Establishing a snowtography site to study long-term effects of high severity wildfire on snow hydrology in the Sierra Ancha Experimental Forest, Arizona

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Abstract

The Southwest United States relies on snowpacks as a critical water resource. Forested areas are subject to a multitude of disturbances and there is limited measurable understanding of the extensive, large-scale effects of these disturbances on snowpack, snowmelt runoff and water availability. The contemporary occurrence of anomalously high severity wildfires further impacts water resources, particularly in regions where water supply is already limited. Rising temperatures and ongoing drought have increased the need to understand the effects forest disturbances have on snowpack characteristics in the highly diverse climates of the Southwest.

The goal of this applied research project is to establish a snow study site and begin a data collection program that will contribute to long term research analyzing the effects of wildfire on ephemeral snowpacks. Ephemeral snowpacks are characterized as snowpacks that last less than sixty days and include repeated periods of accumulation and the complete disappearance of snow. This study analyzes how wildfires impact snow accumulation, ablation and the duration of seasonal snow cover in a forest located in the Sierra Ancha Experimental Forest (SAEF) in Central Arizona. My data collection methodology uses snowtography technology (repeat photography) in conjunction with soil moisture sensors along two transects that extend from a forested area in a 20 year-old burn scar and cross into different burn severity boundaries.

Data show that areas under canopies receive 8-29% less snowfall compared to high severity burned areas. Ablation rates are increased by as much as 21-78% in open areas that experienced high severity burns compared to forested areas. Additionally, areas impacted by high severity burns show a decrease in soil moisture compared to forested areas, most likely resulting from evaporation or sublimation.

This research, in conjunction with other snowtography sites in the Southwest, will improve our understanding of snow accumulation, ablation and the duration of seasonal snow cover and provide better insights on the long term impacts of wildfire on the water budget. Long term snow hydrology research will further aid in the ability for watershed managers to more accurately predict snowmelt runoff yields.

Keywords: high-severity wildfire, snowtography, snow hydrology, Sierra Ancha Experimental Forest, Arizona

TABLE OF CONTENTS

1. Abstract 2

2. Introduction 8

2.1 Southwest Wildfire History 9

2.2 Snowpack Research and Data Collection Tools 11

3. Literature Review 17

3.1 Overview of Workman Creek Complex 17

3.2 History of Arizona Water Resources 22

3.3 Snow as a Water Resource 30

4. Problem Statement and Research Objectives 34

5. Methodology 35

5.1 Study Site Description 35

5.2 Snowtography Transects 38

5.3 Data Collection 40

5.4 Snow Accumulation and Ablation 40

5.5 Soil Moisture Sensors - West Transect 41

5.6 Snow Density Sampling 41

6. Results 42

6.1 Snow Depth and Accumulation 42

6.2 Snow Ablation 48

6.3 SNOTEL Data Comparison to Snowtography Data 49

6.4 Soil Water Content 51

7. Discussion 56

7.1 First Year Findings of Forest Impacts on Snow Depth 56

7.2 Wildfire Impacts on SnowHydrology 57

8. Conclusion 58

8.1 Future Recommendations 60

9. References 63

List of Figures

Figure 1: Flow chart of data for the WCIS Database 12

Figure 2: Workman Creek SNOTEL, Station Id 877 13

Figure 3: Snowtography transect capturing snowfall 16

Figure 4: Rich and Gottfried 1976 map 18

Figure 4: Study area map 20

Figure 5: Coon Creek and Juniper fire burn severity maps 22

Figure 6: Arizona Historical Precipitation Summaries 29

Figure 7: Forest grouping images 36

Figure 8: Cool edge grouping images 37

Figure 9: Open area grouping images 38

Figure 10: Study area, transects and equipment 39

Figure 11: Seasonal snow depth for East and West Transects 43

Figure 12: Average Seasonal Snow Depth by Groupings 44

Figure 13: Average new snowfall accumulation 45

Figure 14: Largest Seasonal snowfall event 46

Figure 15: Largest December snowfall event 47

Figure 16: Maximum snow depth 48

Figure 17: Snowtography site and SNOTEL station Data 49

Figure 18: Snowtography Groupings and SNOTEL Data 50

Figure 19: Workman SNOTEL historical snow data 53

Figure 20: Soil Moisture Data Logger 14243 and Snow depth 54

Figure 21: Soil Moisture Data Logger 14245 and Snow Depth 55

List of Tables

Table 1: Percentage of burn severity type for Coon Creek and Juniper Fires 21

Table 2: Data collection summary 42

Table 3: Average new snowfall values during storm events 45

Table 4: Average snow accumulation and ablation rates for groupings 47

Introduction

Wildfire suppression advanced in 1935 when the Forest Service established a quick action policy known as the 10 a.m. policy (Smith, 2017). This obtuse policy, designed to extinguish fires as quickly as possible, has resulted in a massive build-up of dead fuels on public lands across the country in all fuel models (Swetnam, 1990). Combine this unnaturally large fuel loading with drought-stricken conditions due to climate change and the country's public lands and urban interfaces are primed for catastrophic megafires. The nation's fire managers have seen more frequent, larger wildfires of higher severity than in past years due to a variety of reasons related to a changing climate, including increased temperatures, reduced snowpacks, the earlier disappearance of snow and prolonged drought (Abatzoglou et al., 2021; Neary et al., 2011; Westerling, 2016). Climate change, which exacerbates fire suitability, paired with misguided fire suppression policies will continue to produce a greater propensity toward higher severity fires which in turn will impact the landscape for years to come.

Concurrent with changing characteristics of wildfire activity are observations of declining western snowpacks (Mote et al., 2018) and earlier timing of spring snowmelt (Cayan et al., 2001; Stewart et al., 2005). Snowmelt dominated rivers in the western U.S. are estimated to comprise 50-80% of total annual flows (Stewart et al., 2004). Surface water resources rely on snowpack and spring runoff, with the timing of snowmelt being a key variable in the hydrologic cycle. Earlier snowmelt impacts the water budget by decreasing water availability (Kunkel et al., 2022; Stewart et al., 2004) during dry summers when temperatures are highest and water demands are greatest for economic, environmental and recreational use.

Snow is an invaluable resource, especially in the arid Southwest states that rely on water allocations from the Colorado River. As higher severity fires in the western U.S. become more prevalent in a warming climate, mountain snowpacks, which are affected both spatially and temporally, are becoming more vulnerable to these disturbances. There is an increasing need to better understand the short and long term impacts of high-severity wildfire disturbance on mountain snowpacks and the hydrologic cycle. The first year of data collection investigates high-severity wildfire effects on snow hydrology by assessment and correlation through scientific observation, measurement and analysis of snow accumulation, ablation, and soil water content in a wildfire impacted area in the SAEF.

2.1 Southwest Wildfire History

Fire fundamentally affects watershed hydrology by increasing storm runoff, peak discharge, erosion and downstream sedimentation (Rich, 1962; Pase and Ingebo, 1965). The extent of these effects depends on a number of pre and post fire watershed conditions including terrain, vegetative and edaphic characteristics (Campbell, 1977). Hydrophobic soil can be generated from extreme heat, with burn severity acting as the primary driver on the magnitude of this phenomenon (DeBano, 1981; Huffman et al., 2001), and is ascribed to increases in runoff and erosion post fire (Colorado Water Conservation Board, 1997). Additional impacts on soil that affect watershed hydrology include raindrop impact and overland flow, which can result from exposed soils due to vegetation and tree-understory mortality (Onda et al., 2008).

The southwestern United States has a rich and well-documented wildfire history that includes land management policies and practices of indigenous, settler and current day populations. Natural and cultural history served as two key factors that once controlled the fire regime in the state of Arizona. The deep, cultural history of indigenous populations' dominance over Arizona land is well recorded, and respectfully holds a place in fire history. Lightning and livestock have shaped the Southwest fire regime, with the Apache tribe and other indigenous peoples acting as fire mediators for centuries (Allen, 1989). For example, the Apache used fire as a war and hunting strategy, igniting enemy forests during raids and covering trails, also using smoke as a means of baiting traps to attract game (Holsinger, 1902). The migration of Spanish explorers and settlers in the Southwest led to the introduction of livestock including horse, mule, cattle and sheep (Spicer, 2015). The Apache raids on the Spanish and predation on livestock slowed Spanish settlement and mitigated overgrazing, aiding in the preservation of a grassland environment (Pyne, 1982).

U.S. government motives in the mid 1800s sought control and development of the west, which led to the killing, exportation and settlement of Apaches and other indigenous peoples on reservations (Welch, 2017). During the late 1800s the livestock industry boomed in the Southwest from several causes, most notably, the elimination of Apache threats (Payne, 1982). Decades of overgrazing consequentially ensued and dramatically altered the landscape. Detrimental cattle populations replaced sheep and goats, fire control took place on public lands and a wet cycle returned, causing grassland environments in the Southwest to decline and shift towards an increase in woody vegetation (Cooper, 1960).

Historically, the Southwest landscape had seen frequent but low-intensity fire over the duration of a fire season (Falk, et al., 2011). Arizona experiences the heaviest concentration of lightning fires in the U.S. during monsoon season, often resulting in fires of small size but high frequency (Barrows, 1978). This occurrence of fire in the ponderosa pine ecosystem has been a key variable in maintaining open understory conditions, with low tree densities. Suppression of wildfires has led to a forest landscape that has become unnaturally altered as the result of fire protection policies. Areas of grassland were once interspersed amongst widely spaced pine trees (Biswell et al., 1973). The current pine forest mosaic has become dense and overpopulated, with overcrowding leading to the transition of grassy areas to dense tree seedlings, contributing to an excess of accumulated fuels on the forest floors (Campbell, 1977). Further, because of the intermingling of tree crowns of different aged trees in the forests, continuity now exists from the forest floor to the crown tops of the tallest trees. These factors allow a destructive path for fire often resulting in fires of great size, high-severity and high tree mortality if not suppressed in appropriate response times (Drury, 2019).

2.2 Snowpack Research and Data Collection Tools

Rainfall and snowmelt are vital resources in the arid Southwest, the hottest and driest region in the U.S (U.S. Environmental Protection Agency, 2016). The seven basin states (Colorado, Utah, New Mexico, Wyoming, Nevada, Arizona, California) that use water allotments from the Colorado River heavily rely on winter snowpack to recharge the river, which is key to the Southwest’s hydrology and water supplies. The variability of runoff from intermittent snowmelt in Arizona along with the numerous factors that affect snowfall accumulation create significant challenges for water managers working to predict and administer water resources.

Snow Telemetry (SNOTEL) stations serve as an important data collection method in western snow studies. The SNOTEL program consists of over 900 sites located in remote, high-elevation mountain watersheds across the western United States (National Weather and Climate Center). These automated stations are capable of measuring different variables associated with atmospheric conditions, but often at a minimum are equipped to measure precipitation, snow depth, air temperature and Snow Water Equivalent (SWE). Snow Course programs additionally exist to support SNOTEL information, in which manual snow density and depth measurements are taken at selected remote locations that are in proximity to SNOTEL stations. Data collected at SNOTEL stations is transmitted to a central database, called the Water and Climate Information System (WCIS), and is then used to construct water supply forecasts (National Weather and Climate Center, n.d.). Precipitation, streamflow, and reservoir data is also received by the WCIS from the U.S. Army Corps of Engineers (USACE), the U.S. Bureau of Reclamation (BOR), the Applied Climate Information System (ACIS), the U.S. Geological Survey (USGS), various water districts and other entities (*Water and Climate Information System*, n.d) (Figure 1). Available data such as the Charting Tool, Report Generator, Update Report and Interactive map can be viewed from the following link (https://www.nrcs.usda.gov/wps/portal/wcc/home/aboutUs/monitoringPrograms/wcis/)

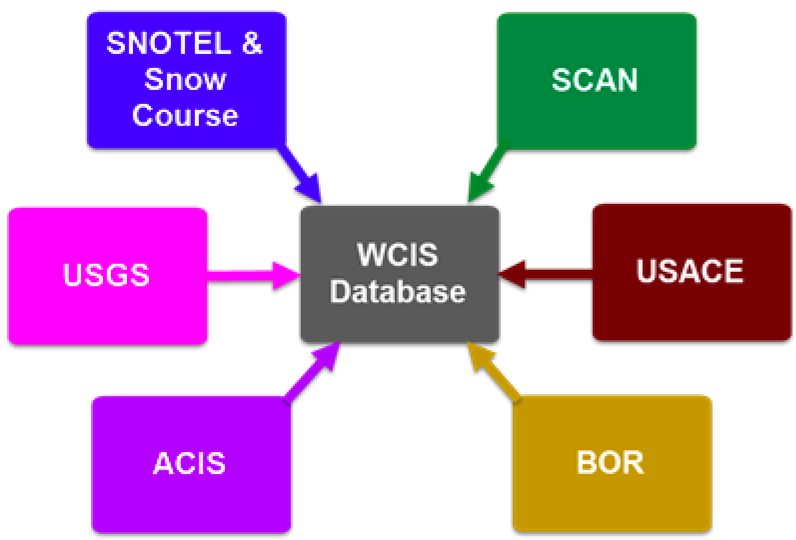


Figure 1: Flow chart of data input for the WCIS Database. Data is then used to construct water supply forecasts, source National Water and Climate Center

The stations are managed by the Natural Resource Conservation Service, with snow and climate monitoring data available for download from [https://www.nrcs.usda.gov/wps/portal/wcc/home/snowClimateMonitoring/snowpack/]. In 1938, the Workman Creek SNOTEL station (Station Id: 877) was established in the SAEF at 33.81 degrees N and 110.92 degrees W, elevation 7,032 ft (Figure 2). This station is in close proximity to the study site of this research project.

Figure 2: Workman SNOTEL, Station Id 877, source National Resources Conservation Service

Additional ongoing regional snow studies in the western U.S. include the application of airborne programs and remote sensing. Airborne Snow Observatories Inc. (ASO) is a private public-benefit company, that was a collaboration from 2013 - 2019 between NASA and the California Department of Water Resources (*Airborne Snow Observatory*, n.d.), designed to collect and provide measurements of water content of snowpack [or Snow Water Equivalent (SWE)], snow depth and snow albedo on a basin-wide scale in the western US, to forecast snowmelt runoff (*Snow measurements and modeling to support sustainable global water* *supplies*, n.d.). ASO uses Light Detection and Ranging (LIDAR) and Imaging Spectrometer technology on aircraft (*Airborne Snow Observatory*, n.d.), as well as the application of remote sensing to provide snowmelt runoff models for water management decision support. During this time frame, the NASA Airborne Snow Observatory was acknowledged as a breakthrough development in snow studies, providing spatial and temporal data to model snowpack across entire basins in California, Colorado and Wyoming, producing the first maps of SWE in the western US (*Snow measurements and modeling to support sustainable global water supplies*, n.d.). The NASA program closed in 2019, with the founders continuing the research under the Airborne Snow Observatories Inc., currently serving as a private public-benefit company with the expanded operation of global customers in need of snow measurements.

The National Operational Hydrologic Remote Sensing Center (NOHRSC) operates and maintains the Airborne Snow Survey Program. This program collects SWE and soil moisture measurements using Gamma Radiation technology (NOHRSC, n.d.) by means of aircraft. National Weather Service (NWS) Forecast Offices and NWS River Forecast Centers use the airborne SWE and soil moisture measurements to issue river and flood forecasts, water supply forecasts and spring flood projections (NOHRSC, n.d.) While this program covers large portions of designated areas across the U.S., not all areas are covered. The flight line map and interactive map page can be viewed from the following link (https://www.nohrsc.noaa.gov/interactive/html/map.html?var=none&o9=1&o14=1&lbl=n&bgvar=dem). The NOHRSC also uses satellite imagery to map snow cover extent in the U.S and Northern Hemisphere. Data can be viewed from the following link (https://www.nohrsc.noaa.gov/nh_snowcover/), made available by the National Oceanic and Atmospheric Administration (NOAA) and NOHRSC. The U.S. National Ice Center uses a software package known as The Interactive Multisensor Snow and Ice Mapping System (IMS) to distinguish the presence of snow and ice in satellite imagery, creating 1 km resolution maps (IMS Snow and Ice Products, n.d.). To view IMS information provided by the National Snow and Ice Data Center, refer to https://nsidc.org/data/g02156/versions/1.

