AN ABSTRACT OF THE THESIS OF

Grace L. Ray for the degree of Master of Science in Rangeland Ecology and Management presented on August 18, 2015.

Title: Long-term Ecohydrologic Response to Western Juniper (*Juniperus occidentalis*) Control in Semiarid Watersheds of Central Oregon: A Paired Watershed Study.

Abstract approved:

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Carlos G. Ochoa

Rangelands span over 50% of the globe and approximately 70% of the United States. Although livestock production is an important use of rangelands, the benefits of rangelands are highly diverse. Humans find intrinsic value in protecting these unique and variable landscapes for wildlife, vegetation, and recreation enthusiasts. Woodland plant encroachment has become a major concern for land management agencies and private landowners across the United States and many rangeland communities worldwide. Studies around the world are characterizing the effect that woody species may have on ecologic and hydrologic function, as well as the potential consequences of prolonged encroachment. This research is an addition to a central Oregon paired watershed study that began in 1993 as way of characterizing ecohydrologic effects of western juniper (*Juniperus occidentalis*) removal.

The overarching goals of the study presented here were to: 1) Characterize vegetation-soil water interactions at the landscape scale; 2) Analyze long-term soil water and groundwater fluctuations for treated versus untreated watersheds; 3) Asses subsurface flow connections between upland watersheds and a downstream valley.

A landscape-scale assessment (2014 – 2015) of shallow soil water content, for to top 12-cm of the soil profile, across both watersheds indicated the treated watershed as having a significantly higher ($P < 0.05$) mean value of soil water content for three (July, January, and May) out of five measurement periods (July, November 2014 and January, March, May 2015). The untreated watershed was 2% higher in March 2015, and no significant difference was found between the two sites in November 2014. Analysis of the structure of canopy cover (i.e. juniper dominated versus juniper removed) using linear regression models found juniper cover to be correlated with decreasing soil water content for three of five months, with the exception of the wettest months of March and May, when juniper canopy was correlated with increases in soil water content. Soil textural properties were also analyzed as an independent variable in the linear models, and clay content was found to be correlated with increases in soil water content during the three wettest months (January, March, and May) across both watersheds.

The long-term (2004 – 2015) analysis of groundwater level and deep soil water content fluctuations showed there to be distinct seasonal and storm-event responses. Groundwater levels in the untreated watershed consistently displayed higher yearly maximum values when compared to the treated, however, groundwater levels in the treated watershed persisted longer into the dry out period. Similar findings were reported in relation to long-term soil water content where the untreated watershed often displayed higher maximum responses but declined back to dry status sooner than the treated watershed. Both watersheds responded to seasonal and storm-event precipitation through soil water content fluctuations in the deep soil profile and through groundwater level fluctuations. Precipitation event responses could be observed on the order of hours for the treated watershed and on the order of days for the untreated. Antecedent soil water content seemed to play a large role in the effectiveness of the storm events. Summer precipitation had little influence on the deeper soil profile and on groundwater response. This may be due to dryer antecedent soil conditions and flashy overland flow. Water content in the top measured soil profile, however, increased and stayed at high levels for up to two weeks following a summer precipitation event which yielded approximately 27 mm of rainfall. Soil water and groundwater response were greatly influenced by winter precipitation events and pre-storm soil water conditions.

The hydrologic connectivity of subsurface water flows, through fluctuations in deep soil water and groundwater levels, was found to be an important process in these watersheds. Temporary subsurface hydrologic connections were observed between upland and valley wells as the wet season progressed. This connection was supported by the results of a stable isotope analysis, which indicated that the origin of the water may be the same. This was concluded given the similar values of oxygen-18 found for both the treated and untreated upland sites and for valley groundwater monitoring locations.

Large-scale juniper manipulation projects are taking place across the western United States and around the world. Many projects have the objectives of increasing water availability and stream flow to no avail. This research provides baseline data towards understanding the importance of the valuable subsurface water resources in landscapes with limited precipitation availability.

Long-term Ecohydrologic Response to Western Juniper (*Juniperus occidentalis*) Control in Semiarid Watersheds of Central Oregon: A Paired Watershed Study

by

Grace L. Ray

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APPROVED:

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Grace L. Ray, Author

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INTRODUCTION

Woody plant encroachment has plagued rangeland managers and intrigued scientists since the early 1900's when Aldo Leopold first mentioned brush and juniper encroachment throughout the American southwest.

> *A cow-man will tell about how in the 1880's on a certain mesa he could see his cattle several miles, whereas now on the same mesa he cannot even find them in a day's hunt. The legend of brush encroachment must be taken seriously…The brush that has "taken the country" comprises dozens of species, in which various oaks, manzanita, mountain mahogany and ceanothus predominate. Here and there alligator junipers of very large size occur. Along the creek bottom the brush becomes a hardwood forest (Leopold 1924).*

Leopold's was the first of many efforts towards understanding the cause and effect of woody plant encroachment on the ecologic and hydrologic function of rangelands across the U.S. and the world. Many species of juniper across the west are the focus of investigative research and have been shown to decrease plant biodiversity and degrade soil and water resources. Efforts to control juniper encroachment into grasslands and sagebrush-steppe ecosystems have had mixed results.

The great debate on juniper and water use stems from the belief that juniper has the ability to utilize all available soil water at any given time (Gedney et al 1999). Research suggests that western juniper (*Juniperus occidentalis*) can tanspire at high rates throughout the winter if soils are above freezing (Jeppesen 1978). Other studies examining streamflow increase after juniper treatment and have found mixed results.

This research, in fulfillment of a Master of Science degree extends a paired watershed study in central Oregon, which originated in 1993 as a long-term research effort aimed at quantifying the effects of large-scale western juniper removal on biological and physical characteristics of semiarid watersheds. Phase I of the project (1992 – 2003) completed pre-treatment data collection. During this time, a complete description of the vegetation, soils and soil erosion, channel morphology, terrain indices, geology, streamflow, and climate was produced (Fisher 2004). Phase II (2003 – Present) was the juniper treatment phase involving measurements of hydrological processes such as streamflow, spring flow, groundwater, and soil water content; physical features such as hillslope and channel morphology, and; biological components such as change in plant community and species composition. These major components were analyzed for response indicators which helped to determine the baseline effects of large-scale juniper removal on hydrologic function (Deboodt 2008).

This thesis details an additional research contribution which was aimed at investigating and elaborating on several of the key findings resulting from Phase I and II efforts. This document is in manuscript format and is organized in two main chapters. Each chapter details one study. The combined overarching goals of the two studies were to provide a scientific understanding of the effects of vegetation manipulation (i.e. juniper removal) on subsurface hydrologic components such as soil water content and groundwater level fluctuations. Understanding these ecohydrologic components and how they interact will provide insight into the larger picture that is how these semiarid watersheds may be hydrologically connected.

Chapter one has been submitted to the journal of Rangeland Ecology and Management and describes a one-year study aimed at characterizing vegetation-soil water relationships across a pair of semi-arid watersheds located in central Oregon. This study specifically examined vegetation composition, soil water content, and soil physical properties. The objectives were to: 1) determine vegetation structure and canopy cover influences on soil water content for one juniper dominated and one juniper removed watershed; and 2) investigate differences in soil water content between the treated and untreated watersheds, and 3) characterize soil water content distribution across the two watersheds.

Chapter two is currently being prepared for journal submission. This study examines the groundwater connectivity of a pair of adjacent, semiarid watersheds in relation to large-scale juniper removal. The objectives of this study were to: 1) characterize long-term groundwater and soil water content fluctuations in response to juniper removal; 2) determine precipitation-soil water-groundwater dynamics in treated versus untreated watersheds; and 3) assess groundwater connections between upland watersheds and a downstream valley.

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VEGETATION-SOIL WATER RELATIONSHIPS IN WESTERN JUNIPER WOODLANDS: A PAIRED WATERSHED STUDY

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Abstract

The effects of western juniper (*Juniperus occidentalis*) control on vegetation and soil water interactions were studied at the watershed-scale. Seasonal differences in soil water content, as affected by vegetation structure and soil texture, were calculated for a pair of previously treated and untreated watersheds. A watershed-scale characterization of vegetation canopy cover and soil texture was completed to determine the driving factors influencing soil water content fluctuations throughout dry and wet seasons for one year (2014 – 2015). In general, shallow soil water content in the top 12 cm of soil was greater in the treated watershed during all seasons, with the exception of one of the wettest months (March), when soil water content in the untreated exceeded that of the treated watershed by < 2%. Total canopy cover, and more specifically functional group cover, was the dominant variable affecting soil water content over time. Increases in perennial grass cover were positively correlated with changes in soil water content during the wettest months. Increases in juniper cover were negatively correlated with soil water content. The soil textural analysis resulted in relatively uniform textural classes across watersheds, and effects of clay content were only evident during the wettest months (January, March, and May) as antecedent soil moisture progressively increased through the year. A geospatial interpolation of soil water content and clay content showed corresponding areas of high clay and high soil water content across watersheds. Interpolated maps also demonstrated the progression from dry to wet season, as well as the influence of topographical features on soil water content. Our research findings add to the understanding of the differences in shallow soil water content between juniper dominated and sagebrush-bunchgrass dominated watersheds. This information develops the understanding of vegetation and soil water relationships at a large spatial

scale and helps to provide a more comprehensive look into the long-term effects of juniper removal on ecological and hydrologic processes.

Keywords

Hydrology, Interactions, Treated, Untreated, Landscape, Juniper

Introduction

In many areas of the western United States, the significant expansion of *Juniperus* spp. observed over the last two centuries is disrupting important ecologic functions. The relationship between soil water content and vegetation are highly impacted by the ongoing shift from shrub steppe and grassland to woodland-dominated landscapes (Breshears et al. 1997; Gifford and Shaw 1973; USDA 1985), which has the potential of modifying the ecologic and hydrologic balance of these water-limited regions (Huxman 2005; Owens 2006; Yager and Smeins 1999). In Oregon, western juniper (*Juniperus occidentalis* spp. *occidentalis* Hook.) has been rapidly expanding (e.g. encroaching) across rangelands since the late 1800s and has sparked many debates about the effects of this species on various aspects of rangeland ecosystems including grazing, wildlife, native plant communities, and as this research discusses, hydrology. Western juniper densities are estimated to range from 100 to 600 individuals per hectare in eastern Oregon (Miller and Rose 1995). These numbers are a significant increase from the Euro-American settlement estimates of < 5 individuals per hectare. This increase in western juniper has accelerated efforts towards the control and removal of post-settlement populations from Oregon rangelands, with the intention of restoring and increasing the economic and ecologic values of rangeland resources. Research results on juniper removal efforts in Oregon have demonstrated an increase in understory vegetation and species richness (Bedell et al. 1993; Coultrap 2008).

Studies on ecological restoration following juniper removal preceded research regarding the hydrologic effects that encroaching species have on western rangelands. The effects of *Juniperus* spp. cover on understory community structure are believed to have a domino effect on hydrologic processes (Huxman 2005; Wilcox and Thurow 2006). Research in native grasslands of Oklahoma found Juniper spp. to be negatively correlated with soil water content, water storage, infiltration rates, and stream flow (Zou et al. 2013). Further research involving juniper has emphasized its ability to utilize and influence horizontal and vertical soil water reserves throughout the intercanopy zones (i.e. the spaces between tree canopies) (Breshears et al. 1997; Madsen et al. 2008; McCole and Stern 2007). Encroachment tends to lead to an increase of bare ground, which significantly alters erosion and overland flow rates, depending on the amount of litter beneath the canopy patches (Buckhouse and Gaither 1982; Pierson et al. 2010; Urgeghe et al. 2010). These plot-scale studies heightened the interest and need for research on the hydrologic effect of juniper encroachment at a larger spatial scale. Wilcox and Thurow (2006) discussed the emerging issues related to juniper encroachment and the need to complete landscape-scale studies detailing ecosystem wide feedbacks that react to encroachment. An analysis of long-term water budgets for nine southwestern, semiarid catchments invaded by *Juniperus pinchoti* found that precipitation had the greatest effect on soil water recharge and evapotranspiration, while surface runoff only contributed 1% of the water to the overall budget (Wilcox et al. 2006).

Western juniper has gained attention as a major concern in changing the function of hydrologic systems throughout western rangelands. In Oregon, western juniper has been studied and found to continue transpiring throughout the winter season while understory species remain dormant. Soils that remain unfrozen during the winter have the potential of limiting the amount of soil water available to understory species during the crucial growing season (Jeppesen 1978). Similarly, western juniper limits transpiration rates throughout much of the year, especially during times of low water availability (Miller 1984). A plot-scale study conducted in central Oregon found that removing western juniper led to higher soil water content over winter months, this was in part due to an increase in soil water recharge and a decrease in transpiration and interception rates (Mollnau et al. 2014). Removing juniper has also shown positive results towards reduced sediment yield and runoff, and increased infiltration rates and infiltration depth during plot-scale rainfall simulations (Peterson and Stringham 2008; Pierson et al. 2007).

Much of the preceding research regarding juniper dominance details analogous results, which support the idea that juniper has the ability to severely alter rangeland ecosystems and hydrologic function. Despite overarching themes within the literature, the majority of research dealing with the effects of juniper encroachment have singular foci related to runoff, infiltration, or soil erosion and have been conducted at the plot-scale. There is a lack of information regarding the longer-term effects of juniper removal on vegetation composition and soil water availability at the watershed scale. There are very few accounts in the literature of ecohydrologic system interactions amongst these narrowly focused views, yet due to these findings, large-scale and costly juniper removal projects have been implemented across the western United States (Aldrich et al. 2005). Findings from these research efforts are important in understanding some of the hydrologic functions but may be limited in their scope by not addressing larger spatial scale interactions that are critical in juniper-dominated landscapes. Our study aimed to enhance base knowledge of the effects that *Juniper* spp., specifically western juniper, encroachment may have on vegetation and soil water dynamics at the watershed-scale. The objectives of this study were to: 1) determine vegetation structure and canopy cover influences on soil water content for one juniper dominated and one understory dominated watershed, 2) investigate the differences in soil water content between the treated and untreated watersheds, and 3) characterize soil water content distribution across the two watersheds.

Methods

Study Site

Our research site is located in the Camp Creek watershed (lat 43.96N, long 120.34W) in central Oregon. The study site comprises an area of approximately 220 ha and includes two adjacent watersheds, one treated (~ 90% of the western juniper removed) and one untreated. In 2005, juniper trees < 140 years of age were cut from the treated watershed, and the boles were removed with the remaining limbs scattered. Old growth juniper trees and those that were host to wildlife were not removed (Deboodt 2008). Each watershed is approximately 110 ha with elevations ranging from 1370 m to 1524 m. The average percent slope for each watershed was measured at ~ 25% (Fisher 2004). The distributions of aspects were also similar across both watersheds at ~ 35% north-facing slopes and ~ 25% west-facing slopes. The treated watershed had 6% more south-facing slopes and 14% less east-facing slopes. The orientation and drainage points of both watersheds are positioned in the northern portion of each site. Fisher (2004) determined the stream gradient to be 115 $m \cdot km^{-1}$ and assigned a low “flatness value” for each watershed, which was determined from an evaluation of terrain indices.

All major stream channels within both watersheds are classified as ephemeral and/or partially intermittent. Frequency of stream orders for each watershed were determined as > 70%, > 13%, > 3%, and 1% for 1st, 2nd, 3rd, and 4th order streams respectively. The wet season in the study area occurs between September and April. The yearly-mean precipitation (2009 – 2014) recorded by four onsite rain gauges was 326 mm. Snowfall was minimal during this study period. A distribution of the daily average precipitation (mm) from the beginning of the research period (June 2014) through the end of the final data collection (May 2015) is described in Figure 1.1. The mean monthly temperature collected by the onsite weather stations was 8°C, with the lowest mean monthly temperature of - 7°C occurring in December and the highest mean monthly temperature of 31°C occurring in August (2009 – 2014). Temperature and precipitation data collected by the onsite weather stations were comparable to data reported from a nearby (10 km southeast) weather station (WRCC 2015).

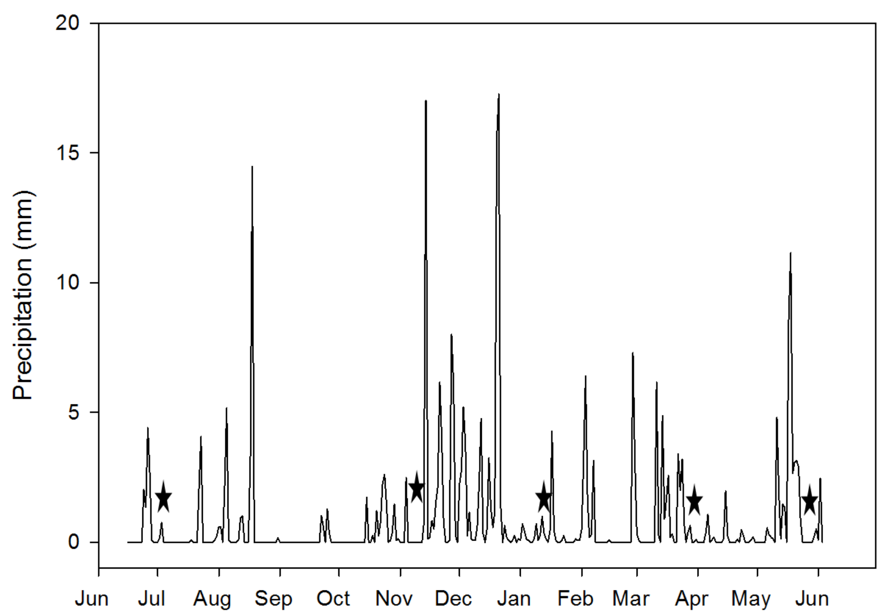

Figure 1.1 Mean daily precipitation measurements for four onsite rain gauges during the study period (June 2014 – June 2015). Stars represent soil water content measurement periods (July, November 2014 and January, March, May 2015).

