HYDROLOGIC ANALYSIS OF SPRINGS IN SEMI-ARID NORTHERN ARIZONA ON THE COLORADO PLATEAU

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ABSTRACT

HYDROLOGIC ANALYSIS OF SPRINGS IN SEMI-ARID NORTHERN ARIZONA ON THE COLORADO PLATEAU

SARAH JEAN ZURKEE

The Four Forest Restoration Initiative (4FRI) is a project supported by the Forest Service that involves collaboration among multiple entities to restore approximately 2,400,000 acres of forest ecosystems in Northern Arizona. The primary goal of the restoration project is to improve the health and resiliency of the forest ecosystems. Few studies have analyzed the relationship between forest management and groundwater responses to forest management actions. Four springs located on the Colorado Plateau, near northern Arizona, underwent continuous observation and documentation over various spans of time. The natural springs analyzed in this study include Hart Prairie Spring, Clover Spring, Hoxworth Spring, and Big Spring. Analysis of the compiled data from these sites involved variations of qualitative and quantitative methods. The depth of analysis varies from site to site, depending on length of record. Hart Prairie Spring has the longest length of recorded data. Analyses were conducted to determine the hydrologic response pre- and post-forest restoration. Hoxworth Spring and Clover Spring are additional treatment sites with a hydrologic analysis prior to forest restoration treatments. Big Spring is a control site recording continuous hydrologic data, without the influence of forest restoration treatments. The accumulated hydrologic data were collected, analyzed, and used to create annual hydrographs. Climate data, such as weather conditions were analyzed in conjunction with the hydrologic analysis.

Understanding the hydrologic effects of the forest restoration efforts will contribute to future water budget predictions and forest management methods. The rapidly growing population, and agricultural and industrial development in the region places added pressure on groundwater supplies and demand. Ecohydrological restoration efforts have increased the number of flowing days for Hart Prairie Springs. This response indicates that groundwater recharge responds positively to restoration actions. Further data collection and analysis are needed to determine and quantify the effectiveness of forest restoration in increasing groundwater recharge, spring discharge and ecological functionality in Northern Arizona.

Acknowledgments

I express my deep gratitude to my advisor Dr. Abe Springer for his guidance and knowledge in the classroom, weekly meetings, and various field excursions. I am additionally incredibly grateful for his continuous mentoring not only in academia, but in preparation for my professional career. I also want to acknowledge my committee members: Dr. Frances O'Donnell and Dr. Lawrence Stevens. Both members provided valuable guidance and knowledge and were especially helpful in providing various perspectives on the project and analyses, in addition to being very flexible and patient with communication. I want to acknowledge all the current students that I am so grateful to have helped me through fieldwork, which may have ranged from a beautiful sunny day to crawling through an insect filled culvert: Katelyn LaPine, Andrew Lewis, Cole Denver, Isaiah Meza, Caelum Mroczek, and Tawfic Yakubu. I would like to thank and acknowledge Max Evans and Keegan Donovan for being patient and helping me when I have questions regarding data or preparing field equipment. With some of these study sites spanning back many years, Hart Prairie Spring spanning back 26 years, I would like to graciously thank all the past students that have contributed numerous working hours out in the field and/or compiling datasets, that I now use towards my thesis. I would like to thank Tucker Herbert and Northern Arizona University's Fleet Services for assisting in planning these field visits and being tremendously helpful towards providing transportation to the study sites. I am additionally acknowledging and thanking the USFS Coconino National Forest and The Nature Conservancy Hart Prairie Preserve for allowing students to conduct research on their land. I would also like to thank the funding sources for this study: Partial financial support was provided by the U.S. Forest Service; Award number 19-CS-11030700-01.

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Preface

This thesis has been structured to meet the requirements for Northern Arizona University graduate thesis standards. Chapter 2 is a manuscript formatted for submission to the journal Groundwater of the National Ground Water Association. The manuscript has in-depth analysis of the Hart Prairie Spring study site from pre- and post-restoration treatments. The thesis expands on the additional study sites, Clover Spring, Hoxworth Spring, and Big Spring, in Chapters 1 and 3. All results and interpretations are entailed in Chapter 3. Final conclusions and recommendations for future research can be found in Chapter 4.

Chapter 1: Introduction

1.1 Introduction

Springs are defined as "ecosystems in which groundwater reaches the Earth's surface either at or near the land-atmosphere interface or the land-water interface" (Springer & Stevens, 2009). Springs are components of watersheds that are of immense importance but can be undervalued (Cantonati et al., 2020; Springs Stewardship Institute, 2021). The hydrology of springs coupled with the ecological component, provide an in-depth understanding of watershed health and resiliency. Ecohydrogeology, also known as the integration of hydrogeology and ecology, provides beneficial context within these scientific entities (Cantonati et al., 2020).

Northern Arizona has a semi-arid climate. Riparian ecosystems are located near water sources and typically are high in biodiversity and are considered "ribbons of life," due to being recognized as the most productive habitats within the United States (Zaimes et al., 2017). In Arizona, riparian ecosystems are considered critical areas, in addition to hosting 80 percent of all vertebrates during at least part of their life cycle and support several hundred rare and sometimes endemic groundwater-dependent species (Cantonati et al., 2020; Hubbard, 1977; Stevens et al., 2020). Hydrologically, riparian areas can reduce the flux and cover of flooding or increased runoff, therefore allowing for an increase in soil moisture and groundwater recharge (Wissmar & Swanson, 1990).

1.2 Forest Restoration

The United States Forest Service is conducting the largest collaborative forest restoration project in the U.S., called Four Forest Restoration Initiative (4FRI) (Stewart et al., 2015). The restoration effort covers approximately 2.4 million acres in the Apache-Sitgreaves, Coconino, Kaibab, and Tonto national forests in Northern Arizona (Figure 1-1). The purpose of this project is to restore the forest ecosystem, reduce the severity of forest fires, improve watershed health, and conserve biodiversity in the semi-arid regions of Northern Arizona through the use and monitoring of tree thinning and prescribed burning. 4FRI is a collaborative effort, with multiple entities involved in restoration, monitoring, and research to improve the understanding of the ecological, hydrological, and economic effects of forest restoration. Implementing tree thinning in forests that have undergone increased stem density because of fire suppression and intensive grazing, are expected to reduce fire severity and improve forest health; however, this is not an entirely new idea, as it has been employed for decades. The U.S Forest Service and the 4FRI stakeholder group established a monitoring and management partnership that involves multiple organizations, including Northern Arizona University. The assessments from these entities will help the U.S Forest Service develop future restoration plans to best manage and restore the forests and the ecosystems within them (Stewart, 2010).

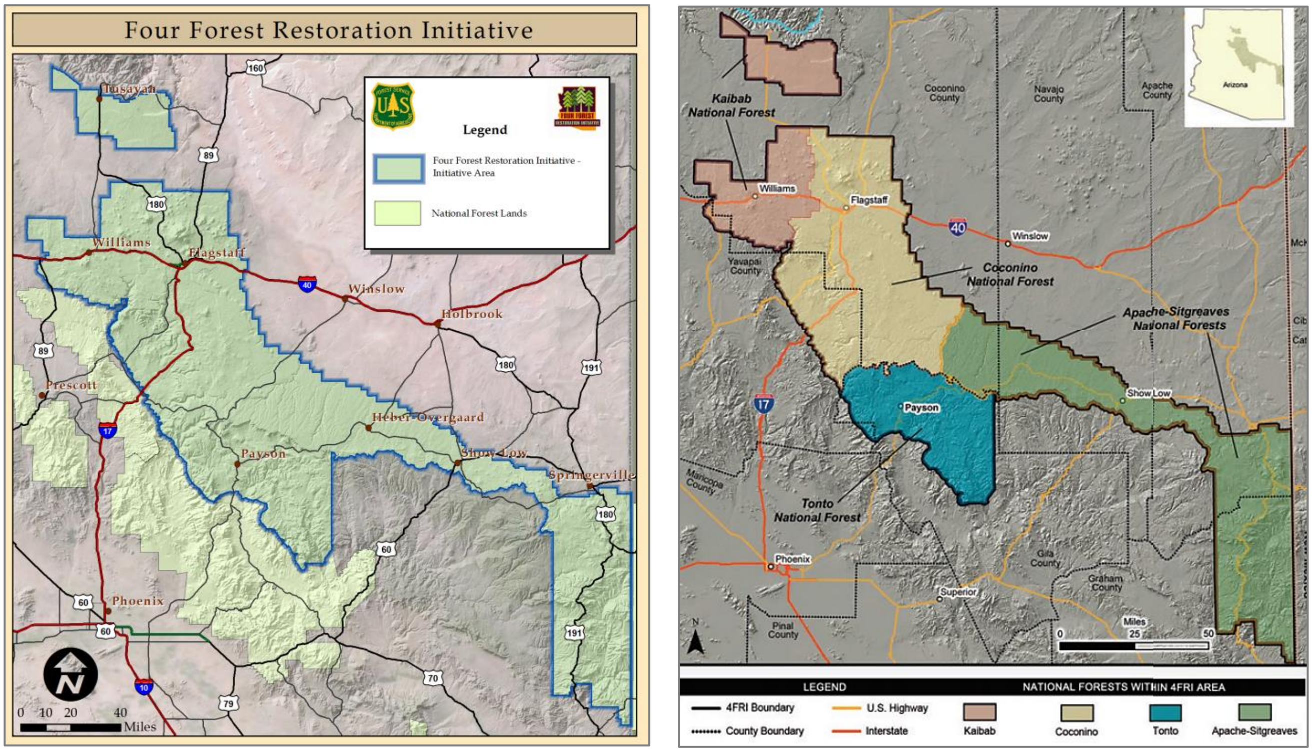


Figure 1-1. The left map is of the 4FRI project area. The right map is also of the 4FRI project area, but labels the four forests involved in the initiative (USDA Forest Service, Coconino National Forest, 2023)

1.3 Monitored Springs

Four natural springs located on the Colorado Plateau, near Northern Arizona were monitored and analyzed in this study (Figure 1-2). The following three springs, Hart Prairie Spring, Hoxworth Spring, and Clover Spring, all lie within the initial Four Forest Restoration Initiative analysis area on the Southern Colorado Plateau within the Coconino Forest. These springs were intentionally selected as long-term hydrologic monitoring locations based on their restoration, ecological, and cultural values (Table 1-1). Hart Prairie Spring and Clover Spring have undergone forest restoration treatments, while Hoxworth Spring is currently receiving forest restoration treatments. Big Spring, located in the Kaibab forest, is a control site and will therefore not undergo forest restoration treatments (Schenk et al. 2019).

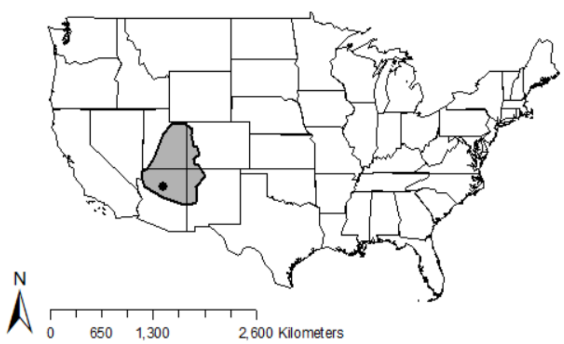


Figure 1-2. Map (above) displays the United States of America with the Colorado Plateau Highlighted. The image on the (right) is a zoomed in map of northern Arizona with the locations of the four studied springs (Hart Prairie Spring, Clover Spring, Hoxworth Spring, and Big Spring).

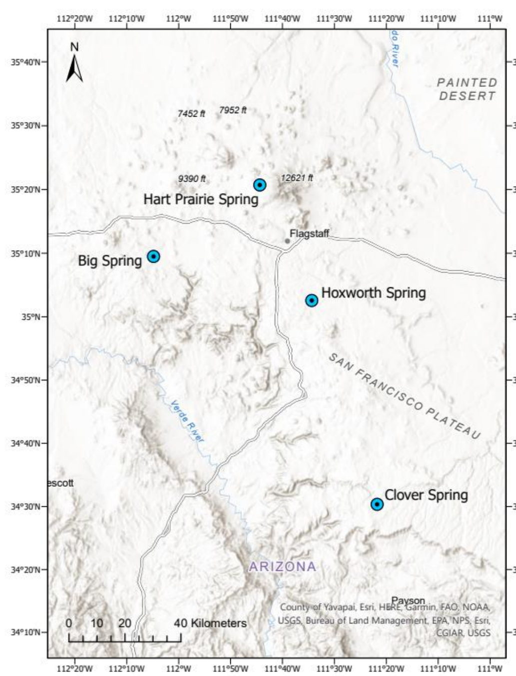
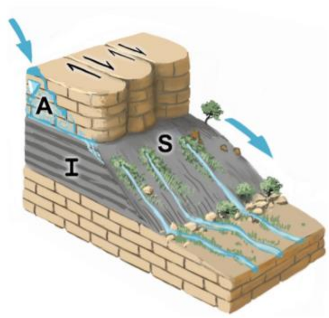
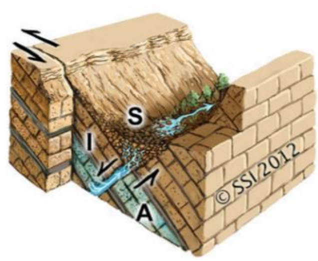
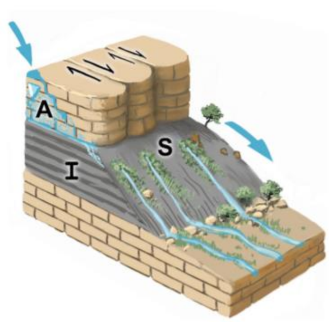
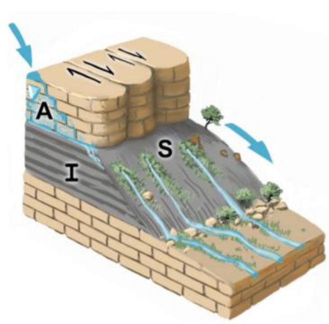


Table 1-1. Conceptual spheres of discharge for the four continuously monitored springs included in this thesis. Table depicting the spring name, spring type, conceptual diagram, and geologic overview (Springer & Stevens, 2009).

Spring Name	*Spring Type*	*Conceptual Diagram*	*Geology Overview*
Hart Prairie Spring	Hillslope		Spring complex that emerges from a hillslope structure (30°-60°). The channel catches both ephemeral spring discharge and runoff.
Hoxworth Spring	Rheocrene		Fault contact, Kaibab Formation aquifer discharges directly into a stream channel.
Clover Spring	Anthropogenic (modified hillslope)		Conduit discharge from the Kaibab Formation in karst terrain. Source modified for highway construction. Discharge into a box, below the road and into a wet meadow through a culvert.
Big Spring	Hillslope		Source from contact between lower fractured basalt flow regional Kaibab Limestone. Discharge from a basalt flow on a hillside into a channel. Spring channel joins surface runoff Southeast of spring.

1.3.1 Hart Prairie Spring

The watershed for Hart Prairie Spring is located on the western slope of the San Francisco Mountains. The surficial deposits in the Hart Prairie watershed are a part of the Sinagua Formation (Q), which is composed of eight depositional fans that radiate outward from the San Francisco Mountains (Amentt, 2002). This formation is composed of poorly sorted, coarse deposits and mudflows that contain clays and boulders with sizes ranging up to 4 m (13.12 ft) in diameter (Holm, 1988; Pewe & Updike, 1976). The headwaters of the Hart Prairie watershed are located at Humphrey's Peak, the highest point in Arizona. The catchment area is approximately 11.64 km^2 with an elevation gain of approximately 1,264 m (4,146 ft) and an average slope of 21.8%. A portion of the spring discharges into Volunteer Wash, near the base of Fern Mountain, that drains into the Salt-Verde River Basin. The remaining catchment area of San Francisco Mountain drains into the Little Colorado River basin. According to the United States Environmental Protection Agency (EPA), this spring is located within 86001, Flagstaff, Arizona watershed code: Volunteer Wash (150602020301) (United States Environmental Protection Agency, 2023). Hart Prairie Spring is defined as a hillslope ephemeral spring that is primarily a snow-driven hydrologic system. Studies at this location began in 1995. This site has approximately 25 years of continuous discharge data that provides an in-depth analysis of the hydrologic response for the forest restoration treatment that were implemented in 2013 and 2014. This site is further described and analyzed in the manuscript (Chapter 2).

1.3.2 Hoxworth Spring

Hoxworth Spring is located near Lake Mary at an estimated elevation of 2,154 m (7,066.92 ft). Near this spring is the Anderson Mesa-Lake Mary fault system, which is approximately 40 km (131,234 ft) long and acts as a control for surface and groundwater occurrences (Brumbaugh, 2011; Miller et al., 2007). Hoxworth Spring lies in a graben, bounded by two normal faults (Donovan et al., 2021; Godwin, 2004). The flow source comes from the highly porous and permeable Kaibab Formation aquifer (Graham, 2008). The spring emerges from a fault that then flows through a tributary stream of Upper Lake Mary within a grassy riparian meadow. According to the United States Environmental Protection Agency (EPA), this spring is located within 86038, Mormon Lake, Arizona watershed code: Walnut Creek-Upper Lake Mary (150200150202) (United States Environmental Protection Agency, 2023). Hoxworth Spring is classified as a rheocrene perennial spring (Springer & Stevens, 2009). The historical modifications of the riparian ecosystem within Hoxworth Spring have led to disturbance in water distributions. Historically, the springbrook channel in the wet meadow was sinuous in shape, with slow to moderate wide-spread flow. This channel geometry supports re-infiltration. Anthropogenic modifications, such as tree logging, roadways, and railways decreased channel sinuosity, which led to increased channel erosion and unhealthy ecosystem characteristic (Godwin, in progress). Hoxworth Spring study site is a 4FRI treatment spring with continuous discharge monitoring since 2014. Partial forest thinning treatments were implemented in 2017 and 2018, and completed in 2022 (Schenk et al., 2019). The current discharge datasets are compiled and analyzed for the pre-restoration treatment calibration period in this study.

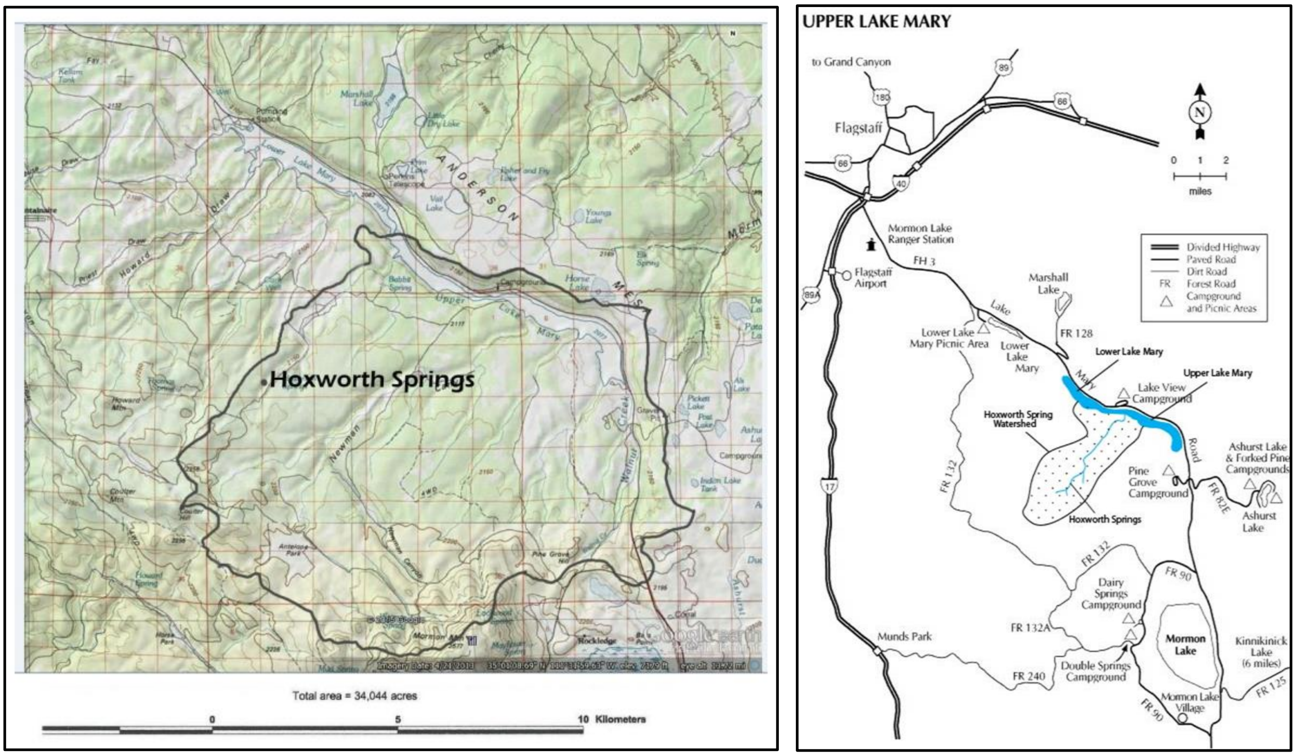


Figure 1-3. The left image shows the Upper Lake Mary Watershed Boundary with Hoxworth Spring Location (Nash et al., 2015) (not modified). The right image shows Hoxworth Spring location and watershed (not modified).

1.3.4 Clover Spring

Clover Spring is located south of the Happy Jack Ranger Station, near the Mogollon Rim. The flow source comes from base of the Kaibab Formation aquifer above the Coconino Formation and into karstic terrain. Clover Spring is defined as an ephemeral hillslope spring with anthropogenic modification. Seasonal flow discharges into an installed spring box underneath Highway 87N, through a culvert, and into a wet meadow. According to the United States Environmental Protection Agency (EPA), this spring is located within AZ-87, Happy Jack, Arizona, 86024 watershed code: Clover Creek (150602030104) (United States Environmental Protection Agency, 2023). Clover Spring is one of the 4FRI initial treatment sites and has continuous discharge data since 2013. The discharge datasets have been compiled and analyzed for the pre-restoration treatment calibration period of 4FRI (Donovan et al., 2021).

1.3.5 Big Spring

Southeast of Williams, Arizona, Big Spring is a control (untreated) 4FRI spring located in the Middle Sycamore River Watershed, upstream from Sycamore Falls. According to the United States Environmental Protection Agency (EPA), this spring is located within the Kaibab National Forest watershed code: Big Spring Canyon (150602020307) (United States Environmental Protection Agency, 2023). As such, no forest restoration treatments are being implemented, other than potentially low intensity burning and fencing to reduce elk and livestock trampling. The source for Big Spring originates from a contact between a fractured basalt flow and the underlying Kaibab Formation limestone, which is exposed in a hillslope and flows into a surface runoff channel (Combs & Springer, 2020). Big Spring is classified as a perennial hillslope spring. This spring site has minimal anthropogenic modifications, such as an installed pipe within the hillslope for a more direct flow. However, there are frequent recurrent disturbances at the site, such as cattle and elk grazing. Big Spring has continuous discharge data since 2019.

1.4 Springs Monitoring Techniques

All spring sites were monitored by conducting quarterly visits to download continuous discharge data, document discrete discharge data, and implement any necessary maintenance on site or equipment. Each site visit had the following objectives: download pressure transducer data, manually measure discrete spring discharge, document discrete water quality parameters, collect water samples, and maintain site equipment.

1.4.1 Continuous Spring Discharge Monitoring

Continuous discharge data were recorded from InSitu™ pressure transducers at each site. The pressure transducer models varied from site to site and changed over the years. The model types of the springs instruments and locations are described in Table 1-2. All pressure transducers were initially set to record at 60-min intervals. This consisted of recording the timestamps, set level measurement preference, and temperature. Temperature changes were continuously measured to assist in determining ephemeral spring activity, the hydro period of the spring, and identify any questionable errors (Schenk et al. 2019).

Each pressure transducer was installed in a stilling well that was crafted for the individual site. The stilling wells for Hoxworth Spring and Big Spring consisted of open-top piping secured by T-posts (Figure 1-3). Clover Springs consisted of an open-top PVC pipe attached to concrete within the spring box. Hart Prairie Spring has a stilling well attached to the H-flume (Chapter 2). Each pressure transducer had desiccant packs attached to the vented cables to prevent moisture accumulation and data error.

Figure 1-4. Hart Prairie Spring Site. From left to right: The first image is of the Hart Prairie Spring H-Flume. The H-flume is situated in Volunteer Wash, as shown in the photo, near the base of Fern Mountain. Near the mouth of the flume, to the left, is the stilling well. The stilling well contains the pressure transducer (04/22/2022). The second image is of the back end of the H-flume where surface water enters (10/02/2022). The third image is the Hart Prairie watershed catchment area (09/04/2022).

Figure 1-5. Clover Spring site. From left to right: The first image is the gated culvert with a smaller pipe to direct flow. The previous stilling well is still installed, but not being used (09/03/2022). The second image is of the spring box. The new pressure transducer was installed in the white PVC pipe (09/03/2022). The third image is of the Baski 1” flume being used in the wet meadow channel (04/29/2022).

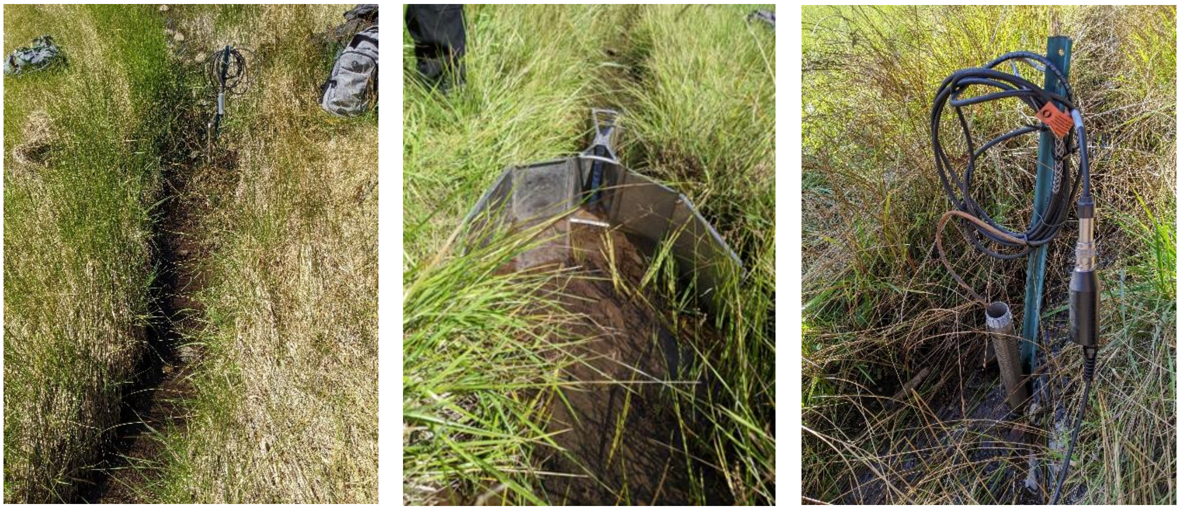


Figure 1-6. Hoxworth Spring site. From left to right: The first image is of the channel with the stilling well and pressure transducer (06/08/2022). The second image is of the Baski 1” flume being used in the channel (09/03/2022). The third image is a close-up of the stilling well and pressure transducer as it was connected to a laptop and downloading data (10/02/2022).

Figure 1-7. Big Spring site. From left to right: The first image is of the installment of the stilling well and pressure transducer at Big Spring (circled in red), in addition to the Baski 4” flume being used in the channel (2019). The installation was done by Abe Springer and Cecily Combs. The second image is of the channel downstream from the stilling well and pressure transducer (03/30/2022). The third image is of the pressure transducer post regular maintenance (06/09/2022).

Table 1-2. Table depicting general spring information. This includes the spring name, geographic coordinates and elevation, instruments used to collect continuous data, and the length of recorded data for each studied site.

