MULTIVARIATE ANALYSIS OF THE 2021 BOISE DROUGHT IN THE CONTEXT OF NATURAL HUMAN SYSTEMS

by

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The following individuals read and discussed the thesis submitted by student Jesus Martinez-Osorio, and they evaluated his presentation and response to questions during the final oral examination. They found that the student passed the final oral examination.

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DEDICATION

First of all I want to thank my beloved wife Sarah. I love you! You are the reason why I persevere, you taught me how to be patient, especially being with a family and having to balance school, work, and family time. You truly showed patience and love… and thank you for feeding me soup during all this time. I would also like to thank Max, Alex, Lauren, Emma, Cris, Dani, Robert, Ale, Fer, my mom, Maria Hermelinda, and my dad, Claudio. I would like to thank Dr. Sadegh for all the support. It truly was an amazing journey, from explaining the meaning of so many English words to patiently answering all my questions. With tears in my eyes, I write heavily for this once in a lifetime accomplishment, the first one in my family to earn a master's degree. I truly consider it an honor and am looking forward to keeping up the effort for the road ahead.

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ABSTRACT

Droughts generally refer to lack of sufficient water to supply specific needs, and has several categories including meteorological, hydrologic, agricultural and socioeconomic droughts [22]. Drought is triggered by the lack of or reduced precipitation, but other factors including low soil moisture, groundwater depletion, insufficient snowpack, reduced surface storage, increased evaporation, and contaminated surface water also contribute to various drought categories [12, 27].

Droughts impact many functional aspects of a community including agricultural production, recreation, access to clean drinking water, and the health of local ecosystems. Arid and semi-arid regions such as Idaho are specifically vulnerable to drought [12]. According to the Idaho State Department of Agriculture, agriculture makes up approximately 18% of the state's total economic output, and hence drought is a major concern in Idaho. As of October 12th, 2021, >90% of Idaho was in a severe, extreme, or exceptional drought according to the U.S. Drought Monitor [32]. This drought was specifically impactful for Idahoans, since a reasonable amount of snowpack and dam storage in the spring convinced local farmers to fully cultivate their farms and they struggled to irrigate their crops later in the season.

I focused this research on a multivariate analysis of the 2021 Boise drought in the context of natural-built systems. I considered two natural storages: (1) snowpack and (2) atmospheric storage, i.e., spring precipitation, as well as the built storage facilities like reservoirs, specifically the three dams on tributaries flowing into the Boise River watershed. I obtained historical (1982-2021) data for the Boise River watershed in terms of snow water equivalent and total dam storage on April 1st for each of the years studied, as well as spring precipitation, which collectively supports irrigation of agriculture in the Treasure Valley [4, 6]. Both univariate and multivariate frequency analyses were conducted to obtain a nuanced understanding of the drivers of the 2021 Boise drought. This provides important insights for the future conditions of drought initiation and evolution in the region in a warming climate.

By utilizing univariate analysis, I noted that snow water equivalent, or SWE, stayed within the range of historical average at more than 30 percent occurrence probability. This gave way to a somewhat "normal" snowpack for the year of 2021. Similarly, cumulative dam storage for Arrow Rock Dam, Anderson Ranch Dam, and Lucky Peak Dam had a combined occurrence probability of 60 percent for that year, meaning it was more than 60% of years in the observation record. Spring precipitation, however, was strikingly low in the Boise River watershed. In fact, it was close to the record low (ranked second lowest in the period of observation), with less than a 10 percent occurrence probability for the area. Multivariate analysis revealed new information about combined effects of natural and built storages that collectively supply water to stakeholders in the Boise River basin. In terms of joint distribution of SWE-dam storage puts 2021 in the lower end of the bivariate distribution, but it was exceeded by 5 other years. In terms of natural storage (SWE-spring precipitation), 2021 claimed the worst rank on record. Combining precipitation and dam storage, 2021 was ranked second worst year (after 2002) in the bivariate distribution. In a trivariate analysis and in a strict AND scenario, 2021 was ranked the worst drought year on record when a combined effect of natural and built storage are considered. This means that there was no year on record with a worse condition in terms of ALL of the three water storages considered herein. My analysis revealed that while natural storages (snow and particularly spring precipitation) were low in 2021, built storage buffered some of the impacts of drought in the Treasure Valley, Idaho. Further analysis using climate projections showed that while spring precipitation in a moderate emission scenario may marginally increase, this is expected to reduce in a high emission scenario. This means that under a high emission scenario, droughts similar to that of 2021 may increase in Treasure Valley, combined with increasing evaporative demand as temperature increases, are expected to occur more frequently and can result in adverse societal impacts. Finding root causes of severe water shortages is crucial for the further understanding of droughts in the Treasure Valley area. Policymakers can use this information to implement detailed plans for the community and to avoid cases like the sudden, dangerously low water levels experienced in 2021 and plan more effectively for the future.

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LIST OF ABBREVIATIONS

SWE	Snow Water Equivalent
SNOTEL	Snowpack Telemetry
BLM	Bureau of Land Management
BSU	Boise State University
CCC	Colorado Climate Center
EPA	Environmental Protection Agency
ha	Hectares
IDEQ	Idaho Department of Environmental Quality
CDP	California Drought Preparedness
CMI	Crop Moisture Index
CHG	Climate Hazard Group
DEWS	Drought Early Warning System
NASA	National Aeronautics and Space Administration
NIFC	National Interagency Fire Center
AAI	Aridity Anomaly Index
SPI	Standard Precipitation Index
AI	Arity Index
KBDI	Keetch-Bryan Drought Index
CMI	Crop Moisture Index
DAI	Drought Area Index

PDSI	Palmer Drought Severity Index
RAI	Rainfall Anomaly Index
SAI	Standard Anomaly Index
NDI	NOAA Drought Index

CHAPTER ONE: INTRODUCTION

1.1 Introduction

Droughts are felt all around the world. In a warming climate, and with an increase of natural disasters and increasing population and urbanization, droughts are more and more impactful to the different communities in countless locations. Drought is generally defined as a prolonged dry period when there is below the normal range water in the natural climate cycle. Similarly, drought is a “condition” that results when average rainfall for an area drops below normal conditions for a long time [2].

This research is focused on the Boise River watershed area located in the western part of the United States, and studies the 2021 drought that adversely impacted this region. The Boise River watershed is located mainly in Ada and Canyon Counties, and also covers parts of Boise, Gem, Elmore, and Malheur Counties [7]. This area of the Treasure Valley in southwestern Idaho is sitting on the Idaho batholith subdivision of the Northern Rocky Mountains and the Malheur-Boise Basin section of the high lava plains subprovince of the Columbia Intermontane Province [7]. The topography is very mixed with lava plains, basalt domes, cinder cones, and the deep canyon of the Snake River [7]. The slopes of the area vary from low to moderate, nearly level on the plain and the river valley, to very steep in Canyon County and the mountain areas [19]. Elevation ranges from around 2,300 feet at the confluence of Boise River with the Snake River, to around 5,800 feet at the Boise Front and around 10,000 feet at the Sawtooth Mountain Range headwaters of the Boise River [19].

To understand the development of the Boise area, I will first discuss some background of human settlement in this region. British trappers were the first on record to enter the area around the years 1830, then abandoned it around the 1850s [7]. However in the 1860s, gold was discovered and a huge "gold rush" fever arose, bringing more people and commerce to the area. In the year 1863, the U.S Army built Fort Boise on the northeast side of present-day Boise [7]. In the next year, 1864, Idaho became a state. For the following years, the area grew exponentially, in part because of its location on the Oregon Trail. Also, being so close to Owyhee County, where mines were sprouting left and right, caused an additional rise in population. In the year 1869, the prison was built, and the Old Oregon Short Line Railroad "reached" Boise and more people moved to the area. In 1977, the population in Idaho was 139,400, and 99,771 of the population was in the Treasure Valley area [7].

The Treasure Valley has cold, but not severe, winters. During the summer, days are hot and nights are cool. The annual precipitation in the area ranges from eight inches along the Snake River to around 24 inches in the mountains [13]. The average annual precipitation in most of the area is around 10 to 12 inches [13]. The Treasure Valley receives 33% of this precipitation in April through September, which includes the growing season. The maximum amount of rain in a 24 hour period ever recorded is around 1.9 inches in Boise on June 12, 1958 [7]. The Treasure Valley experiences around 15 thunderstorms per year, many of them occurring during the summer months [7]. Snowfall around the area usually averages around 23 inches per season [7]. Historically, the largest amount of snow recorded in one day was seven inches [19]. Most of the area experiences "northwesterly" winds, but sometimes "southwesterly" winds are present during the winter and spring months [9]. Heavy air masses "drain" down from the Boise Front into the Boise River Canyon during winter [9].

Farming has been key for the economy of the Treasure Valley, where the production of vegetables and grains has been part of the key for success for the area. Range cattle and sheep are part of the farming and economy of the area. Due to the Reclamation Act in the year of 1902, many farming activities were favored and exploited in the Treasure Valley, giving way for the need of more water and the construction of canals, irrigation control structures, and reservoirs [2]. The main water supply for the area is the Boise River that drains about 27,000 square miles of mountainous terrain by the north and east of the Treasure Valley [7]. The main reservoirs for the area are Lucky Peak, Anderson Ranch, and Arrowrock Dams. Arrowrock Dam was built in 1915 by the Army Corps of Engineers primarily for flood control and irrigation storage. Anderson Ranch and Lucky Peak Dams were completed in the 1950s and were aimed to produce hydropower and support agriculture [4]. In the following years, in coordination with other dams, the storage capacity for irrigation was improved. There are currently about 15 irrigation districts in this area. About 1,200,000 acre-feet of water is diverted annually for irrigation and this number is increasing annually due to the exponential growth and demand of the Treasure Valley [9].

In order to study the hydrological needs and potential hazards, areas have to be classified and addressed based on their local characteristics and needs. In the field of hydrological engineering, the hydrologic unit hierarchy is indicated by the number of digits in groups of two within the HUC code. The Boise River watershed is in the HUC 8, which is defined as the "subbasin level," analogous to "medium-sized river basins" [13]. The

HUC 8 subbasin contains 880,800 acres that includes the Treasure Valley of southwest Idaho [19].

This area features a rapidly developing urban community. Approximately 52% of the subbasin is in Ada County, 34% is in Canyon County, 5% is in Elmore County, 4% is in Gem county, 3% is in Payette County, and 2% is in Boise County [19]. This basin is 76% privately owned, and 24% of the watershed is public land [19]. About 67% of the basin is in shrubland, rangeland, grass, pasture, or hayland [19]. Approximately 24% is cropland and the remainder is forest, water, wetlands, developed or barren elevations ranging from 6,994 feet in the northeast portion of the HUC, to 2,180 feet at the basin outlet on the west [19].