Snowtography [snow photography], the use of on the ground, repeat photography, is a less common approach to studying snow that has been under development more recently. The term snowtography was introduced by the Salt River Project (SRP) in 2017, one of Arizona's largest utility companies providing electricity and water. This study uses snowtography to track and measure snow depth by using repeat photography to collect daily snow measurements over the duration of a winter season (Figure 3) at a forest site in the SAEF. Snowtography sites capture observations and distinguish how variability of snowfall accumulation and ablation is affected by forest structure and terrain.

Figure 3: Snowtography transect facing North, capturing snowfall on the West transect in the cool edge at posts 25, 26 and 27 throughout the winter season.. A) November, first snow has not occurred; B) largest snow event in the month of December; C) snow captured in January; D) largest snow event of the season occurring in February; E) snow captured towards the end of March; F) bare ground in April, no additional snowfall events for the 2021/2022 winter season

While this approach operates on a different and smaller scale, it is complementary to regional and global studies. Regional snow study efforts provide a great foundation for large scale snow analysis, each method capturing different variables related to snow. Airborne imagery collects SWE and soil moisture measurements while lidar imagery allows for snow depth to be estimated.

Satellite imagery is used to estimate snow cover and SNOTEL stations measure atmospheric conditions, most often measuring precipitation, snow depth, air temperature and SWE. This understanding brings attention to knowledge gaps that exist due to limited research and data between large scale snow analysis and small scale studies of the influence of high-severity wildfire disturbance on snow in watersheds. Snowtography provides real time snowpack measurement to incorporate into modeling, fill in field data gaps, and allow wildfire impact analysis. Another benefit to this method is it is relatively low cost and little maintenance. The ability of watershed managers to predict snowmelt-generated streamflow can be improved with access to timely field data and modeling that more accurately represents the impact forest disturbance, terrain and forest structure have on snowpack accumulation, ablation and soil moisture conditions.

3. Literature review

3.1 Overview of Workman Creek Complex

The Sierra Ancha Experimental Forest (SAEF) is located in the forested highlands of central Arizona within the Tonto National Forest. The study site is referred to as the Workman Creek site and is located in the Workman Creek watershed. The area has become collectively known as the Workman Creek Complex. The experimental forest was first established in 1932 as the Parker Creek Experimental Forest, later to be expanded and renamed the SAEF in 1938 (Gottfried and Neary, 2003). The objective of establishing the experimental forest was to determine environmental factors and management practices on water yield and soil erosion. Early concerns of sedimentation in Lake Roosevelt due to livestock grazing, along with increased erosion in the watersheds of the Salt-River Basin, contributed to many research motives.

This area includes the Workman Creek watershed, which is subdivided into three sub-watersheds including the North Fork, Middle Fork, and South Fork (Rich and Gottfried, 1976). Elevations of the watersheds range between 6,590 and 7,724 ft (Gottfriend et. al, 1999). Research initially began in the three Workman Creek watersheds to study the hydrology of southwestern mixed conifer forests in an effort to determine changes in streamflow and sedimentation resulting from forest thinning performed by the Forest Service (Gottfried, 2002). The three watersheds were designated as experimental watersheds during the 1950s and 1960s as part of a hydrological research network known as the Arizona Watershed Program (Neary et al., 2011). The watershed program was created to evaluate forest management treatments on water yields and forest resources.

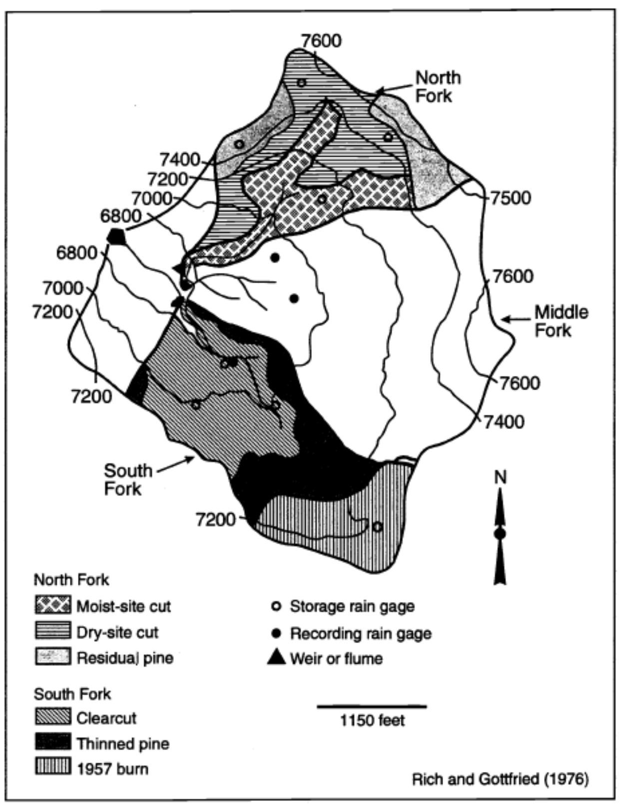


Figure 4: The Workman Creek watersheds including the treatments on the Nork Fork and South Fork. Map additionally includes the 1957 fire. Source, Rich and Gottfriend 1976.

Different forest treatments were performed on the North Fork and South Fork with the Middle Fork serving as the control watershed (Figure 4). Treatments in the North Fork took place during 1953, 1958 and 1966 and included forest removal followed by conversion of the area to a grass cover (Rich, 1962; Rich and Gottfried 1976). Forest manipulation in the South Fork took place during 1953 and 1966. The first treatment followed the single-tree selection thinning method, followed with a second treatment intended to convert mixed conifer vegetation to a pure ponderosa stand by the planting of pine seedlings (Gottfried and Neary, 2003).

In an effort to study stream yields, hydrologic installations were built on the three experimental watersheds and remained in operation from 1938 through 1983 (Gottfried and Neary, 2003). Three weirs were built in the Workman Creek watershed, one weir along each of the sub-divided watersheds (North Fork, Middle Fork and South Fork). Just below the confluence of the three forks is the Main Dam, which measures streamflow from the entire 1087 ac watershed (Gottfried and Neary, 2003). In 1983 the watershed installations at the three Workman Creek watersheds were deactivated as interest in large scale watershed studies in the Southwest was lost (Gottfried and Neary, 2003). The occurrence of the Coon Creek wildfire (2000) burning a portion of the Workman Creek watershed renewed interest in the impacts of natural disturbances and human activities on watersheds, leading to the re-instrumentation of the weirs in an effort to measure fire effects on forest hydrology and sediment dynamics (Gottfried and Neary, 2003). Portions of the Coon Creek burn scar were reburned by the Juniper fire (2016) (Figure 4).

Study Area Map

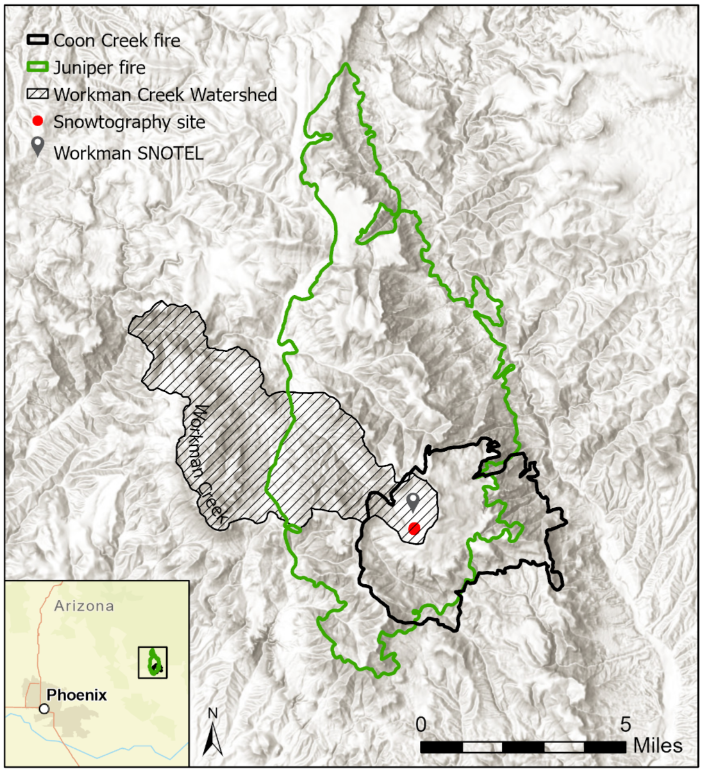


Figure 4: Study area map showing the newly established snowtography site, SNOTEL station 33.81°N and 110.92°W (Figure 2), Coon Creek (2000) and Juniper Fire (2016) perimeters, and the Workman Creek Watershed (Figure 4) on a multidirectional hillshade highlighting the Sierra Ancha Mountain Range.

The Workman Creek watershed is located within the Salt River watershed drainage, which is an area of interest for both private groups and public agencies. Water flows East to West and drains into Workman Creek, a tributary to Salome Creek. Salome Creek runs south and drains into Roosevelt Lake. Roosevelt lake is the primary reservoir for the Phoenix area and is critical to meet the water demands of agriculture, industrial and municipal stakeholders.

The SAEF lies within the Sierra Ancha Mountain range and includes areas in elevation between 3,550 and 7,724 feet. The ranges of elevation and life zones allow a wide variety of plant species to survive in this area. The forest life zones range from semi-desert shrub and grassland to pine-fir forests at high elevations. The Workman Creek Complex supports the following vegetation species; ponderosa pine, Douglas-fir, and white fir, with fewer numbers of aspen, Gambel oak and New Mexican locust (Gottfried, 2002).

Annual precipitation takes place during two seasons, winter and summer monsoon season. Snowfall that occurs during the months October through May accounts for two-thirds of the annual precipitation, with occasional rain-on-snow events occurring during the winter season (Gottfried, 2002). Summer precipitation during the monsoon season accounts for the remainder of annual precipitation. December, March and January have historically been the wettest months of the year and the driest are May and June (Gottfried, 2002).

The first documented wildfire in the Workman Creek watershed occurred in 1957, burning approximately 60 ac near the top of the South Fork watershed (Figure 5). In April of 2000, the Coon Creek wildfire burned a total of 9,644 acres in the SAEF as the result of an unattended campfire. The three Workman Creek watersheds were burned by the wildfire at varying severity levels. The Middle Fork burned at high-severity while the North and South Fork burned at low to moderate severity levels (Gottfried and Neary, 2003). In 2016 the Juniper fire occurred in the Sierra Ancha Mountain Range and reburned portions of the burn scar from the Coon Creek wildfire (2000) (Figure 5). The Juniper wildfire was classified as a low severity fire (Evans, 2017). See Table 1 for burn severity gradients.

Table 1: Percentage of burn severity type for the Coon Creek Fire and Juniper Fire. Source, Data from Monitoring Trends in Burn Severity (MTBS).

	Unburned	**Low**	**Moderate**	**High**	**Total Acres**
Coon Creek Fire	27%	37%	21%	15%	9,229
Juniper Fire	33%	52%	13%	2%	32,293

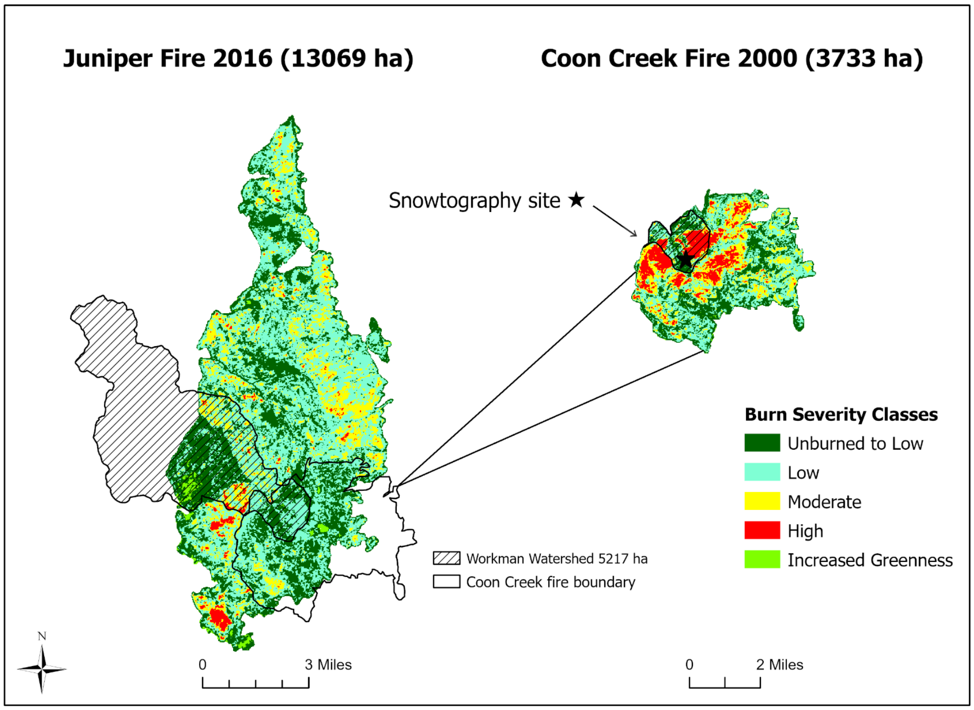


Figure 5: Juniper fire and Coon Creek fire burn severity maps with affected Workman Creek Watershed. Data from (MTBS), USGS Watershed Boundary Dataset and USGS National Hydrography Dataset

3.2 History of Arizona Water Resources

Numerous compacts and laws govern the use of the Colorado River and are collectively known as "The Law of the River." In 1921, the seven basin states formed a commission chaired by the Secretary of Commerce Herbert Hoover, to determine how the Colorado River should be divided amongst the states (Martin, 2017). The following year, in 1922, water officials representing the seven basin states gathered to sign what is known as the Colorado River Compact of 1922, governing water allocation rights of the Colorado River. All states signed the compact except Arizona, which would finally sign and ratify the compact in 1944 (Congressional Research Service, 2022). The compact was an agreement to divide the river into equal shares between the Upper Basin states (Colorado, Wyoming, Utah, New Mexico and a small portion of northern

Arizona) and Lower Basin states (Arizona, Nevada, Colorado). States could not agree on how water rights should be divided among them, so this compact simply divides the river in half, each basin having the right to use 7.5 million acre feet (MAF) annually, totaling 15 MAF (Fradkin, 1981). Lee's Ferry serves as the division point for the two basins. The Upper Basin states are defined by the river networks upstream of this point in northern Arizona, and the Lower Basin states are defined downstream of this location. The water allocation rights each state were to receive within each basin would not be solidified for years to come.

The Boulder Canyon Project Act of 1928 ratified the 1922 compact, authorizing the construction of Hoover Dam and apportioned the lower basin's 7.5 MAF among the states of Arizona (2.8 MAF), California (4.4 MAF) and Nevada (0.3 MAF) (Boulder Canyon Project Act, 1928). Over the next twenty six years the Upper Basin states would negotiate how their allotted 7.5 MAF would be divided between the five states, leading to the 1948 Upper Colorado River Basin Compact (Upper Colorado River Basin Compact, 1948). According to the compact, the states received the following allotments respective to the Upper Basin's allotted 7.5 MAF: Colorado 51.75 %; New Mexico, 11.25 %; Utah, 23.00 %; Wyoming, 14.00 %, Arizona, 50,000 acre-feet per annum (Upper Colorado River Basin Compact, 1948). Arizona is the only state to receive water from both the upper and lower basin allotments as a result of the small portion of northern Arizona that is located upriver of Lee's Ferry. Additionally, water was to be granted to Mexico under the terms of The Mexico Water Treaty of 1944. Colorado River water apportionments in total by state are as follows; Arizona 17.3%, California 26.7%, Colorado 23.4%, Nevada 1.8%, New Mexico 5.1%, Utah 10.4%, Wyoming 6.3%, Mexico 9% (Boepple, 2011). Water use agreements negotiated in the 1922 Colorado River Compact lasted for a century, until 2022 when the first water cutbacks occurred.

Throughout all negotiations of the numerous compacts created to operate and manage the Colorado River, as well as the dam building era that ensued throughout the west in the twentieth century, Arizona took a defensive stance, arguing for their share of water rights, not wanting California to capitalize on the largest share allotment for the Lower Basin states. The Colorado River Storage Project Act of 1956 included a comprehensive development plan of water resources in the Upper Basin, with much of the Lower Basin still being disputed, mainly due to intense conflict between the states of Arizona and California. Significant historical leaders in the state of Arizona, including US Representative Morris Udall, Governor George Hunt, Senators Earnest McFarland, Carl Hayden and Barry Goldwater, paved the way for the creation of the Central Arizona Project (CAP) by the Colorado River Basin Project Act of 1968 that was signed into legislation by President Lyndon Johnson. This act authorized the construction of water storage projects in the Lower Basin states as well as others to be included in the Upper Basin (Colorado River Basin Project Act, 1968). The outcome of this act had massive impacts on development and population growth in the southwest. The sustainability of these reservoirs is now linked to water managers ability to forecast and appropriately administer water resources.