Two major soil series comprise 70 to 74% of the two watersheds: Westbutte, very stony loam, and Madeline, loam. Simas, gravelly silt loam makes up the final portion with additional soil series occupying < 1% (Thomas 1995). The Westbutte series is classified as loamy-skeletal, mixed, superactive, frigid Pachic Haploxerolls (Soil Survey Staff 2011). The Madeline series is classified as clayey, smectitic, frigid Aridic Lithic Argixerolls (Soil Survey Staff 2012). The Simas series is classified as fine, smectitic, mesic Vertic Palexerolls (Soil Survey Staff 2001). The Westbutte and Madeline series are formed in colluvium from weathered basalt, tuff, and andesite materials and tend towards moderately shallow to deep, well drained soils. The Simas series is formed in colluvium and loess from tuffaceous sediments and tend towards very deep, well drained soils. The treated watershed is primarily composed of 26% Westbutte, 48% Madeline, and 21% Simas series. While the untreated watershed is composed of 50% Westbutte, 20% Madeline, and 3% Simas series. Soil similarities within both watersheds are comprised of a frigid temperature regime with historic ash deposition that is typical of volcanic activity of the Cascade Mountain range. Depth of soil across both watersheds ranges from 0.2 m to 1.5 m. Clay content in all three soil series ranges from 18% to > 30% for NRCS particle-size control sections (NRCS 2007).

Ecological site descriptions (ESD) associated with the two watersheds were part of the Snake River (SR) and John Day (JD) land resource units and within the Major Land Resource Area (MLRA) 10. The dominant ESDs were SR Mountain Swale (305-406 mm Precipitation Zone (PZ)), JD Mountain Claypan (305-406 PZ), SR Mountain Shallow North (305-406 PZ), JD Ashy Deep North (305-406 PZ), JD Very Shallow (305-406 PZ), SR Mountain Very Shallow (305-406 PZ), and Mountain Meadow (NRCS 2008). Key perennial grass species found onsite include Idaho fescue (*Festuca idahoensis*), bluebunch wheatgrass (*Pseudoroegneria spicata*), Sandberg bluegrass

(*Poa secunda*), prairie junegrass (*Koelaria macrantha*), and Thurber's needlegrass (*Achnatherum thurberianum*). These species are typical of rangeland ecosystems in the Pacific Northwest and are classified as k ey livestock forage species. Key shrub and tree species onsite consist of mountain big sagebrush (*Artemisia tridentata, spp vaseyana*), green rabbitbrush (*Chrysothamnus viscidiflorus*), gray rabbitbrush (*Ericameria nauseosus*), antelope bitterbrush (*Purshia tridentata*), curlleaf-mahogany (*Cercocarpus ledifolius*), and western juniper (*Juniperus occidentalis*). Vegetative site characteristics in the two watersheds were found to be typical of the John Day ecological province (Fisher 2004). Historic juniper stands local to the study area may have occupied a larger proportion than that of the surrounding landscape due to the clayey, pumice soils that provide desirable calcium and pH values, which are important to juniper growth (Anderson et al. 1998). Current juniper stands typical of the surrounding landscapes are classified as Phase (III) juniper encroachment (Miller et al. 2005). Prior to juniper removal from the treated watershed, juniper occupied both of the watersheds at ~ 26% cover, which is near the 30% cover described for Phase (III) juniper sites (Miller et al. 2000). Dead shrub material was estimated at approximately 4% of total cover. The remaining live shrubs occupied approximately 4% and perennial grasses covered 13% of the total cover throughout both watersheds (Fisher 2004). The extent of juniper encroachment was also identified through measured indices, such as high occurrences of bare ground, reduced infiltration rates, and high soil erosion rates (Deboodt 2008; Fisher 2004).

Field Data Collection

Vegetation

The line-point intercept sampling method, adapted from Herrick et al. (2005), was used to estimate percent foliar cover, percent litter and percent bare ground represented in two individual sampling layers (i.e. top canopy and soil surface) . In the summer of 2014, a total of 289 ten-meter transects were placed throughout both watersheds; 143 in the treated and 146 in the untreated (Fig. 1.2). Transect locations were established to provide equal representation of aspect and elevation. Transects were permanently marked and aligned perpendicular to slope. Transect locations were established to avoid crossing ecotones between plant community types and soil types, thereby reducing risk of spatial heterogeneity effects as a result of differing abiotic and biotic factors. Vegetation points and soil surface cover were read every 1 m along the transect line. Canopy cover was recorded by species, and additional features were characterized as either herbaceous litter or woody litter (> 5 mm). Soil surface measurements were of plant species, rock (> 5 mm), bedrock, moss, lichen crust, soil, embedded litter, or duff. Species functional groups were categorized as annual forb, perennial forb, annual graminoid, perennial graminoid, shrub, or tree. Data from each 10-m transect was used to estimate average percent total canopy cover by vegetative species, relative cover of each functional group, percent bare ground, and percent litter cover. Relative cover was estimated for each transect by dividing to sum of occurrences for each functional group by the sum of all occurrences. A graphical analysis of categorical cover data by soil water content was created to determine the relationships of total cover and relative cover of key functional groups to mean values of soil water content across watersheds.

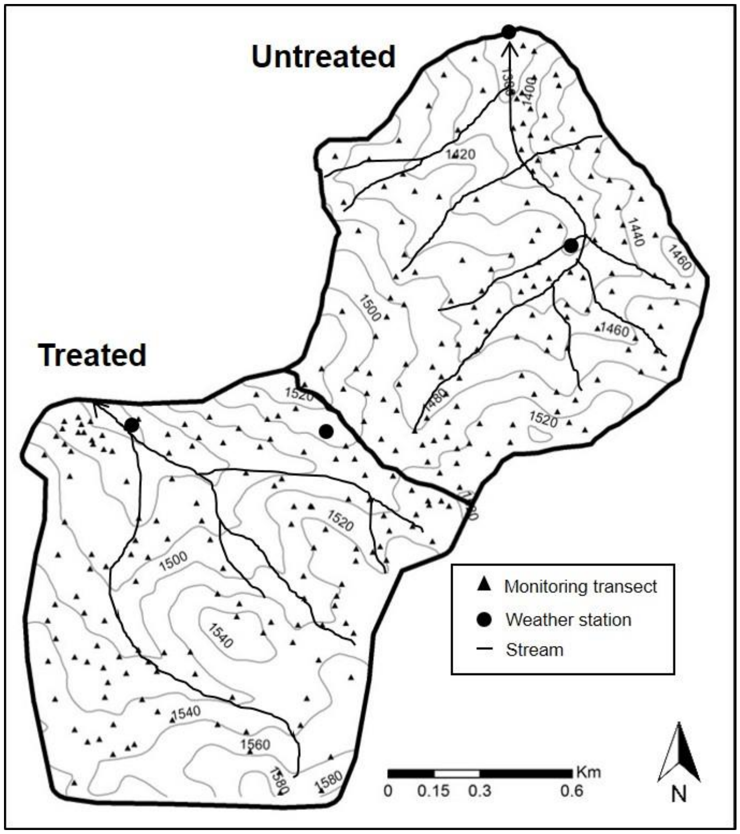

Figure 1.2 Map of the research area including watershed boundaries, 289 transect locations, four weather stations, major streams and 20-m contour lines representing distances in elevation (meters) above mean sea level.

Soil Sampling

Topsoil (12 cm) cores were collected in July 2014. Five soil cores were collected from each of the 289 transects using a soil-step probe (AMS, Inc; American Falls, ID), starting at the 2-m point. A few transects were comprised of rocky soils resulting in several unattainable cores, which reduced the number of samples from 1,445 to a total of 1,349. Each of the soil samples were analyzed for gravimetric water content and soil texture. Sample values were calculated by averaging the results of the five core samples from each transect resulting in a total sample size of 289. Gravimetric water content was determined using the method described by Black (1965). Gravimetric soil weights were converted to soil volumetric water content (%) using the following soil bulk density equation.

$$\theta_{vd} = \theta_d \; x \; \frac{d_b}{d_w} \qquad \textbf{[1]}$$

Where θ_d is the gravimetric water content of the soil, d_b is the bulk density of the soil ($g \cdot cm^{-3}$), and d_w is the density of water ($1 \; g \cdot cm^{-3}$). Soil texture was estimated using the hydrometer method, described by Gee and Bauder (1986). Dry soil bulk density was measured by dividing the dry weight of the soil (g) by the soil volume (cm^3).

Similar to soil core sampling, soil volumetric water content (SVWC) data was collected every two meters along each transect using a portable soil water probe (Model HydroSense II, Campbell Scientific Inc.; Logan, UT), which integrates SVWC for the top 12 cm soil of the soil profile. SVWC measurements resulted in five points per transect. The five points were averaged across each transect for a total sample number of 289 (Treated, n = 143; Untreated, n = 146). In order to represent seasonal changes in SVWC, we collected data in July and November (dry season) of 2014, and during January, March, and May (wet season) of 2015. The duration of each data collection period was approximately three days, with the exception of the July reading, which took place over a four week period. Data collected with the soil water content sensor were used to determine the temporal and spatial distribution of soil water content across watersheds.

Statistical Analysis

To evaluate the differences in percent foliar cover, litter cover, bare ground and the relative cover of each functional group throughout the watersheds, a single-factor analysis of variance (ANOVA) with two-sample t-tests was conducted (Treated, n = 143; Untreated, n = 146). The difference between means for percent relative canopy cover of each functional group were also analyzed. An additional single-factor ANOVA was utilized to test the significance ($P \leq 0.05$) of the differences between mean SVWC for each watershed and at each measurement period (July, November, January, March, and May). To determine the effects of terrain indices on SVWC, a single-factor ANOVA was utilized to test the significance ($P \leq 0.05$) of the differences between aspects (represented in the eight cardinal directions) within each individual watershed.

Linear models were used to test the main effects and interactions of the measured variables between watersheds as well as within each individual watershed ($P \leq 0.05$) using RStudio statistical software (RStudio; Boston, MA). We used a general linear model (hereafter, the full model) to determine the effects of the watershed treatment (*site*), measuring period (month), total canopy cover (*canopy*), and soil clay content (*clay*) on mean SVWC. Within the full model we included *canopy* x *clay*, *site* x *canopy*, and *site* x *month* interactions to account for potential dependencies of these factors on one another. Mean values of SVWC, total canopy cover, and clay for each transect were utilized for model input variables. Clay content was used as the representative textural variable for the analyzed soil cores due to its influence on water holding capacity, and therefore SVWC, and also due to the high abundance of clay represented in each of the three major soil series within the watersheds. We then used reduced linear models to determine the dominant effect of the independent variables, *canopy* and *clay*, on SVWC across each of the five measurement periods (July, November, January, March, and May).

Geospatial Analysis

The program ArcMap (version 10.2.2; Redlands, CA) and the geospatial interpolation method, kriging, were used to demonstrate the spatio-temporal variability of average percent soil water content for each monitoring transect (N = 289). Ordinary kriging (OK) was chosen over the other widely accepted geospatial kriging methods since the number of representative data points is relatively high (~7 SVWC points ha^{-1}), providing an extensive spatial representation of the catchment areas. The general approach of the OK model determines statistical and spatial relationships among measured points to produce a prediction surface of the remaining unmeasured space. It is assumed within this model that predictions are possible due to the existence of spatial correlations, where points that are close in space will display similar soil water content values. The two-step OK method first determines the variance of the points against the mean values in order to fit the model and ultimately uses those values to create the prediction surface. The model was estimated with an 8 x 8 m grid size in ArcMap, and 289 data points, which represent the mean values of each transect resulting from the 1,445 total SVWC points. The mean percent clay content for each transect was used as the textural variable for interpolation. No additional terrain indices were utilized since the range in elevation, slope, and the distribution of aspects was relatively uniform. It has been documented that elaborate interpolation methods are not necessary when landscape terrain indices are constant (Bádossy and Lehmann 1998; Western et al. 2002).

Results

Vegetation

Total canopy cover was analyzed for estimates of canopy cover, litter cover, and bare ground represented by two individual sampling layers; top canopy (total canopy cover) and soil surface (litter, bare ground, and misc. cover). Total vegetation cover was similar

(~ 60%) for both watersheds, however greater litter cover and less bare ground cover were observed in the treated watershed. Total canopy cover was not significantly different ($P \geq 0.05$) across watersheds, with means of 66% (treated) and 61% (untreated) (Fig. 1.3). A significantly higher ($P \leq 0.05$) occurrence of bare ground in the untreated (24% cover) watershed was observed when compared with the treated (13% cover) watershed. This result is supported by literature on long-term, plot-scale vegetation responses in juniper woodlands, where understory vegetation cover increased over time post-juniper removal (Bates et al. 2007; Allen 2008). A significant ($P \leq 0.05$) difference in litter cover between watersheds was observed with 47% in the treated and 32% cover in the untreated (Fig. 1.3).

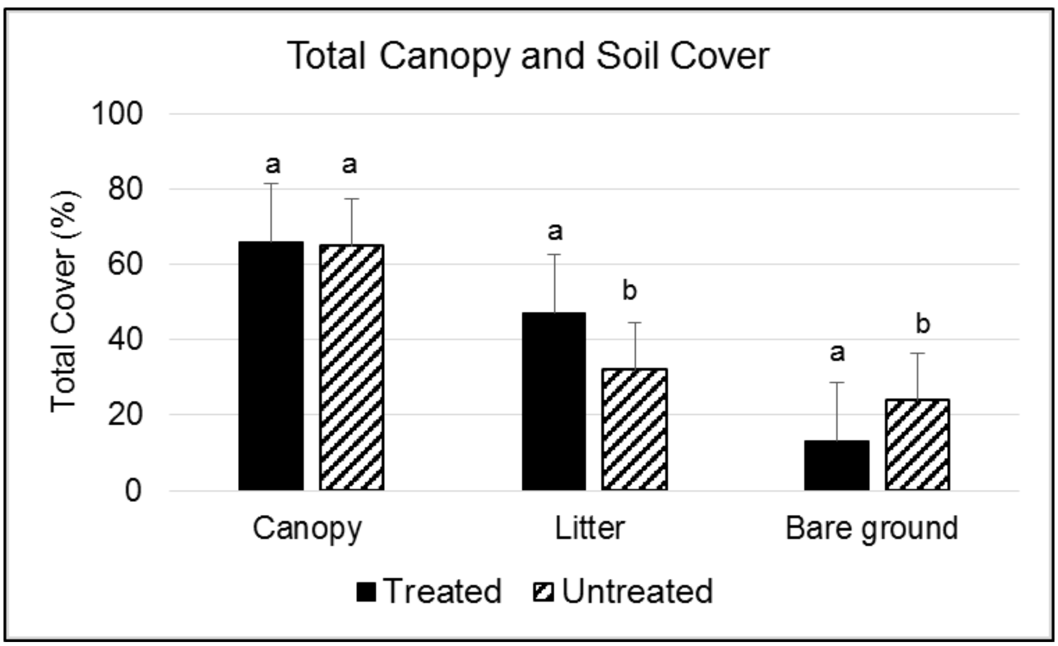

Figure 1.3 Mean values (±SE) of total canopy cover for the treated and untreated watersheds. *Means with the same letter are not significantly different ($P > 0.05$).

Analysis of major functional groups showed the treated watershed had higher relative cover of perennial grasses, shrubs, and annual grasses than the untreated watershed. Relative cover was estimated for each transect by dividing the sum of occurrences for each functional group by the total occurrences. There were significant ($P \leq 0.05$) differences in perennial grass cover for the treated and untreated sites at 61% and 52% relative canopy cover (Fig. 1.4). Annual grass showed significant differences between the treated and untreated watersheds at 12% and 3% relative canopy cover. As expected, juniper tree cover was higher in the untreated (31%) site than in the treated (> 1%). However, it is noteworthy to mention the initial stage of recovery of juniper in the treated watershed 10 years post-treatment, which is mostly comprised of juvenile-stage trees (< 1 m tall). Relative cover of shrubs was significantly different between watersheds at 23% treated and 10% untreated. Perennial and annual forbs showed no significant differences between the treated and untreated watersheds at 3 and 2%, perennial forbs; and 0.5 and 1%, annual forbs.