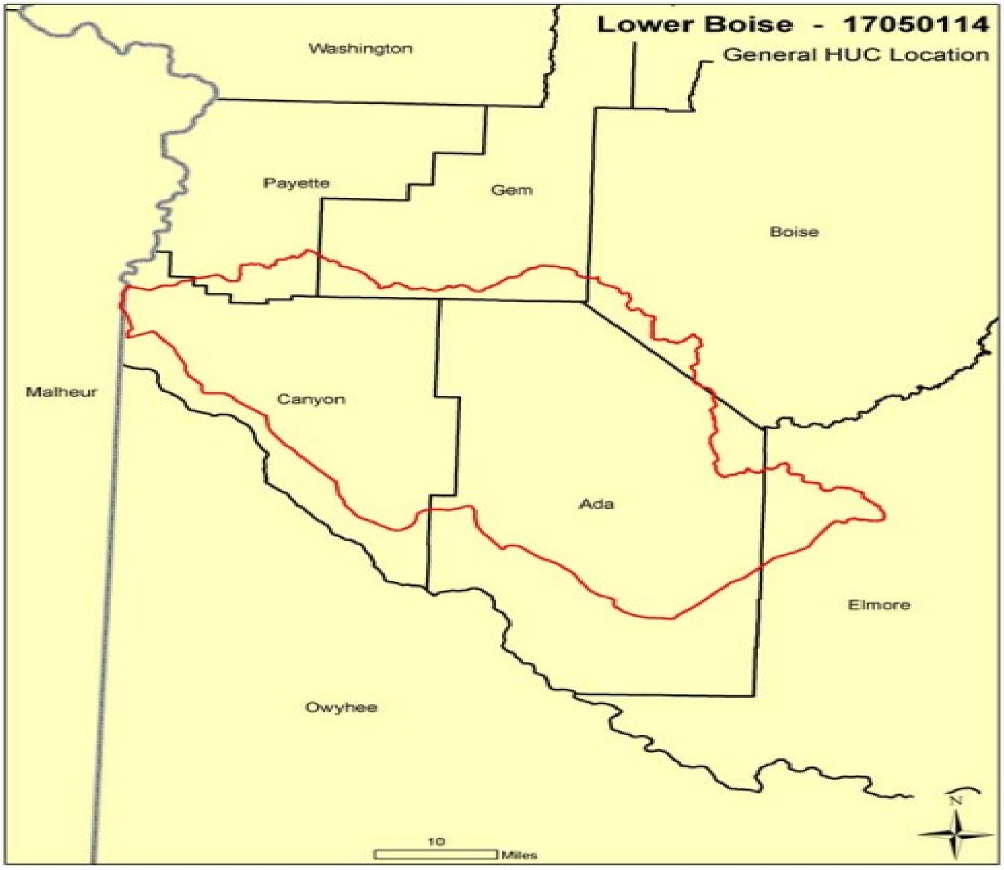


Figure 1.1 Boise River Watershed, and Surrounding Counties. Courtesy of ID NRCS

Figure 1.1 is a general map of the Boise River watershed. It provides a visual for the location of the counties that are part of the Boise River watershed, which can be seen by the red line that goes through Boise County, Elmore County, Ada County, Canyon County, Payette County and Gem County. Figure 1.2 below shows a range of elevations that encompass the Boise River watershed.

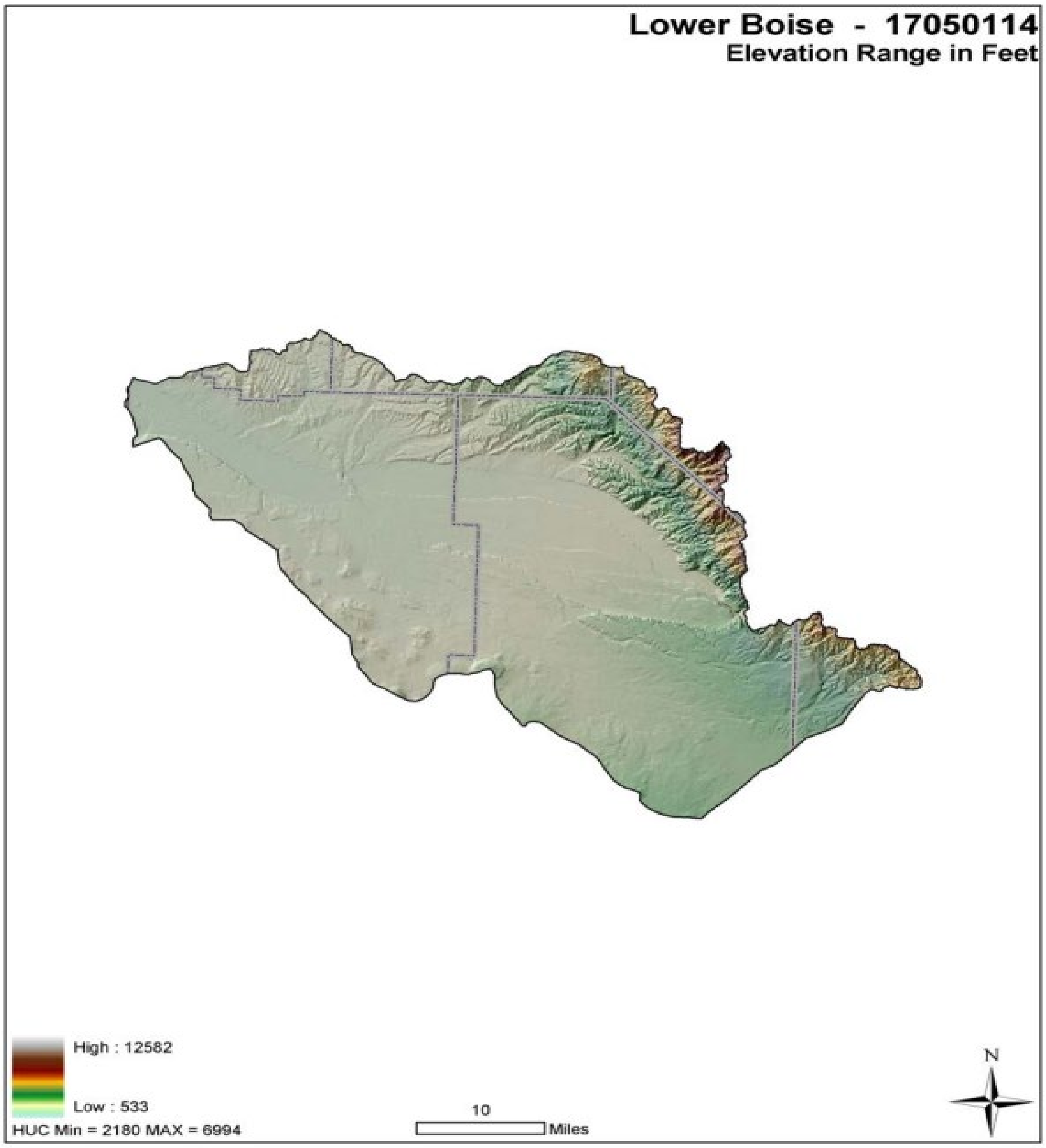


Figure 1.2 Boise River watershed Elevation Map. Courtesy of ID NRCS

The Boise River watershed has two basic types of ownerships: public and private. The large majority is considered private land, and approximately 24% is public land, concentrated mostly in the southeast region [19]. Figure 1.3 shows a map of the private and public ownership of the Boise River watershed with the descriptions mentioned above.

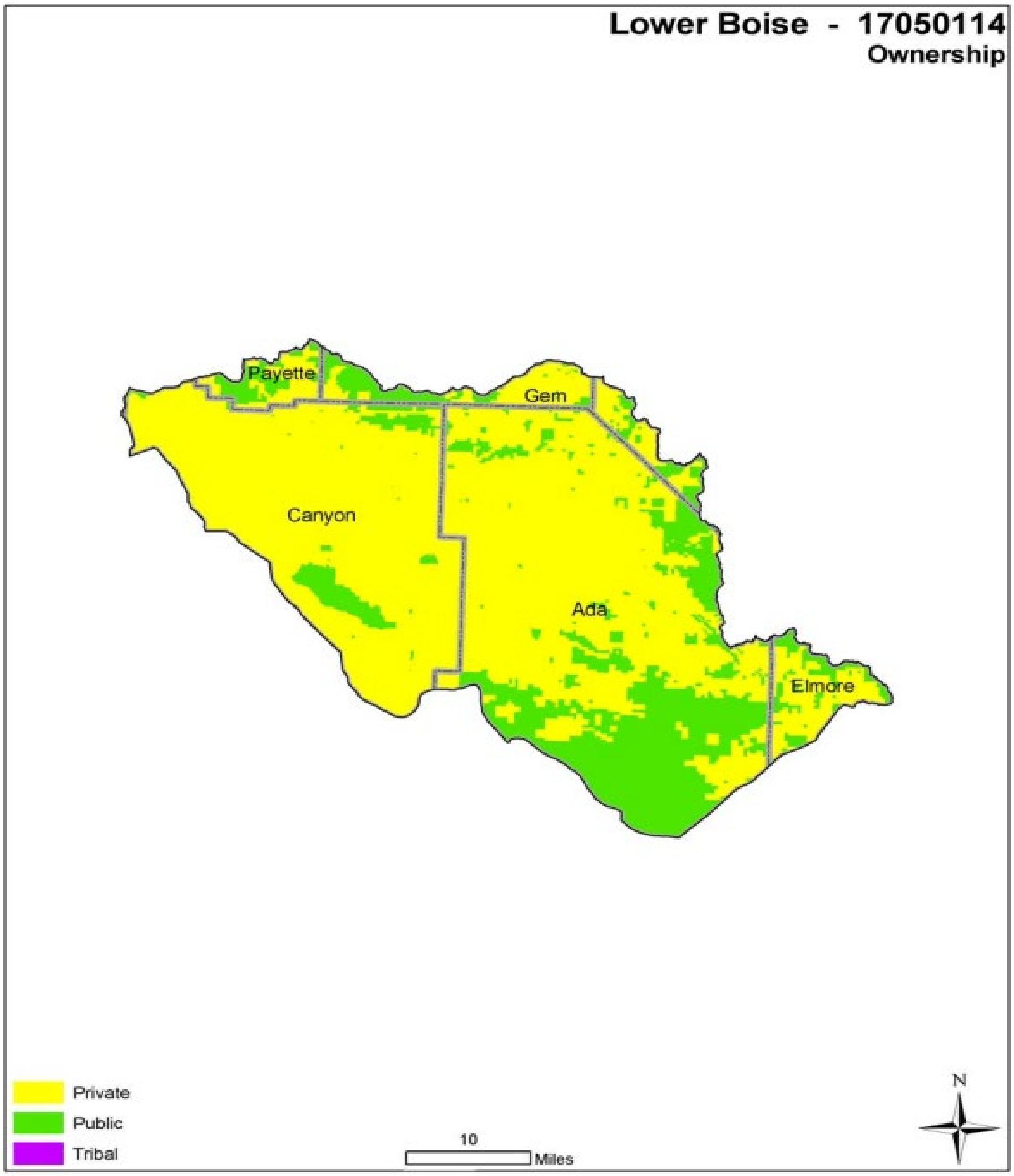
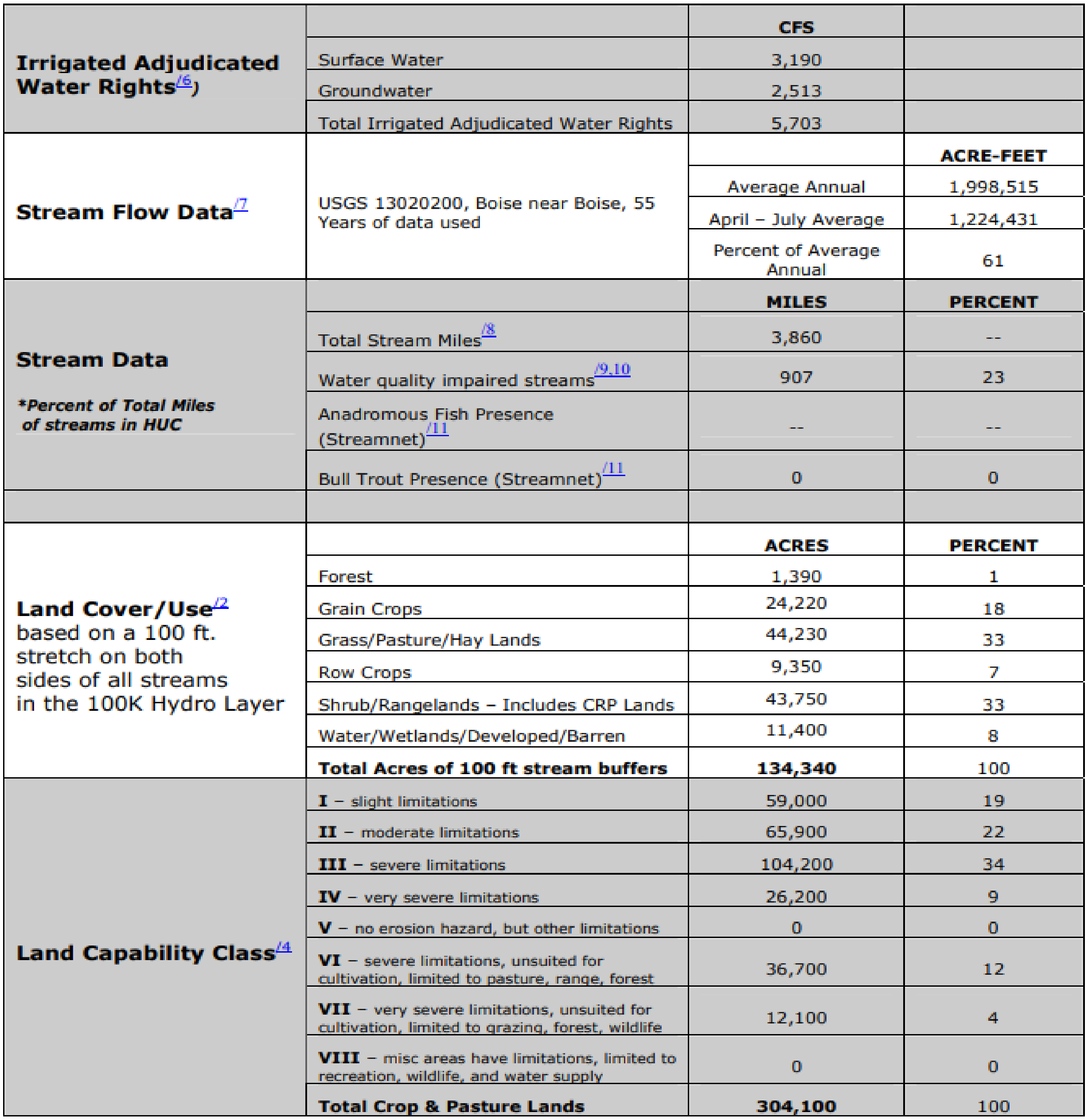