The inception of the CAP is linked to the Colorado River Basin Project Act, one of the larger water resource project initiatives determining how to harness the use of the Colorado River for the Lower and Upper Basin states. The CAP has a long, rich history in the state of Arizona, that stems from conflict over water rights to the Colorado River, with Arizona ultimately demanding its share of the Colorado River in order to sustain development plans of the state. Arizona's 1944 ratification of the Colorado River compact commenced negotiation for the CAP, although this project was not authorized until 1968. The main objective of the CAP was to create a system to bring water from the Colorado River to central and southern Arizona so the state could use its full apportionment of the Colorado River. The most significant outcome was a 336-mile aqueduct, diverting water from the river through portions of Arizona. The CAP has evolved over time to incorporate other projects, including the building of dams and other aqueducts throughout central and southern Arizona, that involve the Salt, Verde and Gila rivers, which either originate in or flow through Arizona and serve as essential river systems for the longevity of the CAP.

Construction began in 1973 for the 336-mile aqueduct, which diverts water from Lake Havasu to a location Southwest of Tucson (Central Arizona Project, n.d.). This project was declared substantially complete in 1993, providing water to Phoenix, Mesa, Glendale, Scottsdale and Tucson areas, and local Native American tribes (Central Arizona Project, n.d.). Water diverted from the Colorado River to Tucson is used for groundwater recharge, with Tucson delivering water to customers that is a blend of more than 50% recharged river water and natural ground water (*Groundwater Recovery*, 2022). The CAP delivers water to Maricopa, Pinal and Pima counties (surrounding counties of Phoenix and Tucson) serving more than 5 million people, or more than 80% of the state's population (*Central Arizona Project - CAP*, 2022).

Theodore Roosevelt Lake is one of many reservoirs that resulted from the dam building era in the state, with construction beginning in 1906. Roosevelt Dam was built for two reasons; (1) to store water for the Salt River irrigation project and (2) flood control for the Salt River Valley (*Roosevelt Dam - National Historic Landmarks (U.S. National Park Service)*, (n.d.). The dam was completed in 1911, making Roosevelt lake the world's largest reservoir at that time (*Roosevelt Dam - National Historic Landmarks (U.S. National Park Service)*, (n.d.). In 1984, Roosevelt lake was incorporated as one of the water resource initiatives for the CAP, leading to project expansion of the original dam in 1906, increasing the reservoir storage capacity by 20% (*Roosevelt Dam - National Historic Landmarks (U.S. National Park Service)*, (n.d.). Modifications to expand Roosevelt Dam were included in the CAP under what is known as Plan 6, and construction took place from 1989 to 1996 (*Roosevelt Dam - National Historic Landmarks (U.S. National Park Service)*, (n.d.). Lake Roosevelt is a cornerstone reservoir that currently serves as a critical water resource for central Arizona. The Workman Creek watershed is one of many watersheds that contributes to the volume of water available in Lake Roosevelt, ultimately to be released for supply into the Salt River and distributed for use.

Headwaters of the Colorado River begin in Rocky Mountain National Park, Colorado, while headwaters for its largest tributary river, the Green River, begin in the Wind River Range of Wyoming. Water conditions of the Colorado River and its tributary rivers depend largely on snowmelt in northern areas of the upper basin states (Congressional Research Service, 2022). The Colorado River is known to have significant fluctuations in volume due to highly variable occurrences of precipitation and runoff (Congressional Research Service, 2022). Reanalyzing observed historical flow data shows water volume in the Colorado River Basin averages about 14.7 million acre-feet (MAF) annually (U.S. Bureau of Reclamation, 2022), rather than the original projected number of 15 MAF in the 1922 compact. Annual flows can fluctuate significantly, which has led to the increasing concern for water scarcity issues revolving around the distribution of allotments of the Colorado River to the basin states. Rising temperature and drought further threatens this critical water resource. The Bureau of Reclamation estimated the driest period in more than 100 years occurred from 2000 - 2018 (U.S. Bureau of Reclamation, 2018). During this drought period, flows have decreased significantly, to average approximately 12.5 MAF (U.S. Bureau of Reclamation, 2022) per year. Climate change impacts, including warmer temperatures, altered precipitation patterns and decrease in snowpack are likely to prolong the drought in the basins and further restrict flows.

Lake Powell, AZ and Lake Mead, NV, are the two most significant reservoirs in the Southwest that not only store water along the Colorado River, but also provide hydroelectricity. Due to critically low levels, the Department of Interior requested drought contingency plans from the seven basin states in 2018. The following year of 2019 marked a historical moment when the first ever Colorado River Drought Contingency Plan Authorization Act was signed into law, allowing the Department of Interior to execute the plan immediately and operate applicable reservoirs in the river system accordingly (National Integrated Drought Information System, n.d**.)** Efforts are emphasized on keeping both Lake Powell and Lake Mead's surface water above a minimum elevation to protect hydropower infrastructure, preventing the loss of hydropower generation (Congressional Research Service, 2022). During 2021, Reclamation declared the first ever *Level One Shortage Condition* in the Lower Basin, and the following year declared a *Level Two Shortage Condition* (Congressional Research Service, 2022). Efforts to address drought in the region and conserve water led to a reduction in water released from Lake Powell to the Lower Basin while simultaneously releasing water from reservoirs upstream to increase the water levels in Lake Powell in order to prevent the loss of hydropower generation (Congressional Research Service, 2022). The reality of climate change influencing water availability, over allocation of the Colorado River and increased population in the basin states, has put pressure on the individual states, which are now tasked with creating a more sustainable solution to managing water resources, ultimately relying less on long-term water supply from the Colorado River. Arizona now faces an imminent threat of water scarcity issues in the state. It is more critical now than ever that researchers and water resources managers have the most accurate representation of the availability of water resources originating in the state.

Arizona receives the majority of annual precipitation in two distinct seasons, summer monsoon season and winter. The region receives 60-80% of annual precipitation in monsoonal rainfall between the months of June-October (Prein et al., 2022). The onset of monsoonal activity in Arizona is variable, but typically occurs in late June or early July and extends through mid to late September depending on atmospheric conditions (Crimmins, 2006). Irregular intervals of precipitation surges and dry spells are typical weather patterns during this seasonal cycle of rainfall (Higgins et al., 2004; Pascale & Bordoni, 2016). Elevation and latitude are strong controls on precipitation patterns across Arizona, with regions of high elevation seeing greater amounts of precipitation during the monsoon season (Crimmins, 2006). While much of the Southwest relies on rainfall to recharge water systems, recharge is not expected yearly or in all locations (Flint et al., 2004). Recharge is affected both spatially and temporally and varies greatly from year to year. Trends in annual precipitation since 1995 highlight the relatively dry years in Arizona (Figure 6), including 17 of the last 26 years to have experienced below average precipitation (Kunkel et al., 2022).

Arizona Precipitation Summaries

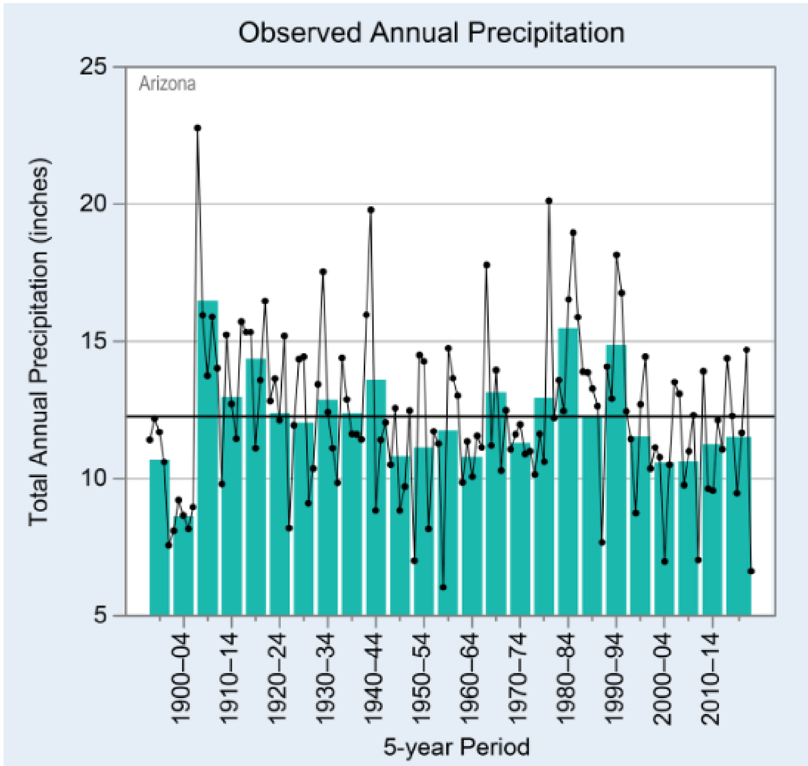


Figure 6: Arizona State Climate Summaries. Graph from National Oceanic and Atmospheric Administration (NOAA) (Kunkel et al., 2022)

Since the beginning of the 20th century, temperatures in Arizona have risen approximately 2.5℉, with the increase in average temperature and extreme heat projected to continue (Kunkel et al., 2022). Snowpack accumulation occurring in the late-season could consequently be impacted, leading to reductions in accumulation due to the warming temperatures. This poses a direct threat to snowmelt water resources (Kunkel et al., 2022). The warming climate is triggering the earlier onset of spring snowmelt (Cayan et al. 2001; Stewart et al., 2005).

3.3 Snow as a Water Resource

Increasing stress from warming temperatures suggests there is a correlation between decreases in snowfall and SWE in western mountain snowpacks (Mote et al., 2005; Stewart, 2009). Mote et al. (2018) revisited earlier work published in 2005, updating statistical modeling with 14 years of recent data with new findings showing over 90% of SNOTEL snow monitoring sites in the western states reveal declines in mountain snowpack. Recent studies show high temperatures have a significant effect on SWE availability in a region (Harpold et al., 2017) and when combined with low precipitation the likelihood of drought events is increased (Mao et al., 2015). Water is stored in significant quantities in mountain snowpack and a decrease or absence in snow accumulation can lead to drought (Mote et al., 2018), contributing to worsening fire conditions.

Gleason et al. (2013) published documentation of the effects of postfire forest conditions on snow accumulation, albedo and ablation in the Oregon Cascades). This study was the first of its kind, providing evidence of the impacts of wildfire on snow accumulation and ablation. The investigation looked into snowpack energy balance and included the first spectral measurements of snow albedo and snow surfaces with burned woody debris (BWD) in a burned forest. Findings showed that snow accumulation was greater in the burned forest, yet the disappearance of snow occurred 23 days earlier and had twice the ablation compared to the unburned forest. The burned forest measurements showed a greater concentration of darker debris in the snowpack, which suggests the snow was affected more by radiative impact which increased snowmelt. Furthermore, snow albedo was 40% lower in the burned forest during ablation, with approximately 60% more solar radiation reaching the snow surface, driving a 200% increase in net shortwave radiation (Gleason, et al., 2013).

Topography (i.e. aspect, slope, elevation, latitude) has known influences on snowpack dynamics (Geddes et al., 2005; Jost et al., 2007,) in montane forests where the majority of snowpack occurs. Further, the intensity of solar radiation and temperature are also impacted by topography, which can influence peak snowpack and the amount of snow available for melt. Elevation and aspect both have been shown to act as primary variables on the influences of snow depth in various studies. Elevation has a strong influence on snowpack and has been shown to reduce the effects of vegetation on snow accumulation (Jost et al.,2007). Study sites located in the Shingle Creek watershed within the Twitchell Canyon fire complex east of Beaver, Utah showed aspect as being the second greatest predictor of snow depth following a year of snowfall, with 44% deeper snowpack in north facing stands than south facing stands (Maxwell et al., 2019). As a result of exposure to solar radiation, the deepest snowpacks typically occur on north-east facing aspects and the shallowest snowpacks on south-west facing aspects (Golding and Swanson, 1986). Melting and evaporative processes experience energy fluxes based on slope angle and angle of sun (Musselman et al., 2008).

Harpold et al. (2014) discussed how little is known about how variation in topography in burned forest mosaics influences snowpack characteristics. Recent studies dedicated to better understanding topographical variables in conjunction with forest cover and/or disturbance on snowpack are revealing mixed hydrological results on two known competing processes: (1) snowpack accumulates in greater quantities in burned forests due to reduction of canopy interception; and (2) reduced capacity of forest canopy in burned forests limits snow accumulation due to lack of forest coverage from solar radiation and turbulent fluxes (Harpold et al., 2014; Musselman et al., 2015). While these are competing processes, other variables are likely at play rather than just burn conditions. Harpold et. al (2014), investigated the high intensity Las Conchas fire that occurred in northern New Mexico. The authors are the first to make observations on watershed-scale and stand snowpack processes in this area following wildfire disturbance. Results concluded that the unburned area had approximately 10% more water available for melt despite the post-burn area having near zero canopy interception and accumulating larger snow depths after a snowfall event. Ablation rates varied widely between the unburned and post-burned areas revealing the winter season ablation reduced snowpacks by roughly 50% prior to melt in the post-burn area.

Varying responses of snowpack in burned vs. unburned forest conditions suggests other variables besides burn condition affect snowpack characteristics. Limited knowledge exists of snowpack measurements in post-fire landscapes, with many studies excluding the influences of topography. Maxwell et al. (2019) peer-reviewed five snowpack studies on SWE that included snowpack measurements in burned and unburned plots. Results showed a wide range of SWE measurements in both environments. Latitude is a known variable affecting snow retention in general, and latitude also plays a role in SWE in burned forests, with southern latitudes experiencing increased insolation and therefore a greater effect of wildfire on snow ablation (Maxwell et al., 2019). Snowtography offers an affordable and relatively convenient approach to further investigate topographic position to better understand the primary drivers of snow ablation in post-fire landscapes.

Land managers face challenges when predicting snowmelt generated stream flows because of the many variables affecting snowfall accumulation and streamflow yields. Hapold et. al (2014) notes snowfall and streamflow are highly variable and discrepancies in results and observations bring attention to the lack of spatially distributed, detailed observations of snowpack accumulation and ablation in forests following disturbances. The acceleration of the geographical overlap between fire and snow further brings attention to modeling deficiencies. Snowmelt runoff models currently do not parameterize landscape disturbances caused by high-severity wildfire and therefore do not accurately account for the effects of wildfire on snow. The effect of forest structure and topography on snowpack-vegetation interactions varies significantly from small to large scales, such as individual trees to watersheds. Consequently, plot-scale observations are difficult to accurately extrapolate to larger areas of a forest creating a significant challenge in decision making for operational managers overseeing reservoir storage.

SNOTEL stations provide the primary database for snow studies in the western U.S. One limiting factor to SNOTEL stations is they rely on a single point for data collection and are typically installed in open, flat areas. Consequently these stations do not account for variability due to terrain and forest structure, neglecting snowfall interception by canopy. Snowtography provides a way to track snow accumulation, taking into consideration terrain and forest structure. While the influences of forest structure on snow may be intuitive, the impacts related to snow accumulation and ablation can be validated based on photographs and results from snowtography sites, further emphasizing the importance of understanding how topography and forest structure affect snowpack. The variability revealed at a snowtography site is critical information needed by hydrologists and water managers for predictive services because it provides a more realistic and comprehensive representation of snowfall and snowpack across varying terrain and forest structure. Pairing data from a snowtography site with SNOTEL data provides a much deeper understanding of the local environmental factors and conditions, which can allow for more accurate runoff yield predictions.