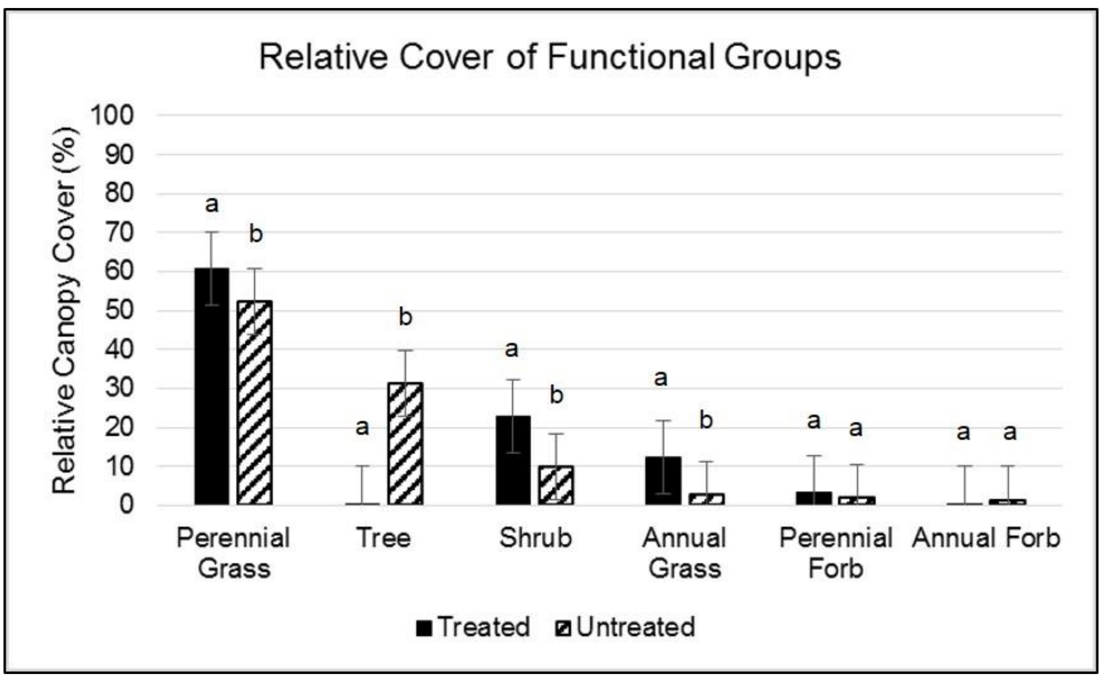

Figure 1.4 Mean values of relative canopy cover (± SE) for each functional group across the treated and untreated watersheds. Means with the same letters are not significantly different ($P > 0.05$).

Soil-Water Relationships

Soil texture was similar across watersheds. The particle-size analysis of the 12-cm depth soil cores resulted in three main soil textural classes across the combined 220 ha study area. Sandy loam made up the majority (83%) of the total soil area. The remaining area was comprised of sandy clay loam (15%) and loamy sand (2%). SVWC values that were obtained from the gravimetric analysis of soil core samples collected in July ranged from 1% to 21% in the treated and 4% to 16% in the untreated watershed. The general trend for this range of values was in agreement with the range of values expressed from the TDR sensor readings (2% to 17%) in July. This analysis resulted in a normal distribution (data not shown) of the moisture data derived from the gravimetric analysis for both watersheds and served as validation for our use of the TDR sensor data for the analysis of SVWC on the subsequent dates.

An overall mean value of soil volumetric water content for each watershed was derived using the mean value for SVWC from each transect. A progressive change in soil water content for both watersheds was observed during all five data collection periods (July, November, January, March, and May) and corresponded to the transition from the dry to wet season. Significant ($P \leq 0.05$) differences in mean SVWC were observed for both watersheds. The overall minimum and maximum mean SVWC for the treated watershed was 8% (July 2014) and 28% (May 2015), and 7% (July 2014) and 27% (March 2015) for the untreated watershed. When comparing treated versus untreated watershed results, the ANOVA showed a significant difference ($P \leq 0.05$) in SVWC for four of the five months, with November being the exception (Table 1.1).

Table 1.1 Analysis of variance (ANOVA) for soil volumetric water content (%) by month. *Means with the same letter are not significantly different P > 0.05.

Month/Year	Treated	Untreated
July 2014	8.2 a	7.08 b
November 2014	9.9 a	10.0 a
January 2015	23.7 a	20.9 b
March 2015	25.6 a	27.2 b
May 2015	28.4 a	25.7 b

Overall, the treated watershed maintained a higher percentage of SVWC, with the exception of the March reading, when the untreated watershed displayed ~ 2% higher mean water content. The TDR sensor readings of SVWC for July resulted in values ranging from 2% to 17% in the treated and 3% to 12% in the untreated (Table 1.2). Mean values for the November reading of SVWC ranged from 4% to 16% in the treated and from 5% to 15% in the untreated. Readings for the January measurement period ranged from 10% to 40% in the treated and from 9% to 37% in the untreated.

Table 1.2 Observed minimum and maximum values of soil volumetric water content (SVWC), total monthly precipitation (PPT), and total annual precipitation (TAP) across the treated and untreated watersheds (June 2014 – June 2015).

	Treated				Untreated			
	SVWC				SVWC			
Month/Year	Min. (%)	Max. (%)	PPT (mm)	TAP (mm)	Min. (%)	Max. (%)	PPT (mm)	TAP (mm)
July 2014	2	17	2.0	322.8	3	12	8.4	347.6
November 2014	4	16	64.3		5	15	69.2	
January 2015	10	40	8.3		9	37	11.3	
March 2015	11	37	29.9		14	40	25.8	
May 2015	17	42	41.2		12	41	46.1	

In March, mean SVWC values ranged from 11% to 37% in the treated, and 14% to 40% in the untreated watershed. In May, mean sample values ranged from 17% to 42% in the treated, and 12% to 41% in the untreated watershed. It is important to note that mean rainfall (mm) logged by the four onsite rain gauges during this period reported approximately 25 mm higher in the untreated watershed when compared to the treated watershed. Yet, higher overall mean values of SVWC were still generally observed in the treated watershed.

A measure of the influence of terrain indices (i.e. aspect) on SVWC was completed using a single-factor analysis of variance of sample means for each individual watershed (Figs. 1.5 and 1.6). Results showed no significant differences ($P > 0.05$) in soil water content by aspect within each watershed for each measurement period. The treated and untreated watersheds displayed similar patterns during the wet season, with slightly lower mean values in the southern aspects. However, this effect was much more apparent in the untreated watershed, yet still did not produce statistically significant differences (P > 0.05). These results led to the exclusion of aspect as independent variable in the linear regression models.

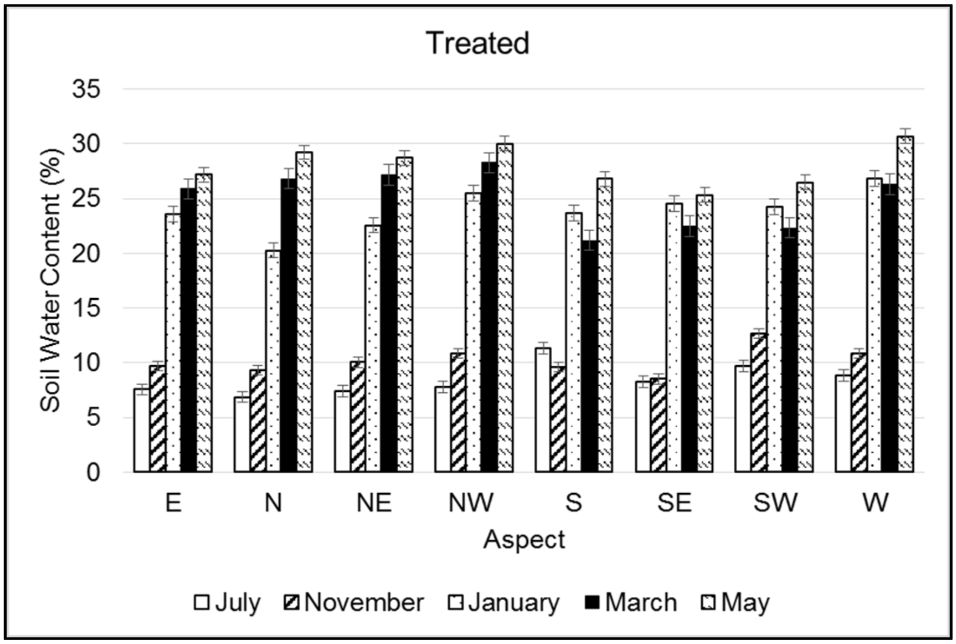

Figure 1.5 Distribution of mean values (±SE) of soil volumetric water content (SVWC) for each transect location and aspect across all measurement periods (July and November 2014, and January, March, and May 2015) in the treated watershed. *Differences in SVWC between aspects are not statistically significant (P > 0.05) for all measurement periods.

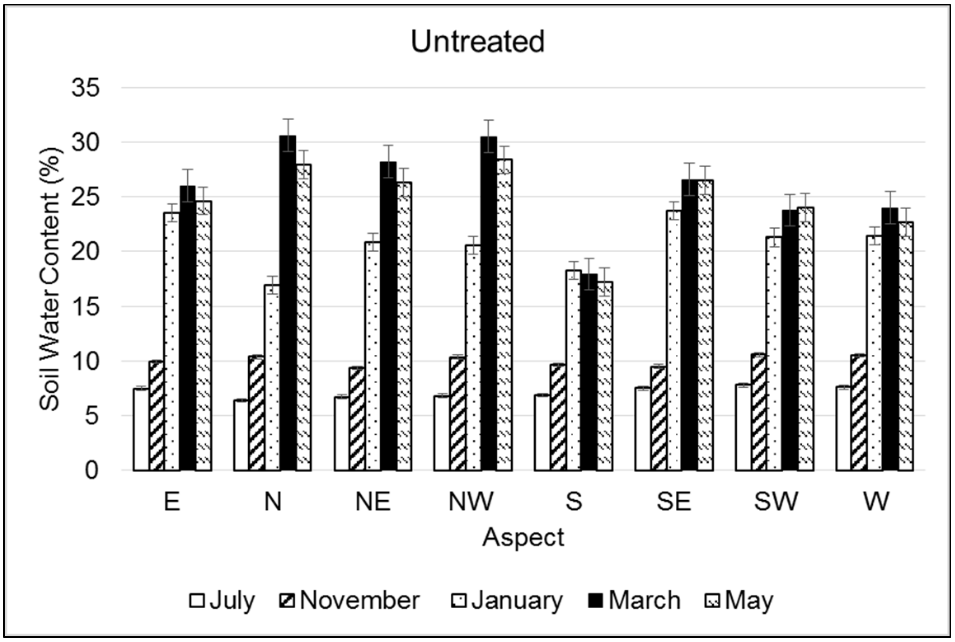

Figure 1.6 Distribution of mean values of soil volumetric water content (SVWC) for each transect location and aspect across all measurement periods (July and November 2014, and January, March, and May 2015) in the untreated watershed. *Differences in SVWC between aspects are not statistically significant (P > 0.05) for all measurement periods.

Linear regression models were used to test the main effects and interactions of the measured variables between watersheds as well as within each individual watershed (P ≤ 0.05). Full model results (data not shown) produced significant *site* x *month* interactions (P ≤ 0.05), and resulted in the *canopy* x *clay* and *site* x *canopy* interactions as nonsignificant (P ≥ 0.05). Therefore, we used reduced models for each site and month combination to understand the source of the significance of the *site* x *month* interaction in the full model.

Analysis of the untreated watershed for the July soil reading showed the independent variable of canopy cover as having a significant influence on soil water content (F = 7.94, P = 0.00) and a nonsignificant effect of clay content (P ≥ 0.05) (Table 1.3). Similarly, the reduced linear model showed a significant effect of total canopy cover in July (F = 8.49, P = 0.00) and a nonsignificant effect of clay content (P ≥ 0.05). November readings displayed analogous results within the linear model for both the treated and untreated sites. Canopy cover significantly influenced SVWC in the untreated (F = 18.96, P = 0.00) and treated (F = 6.04, P ≤ 0.001). Clay content was not significant in either treatments in November (P ≥ 0.05).

January and March exhibited the largest variations in SVWC. Modeled results for January showed a significant effect of canopy for both the untreated (F = 2.37, P ≤ 0.01) and treated sites (F = 8.09, P ≤ 0.00). Clay content in the treated watershed was also a significant (P ≤ 0.01) factor affecting mean moisture values in January. Interestingly, reduced models for March resulted in nonsignificant effects of canopy for either site (P ≥ 0.05). Clay content was observed to have significant effects in both the untreated (F = 5.05, P ≤ 0.001) and the treated (F = 17.67, P ≤ 0.00) sites. The final analysis for the independent variables effects for the May reading resulted in equivalent results to the March reading. Canopy cover was not significant in both watersheds while the effect of clay was significant for both the treated (F = 10.14, P ≤ 0.00) and for the untreated (F = 2.71, P ≤ 0.05) areas.

Table 1.3 Results of the reduced linear model estimating trends in soil volumetric water content (SVWC) under the main effects of total canopy cover and clay for each measurement period. (+) Estimates positive trend with increasing cover, (-) estimates negative trend, (NS) nonsignificant P-Value.

Month/Year	Watershed	Independent Variable	F-value	P-value	Estimated Trend SVWC
July 2014	Untreated	Canopy	7.94	0.00	-
		Clay		NS	-
	Treated	Canopy	8.49	0.00	-
		Clay		NS	+
November 2014	Untreated	Canopy	18.96	0.00	-
		Clay		NS	+
	Treated	Canopy	6.04	0.001	-
		Clay		NS	+
January 2015	Untreated	Canopy	2.37	0.05	-
		Clay		NS	+
	Treated	Canopy	8.09	0.00	-
		Clay		0.05	+
March 2015	Untreated	Canopy	5.05	NS	+
		Clay		0.001	+
	Treated	Canopy	17.67	NS	-
		Clay		0.00	+
May 2015	Untreated	Canopy	2.71	NS	-
		Clay		0.05	+
	Treated	Canopy	10.14	NS	-
		Clay		0.00	+

Results derived from the linear models showed significant influences of total canopy cover on SVWC readings for July, November, and January. A graph of one representative dry period (July) and one representative wet period (March) (Figs. 1.7 and 1.8) is represented here to display the most prominent trends in mean SVWC by transect based on mean canopy cover for each transect. This approach was taken to help explain the relationship of SVWC by categorical values of total canopy cover. There is an observable decreasing trend in SVWC in July as total canopy cover increases in both watersheds (Fig. 1.7). Results from the additional dry period (November) displayed similar graphical analyses. March resulted in an increasing trend in SVWC with increasing total canopy cover (Fig. 1.8) across both watersheds. The additional wet periods (January and May) displayed similar graphical results (data not shown). This graphical analysis supports the results of the reduced linear model which correlates increasing canopy cover with reduced SVWC in the dry season, and conversely, with increasing SVWC during the wet season.

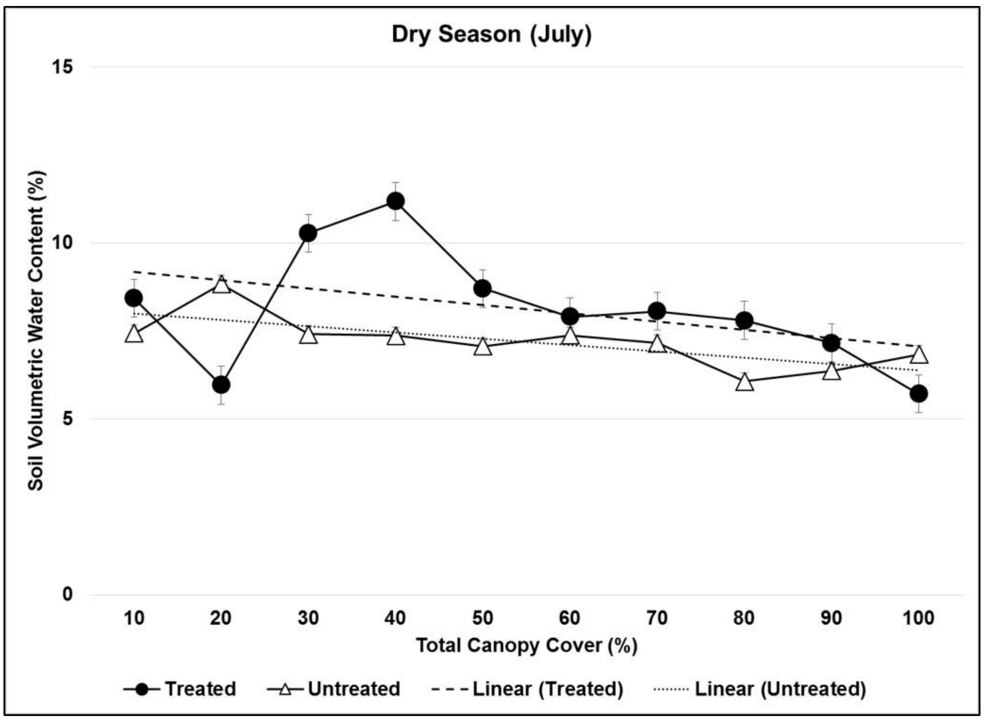

Figure 1.7 Mean values (± SE) of soil volumetric water content for the representative dry season (July), relative to total canopy cover (%) for the treated and untreated watersheds.

