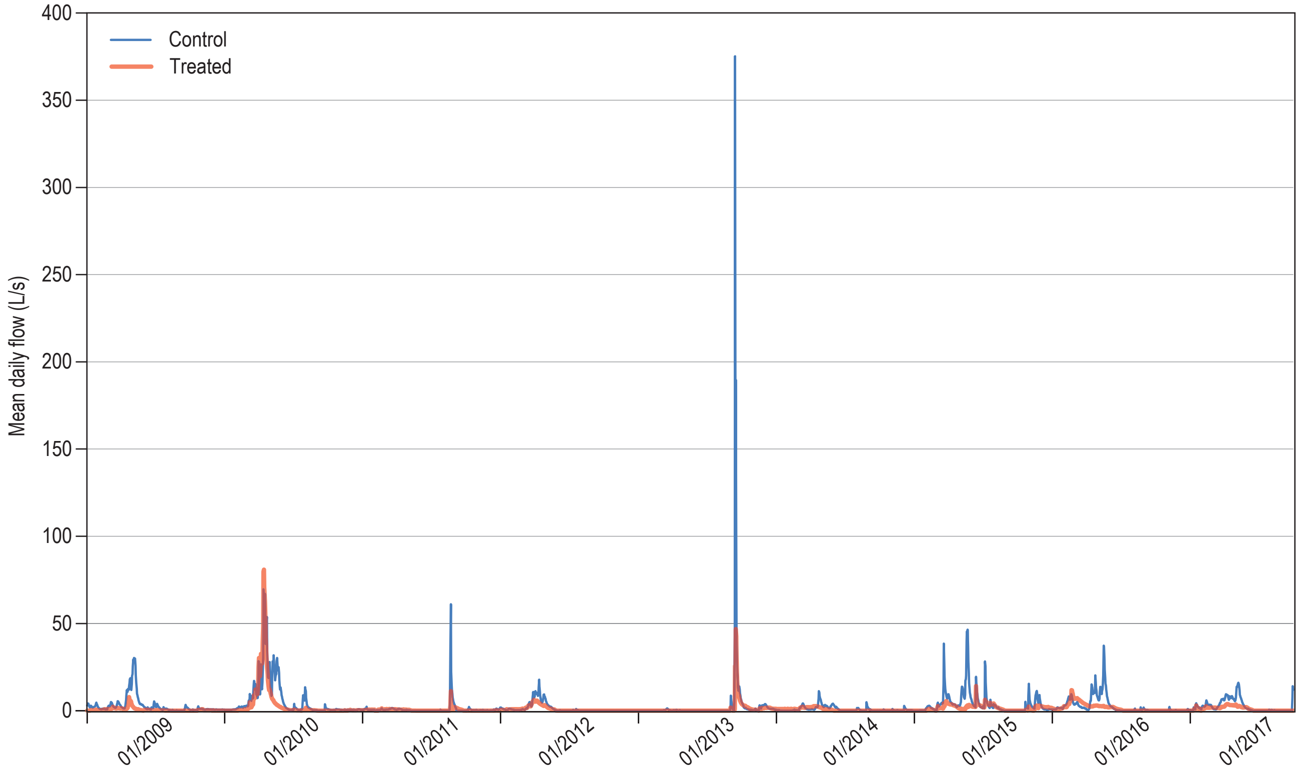


Figure 19. Mean daily streamflow in the treated and control basins 2009 to June 2017.

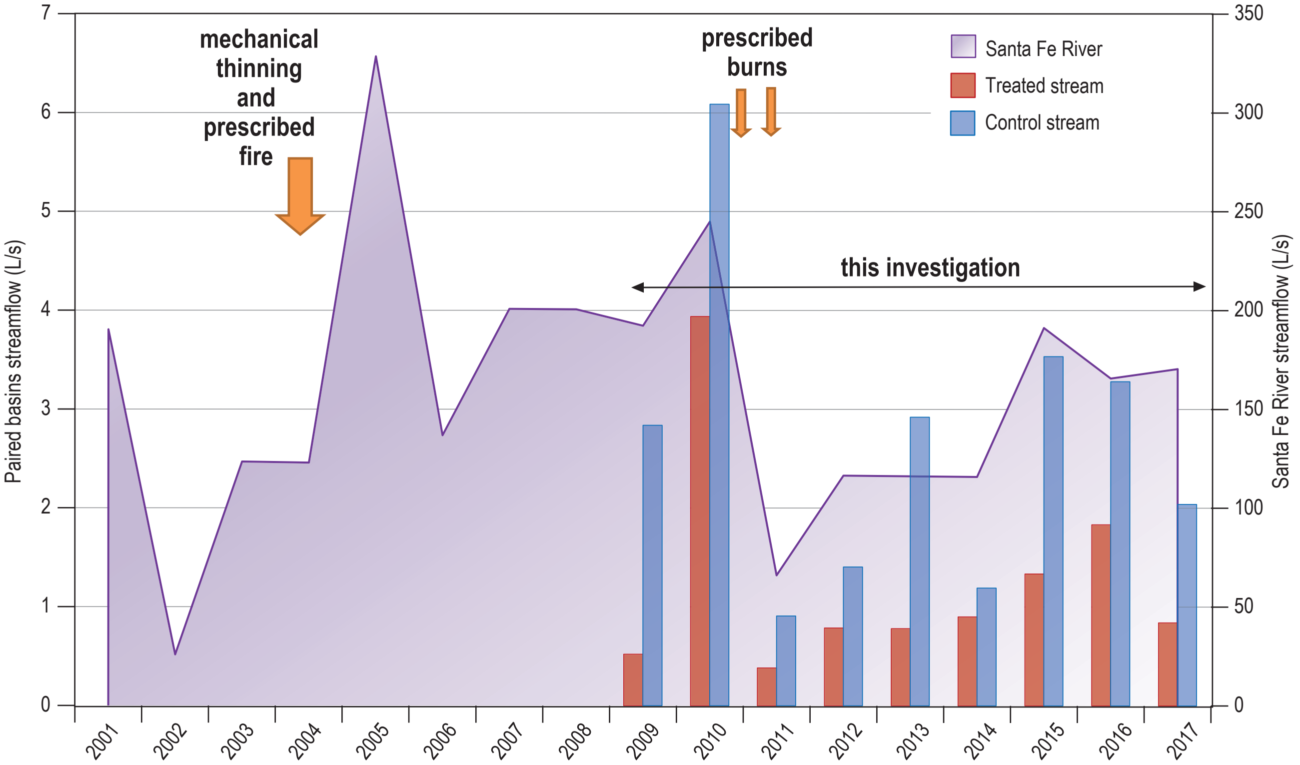


Figure 20. Annual streamflow in the Santa Fe River above McClure Reservoir and in the paired basins.

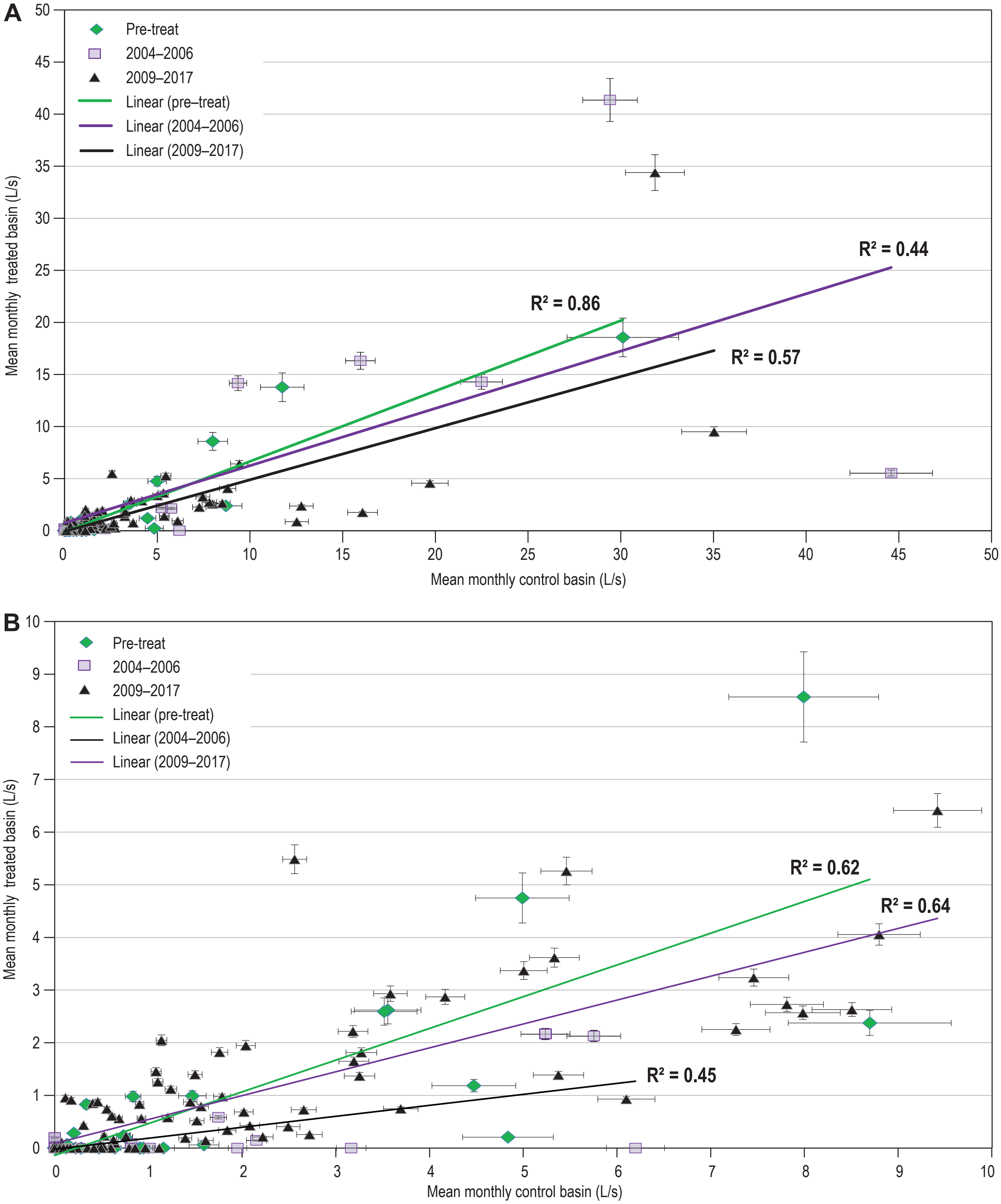


Figure 21. Cross-plot of mean monthly streamflow pre- and post-treatment. The lower plot (B) is an expanded view of the points near the origin in (A).

flow between the two basins was less ($r^2 = 0.86$) prior to treatment than it is after treatments where (r^2 is 0.44 and 0.57). The data collected prior to treatments used flumes that were too large to measure low flows precisely, thus the error bars are larger on the pre-treatment data. The increase in scatter after forest treatments may reflect how the type of precipitation is impacting runoff. With a decrease in forest canopy in the treated basin after treatments, the rate of melting, sublimation and evapotranspiration will vary with precipitation events, perhaps reducing the correlation. For example, when precipitation falls as snow, more of the snow will reach the ground in the treated basin, and less of the snow will be lost to sublimation than in the control. Prior to thinning, each basin had similar canopy densities, thus sublimation rates were the same.

Appendix K provides the time series of mean daily flow at each of the stream gages and daily precipitation (averaged from the three precipitation stations). Flow in each stream is dominated by snow melt (with the exception of September 2013, which recorded the highest flows over the nine-year investigation). Snow melt is initiated between February and May. Generally, both streams begin to flow at the same time, with the control basin producing much more water than the treated basin. Spring snow melt in the control basin is also more variable than the treated basin, which may be due to the thinner soil profile in the control basin.

The response of each basin to summer storm events was examined for differences in the timing of the runoff. By comparing the cumulative flow versus the cumulative precipitation in each basin, changes in the storage capacity of the landscape can be examined. Precipitation (in the form of rainfall or melting snow) will be intercepted by vegetation or reach the ground and infiltrate into the soil until the soil is saturated. The water will subsequently begin to fill the fractures in the bedrock and discharge to the stream or follow a deeper flow path. If the precipitation rate exceeds the capacity of the soil and bedrock to absorb the water, overland flow will occur. The capacity of the landscape to absorb more water after forest treatments occurs because the reduced tree canopy will allow more water and sunlight to reach the ground and encourage the growth of grasses and forbs (which increased from 20% pretreatment to 35% six years later in the treated basin). The increase in storage capacity over time following forest treatments is noticeable in the cumulative flow versus precipitation graphs (Figure 22 through Figure 25).

Four events, one before treatment and three after, show differences in the response to summer precipitation. On May 31, 2003, a rainfall event of 3.8 cm was followed by 2.54 cm on June 18, 2003. Immediately after these rainfall events, both streams responded with an increase in streamflow and little prolonged response as illustrated in Figure 22, which shows the cumulative flow versus precipitation. The control basin response was about twice the amount in the treated basin. Just two years after the forest treatments (Figure 23) the response to the July through September 2006 precipitation of 17 cm of rain shows that the cumulative flow in the control basin is initially about 10 times the cumulative flow in the treated basin, but over time the yield increases such that the difference is about twice (similar to pre-treatment).

An event in August 2011 shows a different response (Figure 24). The cumulative runoff in the control basin in response to 11.9 cm of rain yielded much greater flow than in the treated basin, about 10 times initially. The runoff in the treated basin continued for many days after flow stopped in the control basin (unlike pre-treatment events), such that the overall yield in the control was about five times the treated basin.