Figure 1.3 Boise River Watershed Ownership. Courtesy of ID NRCS

The Boise River watershed has a variety of land cover. Table 1.1 below shows a physical description. This includes land use, irrigated lands/cultivated cropland, and land cover.

Table 1.1 Boise River Watershed Physical Description. Courtesy of ID NRCS



Irrigated Adjudicated Water Rights[/6])		**CFS**	
	Surface Water	3,190	
	Groundwater	2,513	
	Total Irrigated Adjudicated Water Rights	5,703	
Stream Flow Data[/7]	USGS 13020200, Boise near Boise, 55 Years of data used		**ACRE-FEET**
		Average Annual	1,998,515
		April – July Average	1,224,431
		Percent of Average Annual	61
Stream Data ***Percent of Total Miles of streams in HUC***		**MILES**	**PERCENT**
	Total Stream Miles[/8]	3,860	--
	Water quality impaired streams[/9,10]	907	23
	Anadromous Fish Presence (Streamnet)[/11]	--	--
	Bull Trout Presence (Streamnet)[/11]	0	0
Land Cover/Use[/2] based on a 100 ft. stretch on both sides of all streams in the 100K Hydro Layer		**ACRES**	**PERCENT**
	Forest	1,390	1
	Grain Crops	24,220	18
	Grass/Pasture/Hay Lands	44,230	33
	Row Crops	9,350	7
	Shrub/Rangelands – Includes CRP Lands	43,750	33
	Water/Wetlands/Developed/Barren	11,400	8
	Total Acres of 100 ft stream buffers	**134,340**	100
Land Capability Class[/4]	**I** – slight limitations	59,000	19
	II – moderate limitations	65,900	22
	III – severe limitations	104,200	34
	IV – very severe limitations	26,200	9
	V – no erosion hazard, but other limitations	0	0
	VI – severe limitations, unsuited for cultivation, limited to pasture, range, forest	36,700	12
	VII – very severe limitations, unsuited for cultivation, limited to grazing, forest, wildlife	12,100	4
	VIII – misc areas have limitations, limited to recreation, wildlife, and water supply	0	0
	Total Crop & Pasture Lands	**304,100**	100

The Boise River watershed is key for the crop production and overall socioeconomic health of the region. As shown in Figure 1.4, a large part of the total acreage is used for grass pasture/hay lands, row crop, and grain crop. These activities need an immense amount of water.

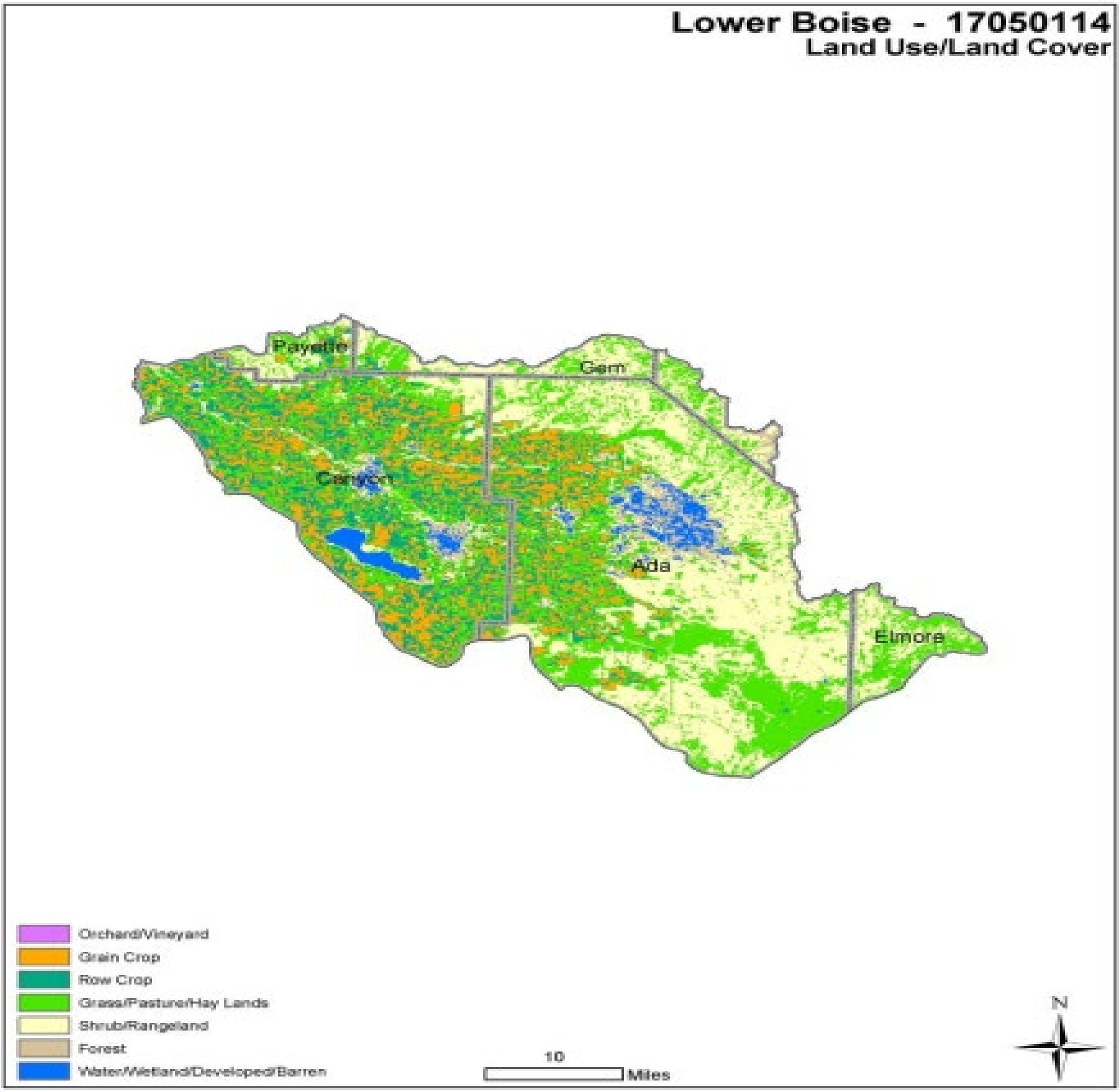


Figure 1.4 Boise River Watershed Land Use. Courtesy of ID NRCS

A sufficient amount of water is key to produce crops, and is expected every year. However, years like 2021 that develop a deficit of water, takes a huge toll on these types of activies. Various factors, like lack of rain, play a key role in these water deficiencies. Figure 1.5 shows that average precipitation for the Boise River watershed is below 14 inches annually.

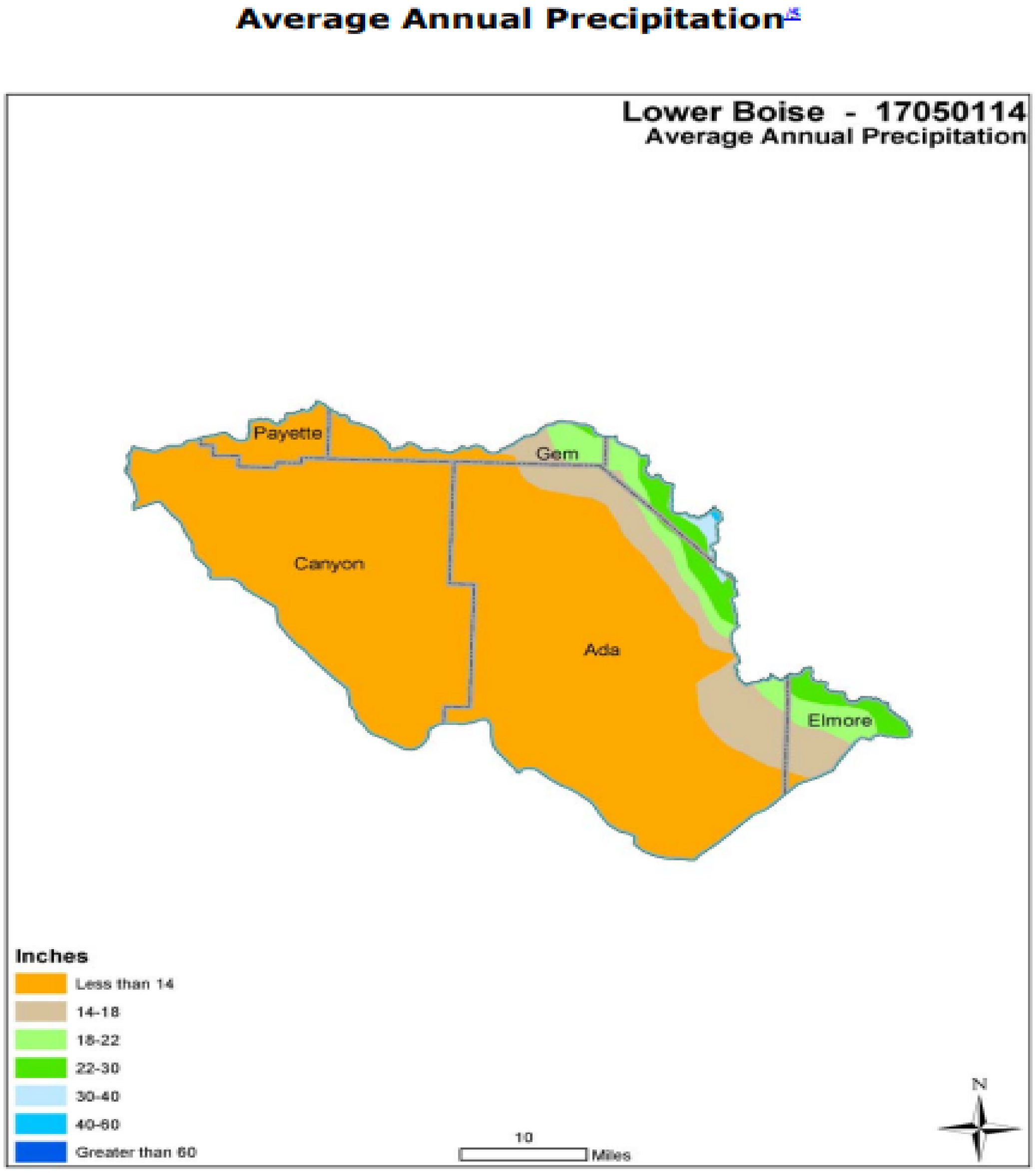


Figure 1.5 Boise River Watershed Annual Precipitation. Courtesy of ID NRCS

Water availability in the Boise River watershed, as any other, is dependent on general trends of climate change and variability. Natural cycles of climate variability do not always have a uniform predictable trajectory; they act as a stochastic "envelope" of conditions that produce various patterns. For example, El Nino conditions in the Pacific Northwest occur every two to seven years and last about 18 months [8]. During El Nino, an upper layer of warm water in the Western Pacific flows eastward instead of its normal westerly direction [14]. This causes earlier snowmelt and warmer, drier summer patterns [14], thus increasing drought risk around the Pacific Northwest, and in this case, around the Boise area. Likewise, the dry weather and warm temperatures increase evapotranspiration, subsequently inducing water deficit [33]. Figure 1.6 below shows some of the common concerns in the Boise River watershed that include crop production, irrigation, livestock grazing, etc.