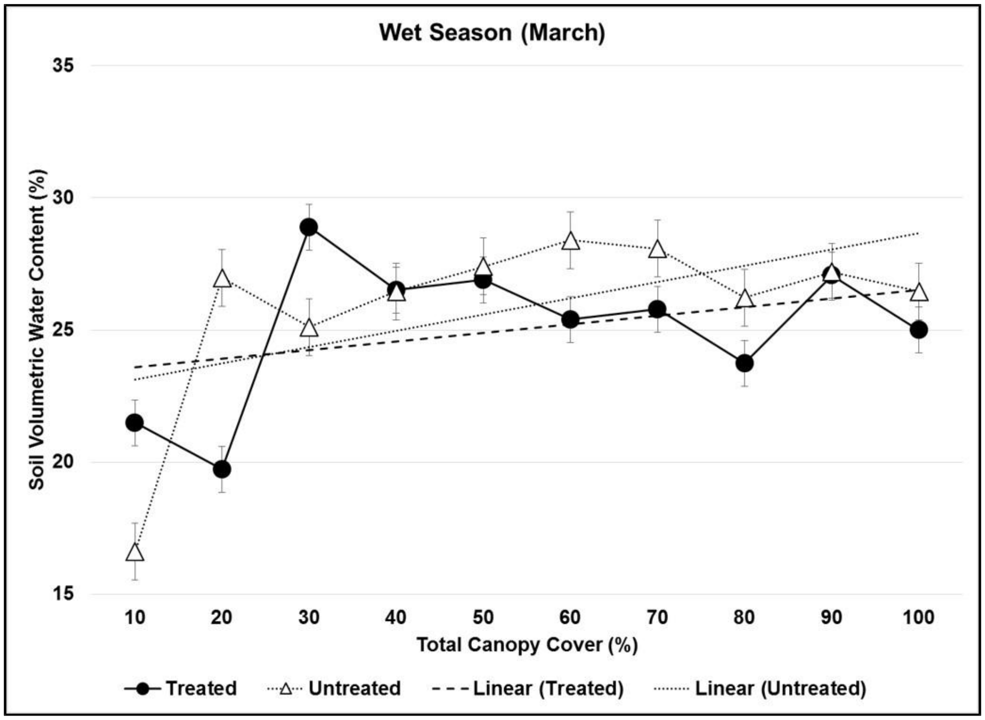

Figure 1.8 Mean values (± SE) of soil volumetric water content for the representative wet season (March), relative to total canopy cover (%) for the treated and untreated watersheds.

Geospatial

Using GIS analysis and the ordinary kriging method, we generated soil water content surfaces across spatial and temporal scales for both watersheds (Figs. 1.9 and 1.10). Interpolated results show an increase in SVWC as time transitioned from the driest month of July 2014 to the wettest months of March and May 2015. SVWC classifications ranged from 5% to 11% in July; 6% to 12% in November; 12% to 30% in January, 15% to 32% in March, and 16% to 40% in May. Interpolated ranges in values were consistent with ranges derived from TDR sensor readings for each measurement period. Spatial correlations in the maps display areas of higher or lower moisture at corresponding sites throughout the watersheds for each measurement period. This effect of subsurface lateral flows is highly evident in the wettest months (March and May), when drainage patterns from subsurface water movement were highly visible in lowland areas of both watersheds (Fig. 1.10). Ochoa et al. (2008) reported similar results in water content trends, where water content values were higher in the valley sites than on hillslope sites in juniper dominated and treated landscapes. This interpolation also helps show the advancing stages of wet season processes and antecedent soil moisture condition as the transition from dry to wet season progresses.

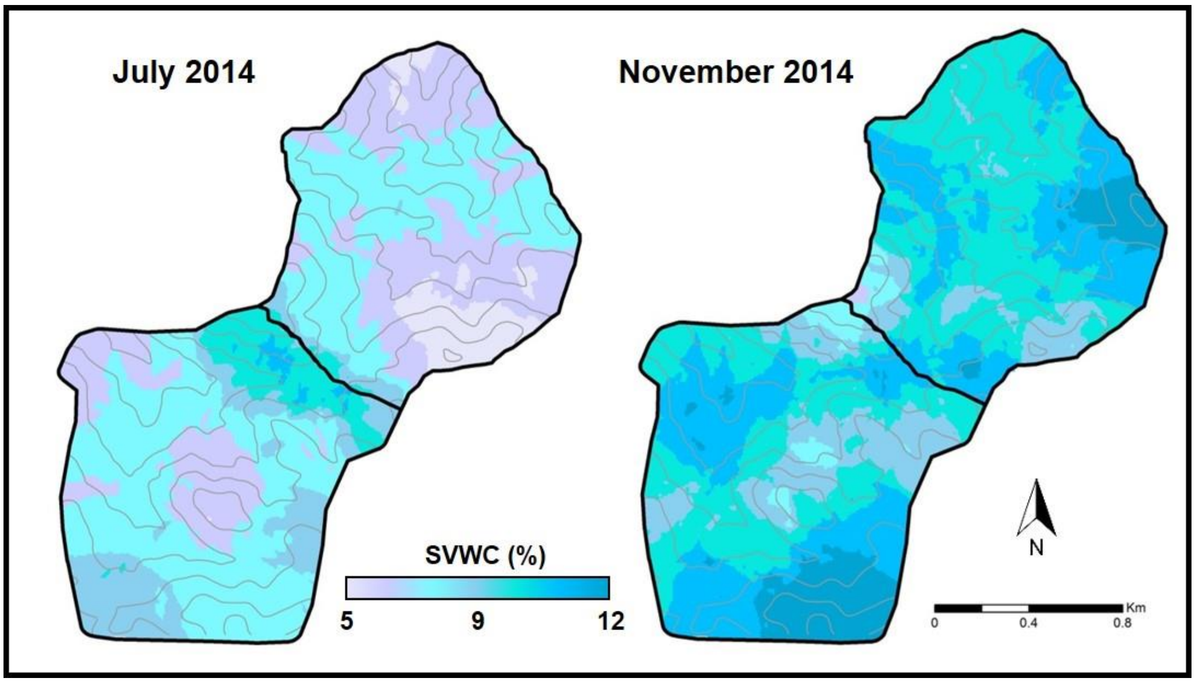

Figure 1.9 Map of the research area displaying the geospatial interpolation of the spatio-temporal differences in soil volumetric water content (SVWC) in the top 12 cm of the soil profile throughout the two driest monitoring periods (July and November 2014).

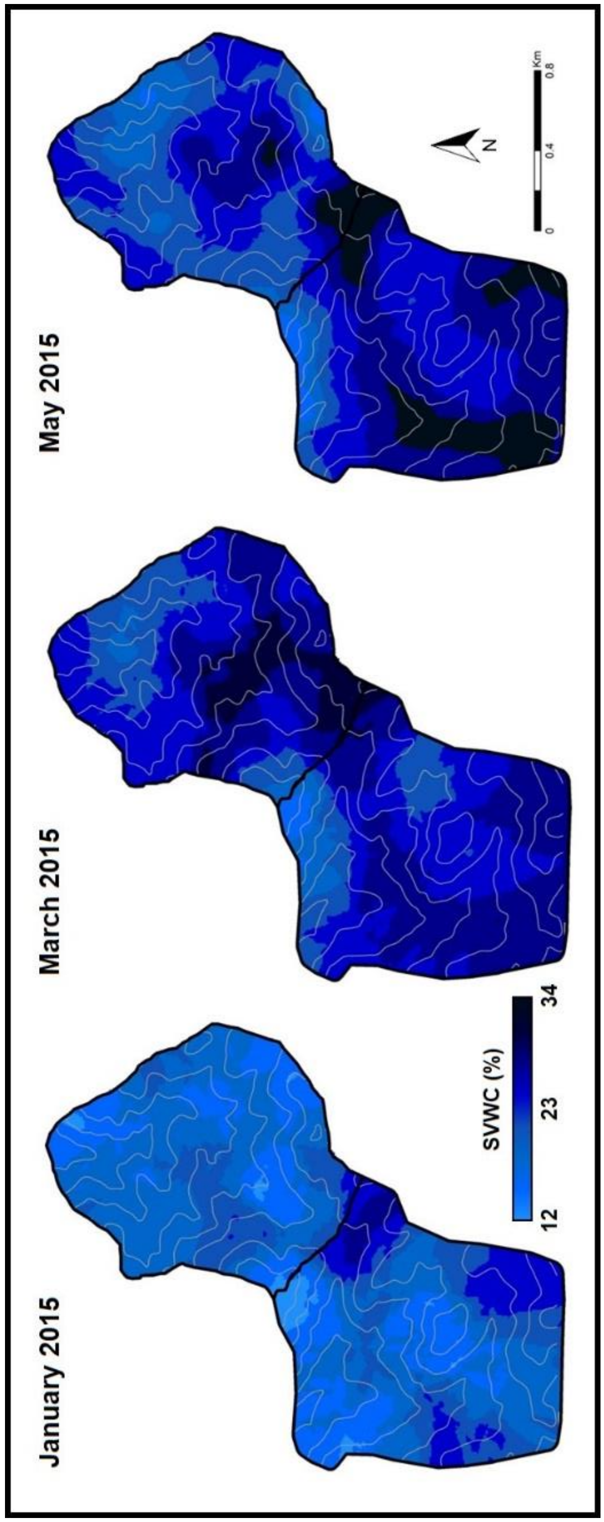

Figure 1.10 Map of the research area displaying the geospatial interpolation of the spatio-temporal differences in soil volumetric water content (SVWC) in the top 12 cm of the soil profile throughout the three wettest monitoring periods (January, March, and May 2015).

A geospatial representation of the distribution of percent clay content (Fig. 1.11) in both watersheds shows corresponding areas of higher clay and higher soil water content. The six clay content classifications of the interpolation range from 13% to 20%, which corresponds to the range of differences in clay content between the three major soil classes reported from the particle-size analysis results. Loamy sand ranges 10% to 15% clay; sandy loam, 15% to 20%; and sandy clay loam, 20% to 35%. This correlation between high clay content and high water content was also expressed in the individual linear models for the wettest months of January, March, and May.

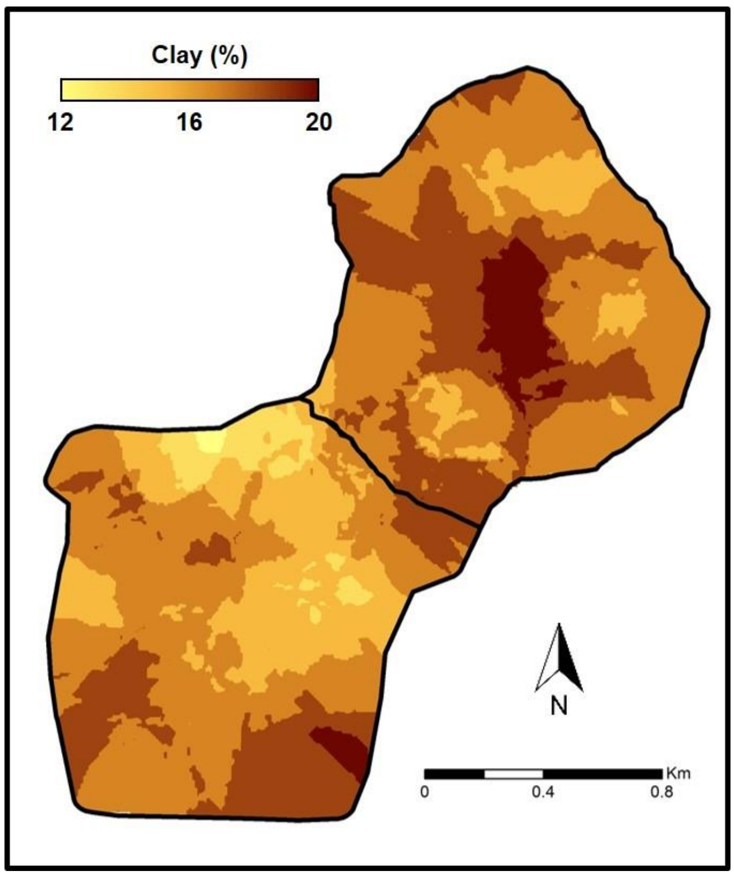

Figure 1.11 Geospatial interpolation of the representative differences in soil clay content (%) for the treated and untreated watersheds.

Discussion

This study resulted in a statistically significant mean value of > 2% higher SVWC in the treated watershed for three of five measurement periods. Many plant species acquire water for plant growth from deeper soil profiles and groundwater sources however, in arid areas dependent on little precipitation, plants must rely heavily on subsurface soil water (McLendon et al. 2008; Ryel et al. 2010). Soil water potential, although not a measured variable in this research, is an important factor in plant growth and water availability. Research suggests that larger precipitation inputs have resulted in increases of soil water potential and corresponded to more efficient water uptake by a wide variety of plant species (Fahey and Young 1984; Mata-Gonzalez et al. 2014). Depending on seasonal availability of soil water, increased water potential would likely provide for an increase in plant biomass production. A 2% increase in soil water content for a 12-cm profile across 110 ha could extrapolate to a significant increase in water availability per hectare for the estimated 60% plant coverage in the treated watershed.

Many factors have the potential for influencing shallow soil water content. Spatial variations in soil water content dynamics were observed in the linear models based on influences of soil texture-driven and vegetation-driven effects. The dominant variable, which was negatively correlated to water content was total canopy cover, and most notably juniper cover. Our results suggest that, despite the similar estimation of approximately 60% total canopy cover in both watersheds, similar coverage of soil textural properties, and similar effects of terrain components, there is an observable difference in soil volumetric water content between the treated and untreated watersheds. The structure and distribution of plant functional groups should be further assessed in order to determine the degree to which these juniper dominated and sagebrush-bunchgrass dominated watersheds effect the amount and distribution of shallow soil water content. Over-winter precipitation events resulting in snow accumulation and spring snowmelt are the major drivers for the spring and summer growing seasons in central Oregon (Sneva 1982; Bates et al. 2006). We speculate that juniper canopy cover in the untreated watershed is limiting the effective precipitation reaching the soil during this crucial time period. Our findings are similar to that of a smaller-scale catchment study on California rangelands where soil water results showed a negative correlation to tree cover and a positive correlation to grass cover (Salve and Allen-Diaz, 2001). Intracanopy (i.e. area underneath juniper canopies) duff layers located directly under adult aged trees were observed up to 20 cm thick, which we speculate may have created an even more extensive barrier to precipitation. This is consistent with findings by Gifford (1970) where effective moisture under the canopy was reduced by thickness of the canopy and litter layer.

Juniper canopy cover has the potential for creating a protective barrier against solar radiation while promoting microsites and cooler soil temperatures (D'Odorico et al. 2007). This shading effect was highly evident in the untreated watershed during one of the wettest months (March), where high juniper cover resulted in the highest overall mean values of SVWC of the five measurement periods. We attribute this to a shading effect by juniper trees, which has the potential to decrease soil evaporation and wind exposure as a result of the larger area of foliar canopy cover when compared to the key bunchgrass species. Several plot-scale studies have also documented higher soil water content under the canopy of juniper trees and have attributed this condition to solar radiation interception (Breshears et al. 2009; Garduño et al. 2010).

Conclusion

The results of this study confirm that there are distinct differences in shallow soil water content between these juniper dominated and understory dominated watersheds at the landscape scale. The progressive changes in soil water content observed across the landscape during the transition from the dry to the wet season are likely due the degree and type of vegetation cover. The role of overstory canopy cover, in regards to soil water distribution, seems to be less important from late winter to early spring after soil moisture has accumulated throughout the wet season. This effect is also observed as a result of larger precipitation events which provide enough moisture to cover the entire spatial domain of the watersheds.

This watershed-scale study provides valuable information regarding vegetation-shallow soil water dynamics in western juniper woodlands as well as in other pinyon-juniper dominated ecosystems of western rangelands. Water is the primary limiting resource in western rangelands, and further investigation into the effects of large-scale vegetation manipulation needs to be taken to assure effective management and conservation efforts are taking place on these valuable ecosystems.

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SUBSURFACE HYDROLOGIC CONNECTIONS OF JUNIPER ENCROACHED WATERSHEDS

Abstract

Semiarid rangelands are categorized amongst the most unique and diverse ecosystems on the planet. Areas that rely on little precipitation and unpredictable streamflow still produce a wealth of biological diversity which are depended on for natural and human uses such as wildlife, grazing, recreation, and agriculture. Upland and valley hydrologic connections have been studied in relation to streamflow and groundwater interactions. However, the importance of subsurface flow in upland watersheds with ephemeral streamflow can often be overlooked. Large-scale vegetation removal projects are taking place throughout rangelands of the west without a baseline understanding of the hydrologic effects of treatment. This research analyzes long-term groundwater and soil water fluctuations and precipitation-soil water-groundwater interactions between a juniper removed (treated) and juniper encroached (untreated) watershed. The subsurface flow connections are also analyzed between the upland watersheds and the downstream valley. Pre-treatment data collection for groundwater table fluctuations began in 2004 and analysis of soil water content fluctuations at three depths (0.2, 0.5, and 0.8 m) began six months pre-treatment in 2005. Long-term groundwater fluctuations show distinctive patterns for both the treated and untreated watersheds. The untreated watershed recorded, on average, higher maximum water level rise each year (> 2 m), when compared to the treated site. The treated watershed tended towards retaining maximum water levels at least one month longer than the untreated monitoring wells. Soil water content fluctuations varied with each year with the longest sustained mximum water content values occurring in the treated watershed. A one-year analysis of precipitation-soil water-groundwater interactions showed strong seasonal responses to storm events, and antecedent soil water content played a significant role in water table response. The analysis of upland-lowland/riparian

connectivity showed temporally based connections which were most pronounced towards the end of the wet season. An analysis of the stable isotope oxygen ($\delta^{18}O$) supported the hydrologic connectivity findings due to the nearly identical isotopic signature between treated and untreated upland wells and springs, and the downstream valley wells.