A record-setting rainfall event in September 2013 (Figure 25) produced nearly 25 cm of precipitation and demonstrated significantly different responses between the two basins. The control basin responded with peak flows that filled both flumes with boulders (removed within the day). Conversely, no sediment was deposited in the flumes within the treated basin. Yield from the control basin was about 5 times that of the treated basin for the September 2013 event.

Each of these storm events were preceded by prolonged dry periods, allowing for comparative responses. However, the variability in subsequent rainfall events in the weeks following each of the storms created challenges in evaluating differences between the two basins.

Chloride concentrations in streamflow and precipitation are shown in Figure 26. Surface water chloride concentrations in the treated basin ranged from 2.0 to 5.0 milligrams per liter (mg/L) and were about three times the concentration in the control basin, which ranged from 0.3 to 1.7 mg/L over the course of this investigation. Figure 26 shows the chloride concentrations from this study and samples collected prior to this investigation by White (2007). Only one sample set was collected

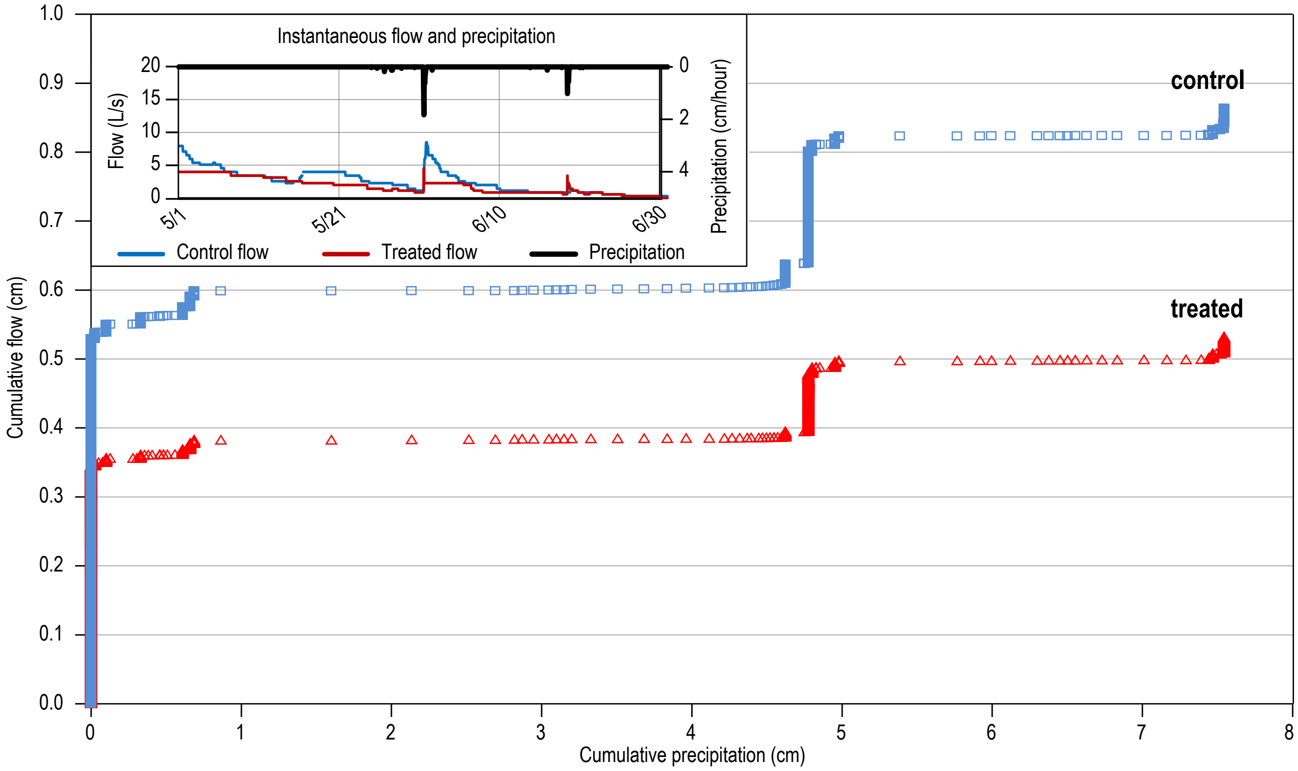


Figure 22. Cumulative flow and precipitation in the paired basins in response to rainfall May 31 to June 27, 2003 (pre-treatment).

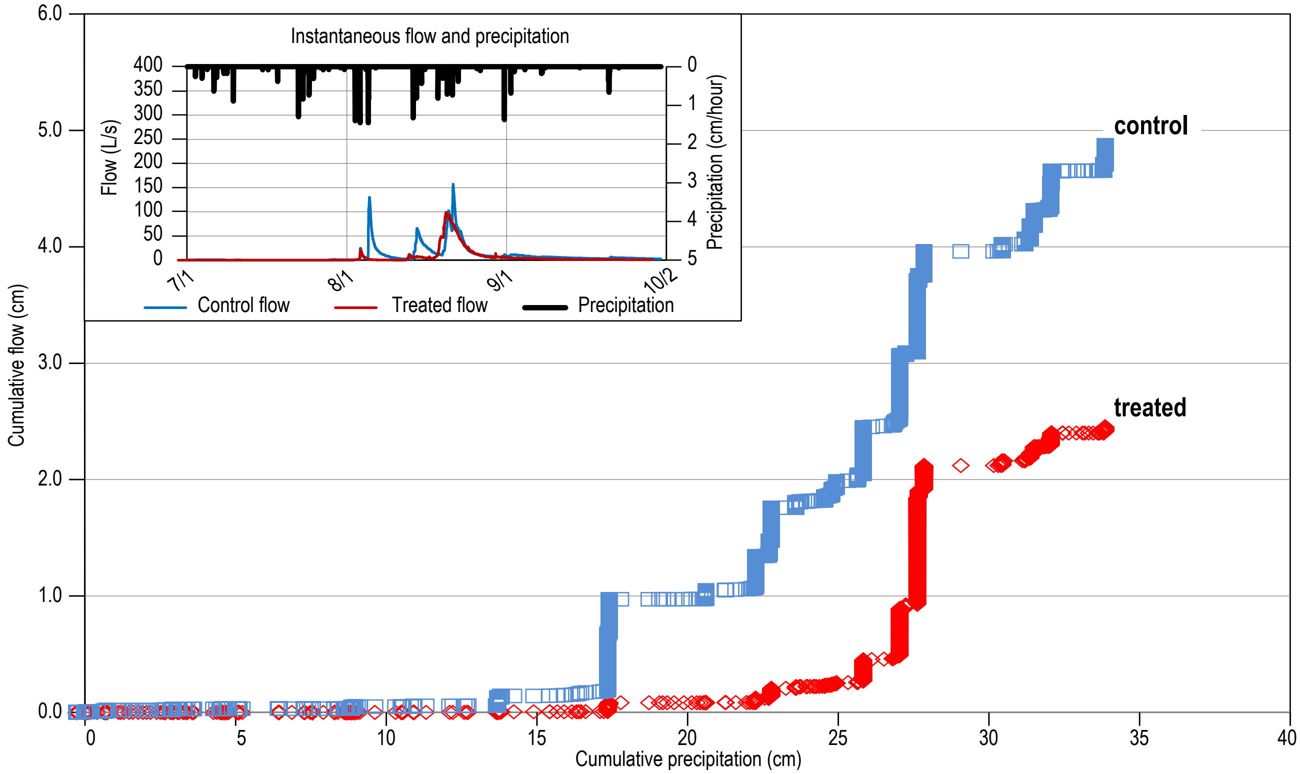


Figure 23. Cumulative flow and precipitation in response to rainfall July–September 2006 (post-treatment).

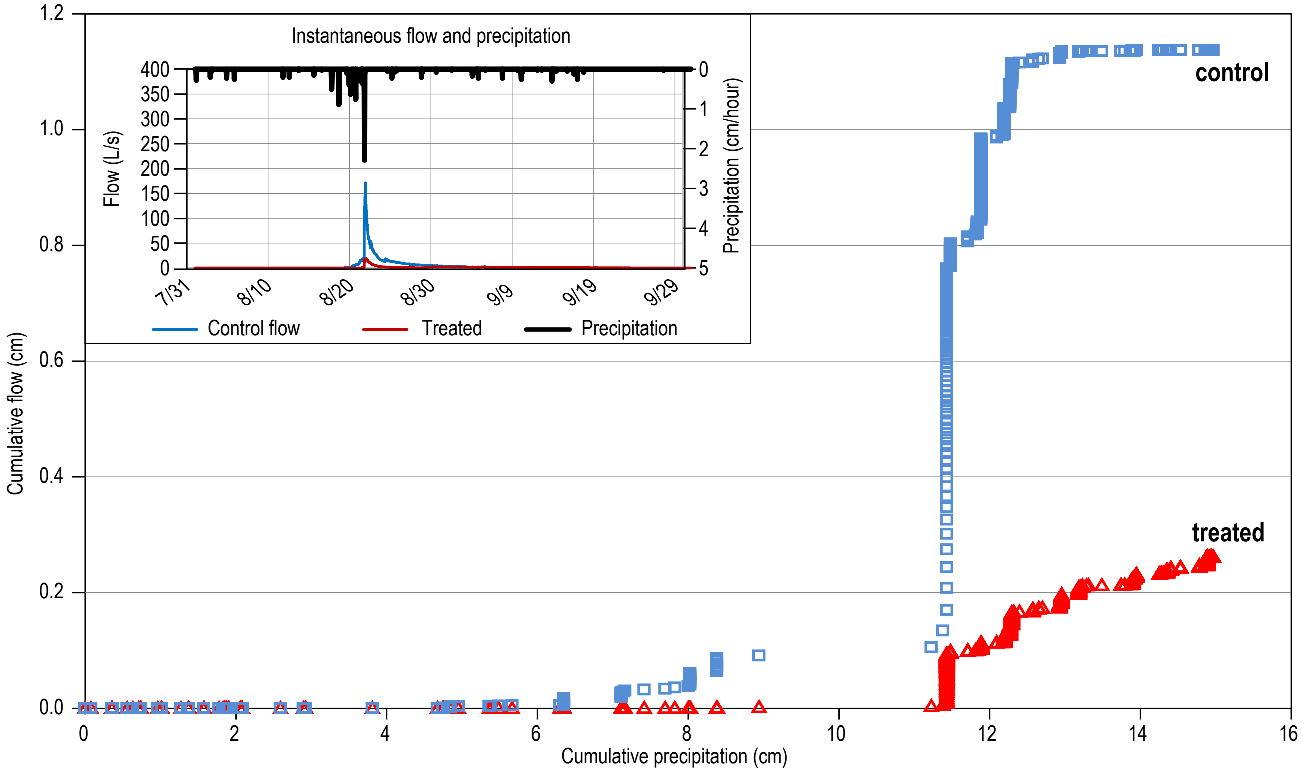


Figure 24. Cumulative precipitation and streamflow following an August 2011 storm event.

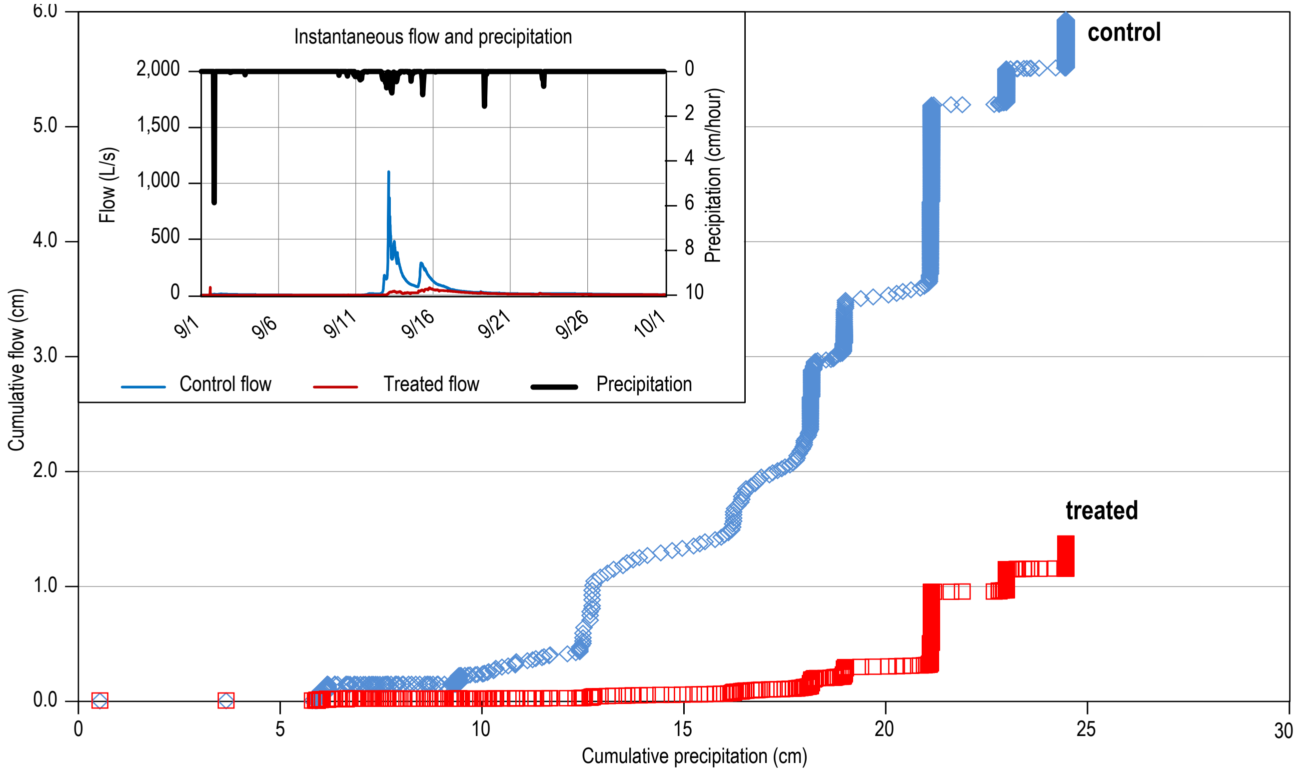


Figure 25. Cumulative flow in the paired basins in response to rainfall in September 2013.

