AN ABSTRACT OF THE THESIS OF

Philip E. Caruso for the degree of Master of Science in Water Resources Science presented on August 25, 2017.

Title: Hydrogeology and Hydrologic Connectivity of a Semiarid Central Oregon Rangeland System.

Abstract approved:

Carlos G. Ochoa

The hydrologic function of a landscape is an important concept for understanding the presence, movement and availability of water. The Camp Creek Paired Watershed Study (CCPWS) site in Central Oregon has been utilized to investigate the impacts of western juniper on watershed hydrologic function since 1993. The research presented here builds upon the work done at the CCPWS to further investigate the hydrologic connections and gain a better understanding of the underlying hydrogeologic system in and surrounding the CCPWS site.

This thesis is organized into two chapters. Each chapter is an individual manuscript detailing a portion of the overall study. The overarching goal of both chapters was to increase the base of understanding of surface water and groundwater interactions, subsurface hydrologic connections and the understanding of the role of local hydrogeology in a semiarid system in central Oregon. Both chapters are being prepared for journal submission.

Hydrologic connectivity is the flow of surface water and subsurface water throughout a landscape [1] and is important for a wide variety of ecosystem services. Most investigations of hydrologic connectivity have focused on forested environments and more humid settings. This study investigated subsurface hydrologic connectivity in a semiarid rangeland system.

Chapter one discusses the movement of both surface and subsurface water within the CCPWS and characterizes the temporary hydrologic connections present and looks at the impact of vegetation canopy cover on those connections. The objectives of this study were to 1) assess surface water and groundwater interactions in one watershed with juniper and one with juniper removed; and, 2) characterize the hydrologic connectivity of upland watersheds and the riparian valley below them.

The hydrogeologic framework of an area describes the structure and properties of a groundwater system. This framework helps us to understand the way water moves through the subsurface and its availability for human and ecosystem needs. A wide-ranging study of groundwater system of the Upper Deschutes Basin was completed in 2002 [2]. However, the southeastern portion of the basin was left out of the larger basin wide study and many of the finer details of the system were not captured at this coarse scale. A better understanding of the hydrogeology in the area surrounding the CCPWS helps to place the more than 20 years of hydrologic research at this site into a proper context for further research and application.

Chapter two describes the local hydrogeology of a region of interest in the southeast portion of the Upper Deschutes Basin. A combination of field data collection and synthesis of existing hydrogeologic data were used for this study. Study objectives were to 1) characterize the hydrogeologic framework of an area of interest surrounding the CCPWS; and, 2) evaluate mechanisms of shallow aquifer recharge and discharge at the CCPWS.

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Hydrogeology and Hydrologic Connectivity of a Semiarid Central Oregon Rangeland System

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APPROVED:

Major Professor, representing Water Resources Science

Director of the Water Resources Graduate Program

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Philip E. Caruso, Author

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Hydrologic Connections in Semiarid Watershed Systems of Central Oregon U.S.A.

Abstract: An improved understanding of landscape hydrologic connections is critical for optimizing the effectiveness of land management prescriptions in semiarid landscapes of the western U.S. Objectives of this study conducted in a western juniper (*Juniperus occidentalis*) dominated landscape of central Oregon were to: (1) assess surface water and groundwater connections in treated (juniper removed) and untreated watersheds; and (2) characterize hydrologic connectivity within and out of the watersheds. Detailed measurements of precipitation, tree canopy cover, and soil moisture were used to evaluate juniper interception effects on soil water recharge. Ephemeral stream runoff, springflow, and groundwater level data were used to characterize seasonal hydrologic connections within and out of the watersheds with a riparian valley. Project results show that juniper dominated landscapes such as the one found in one of the watersheds evaluated can intercept up to 45% of the total precipitation. In general, lower soil moisture values were obtained in the under-canopy locations when compared to the inter-canopy. Results indicate there are seasonal upland-valley hydrologic connections driven by a combination of winter precipitation and local geology that favors transient groundwater storage in the shallow aquifer system characteristic of the region. These study findings contribute to the better understanding of surface and subsurface flow connections occurring in water-scarce precipitation regions such as those found in central Oregon and in other similar regions worldwide.

Keywords: Watershed; Hydrologic Connectivity; Surface water; Groundwater; Ecohydrology; Juniper.

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1. Introduction

In many dryland ecosystems worldwide, woody vegetation has expanded rapidly while open grassland vegetation has declined significantly over the last century or more [1–3]. This progressive shift from grasses to woody species has resulted in larger bare soil areas that decrease vegetation diversity [4] and promote increased runoff velocities and more soil erosion [5]. According to the IPCC, climate change is expected to worsen the loss of biodiversity and decrease water availability and quality in many of these arid and semiarid regions around the globe [6].

Among the array of woody species that have significantly expanded across the western U.S., juniper (*Juniperus* spp.) now covers nearly 40 million hectares [7]. Commonly attributed causes of juniper expansion are climate, livestock introduction, increases in CO_2, and fire suppression [8]. In the case of the dryland ecosystems in eastern Oregon, an estimated ten-fold increase in western juniper (*Juniperus occidentalis*) has occurred in the past 130 years [9]. In this region, western juniper has increased from 420,000 acres in 1936 [10] to more than 3.5 million acres [11].

Water provisioning is the ecosystem service that most directly links human population growth and rangeland ecosystems [12]. The freshwater ecosystem service is fundamentally related to other supporting and regulating services such as soil development, water regulation, and climate regulation [13]. According to Ffolliot and Gottfried [14], juniper woodlands are not considered high water-yielding sources mainly because of the low precipitation and the high evapotranspiration losses associated with these landscapes. Yet, a study conducted by Baker [15] reported annual streamflow increases of up to 157% after juniper mortality following an herbicide treatment. Only a few studies [16–18] have addressed vegetation-groundwater relationships in juniper woodlands. More and better information regarding juniper landscape-scale processes is needed. It is increasingly recognized that comprehensive resource management requires integration of surface water and groundwater components [19,20] and that juniper expansion effects on groundwater recharge must be better understood [8,21].

Surface water and groundwater connections between upland water sources and downstream valleys can determine multiple biophysical relationships occurring throughout the landscape. Several studies have reported there are transient hydrologic connections between upland water sources and valley locations [22–24]. These transient hydrologic connections have been found to vary spatially and temporally and are most often present during wet periods with an increased input of precipitation, snowmelt, runoff and/or irrigation water. Many of these studies related to hydrologic connectivity have shown the relationships between multiple physical features including vegetation, hydrology, topography and geology [25,26]. For instance, a study conducted by Emanuel et al. [27] concluded that vegetation heterogeneity plays a major role in upstream-riparian hydrologic connectivity. Vegetation cover and diversity largely influence water provisioning. Vegetation depends on water provisioning, but at the same is responsible for producing and maintaining the quality of this ecosystem service.

Most studies related to hydrologic connectivity have been done in forested areas in mesic environments, the hydrologic connections between surface water and groundwater systems in dryland regions have not been documented extensively. Objectives of this study conducted in a semiarid landscape in eastern Oregon were to: 1) assess surface water and groundwater connections in treated (juniper removed) and untreated watersheds; and 2) characterize hydrologic connectivity between a grassland riparian valley and its upland water sources.

2. Materials and Methods

2.1. Study Site

This study was conducted in the Camp Creek-Paired Watershed Study (CCPWS) site, 27 km northeast of Brothers, OR. The CCPWS site is a long-term collaborative research project located (43.96° Lat.; -120.34° Long.) in eastern Oregon [17]. The study area comprises one 116-ha watershed (Mays WS), one 96-ha watershed (Jensen WS), and a 20-ha section (Riparian Valley) of the West Fork Camp Creek. Above sea level elevation at the study site ranges from 1370 m in the Riparian Valley to 1524 m at the top of Mays WS. Dominant overstory vegetation in Jensen WS is western juniper. Dominant overstory vegetation in Mays WS is big sagebrush (*Artemisia tridentata*), this was after approximately 90% of the juniper was removed in 2005 [17]. The Riparian Valley site is largely a grassland (various *spp*.) area within two low dams and it is surrounded by sagebrush and western juniper vegetation. This valley section used to be an irrigated pasture for growing hay in the 1950's and 1960's, now it is used as a summer grazing pasture. Both watersheds are also used for grazing purposes depending on water availability. Juniper encroachment in Jensen WS is at phase III level, which according to the classification described by Miller et al. (2005), it is at its highest level, nearly 30% of total area cover [8]. Most precipitation in the area occurs as snow in the winter, with sporadic rainfall events in late summer and fall. For the period of record 2009-2015, average annual precipitation measured by onsite instrumentation was 275 mm.

In 2005, the two watersheds were instrumented to monitor multiple hydrologic variables including precipitation, soil moisture, runoff, and groundwater. Since October 2014, new instrumentation to measure selected variables (i.e., soil moisture, rainfall, and groundwater) has been added to expand the monitoring network in the watersheds and to include the Riparian Valley site (Figure 1).

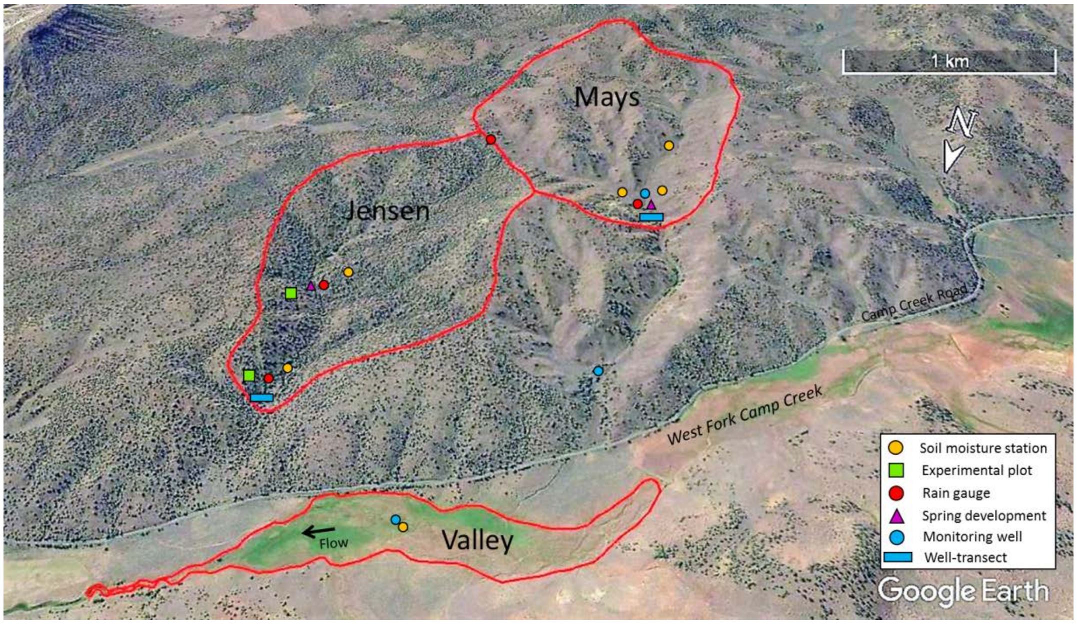

Figure 1. Map of the study site showing the Mays WS (a), the Jensen WS (b), and the Riparian Valley area (c), indicating the location of different monitoring instrumentation used in this study.

Soils in the two watersheds are classified as Westbutte very stony loam, Madeline Loam, Simas gravelly silt loam. Soils in the Riparian Valley site are classified as Bonnieview-Luckycreek complex [28]. Both Westbutte and Madeline series are moderately shallow to deep, well drained soils and are formed of colluvium from weathered volcanic material such as basalt, andesite and tuff. Simas soils are very deep and well drained, formed of colluvium and loess from tuffaceaous sediments. Bonnieview series are very deep moderately well drained, formed from residuum from weathered volcanic rock, and palesols. A series of streams that respond mostly to snowmelt runoff during the spring season are present in both watersheds. Occasional convective storms in the summer and fall also generate some ephemeral streamflow. The main stream draining out of Mays WS connects with the Riparian Valley downstream, however, the stream disappears in some areas at the bottom, only to resurface before reaching the valley. There is one relatively low flow spring in each of the two watersheds and in the Riparian Valley. The springs in the two watersheds were developed for livestock watering in 2004 [17]. The study site overlies a transient shallow aquifer with depth to bedrock of approximately 9 m across the two watersheds and in the Riparian Valley [17,29].

2.2. Field Data Collection

2.2.1. Soil Properties

Soil moisture data used in this study were obtained from four monitoring stations previously installed at upper and lower locations in each watershed [17] and from four new stations installed in the Riparian Valley site and in the two watersheds (see Figure 1). New stations were equipped with sensors based on time domain reflectometry. HydraProbe sensors were installed at the Untreated Valley site (HydraProbe; Stevens Water Monitoring Systems Inc. Portland, OR) while the Untreated Hillslope and Riparian sites had CS650 sensors (CS650; Campbell Scientific, Inc., Logan, UT) installed. At each station, vertical networks of sensors were installed to monitor soil moisture fluctuations at 0.2, 0.5, and 0.8 m depth. All sensors were tested in the lab and were within factory accuracy specifications. Sensors were not calibrated for site specific soil characteristics.

Soil samples for characterizing soil texture and soil bulk density were obtained during the installation of the new soil moisture stations. At each soil sensor depth, three soil cores for bulk density and one loose soil sample for textural classification were collected (Figure 2). Soil texture was determined using the hydrometer method described by Gee and Bauder [30]. Soil bulk density was calculated using the protocol described by Blake and Hartge [31].