These areas are marked by numbers and represent areas that share similar characteristics related to resources, problems, or treatment needs. Below, Table 3, can be used in conjunction with Figure 1.6 to see the many resource concerts each area shares along these delineations of the Boise River watershed. The information from Figure 1.6 shows, in conjunction with that from Table 2, natural features and common concerns. This plays an important role when dealing with natural deficits like lack of precipitation, lack of snowpack or even heat waves. Cases like the 2021 Boise drought prompt the need for research and study of all these factors.

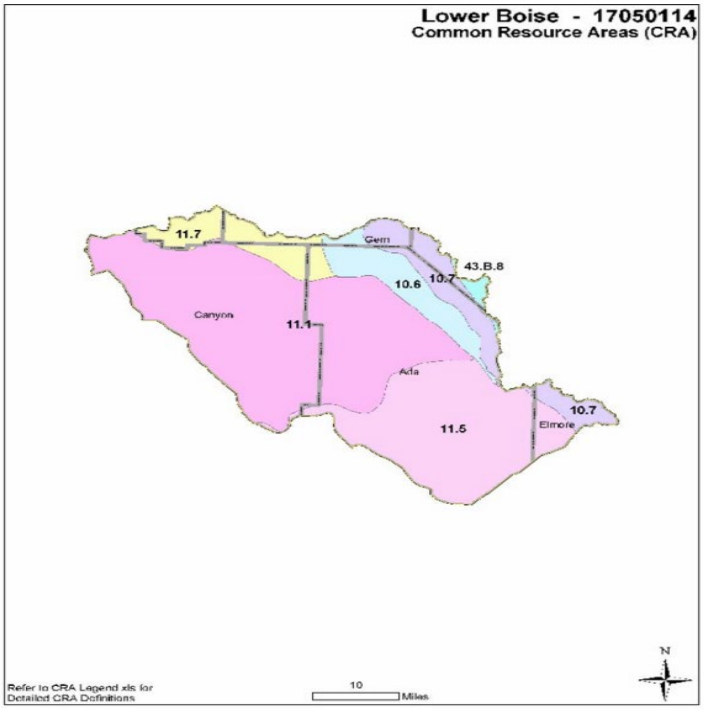
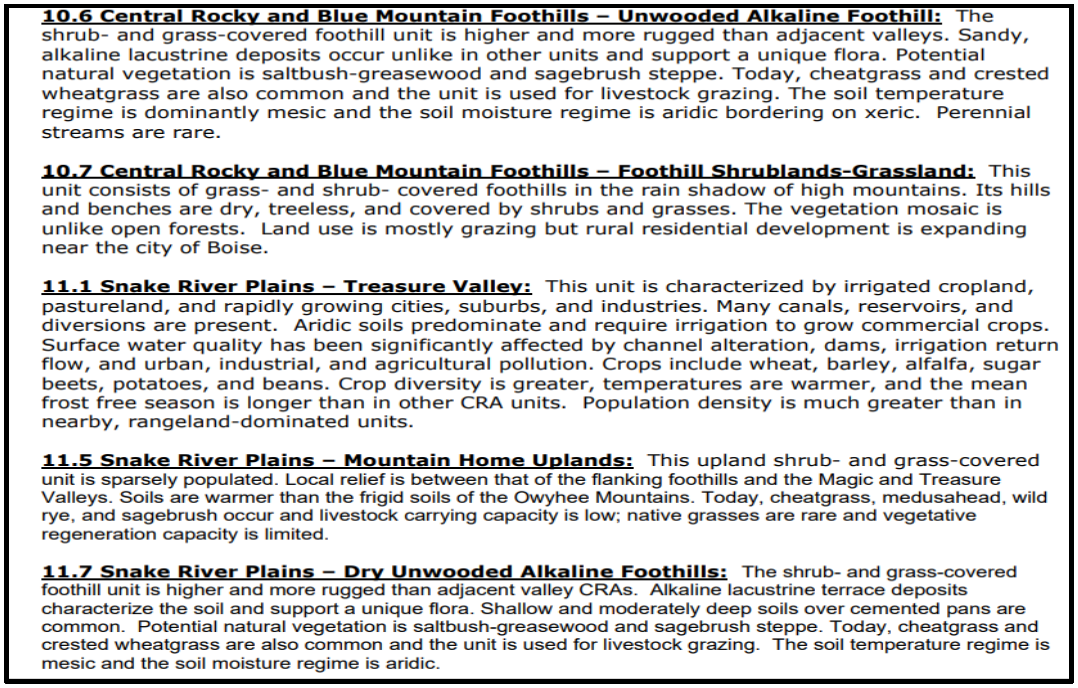


Figure 1.6 Boise River Watershed Resources Concerns CRA. (Should be used in conjunction with Table 2 below) Courtesy of ID NRCS

Table 1.2 Boise River Watershed (Common Resource Areas) CRA Description. Courtesy of ID NRCS



10.6 Central Rocky and Blue Mountain Foothills – Unwooded Alkaline Foothill: The shrub- and grass-covered foothill unit is higher and more rugged than adjacent valleys. Sandy, alkaline lacustrine deposits occur unlike in other units and support a unique flora. Potential natural vegetation is saltbush-greasewood and sagebrush steppe. Today, cheatgrass and crested wheatgrass are also common and the unit is used for livestock grazing. The soil temperature regime is dominantly mesic and the soil moisture regime is aridic bordering on xeric. Perennial streams are rare.

10.7 Central Rocky and Blue Mountain Foothills – Foothill Shrublands-Grassland: This unit consists of grass- and shrub- covered foothills in the rain shadow of high mountains. Its hills and benches are dry, treeless, and covered by shrubs and grasses. The vegetation mosaic is unlike open forests. Land use is mostly grazing but rural residential development is expanding near the city of Boise.

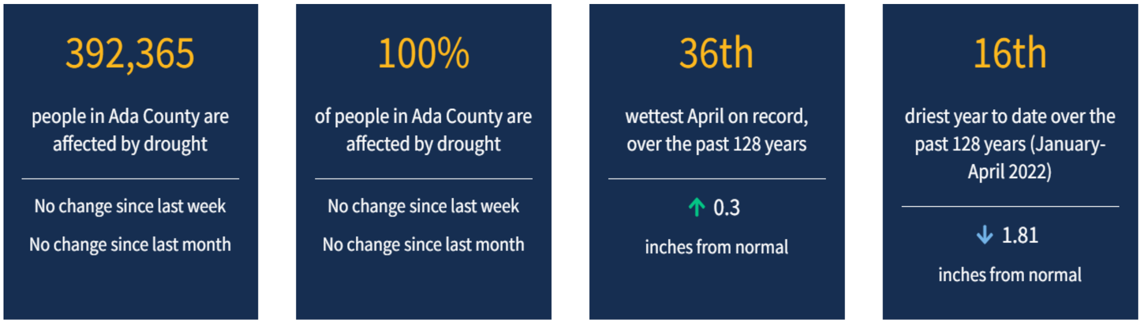
11.1 Snake River Plains – Treasure Valley: This unit is characterized by irrigated cropland, pastureland, and rapidly growing cities, suburbs, and industries. Many canals, reservoirs, and diversions are present. Aridic soils predominate and require irrigation to grow commercial crops. Surface water quality has been significantly affected by channel alteration, dams, irrigation return flow, and urban, industrial, and agricultural pollution. Crops include wheat, barley, alfalfa, sugar beets, potatoes, and beans. Crop diversity is greater, temperatures are warmer, and the mean frost free season is longer than in other CRA units. Population density is much greater than in nearby, rangeland-dominated units.

11.5 Snake River Plains – Mountain Home Uplands: This upland shrub- and grass-covered unit is sparsely populated. Local relief is between that of the flanking foothills and the Magic and Treasure Valleys. Soils are warmer than the frigid soils of the Owyhee Mountains. Today, cheatgrass, medusahead, wild rye, and sagebrush occur and livestock carrying capacity is low; native grasses are rare and vegetative regeneration capacity is limited.

11.7 Snake River Plains – Dry Unwooded Alkaline Foothills: The shrub- and grass-covered foothill unit is higher and more rugged than adjacent valley CRAs. Alkaline lacustrine terrace deposits characterize the soil and support a unique flora. Shallow and moderately deep soils over cemented pans are common. Potential natural vegetation is saltbush-greasewood and sagebrush steppe. Today, cheatgrass and crested wheatgrass are also common and the unit is used for livestock grazing. The soil temperature regime is mesic and the soil moisture regime is aridic.

Important factors for drought in the Boise area include lower than normal precipitation and warm temperatures, which collectively accelerate the release of stored water in the soil into the surrounding air, thus accelerating the drying of soil, and reducing the water available in the soil for plants. The Boise area is in an arid to semiarid set of conditions which accentuates and accelerated drying of soils in the area [2]. In addition, the anthropogenic systems in place are adding extra variables for drought components, both exacerbating and attenuating water shortage, that are difficult to quantify due to the many drivers and contributors. These factors make the study of droughts very important for the preparedness for future droughts. In addition, knowing the many variables from human inputs, hydrological, economic, and social factors, among others, is key to developing strategies to face the challenges of future droughts.

Drought research is very important given it helps scientists and engineers to further understand what causes it, the areas it has occurred in the past, and those areas it is likely to occur in the future, its consequences, and how it can be mitigated. One of the regions where drought has frequently occurred over the last few decades is the western part of the United States, which has also experienced various other disasters, such as wildfires, storms and floods. According to data from the National Center for Environmental Information, the years from 1980 to 1990 had an average of 2.9 drought events per year, and this has been increasing every decade [25]. From 2017 to 2021 alone, the country experienced a total of eight drought events, with a total cost of $742 billion [22]. Since these events in many cases are unpredictable, and even when predictable they are very impactful, mitigation plans have to be conceived in order to prevent excessive damage to communities.



392,365

people in Ada County are affected by drought

No change since last week

No change since last month

100%

of people in Ada County are affected by drought

No change since last week

No change since last month

36th

wettest April on record, over the past 128 years

↑ 0.3

inches from normal

16th

driest year to date over the past 128 years (January-April 2022)

↓ 1.81

inches from normal

Figure 1.7 Ada County Drought Status as of 2022. Courtesy of Drought.gov

Although 2022 has so far been more promising in terms of precipitation and outlook, there continue to be concerns that indicate that the western part of the United States continues to be affected by drought through the year 2022. For example Figure 1.7 shows Ada County which is a big part of the Treasure Valley still affected by drought. The data by U.S. Drought Monitor shows that the western part of the country continues to lack snow-packed areas, and the water availability in such areas is also reduced, which impacts the overall availability of water in the region [32].