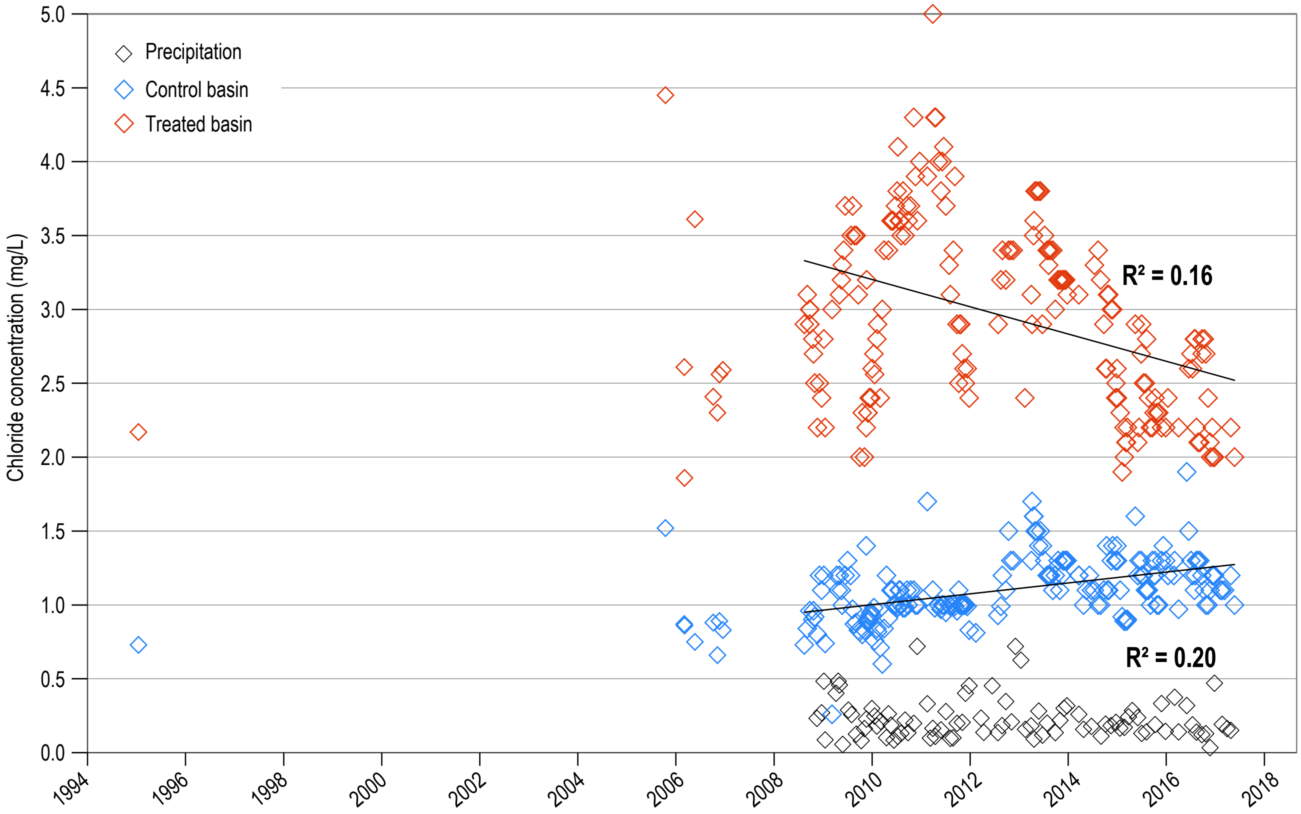


Figure 26. Chloride concentrations in the control and treated streams from 1995 through 2017 (samples from 1995 and 2006 from White, 2007).

(in 1995) before the treatments began and the concentrations are within the range observed from this investigation (2009–2017).

The chloride concentrations and mean daily flow from January 2009 through September 2017, are shown in Figure 27 and Figure 28. Chloride concentrations were lowest in the treated basin (down to 2 mg/L) when the streamflow was highest (79.3 L/s) during spring run-off. Chloride concentrations in the control stream were more consistent and generally less impacted by streamflow. However, concentrations in the control stream were high (1.6 mg/L) in March of 2013 after a dry winter and minimal snowmelt and a high value of 1.7 mg/L was observed during the peak flows (1,100 L/s) on September 13, 2013 (Figure 27 and Figure 28).

The ratio of chloride concentration in the treated stream to the control stream should remain constant if no change in evapotranspiration occurs. Figure 29 shows a downward trend in this ratio with time, which would suggest decreasing ET in the treated basin relative to the control basin following forest treatments. The r^2 value is low (0.49 for the period 2009 to 2017), thus one cannot conclude that ET is definitely decreasing in the treated basin. However, ET does not appear to be increasing due to forest treatments.

Chloride samples collected a few meters upstream of the small flume from a small pool represents the concentration of chloride discharging from groundwater. This very low flow during dry periods disappears into the rocky stream bed before reaching the small flume. As shown on Figure 27 and Figure 28, chloride concentrations of this groundwater discharge is equal to the concentration measured at the stream gage, suggesting that the source of water in the stream is primarily groundwater discharge. Water samples collected in other pools upstream of the stream gage location (see Appendix C), also show the same concentrations of chloride at the stream gage and in springs upstream. For instance, on September 24, 2013, the stream was sampled at the flume and at three locations from 1,315 m to upstream 2,100 m. Concentrations ranged from 3.5 to 3.7 mg/, within the laboratory error of +/- 10%.

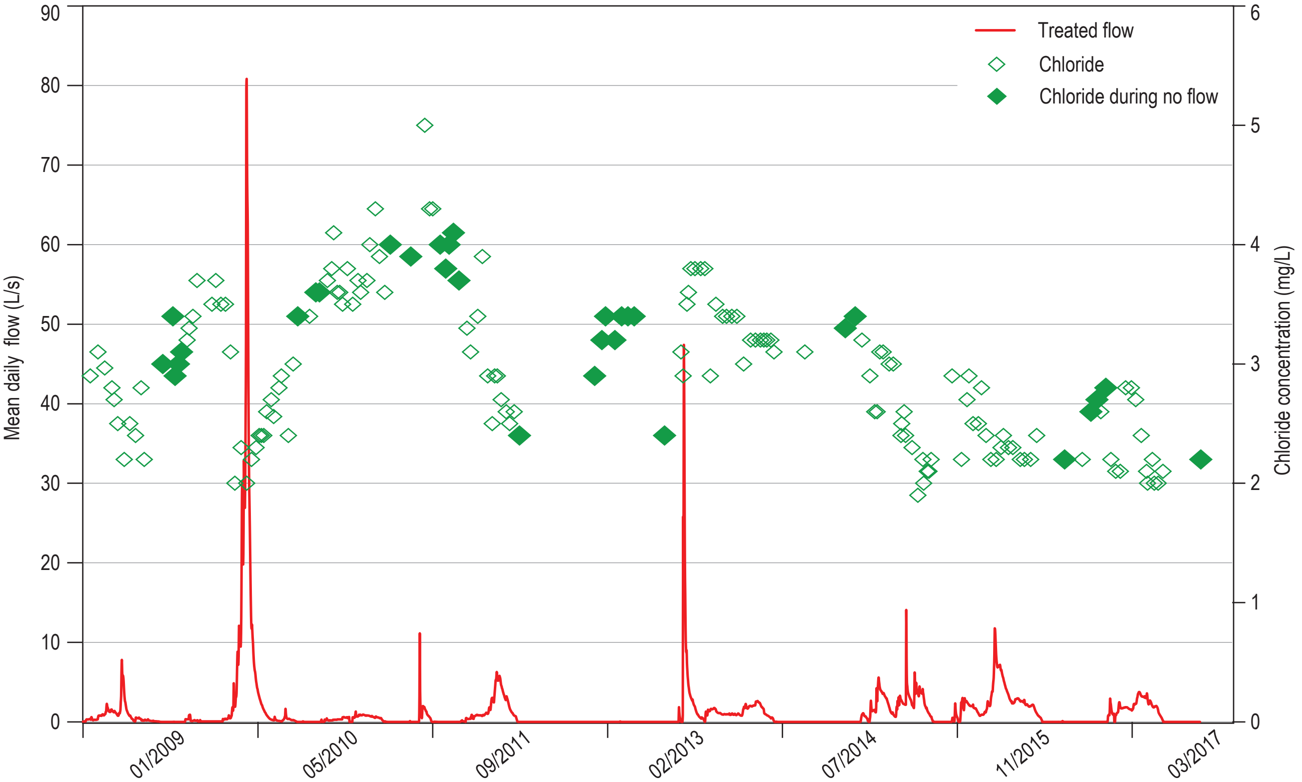


Figure 27. Mean daily streamflow and chloride concentrations of surface waters from laboratory analysis in the treated basin 2009 to Sept. 2017.

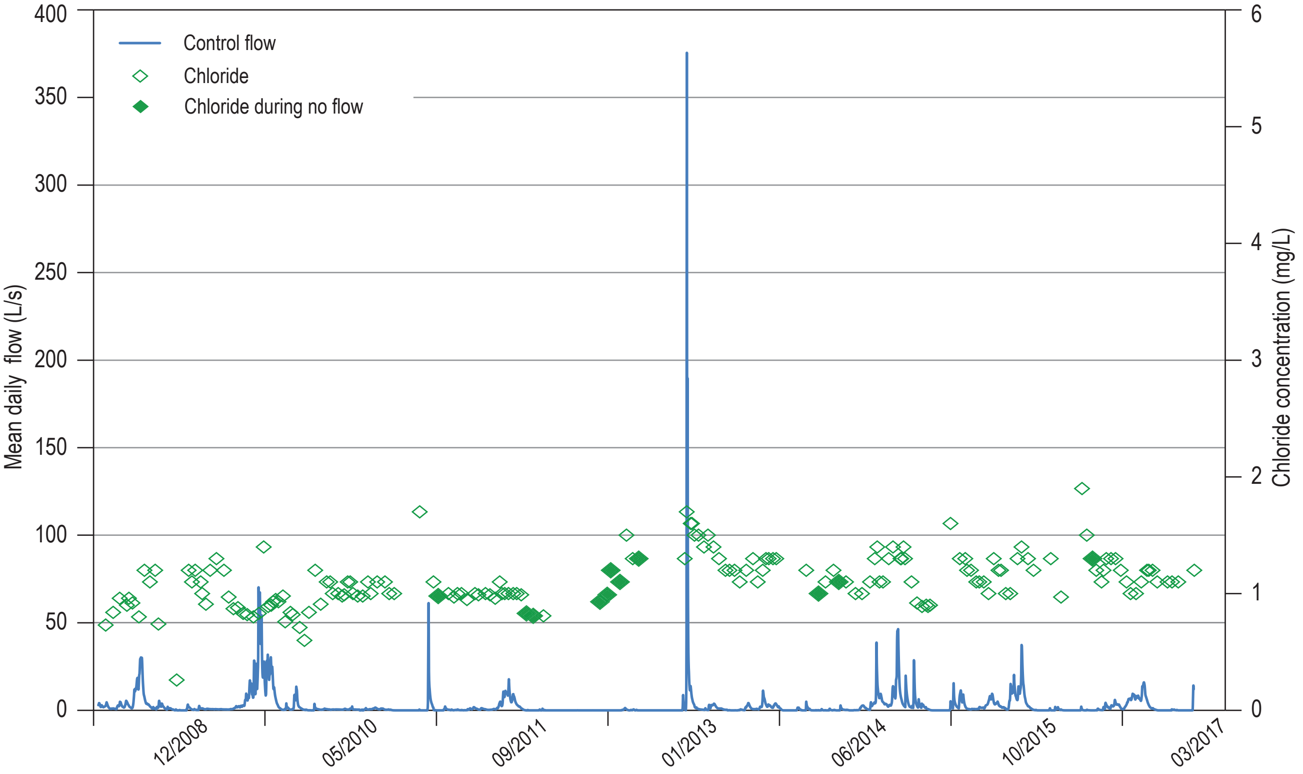


Figure 28. Mean daily streamflow and chloride concentrations of surface waters from laboratory analysis in the control basin 2009 to Sept. 2017.