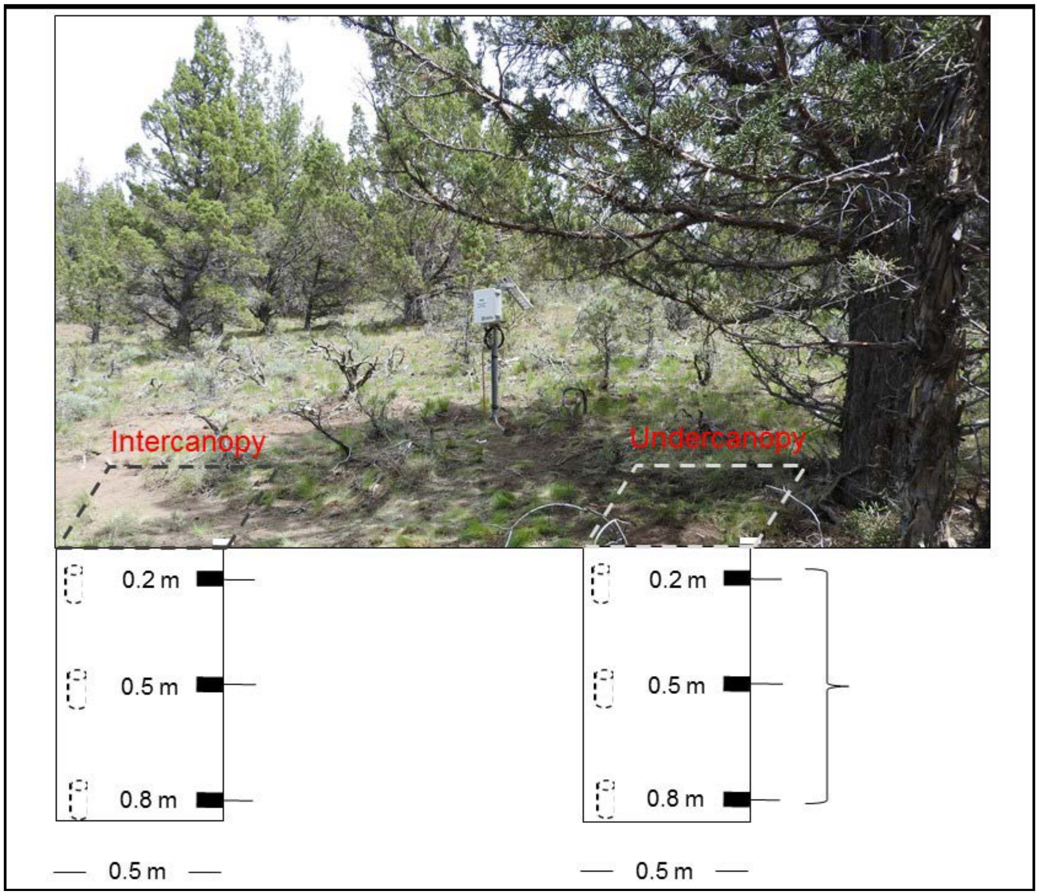

Figure 2. Schematic showing soil water sensor placement and soil sampling depth at under-canopy and inter-canopy locations in the Jensen WS.

2.2.2. Precipitation, Runoff, and Springflow

Automated records of rainfall were obtained using four tipping-bucket rain gauges distributed throughout the study site; from the watershed divide, to mid-slope, to valley bottom locations. Also, a total of 12 non-recording rain gauges were installed in each of two experimental plots in the untreated watershed to characterize precipitation-tree canopy interception dynamics. Snowpack depth was measured using ultrasonic snow-depth recording sensors located in the valley at each watershed. Runoff data were obtained using a Type-H flume [32] model 3.0 equipped with a water level logger installed in the main channel of each watershed (see Figure 1). Manufacturer pre-calibrated equations and water level data were used for estimating runoff discharge. Springflow was measured at the outlet of a lateral pipe installed as part of the spring development in each watershed. Manual measurements of springflow were taken at selected dates during April 2016 through June 2017 using a 5-L container and a stop watch. Field data collected were used for estimating springflow rate in each watershed.

2.2.3. Shallow Groundwater Level Fluctuations

Automated recordings from 15 shallow (< 10 m depth) monitoring wells installed at the study site were used to characterize groundwater level fluctuations. Data were obtained using previously installed transects of wells (six), located perpendicular to the channel in each watershed, and a network of three wells installed in the Riparian Valley site in October 2014 [29]. The six-well transect in Mays WS spans 38 m across the watershed valley bottom and is located at an elevation of 1438 m, in mostly fractured rock substrate. The six-well transect in Jensen WS spans 52 m across the watershed valley bottom and is located at 1373 m elevation, in an alluvium and fractured rock composite. The three riparian wells are clustered in a 20 m^2 area located at 1363 m elevation in the fine-textured soil depositions in the valley. Two additional wells were installed along the streambed for monitoring the timing and duration of streamflow coming out of Mays WS. One of the wells was installed at the outlet of the watershed, 5 m upstream of the Type-H flume. The second well was installed 1000 m downstream of the watershed outlet well (see Figure 1). These two instream-wells were driven until bedrock was reached. The watershed outlet well was driven 1 m into the ground and the downstream well was driven 1.5 m. All wells were equipped with water level loggers (model HOBO U20-001-01, Onset Computer, Corp.; Bourne, MA) that were programmed to record data hourly. Also, a water level meter (Model 101, Solinist Canada Ltd.; Ontario, Canada) was used to collect depth to water table during selected dates. These data were used for verification or calibration of the water level loggers. All wells were geo-positioned with a GPS unit (PN-60 GPS, DeLorme Inc.; Yarmouth, ME).

2.2.4. Effective Precipitation, Soil Moisture, and Shallow Groundwater Relations

The effects of tree canopy cover on effective precipitation and soil moisture were evaluated in the Jensen WS. Effective precipitation was estimated based on precipitation data obtained from the non-recording rain gauges in the two experimental plots located at upstream and downstream places within the watershed. Each plot covered an area of approximately 200 m^2 and it included rain gauges installed at under-canopy (n = 4), inter-canopy (n = 4), and drip line (n = 4) locations. The downstream plot was installed in October 2015 and the upstream plot station was installed in October in 2016. Tree canopy cover above each rain gauge was estimated using a spherical crown densiometer (model A) using methodology adapted from Strickler [33]. Canopy cover for the entire 200 m² plot was estimated using Google Earth®'s polygon features. Canopy cover estimates from Google Earth® were validated using on-the-ground measurements of crown diameter at selected trees (n=10) in the valley site. Precipitation data using the non-recording gauges was collected from October 2015 through March 2017. Two of the new soil moisture stations were used for measuring soil moisture fluctuations at under-canopy and interspace locations in both experimental plots. Both soil moisture stations were programmed to collect soil volumetric water content data hourly. Soil moisture, shallow groundwater, and precipitation data from automated equipment were used to characterize soil water movement through the soil profile and into the shallow aquifer. A One Way Analysis of Variance (ANOVA) was conducted to assess soil moisture content variability between inter-canopy and under-canopy locations at both upstream and downstream experimental plots. SigmaPlot® version 13.0 (Systat Software Inc.; San Jose, CA, USA) was used in this statistical analysis.

3. Results

3.1. Soil Properties

Soil bulk density and soil texture varied across study site locations. For both watersheds, soil texture was classified as sandy clay loam at all sampling depths. For the Riparian Valley site, the soil got progressively more clayey with increasing depth in the soil profile from silt loam (0.2 m), to silty clay loam (0.5 m) to clay (0.8 m) texture (table 1). Greater sand content values at all depths were obatined for the downstream location in the alluvium valley of the Jensen WS. Soil bulk density ranged from 0.93 Mg m^{-3} in the Riparian Valley to 1.60 Mg m^{-3} in the Mays WS location.

Table 1. Soil physical properties for the three locations within the study site, (a) Mays WS, (b) Jensen WS, and (c) Riparian valley, showing the average of (n=3) soil bulk density and soil particle distribution of sand, silt and, clay at each soil depth. The Jensen WS location illustrates data collected at under-canopy and inter-canopy areas in upstream and downstream settings. Standard deviation is shown in parentheses. N/A = Data not available.

Soil depth	Bulk density	Sand	Silt	Clay
	(Mg m^{-3})	(%)	(%)	(%)

(a) Mays WS				
0.2 m	1.51 (<0.01)	67.5 (3.35)	11.2 (1.63)	21.3 (1.72)
0.5 m	1.60 (0.06)	69.6 (<0.01)	9.2 (<0.01)	21.2 (<0.01)
0.8 m	1.55 (0.03)	68.9 (0.94)	9.9 (0.47)	21.2 (0.82)
(b) Jensen WS				
Upstream – Under-canopy				
0.2 m	1.18 (0.07)	59.1 (2.54)	11.7 (0.41)	29.27 (2.13)
0.5 m	1.36 (0.05)	62.4 (1.70)	11.3 (1.46)	26.3 (1.52)
0.8 m	1.53 (0.11)	60.5 (0.75)	12.9 (0.94)	26.5 (1.47)
Upstream – Inter-canopy				
0.2 m	1.29 (0.03)	65.2 (1.99)	13.6 (0.86)	21.2 (2.67)
0.5 m	1.46 (0.06)	62.7 (0.94)	14.8 (0.86)	22.5 (1.05)
0.8 m	1.57 (0.02)	62.0 (<0.0)	16.4 (<0.0)	21.6 (<0.0)
Downstream - Under-canopy				
0.2 m	N/A	81.1 (2.49)	16.5 (1.72)	2.5 (0.90)
0.5 m	N/A	74.4 (1.63)	15.5 (2.23)	10.1 (1.33)
0.8 m	N/A	75.7 (1.89)	16.1 (1.25)	8.2 (2.94)
Downstream – Inter-canopy				
0.2 m	N/A	78.4 (1.63)	15.4 (2.16)	6.2 (3.74)
0.5 m	N/A	79.1 (3.77)	14.1 (3.30)	6.9 (0.47)
0.8 m	N/A	79.1 (4.11)	12.1 (2.36)	8.9 (2.62)
(c) Riparian Valley				
0.2 m	0.93 (0.07)	24.4 (10.3)	59.8 (3.00)	15.8 (7.50)
0.5 m	1.00 (0.07)	19.2 (6.00)	57.1 (5.28)	23.7 (4.46)
0.8 m	0.97 (0.02)	34.7 (0.94)	20.9 (3.90)	44.4 (4.61)

3.2. Canopy Cover Estimates

Tree canopy cover was estimated for both above individual rain gauge locations and at entire experimental plot scale. For individual rain gauge estimates, tree canopy cover at the downstream location averaged 11% for the inter-canopy, 64% for the drip line, and 97% for the under-canopy. At the upstream location, average canopy cover was 15% for the inter-canopy, 34% for the drip line, and 92% for the under-canopy. For the entire experimental plot scale, tree canopy cover was 29.2% at the downstream location and 25.5% at the upstream location.

3.3. Effective Precipitation and Soil Moisture Response

Effective precipitation and soil water transport through the soil profile at inter-canopy and under-canopy locations were evaluated based on data collected at the upstream and downstream valley plots installed in the Jensen WS. Effective precipitation was determined based on the amount of rainfall reaching the non-recording rain gauges installed in each plot. At the downstream experimental plot, we collected rainfall data at five different periods from 31 October 2015 through 28 March 2017. The upstream plot was established in October of 2016 thus only the two rainfall periods were evaluated (Table 2).

At all times, effective precipitation values were greater at inter-canopy locations when compared to drip line and under-canopy locations for both plots. When comparing the last two measured periods, which include data for both plots, average effective precipitation at the downstream plot was 56% (all-period average was 55%). For the upstream plot, average effective precipitation was 64%.

Table 2. Effective precipitation results for the two experimental plot sites, (a) Downstream and (b) Upstream, showing total rainfall, average effective precipitation (Avg. Eff. Ppt.) at under-canopy, drip line, and inter-canopy locations from October 2015 through March 2017. Standard deviation is shown in parentheses. N/A = Data not available.

Period of Record	**Total Rainfall**	**Avg. Eff. Ppt. Under-canopy**	**Avg. Eff. Ppt. Drip line**	**Avg. Eff. Ppt. Inter-canopy**
	(mm)	**(mm)**	**(mm)**	**(mm)**
(a) Downstream				
31 Oct to 21 Nov 2015	24.3	7.2 (2.3)	17.3 (0.1)	23.9 (0.4)
16 Jun to 17 Sep 2016	17.3	4.8 (5.3)	6.9 (6.4)	15.8 (0.4)
18 Sep to 21 Oct 2016	34.0	3.7 (0.5)	19.7 (2.9)	33.8 (0.3)
22 Oct to 10 Nov 2016	30.4	9.1 (1.8)	21.6 (2.2)	29.9 (0.5)
11 Nov 2016 to 28 March 2017	267.4	57.7 (35.3)	97.9 (49.3)	213.1 (18.8)
(b) Upstream				
31 Oct to 21 Nov 2015	N/A	N/A	N/A	N/A
16 Jun to 17 Sep 2016	N/A	N/A	N/A	N/A
18 Sep to 21 Oct 2016	N/A	N/A	N/A	N/A
22 Oct to 10 Nov 2016	29.6	12.6 (5.6)	23.8 (3.8)	29.5 (0.2)
11 Nov 2016 to 28 March 2017	278.0	86.0 (25.6)	156.3 (37.4)	210.3 (42.1)

Soil moisture content fluctuations at both upstream and downstream plots followed a similar pattern where soil moisture levels in the upper 0.2 m where highly responsive to variable precipitation inputs. At the deeper 0.5 and 0.8 m soil depths, sensors in the inter-canopy locations generally responded faster than those in under-canopy locations in both plots.