Spring Name	*Geographic Coordinates*	*Instrument(s)*	*Recorded Parameters*	*Length of Record*
Hart Prairie Spring	35.34523, -111.73944 Elevation: 2,588 m (8,490 ft)	Float Recorder and Stevens F Gauge, TROLL 4000, Aqua TROLL 500, Aqua TROLL 200	Timestamp, Elapsed Seconds, Temperature, Pressure, Depth	4/24/1997 - 9/4//2022 (~ 25 years)
Hoxworth Spring	35.04254, -111.57260 Elevation: 2,154 m (7,066 ft)	Level TROLL 500	Timestamp, Elapsed Seconds, Temperature, Pressure, Depth	7/6/2014 - 10/20/2022 (~ 8 years)
Clover Spring	34.50579, -111.36270 Elevation: 2,093 m (6,866 ft)	Level TROLL 500, Aqua TROLL 600, Aqua TROLL 200	Timestamp, Elapsed Seconds, Temperature, Pressure, Depth	6/17/2010 - 10/1/2022 (~ 12 years)
Big Spring	35.15808, -112.08060 Elevation: 2,077 m (6,814 ft)	Level TROLL 500	Timestamp, Elapsed Seconds, Temperature, Pressure, Depth	8/1/2019 - 10/2/2022 (~ 3 years)

1.4.2 Base-Flow Separation

The environmental locations and spring classification of the monitored springs vary and influence surface runoff, information that is included in the spring discharge record. A base-flow separation process was conducted to separate the spring discharge from the surface runoff. Therefore, the hydrologic properties directly related to the monitored spring could be isolated and analyzed with less interference. The base-flow separation analysis was completed by using Purdue University Web-Based Hydrograph Analysis Tool (WHAT) (Donovan et al., 2021; Lim & Engel, 2003).

Hoxworth Spring was subjected to a base-flow separation analysis. The mean daily discharge values were uploaded into the Web-Based Hydrograph Analysis tool (WHAT). Various filters were applied to best represent the conditions of the spring sites. The following parameters were selected prior to separating base flow from stream flow data:

- Recursive Digital Filter
    - Aquifer type: Perennial streams with porous aquifers
    - Filter Parameter of 0.9 – BFI_{max} of 0.80

The BFI_{max} of 0.80 represents the baseflow index, or the ratio of baseflow to the total flow (Eckhardt, 2004). This value was selected due to aligning with the hydrogeological characteristics of Hoxworth Spring

1.4.3 Discrete Spring Discharge Monitoring

Discrete discharge data were collected at each spring site during quarterly site visits. Discharge was measured by placing a 1-, 4- or 8-in Baski Cutthroat Flume in the stream near the spring source to record discharge in gallons per minute (gpm). A manual stage measurement was recorded at the stilling well where the InSitu™ pressure transducer was located using a hand-ruler. These readings were documented to correlate stage height with the continuous pressure transducer data and were then used to create a rating curve.

1.4.4 Water Sampling

During each quarterly visit a filtered 4 mL water sample was collected for stable isotope testing, when available. This parameter was not analyzed in this thesis but is reported in (Chapter

3). Isotope samples were analyzed at Northern Arizona University in the Arizona Climate and Ecosystems Isotope Laboratory.

1.4.5 Water Quality

At each quarterly visit a ProDSS YSI Multi-Water Parameter Water Quality Probe was used to record discrete measurements of water quality, when available. The following parameters were recorded during this process: GPS location, timestamp, temperature, pH, specific conductivity, dissolved oxygen (DO), salinity, barometric pressure, altitude, turbidity, and total dissolved solids (TDS). These parameter were not analyzed in this thesis but are reported in Chapter 3.

1.5 Study Purpose and Objectives

The purpose of this study was to process and analyze the discharge data from Hart Prairie Spring, Hoxworth Spring, Clover Spring, and Big Spring. The length of calibration data compiled prior to forest treatment implementation should be approximately 6-8 years, followed by monitoring the sites for an additional 7-10 years after treatments have been implemented (O'Donnell et al., 2015). The analyses from Hart Prairie Spring were used to determine if there was a hydrologic response associated with forest restoration treatments that took place in 2013 and 2014; this will be discussed further in Chapter 2. The compiled data from Hoxworth Spring and Clover Spring are for assessment of a pre-treatment analysis. The data compiled from Big Spring was used as a control site analysis.

The forest restoration treatments are completed with the intention of improving forest health resiliency. It is believed that anthropogenic modifications are responsible for the unhealthy characteristics of the forested ecosystem. These characteristics range from an increase in tree density, an increase in fire severity, a decrease in growth and biodiversity of herbaceous and woody plants, and decreased spring and stream flow (Covington & Moore, 1994). Understanding how forest management affects groundwater infiltration and surface water yield is important at Hart Prairie Springs because there is a rare groundwater-dependent ecosystem and is a tributary to the Verde River, which downstream flows to growing communities (Amentt, 2002). The correlation between climate parameters such as weather events and spring discharge were analyzed. The analysis of the data will support an understanding of the effects of forest management on groundwater and changes in hydroperiod trends.

Chapter 2: Hydrologic Responses of the Spring-fed Hart Prairie Watershed to Forest Restoration, Semi-arid Northern Arizona

ABSTRACT

Long-term studies analyzing the relationship between forest management and groundwater responses to forest management actions are uncommon. In this 26-yr study, the hydrologic response of groundwater recharge and spring discharge were monitored and analyzed at spring-fed Volunteer Wash in the Hart Prairie watershed in relation to watershed forest restoration treatments. Water availability in Hart Prairie has been a concern for conservation of a rare, high-elevation Bebb Willow (*Salix bebbiana*) assemblage, which is dependent on shallow groundwater discharge (Amentt, 2002).

Analysis of these long-term data involved both qualitative and quantitative methods, including visual analysis of pre- and post-forest management treatments. Geographic information systems were used to create a Hart Prairie Spring watershed map and tree canopy coverage map prior to and following restoration. The accumulated hydrologic data were collected, analyzed, and used to create annual hydrographs. Climate data, such as precipitation, snow water equivalent, and climatic cyclicity, were compiled and compared with multilinear regression models of the hydrologic response pre- and post-restoration treatment. Rainfall runoff displayed significant results. Snowmelt runoff had significant correlation post-treatment. Peak spring discharge is occurring earlier in the season, depicting climatic changes. These factors indicate that there was a positive hydrologic response due to the forest restoration treatments that were implemented from 2013 to 2014. Understanding the effects of the forest restoration effort helps land and resource managers understand the responses of future forest restoration projects.

2.1 Introduction

2.1.1 Four Forest Restoration Initiative Background Information

The United States Forest Service is conducting the largest Collaborative Forest Restoration Project in the U.S., called the Four Forest Restoration Initiative (4FRI) (Stewart et al., 2015). The restoration effort covers approximately 9,712 km^2 in the Apache-Sitgreaves, Coconino, Kaibab, and Tonto national forests, located in Northern Arizona. The purpose of 4FRI is to restore the forest ecosystem, reduce the severity of forest fires, improve watershed health, and conserve biodiversity in the semi-arid regions of Northern Arizona using tree thinning, prescribed burns, and monitoring. 4FRI is a collaborative effort, as multiple entities are involved in the restoration and monitoring process and efforts to enhance the understanding of the ecological, hydrological, and economic effects of this restoration initiative. Implementing tree thinning in forests that have undergone increased stem density because of fire suppression and intensive grazing, and thereby to reduce fire severity and improve forest health is not entirely a new idea, as it has been used for decades. The U.S Forest Service and the 4FRI stakeholder group established a monitoring and management partnership that involves multiple organizations, including Northern Arizona University. The assessments from these entities will help the U.S Forest Service develop future restoration plans to best manage and restore the forests and the ecosystems within them (Stewart et al., 2015).

2.1.2 Restoration Treatments

The United States Forest Service carried out an environmental assessment of the Hart Prairie Fuels Reduction and Forest Health Restoration Project, which was published in 2010 (Stewart, 2010). The assessment of the project led to the implementation of “Alternative B:

Proposed Action". Actions that were implemented from this decision included various methods of forest restoration treatments, fencing of sensitive areas, protection of soil and water resources, and fire hazard reduction. The methods for forest restoration treatments varied from tree thinning, prescribed burns, and uneven-aged tree management. Spatial arrangement of dense ponderosa pine and mixed-conifer stands were primarily treated using mechanical thinning methods with the significance of replicating a similar structure, prior to anthropogenic modifications. The combination of clear-felling or hand thinning were methods primarily used for Aspens. Bebb Willow restoration included planting local plants and removal of excess debris, primarily to increase the chances of growth. Additionally, installation of fencing around existing or new Bebb Willow was used to reduce ungulate browsing. The implementation of prescribed burns was dependent on the area or tree stand. Prescribed burns were used for areas that were recently thinned to get rid of excess slash and debris. Monitored maintenance burns were implemented with the goal to moderate conditions for forest fires. Spring habitat restoration included the installation of fences to moderate ungulate browsing. The treatments from the "Alternative B: Proposed Action" were to be implemented on approximately 45.86 km^2 of National Forest System Lands (Stewart, 2010). To maintain forest plan consistency, the Hart Prairie restoration project follows recommended guidelines and management area standards (M3) (USDA Forest Service, Coconino National Forest, 1987).

2.1.3 Previous Research

Prior to modern anthropogenic modification, the forest structure in Northern Arizona, was primarily open meadows with copses of mixed age Ponderosa Pine, as compared to the present day dense forest structure (W. Wallace Covington et al., 1997). More than a century of fire exclusion, logging, and livestock grazing led to unhealthy ecosystem characteristics, such as a rapid 20th century increase in Ponderosa Pine tree density, an increase in fuel materials, and an increase of forest floor depth (litter and organic debris) (Cocke et al., 2005). Covington & Moore, 1994 noted that a rapid increase of a dominant species can change the ecosystem by reducing the species diversity, leading to a decline in ecosystem health, including surface water and groundwater availability. Their conclusions prompted multidisciplinary research into forest restoration treatments and how they affect ecosystem function. Specifically, those studies have shown that forest restoration treatments that implement tree thinning rather than clear-cutting increase groundwater recharge, decreased forest stand density, and improved forest ecosystem structure towards pre-settlement conditions (O'Donnell et al., 2015; Schenk et al., 2020). The interaction between forest management actions and groundwater systems are imperfectly known and require long-term monitoring (Smerdon et al., 2009). Following restoration treatments, we expected to see an increase in groundwater recharge; however, the amount and duration of recharge is dependent on the landscape (Schenk et al., 2019; Smerdon et al., 2009).

The Springs Stewardship Institute monitors the health of 56 4FRI springs (Springs Stewardship Institute, 2021), and Northern Arizona University has been monitoring the Hart Prairie Springs watershed for approximately 25 yrs. The groundwater system in this area has been studied, and we compiled those hydrologic data in relation to the forest restoration treatments for analysis in this study (Gavin 1998; Amentt 2002). Long-term monitoring of spring flow, in conjunction with long-term climate analysis, provides a more accurate understanding of the dynamics of the hydrologic cycle and the interactions between the Hart Prairie hillslope spring system. The topography, elevation, and steep slope gradient create dynamic annual bimodal precipitation events (Healy et al., 2007; Zaimes et al., 2017). Hart Prairie Springs are characterized as primarily snow-driven hydrogeology, given their high-elevation location (> 2,600 m). In this region, the duration of snowpack is the most influential factor affecting discharge variation (Donovan et al., 2021).

2.1.4 Purpose and Objectives

The purpose of this study was to determine whether Hart Prairie Spring discharge responded to restoration treatments that occurred in 2013 and 2014. The restoration treatments were completed with the intention of improving forest health resiliency. Anthropogenic modifications have been held responsible for unhealthy characteristics of the forested ecosystem. These characteristics include increased tree density and fire severity, and decreased tree growth, herbaceous and woody plant biodiversity, and spring and stream discharge (W. Wallace Covington et al., 1997). Understanding how forest management affects groundwater infiltration and surface water yield is important because the Hart Prairie Spring study area supports a rare groundwater-dependent ecosystem and is a tributary to the Verde River, which supports rapidly growing human population (Amentt, 2002).

The correlation between climate parameters, such as snow melt duration and spring discharge were also analyzed. Our analyses will help refine understanding of the effects of improved forest management on groundwater availability. Our primary goals at this site were to:

1. Maintain the established monitoring site for Hart Prairie Spring.
2. Compile, analyze, and interpret existing discharge data.
3. Analyze the spring's responses to climate variables measured at nearby climate stations.

The following are research questions that were developed for this study:

1. How did Hart Prairie Springs respond to the restoration treatments conducted in 2013 - 2014?
    a. How significant are the restoration treatments to spring discharge?
2. From the long-term study, is there a climatic trend?
    a. How does Hart Prairie Spring respond to various climatic parameters?
3. Are the hydrologic conditions in Hart Prairie sufficient to establish and maintain Bebb Willow community?

2.2 Site Description

2.2.1 Study Area

Located on the southern edge of the Colorado Plateau, the Hart Prairie watershed is approximately 24 km northwest of Flagstaff on the western side of the San Francisco Mountains. It extends from Humphrey's Peak to the base of Fern Mountain as a high-gradient montane wet meadow (Gavin 1998). The study area is located within the Hart Prairie Preserve of the Nature Conservancy. It includes a wilderness zone but is also divided and managed as a US Forest Service Botanical Area (Mullen 2004). The nation's largest Bebb Willow assemblage lies in the boundaries of the U.S Fern Mountain Botanical Area and the Nature Conservancy preserve and is supported by watershed (Gavin 1998).

The groundwater catchment area is approximately 11.64 km². The headwaters of the watershed are located at Humphrey's Peak, the highest elevation point in Arizona 3,852 m (12,637 ft), and discharge into a channel at the base of Fern Mountain at 2,588 m (8,490 ft). This channel is a tributary of the Verde River, called Volunteer Wash, and is the northernmost portion of the Gila River basin (Amentt 2002). This difference in elevation creates an elevation difference of approximately 1,264 m (4,146 ft) and an average slope of 21.8%, therefore creating a distinctive climatic gradient.

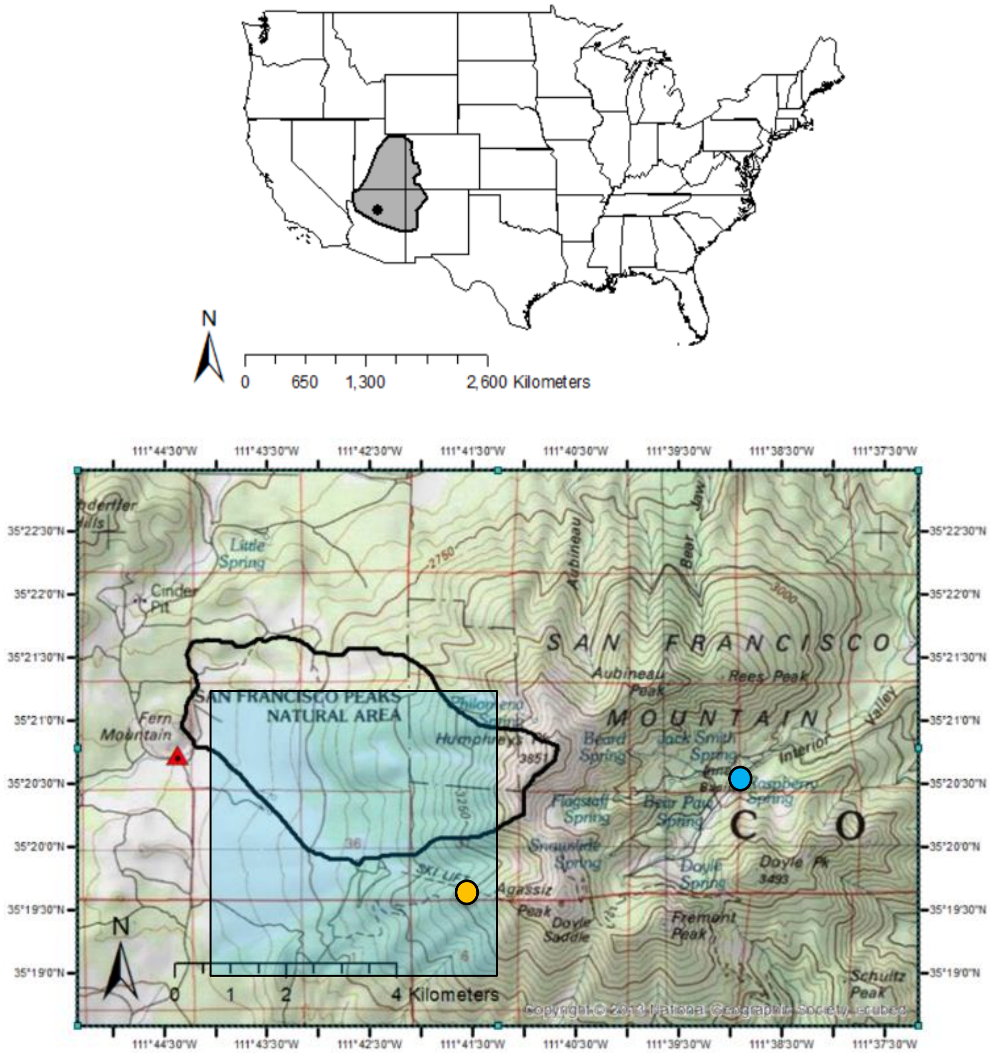


Figure 2-1. Top map: North America with the Colorado Plateau (shaded region) and the Hart Prairie Spring (point) location. Bottom map: red triangle represents the location of the Hart Prairie Spring site, where the H-flume is installed. The light blue (shaded square) represents the PRISM 4km-grided climatic location. The yellow circle represents Snowbowl Station #2 climatic location. The blue circle represents Snowslide Canyon climatic location.

2.2.2 Site History

Prior to Euro-American settlement in the 1860's, the study area was a fairly open riparian wetland meadow that was frequently subject to light surface fires at a 2-5 yr return frequency. The area was dominated by shrubs, forbs, and grasses, along with scattered ponderosa pine trees, pure stands and interspersed aspen trees. The Bebb Willow assemblage is likely to have flourished due to lower levels of ungulate browsing (USDA Forest Service, Coconino National Forest, 2010; W. Wallace Covington et al., 1997), although little is known about the impacts of large predators and pocket gophers, both of which can influence western ecology. Following Euro-American settlement, a combination of factors, such as fire exclusion, livestock grazing, introduced elk grazing, and timber harvesting influenced a dense ponderosa pine regeneration (USDA Forest Service, Coconino National Forest, 2010; W. Wallace Covington et al., 1997). Livestock and non-native elk grazing reduced grass competition with pine seedlings and reduced fuel for the frequent light surface fires, while logging removed older fire-adapted trees. This combination of factors led to widespread deforestation. A mast regeneration event in 1919 resulted in an abundant pine seedling establishment, causing seedling ponderosa pines to grow in great density and form a closed canopy woodland and forest. The dense forest structure led to an altered ecosystem that was subject to increased wildfire severity, increased evapotranspiration, and decreased spring and stream flow. These factors also negatively affected aspen (Populus tremuloides) stands, which were gradually overtaken by coniferous forest growth. Rocky Mountain elk (Cervus canadensis nelsoni) were introduced into the Hart Prairie area in the early 1900's, placing additional stress on aspen regrowth and Bebb willow stand structure, and affecting other wetland and riparian species, and native mule deer (Odocoileus hemionus) (W. Wallace Covington et al. 1997; USDA Forest Service, Coconino National Forest

2010).

Photo 1. Fern Mountain in the Hart Prairie project area taken 1880

Photo 2. Fern Mountain in the Hart Prairie project area taken 1980

Figure 2-2. Photographs visualizing the change in forest structure from 1880 to 1980 (“Northern Arizona University - Ecological Restoration Institute” 2021).

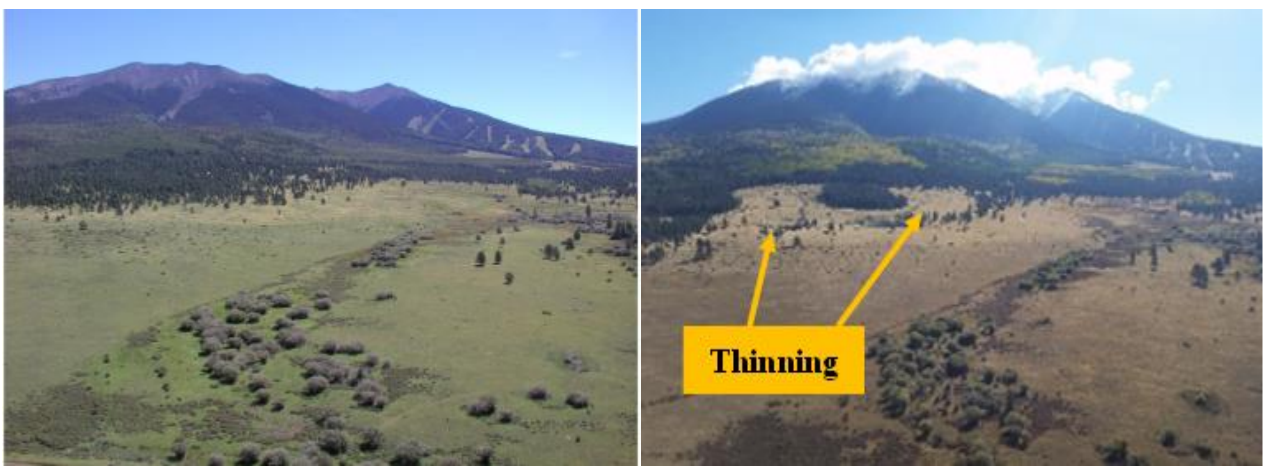


Figure 2-3. Hart Prairie spring watershed catchment area. From left to right: the first image is the catchment area prior to implemented forest restoration treatments. The second image is the catchment area after forest restoration treatments have been implemented.

2.2.3 Climate

Climate variation can range from millennial to century and interannual to decadal periods. The shorter timescale changes (2-7 years) in climate can be affiliated with El Nino and

La Nina patterns (Hereford, Webb, and Graham 2002; NOAA 2023a). During El Nino events, the waters of the Pacific Ocean warm, causing the Pacific jet stream to shift south. This shift tends to result in wetter conditions in the southern U.S. During La Nina events, the waters of the Pacific Ocean cool, shifting the Pacific jet stream northward. This shift tends to result in warmer and drier conditions in the Southern region of the U.S (NOAA 2023a).

The hydrology in this region remains largely dependent on climate (seasonal snow) and is greatly influenced by the Southern Oscillation Index (SOI) and variation in topography. Hart Prairie Spring emerges in a high-elevation alpine setting with a semi-arid climate. The study area has an elevation range from 2,588 m (8,490 ft) to 3,852 m (12,637 ft) with an average elevation gain of approximately 1,297 m (4,295 ft) over 3.6 miles. This catchment provides an approximated maximum elevation slope of 56.5% and an average elevation slope of 21.8%. The topographic features in this area create a dramatic gradient in temperature and orographically influenced precipitation, both of which affect high-elevation riparian assemblages. At this high elevation in the San Francisco Peaks, moist air is pushed up over the mountains and precipitation occurs (Zaimes et al., 2017). Precipitation, in the form of rain and snow, tends to be greatest near the headwaters of the watershed on Humphrey's Peak, rather than at lower elevation (Gavin, 1998). An extended duration of snowmelt can lead to an extended period for groundwater infiltration into the early summer. The extended snowmelt drainage season can provide abundant groundwater for the riparian vegetation at lower levels of elevation. If snowpack is low due to a dry winter, there is a shortened duration of flow (Zaimes et al., 2017).

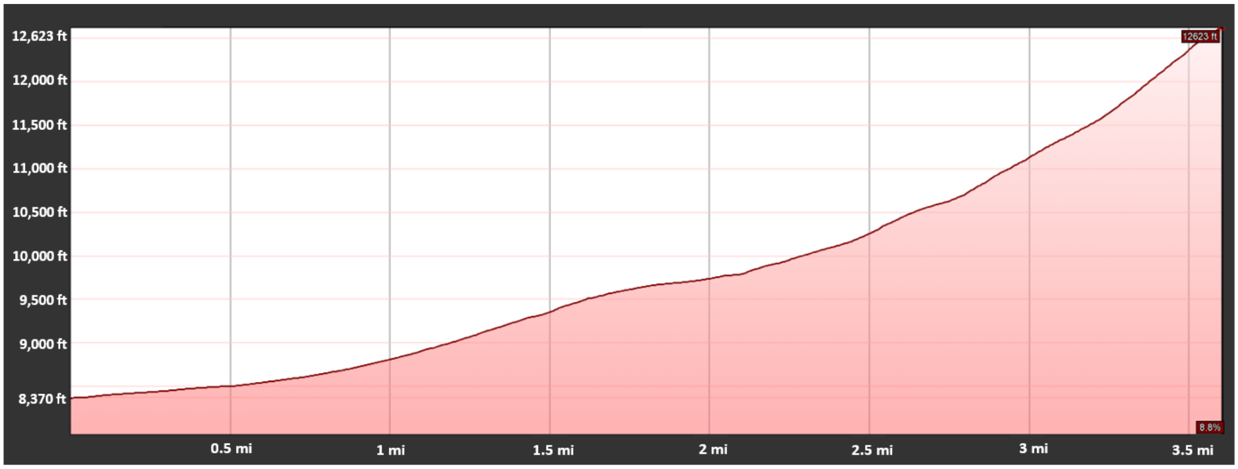


Figure 2-4. Elevation profile of Hart Prairie Springs watershed (Google Earth Pro).

2.2.4 Geology

Lying in the southwestern United States, Arizona is divided into three major physiographic provinces. These physiographic provinces include the Colorado Plateau, the Transitional Zone, and the southern Basin and Range provinces. The San Francisco Volcanic Field emerges on the southern edge of the Colorado Plateau. This volcanic field developed in the late Cenozoic era and covers approximately 3,218 km^2. The volcanic field is made up of approximately 600 cinder cones and lava domes, in addition to lava flows and the San Francisco Mountains (Holm 2019; Bezy and Tindall 2003).

The San Francisco Peaks are remnants of a stratovolcano complex (Pewe & Updike, 1976). The highest point of this stratovolcano complex is Humphrey's Peak 3,852 m (12,637 ft); however, prior to its last eruption, the mountain was estimated to have reached an elevation of 4,725-4,877 m (15,502-16,000 ft) (Bezy & Tindall, 2003). The present-day steep mountain slopes are composed of andesite, dacite, rhyolite, and basaltic cinders (Gavin, 1998). The inner basin of the San Francisco Mountain contains remnants of previous events of glaciation. The sediment-filled inner basin, a variation of volcanic tephra and glacial till, is an important water source for the city of Flagstaff (Montgomery & DeWitt, 1974). The Hart Prairie watershed, the focus of this study, is located on the west side of the San Francisco Mountain, and extends downslope to the base of Fern Mountain. The surficial deposits located in the Hart Prairie watershed are a part of the Sinagua Formation (Q). The Sinagua Formation is composed of eight distinguished depositional fans that radiate outward from the San Francisco Mountains (Amentt, 2002). This formation is composed of poorly sorted, coarse deposits and mudflows that contain clays and boulders with sizes ranging up to 4 m (13 ft) in diameter (Pewe & Updike, 1976).

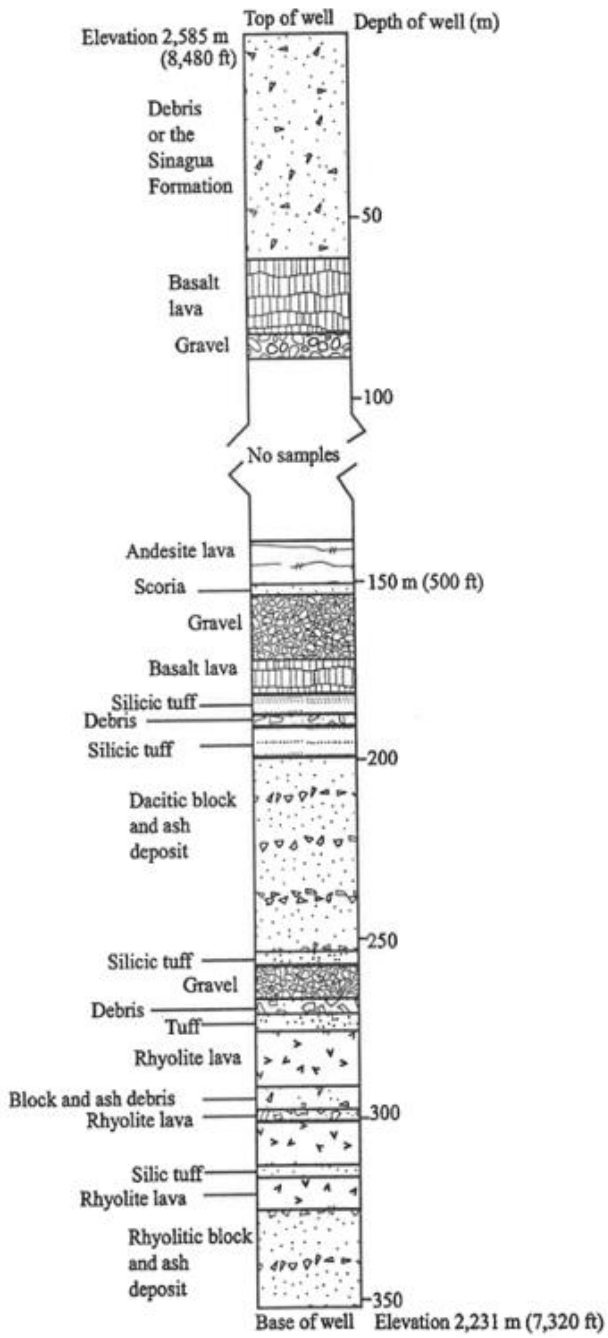
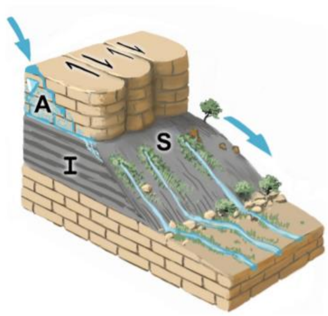


Figure 2-5. Stratigraphic log from Summit Properties (Well log #7) at Hart Prairie (Amentt, 2002) (Not Modified).