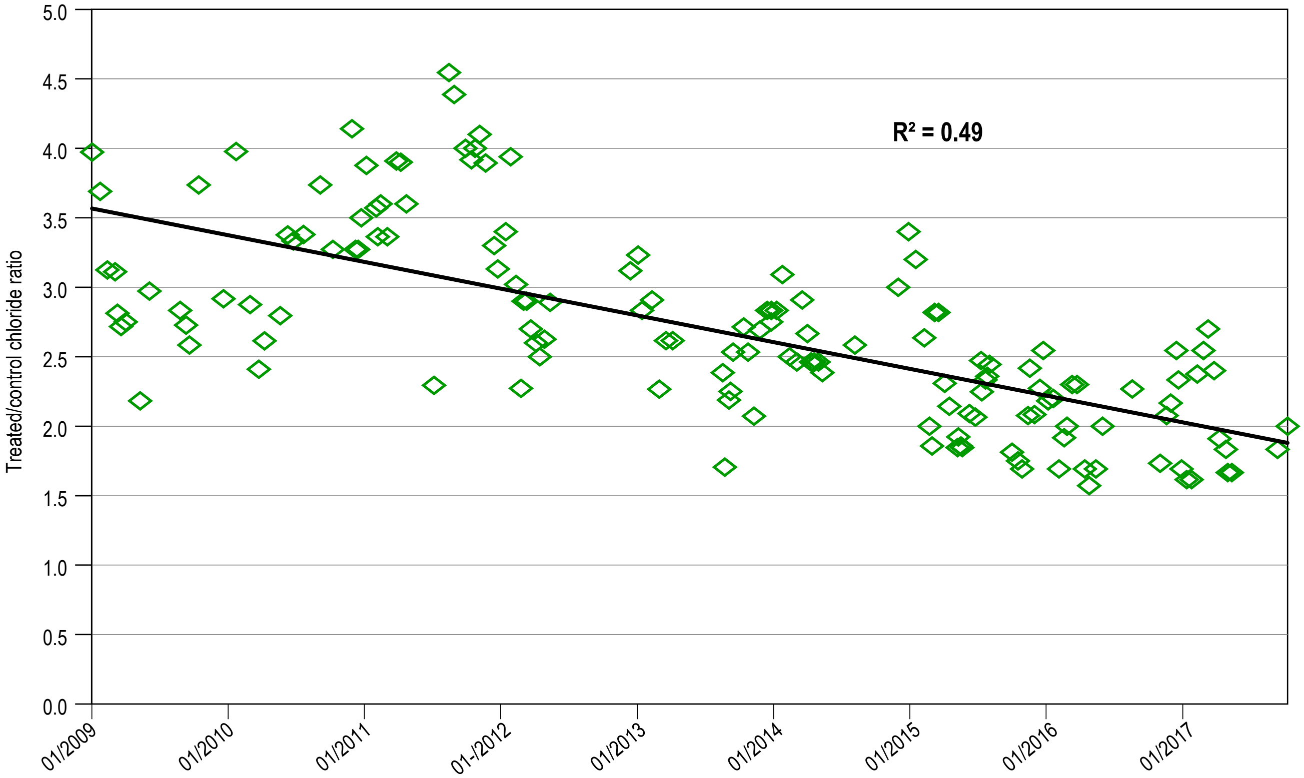


Figure 29. Ratio of chloride concentration in the treated versus control streams.

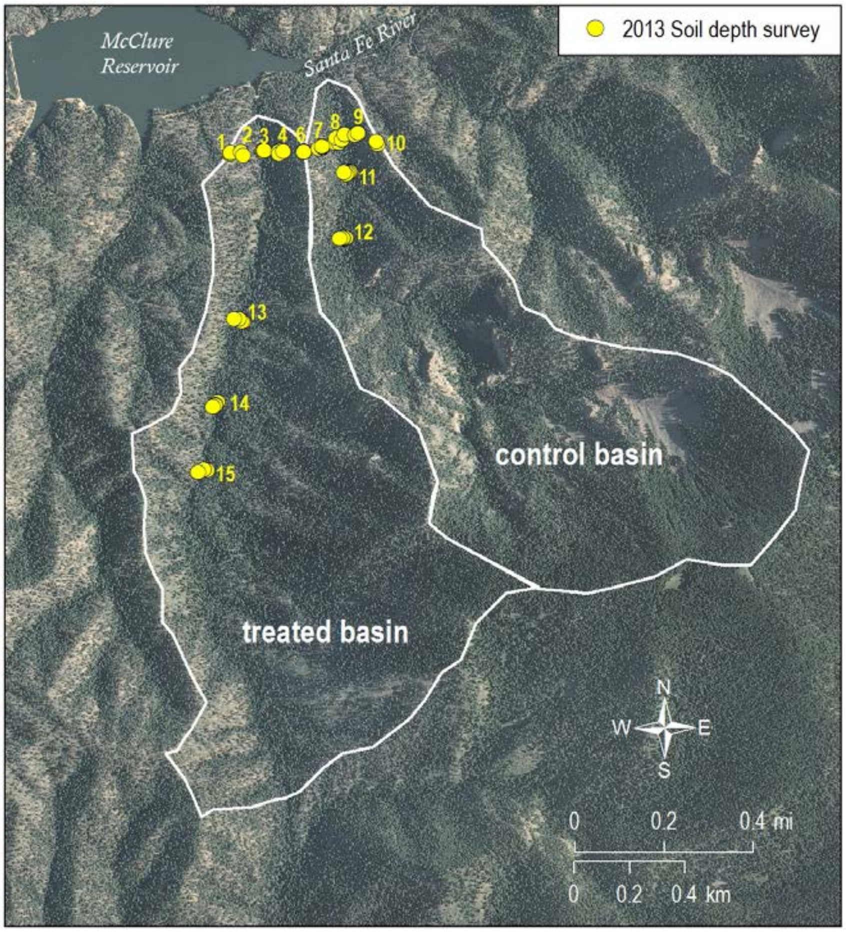


Figure 30. Sampling locations for soil depth survey.

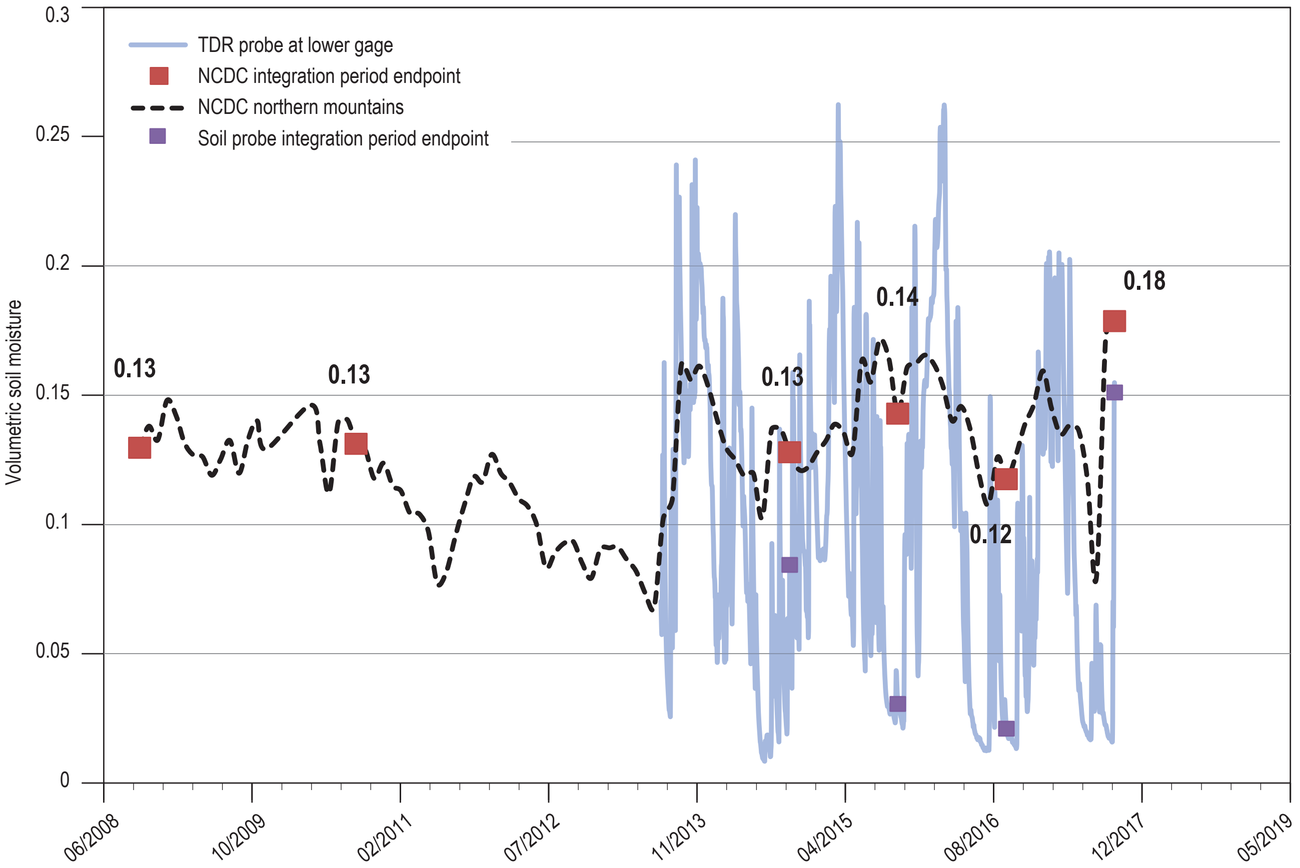


Figure 31. Soil moisture estimates from the TDR probe at the lower precipitation station and northern mountains (Sept. 2008 through Sept. 2017). NCDC is the NOAA National Climatic Data Center.

Soil Survey Results

Soil depth measured at 9 sites in the control basin averaged 0.6 m and at 8 sites in the treated basin averaged 0.8 m (Figure 30). The depth exceeded the length of the rebar in six places and is denoted with a ">" sign in Appendix I. The variability in depth at each of the sites was not very different, and soil was visually dry in all sites, except in the channel.

Soil Moisture Monitoring Results

Soil moisture estimates for the northern mountains of New Mexico (NWS, 2017) are within the range of average daily estimates measured at the 12-cm TDR probe at the lower rain gage (Figure 31). The beginning and end of each integration period is noted for each of the sources of soil moisture data.

A local resident keeping tabs on the upper precipitation station.

IV. WATER BUDGET SUMMARY

The water budgets were developed for integration periods to reflect the cycle of chloride entering and exiting the basins. As mentioned in the introduction, the integration periods were chosen based on water years. As illustrated in the graphs in Appendix K, the streamflow responds to spring snow melt and summer precipitation events. In some years, the streamflows throughout the summer, until September. In dry years, the streamflow is negligible throughout the year. For example, the first integration period begins in October 2008, when significant snowfall contributed to the spring runoff measured in 2009. The streams flowed nearly continuously throughout the fall and winter of 2009, thus the integration period did not end until September 2010. The second integration period begins in October 2010, the start of several years of extreme drought that eased in September 2013. The streams flowed in response to heavy September rains in 2013 and continued to flow until the fall of 2014, the end of the integration period. The third through fifth integration periods are based on single water years where most of the flow occurred in response to snow melt and minor summer precipitation events.

The measured and estimated inflows and outflows to each of the basins differ by a small percentage, demonstrating the success of the monitoring efforts.

This section describes how each water budget component was calculated and the assumptions involved in the various estimates. The parameters used to estimate the volume of water from ET, recharge and change in soil moisture for each integration period are shown in Tables 5, 6, and 7, with all water budget components shown in Table 8.

Estimation of Inflow from Precipitation (P)

The volume of precipitation falling on each of the watersheds was estimated for water years 2009 through 2017 based on the average daily rainfall for each station multiplied by the area of each watershed. Because the investigation began after the beginning of water year 2009, the inflow for precipitation from October through December 2008 was estimated based on the average of Elk Cabin SNOTEL and SFWN5.

Estimation of Runoff Outflow through Stream Gages (RO)

Total runoff was calculated by totaling the mean daily flow from each stream gage. Streamflow for October through December 2008 (prior to instrumenting the flumes) is based on the median flow measured for each October, November, and December during the investigation (2009–2016). Flow in the streams during the months October through December averaged 8 to 10% of the annual flow. A cross plot (Figure 32) of the yield in cm per month shows progressively less flow in the treated basin as compared to the control basin over the period of record. However, note that the error bars in the low range of the flow rates span distance between the regression curves. The few higher monthly flows recorded influence the apparent trend, and additional wet months would have helped this investigation. The error bars included in Figure 32 are based on an accuracy of streamflow of plus or minus 5% of the flow measured at the Parshall flumes.

Estimation of Evapotranspiration (ET)

Quantification of ET was based on the mass-balance of chloride in each watershed (Claassen and Halm, 1996), which assumes that the only source of chloride is derived from precipitation and that all chloride is discharged from the watershed after some period (hence the "integration periods"). Chloride exists in the atmosphere as suspended liquid droplets or solid particles that are then deposited by gravity through dry processes or wet precipitation. Accuracy of the method also depends on the assumption that there is no inter-basin flow and that recharge is a small fraction of ET. Figure 33 and Figure 34 show the cumulative deposition of chloride through precipitation and the amount exiting each basin through streamflow. The total amount of chloride leaving the basin through streamflow does not equal the amount entering through precipitation, thus some chloride is exits the system through recharge.

The relation between the mass of chloride entering the basin and the mass exiting the basin (Claassen and Halm, 1996) is:

$$\sum_{n=0}^{n=\tau} P_n * [Cl_p]_n = \int_0^{\tau} RO[Cl_s]\,(t)\,dt \tag{2}$$

Table 5. Evapotranspiration (ET) estimates for five integration periods.