Figure 3 shows soil moisture fluctuations for the sensors installed at under-canopy and inter-canopy locations in the downstream plot for the period Oct 2015 through Oct 2016. For the entire 0 to 0.8 m profile soil moisture was greater in the inter-canopy location, except for a short period in November 2015, a few weeks following sensor installation. At the 0.2-m depth, soil moisture content varied during the wet season with alternating periods of higher or lower levels for both locations. However, during the dry summer season soil moisture content was substantially higher at the 0.2-m depth in the under-canopy location. All but the sensor at the 0.8-m depth in the under-canopy location responded relatively rapid during early winter precipitation and during the snowmelt runoff period beginning in mid-February. Soil moisture at the 0.8-m depth in the under-canopy remained at marginal levels for nearly six months before it peaked to about 12% in late March (Figure 3).

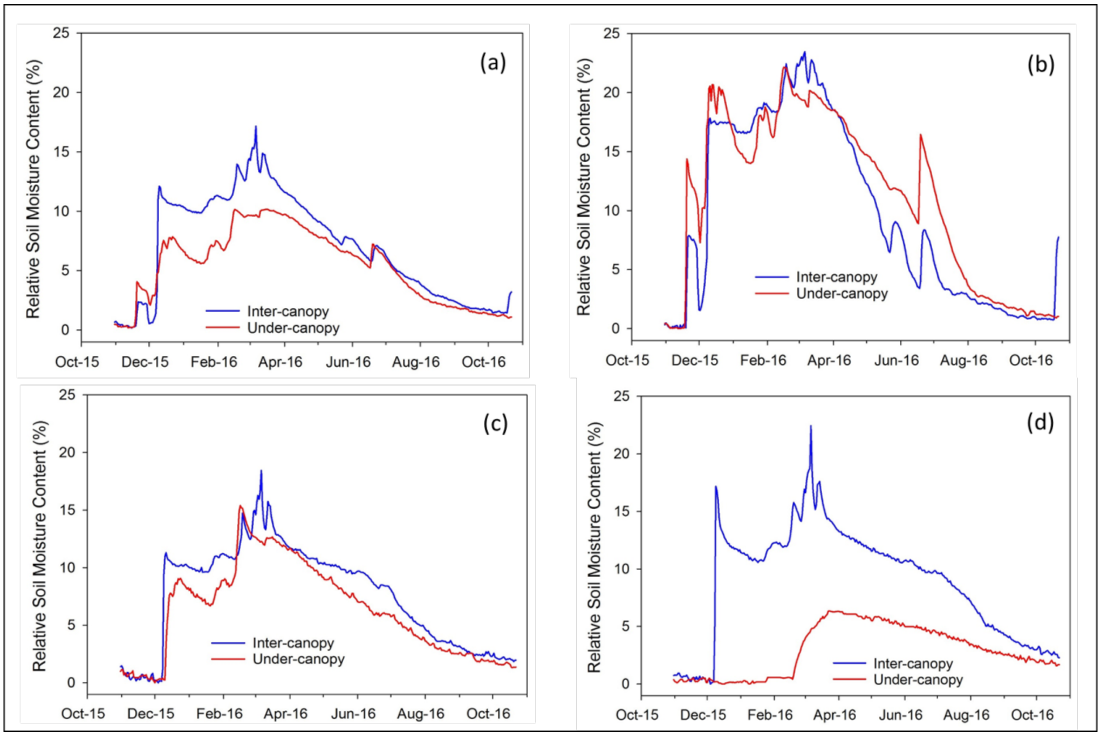

Figure 3. Soil moisture variability for tree inter-canopy and under-canopy locations at the whole 0 to 0.8 m profile (a), and at soil depths 0.2 m (b), 0.5 m (c), and 0.8 m (d), in the downstream experimental plot in the Jensen WS.

Soil moisture content for the entire 0 to 0.8 m profile at under-canopy and inter-canopy locations were evaluated for the period of record May 2016 through June 2017 for the two experimental plots. In general, greater soil moisture content was observed in the inter-canopy locations when compared to the under-canopy locations in both experimental plots. Greater differences in soil moisture content between under-canopy and inter-canopy locations were observed during winter precipitation (late October through January) in both experimental plots. It was noted that during early spring soil moisture was greater in the under-canopy in both plots; this was reversed at the apex of the snowmelt runoff season in late March (Figure 4).

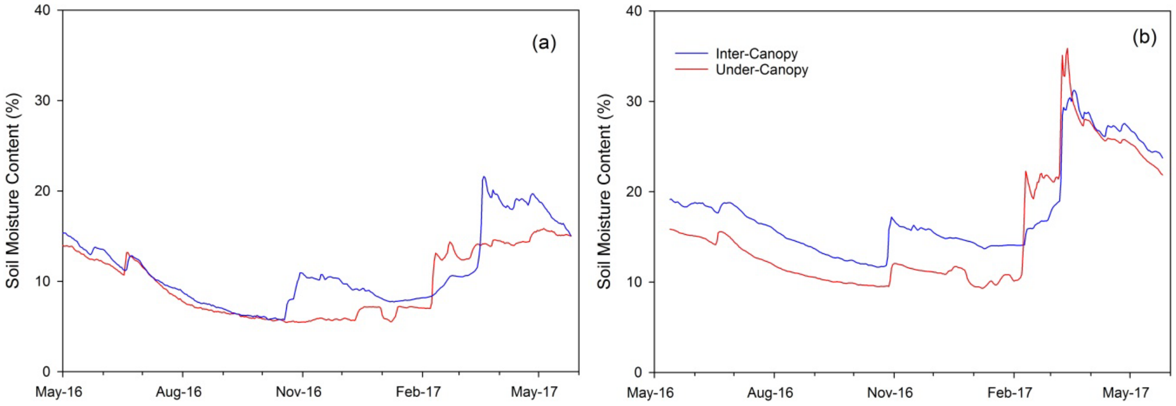

Figure 4. Soil moisture variability for tree inter-canopy and under-canopy locations at the whole 0 to 0.8 m profile for downstream (a), and upstream (b) experimental plots in the Jensen WS.

Daily-averaged soil moisture content values were used to assess soil water relations across different soil depths and experimental plot location. The ANOVA for the entire 0 to 0.8 m soil profile showed there are statistically significant differences ($P<0.001$) between daily soil moisture content across inter-canopy and under-canopy locations for both plots. The ANOVA for specific sensor depth (0.2, 0.5, and 0.8 m) showed there are significant differences ($P<0.001$) across most inter-canopy and under-canopy locations. No significant differences in soil moisture content between inter-canopy and under-canopy locations were found at the 0.8 m sensor depth at the upstream location. Also, no significant differences were found between upstream and downstream inter-canopy locations at the 0.2 m sensor depth.

3.4. Snowpack and Runoff

Snowpack and runoff relationships were evaluated for water years (WY) 2016 and 2017. For WY 2016, snow depth at Mays WS rose 0.4 m in early January and remained at that level until early February when it started melting. For Jensen WS, snowpack depth rose 0.6 m in early January and stayed relatively stable until mid-February when it started melting. Figure 4 shows that the snowmelt period that started in mid-February 2016 generated almost an immediate runoff response in the Mays WS but not in Jensen. For Mays WS, runoff discharge peaked at 440 L min^{-1} on 3 March and yielded 27,787 m^3 for the entire season. For Jensen WS, snowmelt runoff discharge peaked at 24 L min^{-1} on 1 March and yielded 51.6 m^3 (Figure 4).

In WY 2017, snowpack began to build in early December and rose to 0.5 meters by mid-January in both Jenson WS and Mays WS. Snowpack in both watersheds persisted until the early March when they began melting and within two weeks the snowpack was negligible in both watersheds. Unlike in 2016, in 2017 both watersheds saw an immediate response in runoff with the start of snowmelt. However, the differences in magnitude of the response were similar to the previous year. Streamflow discharge peaked at 793 L min^{-1} for Mays WS and yielded 59,848 m^3 for the entire season. For Jensen WS, discharge peaked at 679 L min^{-1} and yielded 19,862 m^3.

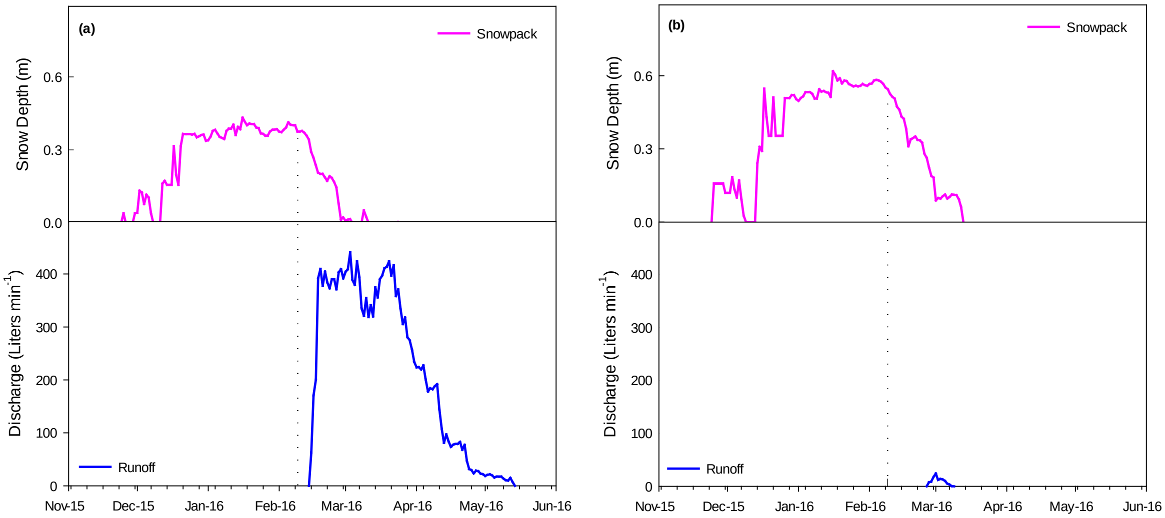

Figure 5. Snowpack depth and runoff discharge during 2016 in Mays WS (a) and Jensen WS (b) watersheds illustrating the onset (dotted line) of runoff discharge measured at each watershed.

Surface and subsurface flows in the stream connecting Mays WS and the Riparian Valley were characterized using data from the wells installed at the outlet of the watershed (WS outlet) and at the monitoring location 950 m downstream of the WS outlet well. Figure 5 shows upland-lowland surface water connections in response to the 2016 snowmelt runoff season along the stream draining out of the Mays WS. In the well installed at the watershed outlet, the first response was observed on 11 February and it was followed by a sharp water level rise that peaked on 16 February, then it was followed by a series of water level fluctuation events until it started steadily declining at the end of April. A delayed response of approximately five days was observed in the well located 950 m downstream of the watershed outlet. Water level in this well started rising on 16 February, peaked on 5 March, and it was negligible by 9 April.

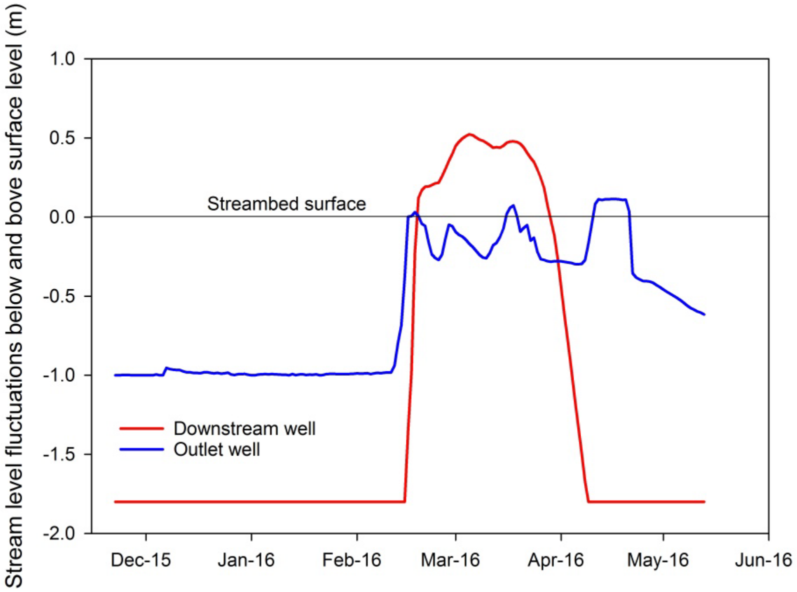

Figure 6. Stream water level response to snowmelt runoff at watershed outlet and downstream well locations in Mays WS in 2016.

3.5. Springflow

Springflow discharge was different across watersheds during the two years (2016 and 2017) evaluated. No data were collected in years 2014 and 2015. On average, excluding the date (17 March 2017) with no record for one of the sites, Mays WS yielded 88 L min^{-1} and Jensen WS yielded 35 L min^{-1}. Manual measurements taken during 2016 and through June of 2017 showed that springflow discharge was substantially higher in Mays WS when compared to Jensen WS.

Highest springflow discharge levels were observed in April 2016 and March 2017. Subsequent readings showed a steady decline in springflow rates down to 9.8 L min-[1] in Mays on 11 November 2016. Springflow was negligible in Jensen by fall season. A similar trend was observed in 2017 for both watersheds, however the highest springflow rates were observed earlier in the spring (Table 3). The maximum springflow rates estimated in 2016 are consistent with peak flow rates observed in two other years (2006 and 2010) since springflow monitoring began at the study site in 2004 (see Chapter II).

Table 3. Springflow rate estimates based on manual measurements of spring discharge in the two watersheds from April 2016 through June 2017. N/A = Data not available.