4. Problem Statement

As higher severity fires in the western U.S. become more prevalent in a warming climate, the associated effects on mountain snowpack dynamics pose a direct threat to snowmelt water resources. Watershed hydrology is fundamentally affected by wildfires due to the restructuring of forest geometry, therefore affecting snowpack dynamics through interception, sublimation and shading (Broxton et al., 2015; Musselman et al., 2008). While burned forests can accumulate more snow, research additionally shows increased ablation rates and the earlier disappearance of snow in burned forests (Burles & Boon, 2011; Gleason et al., 2013; Winkler, 2011). The timing of spring snowmelt affects water availability, with early snowmelt having ecological and societal impacts, including erosion, flooding and reservoir capacity issues (Stewart et al., 2004). Post-fire effects on snow will differ based on fire severity, topography and geographic location. This research seeks to understand the influence of wildfire vegetation disturbances on snowpack accumulation, ablation and soil water content in a wildfire impacted area of the Sierra Ancha Experimental Forest. We hypothesize that in post-fire landscapes, snow will accumulate to the greatest depths in areas with less canopy cover. We also hypothesize that in areas with less canopy cover, increased solar radiation will contribute to faster ablation rates, earlier snow free dates, and less soil moisture availability in burned forests.

Research Objectives

In this practicum project, I initiated a data collection program to study the long-term effects of wildfire disturbance on ephemeral snowpacks. My study used snowtography to assess snow accumulation, ablation, and soil water content (SWC) along transects that extend from closed forest and into adjacent open areas affected by fire in the Sierra Ancha Experimental Forest (SAEF) in Central Arizona. I had four specific objectives:

1. Establish a snowtography site in an area affected by wildfire in the SAEF.
2. Investigate differences in snow accumulation, ablation, and SWC in three distinct zones (forested canopy, cool edge, open area) of two snowtography transects.
3. Analyze differences in variables in the three zones related to accumulation and disappearance of snowpack for the first trial year of data collection (2021-2022 winter season).
4. Transfer lessons learned and findings of my study to contribute to the first publication of the Snowtography Handbook (Payton et al., 2021) My findings provide information for preparation of snow stakes, recommendations for reading snowtography images and recording data, and findings of accumulation and ablation rates at a unique location in central, Arizona.
5. Engage in communication with current stakeholders regarding research at the Workman Creek site to increase the acceptance of snowtography as a more formalized and acknowledged methodology in snow studies.
6. Participate as a facilitator in the Snowtography Handbook webinar hosted by Western Water Assessment discussing preparation and installation of the Workman Creek site.

5. Methodology

5.1 Study Site Description

The study site is located in the upper watershed of the Workman Creek Complex, and will therefore be referenced as the Workman Creek snowtography site. The study area includes two snowtography transects running Southwest- Northeast. The transects will be distinguished by their location in the forest, therefore being referred to as the East and West Transect. The transects capture three different areas with varying vegetation type and cover (open area, cool edge transition zone, under forest canopy). Each transect is 85 m in length and captures the following areas beginning from the North end of the transect; 20 m open area/burn scar, 40 m cool edge zone/burn scar, 25 m forest. Slope and aspect are not variables being considered in this study due to relatively flat terrain.

The Forest grouping consists of mostly ponderosa pine with some douglas fir (Figure 7). No old growth trees are present within the boundary of the snowtography transects. Some trees in the study plot were burned by a surface fire, which is evident by the charring at the base of some trees, most likely from the Juniper fire in 2016. The 25 m forested section of both the transects will be used as control sites as this area represents a boundary of low burn severity in the upper watershed.

Figure 7: Ponderosa pines in forest grouping at southern end of both transects. A) East transect facing South B) West transect facing North

Adjacent to the fire edge is a moderate to high-severity burned area, which will be referred to as the cool edge zone, covering 40 m of each transect (Figure 8). This zone is of interest because the snow has protection from sun and potentially some wind from the neighboring forested stand. The forested stand lies on the southernmost end of the transect. Therefore, a shadow is cast from the ponderosa pines over portions of the cool edge zone. The cool edge zone environment can exist from small to large scales in forests, from singular trees to stands, offering protection from the sun, slowing ablation rates. Vegetation in this area includes the following species; New Mexican locust, Gambel oak, young ponderosa pine and blackberries. Field observations in November, 2021, indicate more vegetation is present in this post-burned area compared to farther North along the transect in the burned/open area zone. New Mexican locust is the greatest concentration of vegetation in the area (Figure 8).

Figure 8: A) Cool edge grouping, moderate/high severity burned area of the West transect facing north; B) Post 25 in the cool edge grouping facing North; C) Panorama of West Transect. Left side facing North, Right side facing South

The northernmost end of both transects cross further into a higher burn severity affected area and will be classified as the burned/open area for this study. The open area has sparse patches of young ponderosa pine trees that have begun to regenerate. Other species in the open area include New Mexican locust as the dominant species, Gambel oak, manzanita and blackberries (Figure 9).

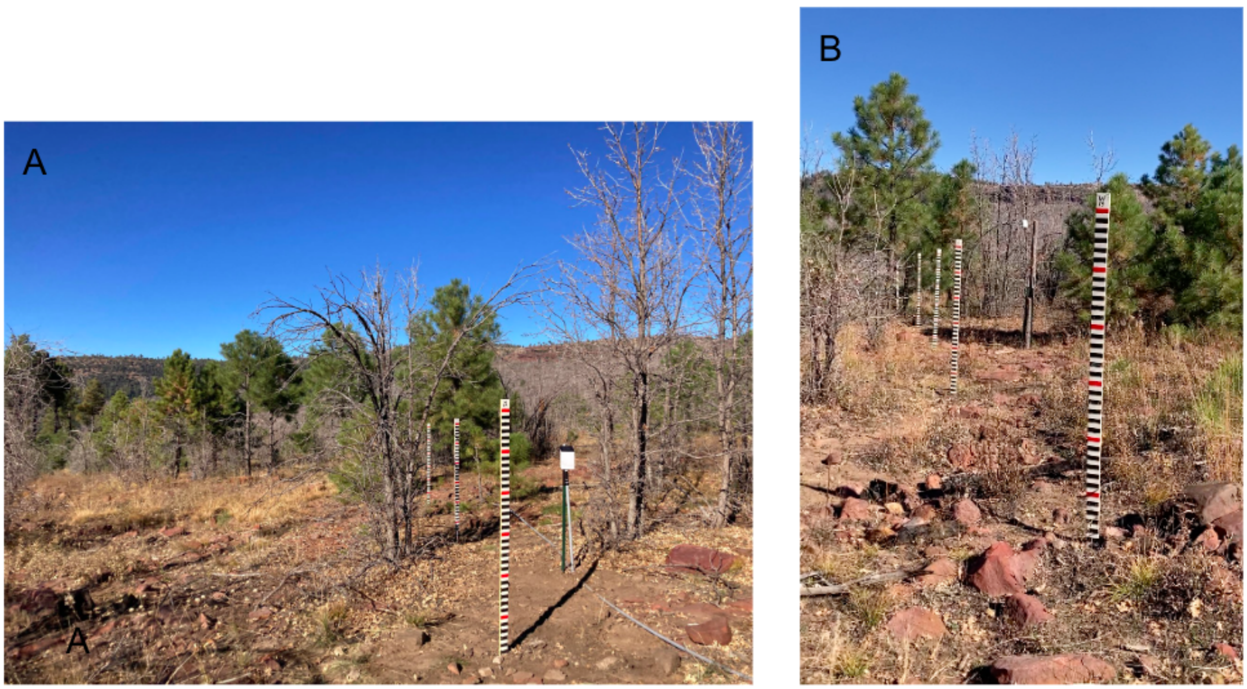


Figure 9: Open area groupings of both transects, high-severity burned areas. A) West transect open area grouping; B) East transect open area grouping

5.2 Snowtography Transects

Two snowtography transects (Figure 10) running Southwest-Northeast capture three different areas of burn severity with varying vegetation types and covers. This mid-elevation site was installed in November, 2021. The transects are located in a 20 year old post-burned area from the Coon Creek Fire (April, 2000). Portions of this burn scar were reburned during the Juniper Fire

(May, 2016). The transects are 85 m in length, include 18 posts per transect marked with a scale to indicate snow depth, and extend from a forested low severity burn plot, crossing burn severity boundaries into a high-severity burned area.

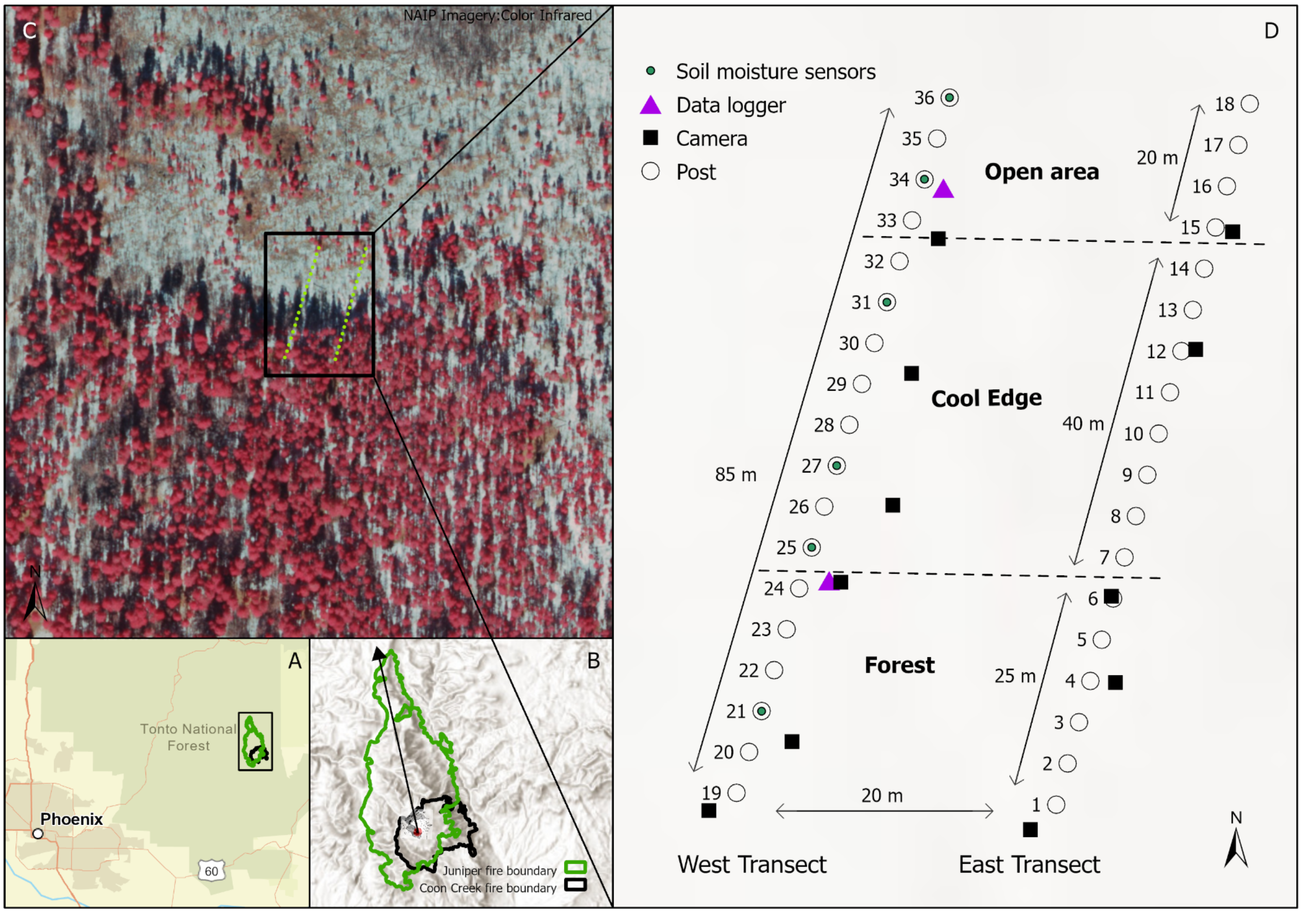


Figure 10: Study area, snowtography transects and equipment (cameras and soil moisture sensors. A) study area in relation to Phoenix, AZ; B) location of snowtography site shown inside the Coon Creek and Juniper fire perimeters; C) NAIP imagery showing aerial view of transects; D) West and East transects including location of groupings and equipment placement

The linear posts are grouped into three categories to investigate different variables affecting snow accumulation and ablation rates. The linear length of the transects will account for different variables known to influence snowpack dynamics; vegetation, canopy interception, sun and wind exposure. The transects aim to reveal how forest cover, structure, and disturbance affect snow accumulation, ablation and soil water content (SWC).

5.3 Data collection

To document continuous snow accumulation and ablation throughout the 2021-2022 winter season, twelve time triggered cameras were installed at the Workman Creek site, with six cameras placed along each transect. The camera brand is BlazeVideo, model A252 trail camera. Camera placement along the East transect includes the following locations based on proximity to the nearest post; 1, 4, 6, 8, 12, 15. Camera placement along the West transect includes the following locations in proximity to nearest post; 19, 21, 24, 27,30, 33. The cameras were time triggered, programmed to take one photo per hour between 8 A.M and 5 P.M. While the disappearance of snow is captured in images, this methodology is not capable of capturing or quantifying sublimation or evaporation.

Snow depth at each post was determined by observation from images collected from twelve trail cameras throughout the winter season. Manual data entry occurred during fall of 2022 following the 2021-2022 winter season. One photograph per day was used to calculate snow depth. The time stamp on the image is used to reference the image. The exact time of day snow depth was recorded is irrelevant in this study. The time of day selected to record snow depth was decided based on optimum image quality.

5.4 Snow Accumulation and Ablation rates

Data analysis included calculating accumulation and ablation rates. Snowpack accumulation was calculated for each post during storm events, then averaged by grouping, and then each grouping was compared to the Forest grouping to determine accumulation rates. Snow ablation rates were calculated by dividing peak snowpack during persistent snow cover events by the number of days it took for snow to disappear. Due to the ephemeral snowpack that occurs in this geographic location and the differing number of days consisting of snow cover along the transect, snow ablation rates were calculated per single post throughout each snow cover time period. Mean ablation rates were then calculated for the three snow environment groupings along each transect.

5.5 Soil Moisture Sensors - West Transect

Twelve TEROS 10 soil moisture sensors and two ZL6 data loggers, both manufactured by METER Group, were installed on the West transect. The soil moisture sensors measure SWC at the point of the sensor, a variable that indicates the volume of water in the soil. SWC provides insight regarding the disappearance of snow, helping distinguish between water infiltration from snowmelt versus snow lost to wind, evaporation or sublimation. The ZL6 data loggers are solar powered and use the ZENTRA cloud to store data through a cellular wireless network. The ZENTRA cloud delivers real time data, allowing the user to access data remotely. Data loggers are installed between post 24 and 25 and between post 34 and 35. Soil moisture sensors were installed below the surface at 10 cm and 30 cm at posts 21, 25, 27 31, 34 and 36. The two depth placements will allow for further understanding of how deep water infiltrates into the soil.

5. 6 Snow Density Sampling

A limited number of snow density samples were taken by Salt River Project employees during the first year of data collection for future SWE studies. SWE is not considered in this project. Density samples are critical for understanding SWE within the site area and making correlations to water availability. SWE can be derived from density samples and depth measurements captured in the photographs. SWC data collected from the ZLC data loggers can then be evaluated with the SWE numbers. Correlations can be made between water content available in the snowpack, water absorbed into the soil and water lost to sublimation. Increased involvement from stakeholders and collaborators in the future is anticipated, so starting a foundation of data tracking for snow density and SWE is considered valuable.