Keywords

Groundwater connectivity, Subsurface flow, Soil Water Content, Isotopes

Introduction

Large-scale vegetation manipulation projects have been conducted throughout the world with hopes of increasing streamflow and water yield for environmental and human benefits (Bosch and Hewlett 1982). Increases in water quantity are thought to be predictable when mean annual precipitation of the site exceeds 450 mm (Hibbert 1979). This claim becomes confounding when considering arid and semiarid ecosystems that rely on very little precipitation and produce little to no streamflow. Catchment experiments focused on vegetation manipulation and resulting water yield in semiarid areas have produced mixed results. A study conducted by Baker (1984) reported annual streamflow increases of up to 157% after juniper mortality following an herbicide treatment. Similar studies on juniper and aspen removal at sites in Colorado and Utah recorded up to 47% increases in water yield following removal, however all studies recorded reduced flow in by the third year post-treatment (Bates and Henry 1928; Brown 1971; Hibbert 1971). Hibbert (1983) reported no increase in stream but significant increases in soil water content for sites removed of juniper. Juniper removal studies at this paired watershed site reported no recordable increases in streamflow post-treatment (Deboodt 2008).

In order to understand the effects of extensive vegetation removal on hydrologic function, we must understand the underlying hydrologic connections through which these complex systems operate. Research has been conducted on the subject of hydrologic connectivity across the landscape (Emanuel et al. 2014; Lexarta-Artza and Wainwright 2009; Nadeau and Rains 2007; Ocampo et al. 2006; Sklash and Farvolden 1979). Hydrologic connectivity originally defined the transport of matter, energy, and biological components through stream systems (Freeman 2007; Pringle 2003b). The term has evolved to encompass the interactions between not only the surface water and groundwater continuum, but also any hydrologic processes that links physical and biological facets which have the ability to regulate or alter a landscape, whether the alterations be localized or evident many miles downstream (Pringle 2003a). In many semiarid areas, the great challenge has been delineating the hydrologic connection between landscape units with either ephemeral, intermittent, or unpredictable streamflow (Constantz et al. 2001; Girard 1996). Izbicki (2002, 2007) discovered the fate of isolated intermittent streams that feed sources up to 180 km away in the Mojave Desert of southern California. Studies have found seasonal and storm-event interactions between groundwater and wetlands sources (Jolly 2008; Rosenberry and Winter 1997; Van der Kamp and Hayashi 2009). Subsurface flow has been shown to be an important facilitator in the transport of sediment, nutrients, and pollutants (Almasri and Mohammad 2004; Stieglitz et al. 2003). Yet, little research has been done which highlights the importance of precipitation-soil water-groundwater flow dynamics in semiarid ecosystems with unpredictable streamflow. Groundwater response due to snow-melt and precipitation events in semiarid areas are considered in relation to stream response, but do not seem to highlight upland-valley connections that are dependent on subsurface lateral flow (McNamara et al. 2005; Patten 1998).

In a world of changing climate and scarce water resources, long-term data collection can be an important factor in understanding any complex problems related to groundwater water availability, hydrologic connection, and hydrologic response to vegetation manipulation (Cooper et al. 2006; Taylor and Alley 2001). Objectives of this study were to: 1) Characterize long-term groundwater and soil water content fluctuations in response to juniper removal; 2) Determine precipitation-soil water-groundwater dynamics in treated versus untreated watersheds; and 3) Assess groundwater connections between upland watersheds and a downstream valley.

Methods

Study Site

The Camp Creek Paired Watershed study was developed in 1993 in central Oregon (lat 43.96N, long 120.34W) with the long-term goal of quantifying the effects of western juniper (*Juniperus occidentallis*) removal on the overall hydrologic functioning of a landscape at the watershed scale. The site comprises an area of approximately 2.3 km^2, and includes two distinct watersheds (Fig. 2.1). The watershed deemed the “treated watershed” had 90% of post-European settlement aged (< 140 yrs) western juniper trees removed in 2005.

Each watershed is approximately 110 ha with elevations ranging from 1370 m to 1524 m. The geology of the landscape is characterized by surface evidence of westerly facing subsurface basalt fractures typical of central Oregon. The average percent slope of each watershed is ~ 25% (Fisher 2004). The orientation and drainage points of both watersheds are located in the northern portion of each catchment. All major stream channels within both watersheds are classified as ephemeral and/or intermittent. The distribution of stream channel orders is ~ 70%, 13%, 3%, and 1% for 1st, 2nd, 3rd, and 4th order streams respectively. The stream gradient, as determined by Fisher (2004), is 115 $m \cdot km^{-1}$.

Soils within this study site are distributed amongst three primary soil series. Westbutte, very stony loam; Madeline, loam; and Simas, gravelly silt loam (Soil Survey Staff 2001). The series are classified as andosols and are formed largely from weathered basalt and colluvium from andesite and tuffaceaous sediments. All soils are well-drained and moderately deep.

Vegetation communities within this study site are typical of northern Great Basin and John Day ecoregions, which are characterized by shrub-steppe and juniper dominated ridge tops. Total vegetation cover in both watersheds is similar at approximately 60% foliar cover. Relative cover of functional groups in the untreated watershed is comprised of 36% cover of western juniper; 35% perennial bunchgrass species, such as bluebunch wheatgrass (*Pseudoroegneria spicata*), Idaho fescue (*Festuca idahoensis*), and Sandberg bluegrass (*Poa secunda*); 16% shrub species, such as mountain big sagebrush (*Artemisia tridentata, spp vaseyana*), green rabbitbrush (*Chrysothamnus viscidiflorus*), gray rabbitbrush (*Ericameria nauseosus*), and antelope bitterbrush (*Purshia tridentata*), 24% annual grasses, mainly consisting of cheatgrass (*Bromus* tectorum), and 10% forbs. Relative cover of functional groups in the treated watershed is characterized by < 10% western juniper, 42% perennial bunchgrasses, 22% shrubs, 27% annual grasses, and 13% forbs.

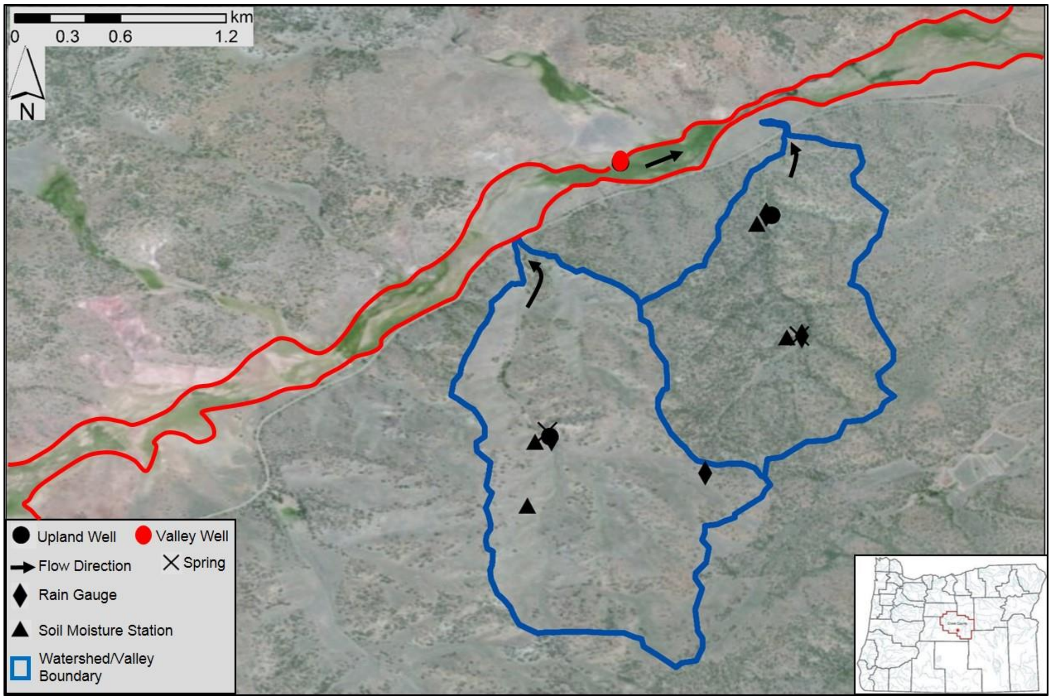

Figure 2.1 Map of the study area showing the location of hydrologic instrumentation installed in upland and valley areas.

The study site is dependent on winter precipitation with a mean value of 286 mm · yr^{-1} (2004 – 2015). Precipitation and weather data was collected using four onsite tipping bucket rain gauges distributed throughout the two watersheds. The mean monthly precipitation ranged from 4 mm in July to 77 mm in November (Fig. 2.2) with the wet season occurring between September and April. The mean monthly temperature was 8°C, with the lowest mean monthly temperature of - 7°C occurring in December and the highest mean monthly temperature of 31°C occurring in August (2009 – 2014). Temperature and precipitation data collected by the onsite weather stations were very similar to data reported from a nearby (10 km southeast) weather station (WRCC 2015).

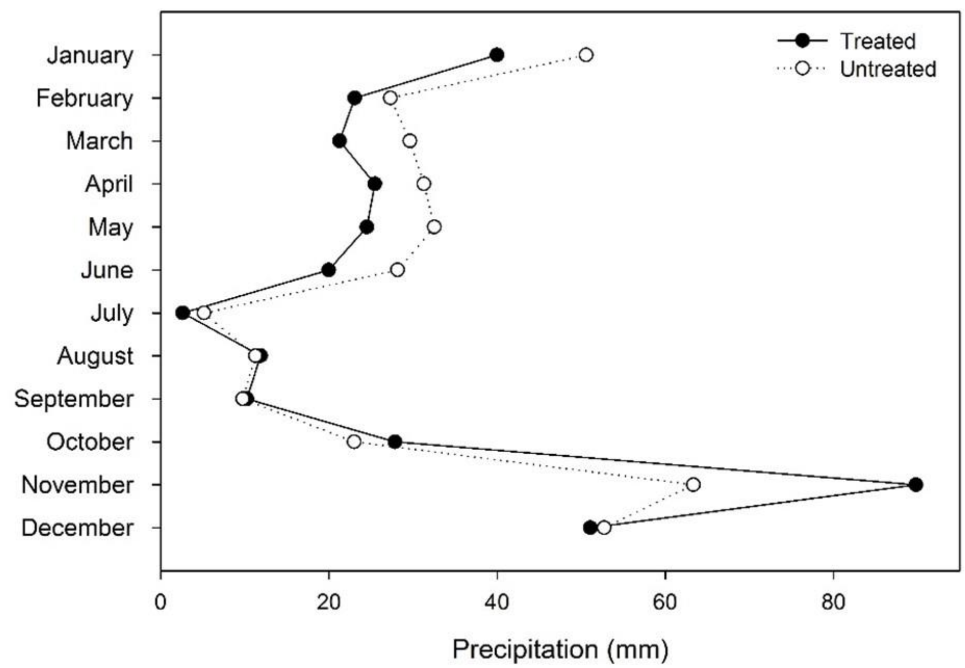

Figure 2.2 Mean monthly precipitation (2004 – 2015) measured by onsite rain gauges in the treated and untreated watersheds.

Field Data Collection

Groundwater

The initial installation of monitoring wells was completed in 2003 (Deboodt 2008). During this time, one transect comprised of six shallow groundwater monitoring wells was installed in each watershed (12 wells total). Both of the 6-well transects were developed in the upper portion of both watersheds and spans approximately 50 m, running west to east from well 1 to well 6. The mean surface elevation of wells in the treated watershed is 1438 m, while the untreated well transect is located at 1373-m elevation (Figs. 2.3 and 2.4). Wells were drilled using a portable drilling rig equipped with a 127 mm diameter drill auger. Wells installed in 2003 were drilled to maximum potential depth until bedrock was hit, which resulted in a maximum depth of 9 m (Table 2.1). Drill holes were filled with crushed rock and cased with 50 mm perforated PVC pipe. The remaining space was filled with crushed rock, followed by a layer of bentonite and finally, cement to help alleviate any preferential flow into the wells. Beginning in 2004, groundwater levels for each of the 12 wells were collected using a handheld water-level indicator (Deboodt 2008).

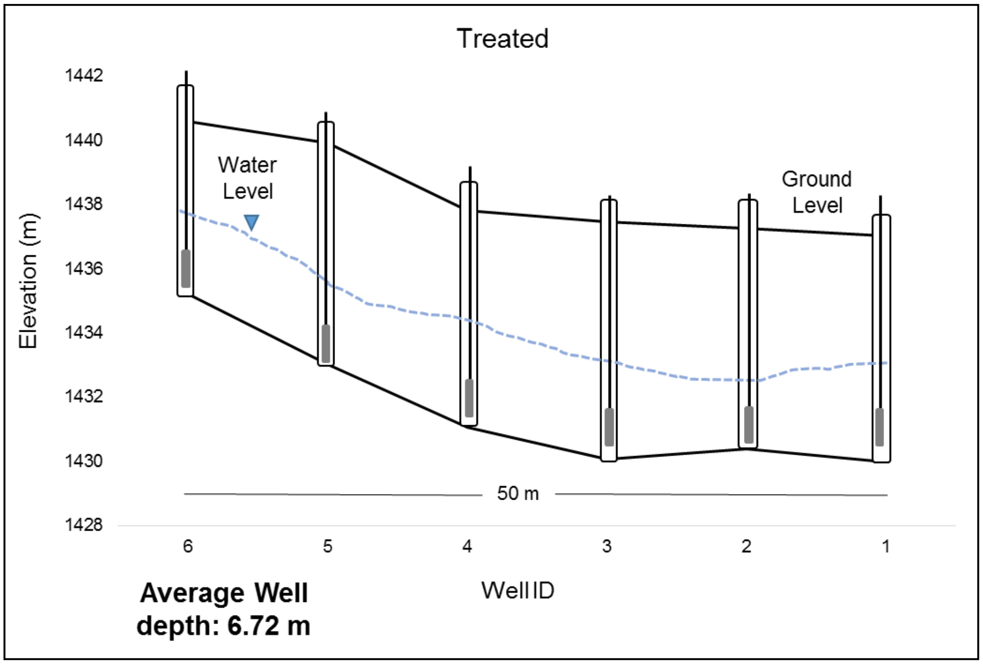

Figure 2.3 Cross sectional diagram of the treated watershed monitoring well transect, wells 1 through 6.

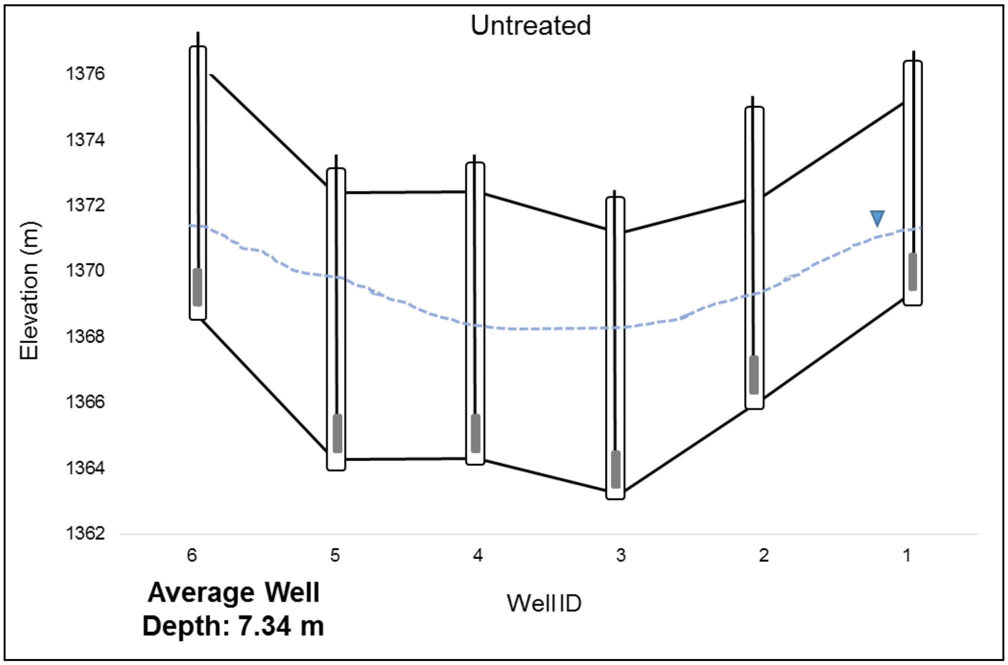

Figure 2.4 Cross sectional diagram of the untreated watershed monitoring well transect, wells 1 through 6.

Table 2.1 Depth to well bottom from ground surface (m).

Site	Well ID	Well Depth (m)	Site	Well ID	Well Depth (m)	Site	Well ID	Well Depth (m)
Untreated	1	5.94	Treated	1	7.06	Riparian	A	9.04
	2	6.17		2	6.86		B	4.97
	3	7.95		3	7.39		C	2.72
	4	8.13		4	6.73			
	5	8.13		5	6.91			
	6	7.72		6	5.39			

In October of 2014, a set of three nested piezometers were installed in the valley below the watersheds. These piezometers are identified as riparian piezometers A, B, and C. Piezometers were constructed using a trailer-mounted drilling equipment model

M-50 Stealth Prepper (DeepRock Manufacturing; Marquez, TX). Bore holes were drilled using a 10 cm drill bit. The inner pipe diameter of piezometers A and B is 50 mm, and the inner pipe diameter of piezometer C is 31.75 mm. The lower section of each piezometer was equipped with a length of stainless steel screen, which provides for lateral water flow, while obstructing heavy sediment buildup. The screen length of piezometers A and B is 2.74 m, and the screen length of piezometer C is 1.2 m. After installation, piezometers were backfilled with crushed gravel up to 150 mm from the ground surface. The remaining 150 mm was filled with a layer of bentonite to prevent preferential flow through the drilled hole. Piezometer A was drilled to maximum depth, bedrock, at 9.04 m. Depth of piezometers B and C were 4.97 m and 2.72 m. Piezometers are designed in a triangular format and are approximately 5 m apart on either side. The difference in surface elevation from the highest monitoring well in the treated watershed to the lowest piezometers in the valley was 75 m. Water level loggers (HOBO U20L, Onset Computer Corp.; Bourne, MA) were installed in two valley piezometers and in five of the previously-installed upland monitoring wells to record water table fluctuations at 1-hr intervals.