	Mays WS	**Jensen WS**
Date	**(L min^{-1})**	**(L min^{-1})**
19 Apr 2016	189.3	75.7
26 Apr 2016	162.8	64.3
13 May 2016	99.9	15.9
14 June 2016	60.6	7.6
14 July 2016	37.5	4.2
18 Sep 2016	11.4	(t)[1]
20 Oct 2016	10.1	(t)
11 Nov 2016	9.8	(t)
17 Mar 2017	187.0	N/A
28 Mar 2017	156.3	109.0
14 April 2017	144.2	102.2
26 May 2017	117.7	31.0
26 June 2017	59.4	8.3

[1] Negligible springflow rate reported as trace *(t)*.

3.6. *Seasonal Soil Moisture and Groundwater Level Fluctuations*

A strong soil moisture response to winter season precipitation inputs was observed in both watersheds during all four years evaluated. Soil moisture conditions in the Riparian Valley site remained at or relatively near saturation conditions since the sensor installation in May 2016 (data not shown).

Figure 6 illustrates daily soil moisture fluctuations collected from the monitoring stations installed at upper and lower locations in each watershed. Overall, higher levels of soil moisture content were observed in the top 0.5 m soil profile. A delayed soil moisture response in the deepest sensor (0.8 m) was observed at all four locations during the drier 2013-2014 winter season (Figure 6).

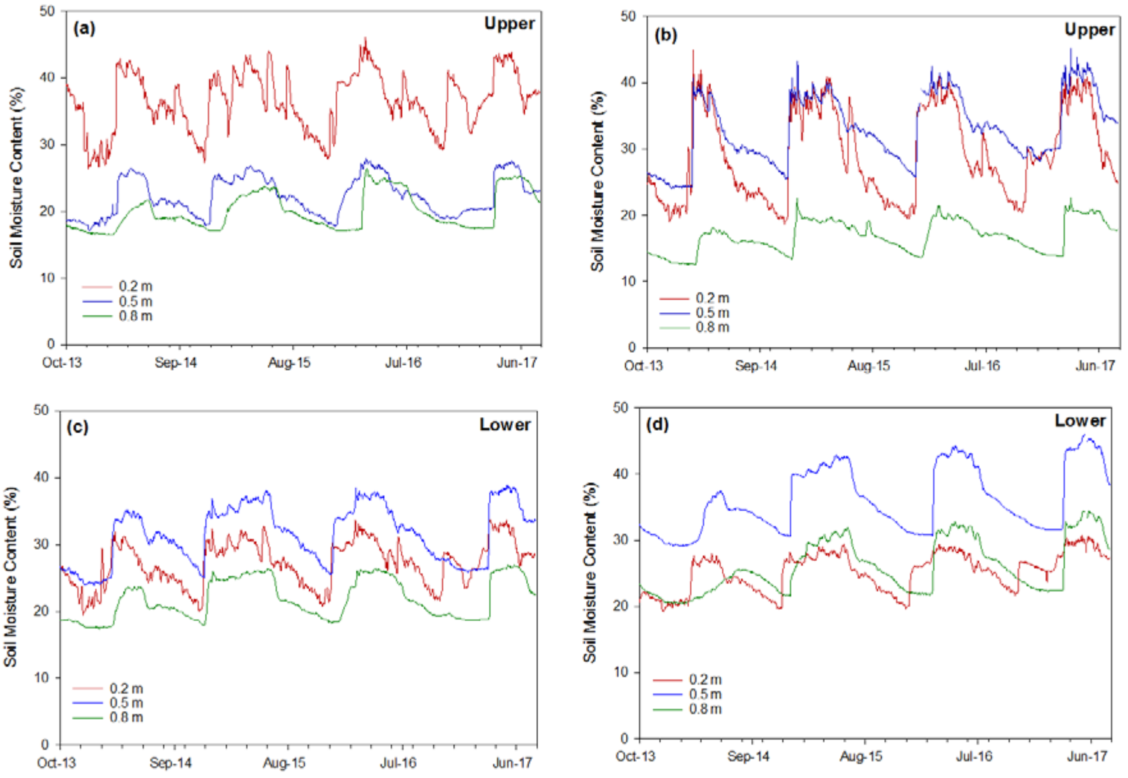

Figure 7. Soil moisture content fluctuations at different soil depths at upper and lower locations in both Mays WS (a, c) and Jensen WS (b, d) watersheds from 1 October 2013 through 27 July 2017.

Figure 7 shows four years of snowpack depth in Jensen WS and shallow groundwater level fluctuations in both watersheds and in the Riparian Valley. A seasonal groundwater level rise and decline was observed for all four years evaluated in both watersheds and for the three years of groundwater data available in the Riparian Valley. It can be observed that snowpack accumulation was considerably greater in 2016 and 2017 when compared to previous years. Also, groundwater level rises were considerably higher in the Jensen and Riparian Valley well locations in 2016 and 2017. Seasonal groundwater response in the well in Mays WS remained at low levels for all four years when compared to the other two sites, however, its response lasted longer during year 2016. A faster response and a higher shallow groundwater peak were observed in the riparian well in 2016 and 2017 when compared to the response in the previous year (Figure 7).

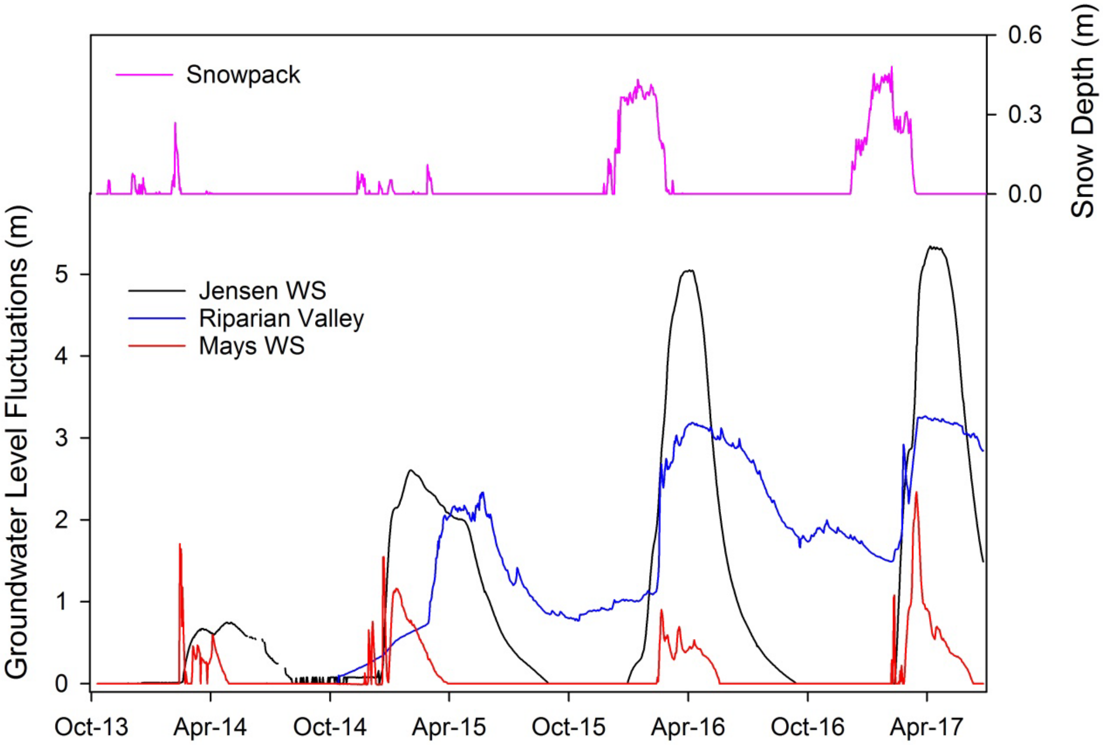

Figure 8. Seasonal water table fluctuations in selected wells in Mays WS and Jensen WS and in the Riparian Valley from October 2013 through May 2017.

A closer look to precipitation, soil moisture, and shallow groundwater relationships in Mays WS during June 2014 through June 2015 can be observed in figure 8. Summer precipitation had an effect on soil moisture levels but not on groundwater. Precipitation that occurred in winter considerably increased soil moisture levels and also had an effect on groundwater level response three weeks after soil moisture increased in the deepest soil sensor at 0.8 m. Groundwater level rise that rose 2.8 m at the end of January stayed above two meters for most of the winter and spring, until it started declining in May (Figure 8).

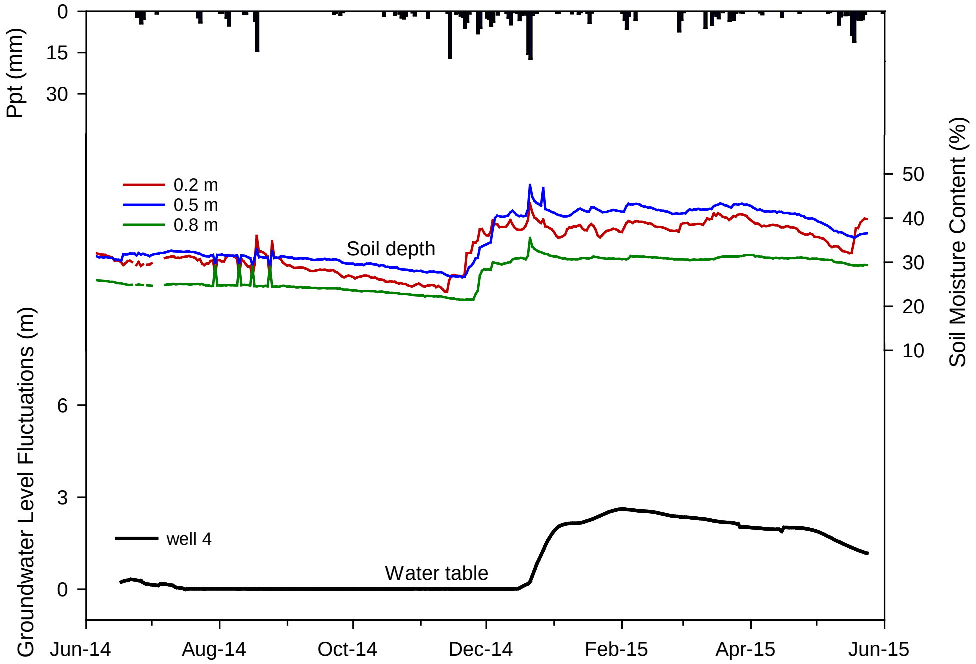

Figure 9. Soil moisture and shallow groundwater level response to precipitation inputs in watershed Jensen during June 2014 through June 2015.

Figure 9 shows groundwater level fluctuations during runoff season along the 6-well transect installed in each watershed. The bottom of all wells are at, or very close to bedrock level, thus it reflects a significant section of the underground channel profile at the outlet of each watershed. In general, all wells showed similar groundwater level fluctuation response throughout the different dates (March 2015, May 2016, and March 2017) evaluated. Greater groundwater levels were observed in March 2017 when depth to groundwater was 3.2 m for both w-4 in Mays and in w-5 in Jensen. This contrasts with the lower response observed in March 2015 when depth to groundwater rose 6.8 m in w-1 in Mays and was at 6-m depth in w-6 in Jensen. Since juniper removal, w-6 in Mays has consistently remained at shallower groundwater depth than the rest of the wells in that transect, this was also shown during the three different dates evaluated (Figure 9).

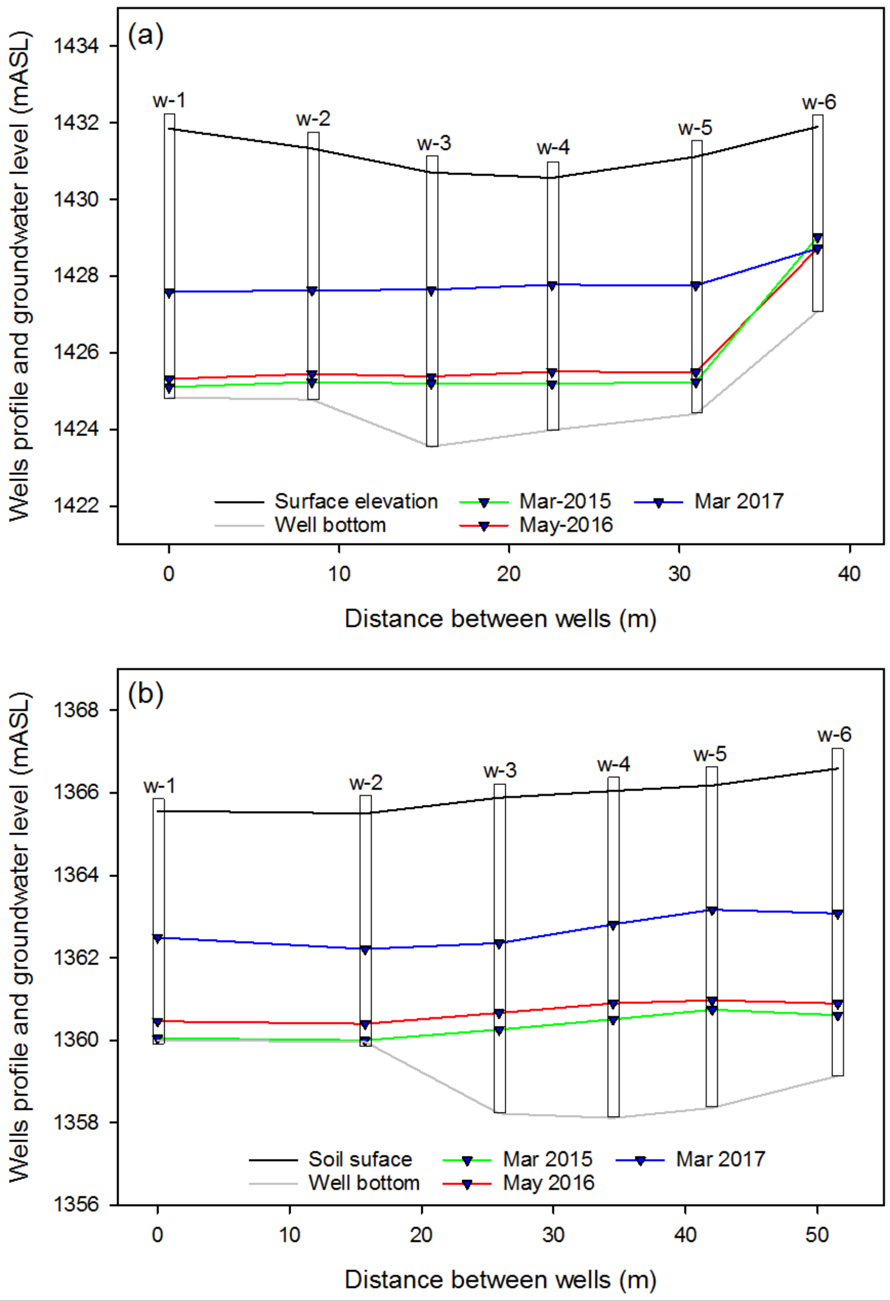

Figure 10. Shallow groundwater level fluctuations at selected dates in well-transects in Mays WS (a) and Jensen WS (b).