6. Results

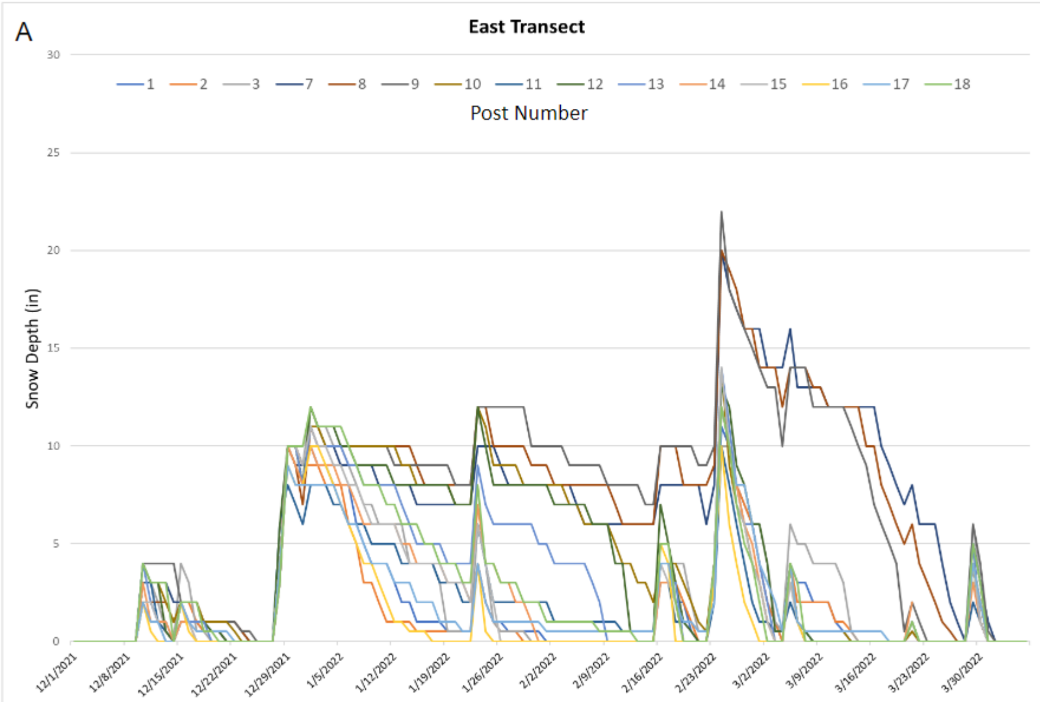
6. 1 Snow depth and accumulation

Data gaps occurred based on certain equipment malfunctions. Nine out of twelve cameras successfully captured snow accumulation and snowloss for the entirety of the winter season accounting for 27 out of the 36 posts between the East and West transects (Figure 11). Two cameras malfunctioned and therefore failed to capture snowfall and snow loss the entire season for the following posts; 4, 5, 6, 35, 36. Additionally, a third camera malfunctioned and failed to capture a portion of the winter season for posts 31, 32 and 33 and 34. Data collection summary for the snowtography transects are included in Table 2.

Cameras Installed	Successful Cameras	Total Posts	Number of posts with complete data	Number of posts with partial data	Unusable posts
12	9	36	27	4	5
First Day of Snow	Last presence Snow	Total post observations		Post number capturing partial data	No data from post number
12/10/2021	4/4/2022	3,388		31, 32, 33, 34	4, 5, 6, 35, 36

Transect	Grouping with complete data	Grouping with partial data
East	Cool edge and open	Forest
West	Forest and cool edge	Open

Table 2: Data collection summary including total post observations, number of posts with usable and unusable data, first and last day of snow recording.



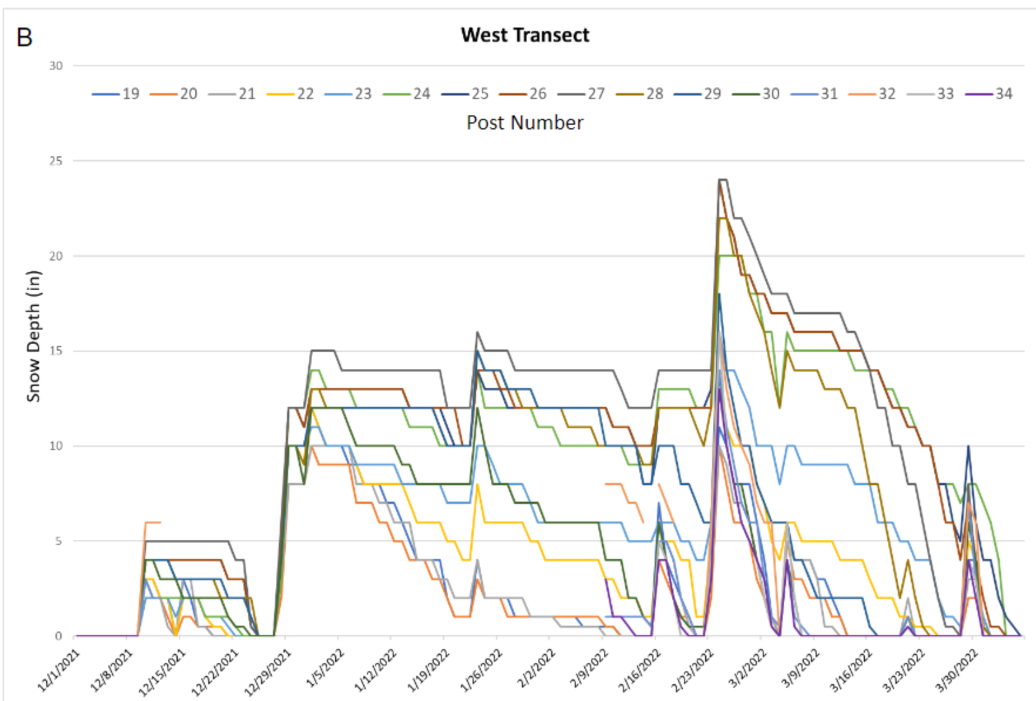


Figure 11: Observations of snow depth along East and West 85 m transects during the 2021/2022 winter season. Multiple episodes of snow accumulation, ablation and intermediate snow-free periods were captured; A) East transect snow depth observations over time; B) West transect snow depth observations over time

Snow Depth by Grouping: Three distinct snow environments (forest, cool edge, open area) were analyzed along two 85 m transects (Figure 12). Transect comparisons reveal the West transect received greater amounts of snow compared to the East transect. The cool edge grouping along the West transect reached the greatest depths throughout the winter season. Overall, both cool edge groupings reached the greatest cumulative depths when comparing transects, suggesting shading contributed to greater depths. Variability in snow depth is observed for the other groupings with ablation rate playing a role in retention and cumulative depth. Lower recordings of snow depth is observed throughout the season along the East transect in the forest and open area groupings as well as along the West transect in the open area compared to both cool edge groupings.

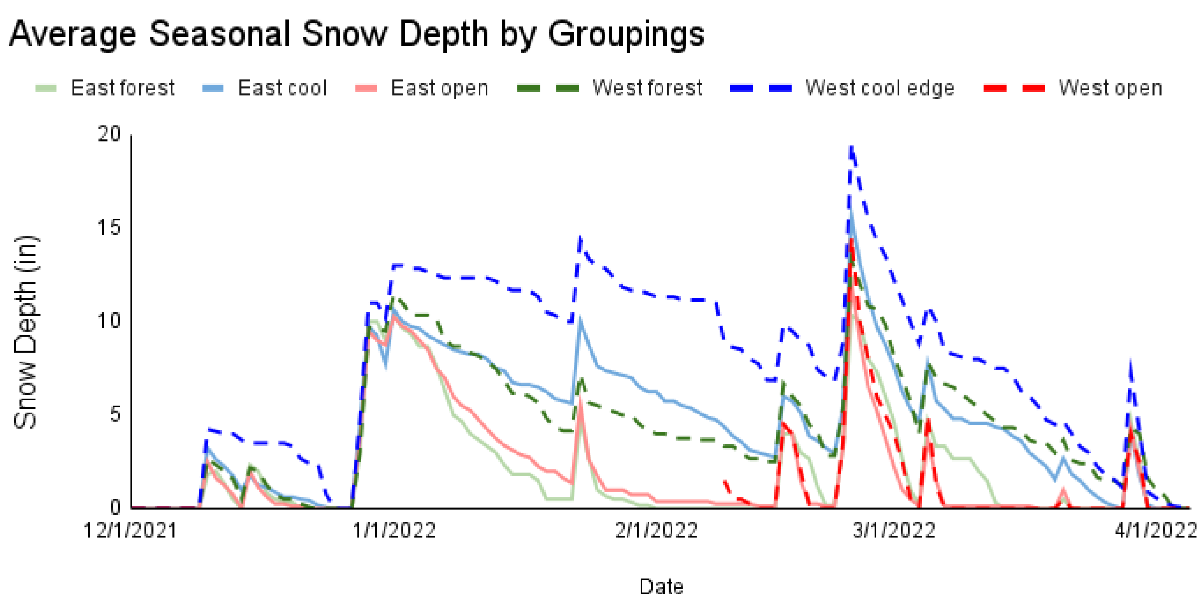


Figure 12: Average seasonal snow depth by grouping showing trends in snow accumulation and ablation through the 2021/2022 winter season. Missing data includes portions of the East Forest, West Cool Edge and West Open area.

Average new snowfall accumulation for three different snow environments (forest, cool edge, open area) are compared during snow storm events (Figure 13). Data from Figure 13 can be viewed in Table 3. Average accumulation rates for new snowfall for the cool edge along the East and West transect were 15-29% greater than compared to the forest groupings. Additionally, the open areas show an increase in snow accumulation during snowfall events compared to the forest grouping averaging 8-16% greater accumulation.

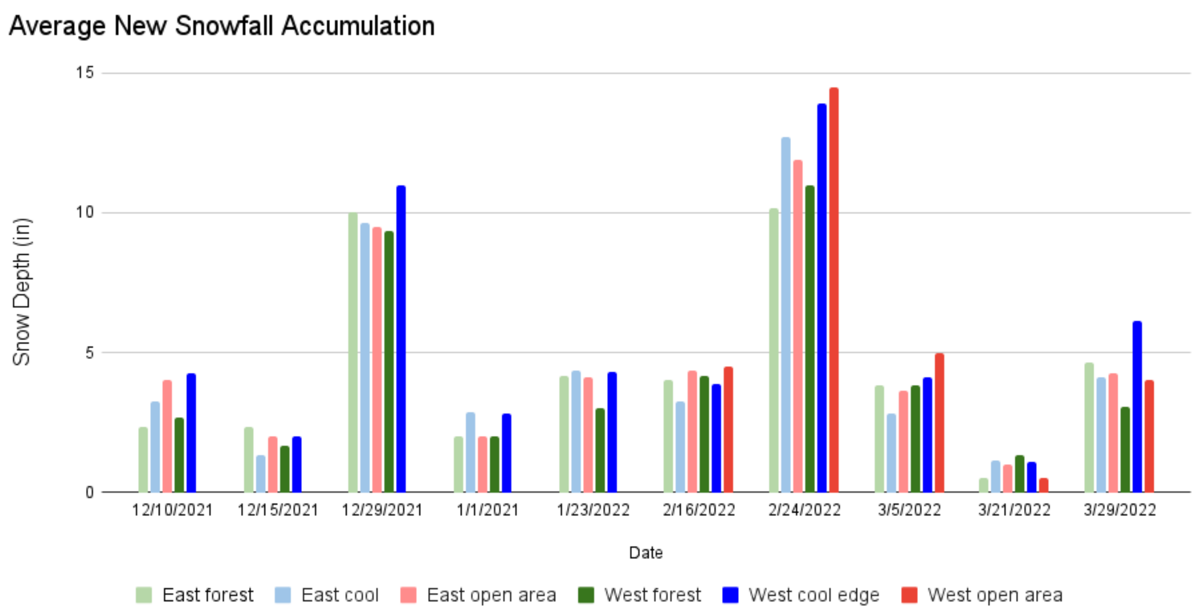


Figure 13: Average new snowfall accumulation along the East and West transects during twelve total snow events during the 2021/2022 winter season. Missing groupings for the following storm events are the result of camera malfunctions; 12/10/21, West open area; 12/29/21, West open area; 1/1/22 West open area; 1/23/22 west open area.

Snow Event	**East Forest** Average Depth (in)	**East Cool Edge** Average Depth (in)	**East Open Area** Average Depth (in)	**West Forest** Average Depth (in)	**West Cool Edge** Average Depth (in)	**West Open area** Average Depth (in)
12/10/2021	2.33	3.25	4.00	2.67	4.25	No Data
12/15/2021	2.33	1.31	2.00	1.67	2.00	No Data
12/29/2021	9.67	9.63	9.50	9.33	11.00	No Data
1/1/2021	2.00	2.88	2.00	2.00	2.83	No Data
1/23/2022	4.17	4.38	4.13	3.00	4.33	No Data
2/16/2022	4.00	3.25	4.38	4.17	3.88	4.50
2/24/2022	10.17	12.69	11.88	11.00	13.93	14.50
3/5/2022	3.83	2.81	3.63	3.83	4.13	5.00
3/21/2022	.50	1.13	1.00	1.33	1.10	.50
3/29/2022	4.67	4.13	4.42	3.08	6.13	4.00

Table 3: Average new snowfall values during storm events for the East and West Transects, categorized by grouping. Missing data includes the West Open area for five storm events.

The largest seasonal snowfall event that occurred on February 24th, 2022 showed the open area groupings accumulating an average increase of 17-32% more snow and the cool edge groupings accumulating an average increase of 25-27% more snow when compared to the forested areas along both transects (Figure 14). New snowfall accumulation trends differed during a less severe storm, but still significant storm, beginning on December 28th, 2021 (Figure 15). The East transect cool edge experienced the same accumulation and open area grouping experienced 2% less accumulation than the forest grouping. The West transect showed the cool edge grouping accumulated an average of 18% more snow during this storm event with no data to compare in the open area.

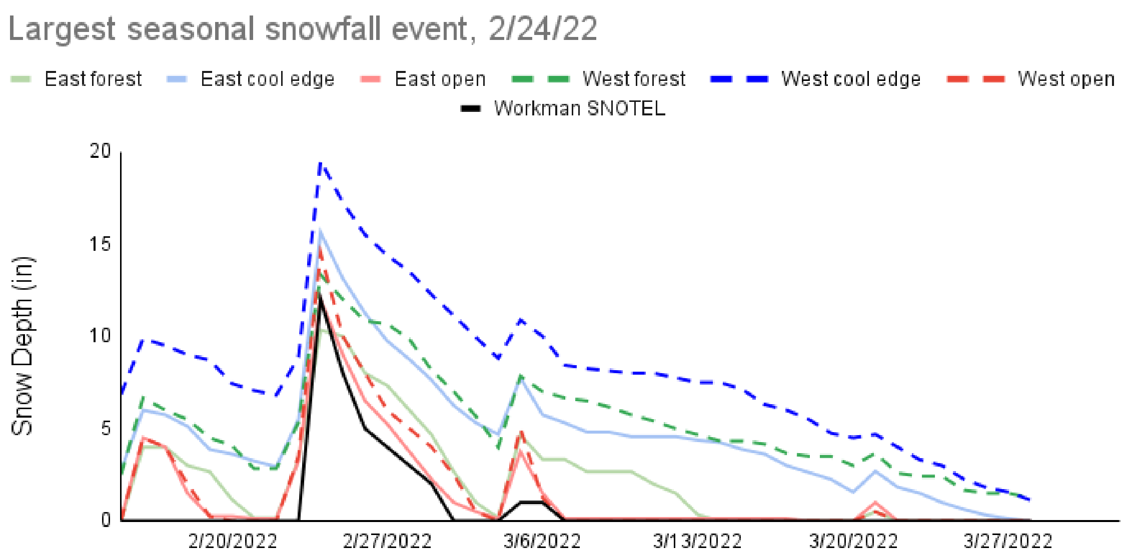


Figure 14: Snowfall event beginning on February 24, 2022 was the largest storm of the season. Average snowfall accumulation and ablation trend shown on the West and East transects in comparison to Workman SNOTEL.

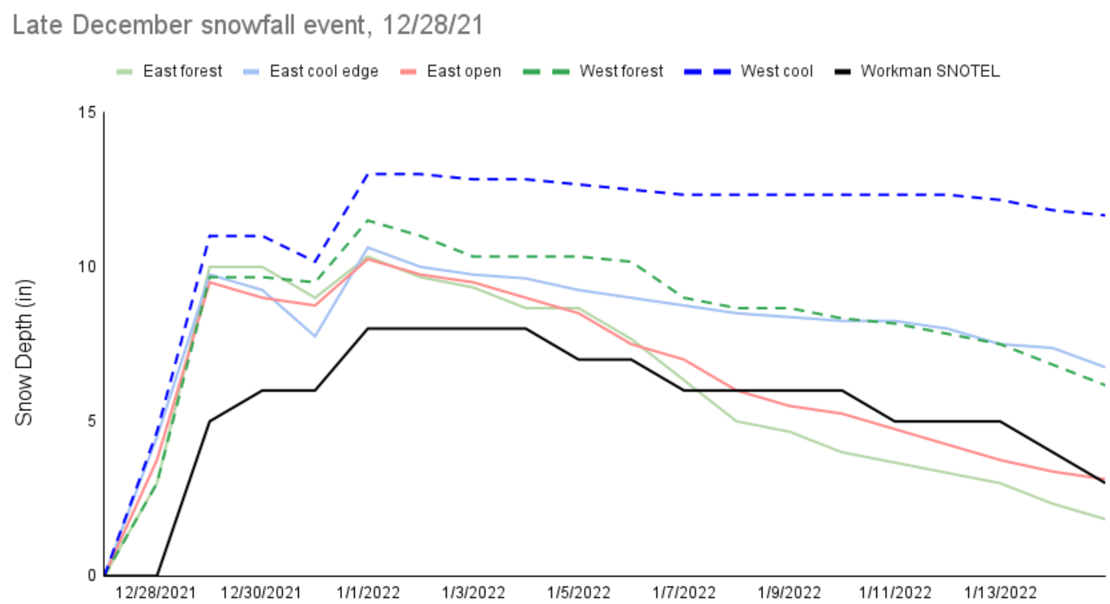


Figure 15: Snowfall event beginning on December, 28, 2021 was the second largest storm of the season. Average new snowfall accumulation and ablation trend shown on the West and East transects in comparison to Workman SNOTEL.