2.2.5 Hydrogeology

The Hart Prairie watershed catchment area is approximately 11.64 km^2 in size. The headwaters of the watershed are located at Humphrey's Peak. Humphrey's Peak reaches an elevation of 3,852 m (12,637 ft), making it the highest elevation in Arizona. The watershed catchment area discharges near the base of Fern Mountain 2,588 m (8,490 ft) and into a channel that resides within a riparian ecosystem. Hart Prairie Spring is classified as an ephemeral hillslope spring in that it is a spring complex where groundwater seasonally emerges from a hillslope structure with an angle range of 30-60° (Table 2-1) (Springer & Stevens, 2009). The position of the water table has a steep westward gradient, which supports the drainage from the Sinagua Formation. The Sinagua Formation, which is the uppermost formation, readily absorbs snowmelt and monsoon rains due to a fairly high permeability and storage capacity (Figure 2-5) (Halpenny, 1971). One of the depositional fans on the San Francisco Mountain covers the Hart Prairie area. This depositional fan contains the Sinagua Formation, which is composed of small, discontinuous, perched aquifers. These fans formed due to clay lenses in the alluvial and colluvial deposits. The perched aquifers have a limited water supply and are highly dependent on annual recharge, primarily snowmelt (Gavin, 1998). The drainage channel flows into a tributary of the Verde River, called Volunteer Wash. This channel catches both surface runoff and ephemeral spring discharge (Amentt, 2002).

Table 2-1. Description of continuously monitored Hart Prairie Spring and visual of spring classification: (A) aquifer, (S) spring source, (I) impermeable stratum (Springer & Stevens, 2009).

Spring Name	Spring Type	Conceptual Diagram	Geology Overview	Geographic Coordinates
Hart Prairie Spring	Hillslope		Spring complex that emerges from a hillslope (30°-60°). The Channel catches both ephemeral spring discharge and runoff.	35.34523, -111.73944

2.2.6 Ecology

Hart Prairie Spring is in a high elevation riparian meadow with diverse vegetation. The Bebb Willow, trembling aspen, and ponderosa pine play a role in maintaining the biodiversity and wildlife habitat of this area (O'Donnell et al., 2021). The United States Forest Service list Bebb Willow and aspen as species of concern. The understory is composed of wet meadow grasses, such as, western bracken fern (*Pteridium aquilinum*), Kentucky bluegrass (*Poa pratensis*), Arizona fescue (*Festuca arizonica*), and Silver lupine (*Lupinus argetenus*) (Amentt, 2002). The nation's largest stand of Bebb Willow exist in this watershed, typically near water channels (Springer et al., 2006). Over 95% of these trees are aged approximately 80 yr or older and are producing viable seeds but are not regenerating. Bebb Willow requires particular conditions for successful germination. The seedlings disperse mid to late June and must germinate within a week of landing on bare mineral-rich soil that is saturated and has sun exposure. To maintain successful germination and establishment the seedlings must then remain in this environment for up to four weeks (Amentt, 2002).

2.3 Research Methods

A variety of field methods, data compilation and processing, spatial analyses, and data analyses were conducted for this study. Monthly to quarterly site visits were conducted, weather permitting, at Hart Prairie Spring by numerous NAU students over the timespan of 1995 to 2022. Given the timespan, there have been significant changes in equipment over the years (Table 2-2). Varying amounts of continuous and/or discrete data were collected each year. A combination of field and data analysis methods were used to analyze the hydrologic response of Hart Prairie Springs over time.

Table 2-2. Description of continuously monitored Hart Prairie Spring, instruments used, parameters recorded, and length of continuous record.

Spring Name	*Geographic Coordinates*	*Instrument(s)*	*Recorded Parameters*	*Length of Record*
Hart Prairie Spring	35.34523, -111.73944 Elevation: 2,588 m (8,490 ft)	Float Recorder and Stevens F Gauge, TROLL 4000, Aqua TROLL 500, Aqua TROLL 200	Timestamp, Elapsed Seconds, Temperature, Pressure, Depth	4/24/1997 - 9/4//2022 (~ 25 years)

2.3.1 Spring Monitoring Techniques

Site visits occurred on a monthly to quarterly timeframe. Typically, discrete data were collected seasonally, in pre-monsoon (May-June) and post-monsoon (September-October) periods, as well as pre-snowmelt (December) and post snowmelt (April). Each site visit included the following objectives: download the pressure transducer data, record stage height, and conduct site maintenance if needed. Observations entailed taking a photograph of the channel, recording channel appearance, equipment details, and impairments, if any. Site maintenance included switching out the desiccant pack, removing debris from the channel, and repairing damaged equipment when necessary.

2.3.2 Continuous Spring Discharge Measurements

In 1995 a metal H-Flume was installed in Volunteer Wash at an area of discharge of the Hart Prairie watershed to measure surface water discharge (Figure 2-6). From 1995 to 1999, stream stage was measured using an analog float recorder and Stevens F gage, with an error range of +/- 0.15 cm (+/- 0.005 ft) (Table 2-2). There was no continuous discharge data for 1995 and 1996 due to it being dry years. From 1999 to 2004, a digital recorder (an Aqua-Troll 4000 pressure transducer) was installed and recorded continuous spring discharge data. The Aqua Troll 4000 has an error range of +/- 0.05%. During the snowmelt season of 1999 to 2000, the combination of the analogous and digital recorders were both used to adjust for shift (Amentt, 2002). From 2005 to late 2022, a digital Aqua Troll Mini 500 was used. Most recently, in late 2022, an Aqua Troll 200 5 psi InSitu instrument replaced the previous pressure transducer. The new digital, submersible data logger stores hourly signals from the pressure transducer. The pressure transducer converts numerous parameters such as pressure, temperature, depth, actual conductivity, specific conductivity, salinity, total dissolved solids, resistivity, and water density into digital data that can be uploaded using Bluetooth or USB through a wireless Troll Com. The Aqua Troll 200 transducer was connected to a vented cable attached with a large desiccant pack. The desiccant pack protects the pressure transducer and vented cable from collecting moisture and reduces the chance of data alteration or loss. The InSitu mobile app VuSitu or the Win-Situ desktop program were used to display the battery life, memory status, and live-readings of the pressure transducer, as well as providing the option to download the recorded data that were collected. The parameters were automatically formatted into a visual line graph in Win-Situ in addition to comma-separated values of recorded data. These data included hourly pressure and temperature signals. Once downloaded, the data were transferred to Microsoft Excel and compiled in chronological order and used to compute the following calculations to derive discharge from a rating curve (Amentt, 2002; Godwin, 2004):

$$Level\ Surface\ Elevation - Reference\ Value = Stage\ Height \quad \textbf{(1.)}$$

Equation (1.): The '*Level Surface Elevation*' is a selected continuous pressure measurement output. It uses a reference value to measure the water level in respect to the water elevation, a known datum. The 'Reference Value' is the hand measured level reference of a point, a known datum. The '*Stage Height*' is the height of the water surface above known datum in the flume.

$$\left((0.5544 \times (Stage\ Height)^3) + (1.6522 \times (Stage\ Height)^2) + (0.0395 \times Stage\ Height) + (0.0053)\right) = Discharge\ (ft^3/s) \quad \textbf{(2.)}$$

Equation (2.): Calculates discharge using a rating curve equation for the H-flume (Amentt, 2002).

$$((Discharge\ (ft^3/s)) \times 0.0283) = Discharge\ (m^3/s) \quad \textbf{(3.)}$$

Equation (3.): This converts '*Discharge*' of cubic feet per second into '*Discharge*' cubic meters per second.

$$(Total\ Volume\ (m^3) \times Watershed\ Area\ (m^2)) = Runoff\ (m) \quad \textbf{(4.)}$$

Equation (4): The ‘Total Volume’ is the sum of the daily average discharge (m^3/s), which was computed in R-studio. The ‘Watershed Area’ is approximately (11,642,276.38 m^2) in size, which was calculated in ArcGIS Pro.

R-Studio is a desktop application for graphical and statistical computing and was used to calculate spring mean daily discharge (m^3/day). This calculation was completed by importing comma-separated values (CSV) file of the year being analyzed. The file includes the recorded date and discharge (m^3/s) (RStudio Team, 2020). Aquarius Time-Series is a database that was used for general data storage, manipulation, and analysis of various environmental, climatic, and hydrometric parameters (Aquatic Informatics ULC, 2023). Hart Prairie Spring has its own established location in the Aquarius Time-Series Springboard. Raw continuous pressure transducer data were appended as individual basic time series and used for storage, manipulation, and analysis.

Figure 2-6. The H-flume in Hart Prairie on March 11, 2015, under snow. San Francisco Mountain is in the background.

2.3.3 Climate Data

Multiple climatic parameters, stations, and resources were used in this study. The three primary climatic parameters that were analyzed included precipitation, snow data, and the southern-oscillation index.

2.3.3.1 Precipitation

The PRISM Climate Group database was used to collect precipitation data (Oregon State University, 2022). It compiles climate datasets from monitoring networks ranging from 1895 to the present. For this study, daily mean seasonal (October-April) precipitation and total seasonal (October-April) precipitation from 1996 through 2022 were downloaded. PRISM data were acquired with the interactive explorer tool and locating the Hart Prairie Watershed area within a

4 km grid. PRISM 30-Year Normal was used to visualize long-term average monthly precipitation and temperature over the past 30 yr (1991 to 2020) (Figure 2-7). The total seasonal (Oct-Apr) precipitation along with the total average seasonal precipitation are illustrated in Figure 2-8. The total average seasonal precipitation from 1996 through 2022 was 467 mm. During this time frame there have been 13 yr of total seasonal precipitation that have exceeded the total seasonal average precipitation of 467 mm (Figure 2-8).

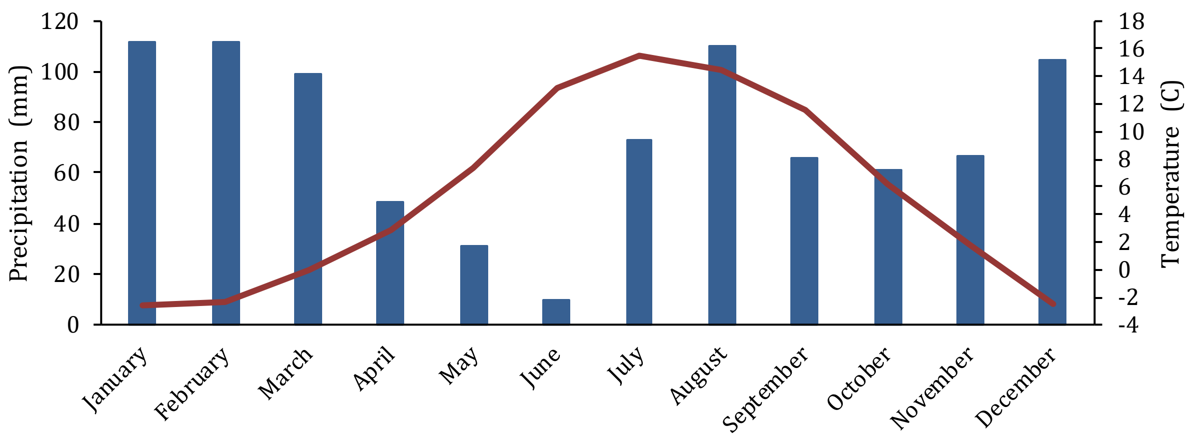


Figure 2-7. The 30-year normal for the Hart Prairie Spring watershed catchment area in the PRISM 4 km grid. The bar chart depicts average precipitation, and the line graph depicts average temperature (Oregon State University, 2022).

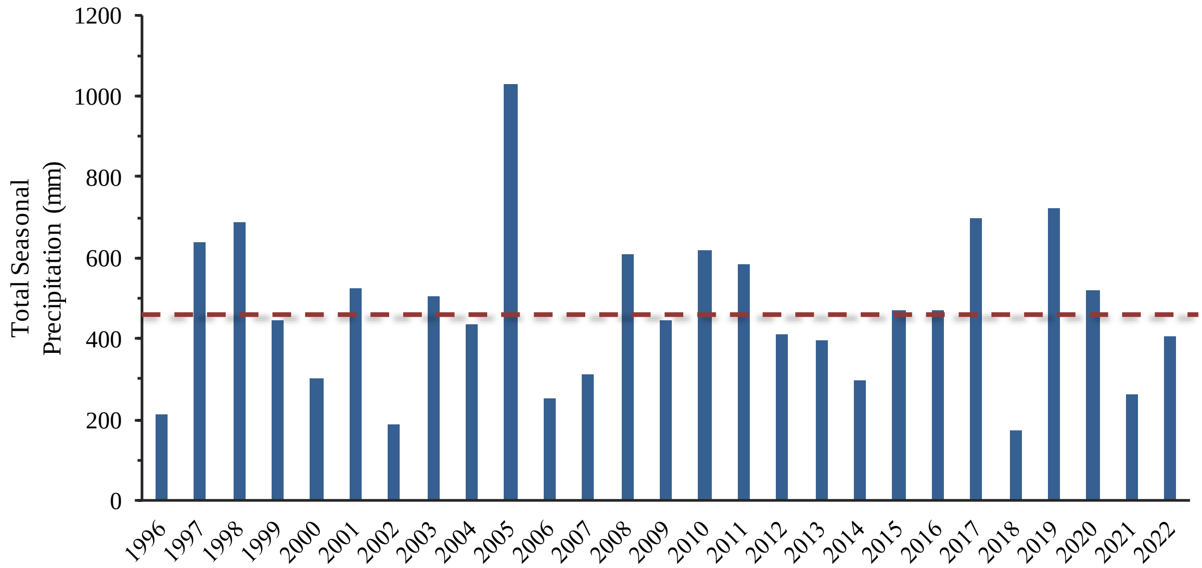


Figure 2-8. The total seasonal (Oct-Apr) precipitation for the Hart Prairie Spring watershed catchment area in the PRISM 4 km grid. The dotted red line depicts the average seasonal precipitation of 467 mm. There are 13 yr where the seasonal precipitation exceeded the total seasonal average (Oregon State University, 2022).

2.3.3.2 Snow Data

The SNOTEL database was utilized to compile snow data from 1997 to 2022. Snow data included the total annual snow water equivalent (SWE), SWE duration, and snow depth (mm). Two high-elevation SNOTEL stations that are close to the Hart Prairie watershed catchment area were used; Snowbowl Station #2 and the Snow Slide Canyon (Figure 2-1) (Table 2-3) (USDA, 2023) Snowbowl Station #2 is a part of a snow course/aerial marker network, with manual snow measurements taken during the winter season. The Snowslide Canyon station is part of the SNOTEL network, with automated measurements transmitted to a central database called the Water and Climate Information System. The SNOTEL network collects daily readings, thereby generating a far more denser data record as compared to the snow course/aerial marker network. The period of record for Snowslide Canyon was 1998 through 2022. The total SWE for each year is displayed (Figure 2-10). The average snow water equivalent from 1998 through 2022 was

1,628.04 mm. There were 11 yrs that exceeded the total average SWE (Figure 2-10). The period of record for Snowbowl Station #2 extended from 1996 through 2022. The total SWE for each year is displayed (Figure 2-11). The average snow water equivalent from 1996 through 2022 was 1,134.07 mm. There were 12 yr that exceeded the total average SWE (Figure 2-11) (USDA, 2023).

Table 2-3. Description of selected snow stations: Snowbowl Station #2 and Snowslide Canyon.

Snow Stations	***Network***	***GPS Coordinates***	***Elevation***
Snowbowl Station #2	Snow Course/Aerial Marker	35.33, -111.7	3,413 m (11,200 ft)
Snow Slide Canyon (Inner Basin)	SNOTEL	35.34, -111.65	2,970 m (9,744 ft)

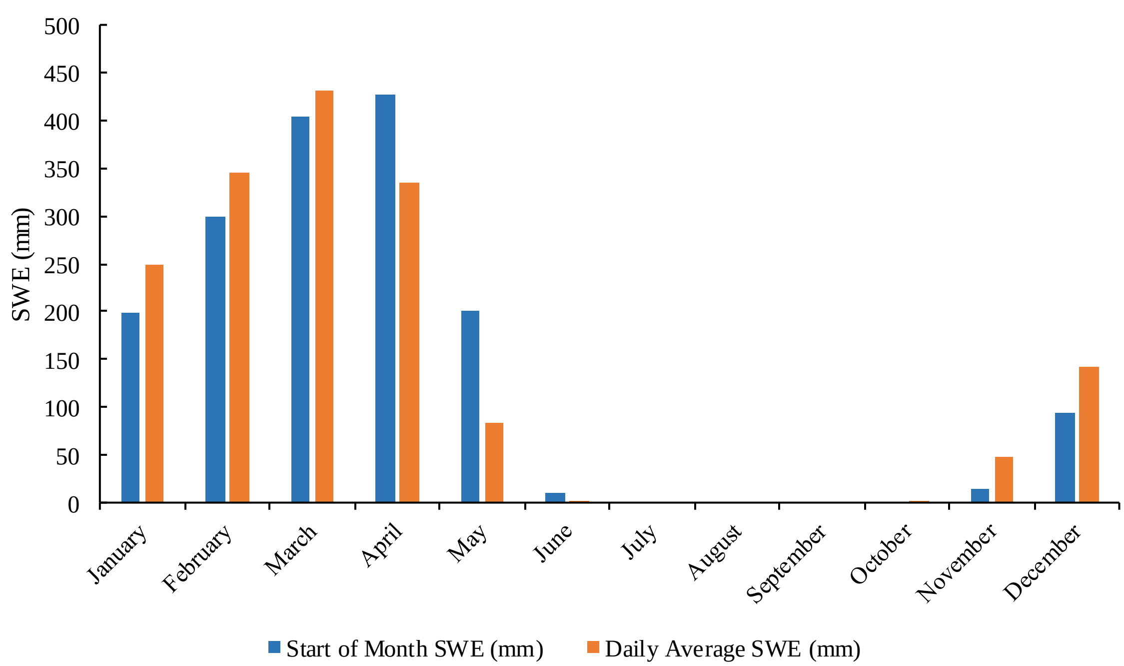


Figure 2-9. 30-Year Normal for Snowslide Canyon (inner basin) by using the SNOTEL's network station. The bar graph (blue) depicts the average snow water equivalent at the start of the month and the adjacent bar graph (orange) depicts daily average snow water equivalent (USDA, 2023).

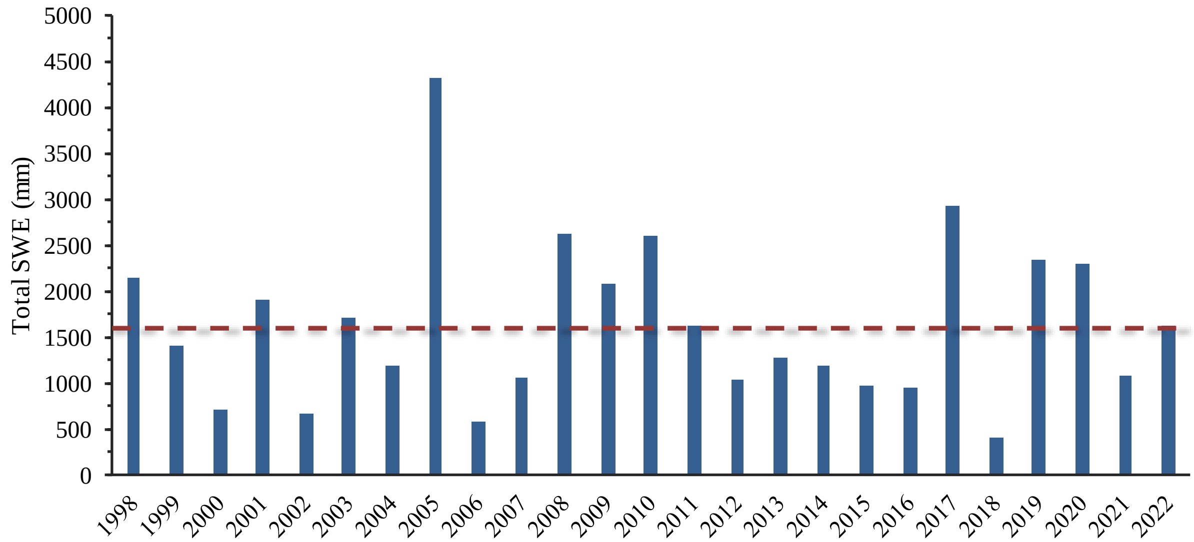


Figure 2-10. Total snow water equivalent for Snowslide Canyon (inner basin) using SNOTEL's network station from 1998 through 2022. The dotted red line depicts the average seasonal precipitation of 1,628.04 mm. There are 11 yr where the total snow water equivalent exceeded the average total snow water equivalent from 1998 through 2022 (USDA, 2023).

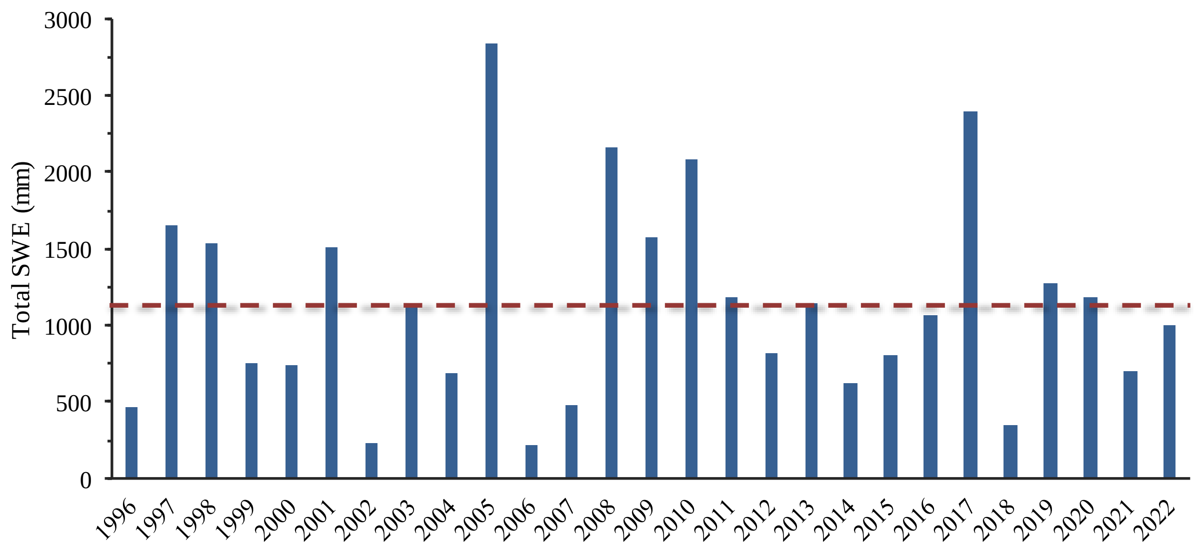


Figure 2-11. Total snow water equivalent for Snowbowl Station #2 using SNOTEL's network station from 1996 through 2022. The dotted red line depicts the average seasonal precipitation of 1,134.07 mm. There are 12 yr where the total snow water equivalent exceeded the average total snow water equivalent from 1998 through 2022 (USDA, 2023).

2.3.3.3 Southern Oscillation Index (SOI)

The climate data analyzed in this study were associated with El Niño and La Niña cycles (Figure 2-12). In Northern Arizona, El Niño winters tend to be more prominent in that there are longer precipitation events with fewer dry breaks. These types of winters additionally tend to be warmer and wetter. El Niño events typically last anywhere from several months to a year. During the La Niña winter in Northern Arizona, colder temperatures and few storm events result in a dry period. La Niña events typically last longer in comparison to El Niño events, generally ranging from 1 to 3 yr (US Dept. of Commerce NOAA, 2023). The Southern Oscillation Index (SOI) was used to generally depict which years were considered wet and dry years. La Niña events are depicted as dry years and El Niño events are depicted as wet years (Table 2-4). Climate data were correlated with spring discharge data given that the topography of Hart Prairie Spring is an influential factor and groundwater recharge in this region is dependent on various climatic parameters (Gavin, 1998; Zaimes et al., 2017).

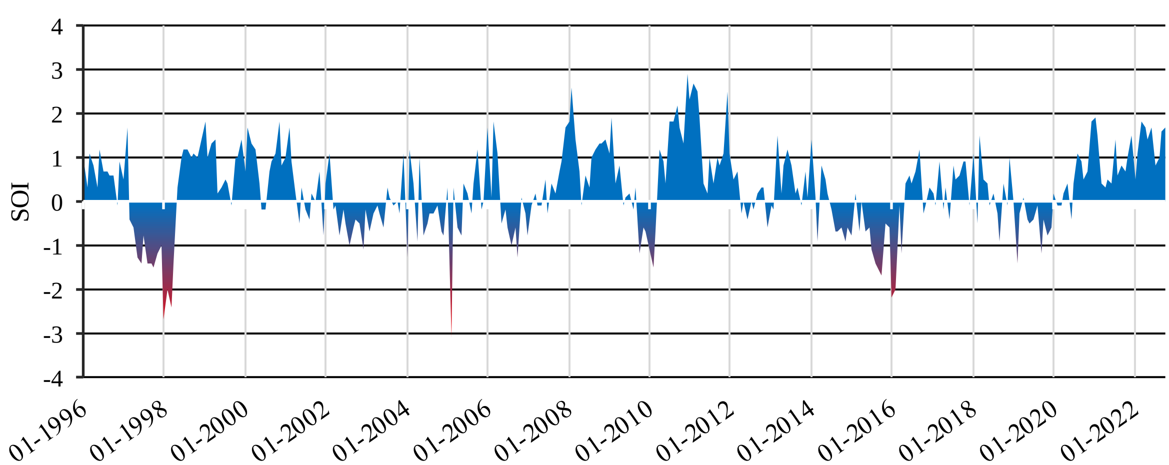


Figure 2-12. Southern Oscillation Index Cycles (SOI) from 1996 to 2022. The red color (-) indicates El Niño events and the blue color (+) indicates La Niña events. (NOAA, 2023a).

Table 2-4. The percentage and generalized year type of La Niña (dry years) or El Niño (wet years), with the wet years highlighted (NOAA, 2023a).

Year	*La Niña (%)*	*El Niño (%)*	*Neutral (%)*	*Year Type (Wet/Dry)*
1996	92	8.3	0	Dry
1997	17	83	0	Wet
1998	67	33	0	Dry
1999	92	8.3	0	Dry
2000	83	17	0	Dry
2001	58	33	8.3	Dry
2002	17	83	0	Wet
2003	25	67	8.3	Wet
2004	25	75	0	Wet
2005	50	42	8.3	Wet
2006	42	58	0	Wet
2007	58	42	0	Dry
2008	92	8.3	0	Dry
2009	58	42	0	Dry
2010	75	25	0	Dry
2011	100	0	0	Dry
2012	50	33	17	Dry
2013	75	25	0	Dry
2014	42	58	0	Wet
2015	8.3	83	8.3	Wet
2016	50	50	0	Neutral
2017	67	33	0	Dry
2018	58	42	0	Dry
2019	8.3	83	8.3	Wet
2020	75	25	0	Dry
2021	100	0	0	Dry
2022	100	0	0	Dry

2.3.4 Tree Canopy Coverage

Tree canopy coverage regulates hydrology and water balance in forested areas (Schenk et al., 2020). Analyzing the changes in tree canopy coverage over time may provide useful insight into infiltration hydrology. Previous studies provide both support for and against the use of “normalized difference in vegetation index” (NDVI) analysis for visualizing changes in tree canopy coverage. NDVI quantifies healthy vegetation by observing the wavelength color bands of aerial images. The calculation for NDVI involves visible red light (absorbed by vegetation) and near-infrared light (reflected by vegetation), as shown below in (Equation 5).

$$\frac{(NIR-RED)}{(NIR+RED)} = NDVI \qquad \textbf{(5.)}$$

Equation (5). ‘*NIR*’ represents the near-infrared light, which is light that is reflected by vegetation. ‘*RED*’ represents the visible red light, which is light that is absorbed by vegetation. ‘*NDVI*’ represents healthy vegetation in a quantifiable range of values between -1 and 1.