4. Discussion

The connections between surface water and groundwater flows have not been extensively documented in arid and semiarid landscapes. This study shows there are temporary hydrologic connections between surface and ground water components in semiarid rangeland watersheds of central Oregon. These short-term hydrologic connections were more apparent during the spring snowmelt-runoff season. Results indicate subsurface flows (i.e. springflow and shallow groundwater) clearly exceeded the span of surface water flows observed during the snowmelt runoff season. This resulted in an increased residence time through the subsurface flow system that may have helped extending the hydrologic connections within and out of the watersheds with the downstream valley. A stable isotope analysis conducted by Ray (2015), and a second analysis we conducted in 2017 (data not shown), showed close similarity in values across all groundwater sources in the study area, which further points to the connective nature of the upland water sources and the downstream valley at this site.

Snowpack accumulation during the winter time played an important role in shallow groundwater response to soil infiltration inputs during the snowmelt runoff season. Greater snowpack depths observed in water years 2016 and 2017 resulted in greater groundwater levels at all sites. A less continuous response until reaching a seasonal peak was observed in the treated watershed, even though cumulative groundwater level rise values were similar and even higher than the untreated watershed in some years. We attributed this less peak response to the location of the monitoring wells in the upper watershed and their installation in fractured rock substrate, conditions that may not have favored transient groundwater storage. One well within the treated watershed has shown unique behavior that continues to pose additional questions. Unlike the other wells in the watershed that follow a pattern of water level rise and decline in response to seasonal precipitation, the water level in this well has remained relatively constant since the watershed treatment 13 years ago. We attribute this water level behavior to the location of the well that may have resulted in the entrapment of water within the well and surrounding substrate.

The role of vegetation, particularly tree canopy cover, can be important in preventing precipitation from reaching the soil surface. Results from this study show that juniper canopy-cover can substantially reduce the amount of rainfall reaching the soil, and consequently decrease soil moisture and potential shallow aquifer recharge. Our findings are similar to those reported by Salve and Allen-Diaz [34] , who concluded there is a negative correlation between tree canopy cover and soil moisture content. Also, similar to our findings Breshears et al. [35] has reported higher inter-canopy soil moisture values when compared to under-canopy locations. Even though we only measured effective precipitation, we were able to document snowpack accumulation at inter-canopy and under-canopy locations using a time-lapse camera that showed there was less snow buildup under the tree canopy. This is consistent with findings from a study conducted in western juniper woodlands of Idaho by Niemeyer et al. [18], who showed there was greater snow accumulation in the interspace when compared to under-canopy locations.

This study is a step further in understanding hydrologic connections in semiarid rangeland ecosystems. We have been able to characterize important surface and subsurface flow relationships occurring in these water-scarce ecosystems. A seasonal soil moisture and shallow groundwater response to winter precipitation inputs was observed in all three locations, the two watersheds and the riparian valley, with different topographic and vegetation cover differences. The similar seasonal response observed across sites indicates there are strong hydrologic connections between surface water and shallow groundwater components in these semiarid rangeland settings of central Oregon. Some of the limitations of this study relate to the topographic differences and placement of instrumentation in the two watersheds and in the riparian valley, which makes it hard for a direct comparison of hydrologic connectivity-causal relationships among the three locations. Also, data were limited to just two snowmelt runoff seasons for some of the variables evaluated. For example, data for springflow, effective precipitation, and streamflow was only available for the 2016 and 2017 seasons.

Results from this study contribute to improved natural resources management through a better understanding of the hydrologic connections occurring in rangeland ecosystems and the role that Western juniper encroachment may have on altering the hydrology of the site. Further work is needed in this study area in central Oregon to expand watershed-scale ecohydrology research to the larger regional landscape-scale.

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A Hydrogeologic Framework of an Area of Interest in the Southeast Deschutes Basin, Oregon, USA.

Abstract: The role of local hydrogeology is important for management of groundwater resources and the ecosystems that depend on them. The objectives of this study conducted in Central Oregon were to 1) characterize the hydrogeologic framework for our area of interest in the semiarid Upper Deschutes Basin, 2) to evaluate surface water and shallow groundwater connections in a long term research site within the area of interest. First, existing data and information on local geology and hydrology was synthesized to construct a hydrogeologic framework and conceptual model of groundwater movement. Second, measurements of springflow and recharge estimates were used to characterize surface water and groundwater interactions. Findings of this study suggest low permeability geology has produced a prominent shallow aquifer that is responsive to changes in vegetation and seasonal weather patterns.

Keywords: Hydrogeology; Surface Water and Groundwater Interactions; Groundwater Dependent Ecosystems; Oregon, USA; Juniper; Shallow Aquifer; Water Table Fluctuation Method; Springflow.

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1. Introduction

Groundwater is an important resource around the globe, relied upon for agriculture, energy production, human consumption and ecosystem services [36]. Its importance is magnified in arid and semi-arid regions where the scarcity of precipitation and surface water often increase the reliance on groundwater sources. Semi-arid central Oregon is no different and groundwater is important for domestic use, irrigation, and ecosystem function. Often when managing groundwater resources, the focus is solely on human water needs but ecosystem needs are also important. Some ecosystems rely on groundwater sources to support their composition, structure and function [37]. These Groundwater Dependent Ecosystems (GDEs) can be lakes, rivers, springs, wetlands, and phreatophytic and subterranean ecosystems [38]. GDEs are often recognized by vegetative communities that depend on surface and subsurface expression of groundwater [39].Although the distribution and frequency of GDEs is not yet fully understood, they have been gaining recognition for their important role in terrestrial biodiversity [40,41], ecosystem services such as fisheries, agriculture, forestry [37] and maintaining streamflow [42]. In Oregon, a recent study by Brown et al. [43] found that more than a third of the state’s watersheds contain some form of GDE, with the majority of those being dependent on springs. It is important to understand the conditions that are favorable to GDEs to better manage, protect, and sustain them into the future [43].

To establish the occurrence of GDEs it is important to identify landscape physical conditions and surface water-groundwater (SW-GW) relationships that favor their establishment A recent study by Aldous et al. [44] investigated the linkages between the hydrogeologic setting and the presence of GDEs in montane setting of the Deschutes Basin of central Oregon. They found some GDEs (fens) to be associated with areas of low permeability geology and local recharge systems [44]. Other work in central Oregon has suggested GDE's in the region could be vulnerable to climatic and human induced changes [45]. These climatic shifts may alter the timing and amount of groundwater recharge and discharge [46]. Awareness of SW-GW connections is important for properly managing GDEs [47]. Understanding the spatial and temporal domains at which these hydrologic connections occur is important for designing land management strategies that help sustain GDEs.

Groundwater flow occurs on different spatial and temporal scales from points of recharge to discharge. Recharge and discharge dynamics are important for understanding groundwater movement. Groundwater originates from areas of recharge, often topographic high points, where water enters the ground then moves downslope to areas of discharge, topographic low points where it is either released into lakes, rivers, wetlands and through springs [48] or into the aquifer system. The flow of groundwater through these different systems has different scales of length and time. They range from extensive regional systems covering large basins where water moves long distances over long time scales to small local flow systems within these larger basins that cover smaller areas over short time scales. Intermediate flow systems fall between the two in their spatial and temporal scale [49]. Local flow systems are typically shallow systems often characterized by the presence of small springs not far from areas of recharge [50]. That is the case of our Camp Creek Paired Watershed Study (CCPWS) site described in this paper. The CCPWS is a long-term collaborative research project focused on western juniper (*Juniperus occidentalis*) effects on watershed hydrology. The CCPWS site is characterized by the presence of a shallow (<10 m) unconfined aquifer system that responds to the seasonal precipitation patterns of the region [17,29]. Shallow groundwater at the CCPWS is of relatively young age, suggesting there are short time-scale connections from recharge to discharge in the shallow aquifer [29].

A comprehensive study of the Upper Deschutes Basin regional groundwater system was completed by the U.S. Geological Survey in 2002 to provide information on groundwater resources to meet central Oregon's growing groundwater demands [51]. Given the regional scope of study, some of the local systems were left out. That is the case of the basin's southeastern section, where the CCPWS site is located, which is not believed to contribute to the regional system [51]. However, the role and function of local hydrogeology in this portion of the basin has not been fully characterized. A deeper understanding of the hydrogeologic framework and mechanisms of recharge and discharge mechanisms in this portion of the basin is needed. Objectives of this paper were to 1) characterize the hydrogeologic framework for an area of interest in the southeastern most portion of the Upper Deschutes Basin, 2) to evaluate surface water and shallow groundwater connections in the CCPWS.

2. Materials and Methods

2.1 Study Site Description

This study took place in Central Oregon, in the southeastern most portion of the Deschutes Watershed. This area is within the John Day Ecological province, a semi-arid region with total precipitation ranging from 250 to 380 mm year^{-1} [52]. The larger extent of this study Included a 280 km^2 region northeast of Brothers, OR. This extent was used to examine the broader hydrogeology that encompasses the smaller CCPWS site where most of the field data collection took place (Figure 1). The CCPWS site (43.96° N; -120.34° W) encompasses two watersheds and the riparian valley they drain into covering approximately 4 km^2. The site ranges in elevation from 1524 m above sea level (ASL) at its highest to 1370 m ASL in the valley. Streams in the watersheds are ephemeral, with seasonal flows occurring during years with substantial snowpack runoff, otherwise only flowing in response to occasional convective storms. Both watersheds have a spring that stays active for most of the year. Onsite average yearly precipitation for the period of record (2004-2016) is 275 mm yr^{-1}. The CCPWS site is instrumented to monitor groundwater, streamflow, spring flow, soil moisture, and weather variables. Investigations in the plot scale expression of the hydrogeologic characteristics were undertaken at the CCPWS to confirm the hydrogeologic framework herein discussed.

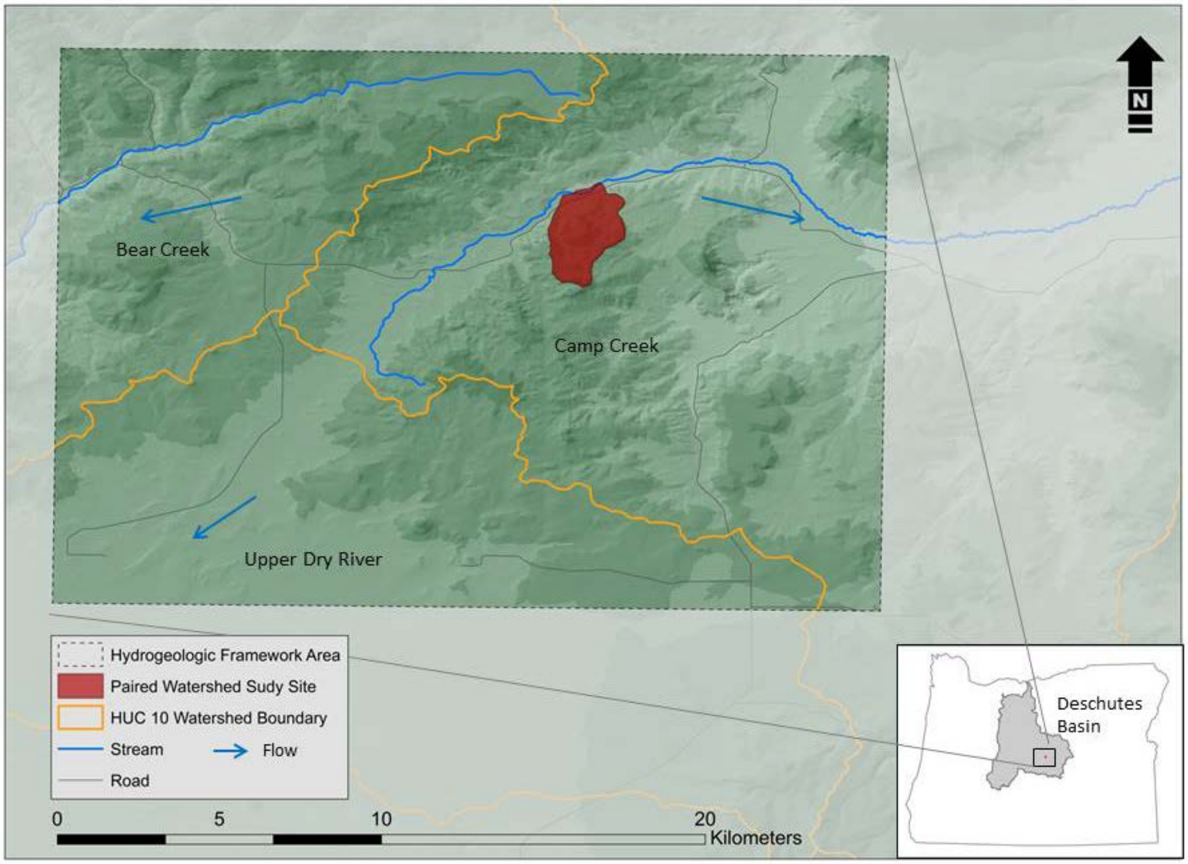


Figure 1. Map of study region illustrating the larger hydrogeologic study extent and paired watershed research site.