Peak Snow: Maximum snow depths occurred on February 24th, the largest snowfall event during the 2021-2022 winter season (Figure 16). Peak snow depths varied for the three groupings along the snowtography transects during the February 24 storm event. Snow depth in the forested groupings varied from 25 cm to 28 cm along the East transect and 25 cm to 51 cm along the West transect, with lower depths under dense canopy and greater depths under canopy gaps. Results are affected due to a camera malfunction in the forest plot of the East transect. Data loss occurred for this grouping along 15 m of the transect, potentially contributing to the lower peak snow depth range along the East transect. Snow accumulated at the greatest depths along both transects in the cool edge grouping, with a range of 25 cm to 56 cm (East) and 36 cm to 61 cm (West). The northernmost end of the transect in the Open Area that burned at high-severity had a similar range of 25 cm to 36 cm depths. Peak depths ranged from 25 cm to 36 cm along the East transect and 36 cm (no lower amount due to no data) along the West transect.

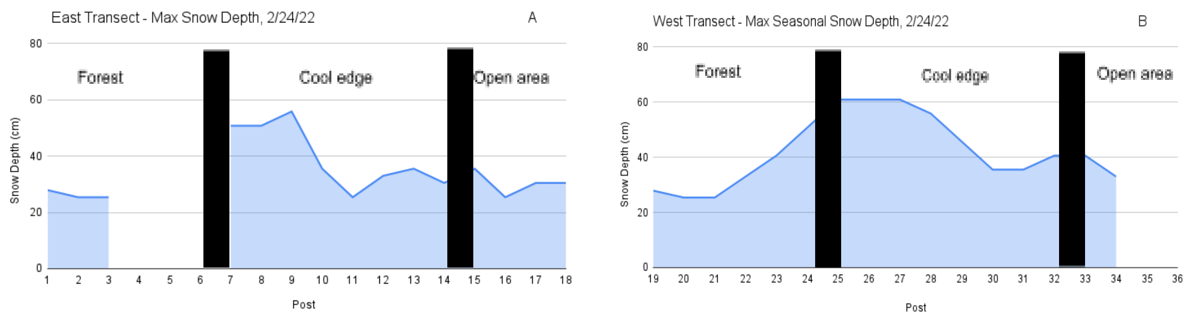


Figure 16: Observations of max snow depth recorded at both transects during peak snowpack on 2/24/22; A) Max snow depth East Transect, missing gaps include no data from posts 4, 5 and 6; B) Max snow depth West transect, missing gaps include no data from posts 34, 35 and 36.

6.2 Snow Ablation

Ablation rates are broken down per grouping for both the East and West transect (Table 4).

Table 4: Average snow accumulation and ablation rates for groupings relative to forest

Transect	Groupings	Average Accumulation for Season (in)	Average Accumulation rate per snowfall event (%)	Ablation rate (cm/day)	Ablation rate (%)
East	Cool edge Open area	46 45	115% 116%	2.3 2.7	132% 156%
West	Cool edge Open area	47 30	129% 108%	2.4 3.5	121% 178%

Note: Rates of snow accumulation and ablation for forest, cool edge and open area are given relative to forest grouping along both the East and West transect. Data is based on 10 snowfall events and 3-8 ablation periods. Limitations exist in the data, the West transect is missing data as follows: cool edge; post 31-32, open area; post 33-36. The East transect is missing the following data in the forest grouping; post 4-6. The West transect open area grouping ablation rate is determined using 5 snowfall events due to no data.

Ablation trends for the three groupings during the two most significant snow storms can be viewed above in Figure 17 and Figure 18. Average ablation rates for both transects varied by 21-32% increase between the cool edge and forest groupings (Table 4). Average ablation rates of both transects varied by as much as 56-78% between the open area and forest groupings (Table 4). The fastest melt rate occurred in the open areas, which burned at high-severity, at an average rate of 3.5 cm/day along the West transect and 2.7 cm/day along the East transect (Table 4). The slowest melt rate occurred in the forested area of low burn severity with an average rate of 1.9 cm/day on the West transect and 1.7 cm/day on the East transect. Snow depth in the cool edge groupings exceeded snow depth in the forested groupings despite the cool edge groupings having faster ablation rates. The differing type of vegetation, absence of mature ponderosa pines and effective shading in the area contributed to greater depths and at times the extended duration of snow cover.

6.3 SNOTEL Data Comparison to Snowtography Data

Results from the snowtography site were compared to snow depth measurements recorded from the Workman SNOTEL station. Average snow depth was calculated for both transects and compared to the Workman SNOTEL daily snow depth measurements throughout the 2021/2022 winter season (Figure 17)**.** Maximum peak snow depths occurred during similar time frames at the Workman SNOTEL station.

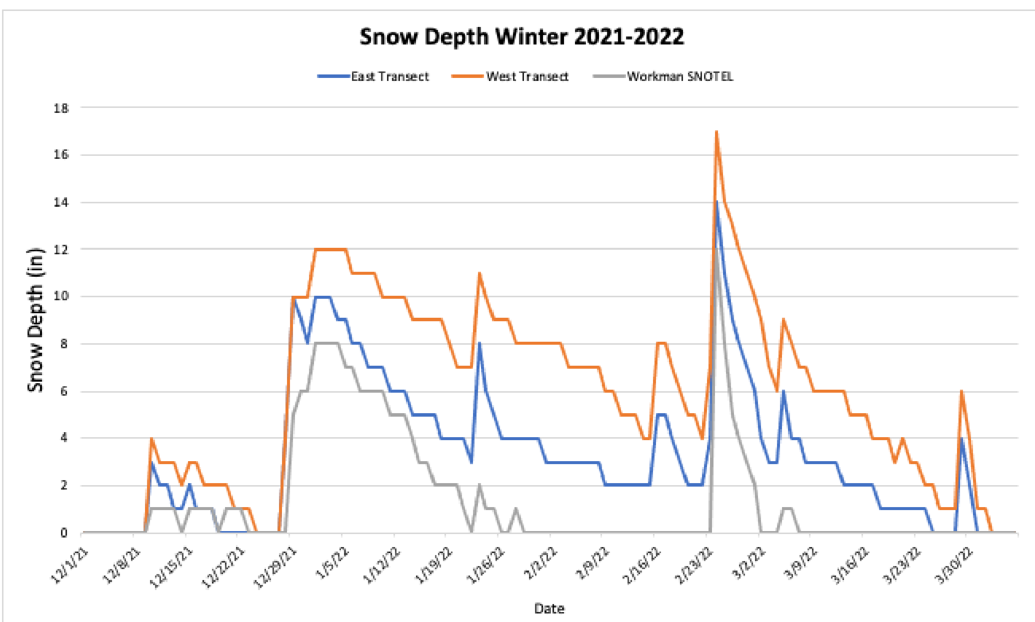


Figure 17: Average snow depth comparing snowtography site to nearby SNOTEL station

Results show similar timing of snow accumulation and loss but difference in magnitude. Further, the Workman SNOTEL station shows more snow free days, additionally showing the final snowpack for the season occurring on March 6th, 2022 whereas portions of both transects in this study had snowpack lasting into late March or the first few days of April.

However, when analyzing average snow depth for the three groupings for both transects (Figure 18), the Workman SNOTEL data correlated most similarly to the open area groupings.

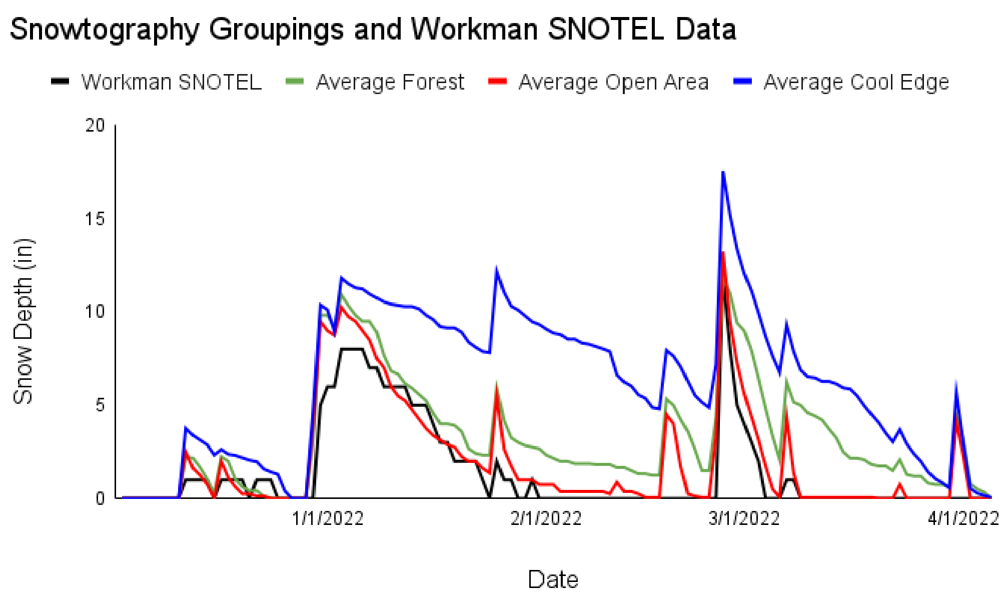


Figure 18: Comparison of snowtography groupings to Workman SNOTEL data for 2021/2022 winter season

Despite close correlations between the open area snowtography data and SNOTEL station, the SNOTEL station recorded lower snow depths consistently throughout the season and as well as snow storm events. This may be attributed to the SNOTEL station being located at a lower elevation of 7,032 ft compared to the snowtography site located at 7,200 ft, therefore receiving less snowfall. Point observations at SNOTEL stations provide great temporal measurements and insight to a general area, but the detriment to this method is the single point observation is usually located in a flat, unforested clearing, not accounting for canopy interception. SNOTEL stations can overestimate snowpack due to the absence of forest canopy, but these conclusions will differ by scenario. Snow accumulation in 2021/2022 was approximately 27% of the historical average from (2004-2020) at Workman SNOTEL (Figure 19).

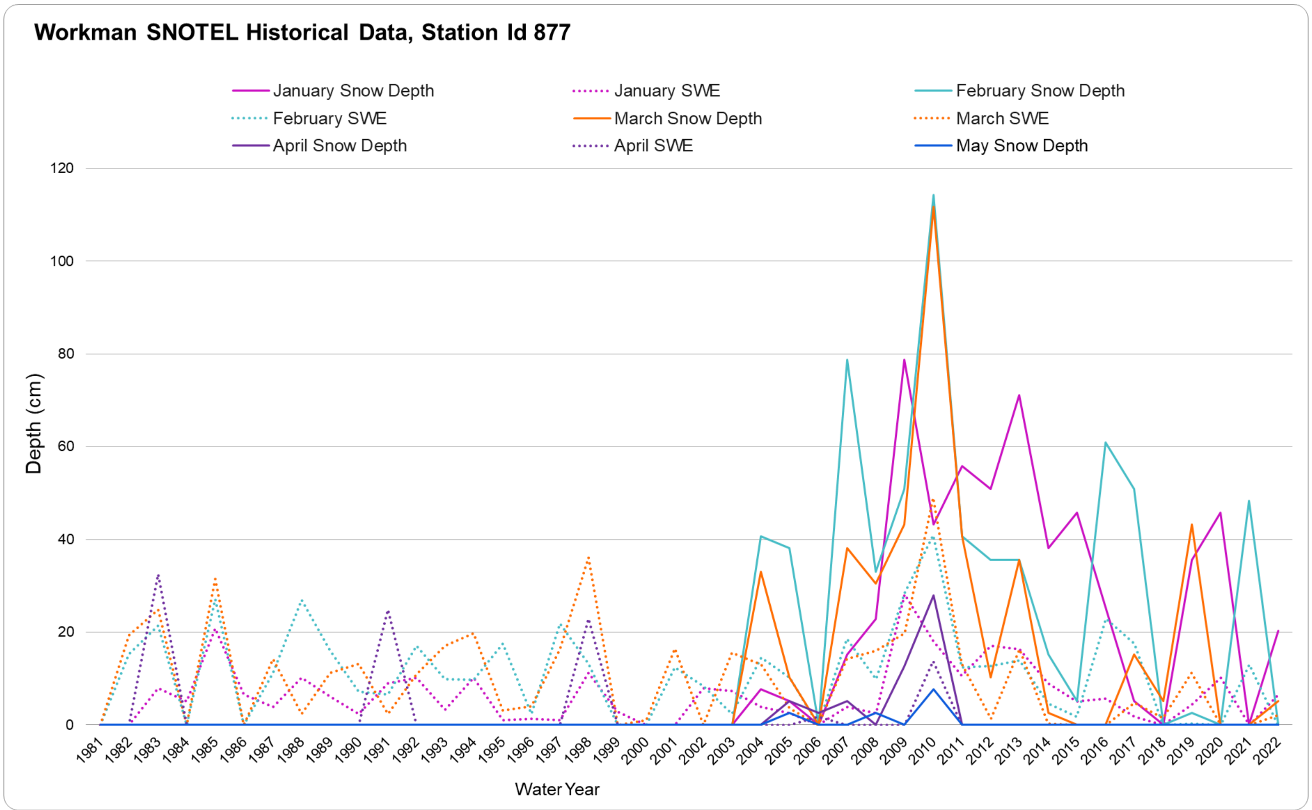


Figure 17: Workman SNOTEL station historical snow data showing

6.4 Soil Water Content (SWC)

Soil moistures sensors captured melt on the West transect at six locations at two varying depths, 10 cm and 30 cm, totaling 11 SWC readings for the winter season. One soil moisture sensor at the 30 cm depth failed for data logger 14243 at post 34 and is excluded from these results. Data logger 14235 captured soil moisture data at one location in the forest (post 21) and two locations in the cool edge (post 25 and 27) (Figure 21). Data logger 14243 captured soil moisture data one location in the cool edge (post 31) and two locations in the open area (post 34 and 36)

(Figure20). In general, shallower soils were dryer and less stable than deeper soils. SWC was measured in greater volume at the 30 cm depth sensor for four out of five locations. One sensor located at Post 36, 30 cm depth in the open area, is an outlier, and consistently recorded the highest water volume levels. Soil readings at post 25 generally showed trends of greater water volume at the 10 cm depth, except during melt events, in which the 30 cm reading would occasionally spike to higher volumes.

Higher SWC readings are recorded in the forest compared to the cool edge, excluding the 30 cm depth at post 27 in the for data logger 14235 (Figure 21). Lower water content is observed in the open area and cool edge locations for data logger 14243 (Figure 20) when compared to the forest grouping. The cool edge location recorded on this data logger is more North along the transect, close to the open area grouping and therefore soil moisture levels behave similar to the open area grouping.

Overall, SWC trends observed for data logger 14235 parallel snow accumulation, snow retention and snowmelt loss events (Figure 21). Spikes in water volume correlated to snow storm and melt events. Soil moisture levels generally held or gradually decreased overtime throughout the season tracking snow events and ablation periods. Precipitation days recorded at the snowtography site matched precipitation days recorded by PRISM data. Lower water volume measurements correlated to periods of snow retention for data logger 14235. The direct correlation of ablation with spikes in SWC indicates that evaporation and sublimation did not steal away all water content within the snow. Instead, snowmelt was able to infiltrate the soil in the Forest and Cool Edge areas and soil was able to maintain moisture levels.

Compare this parallel tracking from data logger 14235 (forest and cool edge grouping) to data logger 14243 (cool edge and open area groupings) and an important difference is observed. Data logger 14243 recorded SWC spikes after snow events, similar to the Cool Edge and Forest, but almost immediately and significantly dropped. There are 2 time periods, each lasting 4 weeks, where lower water volume measurements correlated to ablation periods that did not result in as much melt infiltration, and ultimately led to drier soils. Lower water volume measurements beginning January 12, 2022 through February 20, 2022 and February 25th, 2022 through March 23rd, 2022 correlated to periods of ablation that did not capture increased SWC. Snow events did not have an impact on increased SWC during this time frame.