The calculation for NDVI has a range of -1 to 1. Higher NDVI values represent healthy vegetation, while lower NDVI values represent little to no vegetation (“Measuring Vegetation (NDVI & EVI)”). NDVI measures chlorophyll, the pigment in plant leaves, and canopy structure well, in comparison to overall tree canopy biomass (Gamon et al., 1995). This tool is commonly used in forestry studies, however, NDVI measures the viability of vegetation, which influences the quantitative assessment of tree canopy density. Seasonal changes and climatic fluctuations lead to changes in tree leaf color and density that must be considered in the ratio analysis of tree to no tree (Hein Phu La et al., 2013). Aerial imagery used for NDVI’s are typically acquired during the peak growth season when vegetation is healthiest.

National agricultural imagery program (NAIP) images were downloaded from the USGS EarthExplorer website (USGS, 2022). The following table describes the recorded annual image dates. Two images (NW and NE) were used to fully cover 11.64 km^2 of the Hart Prairie Spring watershed area that were then analyzed in ArcGIS Pro 3.1.0 (Esri Inc., 2023). The NAIP images from 2007 to 2017 have a resolution of 1 m. Recent years from 2019 to 2021 have a better resolution of 0.6 meter. To create uniformity, the images with the better resolution were adjusted to have a resolution of 1 meter. To additionally reduce any bias, 0.29, on the scale of -1 to 1, was the set NDVI pixel value across all images to indicate the colored pixel as “Tree” or “No Tree”.

Table 2-5. The year being analyzed and the date of the NAIP images that were taken.

Year	*NAIP Imagery Dates – NW (m/dd)*	*NAIP Imagery Dates – NE (m/dd)*
2007	6/07	6/13
2010	6/15	7/13
2013	6/07	6/07
2015	06/17	07/27
2017	09/18	09/18
2019	06/24	06/24
2021	11/08	11/08

2.4 Data Analysis

The following analyses include the Hart Prairie Spring discharge data in correlation with climate data, such as precipitation and snow data. Analyses include a general flow summary, hydrograph analysis of precipitation events, and multilinear regression analysis. A qualitative and quantitative interpretation of the tree canopy coverage of the Hart Prairie Spring watershed catchment area was made.

2.4.1 Flow Summary

The Hart Prairie watershed recharges primarily through winter snowmelt, that occurs during spring months, and rarely during the summer monsoon season. Hart Prairie Spring is a snow-driven hydrologic system, given its watershed catchment area having a high elevation and steep slope gradient. Precipitation data from October through April were compiled and correlated with continuous flow data, due to being winter accumulation months. The surface water stream flow discharge would peak during snowmelt season, typically in mid-April (Table 2-6). Pre-treatment, the years 2005 and 2008 had significant spring flow, which correlates with high seasonal precipitation and high seasonal snow-water equivalent events (Figure 2-13). Post-treatment, the years 2017 and 2019 had significant spring flow, which correlated with high seasonal precipitation and high seasonal snow-water equivalent events (Figure 2-13). These four years, separating them by pre- and post-treatment, had the greatest precipitation and snowfall events. When comparing pre-treatment and post-treatment peak flows, visually there is an increase in peak spring flow (Figure 2-14). The pre-treatment period generally had peak flows occurring mid-April and progressed to peak discharges in late-March. Post-treatment peak discharges generally occurred earlier in the season, primarily mid-March. Peak discharge response over time has become earlier (Table 2-6, Figure 2-15). Figure 2-16 shows a graph of the daily temperatures of the PRISM 4km-gridded area. The graph had a positive slope of 0.0002, indicating a gradual incline in temperature. The 30-Year Normal precipitation peaked in January and February. Analysis of daily average SWE revealed that peak precipitation occurred in March (Figure 2-9).

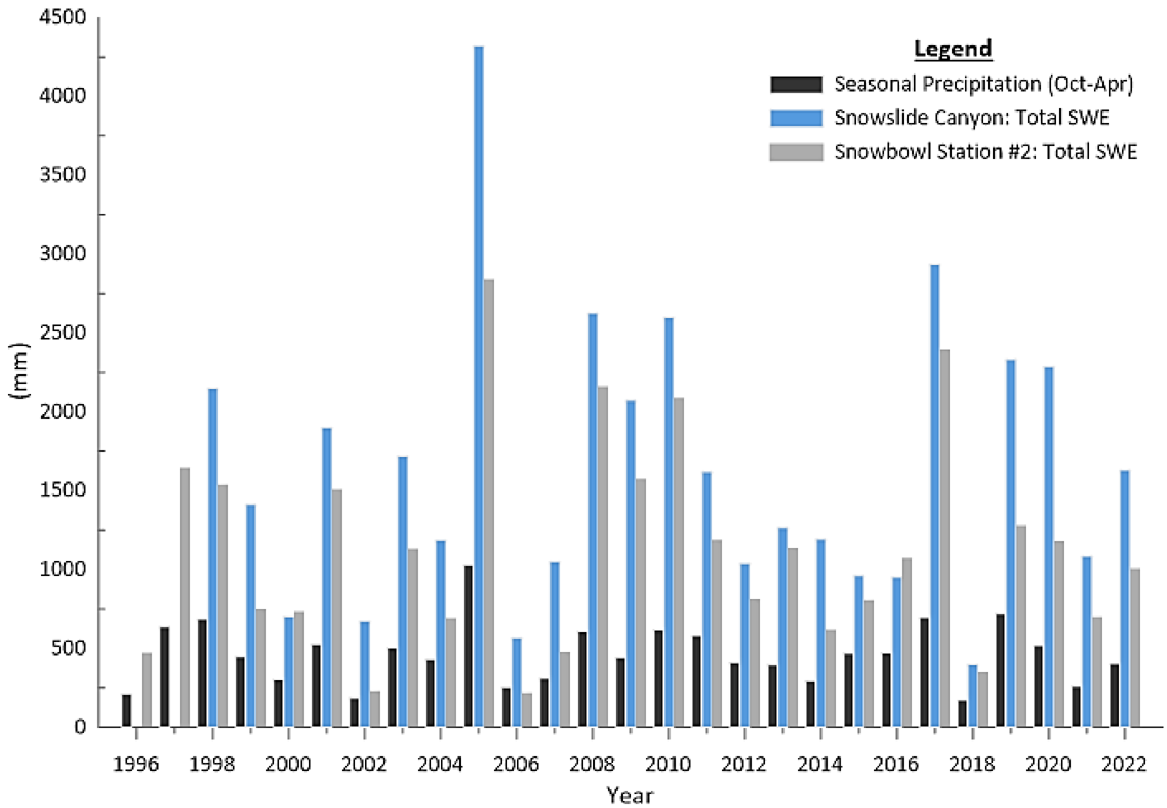


Figure 2-13. Total Seasonal Precipitation Oct-Apr in (black), Snowslide Canyon total snow water equivalent (blue), and Snowbowl Station #2 total snow water equivalent (gray). All measurements are in mm for each year.

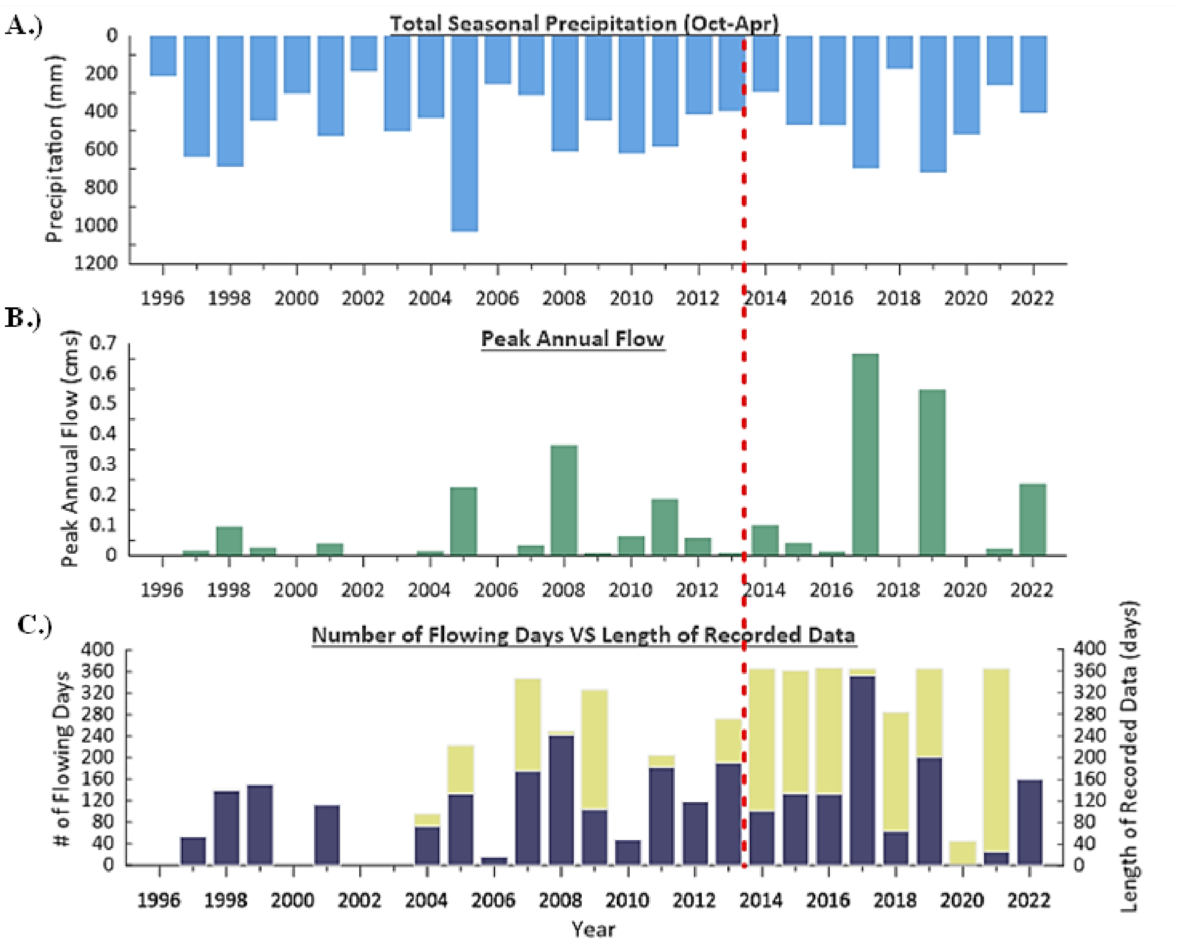


Figure 2-14. (A) total seasonal precipitation (Oct-Apr) from 1996 to 2022. (B) Peak annual flow from Hart Prairie Springs. (C) The number of flowing days at Hart Prairie Spring (purple) and the length of recorded data each year (yellow). The dashed red light symbolizes when the forest treatment occurred in 2013/2014.

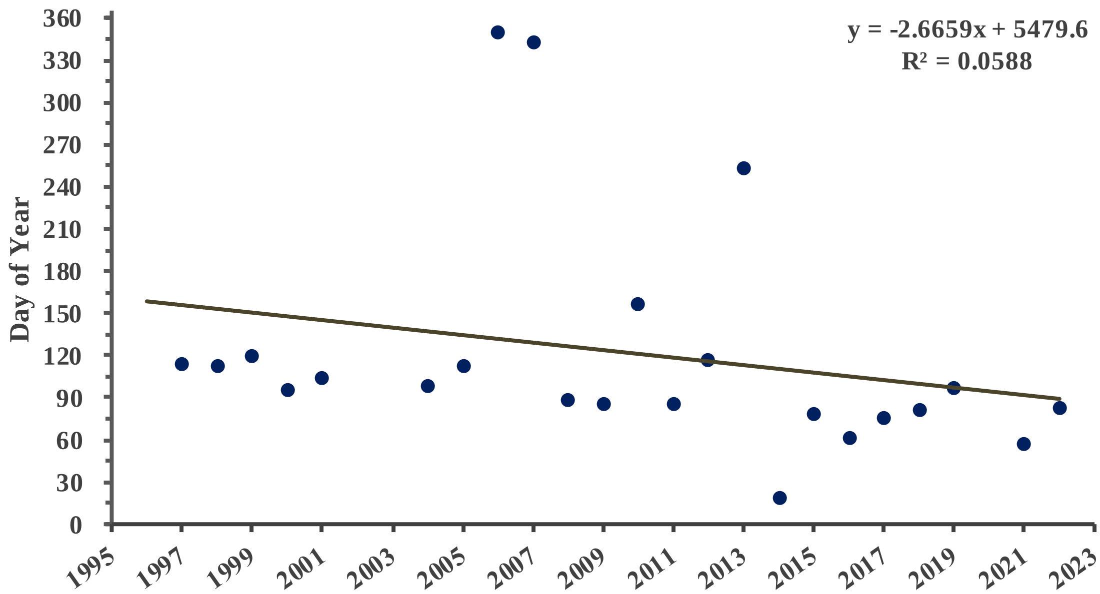


Figure 2-15. Graph illustrating the peak discharge responses occurring earlier in the season.

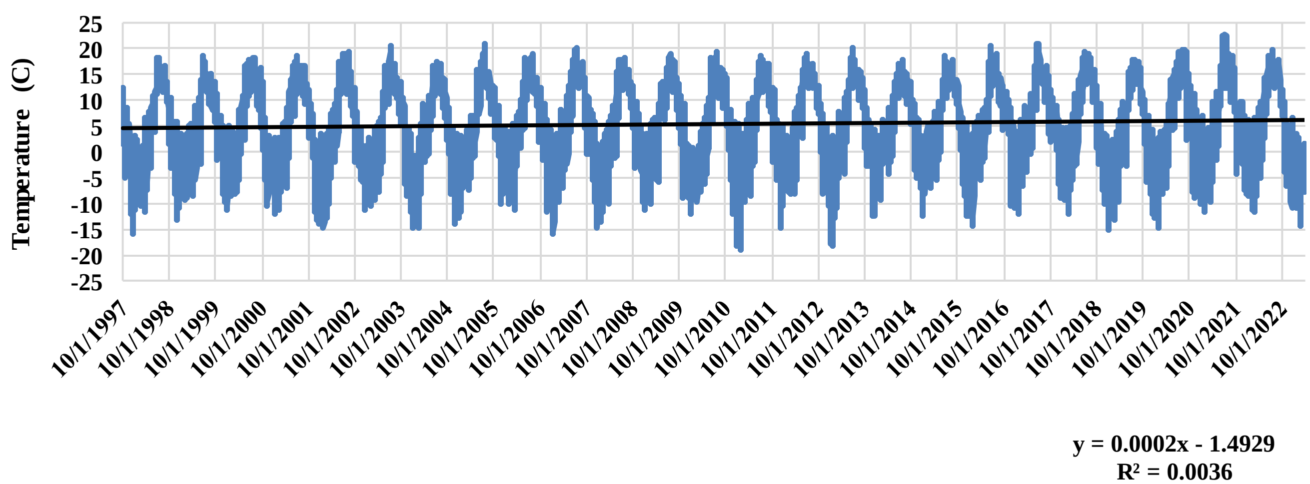


Figure 2-16. Graph illustrating the PRISM 4km-grid daily temperature (blue). The black line depicting the general linear trend with linear equation and R^2 value.

Table 2-6. Hart Prairie Spring flow summary table.

Year	*Seasonal Precipitation Oct-Apr (mm)*	*Peak Discharge (cms)*	*Peak Discharge (cmd)*	*Peak Discharge Date (d-mmm)*	*Average Discharge (cmd)*	*Total Discharge (m^3)*	*Runoff (mm)*
1996	213.14	*Dry*	*Dry*	*Dry*	*Dry*	*Dry*	*Dry*
1997	636.55	0.0164	1,416.24	*25-Apr*	316.65	16,782.48	1.44
1998	688.24	0.0963	8,321.76	23-Apr	1,484.77	209,352.38	17.98
1999	447.55	0.0070	601.44	1-May	124.48	18,671.94	1.60
2000	304.28	0.0764	6,601.50	5-Apr	616.51	62,267.82	5.35
2001	526.85	0.0138	1,196.46	15-Apr	261.61	29,300.44	2.52
2002	185.61	*Dry*	*Dry*	*Dry*	*Dry*	*Dry*	*Dry*
2003	503.51	*Dry*	*Dry*	*Dry*	*Dry*	*Dry*	*Dry*
2004	433.48	0.0145	1,250.75	8-Apr	248.17	23,824.01	2.05
2005	1030.17	0.2264	19,558.49	24-Apr	1,795.73	400,448.17	34.40
2006	254.11	0.0002	1.65	17-Dec	0.31	4.93	0.00042
2007	311.6	0.0331	2,857.42	10-Dec	462.60	160,059.48	13.75
2008	608.1	0.3652	31,549.68	29-Mar	4,799.25	1,195,014.11	102.64
2009	444.24	0.0074	636.22	27-Mar	85.46	27,858.72	2.39
2010	617.89	0.0642	5,544.48	6-Jun	2,375.18	111,633.24	9.59
2011	582.97	0.1875	16,197.87	28-Mar	3,882.37	795,886.12	68.36
2012	412.77	0.0111	960.92	26-Apr	334.72	39,831.19	3.42
2013	395.03	0.0080	690.07	11-Sep	106.63	29,002.77	2.49
2014	295.74	0.1006	8,696.15	20-Jan	68.18	24,885.12	2.14
2015	468.74	0.0412	3,557.34	20-Mar	174.79	63,096.15	5.42
2016	471.5	0.0138	1,192.68	2-Mar	128.00	46,847.51	4.02
2017	698.5	0.6672	57,643.72	17-Mar	1,854.59	676,927.02	58.14
2018	173.67	0.0005	39.77	23-Mar	4.73	1,342.50	0.12
2019	720.61	0.5487	47,408.03	8-Apr	1,659.78	605,819.56	52.04
2020	518.83	0.0000	-	-	-	-	-
2021	260.71	0.0232	2,002.90	27-Feb	14.51	5,295.77	0.45
2022	404.72	0.2342	20,235.85	24-Mar	125.06	30,889.25	2.65

2.4.2 Hydrograph Analysis

Hydrograph analysis was used to describe the climatic and physiographic relationship between precipitation events and runoff (Rogers, 1972). Runoff is the length amount of surface flow that did not infiltrate into the soil, due to the soil being either at full capacity or a high rate of precipitation or snowmelt (Ritter, 2003). The hydrographs have three individual parts: a rising limb, a peak, and a falling limb (recession). These distinctions were labeled on the hydrographs. The duration of the falling limb, or recession period, was analyzed due to its representation of groundwater storage within the watershed by providing information regarding properties of drainage post peak flow (Donovan et al., 2021; Schwartz & Zhang, 2003).

The hydrographs analyzed in this study were selected primarily based on significant discharge events. The analysis includes rainfall precipitation and snow data, including SWE, to assess the aquifer recharge and spring discharge response time. The period between peak recharge event and peak discharge encompasses the total spring response time. The year 2005 exhibited high flows given the significant seasonal precipitation event that peaked in late-December. The 2005 hydrograph displayed an increase in spring discharge during the spring snowmelt season. There was another increase in spring discharge in late July-August due to monsoonal rains (Figure 2-18). Peak snowfall at Snowslide Canyon for the year 2005 occurred in early-April (April 3,2005) and peak spring discharge occurred approximately 21 days later (April 24, 2005) (Figure 2-19).

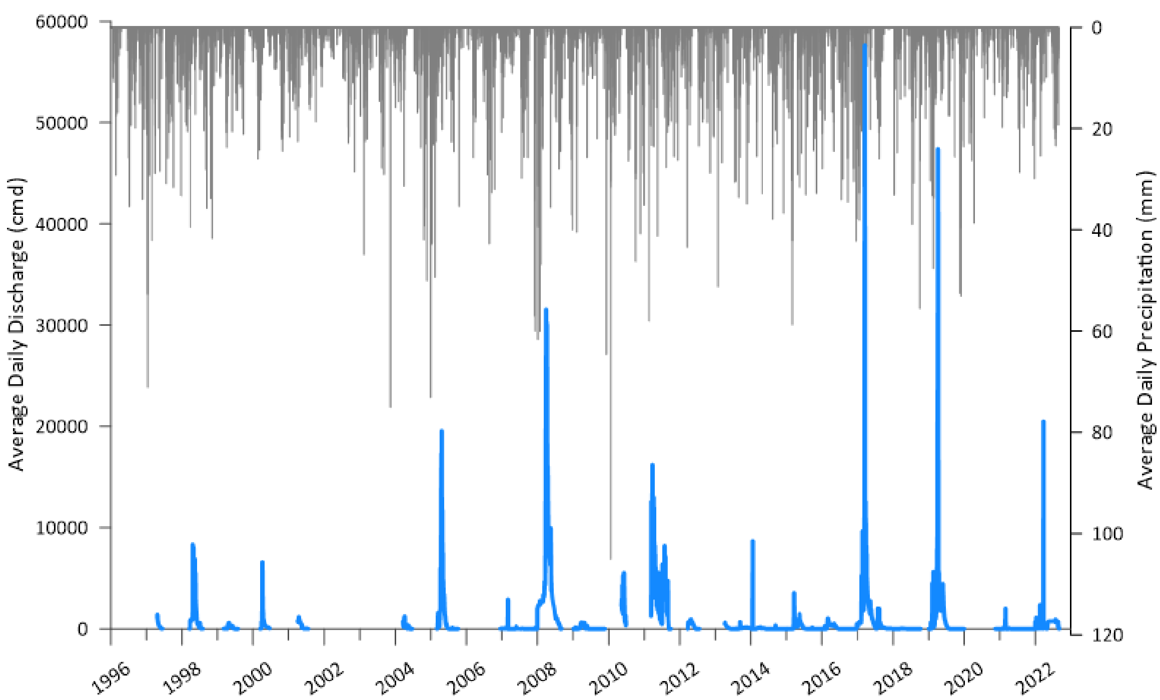


Figure 2-17. Hart Prairie Spring daily average spring discharge (blue) and Hart Prairie Spring PRISM 4 km grid watershed catchment area daily average precipitation (gray).

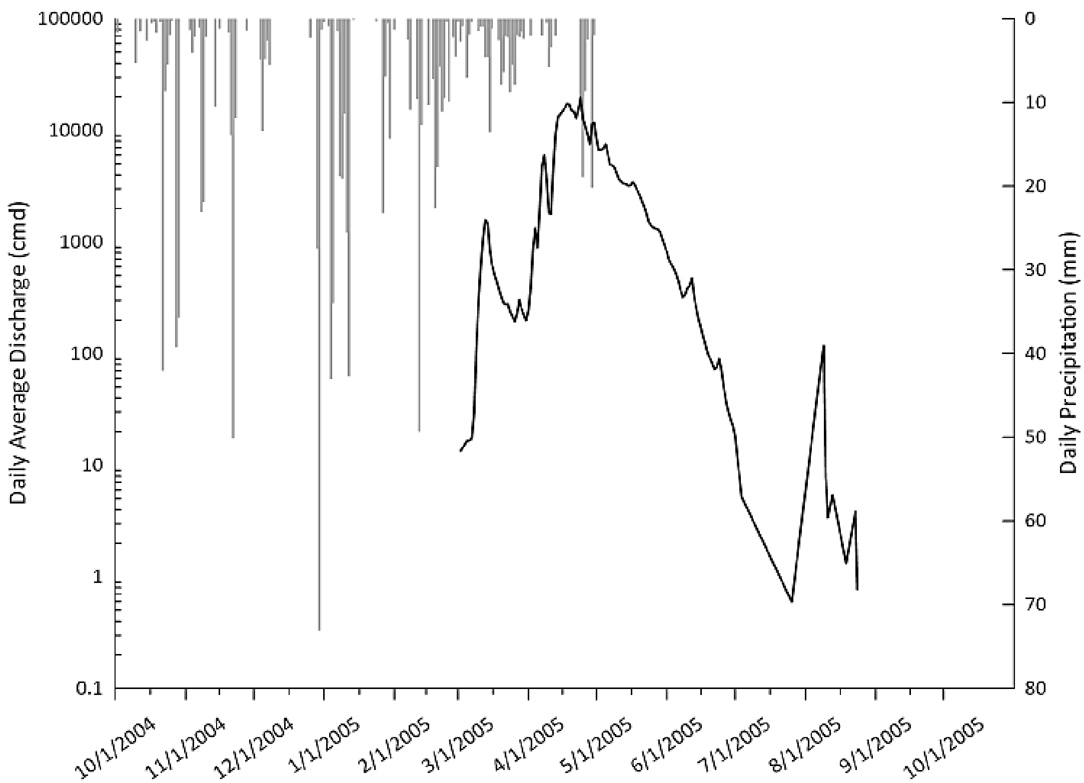


Figure 2-18. Hart Prairie Spring 2005 mean daily discharge and daily seasonal (Oct-Apr) precipitation.

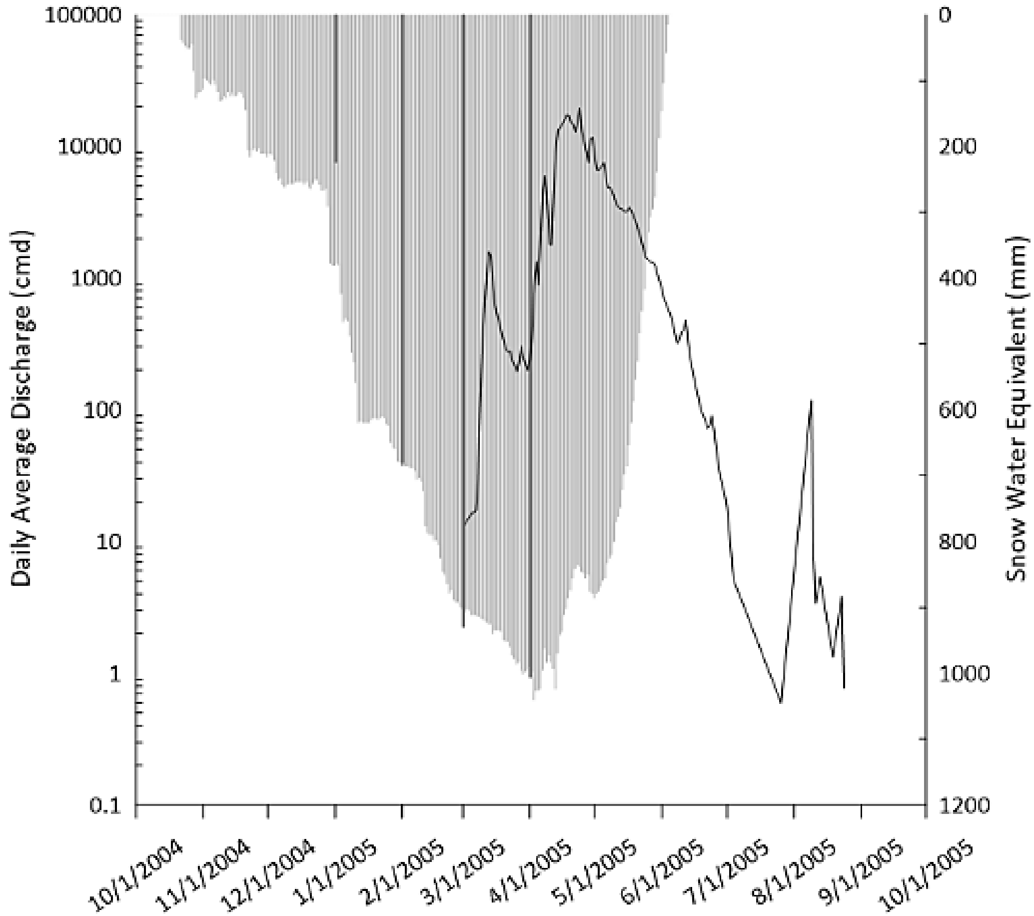


Figure 2-19. Hart Prairie Spring 2005 discharge and daily snow water equivalent from SNOTEL station 'Snowslide Canyon' (gray shaded region), and snow water equivalent from course marker 'Snowbowl Station #2' (4 black descending lines).