The geologic setting of the study area is the High Lava Plains province of Central Oregon. The High Lava Plains are a 240 km long and 80 km wide rectangular plateau trending generally NW to SE. It is bordered by the Basin and Range to the south, the Blue Mountains to the north, the Owyhee uplands to the east and Cascade Range to the west [53]. The High Lava Plains are characterized by a region of irregularly spaced west-northwest trending en echelon normal faults known as the Brothers Fault Zone [54]. The fault zone was created by a clockwise motion that twisted Oregon throughout the Cenozoic era [53]. The CCPWS site sits near the northern border of the High lava Plains just south of the Maury Mountains. The local surface geology is classified as lower Tertiary deposits of Clarno and John Day formations with valley bottoms filled by Alluvial deposits [55]. The John Day formation is characterized by tuffs, tuffaceous sedimentary rocks, ash flow deposits and rhyolites [55]. The permeability of the John Day is very low and the formation is viewed as the basement of the larger Upper Deschutes regional groundwater system [51]. The Clarno formation which covers most of our site is older and deeper than the John Day Formation and is characterized by andesite flows, breccias and volcanogenic sedimentary rocks [55]. The Clarno formation is also recognized as a poor water-bearer with wells located within it having relatively low yields [56].

2.2 Hydrogeologic Framework

2.2.1 Geologic cross-sections

In order to gain a finer understanding of the geologic structure underlying the area of interest we constructed two geologic cross-sections (A and B) illustrated on a surface geology map (figure 2). The two cross sections that are oriented perpendicular to each other provide a three dimensional representation of the geology for the CCPWS. Cross-section A was oriented WSW-ESE, and cross-section B was oriented NNW-SSE. Subsurface geology data were compiled from well borehole descriptions gathered from the Oregon Water Resources Department (OWRD) and from two oil and gas well lithology descriptions [57,58]. Borehole data were plotted on a regional topographic map and boreholes within 2 km of each transect were projected in, using each individual borehole as a discrete point of subsurface geology. When extrapolating the data, knowledge of parent materials, fault location, and depositional environment were taken into account. Descriptions of geologic materials reported by drillers during well installation were used to develop the geologic cross-sections.

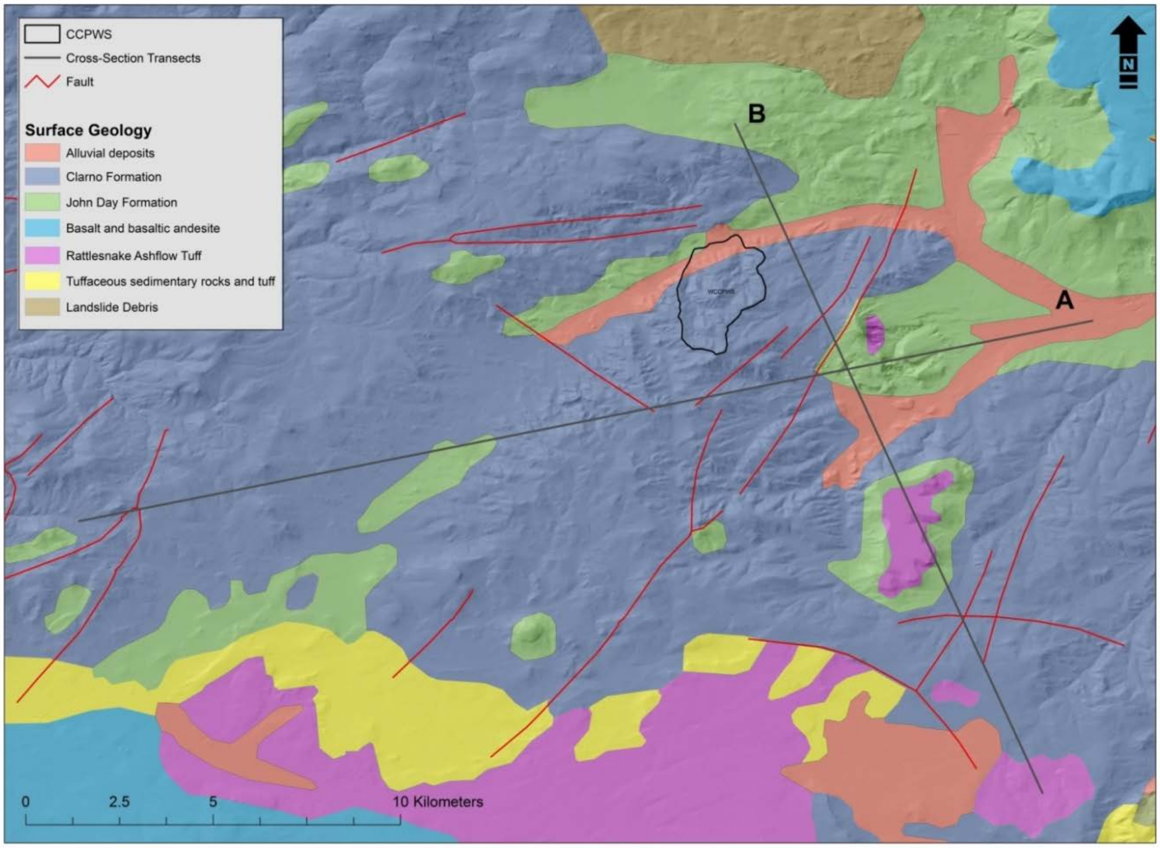


Figure 2. Surface geology map illustrating cross-section locations and main geologic features in both the CCPWS and the larger area of interest

2.2.2 Groundwater Flow

In order to determine the groundwater flow directionality in the region of interest, we developed a potentiometric surface map. This map [Figure 3] was created using static water level data obtained from OWRD well logs, National Hydrography Dataset (NHD) spring elevation, and onsite manually collected water levels. The spring data were obtained from the NHD [59] with the addition of known springs at the CCPWS site. Water table elevations were collected from individual well logs from the OWRD database. State of Oregon observation wells in the area do not show any significant water table declines over their period of record, therefore we assume static water table levels from the time of drilling was a good approximation of water table levels. Elevations for static water table level of each well were transcribed from well logs onto the area map while springs were marked at their surface elevation level. Contour lines were created two ways. First, using ArcMap (version 10.4.1, Esri, Redlands, CA) a surface with 30 m contours was created using the 3D analyst surface contour tool. Second, using water table elevation data contours were drawn by hand in Adobe Illustrator (version CS6, Adobe Systems Inc. San Jose, CA) taking into account topography and reasonable continuations of water table elevation beyond the study area boundary. Contours with a higher level of uncertainty were distinguished with a dashed line.

2.3 Shallow Aquifer Recharge and Discharge

2.3.1 Water Table Fluctuations and Recharge Estimates

Shallow groundwater level data were collected at the CCPWS using automated water level loggers (HOBO U20-001-01, Onset Computer, Corp.; Bourne, MA) installed in 6 monitoring wells in each of the two watersheds and 3 wells in the riparian valley. Data from the deepest well in each watershed and in the valley were used to estimate the extent of water table fluctuations throughout the year. Shallow aquifer recharge estimates were made using the Water Table Fluctuation Method (WTFM). This method outlined by Healy and Cooke [60] has been used to estimate recharge in unconfined aquifers using variations in water table elevation [61–63].

Water Table Fluctuation Method Equation:

$$R = S_y \frac{\Delta h}{\Delta t}, \tag{1}$$

Where R = groundwater recharge, S_y = Specific yield, Δh = change in water table height, and Δt = change in time. R values were calculated based on daily water table fluctuations ($\frac{\Delta h}{\Delta t}$) throughout each water year (Oct 1 - Sep 30). S_y numbers were taken from reference values [64] for substrate materials found during well installation within each watershed at the CCPWS site.

2.3.2 Spring Discharge

In order to account for springflow discharge in each of the two watersheds at the CCPWS site we used data that has been collected manually for the period of record 2004 through 2017. Each watershed has a developed spring that directs flow out of a lateral pipe installed as its outlet [17]. Springflow rate estimates were determined based on manual measurements of springflow volume and time to fill a container of a given volume.

3. Results

3.1 Hydrogeologic Framework

3.1.1 Geologic cross-sections

Figures 3a and 3b show cross sectional views of the region’s subsurface geology. As depicted in both figures, the upper strata in our study area are comprised predominantly of layers of rock types common to Clarno and John Day formations. The most superficial portion (150 to 200 meters) consists primarily of claystones, sandstone and conglomerate. Stark shifts in geologic material from upland to valley regions across surface geology classifications suggest that the presence of valleys in the region may be the result of faults creating a horst-graben structure. Horst-graben structures have been noted in the Brothers Fault Zone previously [65].

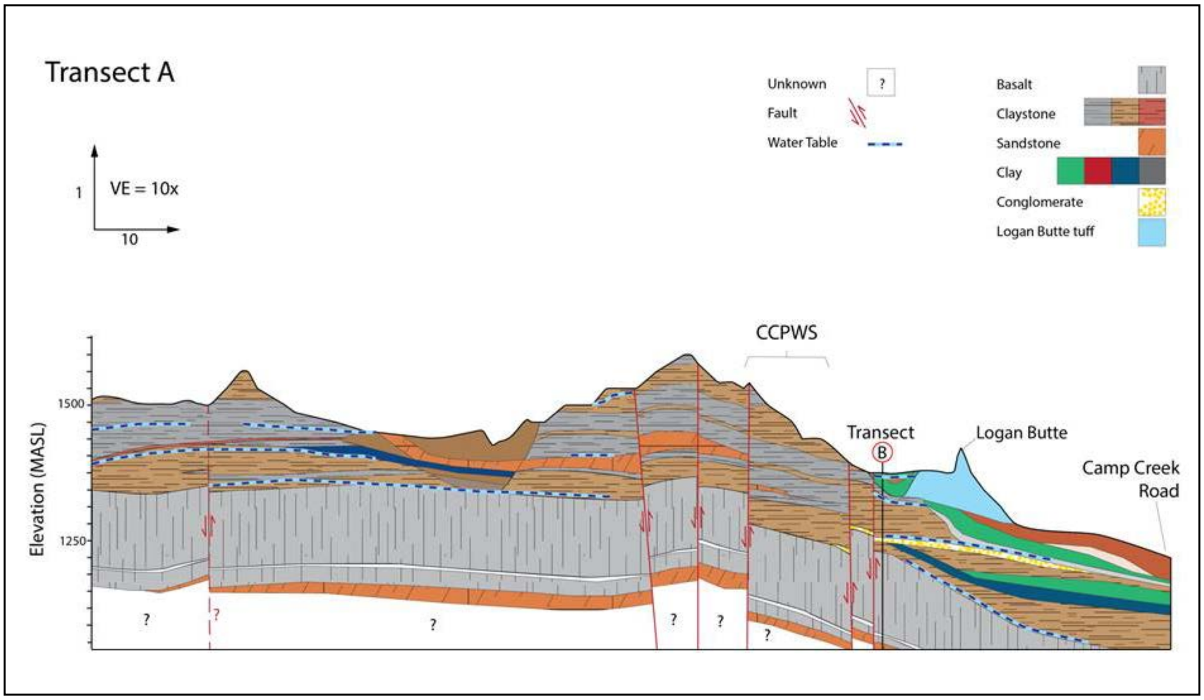


Figure 3a. Cross-section of the subsurface geology of Transect A.