Li et al (2017) observes that in the western United States, the areas that once had a lot of snow have seen a reduction in terms of landmass [17]. This implies that the hydrological cycle taking place in these areas has changed and as a result available water diminished, specifically in summer months that demand is highest. It is, therefore, important to point out that as extreme weather conditions continue to be encountered, the cause, which is a complicated “envelope” of variables, should be monitored at detail levels. These variables include temperature variance, snow (specially in the mountainous area), precipitation and reservoir levels.

From the data provided by the Western Region Climate Center, it is evident that the western part of the country continues to experience high temperatures, which are interconnected with the snow levels in the region [11]. Harpold et al (2017) argues that lack of snow, or *snow drought*, has brought difficulties in water management in the western part of the country [11]. During snow drought, the inflows to reservoirs reduce, and they collect much less water, which may not be enough during the summer. With all these trends in climate behavior, research that is specialized in nuanced understanding of the collection of meteorological and climate variables that govern water availability is evermore important and necessary. Therefore, studies like this are important for the preparedness and awareness of locations prone to natural disasters like drought. In mountainous watersheds of the western US, snowpack and dam reservoirs collectively provide a natural-built system of water storage that support water provision to stakeholders during dry summer months. Irrigated agriculture is the largest consumer of water in the western US, and across the globe, that depend on this system of water storage [24]. Farmers decide on how much to cultivate in the spring based on available snowpack and dam storage, but frequency and magnitude of irrigation not only depends on the extent of cultivated land but also on atmospheric moisture or lack thereof during the growing season. In other words, if spring precipitation provides moisture to the cultivated land, farmers would depend less on irrigation and vice versa. This irrigation demand also depends on air temperature. In this thesis, I studied the 2021 drought in the Treasure Valley, Idaho, by considering snowpack, dam storage and spring precipitation.

1.1.1 Snowpack

In the Rocky Mountains of the western US, runoff from winter snowpack provides 60% to 80% of water supply to 70 million people that live downstream [24]. Snowpack is measured in terms of snow water equivalent (SWE) which is a critical variable for the western US given that it determines whether or not there is enough water for the people and ecosystems that critically depend on it. However, due to stochastic weather conditions, and climate change, it is important to note that SWE is fast becoming lower and lower as more precipitation is coming down as rain rather than snow, and snowpack melts earlier due to warming temperatures [23]. This in consequence affects the amount of water deficit for a certain area. This snow drought trickles down to a deficit of water budget each year. It is important to know that SWE is an integral part of the hydrological cycle [26]. It indicates, therefore, that when the SWE is below normal quantities, is missing or simply not available at normal rates, the hydrological cycle would likely experience interruptions. For instance, when the inadequate supply of solid water -as in snow- changes into liquid water, a water shortage would logically be experienced in dry-warm summer months.

Rad et al (2021) argues that when "snow is lacking, this influences the reservoir operation, flood risk management, recreation, navigation, and river ecology" [26]. It is important to note from this reference that snow influences many things, and its unavailability induces various disruptions, from economic to social aspects of life. Harpold et al. (2017) in the article titled *Defining Snow Drought and Why It Matters*, illustrates that snow drought is a serious concern because projections show that lack of it would lead to longer drought periods in the future [11]. The hydrological cycle is the process in which water moves from the land and ocean surface to the atmosphere and back in the form of precipitation [22]. Precipitation amounts are much higher in the mountains compared to the surrounding lowlands, given the orographic effect [22]. Precipitation in the mountains falls mostly as snow, which stores water for the dry summer months in which snow melts and provides water for the dry-hot lower elevations. Earlier melt or lower snowpack levels mean lack of water availability in summer months. It is therefore important to understand that without the solid water (snow), which is a very crucial aspect of this process, water would not only be severely lacking in the future, but drought periods would increase in length, especially compared to current situations and periods [15].

Climate variability also impacts snowpack. Climate variability is the long-term shifts and patterns in climatic conditions. Mazurkiewicz et al. (2011) observed that in areas where snow is not available, there are more severe weather conditions [21]. In such places, dry seasons are typically much drier and experience lower rainfall. The importance of SWE is, therefore, made clear in terms of how it influences not just the hydrological cycle, but also the weather condition that a given area would experience, which is key to understanding how drought creeps in slowly and with signs like low SWE.

1.1.2 Dam Storage

Mediterranean and continental climates, such as those in the western US, are associated with dry summers and wet winters, so there is a temporal mismatch between water availability and demand. Dams enabled humans to store water when it is abundant and use it when natural flow is low but demand is high. Reservoirs are a key item when it comes to storage of water, and at the same time, mitigation of drought, which is a serious problem today. The importance of a dam is evident in many aspects, which include how the water is stored in a reservoir, regulation of the natural flow, ecosystem rearrangement, and supply the demand of downstream stakeholders, among others.

It is, therefore, important to note that a dam can preserve water when it is abundant and release it when the demand is high. But at the same time, dams can make it hard for those who are found downstream to get adequate water when there is competition for water especially in international contentious watersheds [26]. From the study authored by Lopez-Moreno et al (2009), that focused on Portugal and Spain shared reservoirs, it is suggested that reservoirs have reduced the severity and the magnitude of the drought in the upper basin [18]. Reservoirs are used to consolidate water, and ensure areas that have been experiencing drought, no longer experience the same situation. For example from 1940 to 1969, Spain, which is found upstream of the Tagus River, had previously experienced a high frequency of drought, but that pattern changed immediately when the dam was built [18].

The example of the Tagus River demonstrates that dams have been among the ways that droughts can be mitigated and their severity reduced. During the 1943 through 1969 period, droughts were longer and more intense in the upstream (Spanish) sector of the Tagus River than in the downstream sector (Portugal) [18]. In contrast, from 1970 onward and after the construction of the dam, the Portuguese section has experienced more severe droughts than the Spain section, in terms of drought duration and magnitude [18].

For the most part everyone agrees that anthropogenic systems most benefited from the construction of dams; and in the case of drought, reservoirs are key in the preparedness for the future droughts. This research focuses on this last point mainly. Reservoirs make a human built system that aids communities to manage the potential flood risk and maintains a downstream water flow when upstream flows reduce in summer. In the case of the Treasure Valley reservoirs play an important role for the farming community. Reservoirs provide a constant source of water for the Treasure Valley growing season. For this reason farmers will benefit with the research work found in this study which can aid future farming decisions and inform dam storage policies. It is pertinent to add that dams in the Treasure Valley are also helpful in producing energy just like many reservoirs around the world. For this reason reservoirs in the Treasure Valley share many characteristics and uses like many around the world. With this in mind reservoirs are key to every community they serve.

Figure 1.8 A closed irrigation gate on the Boise River. Courtesy T. Oppie

Reservoirs are also important, given that in snow-packed areas like the Treasure Valley, consumers can use reservoirs to harvest water when snow melt generates much more water than farmers need in the spring, which would then be used for various purposes in dry summer months. Farming in the Boise area began around the 1860s and the Reclamation Act of 1902 gave way for many farmers to own water rights which in turn led to the construction of reservoirs like Arrow Rock Reservoir, which initially was aimed primarily to serve irrigation water storage needs. This action led to the exponential growth of the Treasure Valley. As more water was needed, more reservoirs and Anderson Ranch reservoir and Lucky Peak reservoirs were built [7].

Figure 1.9 depicts the 2021 water year reservoir levels for Lucky Peak Dam and how that compares to the normal range. The year 2021 features a below 30 year normal at 733 KAF. The year 2021 had an overall storage deficit compared to long term normal with values around 650 to 750 KAF.

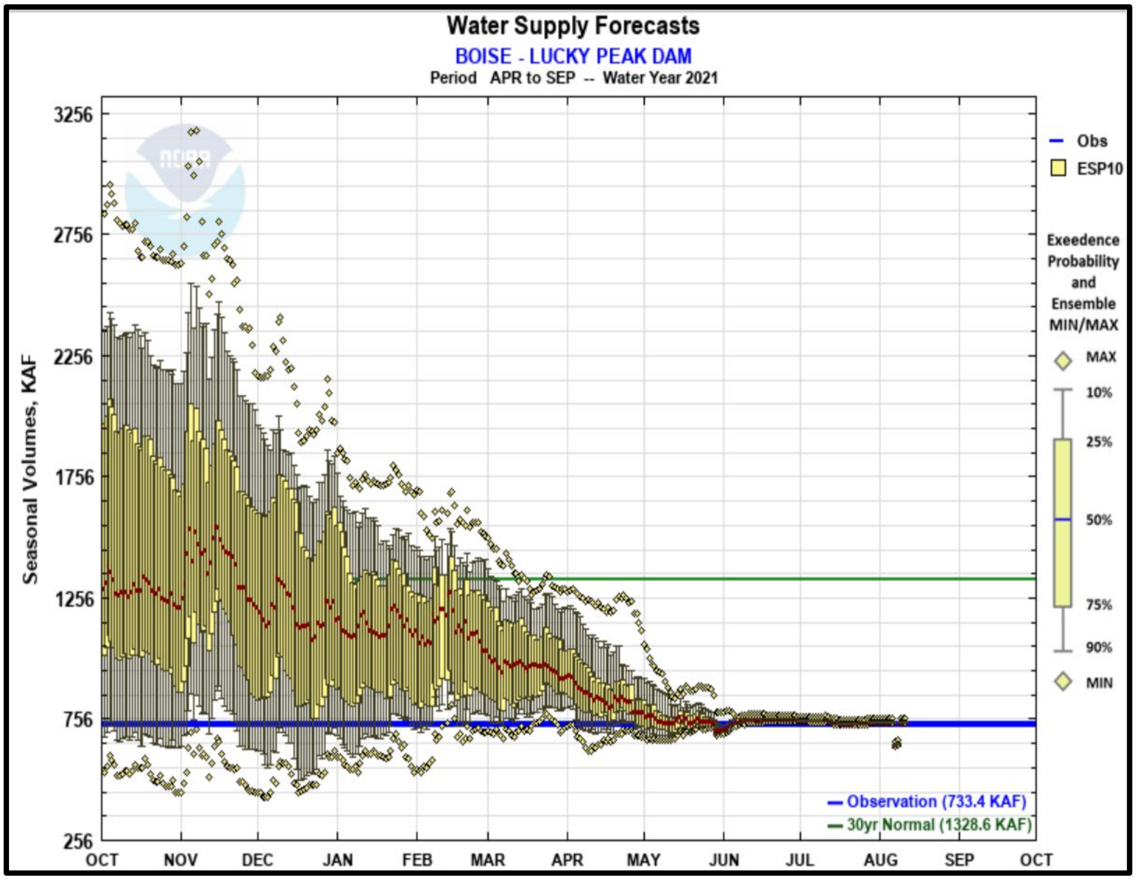


Figure 1.9 Lucky Peak Dam 2021 water year. Courtesy NCRS

1.1.3 Precipitation

Due to the variability of weather prediction, droughts, like the one experienced in Boise in 2021, are difficult to predict, mainly due to the stochastic weather behavior that has changed dramatically in the past century. Many rain events are more intense and, in some cases, can cause significant damage to the crops to the point of killing the entire product [14].

Rainfall has on one hand increased its intensity, but on the other hand, has experienced longer periods between rainfall events [14]. Based on these facts, farmers must make important decisions to maximize their crop productions. Some crops require a longer growing season and more water to mature, some crops require less. Since nowadays weather is more unpredictable, many farmers do not want to risk their crops and sometimes even skip growing seasons altogether. Some farmers may choose to just grow smaller amounts and, consequently, don’t maximize their production. Many of them lose their crop production for the year, setting themselves up for possible economic disasters in the future.

Drylands, like this area near Boise, are in a specific category where rainfall usually falls in a heterogeneous pattern [14]. In the study titled *Consequences of Dryland Maize Planting Decisions Under Increased Seasonal Rainfall Variability* by Krell et al., the authors argue that there is a need to cultivate specific crops of interest for areas that receive highly variable rainfall to maximize food stability [14]. There are many efforts to understand the issue, but unfortunately many have linked the stochastic rainfall dynamics to the probability of crop failure, rather than aiming to find a solution.