The end of season snowmelt event is captured by both data loggers. Data logger 14235 recorded a gradual increase in SWC before tapering off to maintain steady levels at some sensors or a gradual decrease at other sensors throughout April. Data logger 14243 recorded a significant increase in SWC on March 24th, 2022 at the start of the final melt event in the area. A one week period of decrease in SWC occurred before spiking after a snowfall event. Mostly consistent levels of SWC are maintained as spring run off occurred through April.

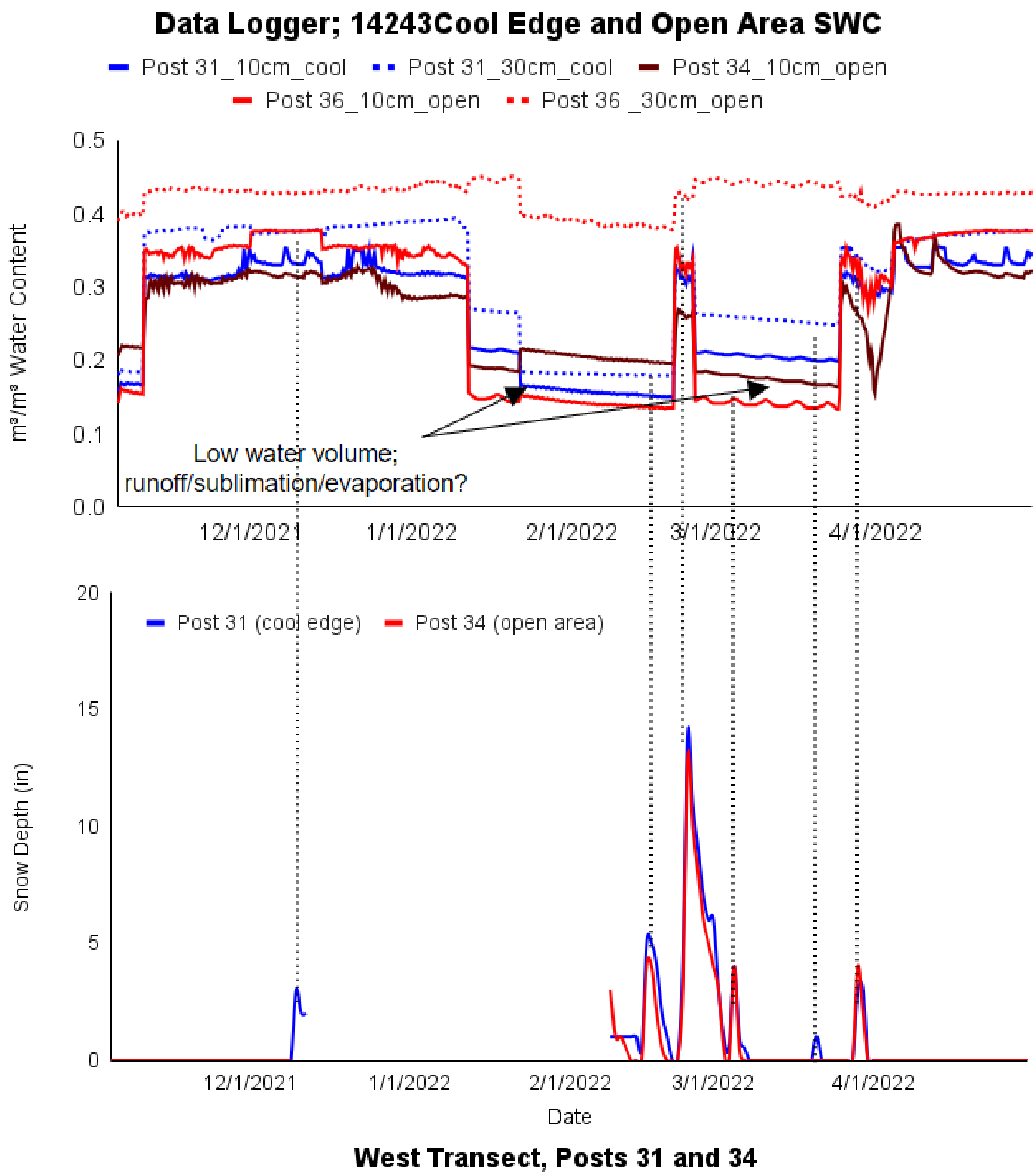


Figure 20: Data Logger 14243 along west transect at posts 31 (cool edge), 34 (open area) and 36 (open area) measuring soil water content. Posts 31 (cool edge) and 35 (open area) on the West transect showing snow depth over time during 2021/2022 winter season

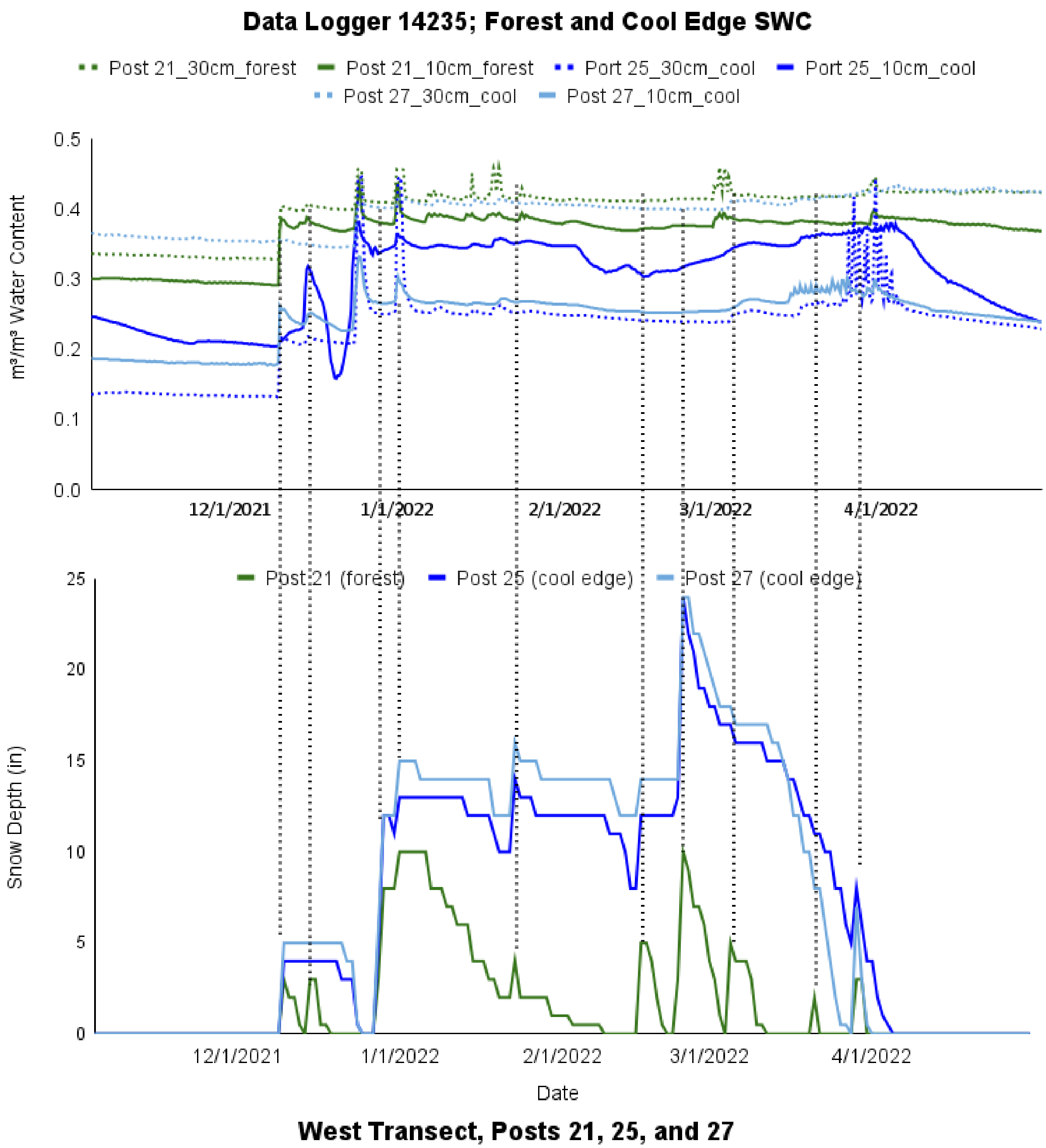


Figure 21: Data Logger 14243 along west transect at posts 31 (cool edge), 34 (open area) and 36 (open area) measuring soil water content. Posts 31 (cool edge) and 35 (open area) on the West transect showing snow depth over time during 2021/2022 winter season

7. Discussion

7.1 First Year Findings of Forest Impacts on Snow Depth

This snowtography research and site infrastructure will serve future long term research interests of hydrologists, resource and watershed managers. This study evaluated two competing processes on snow depth in post-burned forests: (1) reduction of canopy cover in wildfire affected forests results in greater snow accumulation and (2) the reduction or absence of canopy cover and vegetation increase ablation rates of snowpack leading to reduced snow depth and earlier snow-free days. Results of the impacts of varying burn gradients on snow accumulation and peak snowpack were quantified using repeat photography from low severity to high-severity burned forest in the Workman Creek watershed. Results from the two snowtography transects allow for transect-to-transect comparisons. No previous data at this site exists for year-to-year comparisons.

Overall, the results from this first year of data collection at the Workman Creek site show a relationship between wildfire and high-severity burned forest mosaics on snow depth, ablation and SWC. The results suggest that variations in snow accumulation, retention and ablation along both transects are correlated with the presence or absence of vegetation and shade. This research supports other research showing similar findings. During the snowfall accumulation period, snow depth increases with the reduction or absence of canopy cover in burned forests (Harpold et al., 2014; Lundquist et al., 2013). During the ablation period, canopy removal increases solar radiation and contributes to decreased snow depths and earlier melt events in burned forests (Varhola et al., 2010).

The small occurrence of differing results where the forest grouping accumulated more snowfall than the cool edge or open area groupings show how snow accumulation can differ throughout a forest given the storm intensity and type and density of vegetation. The present day burned forest conditions in the cool edge and open area groupings have seen regeneration of vegetation since the Coon Creek fire twenty years prior. Gambel oak has populated the cool edge zone and young ponderosa pines have regenerated in the cool edge and open areas, so neither of these groupings are truly sparse of vegetation resembling a clear cut, open area. Vegetation in these groupings is generally sparse, but low to the ground and near posts so interception of snow is possible. Wind transport of snow is not accounted for in this study, which can affect snow distribution (Winstral and Marks, 2002)

7.2 Wildfire Impacts on Snow Hydrology

High-severity wildfire disturbance can increase snowpack accumulation by reducing interception (Harpold et al., 2014) but consequently can alter snowmelt rates and the timing of runoff (Smoot and Gleason, 2021). Findings at the Workman site show an earlier snow free date in the open area groupings despite increased accumulation compared to the forest groupings along both transects. These findings support related research showing the earlier disappearance of snow and increased ablation rates in burned forests (Burles & Boon, 2011; Gleason et al., 2013; Winkler, 2011).

Further, extreme heat generated by high-severity wildfire can destroy soil properties, causing hydrophobic soil, leading to increased runoff (Wang et al., 2020). One key finding observed in the open area SWC data was immediate drop offs in soil moisture and overall lower water retention. This was not observed at point locations in the forest. This observation can be due to immediate runoff from potential hydrophobic soil in the high-severity burn area. This may also be caused by increased evaporation or sublimation processes, as the area monitored has limited vegetation to shelter snow from wind forces, and receives more sunlight throughout the day, increasing the effects of solar radiation on snowpack, ultimately decreasing water availability for infiltration.

To gain a more complete understanding of the hydrologic impact fire has on snow, quantifying snowpack characteristics, snow accumulation and snowmelt rates across varying topographic terrain and burn severity in wildfire affected forests is necessary. Further, it is imperative that the post-fire effects on snow are accounted for in models to project the most accurate estimates of snowmelt timing and runoff yields. Post-fire effects on snow will differ based on fire severity and geographic location, so replication of studies in both similar and different geographic regions is imperative to provide a more comprehensive understanding of high-severity fire effects on snow.

8. Conclusion

Snow hydrology is fundamentally affected by wildfires. The increasing overlap of fire and snow in a warming climate is the basis for a growing need to observe how landscape-altering events affect snow dynamics and water availability. This research uses repeat photography and soil moisture sensors to study snow accumulation, ablation and SWC along two 85 m transects, crossing burn severity gradients from the Coon Creek and Juniper fires in the Workman watershed. Data show under canopy areas receive 8-29% less snowfall compared to high-severity burned areas. Ablation rates can vary by as much as 21-78% between under canopy areas and high-severity burned areas that present minimal forest canopy protection. Additionally, high-severity impacted areas show a decrease in soil moisture compared to forested areas, most likely resulting from evaporation or sublimation. The open and cool edge groupings recorded lower water content levels during precipitation and ablation events, suggesting a correlation between drier soil and high-severity impacted areas.

Differences in accumulation and ablation rates are attributed to different extents of canopy cover and shading. Canopy cover from the ponderosa pine forests intercepts more snow resulting in lower depths compared to the high-severity burned area, which accounts for 65 m of the transect and has sparse vegetation. Ablation rates were lowest in the forested plot due to increased shading from ponderosa pine trees but the lower accumulation depths contributed to this area reaching snowpack-free days earlier than the cool edge portion of the transect. Persistent snowpack consisting of greater depths was found in the cool edge zone of the transect, which experienced the greatest snow depths due to less canopy interception yet had higher rates of snow ablation compared to the forested area. Despite a higher ablation rate, the duration of snow cover in this area lasted the longest duration of days due to deeper snow depths and efficient shading from the adjacent forested area.

This study contributes to the conversation of wildfires effects on snow accumulation and ablation, but is limited to one year of data collection in one watershed. This research provides insight to snow ablation rates at this unique location in central Arizona, but not processes. Continued data collection at the snowtography site is needed for reliable year-to-year comparison and runoff modeling. Further investigation at the Workman Creek site is needed to understand the quantity of water availability in the snowpacks and the degree of water content lost to evaporation or sublimation. Future studies would benefit from stream yield comparisons to intermittent snowmelt events where snow disappearance occurs. This study excludes the investigation of SWE, snow albedo and snowpack energy balance, which are highly relevant variables for understanding the more comprehensive effect of high-severity wildfire on snow interactions and damage to water resources. The installation of the Workman snowtography site serves as a long term investment, opening the door for endless research opportunities related to the long term effects of wildfire on ephemeral snowpacks. More research will contribute to efforts of understanding the impacts high-severity wildfires have on snow hydrology in this critical era of declining snowpacks and how to best implement these findings into snow accumulation and ablation models as well as snowmelt runoff models for water resource projections and management.

8.1 Future Recommendations

Considering the issues encountered during the initial test year of the Workman snowtography site as well as the history of the area, outcomes of the study and potential for future research, the following recommendations are made.

Snowtography Handbook recommendations

- Develop standardized rules based on logical reasoning and pragmatic decision making for recording snow depth. While recording new snowfall is typically straightforward, recording snow during the ablation process poses challenges. Snow does not melt uniformly so decisions made on how to record a dwindling snowpack is currently left to the discretion of the individual processing data. To help minimize discrepancy and ensure accurate snow depth results amongst snowtography sites, dedicating a section in the Snowtography Handbook to processing images from the trail cameras would be beneficial. Consistent data recording across snowtography sites will allow for reliable results to draw conclusions for site-to-site comparisons.

- Snow retention and ablation look different in regions consisting of ephemeral snowpacks compared to stable, seasonal snowpacks. Typically when calculating ablation rates in seasonal snow zones, rates are calculated by taking peak snow depth divided by the number of days to reach the disappearance of snow. Due to the reoccuring accumulation periods and ablation events that reach the total disappearance of snow throughout the season, calculating ablation rates is again left to the discretion of the researcher. It is recommended that discussion regarding calculating ablation rates in the snow research community continue to develop standard methods and these recommendations be included in the Snowtography Handbook.