	INTEGRATION PERIOD									
	Oct 2008 through Sept 2010 (2 years)		Oct 2010 through Sept 2014 (4 years)		Oct 2014 through Sept 2015 (1 year)		Oct 2015 through Sept 2016 (1 year)		Oct 2016 through Sept 2017 (1 year)	
PARAMETER	**treated**	**control**	**treated**	**control**	**treated**	**control**	**treated**	**control**	**treated**	**control**
Area (km^2)	1.79	1.53	1.79	1.53	1.79	1.53	1.79	1.53	1.79	1.53
Precipitation (cm)	100.9		154.8		56.5		50.5		48.4	
Precipitation (cm/year)	50		39		56		50		48	
Volume of Precipitation (1,000 m^3)	1,810	1,540	2,770	2,360	1,010	860	900	770	870	740
Mass of chloride deposited through precipitation (grams)	380,900	324,100	579,200	492,900	178,200	151,700	203,800	173,400	212,400	180,800
Volume-weighted chloride in precipitation (Cl_p) (mg/L)	0.21		0.21		0.18		0.23		0.24	
Volume of streamflow (1,000 m^3)	140	280	90	200	42	110	58	100	27	64
Mass of chloride discharged through streamflow (grams)	314,000	259,000	291,500	282,000	108,200	140,000	134,600	127,900	62,800	71,700
Weighted chloride in streamflow (Cl_s) (mg/L)	2.2	0.9	3.2	1.4	2.6	1.3	2.3	1.2	2.4	1.1
ET = $(Cl_s-Cl_p)/Cl_s$	91%	78%	94%	85%	93%	86%	90%	82%	90%	78%
ET (1,000 m^3)	1,640	1,190	2,596	2,000	940	740	820	630	780	580
ET (cm per year)	46	39	36	33	53	49	46	41	43	38

Table 6. Recharge estimates for five integration periods.

	INTEGRATION PERIOD									
	Oct 2008 through Sept 2010 (2 years)		Oct 2010 through Sept 2014 (4 years)		Oct 2014 through Sept 2015 (1 year)		Oct 2015 through Sept 2016 (1 year)		Oct 2016 through Sept 2017 (1 year)	
PARAMETER	**treated**	**control**	**treated**	**control**	**treated**	**control**	**treated**	**control**	**treated**	**control**
Precipitation (1,000 m^3)	1,809	1,539	2,774	2,361	1,012	861	905	770	867	738
Volume-weighted Cl in P (mg/L)	0.21		0.21		0.18		0.23		0.24	
Volume-weighted Cl in RO (mg/L)	2.2	0.9	3.2	1.4	2.6	1.3	2.3	1.2	2.4	1.1
Volume of RO (1,000 m^3)	140	280	90	200	42	110	58	100	27	64
Volume of R = $(Cl_p-Cl_sRO)/Cl_s$ (1,000 m^3)	28.7	68.0	79.2	132.6	27.4	9.3	29.7	36.9	63.2	97.8
R as a percent of P	1.7%	4.6%	3.2%	6.4%	2.7%	1.1%	3.3%	4.8%	7.3%	13.3%
R as a percent of RO	21%	25%	99%	75%	65%	8%	51%	36%	238%	152%

where, P is precipitation (L^3), L is a unit of length, Cl_s is the flow-weighted concentration of chloride (M/L^3) in the stream, M is a unit of mass, Cl_p (M/L^3) is the volume-weighted concentration of chloride in precipitation, n is the number of precipitation events, t is the integration period chosen where it is assumed that the chloride input to the watershed equals output for the period (t), and RO (L^3) is equal to runoff.

If recharge to the regional aquifer is a sink for chloride (and one assumes that the chloride concentration of recharge water is equivalent to the chloride concentration in streamflow) then the equation for each integration period water budget (Claassen and Halm, 1996) is:

$$Cl_p * P = Cl_s * RO + Cl_r * R \tag{3}$$

where Cl_r is the chloride concentration in recharge (mg/L) and assumed to be equal to Cl_s.

Rearranging, equation (3) becomes:

$$R = \frac{Cl_p * P - Cl_s * RO}{Cl_s} \tag{4}$$

Table 7. Estimate of the volume of water released from soil moisture storage in the control and treated basins for five integration periods.

	INTEGRATION PERIOD									
	Oct 2008 through Sept 2010 (2 years)		Oct 2010 through Sept 2014 (4 years)		Oct 2014 through Sept 2015 (1 year)		Oct 2015 through Sept 2016 (1 year)		Oct 2016 through Sept 2017 (1 year)	
PARAMETER	treated	control	treated	control	treated	control	treated	control	treated	control
Area (km^2)	1.79	1.53	1.79	1.53	1.79	1.53	1.79	1.53	1.79	1.53
Average soil depth (m)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Porosity of soil	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Change in soil moisture over integration period	-0.1%		-0.3%		1.5%		-2.5%		6.1%	
Change in soil moisture (S) (1,000 m^3)	-0.3	-0.3	-0.7	-0.6	3.2	2.7	-5.5	-4.7	13.4	11.4

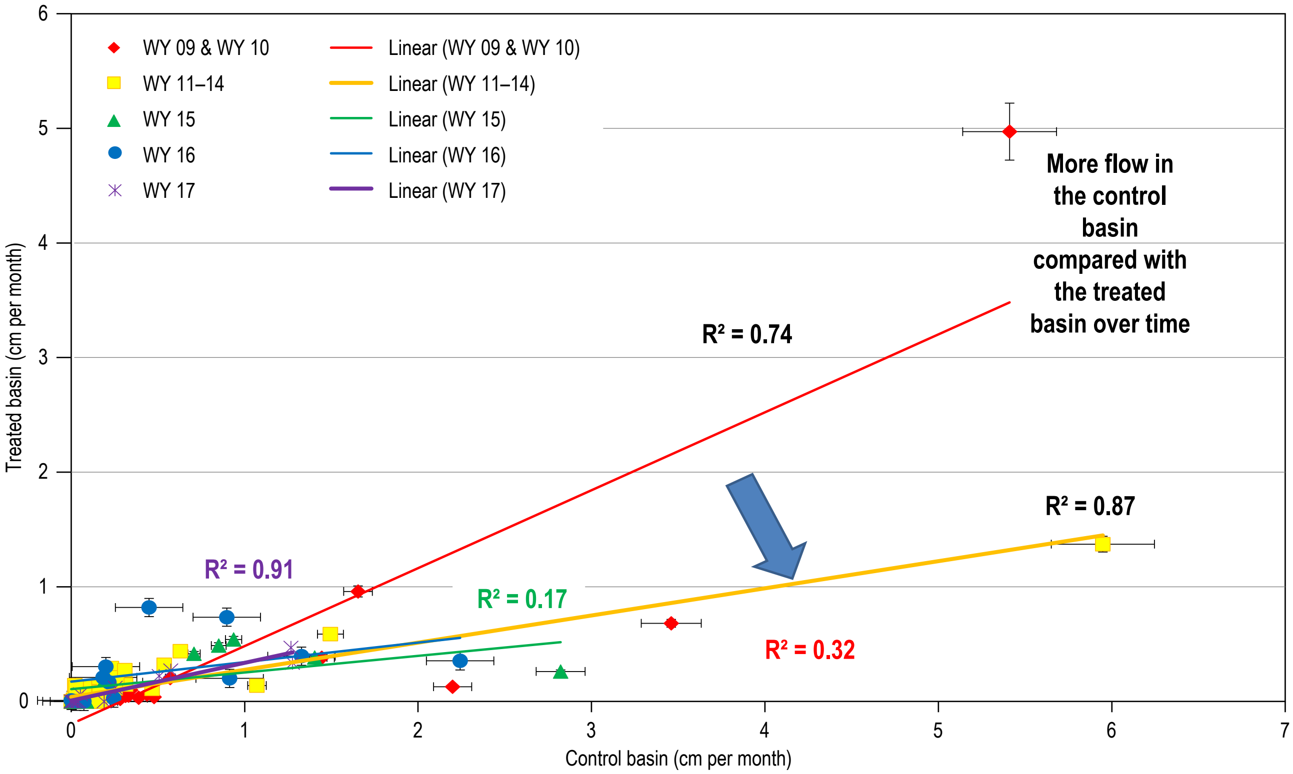


Figure 32. Cross-plot of streamflow yield (RO) per month for each integration period.

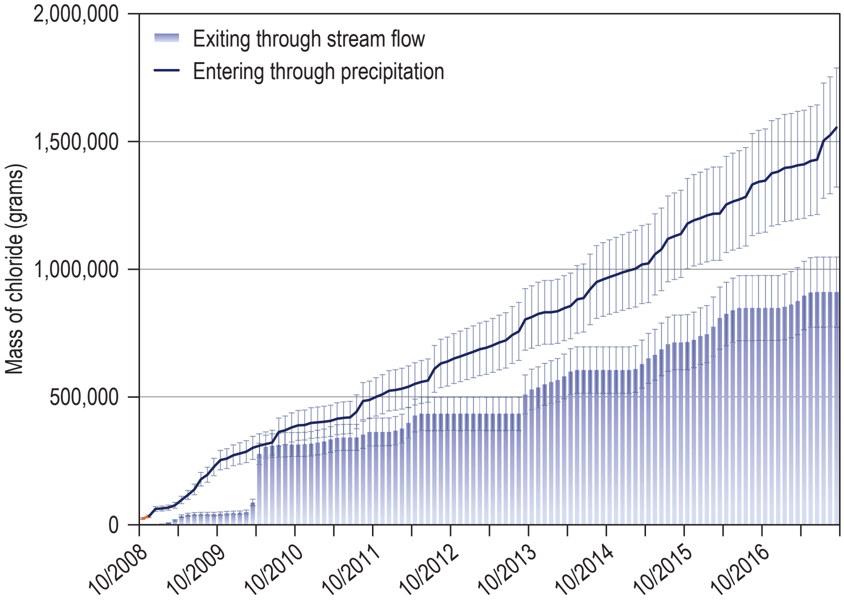


Figure 33. Mass of chloride entering and exiting the treated basin.

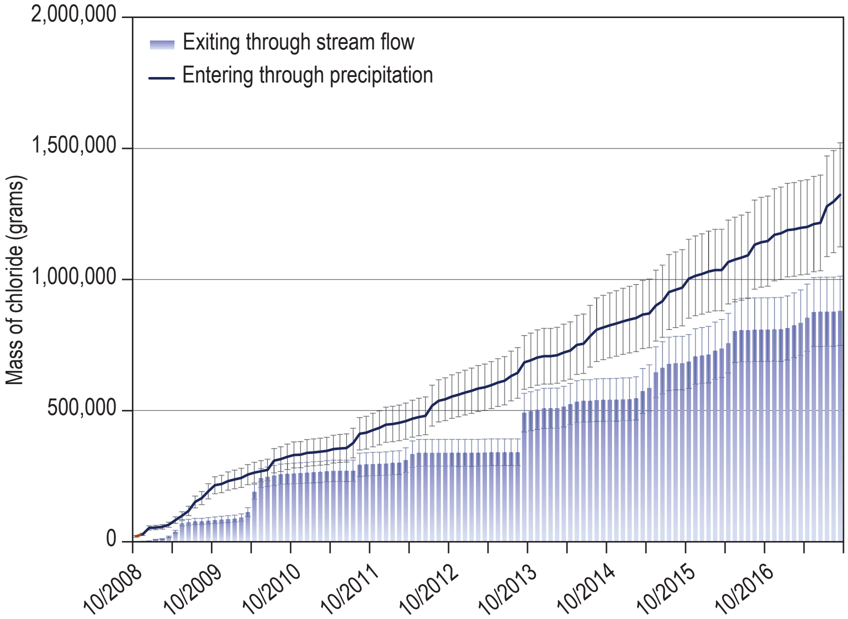


Figure 34. Mass of chloride entering and exiting the control basin.

Assuming that the change in storage is negligible compared to the other terms, equation (4) can be substituted into equation (1):

$$ET = P - RO - R = P - RO - \frac{Cl_p * P - Cl_s * RO}{Cl_s} \tag{5}$$

$$ET = P - RO - \frac{Cl_p * P}{Cl_s} + \frac{Cl_s * RO}{Cl_s} = P * (1 - \frac{Cl_p}{Cl_s}) \tag{6}$$

The volume of recharged water drops out of equation (5); therefore, the chloride mass balance approach can be used to estimate ET without knowing the volume of recharge. Although the volume of runoff is not explicit in equation (6), the amount of runoff is used to estimate the volume-weighted chloride concentration in streamflow.

How good is the assumption that Cl_r=Cl_s? It appears to be valid based on the results of samples collected at various times and locations upstream of the flume. Most of the flow at the flumes is derived from groundwater discharging from shallow soil drainage and fractured bedrock (completed in a few days or weeks after a storm event).

Figure 27 and Figure 28 include the chloride concentrations during the periods when no flow occurred at the flumes. During these dry periods, a small amount of water could usually be found about 50 meters upstream of the flume in a spring. The concentration in the spring water (representing the deeper groundwater component) is nearly the same as the concentration in stream water sampled at the flume before and after dry periods. The difference in chloride concentrations from samples collected in the treated stream at locations upstream were either the same or plus or minus 0.1 to 0.2 mg/l when sampled on the same day, much less than the variation from month to month. Chloride concentrations measured in 2011, from springs issuing along the Borrego fault zone about 1,600 meters upstream were equal to the concentration at the flume, but in April 2012 chloride concentration (2.3 mg/L) at the spring issuing 800 meters upstream was slightly less than at the flume (2.6 mg/L). Samples collected in the treated stream in September 2013 were slightly higher upstream (3.7 mg/L) than at the flume (3.5 mg/L). In late July 2015, the chloride concentration in the control stream varied between 0.89 mg/L at the flume and between 0.85 and 0.89 mg/L upstream.

ET as a percent of precipitation was estimated using equation 6 based on the volume-weighted concentration of chloride entering and exiting the basins in each stream. To obtain the total mass of chloride, the average adjusted chloride concentration in precipitation was multiplied by the average volume of precipitation per day from three stations. The mass of chloride exiting in streamflow was calculated by multiplying the mean daily streamflow by the mean daily chloride concentration. The volume-weighted concentration in precipitation for each integration period was calculated by dividing the total mass of chloride by the total volume of precipitation and the volume percent-weighted concentration in streamflow was calculated similarly.