The National Weather Service issued the following statement in May 2021 regarding Boise's drought conditions:

“Below normal spring precipitation and the early loss of snowpack have led to expanding drought conditions across Idaho. The latest seasonal drought outlook (May 20, 2021-August 31, 2021) indicates that drought will persist in areas already being impacted by drought, and drought development is likely across the rest of Idaho [30].”

Regarding the lack of precipitation in 2021, John Roldan, Boise’s strategic water manager had this to say, “We are taking this very seriously and we are starting to do some long-term planning to address these concerns" [30]. Along with most of Idaho, Boise is feeling the effects of the dryness. Most of Ada County was considered abnormally dry while the rest of the state was in a moderate drought. "We are in the desert, droughts are normal," Roldan said. "They happen. It's a cyclical process but with climate change, we are seeing this happen more frequently and it's projected to be in drought conditions for longer periods of time" [30].

Roldan said people can expect to see local ordinances regarding water conservation if Boise experiences another drought year. "We are reviewing our ordinances right now and looking at ways to have smarter development if you are in an area that doesn't have surface water supply from an irrigation district," he explained. "We also have irrigation districts and canal companies that provide residents with surface irrigation water, and we encourage that to be used whenever possible and preserve our groundwater for droughts like this." According to Roldan, 70% of Boise's water comes from underground and 30% comes from the Boise River. In Meridian, the single source is groundwater. While the city is producing water at a sustainable rate, Meridian's Public Information Officer, Stephany Galbreaith, said increased demand, drought conditions, or changes in the water supply could create possible shortages [31].

Due to the stochasticity of natural systems, precipitation is one of the hardest meteorological variables to predict specifically with month to annual lead times. In addition, the amount of precipitation the Treasure Valley has observed has increased in intensity, but the dry period between rainfall events has been increasing which makes it even more important to understand how drought starts and evolves. Precipitation is the most important source of water in the environment and is a key element of the hydrological cycle. Precipitation in the northwest of the United States is important for the replenishment of the natural aquifers and river streams. The Treasure Valley, due to its location, presents some challenges when getting a large amount of precipitation. One of the reasons is that Treasure Valley is surrounded by mountains that capture the moisture originated from the Pacific Ocean [34].

Precipitation in the Treasure Valley typically ranges between 11 and 12 inches annually, and its data collection is important for the assessment of drought severity [19]. However, in some years, this average falls dramatically, consequently paving the way for an early stage of drought [19]. Precipitation in this area was falling below normal during the spring season and was not replenished for the remainder of the year to the typical average. As seen in Figure 1.9 below, average precipitation received in Ada County varies considerably each year.

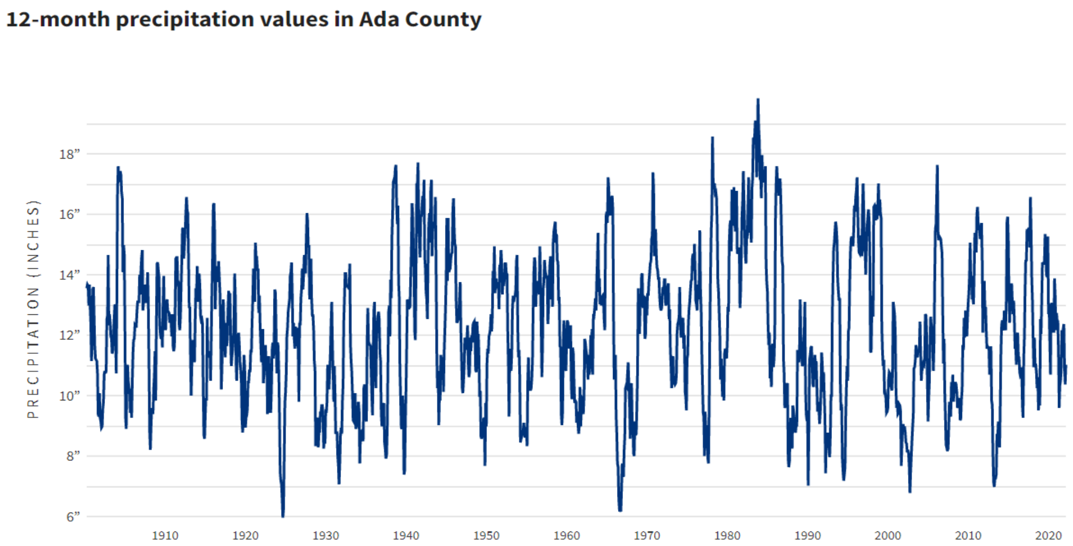


Figure 1.10 **Average Precipitation for Ada County (May 1900 - April 2022)**

1.2 Natural-Built Systems

Natural-built systems include all the elements of the system that work in conjunction to worsen or attenuate drought, including natural aspects like snowpack, precipitation and the human-built components including dams, which are constructed to help mitigate drought. Perhaps one of the most important human built systems is the reservoir. Reservoirs allow human civilizations to grow exponentially. For example, during droughts, some of the stored water is released to maintain ecological flow as well as to meet basic water requirements. However, in some cases, having this false sense that “everything is ok”, allows for bigger disasters. One example of this effect is the Levee effect that can be seen in the case of Hurricane Katrina. Frequent, small flooding events went unnoticed for many years, and only the most extreme one – Hurricane Katrina -- was able to cause immense damage to the city of New Orleans. People seemed to have forgotten about flooding in the area due to being used to the levees protecting them, but when the levee system failed the adverse impact was exponentially larger. For these reasons dams need a comprehensive understanding of their pros and cons when it comes to drought and flooding.

Some pros, for instance, are provided in the study by Lee et al (2009) that argued that dams help in reducing floods, especially in the anthropocene when changing climate conditions have caused floods in various parts of the world [16]. During flooding, dams would help accumulate the excess water that would be used during the time when drought comes. In snow packed areas, floods may also occur, and arguably the best way to deal with this is by constructing dams, which collect water, so that it can be used during dry seasons. Barnett et al. (2005), in the article titled *Potential impacts of a warming climate on water availability in snow-dominated regions*, argued that the warmer climate reduces water availability as this reduces the availability of snow [3]. In such areas, the best thing that can be done is to ensure that dams are constructed since this would not only help in collecting water, but also in preventing any economic and social challenges that may be faced due to lack of water.

Research findings have shown that dam storage is helpful in food production processes in various parts of the world. The study by Ganguly and Cahill (2020) argues that close to 95% of disasters in the world today are related to either availability of water, or lack of it [10]. When there is a severe lack of water, disasters such as drought would occur, and when there is more than what is needed, events such as floods would occur. This clearly demonstrates how important it is to have the built environment, which can regulate water by making sure that when it is available in plenty, it is stored for the period when it would not be available.

Sudden, large amounts of precipitation can lead to flooding, but by having dams, downstream communities can lower the possibility of disasters like floods. According to Ganguly and Cahill (2020), “in the period from 1995 to 2015, floods impacted 2.3 billion people world-wide, killed 157,000, and resulted in US $662 billion in damage, while the corresponding figures for droughts were 1.1 billion, 22,000 and US $100 billion” [10]. This is a huge impact, which can be controlled. Dams can be used as crucial cornerstones to help promote quality living by making sure that humanity does not experience flooding or lack water.

Both natural storages of water (precipitation, snowpack) and bult storages (dams), have a very significant combined role to play in the coexistence with humanity. Without either of the two, people would suffer, which is an indication that society needs to leverage both natural and built storages to avoid drought and flooding consequences, especially as ever-increasing changes in climate bring more severe impacts. Natural-built systems should be managed in conjunction to make sure that the weather conditions do not severely affect humanity.

1.3 Drought Categories and Indexes

Drought is often described as a temporary situation, when the water demand of a hydrological system, which may be an ecosystem or an anthropogenic system, exceeds the water availability [22]. Differences in hydrological, meteorological, and socio-economic variables, as well as the stochastic nature of water demands in specific regions around the world, have become an obstacle to having a unified and precise definition of drought. Thus, when defining droughts, it is important to distinguish between conceptual and operational definitions.

Conceptual definitions are those stated in relative terms. For example, a conceptual definition could be something like, “drought is a long, dry period”. Whereas, operational definitions attempt to identify the onset, severity, and termination of drought periods. Generally, operationally defined droughts can be used to analyze drought frequency, severity, and duration for a given return period. It is pertinent, then, to learn the classifications of drought.

Meteorological drought is defined as a lack of precipitation, over a region, for a period of time. Cumulative precipitation data is commonly used for meteorological drought analysis. Hydrological drought refers to water storages and fluxes falling below long-term averages. Note that hydrological drought is not merely controlled by precipitation and geology is also one of the factors influencing hydrological drought. Agricultural drought usually refers to a period with lower than normal soil moisture that can cause crop failure. Several drought indices, which are based on a combination of precipitation, temperature, and soil moisture, have also been derived to study agricultural drought. Socioeconomic drought is associated with the failure of water resource systems to meet water demands, and thus, associating droughts with supply and demand [30].

Frequency, severity and duration of droughts are being impacted by human activities. Things like production of greenhouse gasses, fertilizers, water pollution, deforestation, and over-drilling of our aquifers, lead to a deficit, and lack of replenishing of natural goods [22]. These amount to the different components of drought (climatic, environmental, agricultural, etc). The hydrological component might be the most important factor in arid and semi-arid regions, given the high dependency of many activities, like food production, economy, hydropower generation, and urban supply, among others.

To more effectively understand droughts, many indices have become popular, many of which have been derived in recent decades. A *drought index* is a prime variable for assessing the effect of a drought. Drought parameters that are incorporated in these indices include intensity, duration, severity, and spatial extent. It could be argued that the *monthly time scale* is the most appropriate for monitoring the effects of a drought in situations related to agriculture water supply and groundwater abstractions [14]. Some of the most common drought indices are Standardized Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), Rainfall Abnormality Index (RAI), Keetch–Byram Drought Index (KBDI), and Crop Moisture Index (CMI).

These indices have been widely used all over the world, and in the case of Boise, Idaho, some of these are key to determining Boise's top climate hazards. In the following figure, we can see the drought severity for the week of August 17, 2021 based on the operational drought categories of the US Drought Monitor for the contiguous US [32].