Soil Water Content

In 2005, soil water content stations were installed at two locations in each watershed (Deboodt 2008). Each location was installed with three soil water stations (12 stations over 4 locations total), each with three probes at depths of 0.2, 0.5 and 0.8 m. Soil temperature and percent soil volumetric water content data were recorded daily, starting in 2005, at varying times that were dependent on satellite to station connection. The soil water content analysis was completed using the daily mean value of each profile and then averaging those individual mean values together (i.e. three values per depth per station) to get a single daily mean value for each profile at each of the four stations. These values were then normalized to provide relative values of trends in soil water content fluctuations for observable dry and wet periods. For detailed information on soil water station, monitoring well, weather station, or other sensor information, reference Deboodt (2008).

Upland-Valley Groundwater Connectivity

The stable isotopes deuterium (δ^2H) and oxygen ($\delta^{18}O$) were used to determine water origin from samples collected in upland and valley sources within the two watersheds. The ratios of the stable isotopes δ^2H and $\delta^{18}O$ in water samples are traditionally tested to determine the amount of water vapor in an air mass, which gives insight into the temperature and conditions to which condensation forms ultimately giving an isotopic signature to precipitation water. Upland sources include precipitation collected from a rain gauge located at the watershed boundary, one spring source and two shallow wells in the treated watershed, and one spring source and three shallow wells from the untreated watershed. The valley collection sites consisted of two riparian piezometers; one 9 m deep and one 5 m deep. The riparian piezometers are situated next to a spring drainage canal and approximately two meters apart. Three water samples were collected from each of the ten sites and totaled 30 samples. Samples were analyzed by the Oregon State University Stable Isotope Laboratory of the College of Earth Ocean, and Atmospheric Sciences. Each sample was tested for $\delta^{18}O$ content using the water-CO_2 equilibration and mass spectrometry method, which was modified from Epstein and Mayeda (1953). Water samples were tested against standard reference water samples as represented by the Vienna Standard Mean Ocean Water.

Craig (1961) determined the linear relationship of $\delta^{18}O$ to $\delta^{2}H$ content of water samples with the equation:

$$\delta^{2}H = 8\ \delta^{18}O + 10 \text{ permil (‰)} \qquad \textbf{[1]}$$

This relationship is characterized by the Global Meteoric Water Line (GMWL), which plots the water samples using a linear relationship based on geographic and climatic differences of precipitation samples across the world with an r^2 value > 0.95. We utilized this equation, in conjunction with results of the direct measurement of $\delta^{18}O$, to plot the linear relationship of oxygen-18 versus deuterium for our localized watershed analysis.

Results and Discussion

Long-term Groundwater Level Fluctuations

The long-term analysis of shallow groundwater fluctuations was completed using manual readings of water level, beginning in 2004, in combination with daily readings logged by the HOBO US20L water level sensors (Onset Computer Corp.; Bourne, MA). Water table fluctuations were observed in all 12 monitoring locations in response to seasonal changes in groundwater. Monitoring wells in the untreated watershed displayed consistent responses throughout each year, as the wells typically recorded dry readings from July to January. Water levels in the six wells began rising around March at a rate of approximately 1-m per month for three months when levels peaked between mid and late-June (Fig. 2.5). The recession limb declined at about 1.5 to 2-m per month until the dry period in mid-October or early November. The yearly mean value, between 2004 and 2015, of maximum water level was 5.93 m (depth to water). Water levels were slightly higher for the first year of data collection and may be attributed to the development of the monitoring wells in 2004.

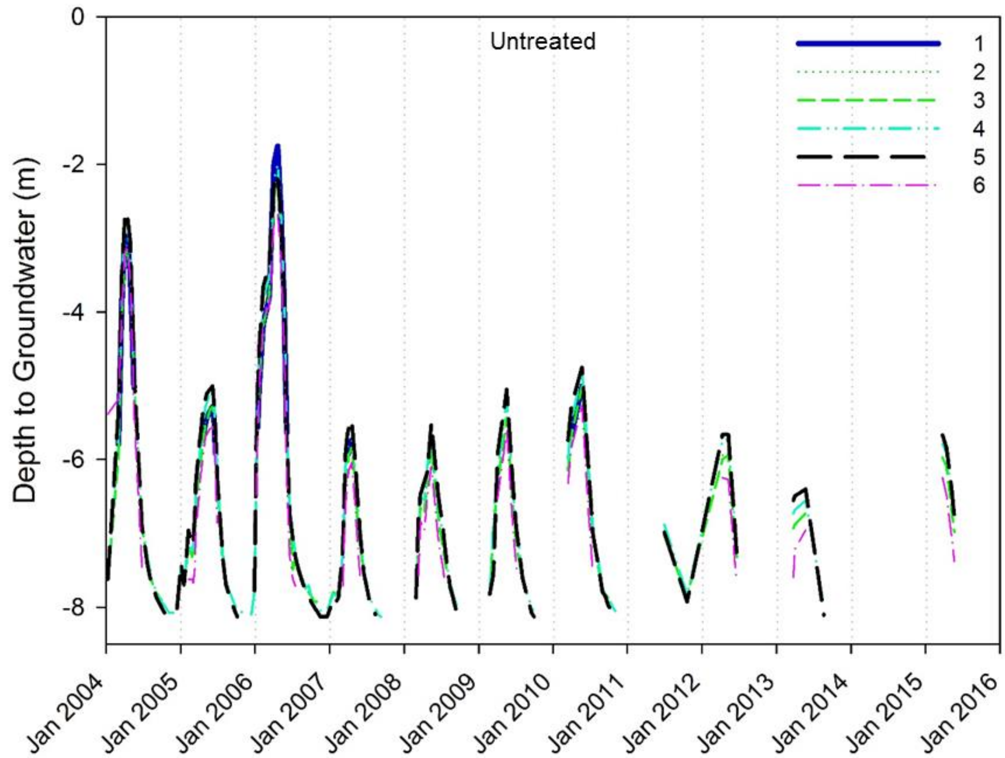

Figure 2.5 Groundwater level response for six upland monitoring wells in the untreated watershed (2004 – 2015).

Monitoring wells in the treated watershed resulted in similar timing of changes in seasonal water table fluctuation, however the degree of water level rise and consistency of these yearly changes were variable. Wells behaved similarly to the untreated wells in 2004 and 2005, which is presented here as pre-treatment data collected before juniper removal in the fall of 2005 (Fig. 2.6). Peak values during pre-treatment data collection also occurred during March. Wells in the treated watershed were also developed in 2004, so the higher than average peak water levels in 2004 are likely attributed to this development period.

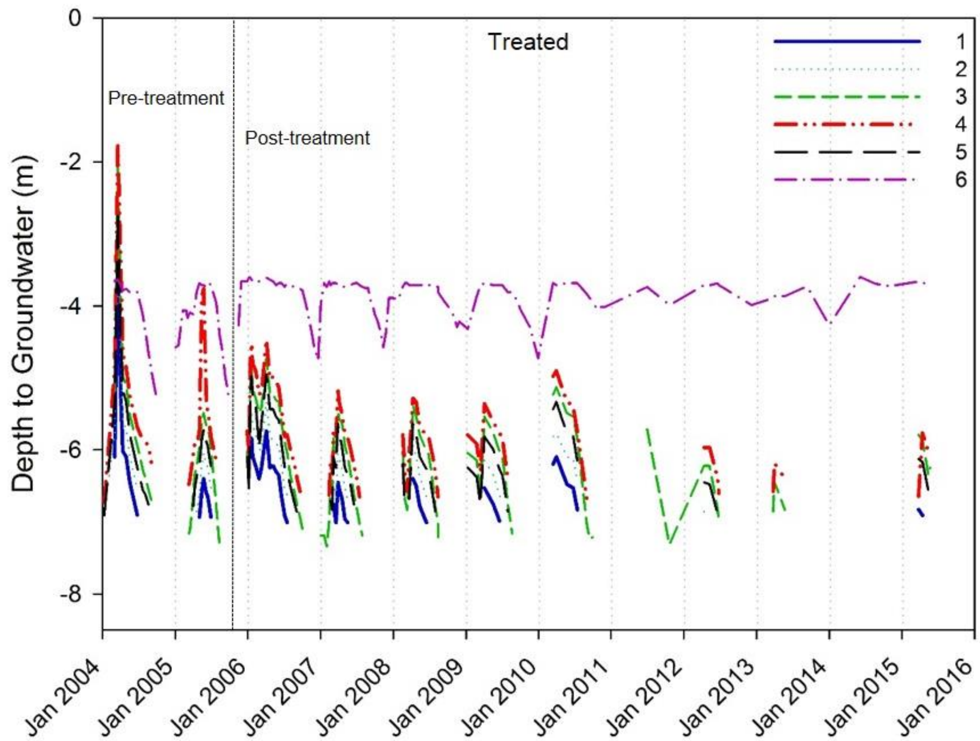

Figure 2.6 Long-term water level response for six upland monitoring wells in the treated watershed (2004 – 2015).

In the first year post-treatment, 2006, water levels of all six wells in the treated watershed began to rise in late December, when maximum water levels reached 4.47 m (depth to water) approximately one month later in late January. Water levels decreased approximately 0.5 m through February and March. Groundwater began to rise to a second distinctive peak event during April, 2006. Maximum water level during this period was 4.47 m (depth to water). The water table slowly declined through the rest of 2006 by approximately 0.32 m per month until the well became dry. The monitoring wells in the treated watershed deviated from the behavior of the wells in the untreated watershed starting one year post-treatment for years 2007 through 2009. During this three year time period, maximum water levels in all six wells reached an average of 5.30 m at the end of March. Water levels then declined until dry conditions at the beginning of August at a rate of 0.32 m per month. Above average precipitation in 2010 resulted in a similar timing to peak water level, when compared to 2007 – 2009 data, and recorded a longer, more gradual recession time to dry conditions. The remaining observed years (2011 – 2015) again behaved differently than the data collected pre-treatment and in the year post-treatment in the treated watershed. Maximum water levels in the wells were slightly lower in the remaining years at approximately 5.74 m (depth to water). The timing and rate of the recession limb were much earlier and steeper during these years, with the dry period occurring as early as July.

The treated watershed often recorded two yearly peaks throughout the recorded measurement period. The first peak typically occurred in January or February and the maximum peak occurred during spring in March and April. Wells in the treated watershed also displayed a rapid rate of increase in water level from January to late spring, however the maximum water level rise remained high with a slightly slower rate of decline to dry conditions during mid-summer. This change in water level rise and slower rate of decline became more apparent after juniper removal, which took place in the fall of 2005. Well 6 in the treated watershed had a consistent recorded depth to the water table of approximately 3.8 m until mid-winter when water levels would reach less than 5 m to recorded water depth (data not shown). Since the 2005 juniper treatment, well 6 was the only well observed to retain water throughout the entire course of the year. This well has a total depth to bottom of 5.4 m, which is just above the depth of the adjacent stream channel. The position of well 6 in relation to the location of the stream bottom lead us to speculate that it is disconnected from the shallow groundwater source that feeds the remaining five monitoring wells within the upland transect. Previous analysis of groundwater data by Deboodt (2008) showed all six wells in the treated watershed as having longer annual residence times ranging from 14 to 90 extra days of water when compared to pre-treatment observations. Five of the six wells in the untreated watershed also recorded increased annual residence times of 11 to 47 days extra days (Deboodt 2008).

Long-term Soil Water Content Fluctuations

Long-term soil water content fluctuations were analyzed at two soil water content stations in each watershed. Each location represents three soil moisture stations each equipped with probes at three depths (0.2, 0.5, and 0.8 m).

Preliminary analysis of this soil water content data (2005 – 2008) by Deboodt (2008) found that the most notable differences between the two watersheds were the recorded differences at the end of season. End of season soil moisture is defined by the point at which the mid-summer decline in soil water content stops and the effective soil water storage begins prior to the following wet season. The bottom soil profile (0.8 m) in the treated watershed held a slightly higher end of season value than the untreated watershed in 2005. This value became much greater in the subsequent years following the 2005 juniper treatment. The top and middle profiles in the untreated watershed recorded slightly higher values than the treated (Deboodt 2008).

Long-term soil water content fluctuations were variable across all years. However the upper and lower sites within each watershed followed similar timing to peak and recession of soil water content on a year to year basis. Soil water content for the lower site of the treated watershed displayed an upward increasing trend post-treatment treatment during fall of 2005 (Fig. 2.7). The top-most profile (0.2 m) steadily increased in soil water content values post-treatment while also retaining this moisture into July, 2006. Soil water content values across each profile remained similar until March and April when values begin to rise as the wet season progressed. Peak values occurred in

April and May in the treated watershed and remained high for three to six months. The recession period lasted up to six months until the lowest readings were reached in November. At this point in the year, it is typical for all three profiles to maintain like values across all depths. Time sustained at the lowest values was variable across years and was dependent on early wet season precipitation. Rate of increase to the next year’s peak values ranged from one month, with abundant fall precipitation, to three months, as a result of little fall precipitation. The top and middle profiles (0.2 and 0.5 m) typically responded early in the wet season, and the lowest profile (0.8 m) peaked at the end of each wet season for each year. The treated lower station recorded an overall increasing trend for all profile depths from 2005 to 2015.

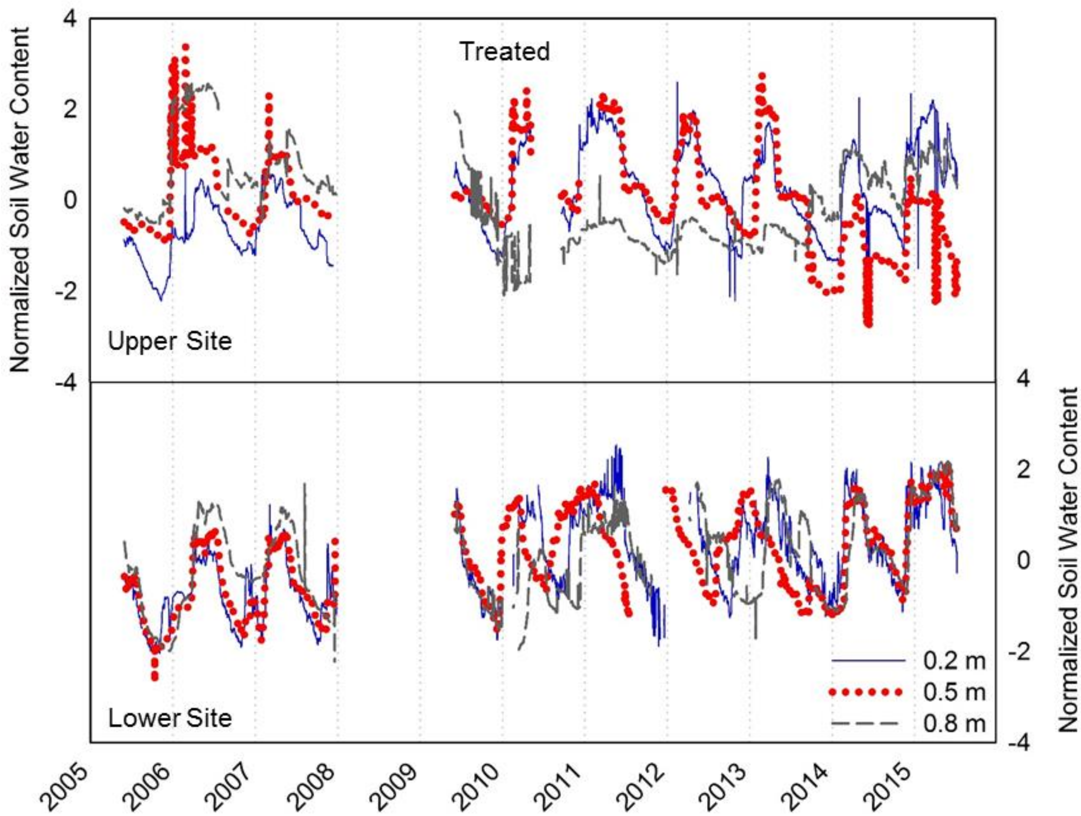

Figure 2.7 Long-term soil moisture response for three depths at two upland locations in the treated watershed (2005 – 2015).

The upper soil water station in the treated watershed responded similarly to the lower site in time to peak and time to lowest yearly values (Fig 2.7). Fluctuations were dependent on early-season and late-season precipitation, which precede and follow the wettest months of November, December, and January. Peak values often occurred from late-November to April and as late as June. Mid-winter intermediate peaks were recorded during several years, where spikes in soil water content occurred from November to January before the typical yearly maximum peaks were reached. The top and middle profiles responded earliest and were followed by the deepest profile. However, individual profile behavior was not consistent across years for both the upper and lower sites and is likely due to the differences in topographic position, surrounding vegetation characteristics, and soil physical properties. An analysis of stations soil physical properties was not completed at time of construction in 2005. The upper soil station in the treated watershed had an overall increasing trend for the top profile (0.2 m) and a decreasing trend for the lowest two profiles from 2005 through 2015.