Estimates of ET for each integration period (Table 5) are based on the volume-weighted chloride concentration in precipitation, which ranges from 0.19 to 0.24 mg/L. The flow-weighted mean concentration in the treated basin stream ranged from 2.23 to 3.24 mg/L as compared to the concentrations of 0.9 to 1.4 mg/L in the control basin stream. ET is consistently higher in the treated basin (ranging from 90 to 94%) than the control basin, where ET is 77 to 86% of precipitation. ET was higher prior to treatments based on one set of chloride samples collected in 1995 (White, 2007), thus it is important to remember that the treatments did not cause the increase in ET. The higher ET in the treated basin as compared to the control is due to intrinsic differences between the two basins as discussed earlier.

Stream samples collected from springs along the length of the treated basin stream on April 1, 2011 and in Sept 2013 produced chloride concentrations that were equivalent, confirming that the chloride is not further concentrated in the stream (during low flows). At the other extreme, during rapid runoff events it is possible that the concentrations of chloride in surface water and ground water are not equal.

Because the chloride mass-balance technique for estimating ET assumes that all chloride entering the basins will exit the basin over some integration period, the total mass of chloride input in precipitation and outflow through streamflow is examined. Figure 35 and Figure 36 show the cumulative mass of chloride deposited through precipitation and exiting through streamflow for each integration period. Chloride continues to be deposited through precipitation and dry deposition even in dry years, but none exits the stream, obviously, when it is dry. Thus, the chloride builds up in the soil profile during dry periods. For instance, from June 2012 through August 2013 very little chloride exited the basins because both streams had minimal or no flow. Then, in September 2013, over 20 centimeters of rain fell, resulting in the highest measured flows and relatively high chloride concentrations. The streams continued to flow for months after this event, diminishing after the following summer.

Estimation of Recharge (R)

As discussed previously, Figure 33 and Figure 34 show the cumulative deposition of chloride through precipitation and the amount exiting each basin through streamflow. Over time, the amount exiting through streamflow does not equal the total entering the system, indicating that some chloride is lost to recharge. If the total mass of chloride exiting through streamflow equaled the amount deposited, one would assume that the volume of recharge was insignificant. As shown in Figure 33 and Figure 34 the gap between the mass of chloride entering through precipitation and exiting through streamflow is greater than the error in the estimates of the mass of chloride.

The volume of recharge is estimated for each integration period and each basin as shown in Table 6 using equation 4. Recharge is estimated based on the cycles of chloride presented for the integration periods shown in Figure 35 and Figure 36. The volume of recharge for each period is then compared to the volume of runoff over the same period to obtain a multiplier for estimating the volume of water recharging the deeper regional aquifer per month (or otherwise not reappearing as

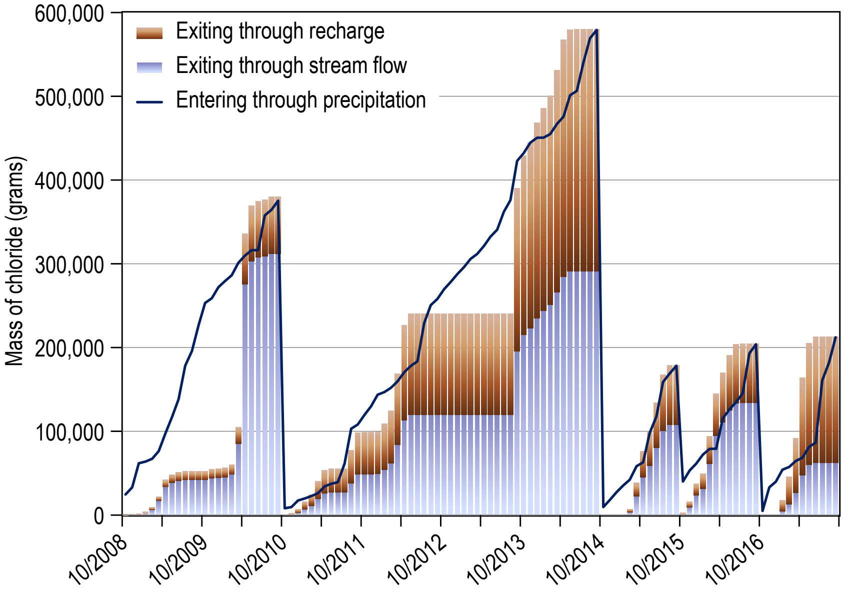


Figure 35. Cumulative mass of chloride deposited through precipitation in the treated basin and exiting through streamflow.

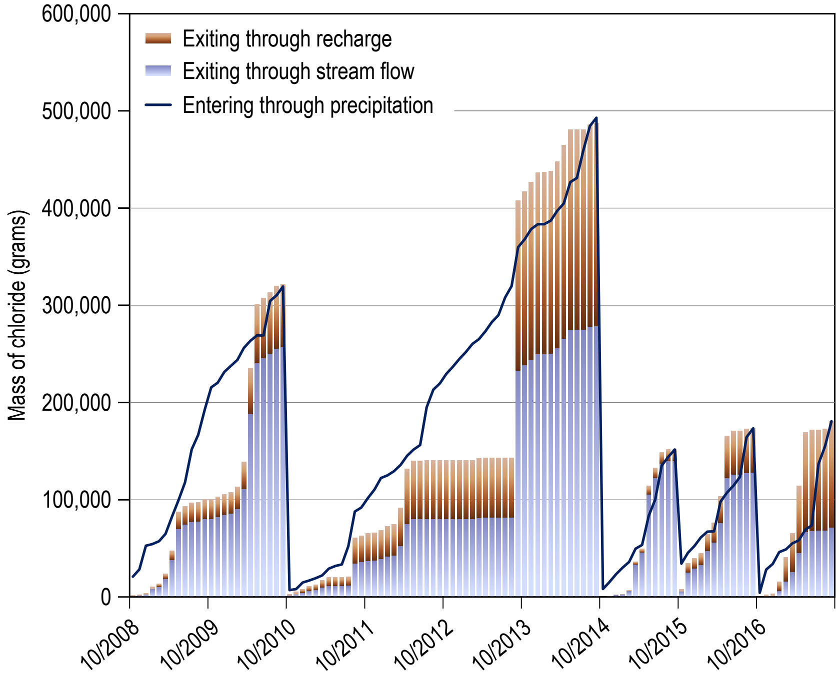


Figure 36. Cumulative mass of chloride deposited through precipitation in the control basin and exiting through streamflow.

streamflow at the stream gage). The cumulative volume entering and exiting the treated basin and the control basin is based on the volume of runoff because recharge to the deeper aquifer would primarily occur when the streams are flowing. The mass of chloride exiting through recharge is also calculated by multiplying the mass of chloride exiting each basin monthly through streamflow by the same multiplier.

A cross-plot (Figure 37) of the monthly recharge shows no trend over the period of investigation. As with the cross-plot of streamflow, the linear fit is controlled by a few wetter months amongst mostly dry periods. The error bars shown on this plot assume plus or minus 15%.

Estimation of Change in Soil Moisture

To estimate the total change in the volume of water in storage in each basin, the thickness and porosity of the soil are approximated. The dominant soils are described as Entisols that are Typic Dystrocryepts (loamy soil),

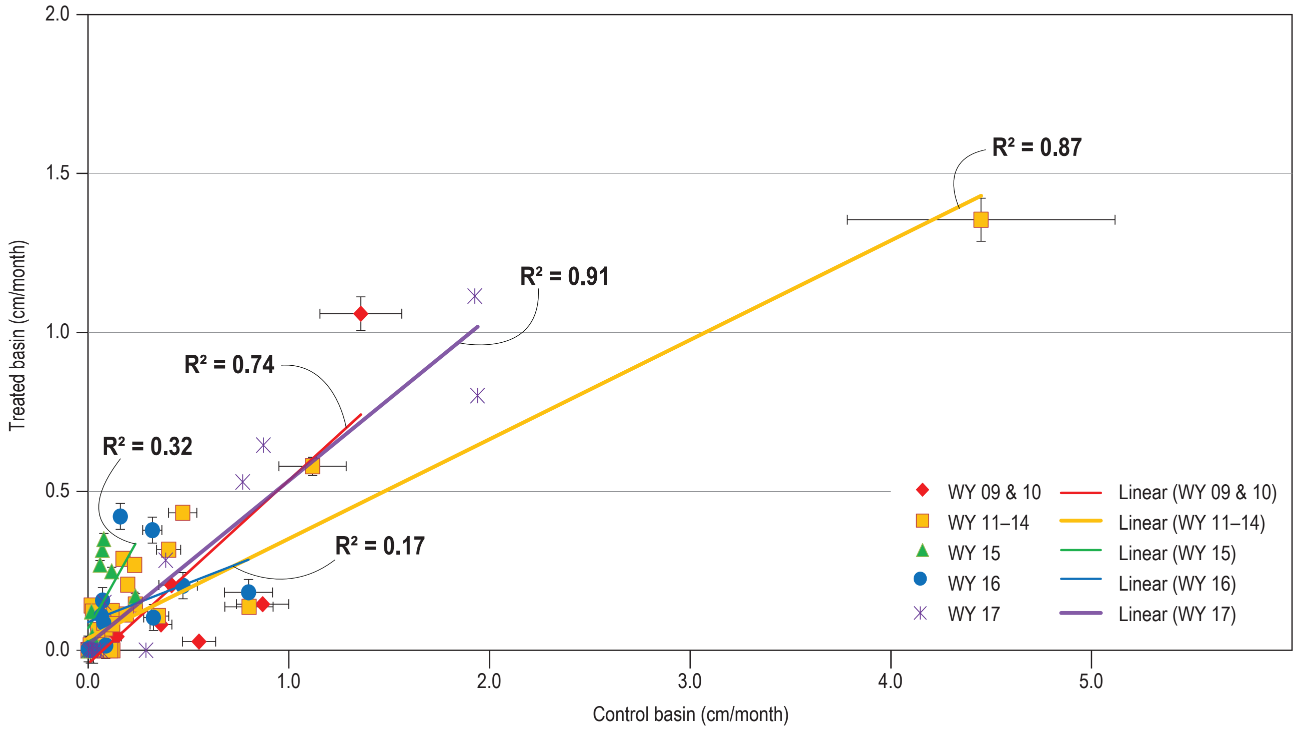


Figure 37. Cross-plot of recharge (R) yield per month for each integration period.

which do not have a distinct soil horizon (USFS, 2009). The soil thickness measured in the lower reaches of the basins averaged 0.8 meters in the treated basin and 0.6 meters in the control basin. The percent of rock coverage varies from 40% in the upper third of the control basin to 70% at the top of the treated basin. Much of the area has 60% rock cover, thus the soil horizon is very thin. For calculating the volume of soil, it is assumed that the soil profile in this steep, mountainous terrain is 0.3 meters deep, with a porosity of 40%. The water budgets are not significantly impacted by a change in the depth of soil from 0.3 to 1 meter.

While the soil moisture fluctuates throughout the year the difference between the beginning and end of the integration periods has been relatively insignificant for water budget accounting (Figure 31 and Table 7). The estimated change in volumetric soil moisture was less than two percent for the five integration periods. In the third and fifth integration periods the soil moisture increased, thus for the water budget, the increase represents an outflow of water into soil storage.

Estimated Water Budgets

Streamflow is 3 to 8% of precipitation in the treated basin and 9 to 18% in the control basin. ET is overwhelmingly the largest component of outflow with up to 94 and 86% of the outflow in the treated and control basins, respectively (Table 8 and Table 9). The estimates of ET fall within the range of other studies conducted in Rocky Mountain watersheds. Claassen and Halm (1996) estimated ET for Deep Creek, Colorado from 1985 through 1992 to be between 67 and 87% of precipitation using the chloride mass balance approach. The estimated ET for 19 watersheds in the Rocky Mountains ranges from 22 to 98% of precipitation as summarized by Claassen and Halm (1996). Yaseef et al. (2009) measured ET in semi-arid pine forests and found the ET accounted for 94% of P over a four-year investigation and ranged from 85% to 100% depending on the amount of precipitation.

Recharge estimates range from 1.6 to 7.3% in the treated basin and 1.1 to 13% of precipitation in the control basin, which are values consistent with recharge estimates in the Southern Sangre de Cristo Mountains of New Mexico (Wasiolek, 1995). Wasiolek (1995) calculated precipitation based on an equation relating elevation to precipitation, calculated evapotranspiration based on the elevation and aspect of subareas within five watersheds, including the Santa Fe River Watershed (Table 10). The average precipitation and evapotranspiration were calculated (not measured) for winter, spring and summer and compared to the stream gage

Table 8. Water budget components estimated for five integration periods.

	INTEGRATION PERIOD									
	Oct 2008 through Sept 2010 (2 years)		**Oct 2010 through Sept 2014** (4 years)		**Oct 2014 through Sept 2015** (1 year)		**Oct 2015 through Sept 2016** (1 year)		**Oct 2016 through Sept 2017** (1 year)	
PARAMETER	**treated**	**control**	**treated**	**control**	**treated**	**control**	**treated**	**control**	**treated**	**control**
Area (km^2)	1.79	1.53	1.79	1.53	1.79	1.53	1.79	1.53	1.79	1.53
Volume in										
Precipitation (1000 m^3)	1,808	1,539	2,774	2,361	1,012	861	905	770	867	738
Decrease in soil storage (1,000 m^3)	0.3	0.3	0.7	0.6	–	–	5.5	4.7	–	–
Total in (1000 m^3)	**1,809**	**1,540**	**2,775**	**2,362**	**1,012**	**861**	**911**	**775**	**867**	**738**
Volume out										
RO (1,000 m^3)	141	281	90	203	42	111	58	103	27	64
ET (1,000 m^3)	1,638	1,187	2,595	2,007	943	741	817	630	777	576
Increase in soil storage (1,000 m^3)	–	–	–	–	3.2	2.7	–	–	13.4	11.4
Recharge (1,000 m^3)	30	71	89.7	151.6	27.2	93	29.7	36.8	63.2	97.8
Total in (1,000 m^3)	**1,809**	**1,539**	**2,774**	**2,361**	**1,015**	**864**	**905**	**770**	**880**	**749**
Remaining (1,000 m^3)	0.3	0.3	0.7	0.6	-3.2	-2.7	5.5	4.7	-13.4	-11.4
Percent remaining of total precipitation	0.0%	0.0%	0.0%	0.0%	0.3%	0.3%	0.6%	0.6%	1.5%	1.5%

Table 9. Summary of water budget components as a percent of precipitation by integration period.