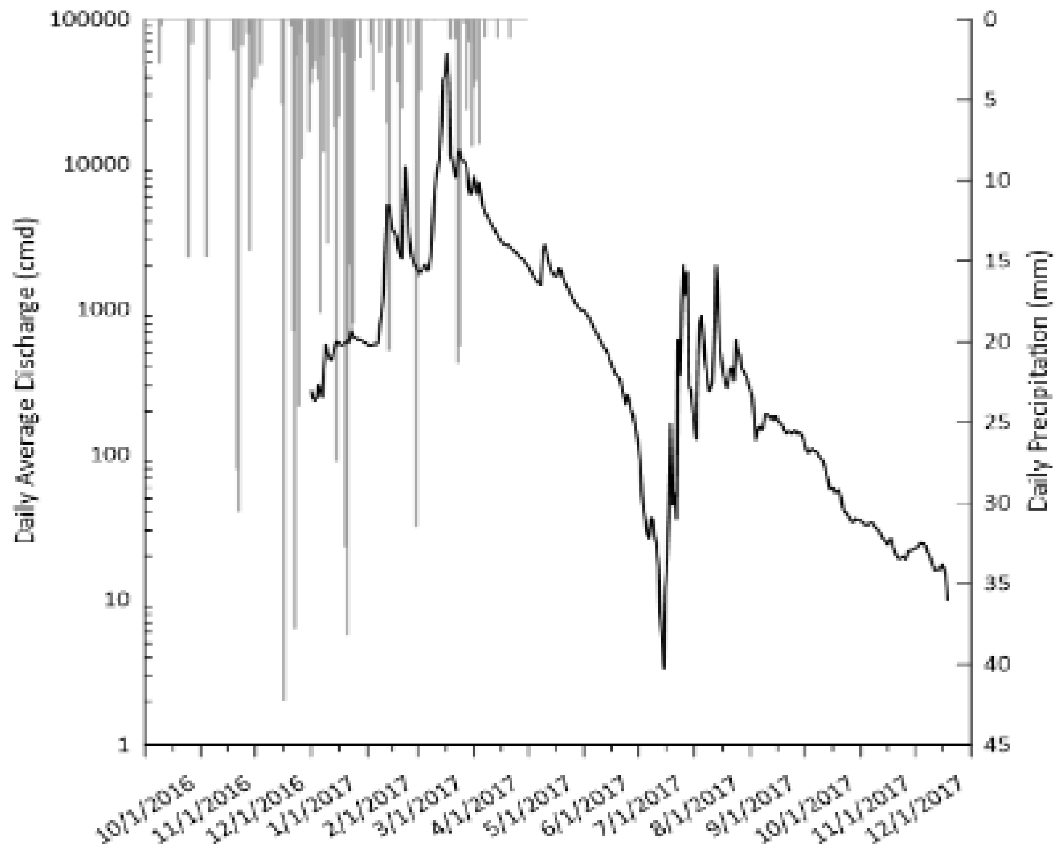


Figure 2-20. Hart Prairie Spring 2017 mean daily discharge and daily seasonal (Oct-Apr) precipitation.

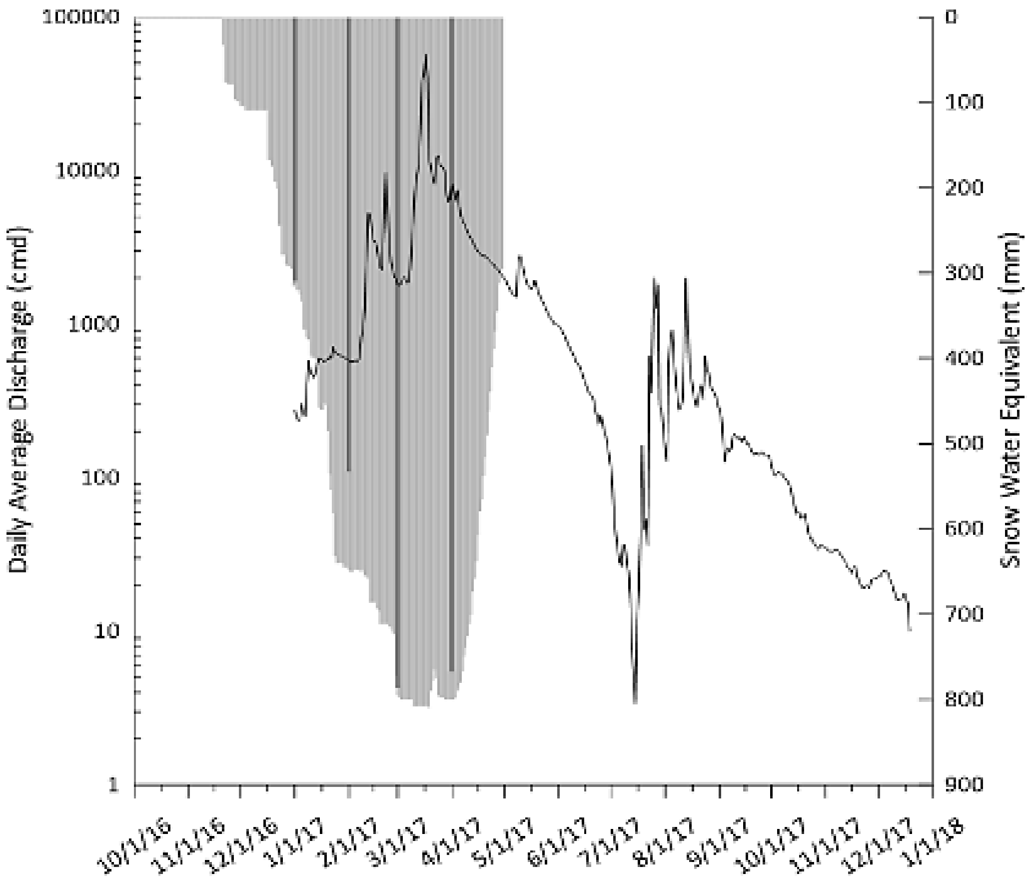


Figure 2-21. Hart Prairie Spring 2017 average daily discharge and daily snow water equivalent from SNOTEL station 'Snowslide Canyon' (gray – shaded region), and snow water equivalent from course marker 'Snowbowl Station #2 (4 – black descending lines).

2.4.3 Multilinear Regression Analysis

Multilinear regression modelling of spring runoff with seasonal precipitation (October – April) and snow data from the two monitoring stations were analyzed to quantify the significance of the forest restoration treatments implemented from 2013 to 2014.

2.4.4 Outlier Test Analysis

An outlier test was conducted using RStudio to identify data points that significantly differed from the other observational data points (Table 2-7, 2-8, 2-9). The outliers that were identified from this test were applied to multilinear regression models by creating a duplicate model and removing the significantly different datapoint. For the precipitation 4k grid analysis, the pre-treatment outlier year 2005 was selected. This year had a runoff of 34.39 mm and the precipitation for that year was 1,030 mm. For post-treatment, the outlier year 2018 was selected. The runoff was 0.115 mm, and the precipitation was 174 mm. For Snowslide Canyon, the pre-treatment outlier year was 2005. This year had a runoff of 34.39 mm and the snow water equivalent from Snowslide Canyon was 4,323.08 mm. For post-treatment, the outlier year was 2020. This year had a runoff of 0.00 mm, likely due to a short continuous data record (46 days), and the snow water equivalent from Snowslide Canyon was 2,288.54 mm.

Table 2-7. Runoff vs precipitation, displaying the outlier test results from RStudio. The table is divided into "Pre-treatment" and "Post-treatment" periods, with an outlier data point (year) selected and computed for each.

Pre- Treatment				***Post-Treatment***			
Year	***Studentized Residual***	***Unadjusted p-value***	***Bonferroni P***	***Year***	***Studentized Residual***	***Unadjusted p-value***	***Bonferroni P***
2005	3.69	0.00354	0.0496	2018	-2.3	0.0549	0.549

Table 2-8. Runoff vs Snowslide Canyon SWE, displaying the outlier test results from RStudio. The table is divided into "Pre-treatment" and "Post-treatment" periods, with an outlier data point (year) selected and computed for each.

Pre- Treatment				***Post-Treatment***			
Year	***Studentized Residual***	***Unadjusted p-value***	***Bonferroni P***	***Year***	***Studentized Residual***	***Unadjusted p-value***	***Bonferroni P***
2005	3.83	0.00332	0.0432	2020	3.39	0.0115	0.115

Table 2-9. Runoff vs Snowbowl Station #2 SWE, displaying the outlier test results from RStudio. The table is divided into "Pre-treatment" periods, with an outlier data point (year) selected and computed for each.

Pre- Treatment				***Post-Treatment***			
Year	***Studentized Residual***	***Unadjusted p-value***	***Bonferroni P***	***Year***	***Studentized Residual***	***Unadjusted p-value***	***Bonferroni P***
2005	2.59	0.02331	0.3496	2019	-2.53	0.0448	0.403

Precipitation – PRISM 4k Grid:

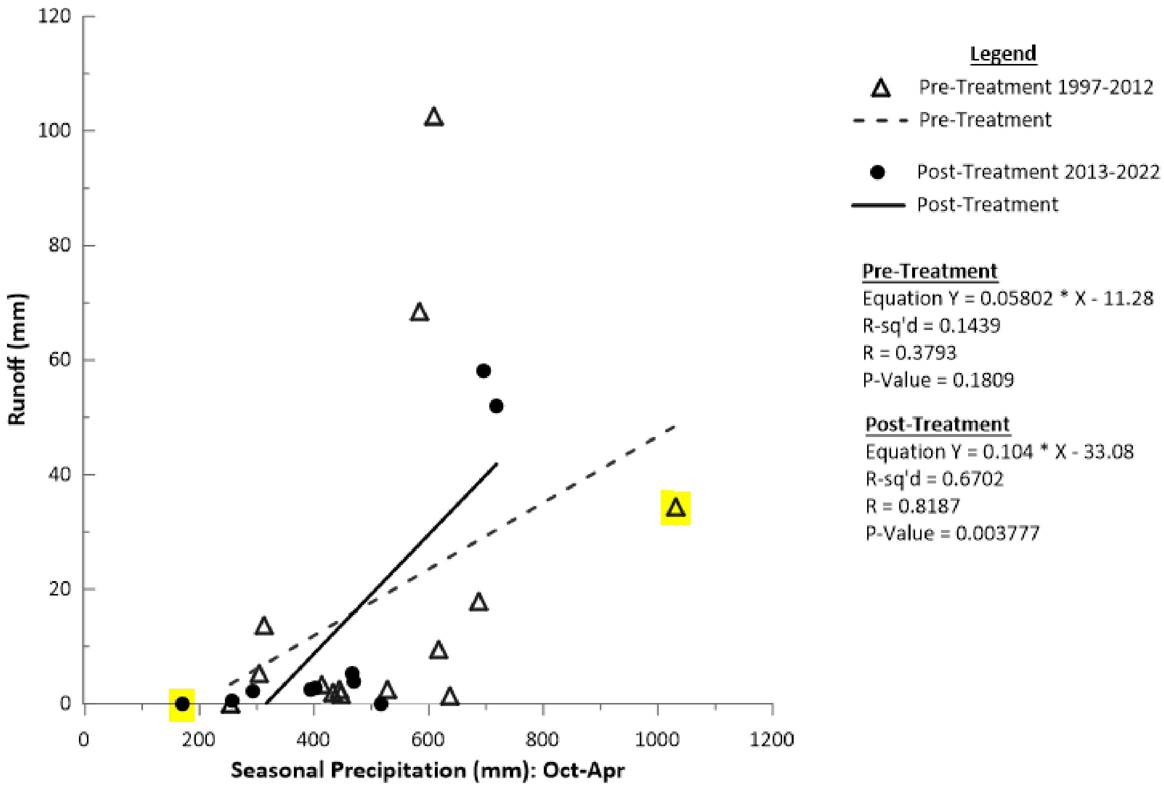


Figure 2-22. Hart Prairie Spring multilinear regression model of "Runoff (mm)" and "Seasonal Precipitation (mm)" from 1997 to 2022. The outliers that were selected from the outlier test analysis (Table 2-7) are highlighted.

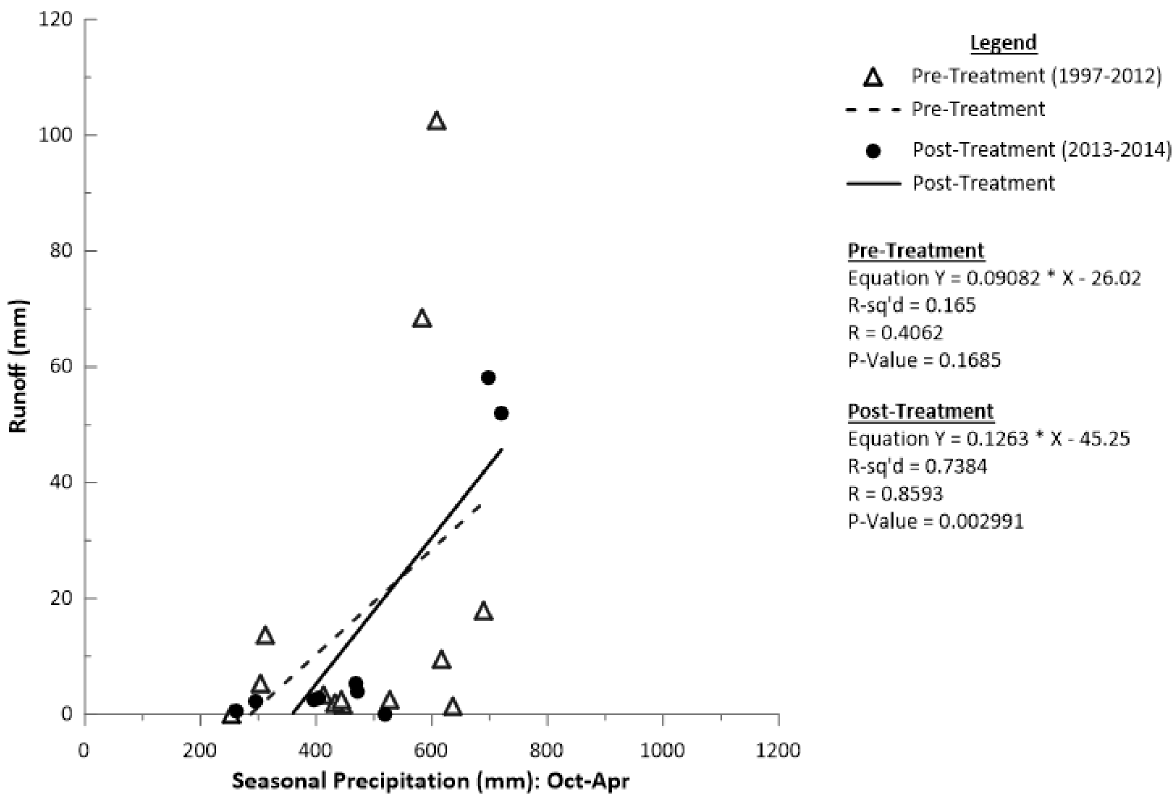


Figure 2-23. Hart Prairie Spring multilinear regression model of "Runoff (mm)" and "Seasonal Precipitation (mm)" from 1997 to 2022. The outliers that were selected from the outlier test analysis (Table 2-7) are removed.

SNOTEL Site - Snowslide Canyon (Inner Basin):

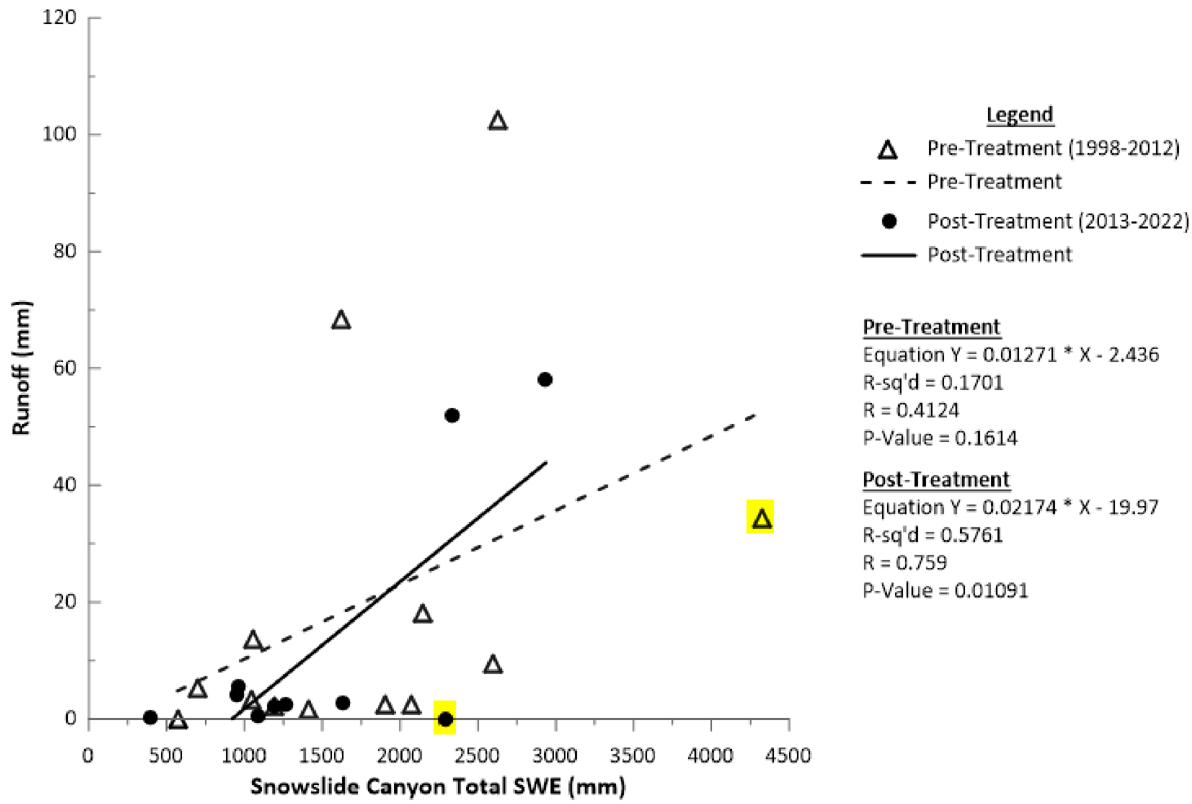


Figure 2-24. Hart Prairie Spring multilinear regression model of "Runoff (mm)" and "Snowslide Canyon Total SWE (mm)" from 1998 to 2022. The outliers that were selected from the outlier test analysis (Table 2-8) are highlighted.

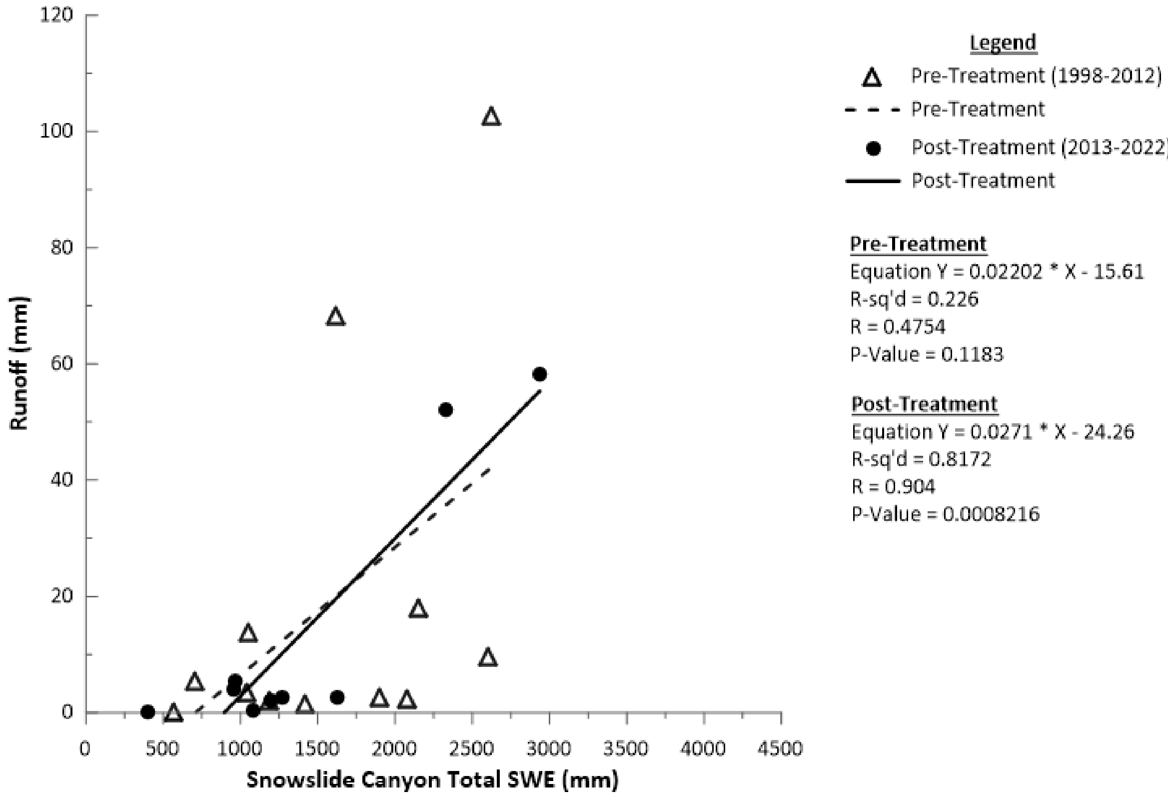


Figure 2-25. Hart Prairie Spring multilinear regression model of Runoff (mm) and Snowslide Canyon Total SWE (mm) from 1998 to 2022. The outliers that were selected from the outlier test analysis (Table 2-8) are removed.

Snow Course/Aerial Marker - Snowbowl Station #2:

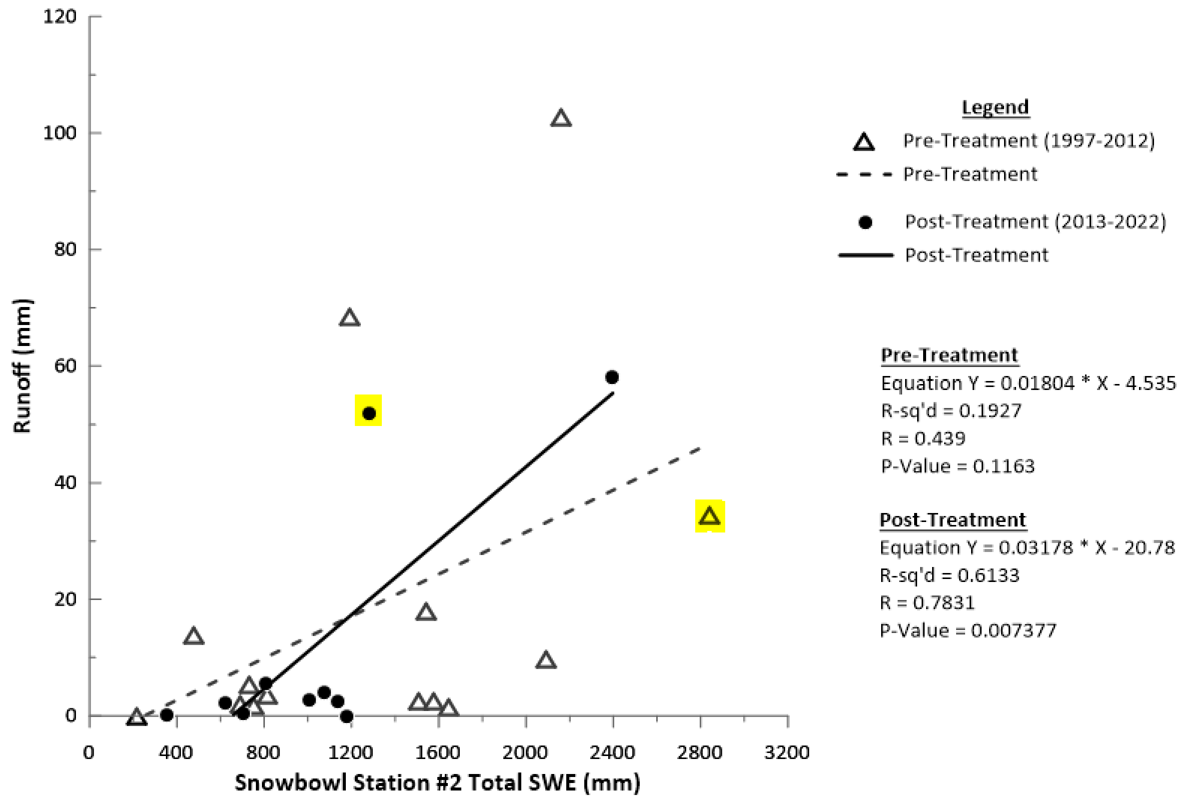


Figure 2-26. Hart Prairie Spring multilinear regression model of "Runoff (mm)" and "Snowbowl Station #2 Total SWE (mm)" from 1997 to 2022. The outliers that were selected from the outlier test analysis (Table 2-9) are highlighted.

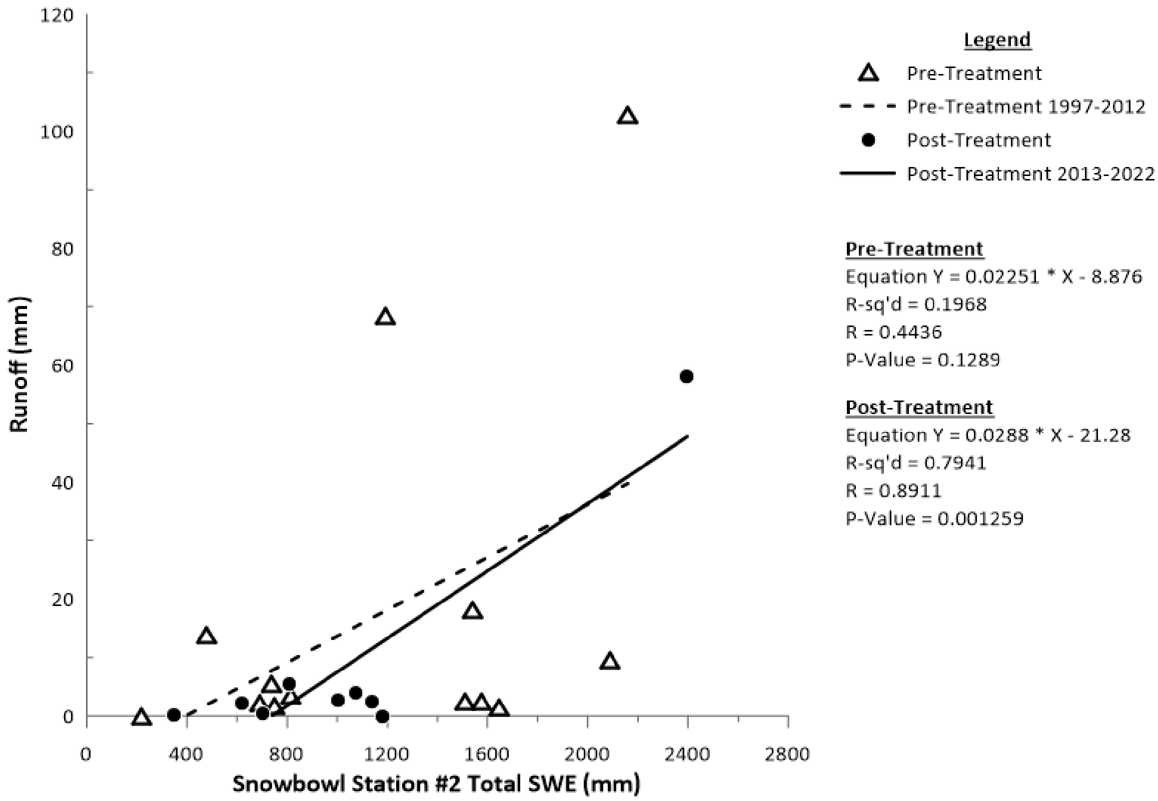


Figure 2-27. Hart Prairie Spring multilinear regression model of "Runoff (mm)" and "Snowbowl Station #2 Total SWE (mm)" from 1997 to 2022. The outliers that were selected from the outlier test analysis (Table 2-9) are removed.