The untreated soil water content fluctuations were also variable across years but behaved similarly to the treated watershed in regards to timing of annual fluctuations of soil water content. Soil water content in the untreated lower site recorded highest peaks from April to June and July. Years of higher moisture resulted in an earlier rate of response, especially for the top (0.2 m) profile, in November. Maximum peak duration was slightly shorter than those in the treated watershed. Peak soil water periods averaged two to three months, when compared to the three to six month peak plateaus in the treated. There were two recorded intermediate plateaus in 2007 and 2013, the duration of both were approximately three months, from November to January, and were similar to those observed in the treated watershed. As expected, the top profile typically recorded increasing values first in response to early wet season precipitation. The bottom and middle profiles corresponded to the highest peak and plateau periods. This is attributed to late-season infiltration, which is a result of cumulative precipitation events occurring as the wet season progressed. This response of the lower profiles was observed throughout all four sites across the watersheds. The lower soil water station in the untreated site displayed no overall trend, while the middle and lower profiles displayed increasing trends throughout the entire measurement period (2005 – 2015).

The upper soil water station in the untreated watershed behaved similarly to the timing and seasonality to the other three soil stations. However, the rise to maximum peaks and plateaus were much smaller. This again was likely due to soil physical properties, spatial differences in precipitation, and other characteristics surrounding the sites. The duration of the seasonal plateaus were longer than that of the lower untreated site and lasted from three to six months, typically January to May. Low periods were approximately five months from July to November. Similar to the lower site in the untreated watershed, there were two recorded intermediate peaks in 2007 and 2013, which occur from November to January, and are likely a result of fall precipitation that are typical of the study area. There was an overall increasing trend for all three profile depths for the entire duration of the study period (2005 – 2015) (Fig. 2.8).

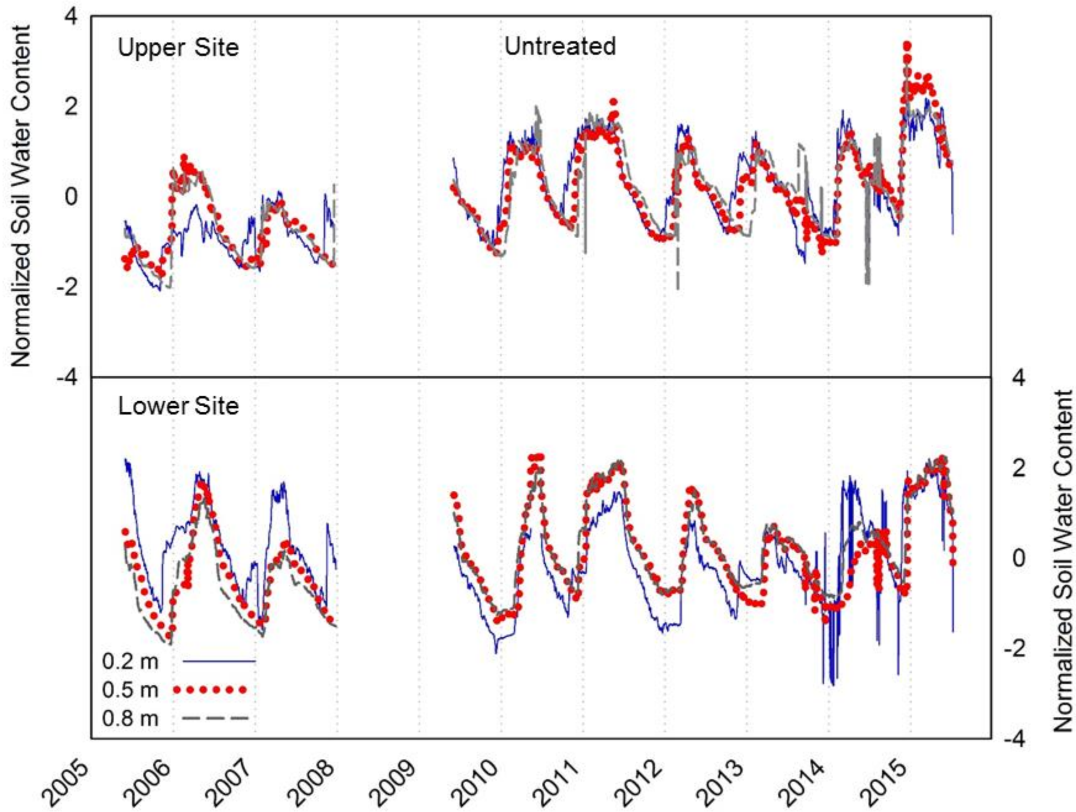

Figure 2.8 Long-term soil moisture response for three depths at two upland locations in the untreated watershed (2005 – 2015).

Precipitation-Soil Water-Groundwater Dynamics

Annual Hydrologic Response

To better understand precipitation-soil water-shallow groundwater dynamics within these watersheds, an analysis was completed for a one year period for upland sites in both the treated and untreated watershed. Precipitation during this one year analysis (June 2014 – June 2015), averaged across the four onsite rain gauges, was 332 mm, which is approximately 102% of the mean annual precipitation for the study area (Table 2.2). The significant wet period occurred from November through January, with an uncharacteristic 30 mm rain storm taking place in August. September recorded the lowest total precipitation for the year at 3 mm, while December recorded the highest precipitation at

87 mm. Table 2.2 shows the spatial distribution of precipitation across both watersheds where the treated watershed received a total of 322 mm and the untreated watershed received a total of 342 mm for the one year period.

Table 2.2 Total monthly precipitation (mm) for each rain gauge in the treated and untreated watersheds (June 2014 – June 2015).

Date	Treated Upper	Treated Lower	Untreated Upper	Untreated Lower
June 2014	NA	11.4	11.4	9.4
July	NA	2.0	8.9	7.9
August	NA	35.1	31.2	20.1
September	NA	3.8	3.3	2.5
October	NA	15.7	19.1	15.7
November	NA	64.3	74.2	64.3
December	NA	84.6	93.7	85.6
January 2015	9.2	7.4	11.7	10.9
February	28.6	17.3	25.9	31.0
March	32.8	26.9	15.2	36.3
April	1.6	3.8	5.1	10.2
May	52.4	30.0	51.8	40.4
June	0.0	0.0	0.0	0.0

Soil water content values varied for both watersheds but remained within the same general range of values (20% - 50%) throughout the year (Table 2.3). As the wet season progressed, the highest potential increase in soil water content generally occurred over one month from mid-November to mid-December in both watersheds. Soil water content values of each profile were affected by isolated precipitations events in both watersheds, however in most cases, values returned back to antecedent conditions within several days following the events, rather than contributing to the overall increase in water content.

Table 2.3 Seasonal range of soil volumetric water content (SVWC) from time of response to yearly maximum values (2014 – 2015).

		Date Range of Rising Limb		SVWC (%)	
	Probe Depth (m)	Min.	Max.	Min.	Max.
Treated	0.2	Nov	Dec	21.9	37.2
	0.5	Nov	Mar	22.5	33.6
	0.8	Nov	May	20.5	29.5
Untreated	0.2	Nov	Dec	23.3	43.3
	0.5	Nov	Dec	26.6	47.5
	0.8	Nov	Dec	21.4	35.5

A delayed infiltration response of 14-days was observed in the middle profile (0.5 m) for the treated watershed. Values began to increase in mid-November until peak recorded values in mid-March. The deepest profile (0.8 m) had a delayed response time of 23-days, when compared to the initial climbing limb of the top profile. This profile held a 156-day response time from minimum to maximum peaks values. Values for all profiles remained high through the recorded data collection, June 2015. Groundwater levels in the treated watershed followed the same timing of response pattern as soil water content values with response time to maximum peak occurring in December through February. The reported well 4, which is located in the center of the six well transect, recorded depth to water ranging from minimum 5.13 m to 6.73 m. which is an overall increase 1.61-m from dry conditions (Table 2.4). Time to peak for well 4 was 42 days. Water levels then drastically dropped 1.53 m to a depth of 6.66 m over seven days before beginning another 7-day rising limb to a minimum depth to water of 5.51. These responses in soil water content and water level rise correspond to relatively large storm events that were preceded by smaller storm events in November. Five of the six wells in the untreated watershed behaved similarly throughout this study period. Well 6 (data not shown) was the only monitoring well, of the 12 upland wells, that did not dry out throughout the year and recorded the smallest range of water level change (min. 3.60 m, max. 3.72 m).

Table 2.4 Timing of rising limb from minimum to maximum values of groundwater level response for selected wells in the treated and untreated watersheds (2014 – 2015).

		Date Range for Rising Limb		Depth to Groundwater (m)		
	Well ID	Min. Depth to Water	Max. Depth to Water	Min.	Max.	Water Level Rise (m)
Treated	4	Dec	Nov	-5.13	-6.73	1.61
Untreated	3	Dec	Feb	-5.47	-7.95	2.48
	4	Dec	Feb	-5.31	-7.91	2.6
	5	Dec	Jan	-5.13	-8.14	3.01

Soil water content values in the untreated watershed reported similar timing of response to seasonal precipitation. Values began to increase in mid-November from lows of 23.3, 26.6, and 21.4 for the 0.2, 0.5, and 0.8 m probe depths, respectively (Table 2.3). The water level in the untreated watershed remained in dry conditions from June until December 2014, when water levels increased over an average of 52-days across the three reported wells and peaked at the beginning of February. All three reported wells in the untreated watershed behaved similarly with minimum and maximum depths to water ranging from 5.13 m to 8.14 m (Table 2.4). Average groundwater level rise for the three wells was 2.70 m. A series of composite diagrams (Figs. 2.9 and 2.10) are presented here to aid in visualization of precipitation-soil water-groundwater responses.

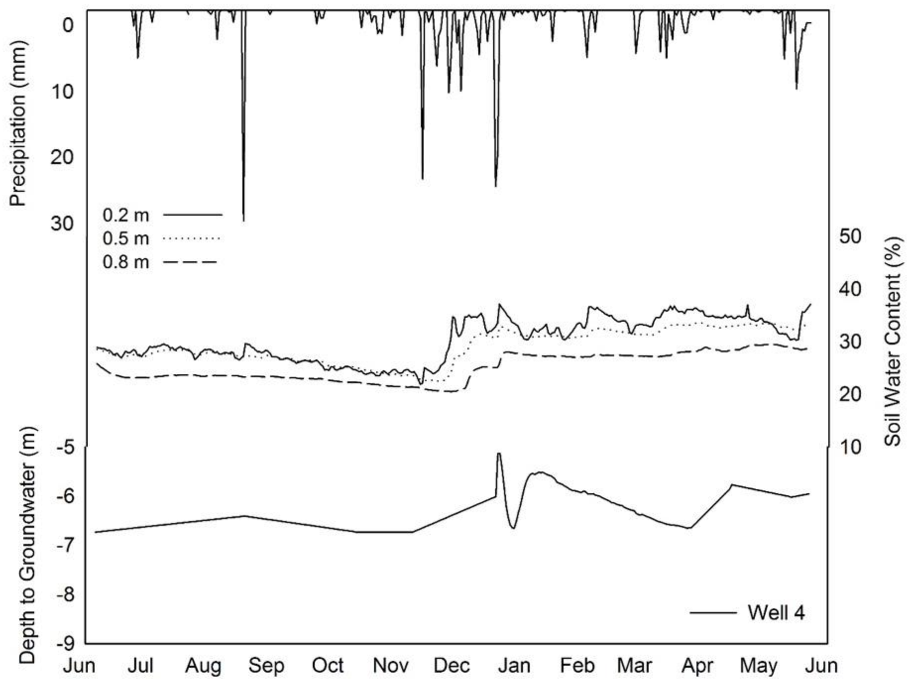

Figure 2.9 Precipitation-soil water-shallow groundwater responses for one year (June 2014 – June 2015) in the treated watershed.

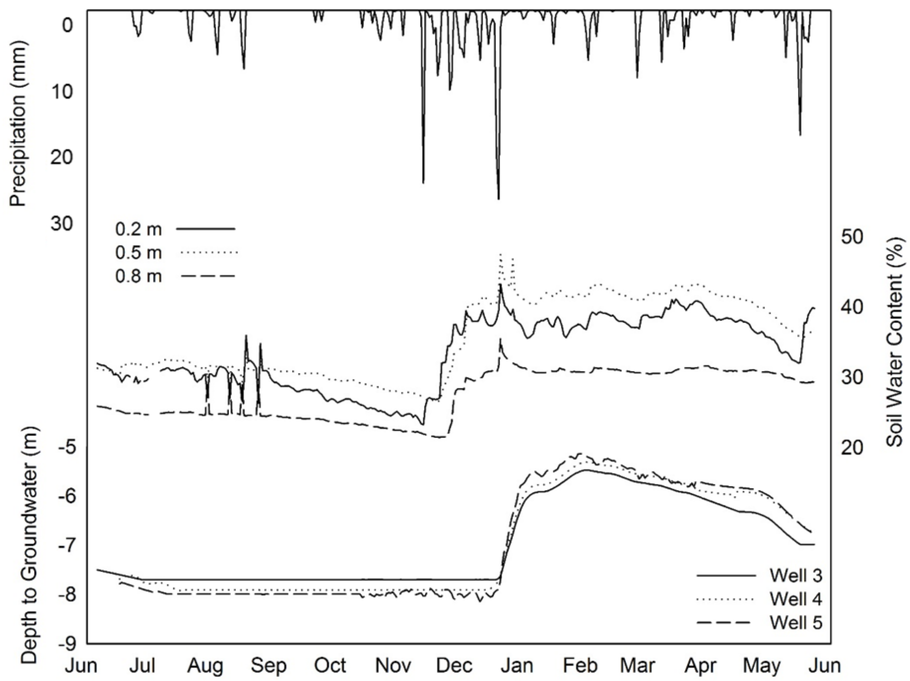

Figure 2.10 Precipitation-soil water-shallow groundwater interactions for one year (June 2014 – June 2015) in the untreated watershed.

Hydrologic Response to Seasonal Precipitation Events

Soil water content and shallow groundwater levels were analyzed following seasonal precipitation events which occurred during the dry (August) and wet (December) seasons. A high intensity, short duration rain event (27 $mm \cdot hr^{-1}$) occurred August 18, 2014. For the treated watershed, the shallow groundwater level response following the event was negligible in all six monitoring wells. The soil water content response for the shallowest probe depth of 0.2 m was immediate following the event. Soil volumetric water content for this upper most probe increased 3% over a six hour period and did not return to pre-storm values for the next 13 days. Soil volumetric water content readings for the deepest probe (0.8 m) responded at a 2% increase one day following the storm and continued to gradually increase for eight days. All three probe depths (0.2, 0.5, and

0.8 m) recorded the same value of 28% by the 13th day following the storm (Fig. 2.11). The groundwater and soil water content responses were low considering the magnitude of rainfall. This is attributed to the nature of high intensity, short duration events which create extensive Hortonian overland flow (rainfall exceeds infiltration capacity of the soil) and flashy floods. This event produced large amounts of sediment and debris movement, and overland flow quickly diminished immediately following the storm (Fig. 2.12).

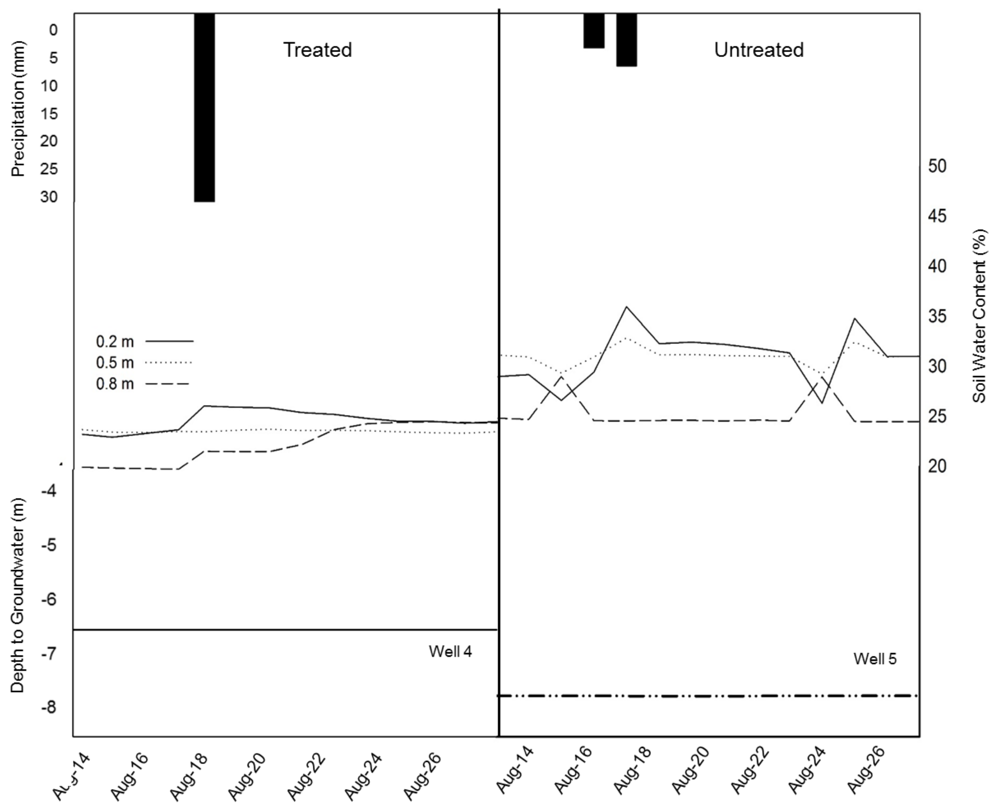

Figure 2.11 Soil water-shallow groundwater response for both the treated and untreated watersheds for a dry season precipitation event (August, 2014).