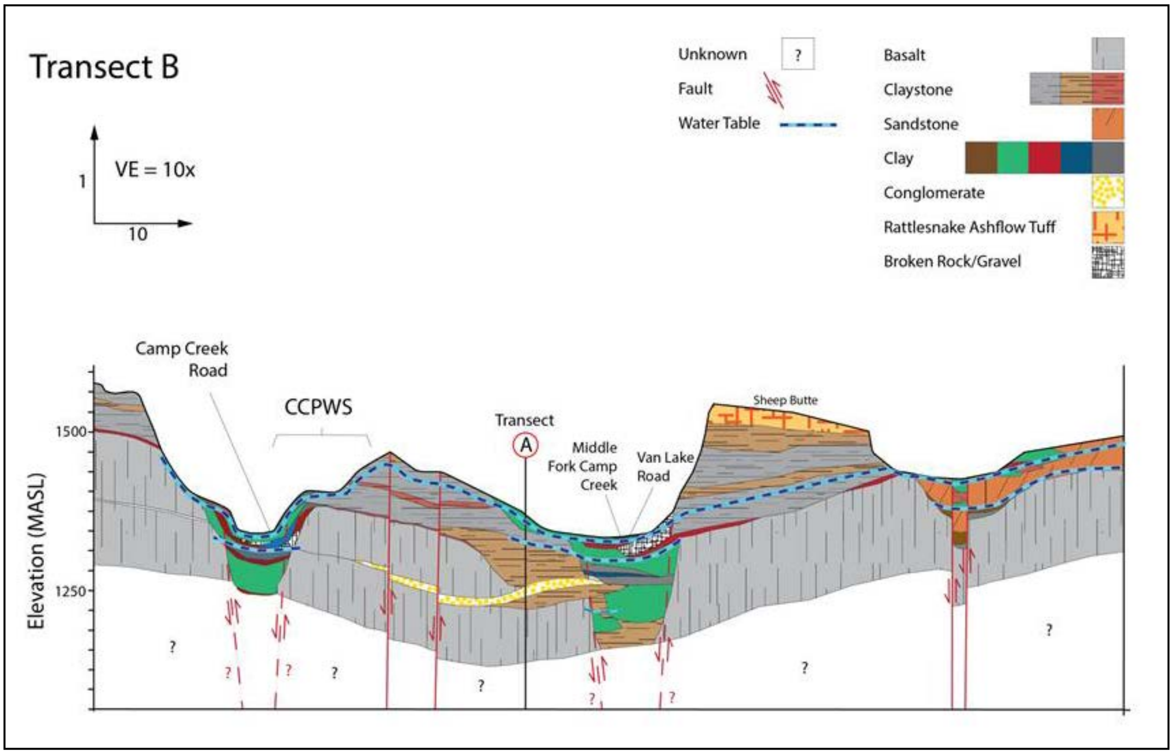


Figure 3b. Cross section of subsurface geology of Transect B.

3.1.2 Groundwater Flow

The potentiometric surface map was generated from static water level and spring elevation data showed that the water table generally followed surface topography across the study area. Overall, groundwater moved from higher elevations of the north and center of the study area to the lower elevation areas in the valleys, to its lowest point at the eastern end of our study area. In the valleys, a downward vertical gradient characterized by the presence of several aquicludes and aquitards have resulted in a multilayered aquifer system. The presence of faults appears to play an important role in groundwater flow. In some parts of the study area faults appear to act as barriers to water movement, causing abrupt drops in water level from one side of a fault to the other, similar behavior has been described by a recent study within the Deschutes watershed in the Sisters Fault Zone [66]. In addition, the appearance of springs was noted as possible evidence of faults acting as a barrier to horizontal groundwater flow when water tries to move perpendicular to the direction of faults. In other cases, the faults may be acting as conduits for

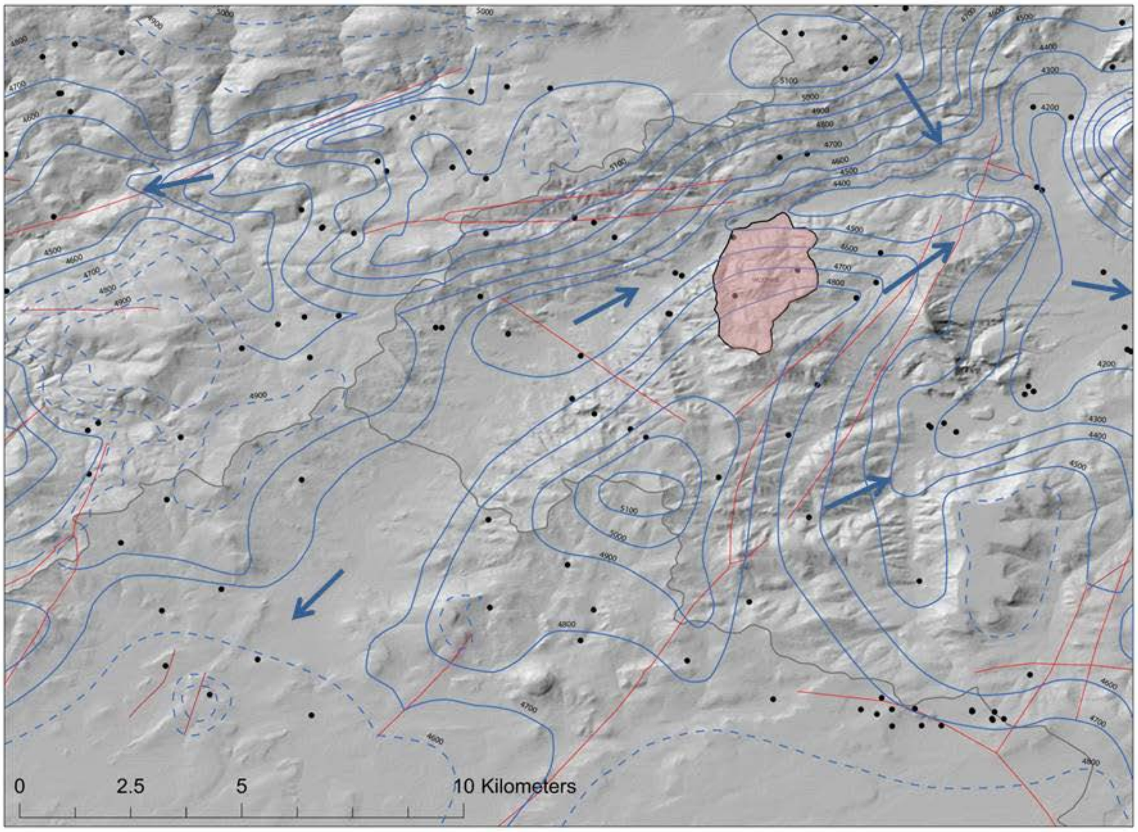


Figure 4. Potentiometric surface map showing groundwater level contours (solid blue lines), direction of flow (blue arrows), based on well static water and spring (black dots) elevation data within hydrogeologic study area. Dotted lines indicate higher degree of uncertainty on delineating groundwater level contours. Red lines indicate geologic faults.

groundwater flow when fault and flow direction are parallel. When there are several faults running together, as it is the case in an area southeast of the CCPWS site, the group of faults appear to act together creating a region of anisotropy pushing groundwater out into the valley below (Figure 4).

3.2 Shallow Aquifer Recharge and Discharge

3.2.1 Spring Discharge

Springflow data analysis showed spring discharge in both watersheds followed a seasonal pattern corresponding to regional precipitation dynamics (dry summers, wet winters). In general, springflow rates began increasing in late winter, peaked in mid-spring, and then followed a steady decline until reaching baseline levels in autumn (Figure 5). It was always the case that the treated watershed had higher springflow rates than the untreated watershed. However, while flow rates in the untreated watershed remained relatively flat throughout the entire period of record (2005-2017), springflow rates in the treated watershed had shown an upward positive trend after juniper removal that happened during 2005-2006. It is noteworthy to mention that no data were collected in years 2014 and 2015, however, the average precipitation conditions observed during those two years (see Figure 5) indicated that springflow rate trends may have remained the same for both watersheds.

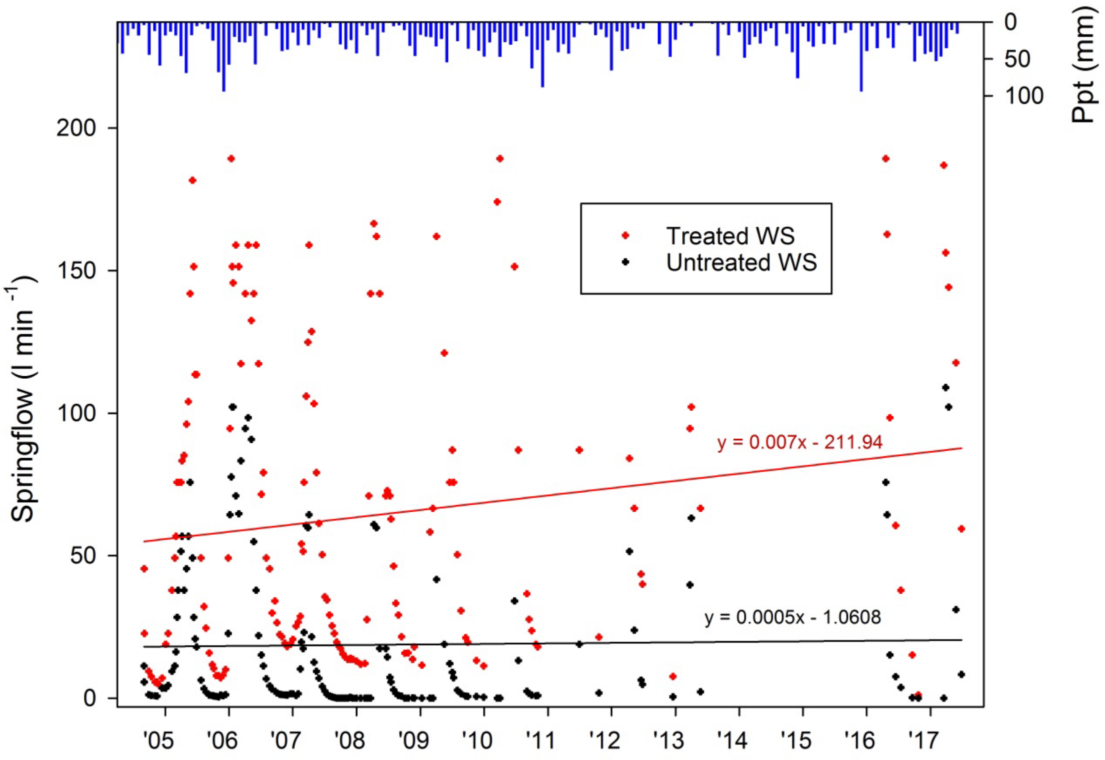


Figure 5. Springflow rate estimates for selected dates and monthly precipitation (Ppt) totals obtained for both watersheds (WS) from September 2004 through June 2017.

Total amount of precipitation observed in wet vs dry years was important in springflow discharge response observed in each watershed. For instance, the above average (275 mm) total precipitation of 418 mm in water year 2005-06 yielded relatively high springflow rate estimates for both watersheds. Conversely, a below average total precipitation of 215 mm in water year

2006-07 resulted in lower springflow rate estimates when compared to the previous year (Table 1).

Table 1. Springflow rate estimates in both watersheds during a wet (2005-2006) followed by a dry (2006-2007) water year.

	Wet Year (2005-2006)			**Dry Year (2006-2007)**		
	Precipitation (mm)*	Springflow (L min^{-1})		Precipitation (mm)*	Springflow (L min^{-1})	
		T	UT		T	UT
Oct	25.4	7.9	0.8	9.4	22.3	1.5
Nov	67.8	7.2	1.1	39.4	19.3	1.1
Dec	94.0	49.2	22.7	37.3	18.9	1.5
Jan	57.7	151.4	102.2	14.0	25.4	0.8
Feb	19.8	159.0	71.2	31.5	54.1	19.7
Mar	27.2	117.3	83.3	9.9	106.0	60.6
Apr	27.4	159.0	98.4	31.2	128.7	21.6
May	19.1	141.9	54.9	10.9	79.1	9.5
Jun	57.4	117.3	22.0	21.6	50.3	4.2
Jul	2.5	79.1	11.4	2.5	34.4	1.1
Aug	18.5	45.4	4.2	7.1	25.4	0.4
Sep	0.8	34.1	2.6	0.5	18.2	0.0
	417.6 (total)	89.1 (avg)	39.6 (avg)	215.3 (total)	48.5 (avg)	10.2 (avg)

* Precipitation data obtained from Western Regional Climate Center: BARNES STN (350501-07), Crook County, OR

3.2.2 Groundwater Level Fluctuations

Similar to springflow discharge, shallow groundwater fluctuations followed a seasonal pattern dictated by precipitation dynamics. Water table levels of up to 2 m below the ground surface were observed at the peak of groundwater response to snowmelt contributions in the springtime. Most wells went dry at 8 or 9 m depth below ground surface except one well in the treated watershed that has remained at high groundwater levels since it was installed in 2005. In general groundwater levels start rising with onset of winter precipitation, reach its peak level in spring, then followed a steady decline until it reached baseline conditions in mid to late summer.

Figure 6 shows groundwater level response in one well in the untreated watershed for years 2014 through 2017. The smaller groundwater level peak (2.6 m) reached in late February corresponds to a dry year (2014-15) dominated by precipitation that came in autumn and earl winter primarily as rain and with a maximum snowpack depth of 110 mm that did not last more than a week. Conversely, the other two years were dominated by snow precipitation that resulted in greater groundwater peak levels that showed later in the season. For instance, year 2016-17 had less rain and a sustained snowpack of up to 533 mm depth that lasted from early December through late March: this resulted in peak groundwater level of (5.3 m) reached in early April.