	INTEGRATION PERIOD									
	Oct 2008 through Sept 2010 (2 years)		**Oct 2010 through Sept 2014** (4 years)		**Oct 2014 through Sept 2015** (1 year)		**Oct 2015 through Sept 2016** (1 year)		**Oct 2016 through Sept 2017** (1 year)	
PARAMETER	**treated**	**control**	**treated**	**control**	**treated**	**control**	**treated**	**control**	**treated**	**control**
Precipitation (cm)	100.9		154.8		56.5		50.5		48.4	
Precipitation (cm/year)	50		39		56		50		48	
Evapotranspiration	91%	78%	94%	85%	93%	86%	90%	82%	90%	78%
Runoff	7.8%	18.3%	3.2%	8.6%	4.0%	12.9%	6.4%	13.5%	3.0%	8.6%
Recharge	1.7%	4.6%	3.2%	6.4%	2.7%	1.1%	3.3%	4.8%	7.3%	13.3%

Table 10. Annual water budgets calculated for five drainage basins in the southern Sangre de Cristo Mountains (Wasiolek, 1995).

Location	**Elevation range** (meters)	**Annual precipitation** (cm)	**Evapotranspiration** (cm)	**% ET**	**Runoff** (cm)	**% RO**	**Recharge** (cm)	**% R**
Tesuque Creek	2,300 –3,900	61.4	42.4	69%	12.8	21%	6.2	10%
Little Tesuque Creek	2,200–3,400	58.3	41.8	72%	5.4	9%	11.2	19%
Rio en Medio	2,100–3,700	61.1	42.1	69%	9.6	16%	9.5	16%
Rio Nambe	2,000–3,840	62.9	42.3	67%	12.9	21%	7.7	12%
Santa Fe	2,300–3,700	60.0	41.8	70%	11.4	19%	6.9	11%

estimates of runoff. The remainder of the water budget was assumed to be recharge. Results of Wasiolek's (1995) work shows recharge estimated to be 10 to 19% of precipitation and ET up to 72% of precipitation.

Changes in soil moisture storage were not significant between the basins or at the start or ending of the five integration periods.

The cumulative water budgets are illustrated in Figure 38 (treated basin) and Figure 39 (control basin) for the five integration periods. The error in the water balance is up to 1.5% in the fourth integration period and less than 1% in the four other integration periods. The amount of error in the water budgets is equivalent to the estimated inflow or outflow into in soil moisture storage. One assumption for the equations to balance without any error is that no change in soil moisture occurs from the beginning to end of each calibration period. Soil moisture changed slightly with each period, thus the error is very small.

Recharge (R) can be also calculated by subtracting streamflow (RO) and evapotranspiration (ET) from precipitation (P) to reach the same values recharge values estimated with the chloride mass balance equation. However, the integration periods that are chosen will impact the estimates of ET and R and thus consideration of the cycle of chloride through the system is important. If random integration periods were chosen without regard to the

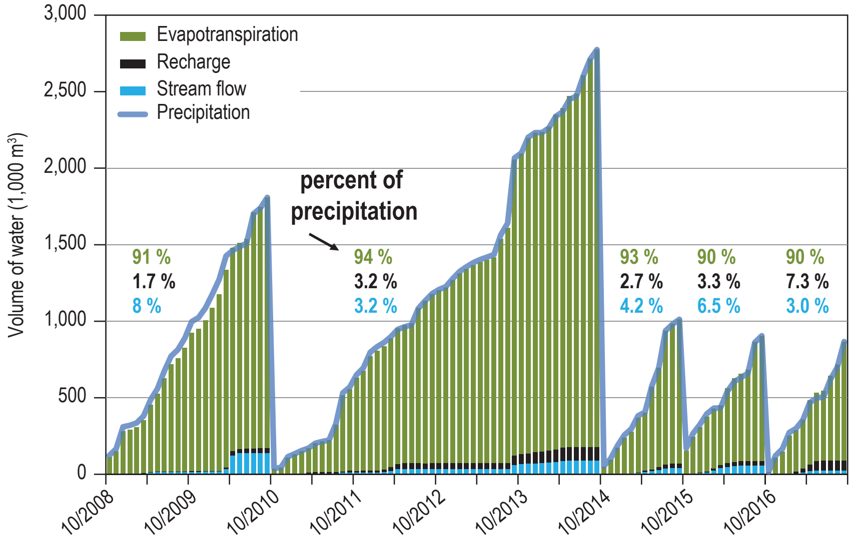


Figure 38. Cumulative water volume entering and exiting the treated basin for five integration periods.

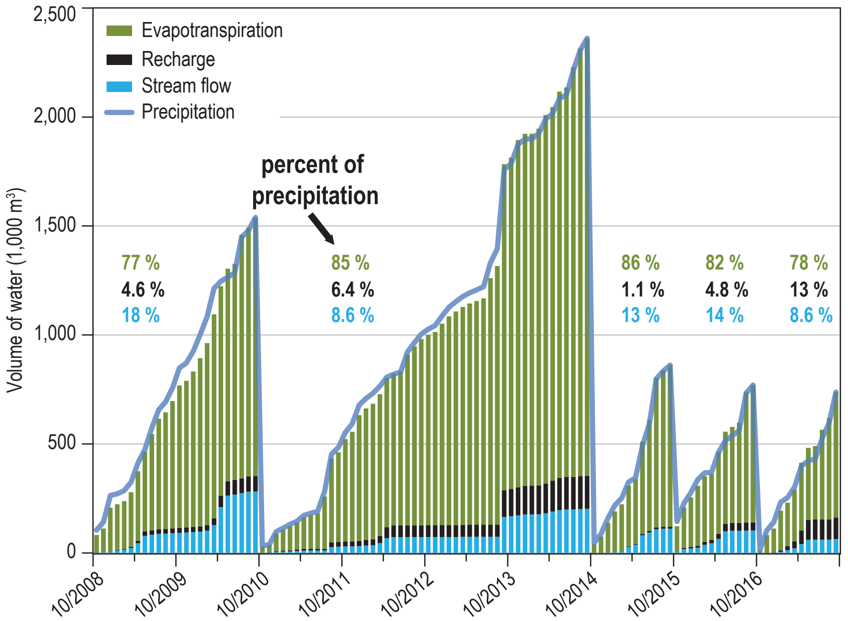


Figure 39. Cumulative water volume entering and exiting the control basin for five integration periods.

cycling of chloride in each basin, the equations will force a good agreement, but the values for recharge may be negative, which would suggest that inflow from an adjacent basin flow was occurring. The cumulative mass balance of chloride entering the basins through precipitation is always larger than the amount exiting through streamflow in the paired basins, thus no interbasin flow is occurring. If interbasin flow was occurring, the amount of chloride exiting the streams would exceed the amount entering through precipitation.

Control basin forest above, treated basin forest below. *Photos by Amy C. Lewis.*

V. DISCUSSION

The calculated rate of ET in the treated basin remains above 90% and peaked at 94% in the second integration period, a period that included extended drought. ET in the control basin, in contrast, has a larger fluctuation with a low of 77% of precipitation and peak of 86% in the third integration period. The ET rate is between 8 to 14% greater in the treated basin as compared to the control basin, but this is not due to forest treatments. The treated basin receives much more solar radiation in summer months than the control due, in part, to a large west-facing slope (Figure 40). The control basin is rockier, steeper (and more shaded) and has a greater area at a higher elevation. While no increase in precipitation was observed with elevation, the temperature is cooler at higher elevations, which impacts the rate of evapotranspiration and snow melt. These differences existed prior to forest treatments and the goal of this study was to determine if relative changes over time could be observed. The ratio of ET in the treated versus the control appears to be declining slightly in the treated basin with respect to the control basin over the course of this investigation (2009–2017), based on the ratio of chloride concentrations in the streams and calculated ET.

ET is expected to decrease following forest treatments due to fewer trees available to consume water, but reasons that might not occur are many and are one of the primary reasons that this study was initiated. Numerous studies on the impacts from logging (not thinning), (summarized by Brown et al., 2005 and Bosch and Hewlett, 1982), show an initial increase in streamflow in the first few years after tree cutting, followed by diminishing returns after the forest regrows. The impact on the water budget from a forest that is thinned with periodic maintenance burns is not well understood, and hence is considered as part of this investigation. While more precipitation reaches the ground after forest thinning due to less interception by trees, more sunlight also reaches the ground allowing the soil to warm and understory to develop. Evaporation of water from bare soil will occur at a faster rate when sunlight reaches the ground. Welder (1988) found that evapotranspiration from bare ground was significant following the removal of phreatophytes along the Pecos River, offsetting the decrease in consumptive use of the removed salt cedar. Guardiola-Claramonte et al. (2011) found a decrease in streamflow in semi-arid basins in response to tree mortality, an unexpected response.

Groundcover, such as grasses and scrub oak, has begun to replace the areas where trees were removed, which also results in ET and may offset the decrease in ET from the removed trees. Furthermore, in a water-starved season, the remaining trees may consume all water available, resulting in no decrease of ET. The groundcover is also retaining snow melt and rainfall to a greater degree, thus reducing the rate of runoff and allowing more time for ET to occur or the rate of recharge to be enhanced.

If ET is decreasing, then streamflow or recharge should increase in the treated basin relative to the control, but this change is not evident in the data. Comparison of monthly streamflow data between the two basins appear to show a trend towards less flow in the treated stream versus the control basin. The streamflow ratio may be a response to the seasonality of precipitation rather than changes in vegetation over the 9 years of investigation. The amount of precipitation that has occurred during winter months has declined over the 9 years, from the highest in 2010. Total water yield in runoff in the treated basin in water years with greater winter precipitation appears to increase relative to the control basin. Figure 18 illustrates a clear difference in the water budgets in response to snow fall between the two basins. Water year 2014 is an outlier, likely due to the significant rainfalls that occurred in September 2013, when nearly 24 cm of rainfall occurred, just prior to the start of the 2014 water year. The relative increase in streamflow in the treated basin in years with a greater percentage from winter precipitation could be a result of less sublimation from snow intercepted by the tree canopy. Research by Veatch et al. (2009) and Gustafson et al. (2010) concluded that sublimation of snow is less when the canopy cover is less. The winters with large snow packs may also even out runoff production between the two basins by reducing the significance of the intrinsic difference of the large western-facing slope in the treated basin. While both basins are sloping towards the north, in the winter the sun is at a lower angle and sets further south than in the summer months. Thus, when a greater percentage of the annual precipitation is from winter precipitation, more yield will be produced in the treated basin than if the precipitation fell in summer months.

The Borrego fault zone in the treated basin may impact the conceptual model and the calculated estimates of ET and recharge (Figure 41). It is possible that some water infiltrates past the root zone and discharges to this fault with a lower concentration of chloride than the concentrations measured in the springs and stream. As described by Wilson and Guan (2004), fractured bedrock in mountain blocks may provide a pathway for recharge below the valley floor. If the system is not well mixed, as postulated in this investigation, then the assumption that the concentration of chloride in recharge is equal to the concentration in streamflow would not be true. If wells could be drilled in a transect across each basin, the gradient across the fault zone and the concentration of chloride in groundwater could be measured to verify the assumed conceptual model. The springs in the upper reaches and at the flume in the treated basin occur within the Borrego fault zone, which most likely represents discharge of groundwater; thus the assumption that the system is well mixed appears to be valid. Regardless of a possible different conceptual model for the treated basin, intrinsic differences exist between the two basins and this study aims to detect relative changes between the two basins.

The high chloride concentrations in the runoff from the September 2013 event were surprising. Chloride in the control basin increased from 1.3 to 1.7 mg/L between sampling events one week apart and remained relatively high for several months (Appendix C). Concentrations in the treated basin did not increase immediately but decreased initially from 3.1 to 2.9 mg/L over the same period but increased to 3.5 mg/L after two weeks and 3.8 mg/L a month later. The rapid change in chloride concentration and the sustained concentration provide evidence that precipitation falling on the watersheds is relatively well mixed, even when overland flow may be occurring. The rainfall that occurred during the intense rainfall events mixed with the soil and mobilized the chloride that had accumulated over the preceding dry years. The chloride then discharged to the stream and infiltrated into the fractured bedrock, which continued to drain for many months. The treated basin produced some overland flow as evidenced by some sediment transport on the hill slopes near the channel bottom, but no sediment was deposited in the flumes. The response to the rainfall was much slower because the treated basin, with a greater density of groundcover, was able to absorb the rainfall intensity to a greater degree, which allowed infiltration into the fractured bedrock, and displacement of relatively older groundwater that discharged to the stream.

To illustrate the relatively dry conditions of the period covered by this investigation, the Palmer Drought Severity Index (PDSI) is used to illustrate the level of moisture in the system (Palmer, 1965). The PDSI incorporates precipitation and potential evapotranspiration and indicates wet (+) and dry (-) periods. The soil moisture content and PDSI (NCDC, 2017) for the northern mountains shows a strong correlation between the two parameters (Figure 42) and reveals the relatively dry period for about four years of this investigation (March 2011 through Oct. 2014). Values below -2 represent moderate drought, -3 represent severe drought and -4 represent extreme drought. The only unusual moist spell is observed for about 8 months (June 2015 through February 2016).