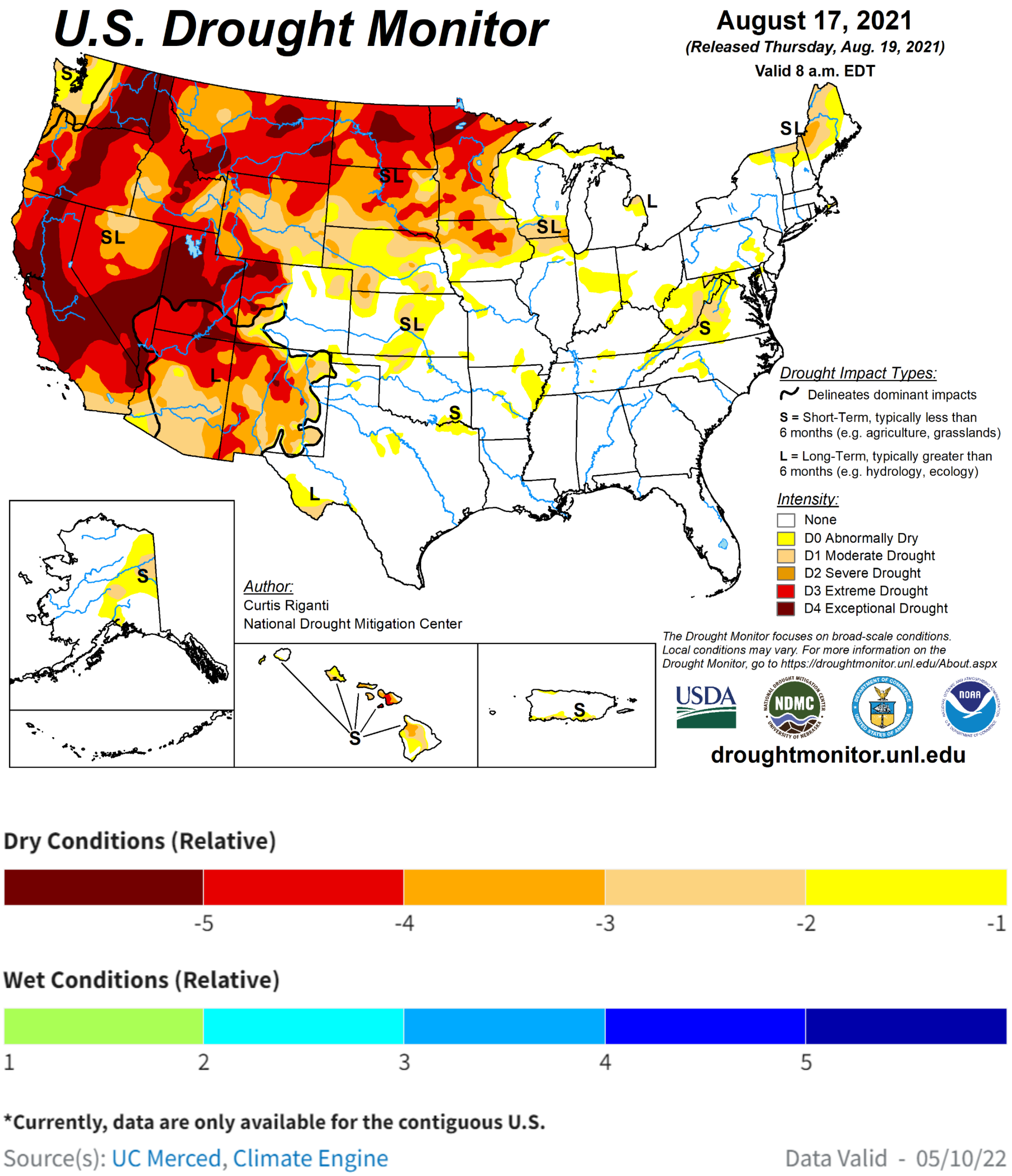


Figure 1.11 1Example of Drought Severity based on the US Drought Monitor

CHAPTER TWO: BOISE DROUGHT 2021 ANALYSIS

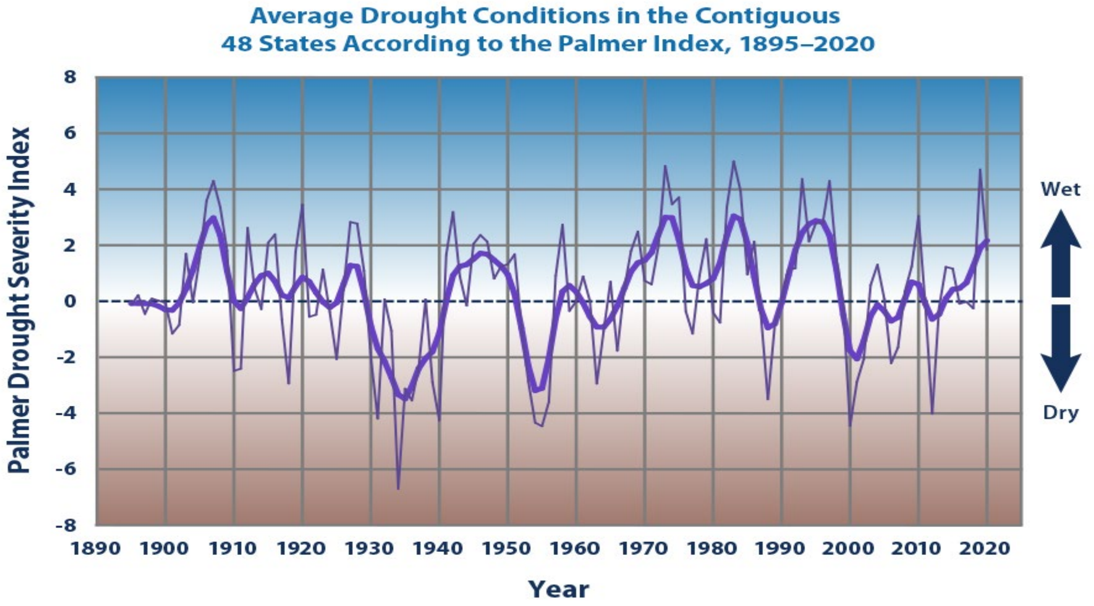
2.1 Introduction

This chapter focuses on multivariate analysis of the 2021 Boise drought in the context of human and natural systems. To that end, this section analyzes the collected data from the Boise River watershed, and discusses the impacts in the Treasure Valley, Idaho, that directly depends on the Boise River as its main water source. Specifically, this section discusses the three main variables that govern drought onset, evolution, and termination in mountainous watersheds, such as the Boise River watershed, in the context of natural-human systems, namely precipitation, snow storage and dam storage. Importantly, this section analyzes historical time series of each of these variables, and views each variable individually in the historical context, and also assesses them in multivariate (bi- and tri-variate) contexts. This analysis helps shed light on the main driver of the 2021 drought in the Treasure Valley, Idaho, and can inform future drought mitigation plans. Finally, this chapter provides a ranger of future projections of climatic variables, specifically precipitation, to describe expected future drought conditions.

2.2 Drought in the US

Drought is a natural phenomenon and is not only constrained to a certain region, like the Treasure Valley. Even the wettest places of the Earth, such as the Amazon Rainforest, also observe episodic periods of drought, which facilitate other extremes such as the recent years' extreme wildfires in the Amazon [30]. The same applies to the United States of America, which possesses a wide range of climates, from cold and wet in Alaska, to dry and hot in southern California, and humid and hot in Florida. The US expectedly can oscillate between wet to dry conditions. Figure 2.1 shows an average Palmer Drought Severity Index (PDSI) in the continental US (lower 48 states; aka CONUS), attesting to this oscillation (22). PDSI is a measure of water balance, incorporating the impacts of precipitation and temperature on potential water availability. Note that Figure 2.1 presents average PDSI for the entire CONUS, and while the average CONUS' PDSI can point to being wet (positive values), specific places can be dry (negative PDSI).

Figure 2.1 shows that PDSI values fluctuate between "wet years" (in the mid 1980s and 1990s) and "dry years" (from approximately 1930 to 1940) (25). This type of information helps to analyze drought impacts, and prepare for the cascading disasters that follow drought, such as rather short-term impacts being manifested in wildfires, mid-term impacts such as food insecurity, and long-term impacts such as vegetation type conversions (e.g., from forest to shrublands). Various regional, state, federal and international agencies collect observed meteorological variables that are needed for drought analysis and prediction. In the US, the National Oceanic and Atmospheric Administration (NOAA) is in charge of observing detailed hourly, daily, monthly, and yearly meteorological data (e.g., precipitation and temperature) that can easily be accessed. NOAA also provides a variety of meteorological forecasts, ranging from short-term (1-14 days), subseasonal (monthly), to seasonal (season to year) scales [25].



Data source: NOAA (National Oceanic and Atmospheric Administration). 2021. Climate at a glance. Accessed March 2021. www.ncdc.noaa.gov/cag.

For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climate-indicators.

Figure 2.1 USA Land Drought Averages

2.3 Drought in the Boise River Watershed: Data Collection

For the purpose of this research climatic data was downloaded from www.climateengine.com from the years 1982 to 2021, daily snow water equivalent (SWE) data was downloaded from the Natural Resource Conservation Service of the US Department of Agriculture for the SNOTEL sites in the Boise River Basin, and daily dam storage data for Arrowrock, Anderson Ranch, and Lucky Peak dams was acquired from the US Bureau of Reclamation [4]. It is noteworthy that ClimateEngine is a wrapper for a variety of data sources, such as PRISM, which can be used to subset (both spatially and temporally) the data from the original source for final usage. Here, I extracted monthly precipitation data from PRISM through ClimateEngine [6]. Also I used April 1st dam storage and SWE as built and natural water storage, respectively, in the watershed, and used April-May-June precipitation as atmospheric storage (natural). All these storage compartments determine water availability for the stakeholders (e.g. farmers) in each year. Note that farmers use dam storage and snow storage in spring to make decisions for the extent of cultivated land in each year, while spring precipitation is yet not certain at the time of this decision. This information was analyzed with software like Excel and MATLAB to perform the univariate and trivariate probability analyses.

The study period of 1982-2021 (40 years) was selected as the common timeline during which data for all variables were available. While the precipitation and dam storage data were relatively clean and straightforward to work with, the SWE data needed some preprocessing. In some cases, SWE values for April 1st were not available, in which case, I linearly interpolated between the preceding and succeeding days to derive April 1st SWE. Note that I selected the SNOTEL sites used in this study based on their long-term data availability.

2.4. Drought in the Boise River Watershed: Methods

Many studies in the past have come to a conclusion that a single drought index is not the most effective way to describe or determine all the related aspects of droughts. Different aspects should be considered in order to extend drought indicators to provide a more comprehensive assessment of this natural hazard, such as the moisture of the soil, the precipitation, snow water equivalent, and water storage level. For the purpose of this paper, I considered the precipitation, SWE, and the available dam storage in the three dams that feed into the Boise River, from the Anderson Ranch, Arrowrock, and Lucky Peak dams.

This research mostly focused on the probabilities and the exceedance probabilities of three factors of interest, and their joint behavior. These factors are the precipitation the

Boise River watershed received, the available SWE within the Boise River watershed, and the available water stored in the three dams in the Boise River watershed.

The total water storage of the three dams on April 1st of every year during the period of analysis was collected from the Bureau of Reclamation website [4]. SNOTEL data was used for the SWE time series data across the Boise River watershed for the period of analysis and was collected from the Natural Resources Conservation Service National Water and Climate Center website [24]. Additionally, the total precipitation data for the Boise River watershed was collected for the months of April, May and June during the period of analysis. PRISM daily precipitation data was collected from the Climate Engine website [6].

April 1st was chosen as the date for data collection for both dam storage and SWE because it was deemed that data from this date would be a representative measure of the available SWE and dam storage that was left over from the previous year in addition to what was collected and accumulated during the winter and early spring months. The precipitation data was collected for the months of April, May, and June and then aggregated to provide a total value of the spring precipitation for the Boise River watershed. These three values were used to run a frequency analysis in order to find the joint probability of a drought occurring which in turn was used to calculate the exceedance probability of the drought event and ultimately calculate the return period of the drought experienced in 2021 by the Boise River watershed.

All of the analyses were implemented using Microsoft Excel and MATLAB software. The precipitation, Pr, snow water equivalent, SWE and available dam storage, S, are the three intercorrelated drought characteristics that were used in the multivariate probability distribution calculations which merge these random variables into a joint probability distribution, X. The univariate ranks (worst is ranked 1) and probabilities ($P(SWE \leq swe)$, $P(Pr \leq pr)$, $P(S \leq s)$) are first calculated based on the historical values and then compared to the joint probability, $X = P(SWE \leq swe, Pr \leq pr, S \leq s)$.

A high occurrence probability in the case of these three variables is associated with a common value which indicates a low probability of that variable contributing to the likelihood of a drought. A high exceedance probability, however, indicates a rare event which, in this case, is associated with a higher likelihood of a drought occurring. For the purpose of this study we considered a low occurrence probability or high exceedance probability in the joint probability distribution to be an indication of drought occurrence.

The return period of the drought was then calculated using Equation 1:

$$T=1/P \qquad (1)$$

where T is the return period and P is the occurrence probability. In case of univariate drought, P refers to the probability of each variable (e.g., $P(SWE \leq swe)$, $P(Pr \leq pr)$ and $P(S \leq s)$). In bivariate case, this probability is defined as $P(SWE \leq swe \wedge Pr \leq pr)$, $P(SWE \leq swe \wedge S \leq s)$, $P(Pr \leq pr \wedge S \leq s)$. In a trivariate case, probability is defined as $P(SWE \leq swe \wedge Pr \leq pr \wedge S \leq s)$. Note that we use probability in this study to calculate return period level, as opposed to the traditional use of exceedance probability to calculate return period level of floods. This is because a worse flood is the one with higher value, and exceedance probability refers to a phenomenon that is worse than what was observed. In case of drought, it is the other way around, meaning that a lower precipitation, for example, refers to a worse drought.