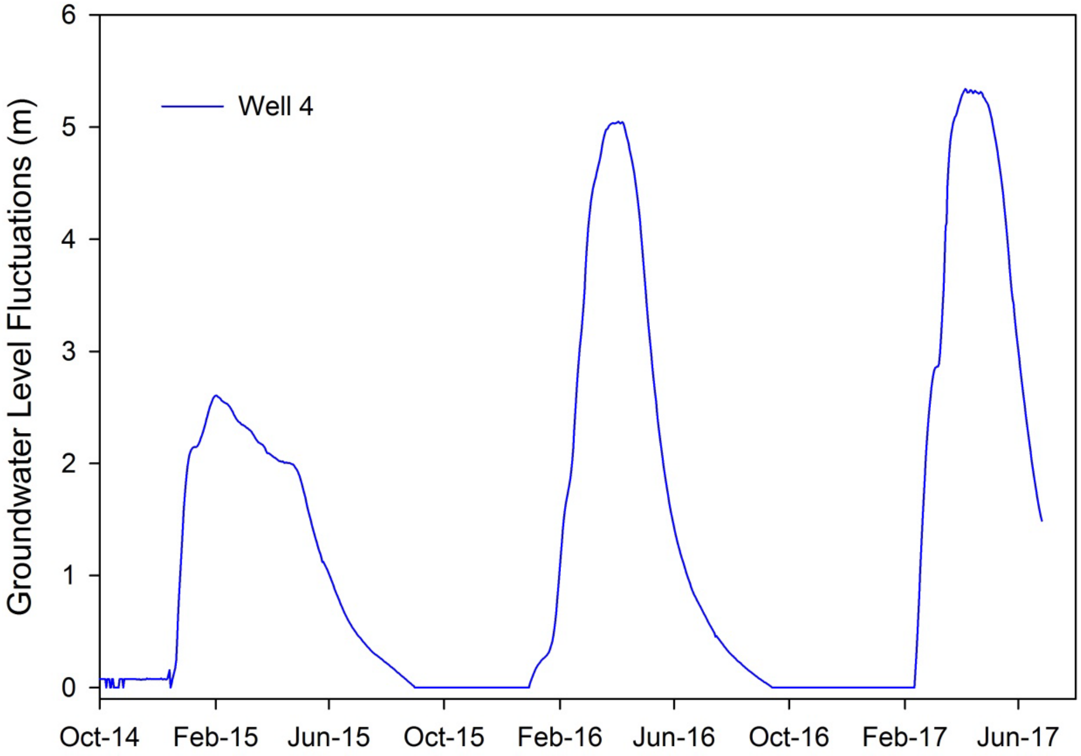


Figure 6. Shallow groundwater level fluctuations in one monitoring well in the untreated watershed for October 2014 through June 2017

3.2.3 Shallow Aquifer Recharge

Aquifer recharge estimates for the two watersheds and riparian valley were calculated using automated data collected over the past three and a half years (2014-2017). Highly variable recharge estimates were obtained from the three different locations. However, the two watersheds followed a similar aquifer recharge pattern, which is consistent with the groundwater level rise dynamics discussed in the section above. In general, the treated watershed had greater aquifer recharge estimates when compared to the untreated watershed and the riparian valley sites. The greatest aquifer recharge estimate of 784 mm in the riparian valley corresponds to the observed replenishment of the shallow system following a drier 2015 year. Because the shallow groundwater system in the riparian valley remained at relatively high levels during year 2016, the level of recharge was considerably less in year 2017 (Table 2).

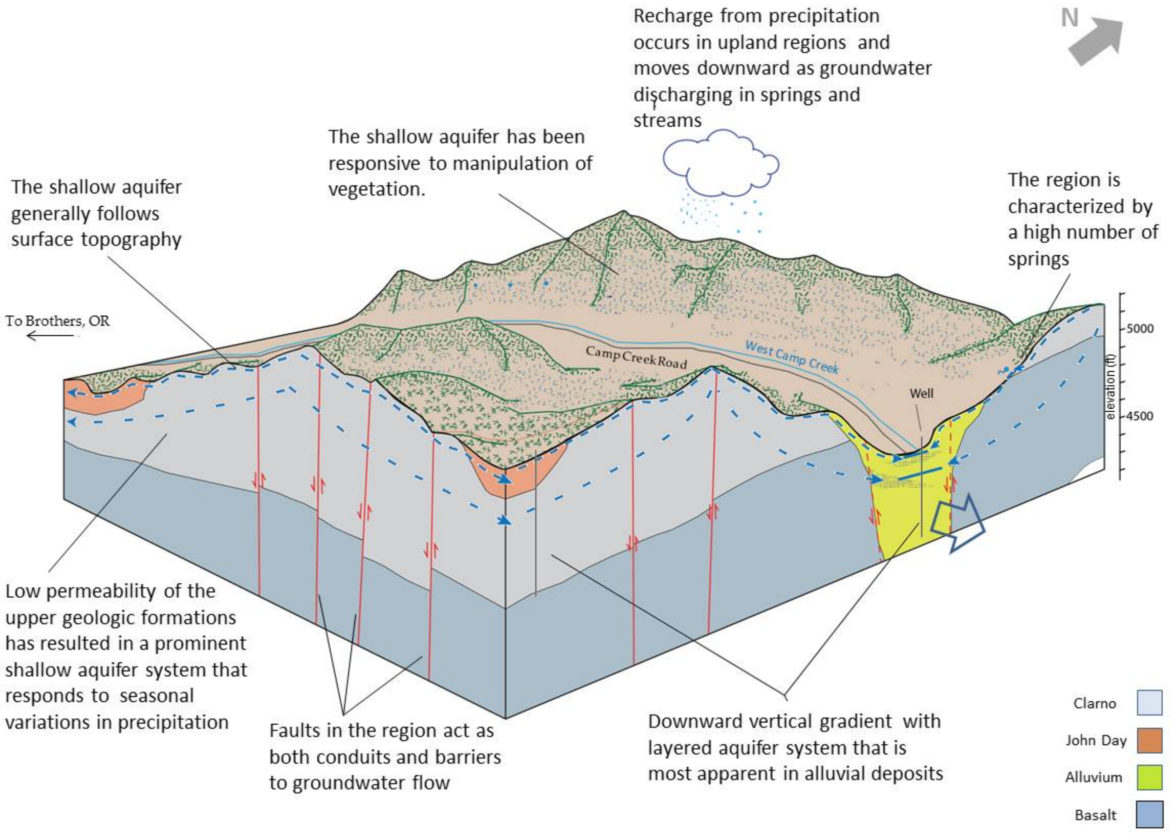
Table 2. Aquifer recharge estimates based on the Water Table Fluctuation Method for the two watersheds and the riparian valley.

Water Year	Untreated (mm)	Treated (mm)	Riparian (mm)
2015	693	1158	678
2016	1326	1173	784
2017	1410	1445	651

3.3 Conceptual Model

The information from hydrogeologic framework and plot scale recharge and discharge estimates were used to create a conceptual model of groundwater flow throughout the study area [Figure 7]. We characterized the main hydrogeologic properties of the area of larger area of interest using data from secondary sources, and we assessed surface water and groundwater relationships in the Camp Creek Paired Watershed Study Site near Brothers, Oregon using our own field collected data. The conceptual model illustrates that the region is dominated by low permeability geology characteristic of the John Day and Clarno formations. This low permeability of the deeper geologic formations has resulted in a prominent shallow unconfined aquifer system, which primarily follows surface topography. In this shallow aquifer system groundwater moves on short, one-year-scale cycles that are reflected in seasonal water table and springflow level fluctuations. Both demonstrate yearly cycles that are a product of variability in yearly precipitation totals and patterns. The shallow unconfined aquifer is not the only groundwater component in the system.

An analysis of drilling records indicated there is a downward vertical gradient that shows a multi-layered aquifer system. Deeper aquifers were most prevalent in the alluvial deposits on valley floors but were also found in the upland sections of the study area. Within the alluvial deposits are layers of clays and gravels that act to store or restrict movement of water as permeability changes creating layers of water bearing zones. The region is also with the Brothers Fault Zone and contains a large number of faults. The faults appear to influence the movement of water in the groundwater system. These faults can act as both barriers and conduits to groundwater flow. The effect of a fault on groundwater flow appears to have some relationship to the orientation of the fault to the direction of flow and may also be influenced by the character of individual faults and their presence to one another. Some faults, particularly when groundwater is moving perpendicular to the direction of the fault seem to create a barrier to flow, at times producing springs along the fault line. Others faults, especially when groundwater flow in parallel to the fault orientation appear to act as conduits to its movement, facilitating flow and creating regions of anisotropy (Figure 7).



Recharge from precipitation occurs in upland regions and moves downward as groundwater discharging in springs and streams

The shallow aquifer has been responsive to manipulation of vegetation.

The shallow aquifer generally follows surface topography

The region is characterized by a high number of springs

Low permeability of the upper geologic formations has resulted in a prominent shallow aquifer system that responds to seasonal variations in precipitation

Faults in the region act as both conduits and barriers to groundwater flow

Downward vertical gradient with layered aquifer system that is most apparent in alluvial deposits

Figure 7. Conceptual model of local groundwater flow system based on synthesis of topographic features and hydrogeologic information described in this paper.

4. Discussion

The main study goal was to enhance base knowledge regarding hydrogeologic features and the associated mechanisms of shallow aquifer recharge and discharge in a portion of the Upper Deschutes Basin in central Oregon. This study indicates that precipitation infiltration can substantially contribute to shallow aquifer recharge in the semiarid ecosystems of the Pacific Northwest, USA and potentially other similar regions worldwide. Study results show that site hydrogeology and the winter-dominated precipitation regime play a critical role in the replenishment of the shallow groundwater system. The low permeability geologic formations that underlie the area of interest have resulted in transient unconfined aquifers that are primarily recharged during winter precipitation and the spring snowmelt runoff season. These shallow aquifers are highly dependent on local recharge areas. The yearly capture of seasonal precipitation by the shallow aquifer is released through the large number of small springs and subsurface flow that moves groundwater to local riparian systems (see chapter I). These conditions allow for the presence of groundwater dependent ecosystems, as seen in other studies within the Pacific Northwest [44], and drive many land management decisions in the area such as those in ranching and farming.

With increasing uncertainty surrounding water availability exacerbated by population growth and predicted changes in precipitation patterns due to climate variability, the demand on groundwater resources is expected to increase. This pressure on groundwater supplies can be particularly problematic in water limited regions like central Oregon [6]. Increased pressures on groundwater suggest the need for a more integrated understanding of smaller-scale hydrogeologic settings responsible for sustaining local aquifer systems which are often ignored in broader hydrogeologic studies. That is the case of the southeastern portion of the Upper Deschutes Basin which is not considered an important component of the regional groundwater system but that is critical to sustaining local ecohydrologic function and ecosystem services.

Results from this study highlight interactions between surface and groundwater systems, an area that is increasingly recognized for its importance to comprehensive resource management [19,20], and discusses the role of woody vegetation effects on shallow aquifer recharge and discharge. Several authors [8,67] have pointed out the need for having a better understanding of woody vegetation's effect on groundwater replenishment in arid and semiarid regions.

The combination of hydrogeologic framework and watershed scale estimates of shallow aquifer discharge and recharge presented in this document offer a unique perspective regarding the multiple connections between vegetation, soil, geology and precipitation that influence water distribution across the landscape. These conditions allow for the presence of groundwater dependent ecosystems, which are critical for wildlife habitat and economic activites. Groundwater dependent ecosystems throughout the world, as well as in Oregon [43], are vulnerable to negative impacts from both extreme climate conditions and anthropogenic influences [68]. The hydrogeologic setting and interactions of surface water and groundwater observed at our study site suggest land management strategies to manipulate vegetation for increasing subsurface flows may have a positive effect on local GDEs by improving precipitation capture and prolong springflow release season.

Acknowledgments: The authors gratefully acknowledge the continuous support of the Hatfield High Desert Ranch, the U.S. Department of Interior Bureau of Land Management – Prineville Office, and the OSU's Extension Service, in this research effort. Our thanks go to John Buckhouse, Michael Fisher, and Mike Borman who had provided critical guidance throughout this long-term study journey. Also, we want to thank the multiple graduate and undergraduate students from Oregon State University, and volunteers, who participated in various field data collection activities related to the results here presented. This study was funded in part by NSF-STEM Scholarship Program, the Oregon Beef Council, the Oregon Watershed Enhancement Board, the Oregon Agricultural Research Foundation, and the Oregon Agricultural Experiment Station.

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General Conclusions

This study investigated the hydrogeology and the hydrologic connectivity of a study area in central Oregon. Hydrologic data were collected through onsite measurements at the Camp Creek Paired Watershed Study site and hydrogeologic data were synthesized from a wide variety of secondary sources.

The first chapter of research highlights the hydrologic connectivity found at the CCPWS. Temporary subsurface hydrologic connections have been identified as water moves from the upland watersheds to the riparian valley at the bottom of the study site. The connections are primarily influenced by the winter precipitation and spring snowmelt runoff period. The type, timing, and amount of precipitation all play a role in the level of groundwater response. Snowpack presence also has a positive impact on shallow aquifer recharge. Alternatively, juniper canopy cover has a negative effect on the amount of precipitation reaching the soil surface and decreases soil moisture levels and potential aquifer recharge. This study helps us to further our understanding of hydrologic connectivity in semiarid ecosystems.

The second chapter of research investigated the local hydrogeologic framework for a region of interest surrounding the CCPWS and evaluated the mechanisms of recharge and discharge of the shallow aquifer. Results suggest the predominantly low permeability geologic formations play a major role in shaping the local groundwater system. The area is within the Brothers Fault Zone and the faults appear to act as both conduits and barriers to groundwater flow. The geology, in part, has produced a system with a prominent unconfined shallow aquifer that follows surface topography and is characterized by a high number of springs. The springflow and groundwater level fluctuations follow year-long cycles that are effected by the type and amount of precipitation that comes during the wet season. Both groundwater levels and springflow show little to no response to convective summer storms. This study also found the system to be responsive to vegetation manipulation. Over a 13 year period of record springflow has shown a positive upward trend in the treated (juniper removed) watershed compared to a steady trend in the untreated (juniper present) watershed.

This research helps to continue to build on the work at the Camp Creek Paired Watershed Study site and its goal to understand the effects of juniper on hydrologic function. A better understanding of the hydrogeology and the hydrologic connectivity at this site can help to inform future research and provide land managers and stake holders with information to make informed decisions in a continually changing world.

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