Table 2-10. Statistical summary table of climatic data logging locations versus runoff. These results are from the multilinear regression models with the outlier intact (Figures 2-22, 2-24, 2-26).

Pre-Treatment			
Climatic Location	***P-Value***	***Correlation Coefficient (R)***	***Coefficient of Determination (R^2)***
PRISM 4k-Grid	0.1809	0.3793	0.1439
Snowslide Canyon	0.1614	0.4124	0.1701
Snowbowl Station #2	0.1163	0.439	0.1927
Post-Treatment			
Climatic Location	***P-Value***	***Correlation Coefficient (R)***	***Coefficient of Determination (R^2)***
Prism 4k-Grid	0.003777	0.8187	0.6702
Snowslide Canyon	0.01091	0.759	0.5761
Snowbowl Station #2	0.007377	*0.7831*	0.6133

Table 2-11. Statistical summary table of climatic data logging locations versus runoff. These results are from the multilinear regression models with the outlier removed (Figures 2-23, 2-25, 2-27).

Pre-Treatment			
Climatic Location	***P-Value***	***Correlation Coefficient (R)***	***Coefficient of Determination (R^2)***
PRISM 4k-Grid	0.1685	0.4062	0.165
Snowslide Canyon	0.1183	0.4754	0.226
Snowbowl Station #2	0.1289	0.4436	0.1968
Post-Treatment			
Climatic Location	***P-Value***	***Correlation Coefficient (R)***	***Coefficient of Determination (R^2)***
Prism 4k-Grid	0.002991	0.8593	0.7384
Snowslide Canyon	0.0008216	0.904	0.8172
Snowbowl Station #2	0.001259	0.8911	0.7941

Table 2-12. Difference in slope from the climatic locations. Results are from the multilinear regression models with the outlier removed (Figures 2-23, 2-25, 2-27).

PRISM-4km		***Snowslide Canyon***		***Snowbowl Station #2***	
Pre-Treatment	***Post-Treatment***	***Pre-Treatment***	***Post-Treatment***	***Pre-Treatment***	***Post-Treatment***
Y=0.09082*X-26.02	Y=0.1263*X-45.25	Y=0.02202*X-15.61	Y=0.0271*X-24.25	Y=0.02251*X-8.876	Y=0.0288*X-21.28
0.09082	0.1263	0.02202	0.0271	0.02251	0.0288
Difference:	0.03548	Difference:	0.00508	Difference:	0.00629

The results from the multilinear regression models analyze the dependent variable runoff and the independent variable, such as PRISM 4k-Grid seasonal precipitation (Figure 2-23), Snowslide Canyon total SWE (Figure 2-25), and Snowbowl Station #2 total SWE (Figure 2-27) prior to and following forest restoration treatments. The results from the multilinear regression models without outliers were chosen to be interpreted since it removes observations that are vastly different than the majority dataset. Table 2-10 presents a statistical summary of the results from the multilinear regression models with the outliers included. There was a small to moderate difference between the statistical results of retaining or removing the outliers. Analyzing the statistical table with the ourliers removed, all three climatic data logging locations generally reflect similar results, with the snow climatic data logging locations showing greater statistical significance. Hart Prairie Spring is a snow-driven hydrologic system, and this was reflected in the results (Table 2-11). The following are general interpretations of the results from (Table 2-11) (Boston University, 2023; The Pennsylvania State University, 2023).

1.) Pre-treatment rainfall:runoff regressions were not statistically significant.

   a. The lack of significance may be attributed to not attaining equivalent lengths of recorded data or climate cyclic variations. When comparing all three climatic locations, Snowslide Canyon and Snowbowl Station #2 have a lower p-value in comparison to PRISM 4k-grid (Table 2-11).

2.) Post-treatment rainfall:runoff regressions were statistically significant.

   a. The results indicate that post-treatment results occurred by an attributed cause, such as the implemented forest restoration treatments. The results from (Table 2-11) indicate that all three climatic parameters show significant values. The climatic location, Snowslide Canyon, indicates a greater significance (p value = 0.0008216). The results from Snowslide Canyon affirm Hart Prairie Spring as a predominantly snow-driven hydrologic system.

3.) Pre-treatment runoff had a positive and a weak to moderate correlation.

   a. The linear relationship between runoff and all three climatic locations have a positive trend indicating that as the independent climatic parameter increases as does the dependent amount of runoff. The correlation coeficient R-value of all three climatic locations have weak to moderate values ranging between 0.40 to 0.48. This value range indicates that there may be uncertainty in the relationship between the two independent and dependent parameters.

4.) Post-treatment runoff had a positive and very strong correlation.

   a. The linear relationship between runoff and all three climatic locations have a positive trend indicating that as the independent climatic parameter increases as does the dependent variable runoff. The correlation coeficient R-value of all three climatic locations have very strong values ranging between 0.85 to 0.90. This value range indicates that there is little uncertainty in the relationship between the two independent and dependent parameters.

5.) Pre-treatment runoff had moderatly high variability leading to insignificant correlation.

   a. The linear relationship between the dependent variable runoff and independent climatic parameters have high variablilty leading to insignificant correlation, indicating that there is more variation between the datapoints and the linear relationship. The coefficient of determination R^2 value for pre-treatment range between 0.16 to 0.20.

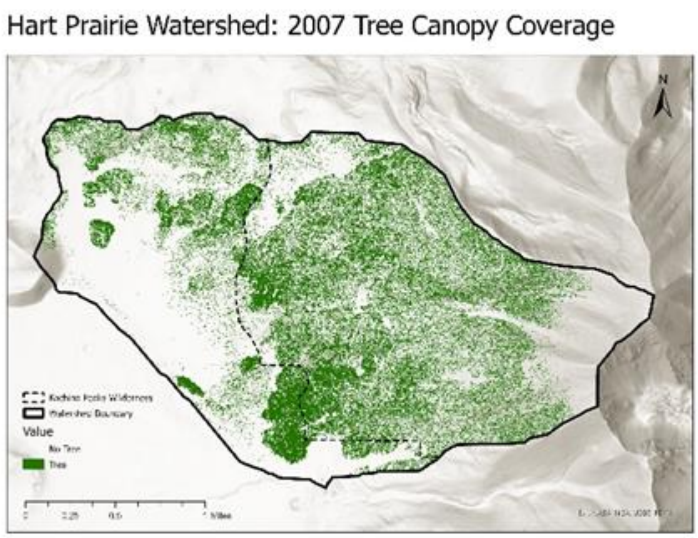
6.) Post-treatment runoff had moderate to low variability leading to significant correlation.

   a. The linear relationship between the dependent variable runoff and independent climatic parameters have moderate to low variablilty leading to significant correlation, indicating that there is low variation between the datapoints and the linear relationship. The coefficient of determination R^2 value for pre-treatment range between 0.73 to 0.82.

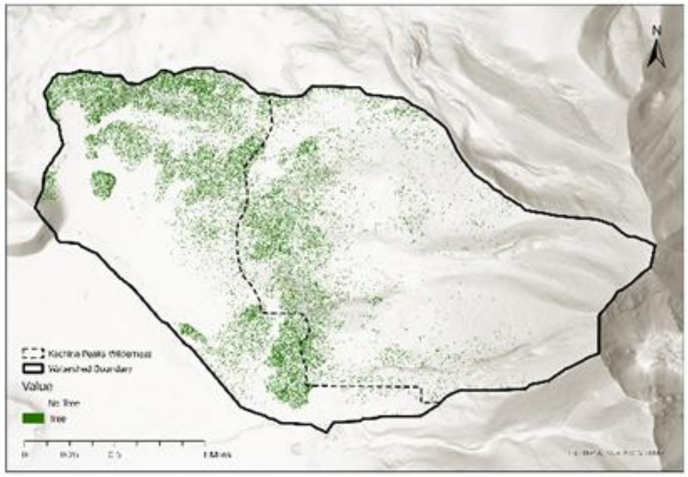
2.4.5 Tree Canopy Coverage

The forest treatments implemented in 2013-2014 can be seen in the areas near the Kachina Peaks wilderness boundary line (Figure 2-28). The year 2007 shows dense forest near this area. The year 2010 appears to have less density, but this could be due to the vitality of the leaves during this year. The original NAIP image for 2010 displayed more trees than is shown. The year 2010 was a dry year, which could lead to decreased forest health or leaf “greenness”. The year 2013 visibly shows high tree density near the Kachina Peaks wilderness boundary line. Forest restoration treatments were implemented late 2013 through early 2014. Year 2015 visibly displays the implemented forest structure of open meadow to patchy forest stands. The year 2017 shows high forest density or high vegetative health overall. In addition, this year is considered a wet year as shown, which correlates with the forest vitality. 2019 is considered a dry year and 2021 is considered a partially wet year (Figure 2-28). The estimated climatic cycles correspond well with the visual analysis and ratio value of forest vitality and density. The process of using NDVI to analyze tree canopy coverage change over time can be resourceful to display forest vitality and structure but does not necessarily show overall tree canopy biomass well. This error is displayed in the year 2010 but is also shown sparsely in other years that were analyzed. The NAIP image dates for each year were generally similar. The NAIP image for year 2017 was taken during monsoon season, which shows high forest vitality. Forest vitality corresponds well to the Southern Oscillation Index Cycles, which is important in regard to the overall hydrologic cycle.

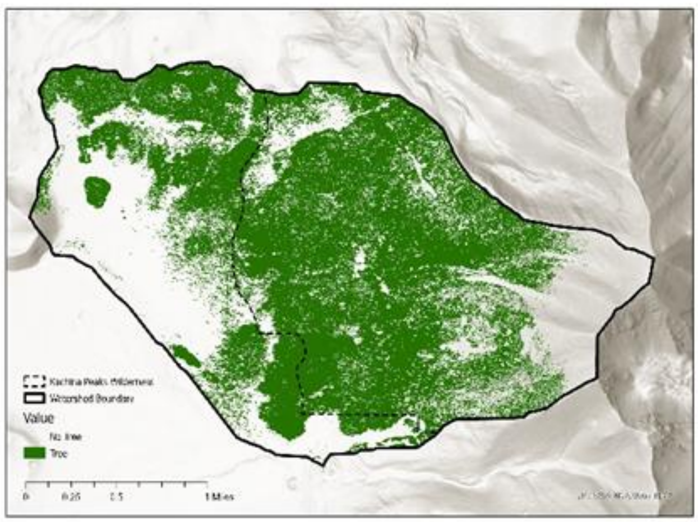
a.)



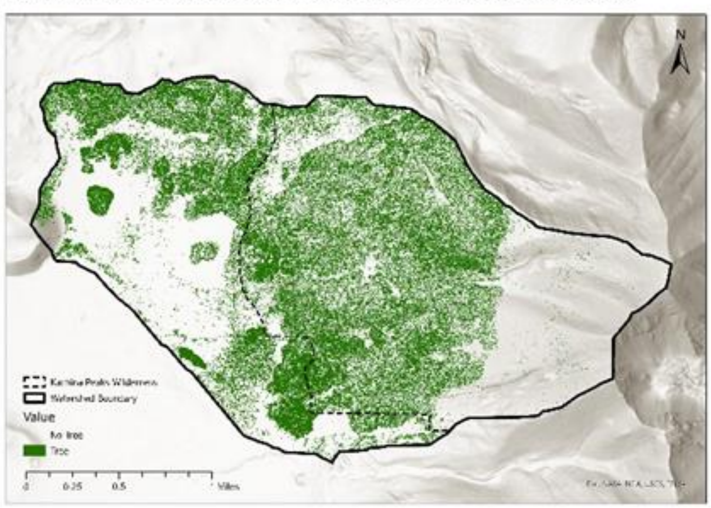
b.) Hart Prairie Watershed: 2010 Tree Canopy Coverage



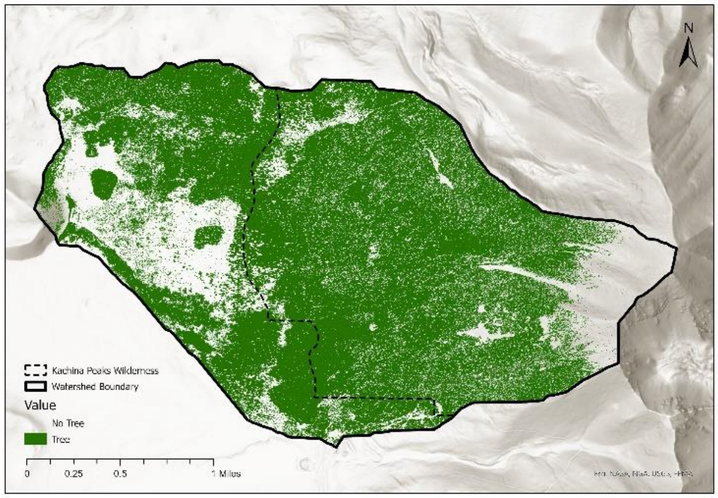
c.) Hart Prairie Watershed: 2013 Tree Canopy Coverage



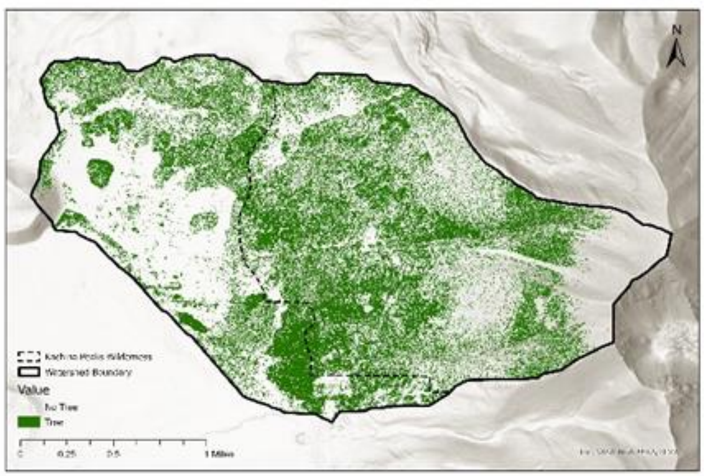
d.) Hart Prairie Watershed: 2015 Tree Canopy Coverage



e.) Hart Prairie Watershed: 2017 Tree Canopy Coverage



f.) Hart Prairie Watershed: 2019 Tree Canopy Coverage



g.) Hart Prairie Watershed: 2021 Tree Canopy Coverage

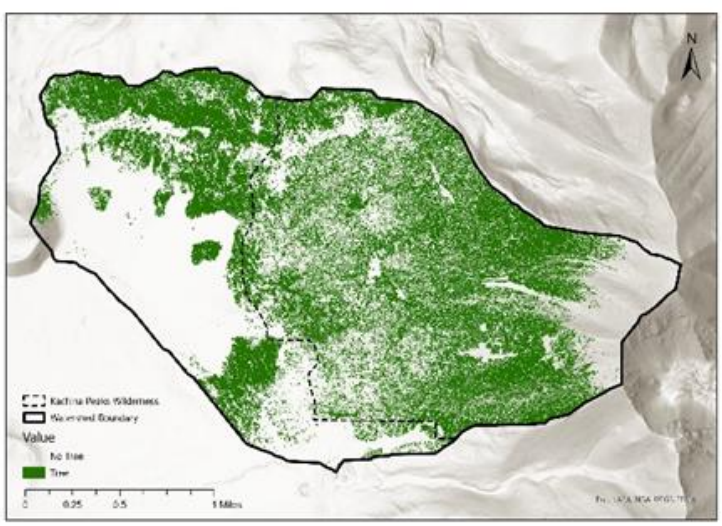


Figure 2-28. 1-m resolution tree canopy coverage maps of the Hart Prairie Spring watershed area for a) 2007, b) 2010, c) 2013, d) 2015, e) 2017, f) 2019, and g) 2021. The green represents "Tree", and no color represents "No Tree". The dotted black line represents the Kachina Peaks Wilderness boundary.

2.5 Summary

The purpose of the study was to characterize the hydrologic response of Hart Prairie Spring to the forest restoration treatments that were implemented in 2013-2014. Monitoring and quantifying of the parameters of continuous spring discharge, precipitation, snow data, southern oscillation cycles, and tree canopy coverage analysis were conducted. The parameters were analyzed through multiple methods such as hydrograph analyses, multilinear regression analyses, tree canopy cover analyses, and correlations with climatic data.

The following list the general conclusions from this study:

1.) Hart Prairie Spring is predominately a snow-driven hydrologic system and is highly dependent on snow fall and spring snowmelt for groundwater recharge.

2.) Rain fall runoff generally indicates significant results. Particularly the snowmelt runoff had significant correlation post-treatment. Peak flow is occurring earlier, depicting climatic changes. These factors indicate that there was a positive hydrologic response due to the forest restoration treatments that were implemented from 2013 to 2014.

3.) Hart Prairie Spring responds strongly to climatic cycles of wet and dry years, as indicated by hydrographic analysis and forest vitality analysis.

Additional analyses and collaborations are needed to sufficiently understand if the implemented forest treatments that did influence the hydrologic response can efficiently supply, maintain, and establish the Bebb Willow community. Various riparian species, particularly Bebb Willow, undergo extensive and detrimental grazing from ungulate mammals in conjunction with having a low regeneration success rate in recent years. Fencing barriers have been installed around select Bebb Willows to prevent grazing from ungulate mammals.

The Bebb Willow require specific environmental factors to establish successful germination (Amentt, 2002). Saturated surface soil conditions are necessary during Bebb willow seed dispersion in late June to promote seed germination and establishment. Even though the forest restoration improved the hydrologic conditions of Hart Prairie, there is no evidence of any new seedling establishment post-treatment. The implemented forest restoration contributes to positive establishment conditions, but further restorative practices may need to be considered to establish seedlings. Modifications to an ecosystem can lead to various changes in function (Gordon et al., 2008; Western, 2001). Springs in general are vital sources to riparian ecosystems and numerous ecological factors within them. Vegetation within riparian ecosystems are vital entities that provide healthy characteristics and should be analyzed in conjunction with hydrologic properties (Zaimes et al., 2017). The convergence of hydrogeology and ecology for groundwater-dependent ecosystems (GDE), such as Hart Prairie Springs, and ecosystem analysis in general, provides a more thorough investigative and analytical approach to ecosystem monitoring in relation to assessment of management actions (Cantonati et al., 2020).

Potential Errors

The datasets that have been acquired and compiled over the past 26 years have the potential of compounded error. Factors such as equipment changes, software and computer upgrades, changes in the method process, and transfer of data over the research period. The analysis of the compiled data potentially has errors due to numerous factors relating to tree canopy coverage, multilinear regression, and climate data from various weather stations and models.

Importance of Results

This study increases our understanding of how the Hart Prairie Spring watershed generally functions and responds to forest restoration treatments. The results from this monitoring project will benefit the continuation of future forest restoration projects. The hydrologic responses described here will help improve land management and planning. The scale of the response will additionally help improve future restoration treatments of this study site and those in other regions.

Chapter 3: Additional Results and Conclusions

3.1 Springs

The following results and conclusions correspond with three springs that had ample spring discharge data, water quality records, and climatic data. The results for each study site include the full continuous record of spring discharge data in the form of a hydrograph and a flow data summary table. Hoxworth Spring and Big Spring report water quality results from the ProDSS YSI Multi-Water Parameter Water Quality Probe. All three springs had complete water quality analyses, including isotope and ion data. Climatic data, such as precipitation and snow water equivalent, are reported from publicly available data.

Aquarius Time-Series is a database that was utilized for general storage, manipulation, and analysis of various environmental, climatic, and hydrometric parameters (Aquatic Informatics ULC, 2023). Each monitored spring had its own established location within the Aquarius Time-Series Springboard. Raw continuous pressure transducer data, from each spring, were appended and processed as individual basic time series. A rating curve model was derived using a stage-discharge relationship method from hand-measured discharge measurements.

3.1.1 Hoxworth Spring

The climatic data for the Hoxworth Spring area, such as precipitation and snowfall, were reported by utilizing the Pulliam Airport weather station. The hydrology in this area is primarily recharged by snow fall and spring snowmelt. The spring snowmelt season typically occurs from April through May, but can start as early as March (Schenk et al., 2021). Monsoon season typically begins mid-June; However, in Northern Arizona it may not start until early-July, which can be seen from the increase of precipitation in (Figure 3-2) (NOAA, 2023b) Hoxworth Spring is a perennial floodplain rheocrene spring, which receives an approximate mean annual total precipitation of 504.6 mm (Stevens et al., 2020). From the year 2000 through 2023, there were 11 yr that exceeded the mean total annual precipitation. Year 2023 had three months of precipitation data and will most likely exceed the mean total annual precipitation (Figure 3-1) (Western Regional Climate Center, 2023). The mean total annual snowfall from the years 2000 through 2023 was approximately 2,100.0 mm, which is indicated by the red dotted line (Figure 3-3). From this time range there were 11 yr that exceeded the mean annual total snowfall accumulation (Figure 3-3).

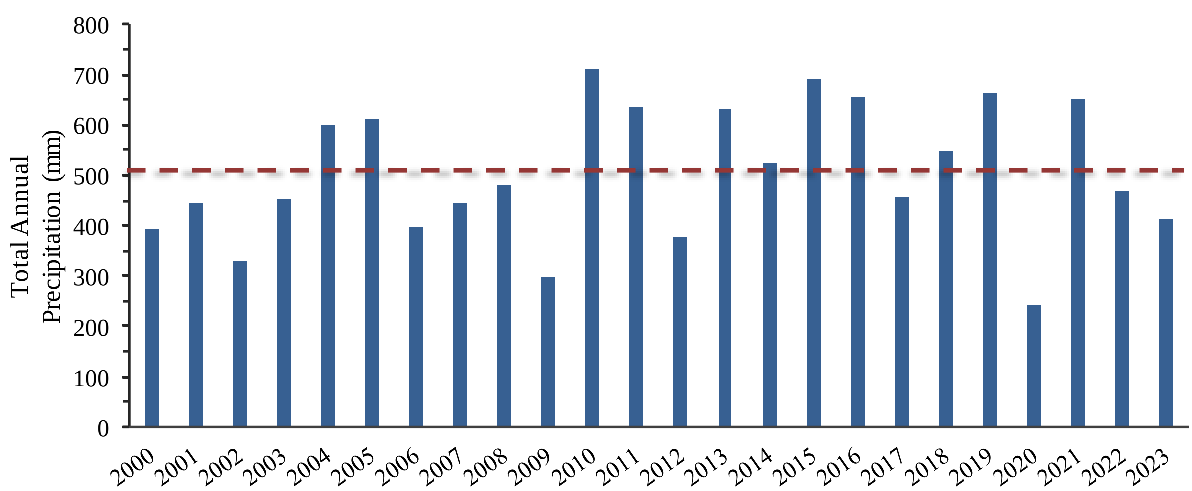


Figure 3-1. The total annual precipitation from the Pulliam Airport weather station. The mean annual total from the year 2000 through 2023 is approximately 504.58 mm, as indicated by the red dotted line. Year 2023 only had 3 months of data. There are currently 11 years from 2000 through 2023 that exceeded the average total precipitation (Western Regional Climate Center, 2023).

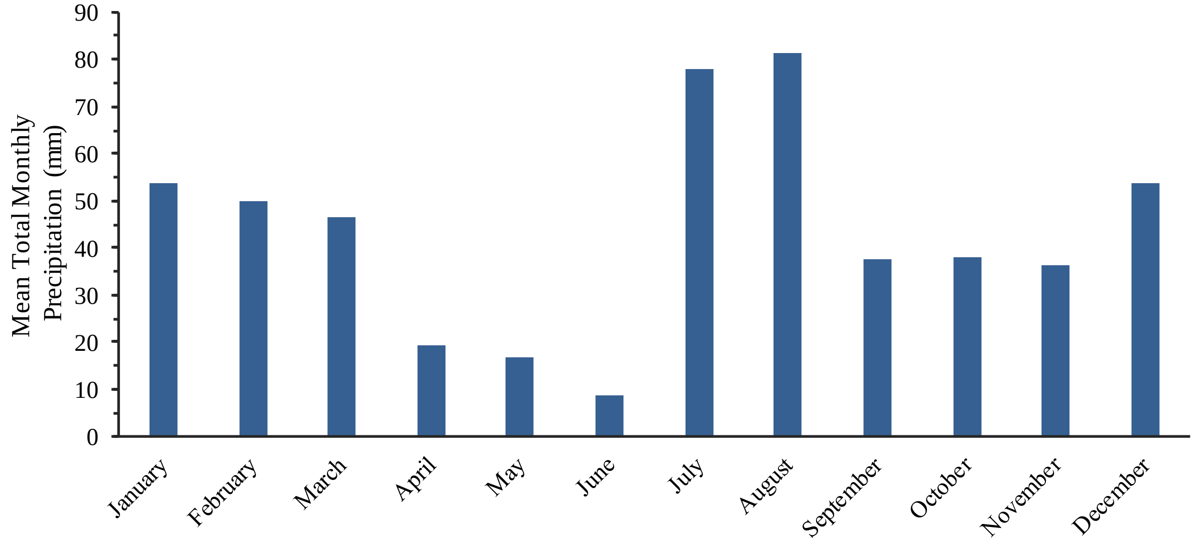


Figure 3-2. The mean total precipitation for each month from Pulliam Airport near Hoxworth Spring. This is reflective of the total average precipitation from year 2000 through 2023 (Western Regional Climate Center, 2023).

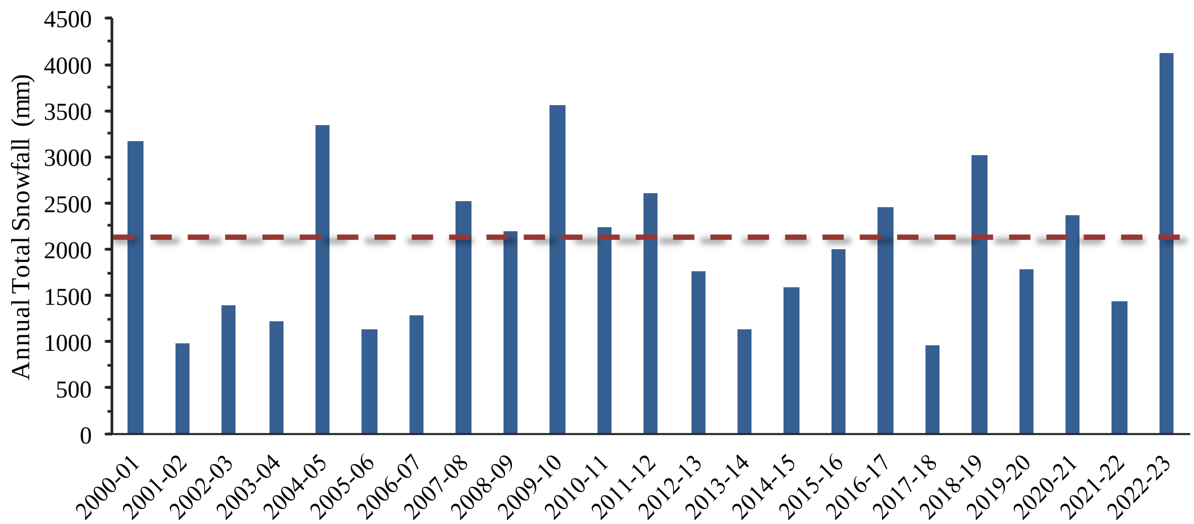


Figure 3-3. The total annual snowfall from the Pulliam Airport weather station. The mean annual total from 2000 through 2023 is approximately 2,100.03 mm, as indicated by the red dotted line. There are currently about 11 years from 2000 through 2023 that have exceeded the mean annual total snowfall accumulation (Western Regional Climate Center, 2023).