Workman Creek Recommendations

- The Workman area offers a unique opportunity as an experimental forest to study long term impacts from two wildfires that occurred in the 2000 and 2016. Install additional snowtography sites in the Workman watershed. As snow hydrology research in post-fire landscapes gains momentum, it is important to understand how results can vary in areas with ephemeral snowpacks based on topographic position. Replication is needed to study, for example, how latitude, elevation, slope or aspect affect snowpack dynamics spatially and temporally.
- It is recommended that when processing images from trail cameras during new snowfall events, snow depth is recorded during the time of day when snow has reached peak accumulation. The Workman study site is geographically located at a more southern

latitude within the states, and is considered a mid-elevation site ranging between 6,500 - 7,700 ft that consists of intermittent snowpacks throughout the duration of the winter season. Observations at the Workman Creek site revealed new snowfall can accumulate and ablate in less than a 24 hour window before results for the following day are recorded. Recording peak snowfall during a storm event each day will provide the most realistic results of actual snow depth along the transect across varying terrain.

- Coordinate with SRP to regularly collect snow density samples at the site to better understand snowpack characteristics and SWE availability at this unique site location. This will allow SWE to be estimated throughout the winter season, and better understand end of season water availability that can be anticipated into Roosevelt Lake.

Literature Cited

Airborne Snow Observatories, INC. *Snow measurements and modeling to support sustainable global water supplies*. (n.d.). Retrieved October 13, 2022, from https://www.airbornesnowobservatories.com

Abatzoglou, J. T., Battisti, D. S., Williams, A. P., Hansen, W. D., Harvey, B. J., & Kolden, C. A. (2021). Projected increases in western US forest fire despite growing fuel constraints. *Communications Earth & Environment*, *2*(1), 227.

Allen, L. S. (1989). Roots of the Arizona livestock industry. *Rangelands Archives*, *11*(1), 9-13.

Barrows, J. S. (1978). Lightning fires in southwestern forests. *Final Report for Northern Forest Fire Laboratory, Intermountain Forest and Range Experiment Station. Cooperative Agreement 16-568. Fort Collins, CO: US Department of Agriculture, Rocky Mountain Forest and Range Experiment Station Forest Service. 154 p.*

Boepple, B. (2011). The Colorado River Basin: An Overview. *By the State of the Rockies Project 2011-12 Research Team*.

Biswell, H., Kallander, H., Komarek, R., Vogl, R. Harold, W. (1973). Ponderosa fire management: A task force evaluation of controlled burning in ponderosa pine forests of central Arizona. Tall Timbers Res. Sta., Misc. Publ. No. 2, Tallahassee, FL

Boulder Canyon Project Act, H.R. 5773, 70th Cong. (1928). https://www.usbr.gov/lc/region/g1000/pdfiles/bcpact.pdf

Broxton, P.D., Harpold, A.A., Biederman, J.A., Troch, P.A., Molotch, N.P., Brooks, P.D., (2015). Quantifying the effects of vegetation structure on snow accumulation and ablation in mixed-conifer forests. Ecohydrology 8, 1073–1094. https://doi.org/10.1002/eco.1565.

Burles, K., & Boon, S. (2011). Snowmelt energy balance in a burned forest plot, Crowsnest Pass, Alberta, Canada. Hydrological Processes, 25(19), 3012–3029. https://doi.org/10.1002/hyp.8067

Cayan, D. R., S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio, and D. H. Peterson (2001). Changes in the onset of spring in the western United States. Bull. Amer. Meteor. Soc., 82, 399–415

Campbell, R. E. (1977). *Wildfire effects on a ponderosa pine ecosystem: an Arizona case study* (Vol. 191). Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.

Central Arizona Project. (n.d.). Bureau of Reclamation. Retrieved October 9, 2022, from https://www.cap-az.com

Colorado River Basin Project Act, S.1004, 90th Cong. (1968). https://www.usbr.gov/lc/region/g1000/pdfiles/crbproj.pdf

Colorado Water Conservation Board (1997). Emergency response, flood hazard mitigation, and flood hazard awareness for residents of Buffalo Creek, Colorado. Department of Natural Resources, Denver, Colorado; 18.

Congressional Research Service. (September, 7, 2022) "Management of the Colorado River: Water Allocations, Drought, and the Federal Role" https://crsreports.congress.gov/product/pdf/R/R45546

Cooper, C.F. (1960). Changes in Vegetation, Structure, and Growth of Southwestern Pine Forests since White Settlement. *Ecological Monographs, 30*, 129-164

Crimmins, M. (2006). Arizona and the North American monsoon system

DeBano, L. F. (1981). *Water repellent soils: a state-of-the-art* (Vol. 46). US Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station.

Drury, S. (2019). Fuel continuity. *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*.

Evans, A. (2017) 2016 Wildfire Season: An Overview, Southwestern U.S. Technical Report. Ecological Restoration Institute and Southwest Fire Science Consortium, Northern Arizona University. 12 p

Falk, D. A., Heyerdahl, E. K., Brown, P. M., Farris, C., Fulé, P. Z., McKenzie, D., ... & Van Horne, M. L. (2011). Multi‐scale controls of historical forest‐fire regimes: new insights from fire‐scar networks. *Frontiers in Ecology and the Environment*, *9*(8), 446-454.

Flint, A. L., Flint, L. E., Hevesi, J. A., & Blainey, J. B. (2004). Fundamental concepts of recharge in the Desert Southwest: a regional modeling perspective. *Groundwater Recharge in a Desert Environment: The Southwestern United States*, *9*, 159-184.

Fradkin, P. L. (1981). *A River No More: The Colorado River and the West* (1st ed.). The University of Arizona Press

Geddes, C. A., Brown, D. G., & Fagre, D. B. (2005). Topography and vegetation as predictors of snow water equivalent across the alpine treeline ecotone at Lee Ridge, Glacier National Park, Montana, USA. *Arctic, Antarctic, and Alpine Research*, *37*(2), 197-205.

Gleason, K. E., Nolin, A. W., & Roth, T. R. (2013). Charred forests increase snowmelt: Effects of burned woody debris and incoming solar radiation on snow ablation. Geophysical Research Letters, 40(17), 4654-4661.

Golding, D. L., & Swanson, R. H. (1986). Snow distribution patterns in clearings and adjacent forest. *Water Resources Research*, *22*(13), 1931-1940.

Gottfried, G. J., DeBano, L. F., & Ffolliott, P. F. (1999). Creating a basis for watershed management in high elevation forests. *Baker, MB, Jr., compiler. History of watershed research in the Central Arizona Highlands. Gen. Tech. Rep. RMRSGTR-29. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station*, 35-41.

Gottfried, G. J. (2002). *Snowpack-runoff relationships for mid-elevation snowpacks on the Workman Creek watersheds of central Arizona*. US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Gottfried, G. J., & Neary, D. G. (2003). Preliminary Assessment of Sediment Measurements at the Weir Basins at Workman Creek, Central Arizona. Arizona-Nevada Academy of Science.

Groundwater Recovery. (2022). City of Tucson. Retrieved October 11, 2022, from https://www.tucsonaz.gov/water/groundwater-recovery

Harpold, A. A., Biederman, J. A., Condon, K., Merino, M., Korgaonkar, Y., Nan, T., ... & Brooks, P. D. (2014). Changes in snow accumulation and ablation following the Las Conchas Forest Fire, New Mexico, USA. *Ecohydrology*, *7*(2), 440-452.

Harpold, A., Dettinger, M. & Rajagopal, S. (2017) Defining snow drought and why it matters. EOS-Earth and Space Science News.

Higgins, R. W., Shi, W., & Hain, C. (2004). Relationships between Gulf of California moisture surges and precipitation in the southwestern United States. *Journal of Climate*, *17*(15), 2983-2997.

Huffman, E. L., MacDonald, L. H., & Stednick, J. D. (2001). Strength and persistence of fire‐induced soil hydrophobicity under ponderosa and lodgepole pine, Colorado Front Range. *Hydrological Processes*, *15*(15), 2877-2892.

Holsinger, S. J. (1902). The boundary line between the desert and the forest. *Forestry and Irrigation*, *8*, 21-27.

IMS Snow and Ice Products. (n.d.). United States National Ice Center. Retrieved October 13, 2022, from https://usicecenter.gov/Products/ImsHome

Jost, G., Weiler, M., Gluns, D. R., & Alila, Y. (2007). The influence of forest and topography on snow accumulation and melt at the watershed-scale. *Journal of Hydrology*, *347*(1-2), 101-115.

Kunkel, K. E., Frankson, R., Runkle, J., Champion, S. M., Stevens, L. E., Easterling, D. R., ... & Lemery, C. R. (2022). *State Climate Summaries for the United States 2022. NOAA Technical Report NESDIS 150*. NOAA NESDIS.

Lundquist, J. D., Dickerson‐Lange, S. E., Lutz, J. A., & Cristea, N. C. (2013). Lower forest density enhances snow retention in regions with warmer winters: A global framework developed from plot‐scale observations and modeling. *Water Resources Research*, *49*(10), 6356-6370.

Mao, Y., Nijssen, B., & Lettenmaier, D. P. (2015). Is climate change implicated in the 2013–2014 California drought? A hydrologic perspective. *Geophysical Research Letters*, *42*(8), 2805-2813.

Maxwell, J. D., Call, A., & Clair, S. B. S. (2019). Wildfire and topography impacts on snow accumulation and retention in montane forests. *Forest ecology and management*, *432*, 256-263.

Mote, P. W., Hamlet, A. F., Clark, M. P., & Lettenmaier, D. P. (2005). Declining mountain snowpack in western North America. *Bulletin of the American meteorological Society*, *86*(1), 39-50.

Mote, P. W., Li, S., Lettenmaier, D. P., Xiao, M., & Engel, R. (2018). Dramatic declines in snowpack in the western US. Npj Climate and Atmospheric Science, 1(1), 2.

Musselman, K. N., Molotch, N. P., & Brooks, P. D. (2008). Effects of vegetation on snow accumulation and ablation in a mid‐latitude sub‐alpine forest. *Hydrological Processes: An International Journal*, *22*(15), 2767-2776.

Musselman, K. N., Pomeroy, J. W., Essery, R. L., & Leroux, N. (2015). Impact of windflow calculations on simulations of alpine snow accumulation, redistribution and ablation. *Hydrological Processes*, *29*(18), 3983-3999.

National Operational Hydrologic Remote Sensing Center. (n.d.). *Airborne Snow Survey Program - NOHRSC - The ultimate source for snow information*. Retrieved October 17, 2022, from https://www.nohrsc.noaa.gov/snowsurvey

National Integrated Drought Information System. *Colorado River Drought Contingency Plan*. (n.d.). Drought.gov. Retrieved October 11, 2022, from https://www.drought.gov/colorado-river-drought-contingency-plan

National Water and Climate Center. Monitoring Programs. Natural Resources Conservation Service, United States Department of Agriculture. Retrieved from October 15, 2022 from https://www.nrcs.usda.gov/wps/portal/wcc/home/aboutUs/monitoringPrograms

Neary, D. G., Koestner, K. A., & Youberg, A. (2011). Hydrologic impacts of high severity wildfire: Learning from the past and preparing for the future. In *24th Annual Symposium of the Arizona Hydrological Society* (pp. 18-20).

Onda, Y., Dietrich, W. E., & Booker, F. (2008). Evolution of overland flow after a severe forest fire, Point Reyes, California. *Catena*, *72*(1), 13-20.

Pascale, S., & Bordoni, S. (2016). Tropical and extratropical controls of Gulf of California surges and summertime precipitation over the southwestern United States. *Monthly Weather Review*, *144*(7), 2695-2718.

Pase, C. P., and P. A. Ingebo (1965) Burned chaparral to grass: Early effects on water and sediment yields from two granitic soil watersheds in Arizona. Ariz. In *Proc. 9th Ariz. Watershed Symp., Phoenix* (pp. 8-11).

Payton, Elizabeth, Joel Biederman, and Marcos Robles. 2021. "Snowtography: Snowpack & Soil Moisture Monitoring Handbook." Western Water Assessment, University of Colorado Boulder. https://doi.org/10.25810/r9s7-4t28.

Prein, A. F., Towler, E., Ge, M., Llewellyn, D., Baker, S., Tighi, S., & Barrett, L. (2022). Sub‐Seasonal Predictability of North American Monsoon Precipitation. *Geophysical Research Letters*, *49*(9), e2021GL095602.

Pyne, SJ (1982) 'Fire in America: a Cultural History of Wildland and Rural Fire.' (Princeton University Press: Princeton, NJ)

Rich, L. R. (1962) *Erosion and sediment movement following a wildfire in a ponderosa pine forest of central Arizona.* USDA, Forest Service Rocky Mountain Research Station

Rich, L. R., & Gottfried, G. J. (1976). Water yields resulting from treatments on the Workman Creek experimental watersheds in central Arizona. *Water Resources Research*, *12*(5), 1053-1060.

Roosevelt Dam - National Historic Landmarks (U.S. National Park Service). (n.d.). Retrieved October 15, 2022, from https://www.nps.gov/subjects/nationalhistoriclandmarks/roosevelt-dam.htm

Smith, D. (2017). Sustainability and Wildland Fire: The Origins of Forest Service Wildland Fire Research. Missoula, MT: USDA Forest Service, Rocky Mountain Research Station.

Smoot, E. E., & Gleason, K. E. (2021). Forest fires reduce snow-water storage and advance the timing of snowmelt across the Western US. *Water*, *13*(24), 3533.

Spicer, E. H. (2015). *Cycles of conquest: The impact of Spain, Mexico, and the United States on the Indians of the Southwest, 1533–1960*. University of Arizona Press.

Stewart, I. T. (2009). Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrological Processes: An International Journal*, *23*(1), 78-94. https://doi.org/10.1002/hyp.7128

Stewart, I. T., Cayan, D. R., & Dettinger, M. D. (2004). Changes in snowmelt runoff timing in western North America under a business as usual' climate change scenario. *Climatic Change*, *62*(1), 217-232.

Stewart, I. T., Cayan, D. R., & Dettinger, M. D. (2005). Changes toward earlier streamflow timing across western North America. *Journal of climate*, *18*(8), 1136-1155.

Upper Colorado River Basin Compact (1948). https://www.usbr.gov/lc/region/g1000/pdfiles/ucbsnact.pdf

U.S. Bureau of Reclamation (2018), Annual Operating Plan for Colorado River Reservoirs, 2019. November 20, 2018 https://www.usbr.gov/lc/region/g4000/aop/AOP19.pdf

U.S. Bureau of Reclamation, "Colorado River Basin Natural Flow and Salt Data-Current Natural Flow Data 1906-2022," April 2022, 24 Month Study, https://www.usbr.gov/lc/region/g4000/NaturalFlow/provisional.html. Hereinafter, "1906-2020 Natural Flows."

U.S. Environmental Protection Agency (2016). Adapting to climate change:southwest. EPA-230-F-16-017

Varhola, A., Coops, N. C., Weiler, M., & Moore, R. D. (2010). Forest canopy effects on snow accumulation and ablation: An integrative review of empirical results. *Journal of Hydrology*, *392*(3-4), 219-233.

Wang, J., Stern, M. A., King, V. M., Alpers, C. N., Quinn, N. W., Flint, A. L., & Flint, L. E. (2020). PFHydro: A new watershed-scale model for post-fire runoff simulation. *Environmental Modelling & Software*, *123*, 104555.

Water and Climate Information System. (n.d.). National Water and Climate Center. Retrieved October 18, 2022, from https://www.nrcs.usda.gov/wps/portal/wcc/home/aboutUs/monitoringPrograms/wcis/

Water Science School. (2019, July 12). *Snowmelt Runoff and the Water Cycle*. Snowmelt Runoff and the Water Cycle | U.S. Geological Survey. Retrieved October 13, 2022, from https://www.usgs.gov/special-topics/water-science-school/science/snowmelt-runoff-and-water-cycle?_ga=2.237798528.1640091738.1665675931-1144396957.1665675931

Welch, J. R. (2017). Earth, wind, and fire: Pinal Apaches, miners, and genocide in Central Arizona, 1859-1874. *Sage open*, *7*(4), 2158244017747016.

Westerling, A. L. (2016). Increasing western US forest wildfire activity: Sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1696), 20150178.

Winkler, R. D. (2011). Changes in snow accumulation and ablation after a fire in south-central British Columbia. *Streamline Watershed Management Bulletin*, *14*(2), 1-7.

Winstral, A., & Marks, D. (2002). Simulating wind fields and snow redistribution using terrain‐based parameters to model snow accumulation and melt over a semi‐arid mountain catchment. *Hydrological Processes*, *16*(18), 3585-3603.