The relative stress that the vegetation has experienced over the period of this study has likely impacted the ability to discern differences between the two basins. Emanuel et al. (2010) modeled spatial and temporal controls on watershed ecohydrology in the Rocky Mountains and concluded that high leaf-area index and “small contributing areas both may lead to shortages in soil moisture and reduction in ET.” The “water stress represents a decoupling of ET from the atmosphere control…” and increasing dependence on local soil moisture.

The chloride mass balance method as applied here assumes that all the chloride entering the watersheds through precipitation will exit through streamflow or recharge. The mass exiting through streamflow was less than the amount entering through precipitation for each of the integration periods presented (Figure 33 and Figure 34). Thus, no additional input of chloride is occurring and therefore, no interbasin flow occurred during each of the integration periods.

While the amount exiting through streamflow is measured, the mass that is discharged through recharge to groundwater is assumed to be the remainder of the chloride mass-balance. Another possible sink for chloride is the decaying vegetation, but this impact on the chloride mass balance is

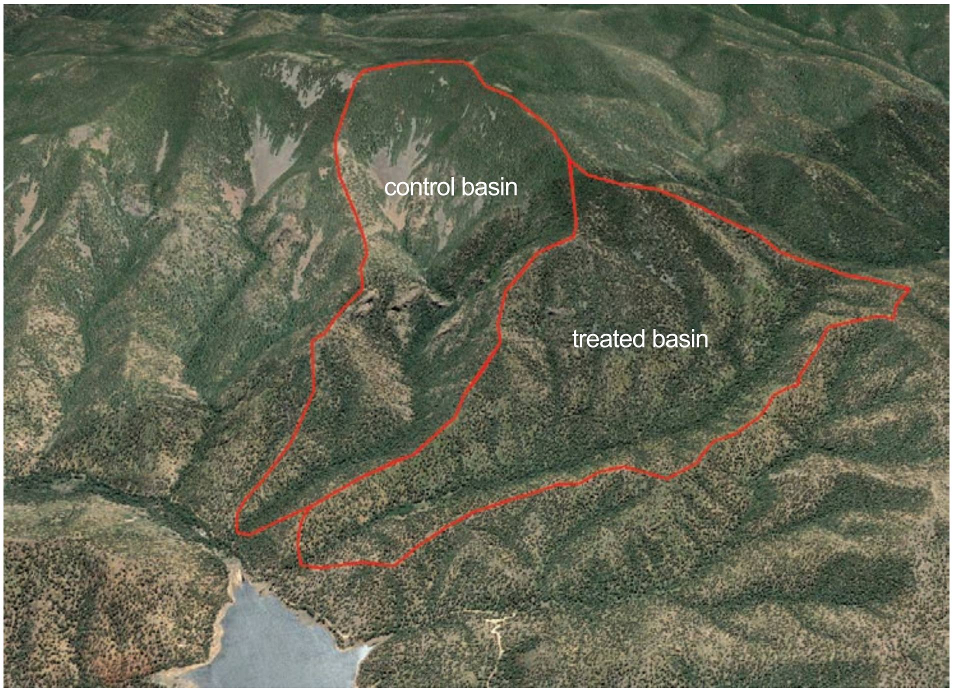


Figure 40. Aerial view of the paired basins looking to the southeast. Source: 35°40'32.94"N 105°49'19.95" E. Google Earth (accessed June 10, 2017, July 12, 2018).

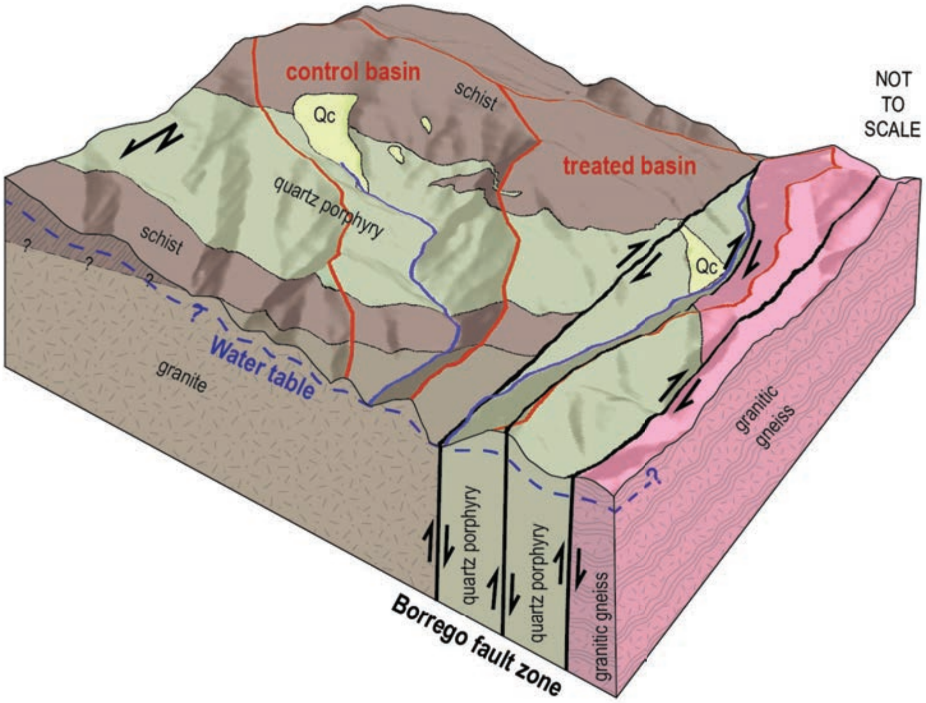


Figure 41. Block diagram showing geologic detail of paired basins and the Borrego fault zone.

not well understood. Previous researchers believed that chloride was a conservative element and not botanically active (Graustein,1981), but recent studies indicate that chloride can be retained or released from the soil as part of a biogeochemical cycle (Öberg, 2002, Bastviken et al., 2007, Matucha, 2007, Matucha et al., 2010). Likens and Bormann (1995) noted a release of chloride after disturbance by deforestation at the Hubbard Brook Ecosystem study in New Hampshire, suggesting that chloride may be accumulating in the forest ecosystems, but assumes that the amounts are small. The rates and

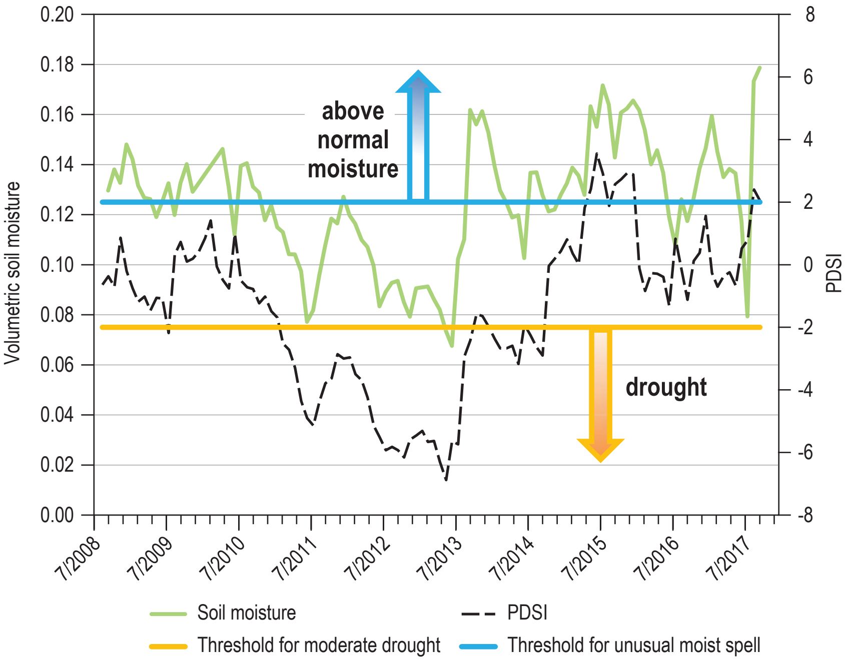


Figure 42. Volumetric soil moisture content and PDSI for the northern mountains (2008–2017) showing relative wet and dry periods of this investigation (NWS, 2017 and NCDC, 2017).

conditions for release or retention remain unknown (Bastviken et al., 2007). If the watershed productivity is in a steady-state condition such that the rate of growth equals the rate of decay, then the vegetation is not considered a source or sink of chloride (Claassen and Halm, 1996). The forest treatments in the treated basin, which consisted of the felling of trees and burning of the small branches, have changed the forest conditions and thus, it is not in a steady-state condition with respect to vegetation. However, the large boles remain on the ground in the treated basin, and therefore, a relatively small amount of organic material was burned during the treatments.

Chloride is converted to organic chlorinated compounds by organisms involved in the decay of organic matter (Öberg, 2002). Therefore, the organic material decaying on the forest floor may serve as a sink for chloride as it decays, producing chlorine gas that escapes the ecosystem. The significance of the output of chloride through volatilization is not known but thought to be less than one percent in a small watershed in Sweden (Öberg, 2002).

VI. CONCLUSIONS

The paired basin investigation has estimated water budget components with a high degree of confidence for the integration periods selected. ET, while greater in the treated basin compared to the control basin, was greater prior to treatments (based on one chloride sampling event in 1995) and appears to be declining in the treated basin over successive integration periods. However, no overall increase in streamflow in the treated basin from the forest treatments has been detected, except in years with a greater percentage of winter precipitation. Streamflow in the treated basin appears to increase relative to the control basin in response to winters with significantly large snow fall. When snow is the predominant form of precipitation, more of the moisture reaches the ground due to the reduced tree canopy. During the winter, the impact of the western facing slope in the treated basin is less significant because the sun is at a low angle. Thus, while more rainfall also reaches the ground in the treated basin following forest treatments, more sunlight also reaches the ground in summer months.

Precipitation and streamflow were measured year-round, but ET and recharge were estimated using the chloride mass balance approach, which assumed that the chloride concentration in the streamflow is equal to water that recharges the regional aquifer. If the concentration of chloride in the recharge water is significantly lower, then the calculated ET would be less, and recharge would be greater. However, no wells are available to confirm this assumption and the terrain is not amenable to drilling a well.

While the chloride mass balance and water budget equations force agreement in the water budget components, the choice of integration periods impact the estimated ET and recharge rates. Integration periods that do not consider the cycling of chloride through each basin can result in apparent negative recharge rates (or inter-basin flow) that are not observed. The cumulative mass of chloride entering the basin through precipitation is always more than the amount exiting through streamflow, thus some chloride must exit through recharge and no inter-basin flow is occurring.

This paired basin study would have benefited from more complete pre-treatment data (in line with the data collected for this investigation), and ideally, the pre-treatment and post-treatment years would be wetter than average, rather than drought years. Wells that tap the fractured bedrock would allow for water level measurements to determine flow direction and chloride samples to test the hypothesis that the chloride concentration in streamflow is equivalent to recharge.

The landscape is continuing to be treated, with prescribed fires every five to seven years that will result in tree mortality and continued changes to the vegetation. This report provides an important baseline of the current state of the basins and outlines methods to pursue during continued investigations of the Santa Fe paired basins or establishment of new field areas.

Looking upstream at the large Parshall fume in the control basin.

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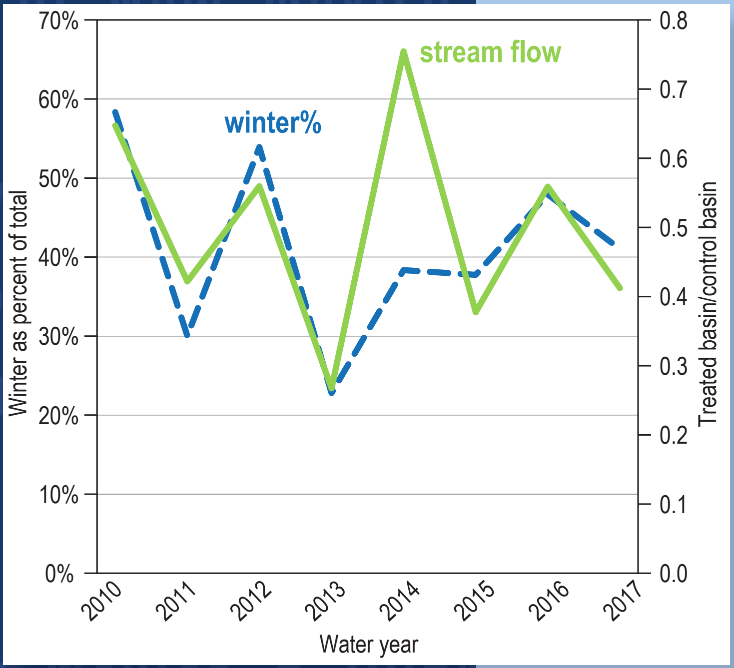

A paired basin study in the Upper Santa Fe River watershed following forest restoration has successfully measured water budget components in a treated and an untreated (control) basin. The paired basin study was established to investigate questions that have arisen with regards to changes in water yield from forest treatments. The chloride mass balance and water budget equations force agreement in the water budget components, and thus, the integration periods that consider the cycling of chloride through each basin, will impact the estimated evapotranspiration and recharge rates. The results from nine years of data collection and analysis show that evapotranspiration, while greater in the treated basin than the control before and after treatments, appears to be declining in the treated basin. An increase in stream flow in the treated basin is only evident in years with a greater percentage of winter precipitation.

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