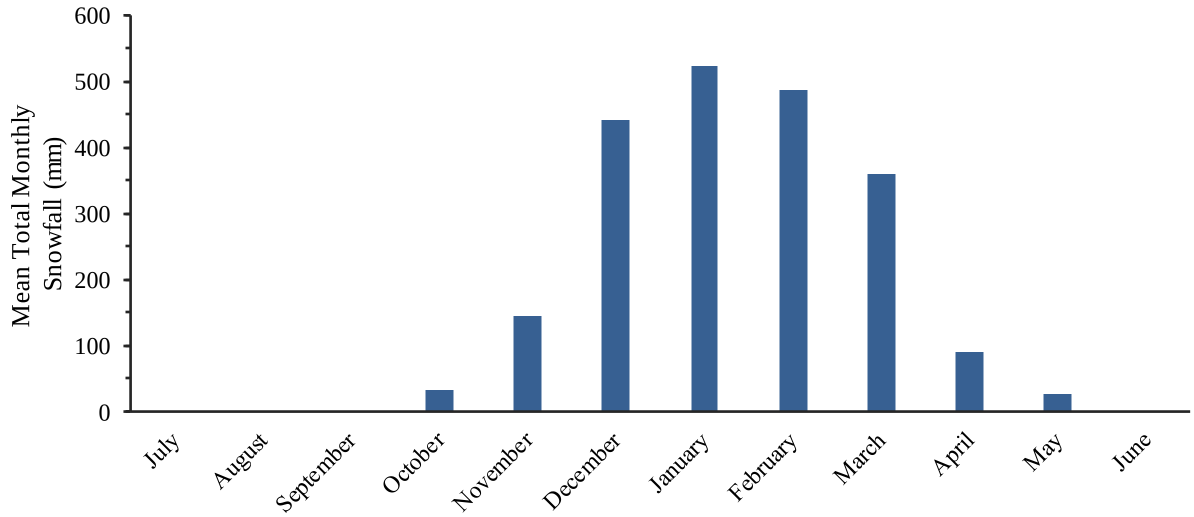


Figure 3-4. The mean total snowfall for each month from Pulliam Airport near Hoxworth Spring. This is reflective of the total average snowfall for each month from year 2000 through year 2023 (Western Regional Climate Center, 2023).

Hydrograph

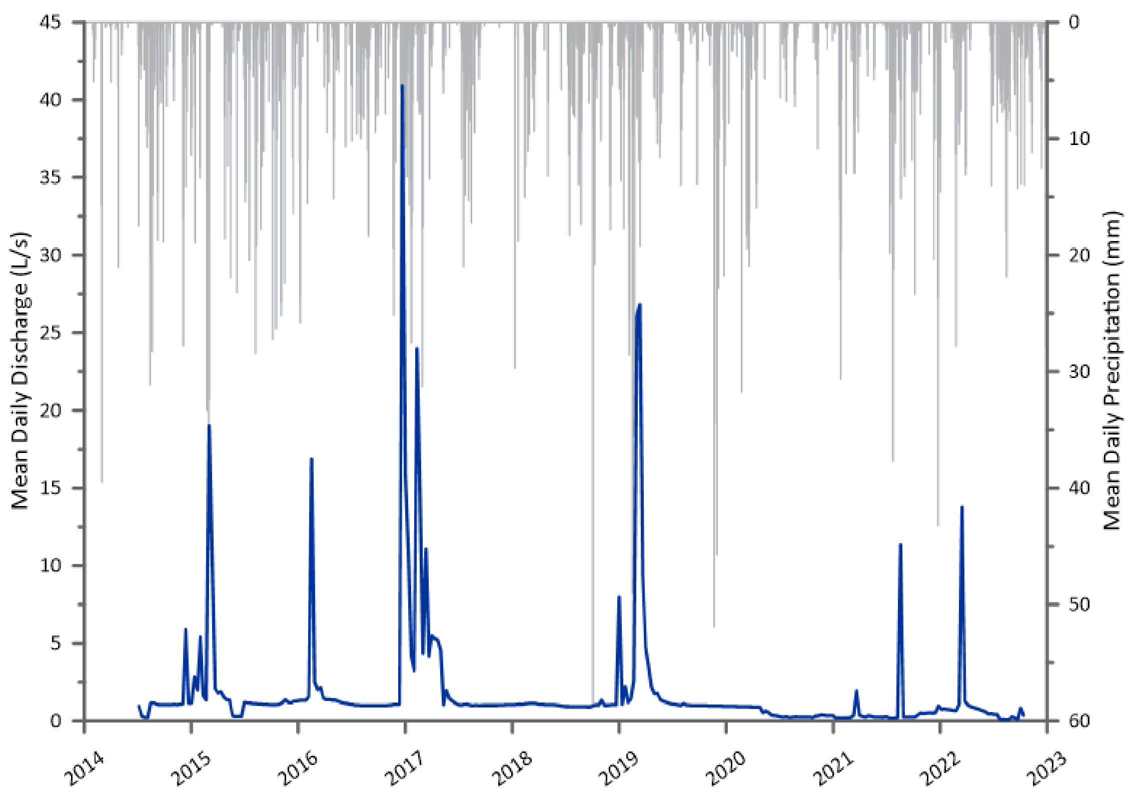


Figure 3-5. Hoxworth Spring daily average spring discharge (blue) and Hoxworth Spring daily average precipitation of PRISM 4-km grid watershed catchment area (gray)

Base-Flow Separation

Hoxworth Spring is described as perennial floodplain rheocrene spring located in a wet meadow and flows in a discrete channel. Because of the environmental location of Hoxworth Spring, surface runoff is included in the spring discharge record. A base-flow separation process was conducted to separate spring discharge from surface runoff. Therefore, the hydrologic properties of Hoxworth Spring could be isolated and analyzed with less interference. The base-flow separation analysis was completed by using Purdue University Web-Based Hydrograph Analysis Tool (WHAT) (Lim & Engel, 2003).

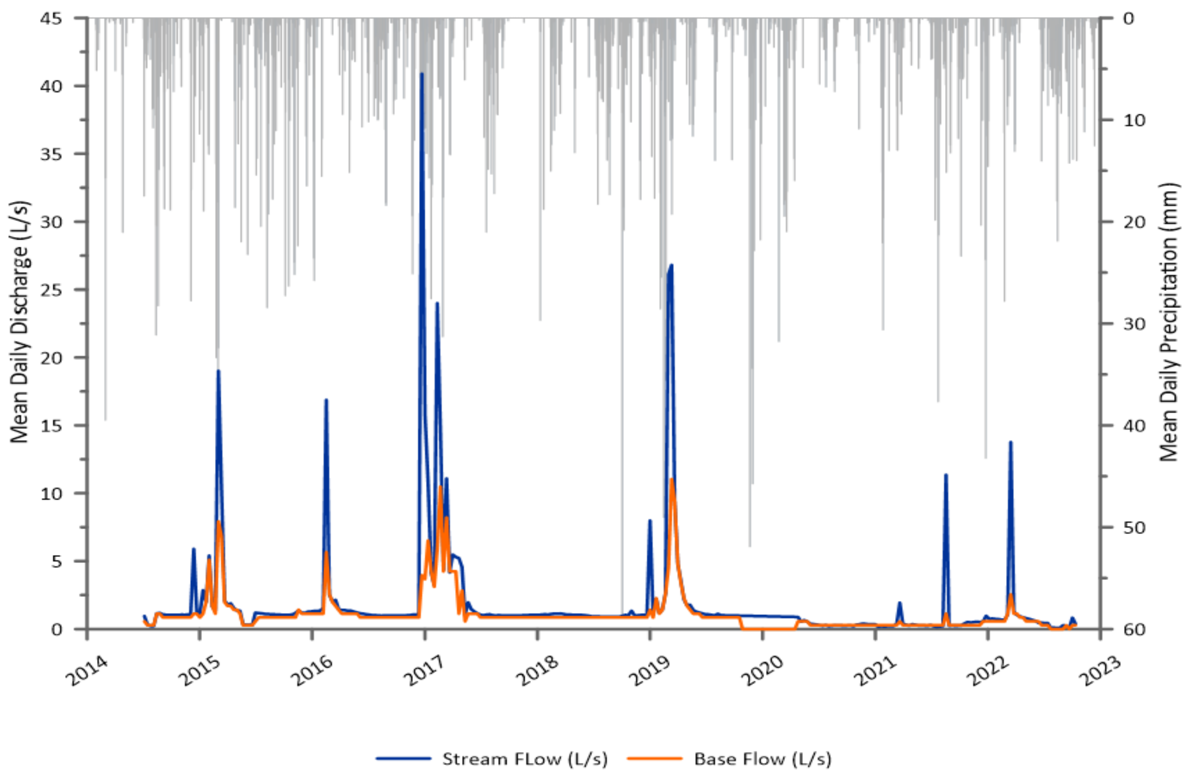


Figure 3-6. Hoxworth Spring daily average spring discharge (black), Hoxworth Spring daily average base flow (orange), and Hoxworth Spring daily average precipitation of PRISM 4 km grid watershed catchment area (gray).

Water Quality Sampling

Table 3-1. Water samples that underwent isotope testing at the Arizona Climate and Ecosystems Isotope Laboratory at Northern Arizona University.

Hoxworth Spring Isotope Analysis			
Collection date	*Analysis Date*	*dD (‰)*	*D18O (‰)*
10/18/2019	11/15/2019	-82.21	-11.89
4/17/2020	6/16/2020	-81.45	-11.75
10/8/2020	2/5/2021	-80.40	-11.29
4/26/2021	5/23/2021	-78.75	-10.99
10/14/2021	12/10/2021	-69.76	-10.14
4/12/2022	6/29/2022	-80.40	-11.49
6/15/2022	6/29/2022	-79.40	-11.33
9/3/2022	10/26/2022	-73.31	-10.51
10/1/2022	10/26/2022	-75.92	-10.89

Table 3-2. Water sample that underwent cation testing at Arizona Laboratory for Emerging Contaminants at the University of Arizona.

Hoxworth Spring Cation Analysis				
Collection Date	*Na^+ (mg/L)*	*Mg^+ (mg/L)*	*K^+ (mg/L)*	*Ca^+ (mg/L)*
10/8/2020	3.332	34.464	0.701	65.975

Table 3-3. Water sample that underwent anion testing at Arizona Laboratory for Emerging Contaminants at the University of Arizona. BDL "Below Detection Limit".

Hoxworth Spring Anion Analysis							
Collection Date	*F^- (mg/L)*	*Cl^- (mg/L)*	*NO^{2-} (mg/L)*	*Br^- (mg/L)*	*NO^{3-} (mg/L)*	*PO^{4-} (mg/L)*	*SO^{4-} (mg/L)*
10/8/2020	0.081	1.637	BDL	0.083	BDL	BDL	1.643

Water Quality Results

Table 3-4. Discrete water quality parameters recorded with a YSI Pro DSS at Hoxworth Spring on 10/01/2022 09:26:40.

Hoxworth Spring YSI Readings						
Conductivity (µS/cm)	*nLF Conductivity (µS/cm)*	*ODO % sat*	*ODO mg/L*	*Salinity (psu)*	*Specific Conductivity (µS/cm)*	*TDS (mg/L)*
334.7	457.2	32	3.47	0.22	449.4	292
Turbidity (FNU)	*TSS (mg/L)*	*pH*	*pH (mV)*	*Temp (°C)*	*Altitude (m)*	*Barometer (mmHg)*
-0.08	0	7.33	-39.5	11.64	2133.6	591.7

3.1.2 Clover Spring

Climatic data for the Clover Spring area, including precipitation and snowfall, were reported by utilizing the Happy Jack Ranger Station climate station. The hydrology in this area is primarily recharged by snow fall and spring snowmelt (Donovan et al., 2021). Clover Spring is an ephemeral hillslope spring, and its catchment receives an approximate mean annual total precipitation of 417.1 mm. From the year 2000 through 2023, there were 13 yr that had exceeded the mean total precipitation. From the year 2000 through 2023 there were a few months of data missing, resulting in a downward trend (Figure 3-7) (Western Regional Climate Center, 2023). The mean total annual snowfall from the year 2000 through 2023 is 936.7 mm, which is indicated by the red dotted line in Figure 3-7. From the year 2000 through 2023 there were 10 yr that exceeded the mean annual total snowfall accumulation. From the year 2000 through 2023 there are a few months of data missing, resulting in a downward trend (Figure 3-7).

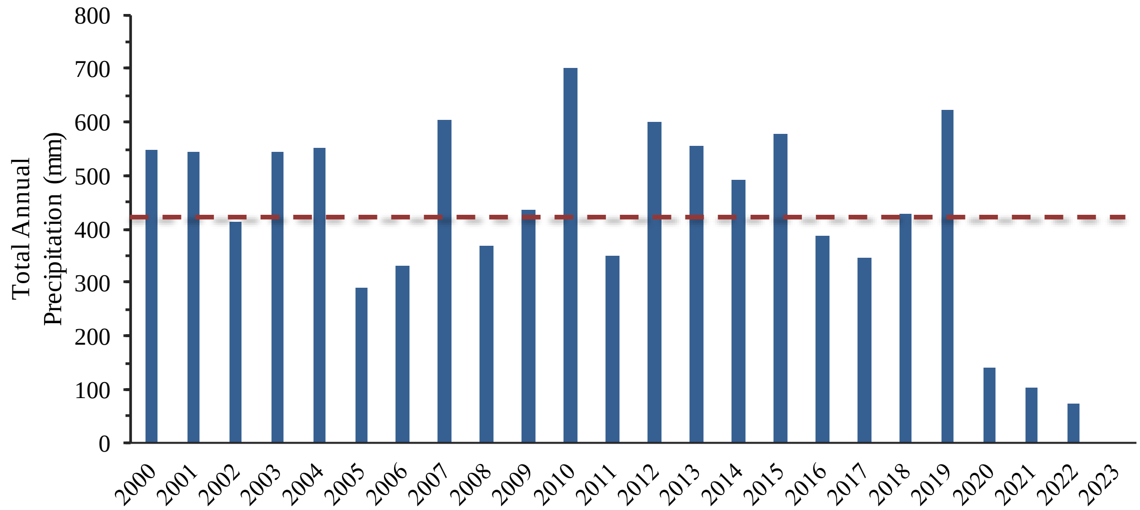


Figure 3-7. The total annual precipitation from the Happy Jack Ranger Station. The mean annual total from the year 2000 through 2023 is approximately 417.09 mm, as indicated by the red dotted line. There are currently 13 years from 2000 through 2023 that have exceeded the average total precipitation (Western Regional Climate Center, 2023).

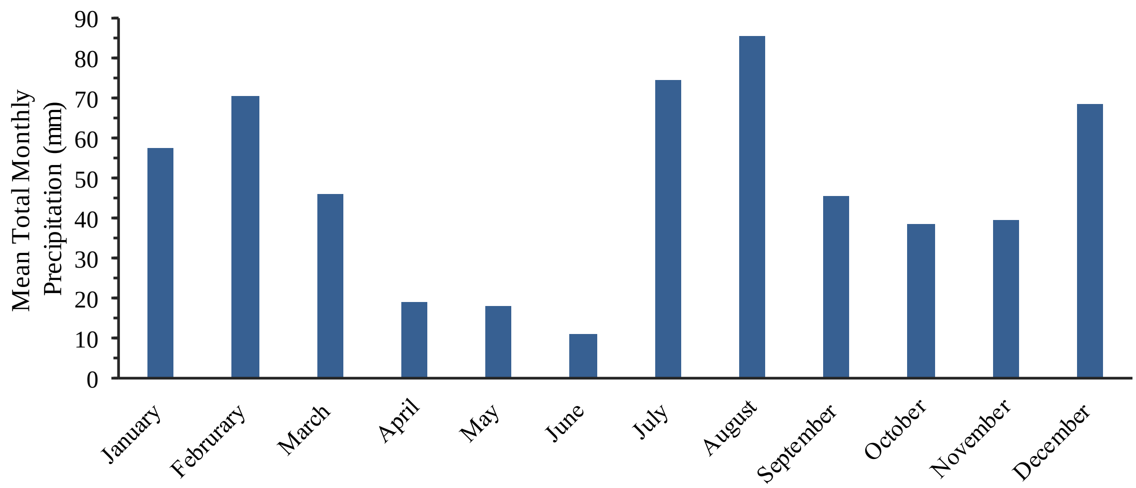


Figure 3-8. The mean total precipitation for each month from the Happy Jack Ranger Station near Clover Spring. This is reflective of the total average precipitation from year 2000 through 2023 (Western Regional Climate Center, 2023).

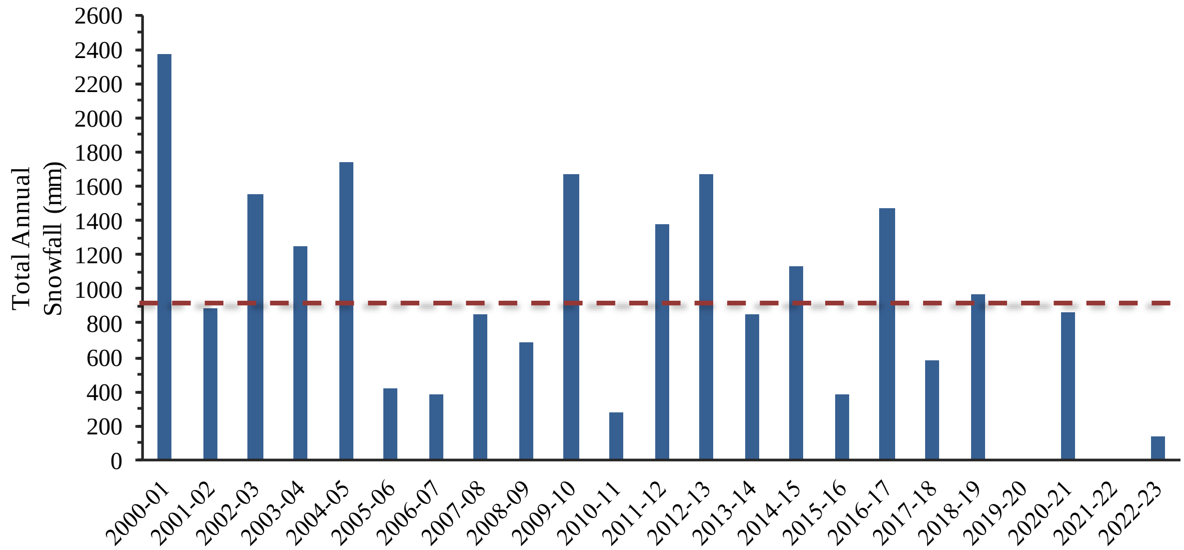


Figure 3-9. The total annual snowfall from the Happy Jack Ranger Station near Clover Spring. The mean annual total snowfall from the year 2000 through 2023 is approximately 936.71 mm, as indicated by the red dotted line. There are currently about 10 years from 2000 through 2023 that have exceeded the mean annual total snowfall accumulation (Western Regional Climate Center, 2023).

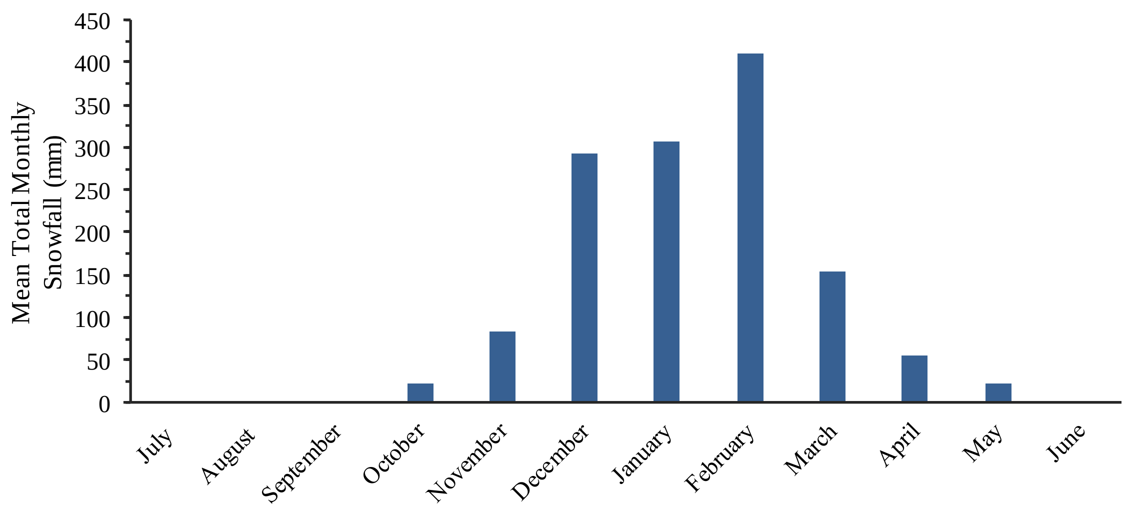


Figure 3-10. The mean total snowfall for each month from the Happy Jack Ranger Station near Clover Spring. This is reflective of the total average snowfall for each month from year 2000 through year 2023 (Western Regional Climate Center, 2023).

Hydrograph

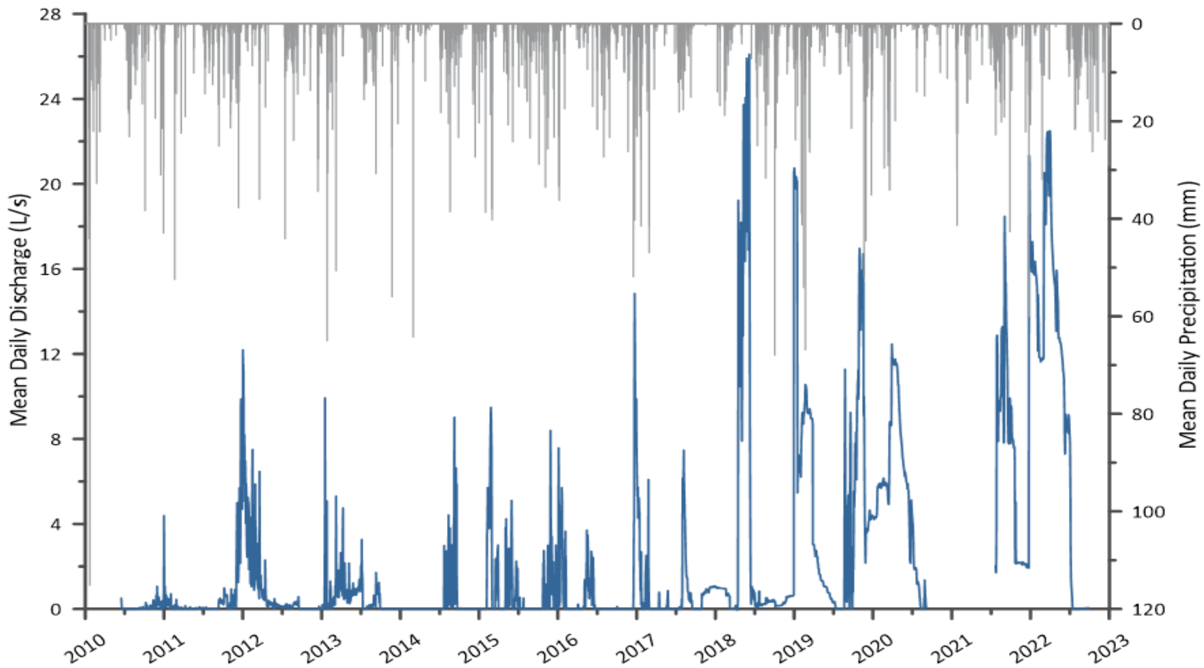


Figure 3-11. Clover Spring daily average spring discharge (blue) and Clover Spring daily average precipitation of PRISM 4 km grid watershed catchment area (gray). Clover Spring is ephemeral as indicated by dates with no flow.

Water Quality Sampling

Table 3-5. Water samples from Clover Spring that underwent isotope testing at the Arizona Climate and Ecosystems Isotope Laboratory at Northern Arizona University.

Clover Spring Isotope Analysis			
Collection date	*Analysis Date*	*dD (‰)*	*D18O (‰)*
3/1/2019	6/20/2019	-96.51	-13.97
3/29/2019	6/20/2019	-97.68	-14.43
7/1/2019	8/5/2019	-77.21	-11.15
6/18/2019	8/5/2019	-76.82	-11.00
2/7/2019	6/16/2020	-79.59	-11.67
2/7/2019 (Spring Box)	6/16/2020	-74.14	-10.23
3/12/2020	6/16/2020	-80.39	-11.59
3/28/2020	6/13/2020	-81.13	-11.58
4/28/2020	6/13/2020	-78.93	-12.16
6/9/2020	8/13/2020	-77.68	-11.36
6/19/2020	8/13/2020	-77.81	-11.20
7/22/2020	8/13/2020	-77.90	-11.26
7/27/2020 (Rain Gauge)	8/17/2020	-77.47	-11.57
7/27/2020	8/17/2020	-95.56	-13.65
9/4/2020	2/5/2021	-77.32	-11.43
9/4/2020	2/5/2021	-31.68	-5.05
10/23/2020	2/5/2021	-74.59	-10.49
4/28/2021	5/23/2021	-75.35	-10.95
4/29/2022	6/29/2022	-74.98	-10.93

Table 3-6. Water samples from Clover Spring that underwent cation testing at Arizona Laboratory for Emerging Contaminants at the University of Arizona.

Clover Spring Cation Analysis				
Collection Date	*Na^+ (mg/L)*	*Mg^+ (mg/L)*	*K^+ (mg/L)*	*Ca^+ (mg/L)*
2/7/2020 (Pipe)	2.05894	14.22144	0.36126	28.62938
3/12/2020	1.87491	9.55559	0.50498	19.2602
3/28/2020	2.02093	12.06532	0.40026	22.7307
4/28/2020	2.09302	14.92128	0.45999	28.96655
6/9/2020	2.40222	20.62431	0.439	40.25578
6/19/2020	2.36954	20.60523	0.41414	39.76029
7/22/2020	2.5156	22.5551	1.9943	47.1563
7/27/2020	2.3625	22.2089	2.0819	47.0859
9/4/2020	2.873	23.804	0.509	46.918
10/23/2020	3.004	25.179	0.491	47.743

Table 3-7. Water samples from Clover Spring that underwent anion testing Arizona Laboratory for Emerging Contaminants at the University of Arizona. BDL "Below Detection Limit".

Clover Spring Anion Analysis							
Collection Date	*F^- (mg/L)*	*Cl^- (mg/L)*	*NO^{2-} (mg/L)*	*Br^- (mg/L)*	*NO^{3-} (mg/L)*	*PO^{4-} (mg/L)*	*SO^{4-} (mg/L)*
2/7/2020 (Pipe)	0.071	0.688	BDL	BDL	BDL	BDL	2.297
3/12/2020	0.073	0.664	BDL	BDL	0.767	BDL	2.505
3/28/2020	0.069	0.712	BDL	BDL	0.420	BDL	2.702
4/28/2020	0.071	0.664	BDL	BDL	0.176	BDL	2.425
6/9/2020	0.072	0.671	BDL	BDL	0.149	BDL	2.389
6/19/2020	0.063	0.666	BDL	BDL	BDL	BDL	2.230
7/22/2020	0.057	0.685	BDL	BDL	BDL	BDL	2.144
7/27/2020	0.061	0.648	BDL	BDL	0.162	0.290	2.128
9/4/2020	0.041	1.871	BDL	BDL	0.152	BDL	2.158
10/23/2020	0.040	2.113	BDL	BDL	BDL	BDL	2.043

3.1.3 Big Spring

The climatic data for the Big Spring area, including precipitation and snowfall, were reported by the Williams, Arizona weather station. The hydrology in this area is primarily recharged by snow fall, spring snowmelt, and monsoon season. The spring snowmelt season typically occurs from April through May, but can start as early as March (Schenk et al., 2021). Monsoon season typically begins early July, as which can be seen in the increase of precipitation in Figure 3-9 (NOAA, 2023b). Big Spring is a perennial hillslope spring and its catchment area receives an approximate mean annual total precipitation of 497.3 mm. From the year 2000 through 2023, there were 11 yr that exceeded the mean total precipitation. From the year 2000 through 2023 there are a few months of data missing, resulting in a downward trend (Figure 3-12) (Western Regional Climate Center, 2023). The mean total annual snowfall from 2000 through 2023 is 1,435.2 mm, as indicated by the red dotted line in Figure 3-11. From year 2000 through 2023 there were 9 yr that exceeded the mean annual total snowfall accumulation. From the year 2000 through 2023 there were a few months of data missing, resulting in a downward trend (Figure 3-12).