Figure 2.12 Front perspective of treated watershed flume following the high intensity storm, August 18, 2014, which highlights the extensive overland flow and debris movement.

The untreated watershed received approximately 13 mm of precipitation over a two day period (August 17 - 18, 2014). The top profile (0.2 m) recorded the highest level of soil water content increase, from min. 26% to max. 32%, following the storm and slowly declined over the next six days to the original status. The middle profile (0.5 m) recorded a slight spike of 3% and slowly declined over the next six days. The bottom profile (0.8 m) displayed a spike in soil water content of 4%, which lasted for approximately one day. Any change in water table fluctuations was negligible for the untreated watershed (Fig. 2.11).

Approximately 47 mm of precipitation fell in the treated watershed over 14 days from December 18 to December 31, 2014. This precipitation event was preceded and followed by a series of small storms of approximately 1 mm. All three soil moisture probes displayed the most pronounced response after the storms on December 19th and 20th. Top profile recording the highest increase of 5% over two days. Values declined by back to pre-event soil water conditions over the next 10 days. Water level increase in the treated watershed was greater than 1 m from 6.04 m to 5.13 m over a 10-hr period. Water levels began to gradually decline for the next week but never reached pre-storm conditions.

The untreated watershed received 50.9 mm of water over five day period following a week of < 1-mm rain events. Soil water content was affected by the largest precipitation events to which all three profiles responded with spikes in values. The top most profile increased 13% over 10 days and remained at 46% soil volumetric water content for the remainder of the study period. The middle profile had a slight increase of 2% and declined 1% where values remained constant for the remainder of the period. The deepest profile increased 3% over four days and remained high for the remainder of the period. Groundwater levels in the untreated watershed gradually increased over the 2-week period. A small response peak can be observed on December 22 (Fig. 2.13). This gradual increase from 7.96 m to 5.78 m (depth to water) through the end of the study period. The untreated well response to storm inputs was not as pronounced as the > 1 m increase over 10 hrs, which was observed in the treated watershed. Still, water levels in the untreated site increased at a rate of ~ 23 $mm \cdot d^{-1}$. Our analysis of hydrologic response to seasonal precipitation events has given insight into the temporal and spatial dynamics of storm response as a function of detailed hydrologic fluctuations, which are highly dependent on pre-event soil water and groundwater conditions.

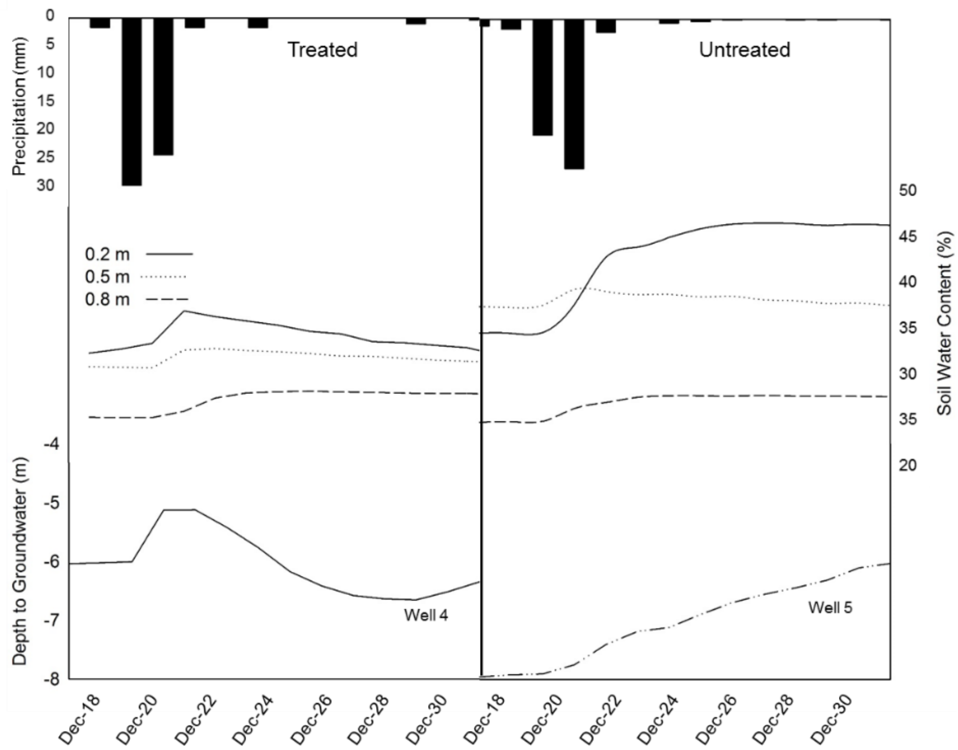

Figure 2.13 Soil water-shallow groundwater response for both the treated and untreated watersheds for a wet season precipitation event (December, 2014).

Groundwater Connections between Upland and Valley Sites

Results from this study indicate temporary hydrologic connections between upland and valley monitoring wells during the wet season. A sharp water level rise observed in the upland sites early in the winter season (December) was followed by a steady increase in water levels at the valley site as the wet season progressed (Fig. 2.14). There was a transition from gradual water level increases to a sharp water level rise which occurred in March at the valley site. This sharp rise continued for approximately one month until early-April. This increase in water level in the valley site was likely due to stream seepage contributions which were observed from an adjacent stream that is primarily fed by spring flow in the late part of the wet season. Water levels in the valley site continued to fluctuate, yet gradually increase for the remainder of the recorded period. Whereas, water levels in the upland site had already begun a seasonal shift towards gradual water level decline. In general, the lag time between peak water level responses in the upland versus valley sites was approximately two months.

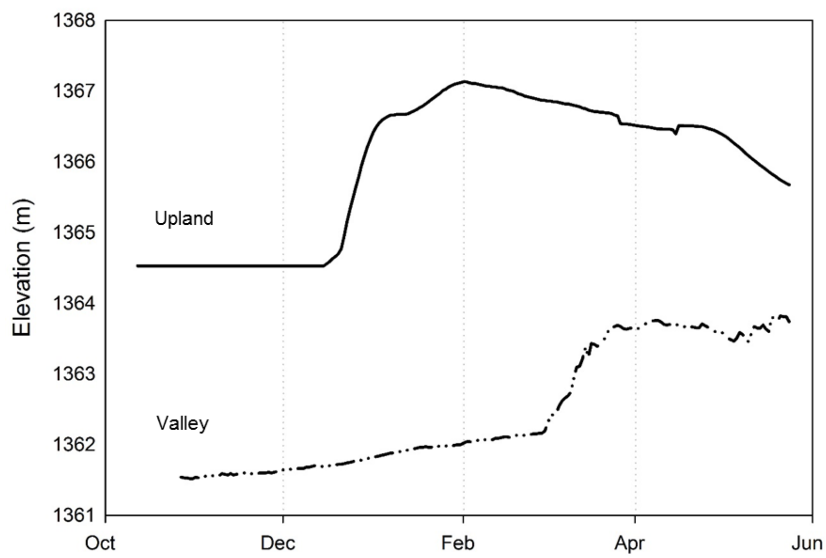

Figure 2.14 Shallow groundwater level fluctuations from dry to wet season for one upland and one valley well.

These indications of watershed connectivity are supported by the results of the isotopic analysis for deuterium (δ^2H) and oxygen ($\delta^{18}O$) composition of various samples. The relationships between the origins of precipitation, shallow groundwater, and spring water were assessed at a precision of ± 0.05 ‰ for $\delta^{18}O$ using the stable isotope composition of water samples collected from upland and valley sites (Fig. 2.15). The equation for the global meteoric water line was utilized, in combination with direct measurements of oxygen-18 values, to derive deuterium values from water samples. Results for the precipitation sample were -10.1 ‰. McGuire and McDonnell (2008) recorded similar results for values of rainwater across the western united states. Riparian well A held a $\delta^{18}O$ content of -14.1 ‰, while Riparian well B held a slightly lower content of -12.7 ‰. All three upland wells in the juniper dominated watershed held a consistent mean value over all samples of -14.3 ‰. Well 4 in the treated watershed also resulted in a $\delta^{18}O$ composition of -14.3 ‰, while well 6 displayed a slightly lower composition of -13.1 ‰. This slightly different isotopic reading in well 6 is again attributed to its position in relation to the stream bottom. We believe that this particular monitoring well may have an independent spring source. One spring from each watershed was tested and resulted in a like value of -14.3 ‰. Overall, the majority of the upland wells, valley wells, and spring sites delivered $\delta^{18}O$ values of -14.3 ‰, which indicates the likelihood of a common water source for all of the tested subsurface flow locations.

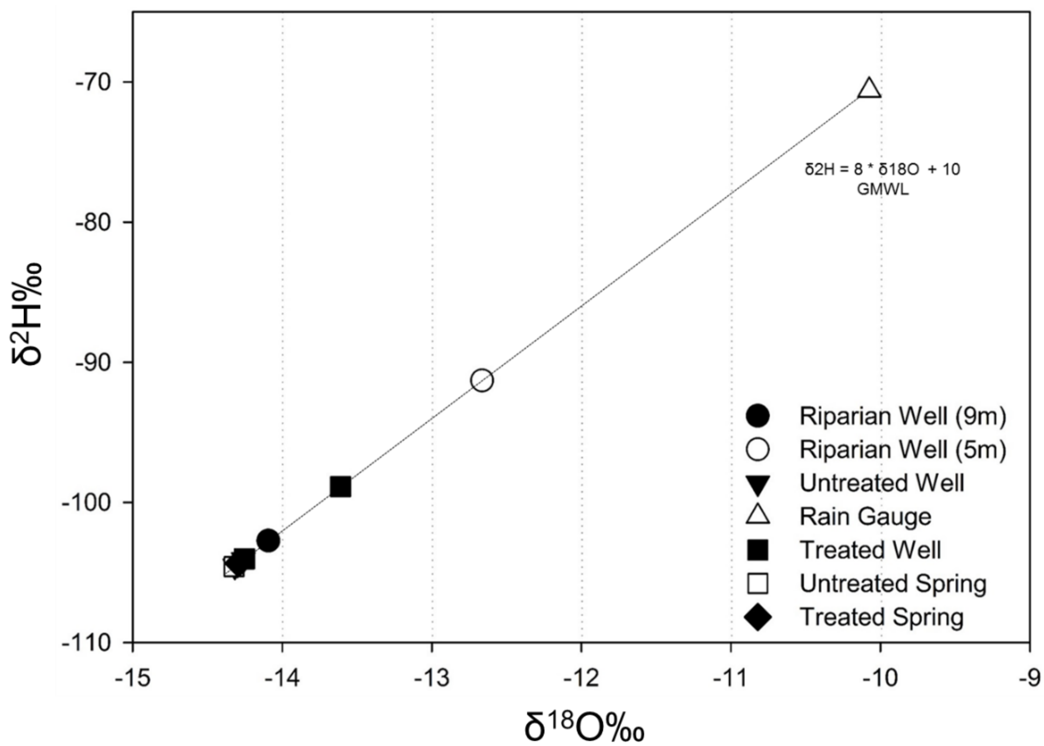

Figure 2.15 Stable isotope composition deuterium and oxygen (δ18O/ δ2H) of precipitation, spring, and monitoring well samples taken from upland and valley sites for the treated and untreated watershed and plotted against the Global Meteoric Water Line (GMWL).

Oxygen-18 and deuterium are not easily subject to the chemical reactions in the soil and differences in isotope composition between precipitation and groundwater samples are likely attributed to the timing of precipitation and mixing with water sources and/or with pre-event precipitation of different ages (Drever 1988; Ersek et al. 2010; Kendall and McDonnell 1998). Ersek et al. (2010) collected precipitation samples in southern Oregon over a period of four years and reported delta $\delta^{18}O$ values ranging from -23‰ to -3‰. The inherent variability in regional isotopic signatures can be attributed to the effects of altitude, latitude, and quantity of rainfall. Precipitation samples described here were collected in May shortly after a series of rain events which were followed by cool, overcast days. This likely prevented excess evaporation which would have altered the isotope composition of the rain water towards a heavier $\delta^{18}O$ value. Although this isotopic analysis cannot determine the exact source of groundwater flows, the similarity in values across all groundwater sources further points to the connective nature of these paired watersheds.

Conclusion

Objectives of this study were to: 1) Characterize long-term groundwater and soil water content fluctuations in response to juniper removal; 2) Determine precipitation-soil water-groundwater dynamics in treated versus untreated watersheds; and 3) Assess groundwater connections between upland watersheds and a downstream valley and riparian areas. Analysis of the long-term shallow groundwater and soil moisture data show restoration of subsurface flows which were preceded by increased soil water content levels, annually, in the treated watershed. Although soil water content was variable across profile depths, there was an overall increasing trend post-treatment

(2005 – 2015) in the treated watershed as well as longer sustained yearly maximum values. Soil water content also displayed an overall long-term increasing trend in the untreated watershed.

There was a distinct response by the watersheds to seasonal and isolated precipitation events. The timing, rate, and degree of response varied from the treated to the untreated watershed. Wet season precipitation and antecedent soil water content largely influenced the soil water fluctuations and groundwater level rise across both watersheds. Isolated precipitation events also contributed to subsurface flow responses. For the summer events, groundwater response was negligible, but the top-most soil profile (0.2 m) increased for several days following the event. This is speculated to be attributed to the large-scale overland water flow event that occurred with the storm in the treated watershed. Similar to the summer events, the top soil profile was most affected by the winter precipitation events. However, the lower profiles (0.5 and 0.8 m) did show slight responses over the several following days. Water level fluctuation in the treated watershed occurred at a rapid rate over the span of 10-hrs while the untreated watershed continued to gradually rise over the course of the study period. The untreated watershed did display a slight, approximately 0.5 m rise, after which the rate of increase immediately slowed.

Our results suggest that there are distinct hydrologic connections between upland and lowland groundwater sources, especially during the winter precipitation season. This data is supported by the results of a stable isotopes analysis of upland groundwater, springs, and valley groundwater, which found the oxygen-18 composition of the subsurface water samples to nearly identical.

Understanding hydrologic interactions within an entire watershed is a difficult and detailed process and varies with the many discrete physical and ecological properties that comprise each watershed. Subsurface flow dynamics are just a piece of one whole that makes up the complex cycle of hydrologic processes. This research gives insight into some of the alternative hydrologic connections that take place in semiarid watersheds with unpredictable streamflow.

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GENERAL CONCLUSIONS

The ecohydrologic effects of western juniper (*Juniperus occidentalis*) removal were studied at the watershed scale. Two semiarid paired watersheds, of approximately 1.1 km^2 each, were equipped with hydrologic data sensors to measure weather parameters, precipitation, soil water content, and groundwater level rise. Phase I (1993 – 2003) was the pre-treatment and reconnaissance phase, and Phase II (2003 – Present) began the long-term data collection for analysis of hydrologic processes.

This research project is in addition to Phase I and II and has the overarching goal of characterizing precipitation-vegetation-soil water-groundwater interactions at the landscape-scale. The first chapter of this research highlights data collected on vegetation, soil texture, and soil water content over the course of one year. Soil water content data was collected approximately every two months with the hopes of gaining a sufficient understanding of the seasonality and distribution of shallow soil water content. Data collected for canopy cover and soil textural variables were utilized to help investigate differences in soil water content between the treated and untreated watersheds. Results showed distinct differences in seasonality and distribution across each watershed. Although the treated watershed showed significantly ($P < 0.05$) higher values of soil water content for three of five measurement periods, more research needs to be conducted to determine the ecological benefits of the 2% average soil water content difference. Total canopy cover was determined to be an important role in determining soil water content distribution although the exact effects of vegetation structure and plant species promote further investigation. Analysis of clay content across the two watersheds showed clay to be a contributing factor in retaining soil water content for the wettest seasons measured (January, March and May).

The second portion of this research sought to investigate long-term soil water and groundwater fluctuations and identify subsurface flow connections between deep soil water and groundwater level fluctuations for the two upland watersheds and the downstream valley bottom. Long-term evidence suggests that the treated watershed retains deep soil water and groundwater longer into the dry season, when compared to the untreated. Both watersheds respond to seasonal and storm-event precipitation but vary in the degree of response. Results also suggest that there are direct connections between upland groundwater flows and valley groundwater sources, especially as the wet season progresses in these watersheds. More research needs to be done to assess the timing and rate of subsurface flow between upland and valley sites.

The extensive and long-term field data collected throughout this research can be utilized as baseline information for future watershed-scale vegetation removal projects. Water availability is not only attributed to surface water flows in lakes and streams but also in the availability of shallow soil water, deep soil profile water, subsurface groundwater flows. Further investigation into the importance of these subsurface components needs to be completed in arid and semiarid areas to help provide managers and stakeholders with appropriate tools necessary to manage these ever changing landscapes.

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