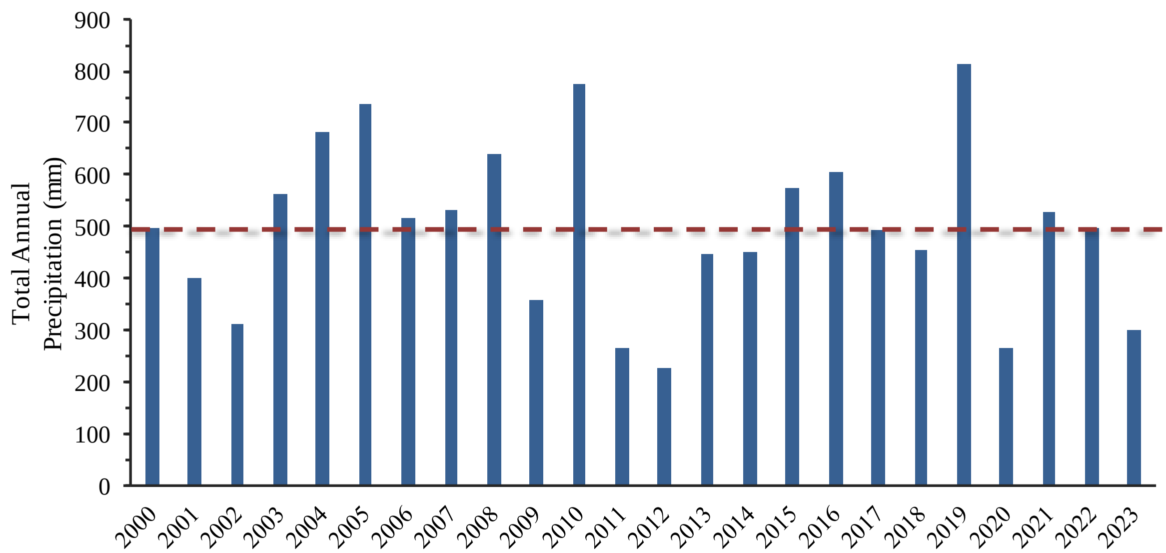


Figure 3-12. The total annual precipitation from Williams, Arizona weather station. The mean annual total from the year 2000 through 2023 is approximately 497.26 mm, as indicated by the red dotted line. There are currently 11 years from 2000 through 2023 that have exceeded the average total precipitation (Western Regional Climate Center, 2023).

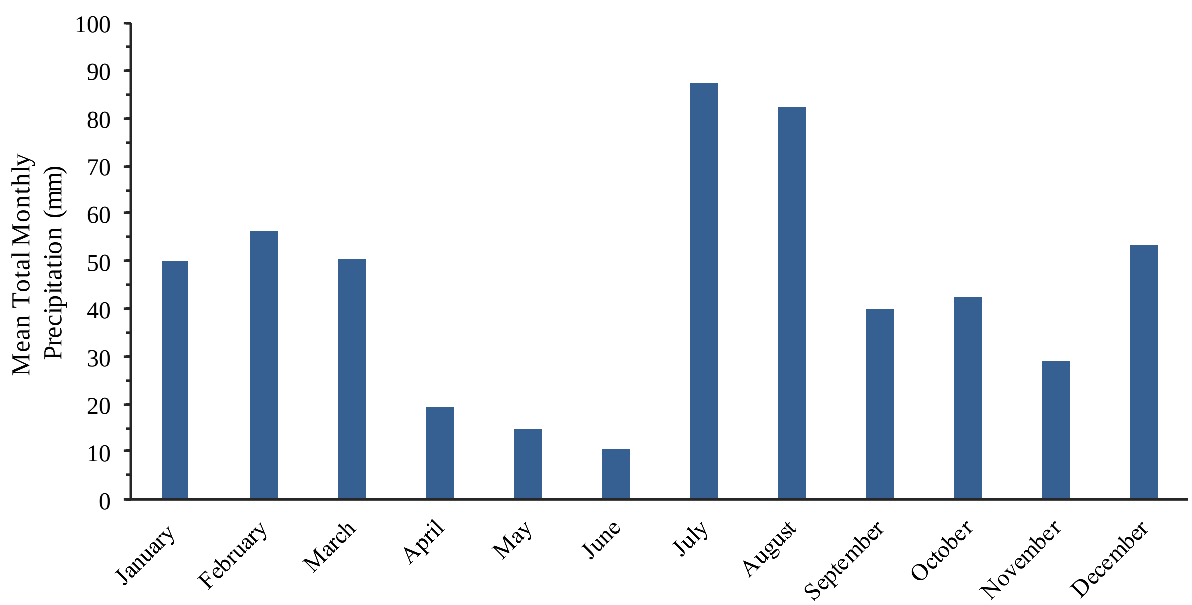


Figure 3-13. The mean total precipitation for each month from Williams, Arizona weather station near Big Spring. This is reflective of the total average precipitation from year 2000 through 2023 (Western Regional Climate Center, 2023).

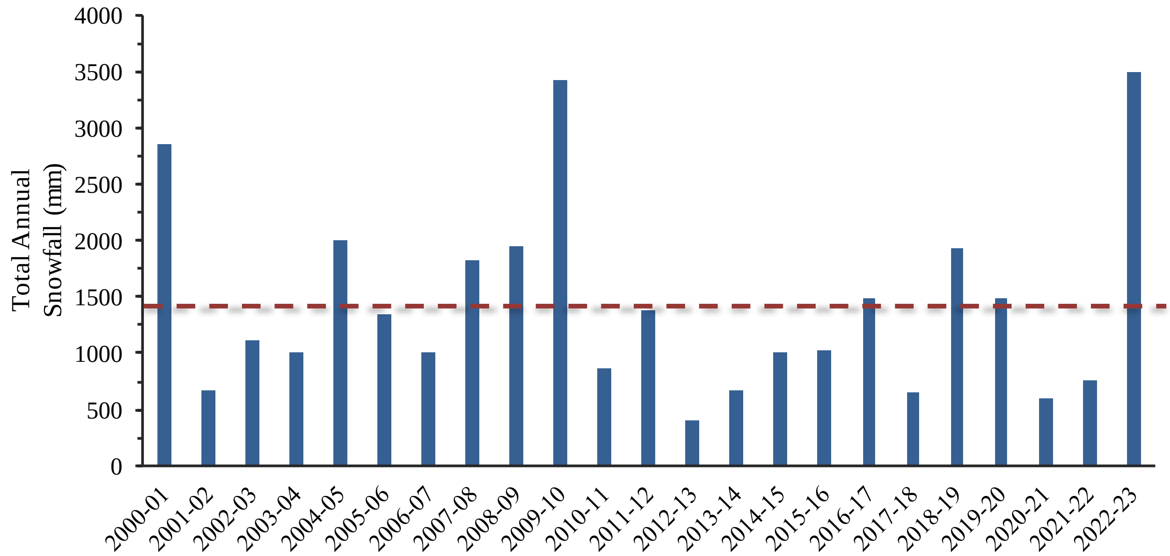


Figure 3-14. The total annual snowfall from Williams, Arizona weather station near Big Spring. The mean annual total snowfall from the year 2000 through 2023 is approximately 1,435.21 mm, as indicated by the red dotted line. There are currently about 9 years from 2000 through 2023 that have exceeded the mean annual total snowfall accumulation (Western Regional Climate Center, 2023).

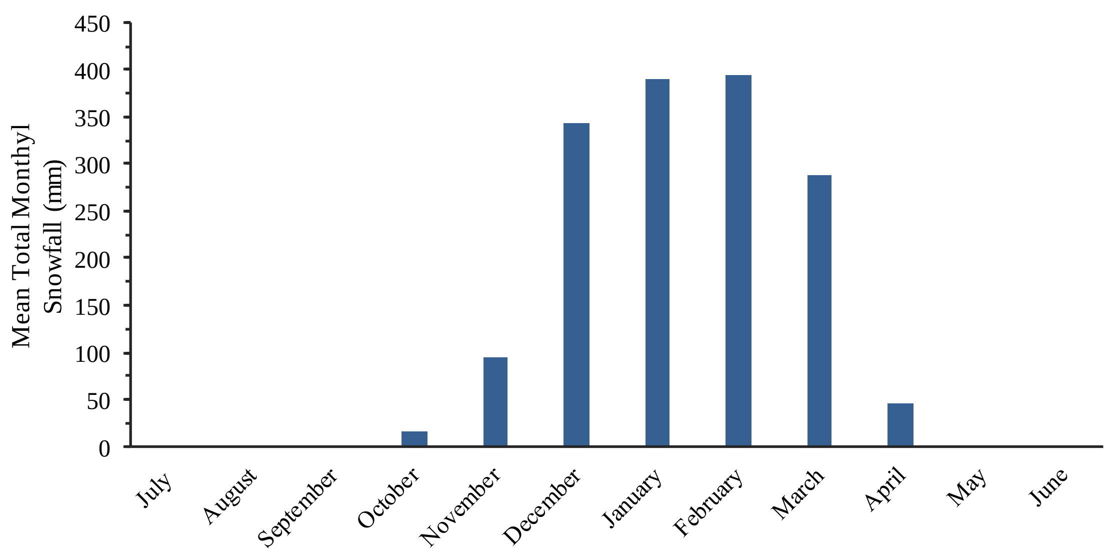


Figure 3-15. The mean total snowfall for each month from Williams, Arizona weather station near Big Spring. This is reflective of the total average snowfall for each month from year 2000 through year 2023 (Western Regional Climate Center, 2023).

Hydrograph

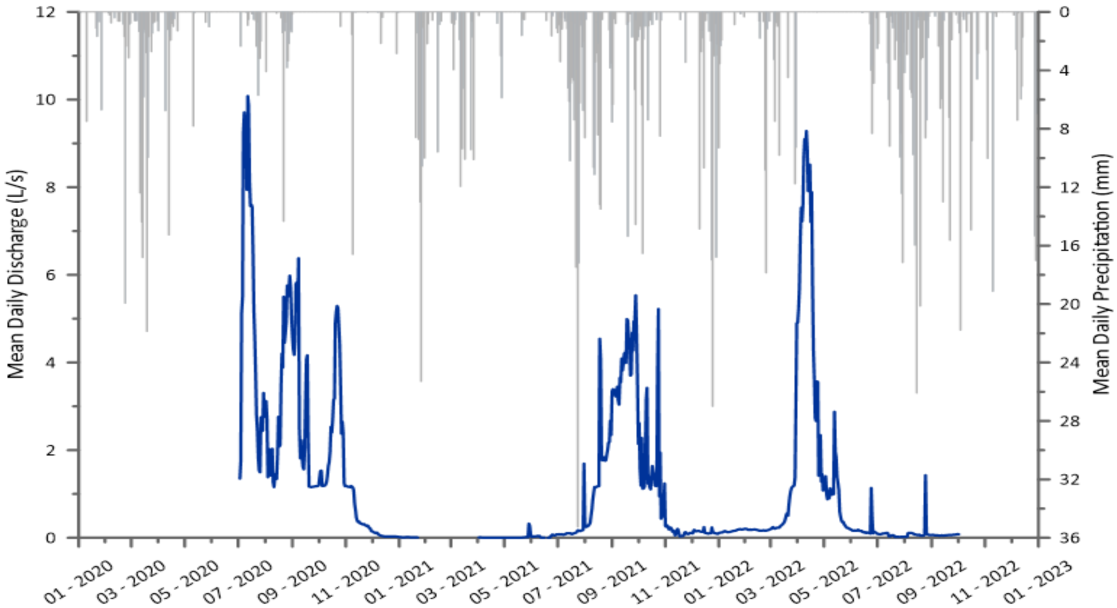


Figure 3-16. Big Spring mean daily spring discharge (blue) and Big Spring daily average precipitation of 4 km grid watershed catchment area (gray).

Water Quality Sampling

Table 3-8. Water samples from Big Spring that underwent isotope testing at Arizona Climate and Ecosystems Isotope Laboratory at Northern Arizona University.

Big Spring Isotope Analysis			
Collection date	*Analysis Date*	*dD (‰)*	*D18O (‰)*
7/1/2019	11/17/2019	-82.80	-11.71
4/18/2020	6/16/2020	-83.76	-12.01
7/3/2020	8/13/2020	-83.34	-11.81
9/19/2020	2/5/2021	-83.25	-11.71
12/9/2020	2/6/2021	-83.22	-11.60
4/2/2021	5/23/2021	-83.75	-12.43
7/16/2021	9/23/2021	-83.80	-11.65
9/26/2021	12/10/2021	-82.09	-12.16
6/9/2022	6/29/2022	-81.96	-11.70
9/4/2022	10/26/2022	-81.91	-11.63
10/2/2022	10/26/2022	-81.29	-11.46

Table 3-9. Water sample from Big Spring that underwent cation testing at Arizona Laboratory for Emerging Contaminants at the University of Arizona.

Big Spring Cation Analysis				
Collection Date	*Na^+ (mg/L)*	*Mg^+ (mg/L)*	*K^+ (mg/L)*	*Ca^+ (mg/L)*
12/9/2020	4.424	6.989	1.748	14.798

Table 3-10. Water sample from Big Spring that underwent anion testing at Arizona Laboratory for Emerging Contaminants at the University of Arizona. BDL "Below Detection Limit".

Big Spring Anion Analysis							
Collection Date	*F^- (mg/L)*	*Cl^- (mg/L)*	*NO^{2-} (mg/L)*	*Br^- (mg/L)*	*NO^{3-} (mg/L)*	*PO^{4-} (mg/L)*	*SO^{4-} (mg/L)*
12/9/2020	0.034	1.614	0.118	0.086	0.427	BDL	3.141

Water Quality Results

Table 3-11. Field water quality parameters recorded with a YSI Pro DSS at Big Spring on 10/02/2022 12:59:30.

Big Spring YSI Readings						
Conductivity (µS/cm)	*nLF Conductivity (µS/cm)*	*ODO % sat*	*ODO mg/L*	*Salinity (psu)*	*Specific Conductivity (µS/cm)*	*TDS (mg/L)*
102.3	130.7	71.9	7.36	0.06	128.7	84
Turbidity (FNU)	*TSS (mg/L)*	*pH*	*pH (mV)*	*Temp (°C)*	*Altitude (m)*	*Barometer (mmHg)*
5.29	0	7.46	-47.2	14.267	2089.6	597.4

Chapter 4: Summary

The purpose of the study was to characterize the hydrologic response of Hart Prairie Spring to the forest restoration treatments that were implemented in 2013-2014. In addition, I summarized hydrologic data from Hoxworth Spring, Clover Spring, and Big Spring in relation to climatic parameters. Forest and spring restoration and monitoring efforts have been implemented in the semi-arid Northern Arizona, and such information compilation and analysis enhance understanding of how these ecosystems function, and my results may benefit future ecosystem management planning and action.

Hart Prairie Spring

1.) Hart Prairie spring is an ephemeral, predominately snow-driven hydrologic system and is highly dependent on snow fall and spring snowmelt for groundwater recharge.
2.) Rain fall runoff in general indicates significant results. Particularly the snowmelt runoff had significant correlation post-treatment. These factors indicate that there was a positive hydrologic response due to the forest restoration treatments that were implemented from 2013 to 2014.
3.) Hart Prairie Spring responds well to climatic cycles of wet and dry years. This is indicative in hydrograph analysis and forest vitality. Peak spring flow appears to be responding earlier in the season compared to years earlier in the study.

Potential Errors

The datasets and analyses of these spring sites have been acquired and compiled over various periods of time and have potential errors. Factors such as equipment changes, environmental disturbances and site maintenance, software and computer upgrades, minor changes in the method process, and transfer of data over the research period between numerous people may contribute to uncertainty of the integrity of the data.

Importance of Results

This study increases the understanding of how springs and watersheds generally function and respond to climate change and forest restoration treatment. The results from this monitoring project will benefit future forest restoration projects. Clarifying the hydrologic responses to climate and forest treatment will influence land management planning and actions. The scale of the responses will additionally be influential in potentially increasing future restoration treatments of these study sites or towards other on-going studies.

On a global scale, springs are vital sources to riparian ecosystems and the numerous ecological factors within them. Vegetation within riparian ecosystems are vital entities that provide healthy characteristics and should be analyzed in conjunction with hydrologic properties (Zaimes et al., 2017). The semi-arid climate in Northern Arizona contain highly diverse riparian ecosystems near springs sources that are recognized as vastly productive habitats in addition to being considered critical areas (Zaimes et al., 2017). Integrating hydrogeology and ecology provide a more thorough understanding of ecosystem function, which can lead to efficient management implementations to support these ecosystems deemed “ribbons of life” (Cantonati et al., 2020; Springer & Stevens, 2009).

References

Amentt, M. (2002). *Hydrogeology and Evapotranspiration of the Herbaceous Understory at a High-Elevation Riparian Community, Hart Prairie, Arizona*. Northern Arizona University.

Aquatic Informatics ULC. (2023). *Aquatic Informatics ULC*.

Bezy, J. V., & Tindall, S. (2003). *A Guide to the Geology of the Flagstaff Area*. Arizona Geological Survey. http://repository.azgs.az.gov/sites/default/files/dlio/files/nid1540/dte-14_guideflagstaffgeology400dpi.pdf

Boston University. (2023). *BUSPH Learning Modules*. https://www.bumc.bu.edu

Brumbaugh, D. (2011). *Lake Mary, Anderson Mesa Fault, AZ*. Arizona Earthquake Information Center. https://aeic.nau.edu/bulletins/062711LakeMary.html

Cantonati, M., Stevens, L. E., Segadelli, S., Springer, A. E., Goldscheider, N., Celico, F., Filippini, M., Ogata, K., & Gargini, A. (2020). Ecohydrogeology: The Interdisciplinary Convergence Needed to Improve the Study and Stewardship of Springs and Other Groundwater-Dependent Habitats, Biota, and Ecosystems. *Ecological Indicators*, *110*. https://doi.org/10.1016/j.ecolind.2019.105803

Cocke, A. E., Fulé, P. Z., & Crouse, J. E. (2005). Forest Change on a Steep Mountain Gradient After Extended Fire Exclusion: San Francisco Peaks, Arizona, USA. *Journal of Applied Ecology*, *42*, 814–823. https://doi.org/10.1111/j.1365-2664.2005.01077.x

Combs, C., & Springer, A. E. (2020). *Intensive Monitoring of 4FRI Springs Discharge Pre and Post Forest Restoration in a Semi-Arid Environment on the Colorado Plateau* (p. 27). Northern Arizona University.

Covington, W. W., & Moore, M. M. (1994). Southwestern Ponderosa Pine Forest Structure: Changes Since Euro-American Settlement. *Journal of Forestry*, *92*(1). https://www.researchgate.net/publication/262687689_Southwestern_ponderosa_pine_forest_structure_Changes_since_Euro-American_settlement

Donovan, K. M., Springer, A. E., Tobin, C. W. B., & Parnell, R. A. (2021). *Karst Spring Processes and Groundwater Storage Implications in High-Elevation, Semi-Arid Southwestern United Stated*. Northern Arizona University.

Eckhardt, K. (2004). *How to construct recursive digital filters for baseflow separation*.

Esri Inc. (2023). *ArcGIS Pro 3.1.0*. file:///C:/Program%20Files/ArcGIS/Pro/Resources/SupportDocs/ArcGIS_Copyright.pdf

Gamon, J. A., Field, C. B., Goulden, M. L., Griffin, K. L., Hartley, A. E., Joel, G., Penuelas, J., & Valentini, R. (1995). Relationship Between NDVI, Canopy, Structure, and Photosynthesis in Three Californian Vegetation Types. *Ecological Applications*, *5*(1), 28–41.

Gavin, A. J. (1998). *Hydrogeology and Numerical Simulation of a Spring-Dominated High-Elevation Riparian Community, Hart Prairie, Arizona*. Northern Arizona University.

Godwin, T. N. (2004). *Restoration of Rheocrene Spring: Hoxworth Springs, Arizona*. Northern Arizona University.

Gordon, L. J., Peterson, G. D., & Bennett, E. M. (2008). Agricultural Modifications of Hydrological Flows Create Ecological Surprises. *Trends in Ecology and Evolution*, *23*(4), 211–219. https://doi.org/10.1016/j.tree.2007.11.011

Graham, J. (2008). *Walnut Canyon National Monument Geologic Resource Evaluation Report* [Natural Resource Report NPS/NRPCS/GRD/NRR-2008/040]. National Park Service, U.S Department of the Interior.

Halpenny, L. C. (1971). *Memorandum Report on Water Supply at Hart Prairie, Coconino County, Arizona*. https://cdm16748.contentdm.oclc.org/digital/collection/cpa/id/46257

Healy, W. R., Winter, C. T., LaBaugh, W. J., & Franke, O. L. (2007). *Water Budgets: Foundations for Effective Water-Resources and Environmental Management USGS/Circular 1308* (Circular No. 1308; p. 90). U.S. Geologic Survey.

Hein Phu La, Yang Dam Eo, Jong Hwa Kim, Changjae Kim, Mu Wook Pyeon, & Hyun Seung Song. (2013). Analysis of Correlation Between Canopy over and Vegetation Indices. *International Journal of Digital Content Technology and Its Applications*, *7*(11).

Holm, R. F. (1988). *Geologic Map of San Francisco Mountain, Elden Mountain, and Dry Lake Hills, Coconino County, Arizona* (IMAP). https://doi.org/10.3133/i1663

Hubbard, J. P. (1977). Impurtance of Riparian Ecosystems: Biotic Considerations! In *Importance, Preservation, and Management of Riparian Habitat: A Symposium at Tucson, Arizona on July 1977*.

Lim, K. J., & Engel, B. A. (2003). *Development of the Web-based Baseflow Separation System* [ISep Web GIS. Ag. and Biological Engineering Departmental Report]. Purdue University.

Miller, C. A., Brewer, D. G., & Covington, W. W. (2007). Forest Structure and Surface Runoff in the Upper Lake Mary Watershed, Arizona. *Hydrology and Water Resources in Arizona and the Southwest, 37*. http://hdl.handle.net/10150/296679

Montgomery, E. L., & DeWitt, R. H. (1974). Water Resources of the Inner Basin of San Francisco Volcano, Coconino County, Arizona. *Hydrology and Water Resources in Arizona and the Southwest*. https://repository.arizona.edu/handle/10150/300367

Nash, C., Tecle, A., & Craig, A. (2015). *Restoration Benefits to Natural Springs in the Lake Mary Watershed*. *46*(1), 30–36.

NOAA. (2023a). *El Niño & La Niña (El Niño-Southern Oscillation)*. Climate.Gov. https://www.climate.gov/enso

NOAA. (2023b). *Northern Arizona Monsoon Season*. Weather.Gov.

Northern Arizona Univeristy—Ecological Restortion Institute. (2021). Hart Prairie Historic vs. Current. https://eri.nau.edu/hart-prairie-before-and-after/

O'Donnell, F. C., Donager, J., Sankey, T., Lopez, S. M., & Springer, A. E. (2021). Vegetation Structure Controls on Snow and Soil Moisture in Restored Ponderosa Pine Forests. *Hydrological Processes*, *35*(11). https://doi.org/10.1002/hyp.14432

O'Donnell, F. C., Lopez, S. M., & Springer, A. E. (2015). *Understanding Forest Restoration Effects on Water Balance: Study Design for the Four Forest Restoration Initiative Paired Watershed Study* (U.S Geological Survey Investigations Report No. 2015–5180; Proceedings of the 12th Biennial Conference of Research on the Colorado Plateau, pp. 79–87). Northern Arizona University.

Oregon State University. (2022, August). *PRISM Climate Group*. https://prism.oregonstate.edu

Pewe, T. L., & Updike, R. G. (1976). *San Francisco Peaks: A Guidebook to the Geology* (2nd ed.).

Ritter, M. E. (2003, 2016). *The Physical Environment: An Introduction to Physical Geography*. The Hydrosphere: Surface Water. https://www.thephysicalenvironment.com/Book/hydrosphere/surface_water.html

Rogers, W. F. (1972). A New Concept in Hydrograph Analysis. *Water Resources Research*, *8*(4).

RStudio Team. (2020). *RStudio*. http://www.rstudio.com/

Schenk, E. R., O'Donnell, F. C., Springer, A. E., & Stevens, L. E. (2020). The Impacts of Tree Stand Thinning on Groundwater Recharge in Aridland Forests. *Ecological Engineering*, *145*. https://doi.org/10.1016/j.ecoleng.2019.105701

Schenk, E. R., Schiefer, E., Young, E., & Helton, C. (2021). *Surface Water Hydrology and Flood Recurrence in the Flagstaff Arizona Area, 2008-2019* (p. 91). City of Flagstaff. https://doi.org/10.4211/hs.8da8bb7cb66d475ea03af1a79b38a446

Schenk, E. R., Stevens, L. E., Jenness, J. S., & Ledbetter, J. (2019). *Groundwater Yield and Springs Monitoring Plan in Forest Thinning Treatments of the Four Forest Restoration Initiative (4FRI)* (Springs Stewardship Institute Technical Report, p. 51).

Schwartz, F. W., & Zhang, H. (2003). *Fundamentals of Groundwater*. John Wiley and Sons, Inc.

Smerdon, B. D., Redding, T. E., & Beckers, J. (2009). An Overview of the Effects of Forest Management on Groundwater Hydrology Selection of papers related to Regional Groundwater Flow View project Effect of clearcut logging on headwater streams in BC View project. *BC Journal of Ecosystem and Managment*, *10*(1), 22–44.

Springer, A. E., Amentt, M. A., Kolb, T. E., & Mullen, R. M. (2006). Evapotranspiration of Two Vegetation Communities in a High Elevation Riparian Meadow at Hart Prairie, Arizona. *Water Resources Research*, *42*. https://doi.org/10.1029/2004WR003863

Springer, A. E., & Stevens, L. E. (2009). Spheres of Discharge of Springs. *Hydrogeology Journal*, *17*(1), 83–93. https://doi.org/10.1007/s10040-008-0341-y

Springs Stewardship Institute. (2021). *Spring Health Monitoring for the Four Forest Restoration Initiative 2020 Annual Progress Report* (pp. 1–33) [Annual Progress Report]. Meuseum of Northern Arizona Springs Stewardship Institute. SpringStewardshipInstitute.org

Stevens, L. E., Jenness, J., & Ledbetter, J. D. (2020). Springs and Springs-Dependent Taxa of the Colorado River Basin, Southwestern North America: Geography, Ecology and Human Impacts. *Water*, *12*(1501). https://doi.org/10.3390/w12051501

Stewart, E. M. (2010). *Decision Notice and Finding of No Significant Impact: Hart Prairie Fuels Reduction and Forest Health Restoration Project* (pp. 1–24). USDA Forest Service.

Stewart, E. M., Williams, M. R., & Fredette, A. (2015). *Final Environmental Impact Statement for the Four-Forest Restoration Initiative with Errata and Objection Resolution Modifications* (Volume 1). USDA Forest Service, Coconino National Forest.

The Pennsylvania State University. (2023). *PennState Eberly College of Science*. Applied Statistics: Stat 500. https://online.stat.psu.edu/stat500/lesson/9/9.3

United States Environmental Protection Agency. (2023). *How's My Waterway? Informing the converstation about your waters.* https://mywaterway.epa.gov

US Dept. of Commerce NOAA. (2023). *La Nina, El Nino, and Northern Arizona*. https://www.weather.gov/fgz/Ella

USDA. (2023). *Natural Resource Conservation Service National Water and Climate Center*. https://www.nrcs.usda.gov/wps/portal/wcc/home/snowClimateMonitoring

USDA Forest Service, Coconino National Forest. (1987). *Coconino National Forest Plan* [Land and Resource Management Plan]. USDA Forest Service, Coconino National Forest. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5420011.pdf

USDA Forest Service, Coconino National Forest. (2010). *Environmental Assessment for the Hart Prairie Fuels Reduction and Forest Health Restoration Project* (pp. 1–156). USDA Forest Service, Coconino National Forest.

USDA Forest Service, Coconino National Forest. (2023). *4FRI Overview*. https://www.fs.usda.gov/4fri

USGS. (2022). *EarthExplorer*. EarthExplorer. https://earthexplorer.usgs.gov/

W. Wallace Covington, Peter Z. Fule, Margaret M. Moore, Stephen C. Hart, Thomas E. Kolb, Joy N. Mast, Stephen S. Sackett, & Michael R. Wagner. (1997). Restoring Ecosystem Health in Ponderosa Pine Forests of the Southwest. *Journal of Forestry*, *95*(4), 23–29.

Western, D. (2001). *Human-modified Ecosystem and Future Evolution*. *98*(10). https://doi.org/www.pnas.orgycgiydoiy10.1073ypnas.101093598

Western Regional Climate Center. (2023). *Flagstaff Pulliam AP, Arizona* [Station Metadata]. wrcc.dri.edu

Wissmar, R. C., & Swanson, F. J. (1990). Landscape Disturbances and Lotic Ecotones. In *Ecology and Management of Aquatic-terrestrial Ecotones* (pp. 65–89).

Zaimes, G. N., Crimmins, M., Green, D., & Nichols, M. (2017). *Understanding Arizona's Riparian Areas*.