2.5 Drought in the Boise River Watershed: Results

Cumulative SWE data for April 1st for the Boise River watershed can be seen in Figure 2.2, below. This figure enables assessing the 2021 SWE storage on April 1st in the context of historical snow storage. Snow water equivalent (SWE) data was used as a measure of the spring snow storage in the Boise River watershed and SWE measurements on April 1 were used as a representative value of the available spring snowpack. SNOTEL SWE data was collected from the Natural Resources Conservation Service National Water and Climate Center website for April 1 for the period of 1982-2021 for seven sites within the Boise River watershed [6, 24]. These seven SNOTEL stations and their characteristics were enlisted in Table 2.1. The SWE data for the seven stations used were added together to get a cumulative SWE value for each year in the analysis period. As shown in Figure

2.2, the 2021 spring SWE storage was at more than 30th percentile of the long-term record, making this year a rather normal year in terms of snow storage, although being below average. The shaded red band shows the region that falls below the spring SWE value of 2021, which expectedly includes many years such as 2005, 2010 and 2015.

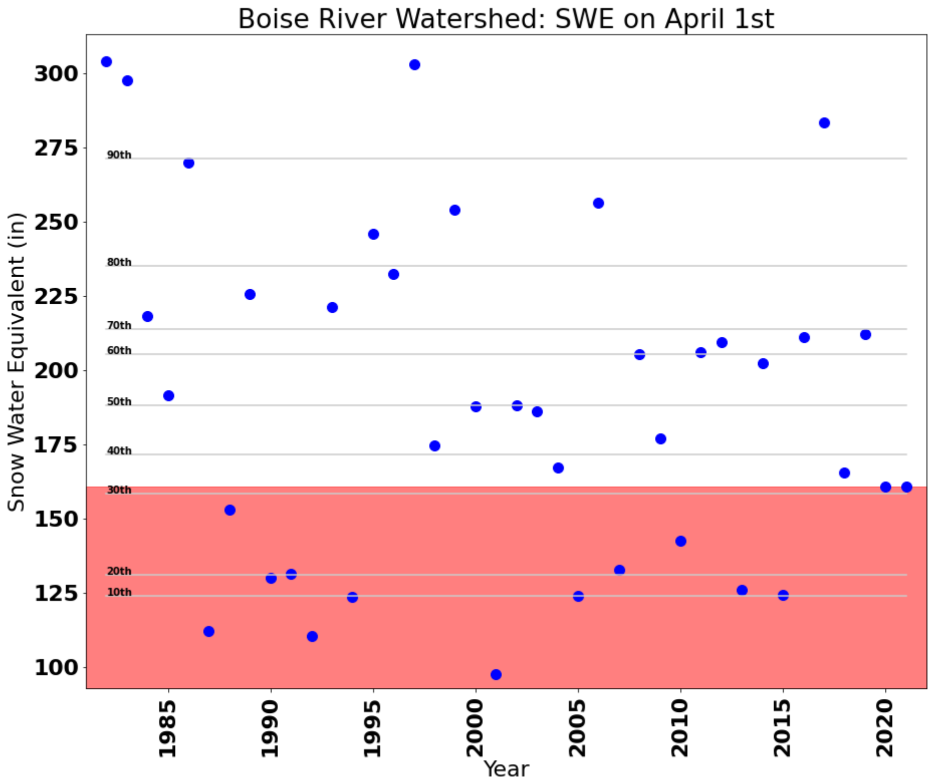


Figure 2.2 Annual April 1st Values of Cumulative Snow Water Equivalent (SWE) at Seven SNOTEL Sites in the Boise River Watershed

Table 2.1 Seven SNOTEL Stations Used for SWE Analysis in this study and Their Characteristics

SNOTEL SITE	STATE	SITE #	COUNTY	ELEVATION (Ft)	REPORTING SINCE
Atlanta Summit	ID	306	Elmore	7550	1978-10-01
Dollarhide Summit	ID	450	Blaine	8420	1979-10-01
Graham Guard Sta.	ID	496	Elmore	5690	1978-10-01
Jackson Peak	ID	550	Boise	7070	1979-10-01
Mores Creek Summit	ID	637	Boise	6100	1978-09-30
Trinity Mtn.	ID	830	Elmore	7770	1978-10-01
Vienna Mine	ID	845	Blaine	8960	1978-10-01

Figure 2.3 shows the SWE characteristics at Atlanta Summit SNOTEL station. The 2021 SWE values are below the median in this station which is represented by the green line for this site station. Similar information for Dollarhide Summit Station, Graham Guard Station, Jackson Peak Station, Mores Creek Summit Station, Trinity Mountain Station, and Vienna Mine Station are shown in Figures 2.4 to 2.9.

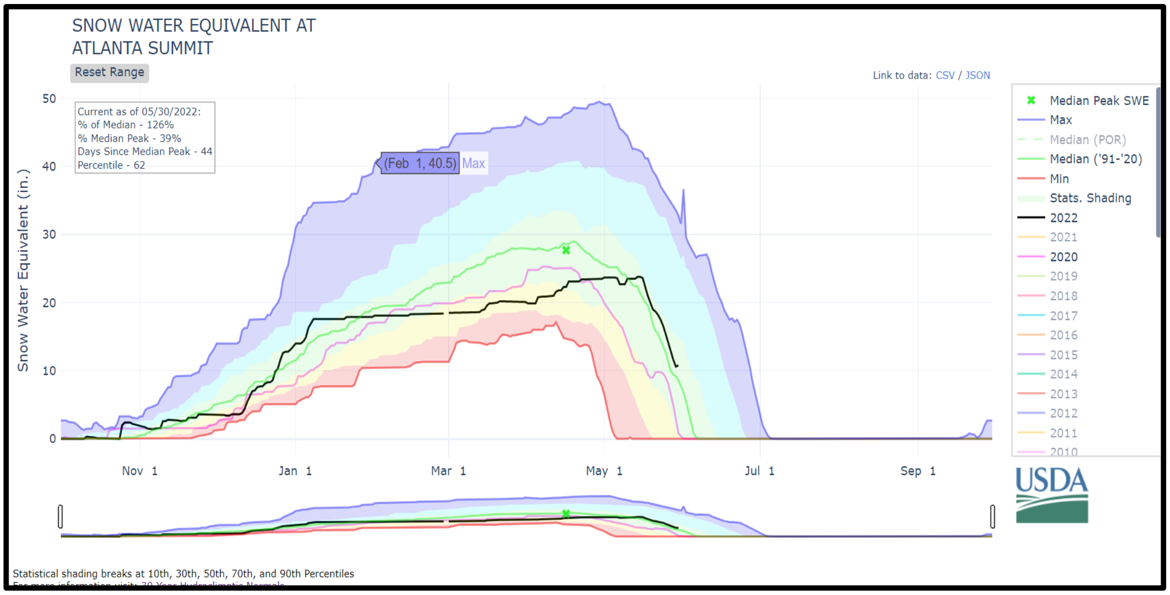


Figure 2.3 Atlanta Summit SNOTEL Station; Max, Median and Min. 2010 to 2022

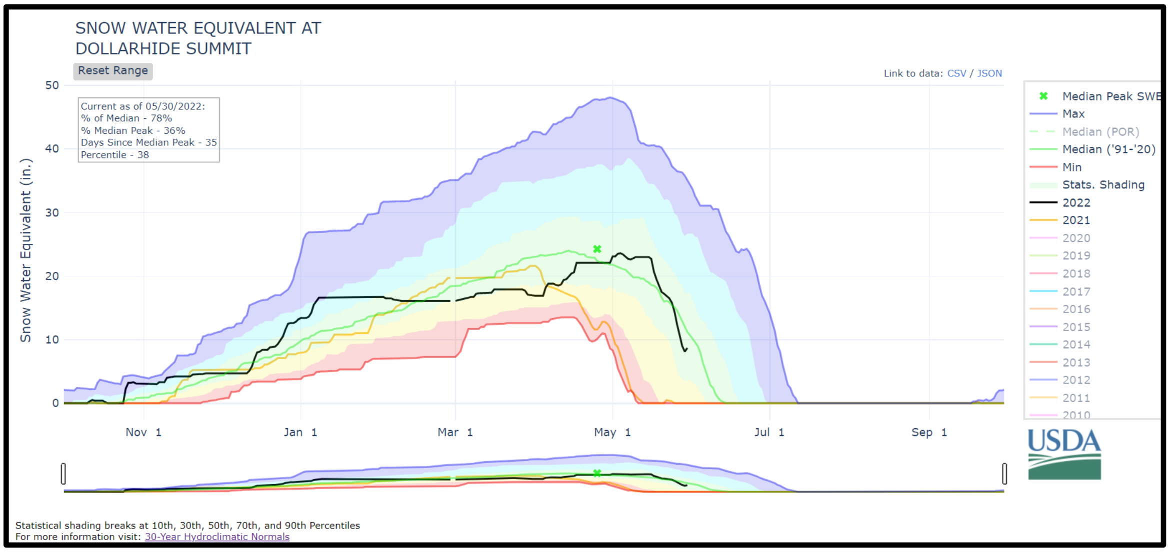


Figure 2.4 Dollarhide Summit SNOTEL Station: Max, Median and Min. 2010 to 2022

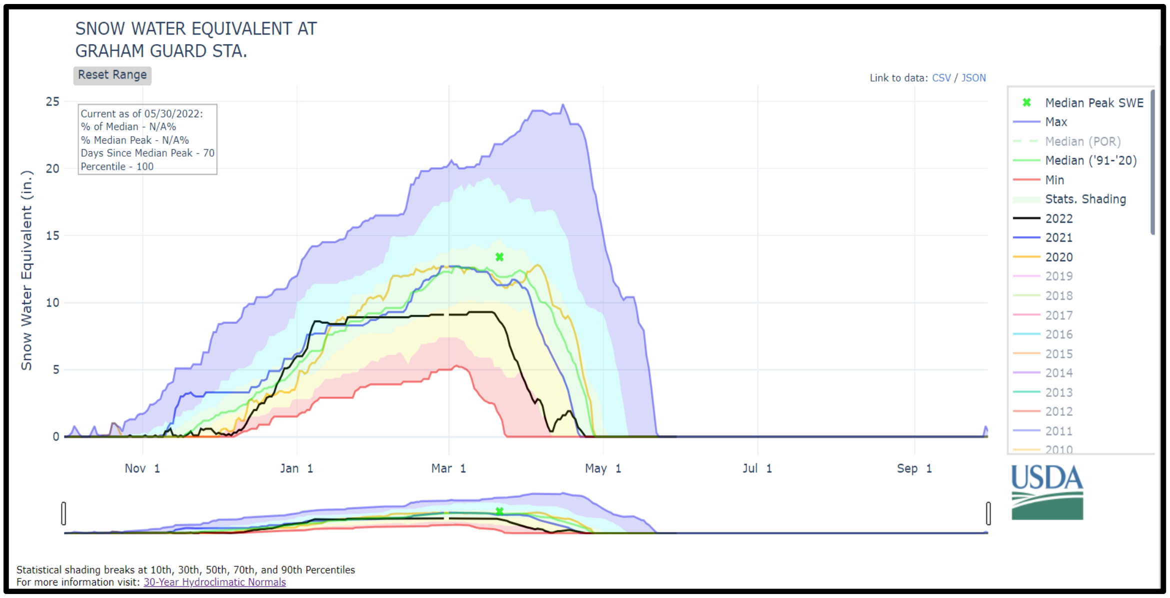


Figure 2.5 Graham Guard SNOTEL Station: Max, Median and Min. 2010 to 2022

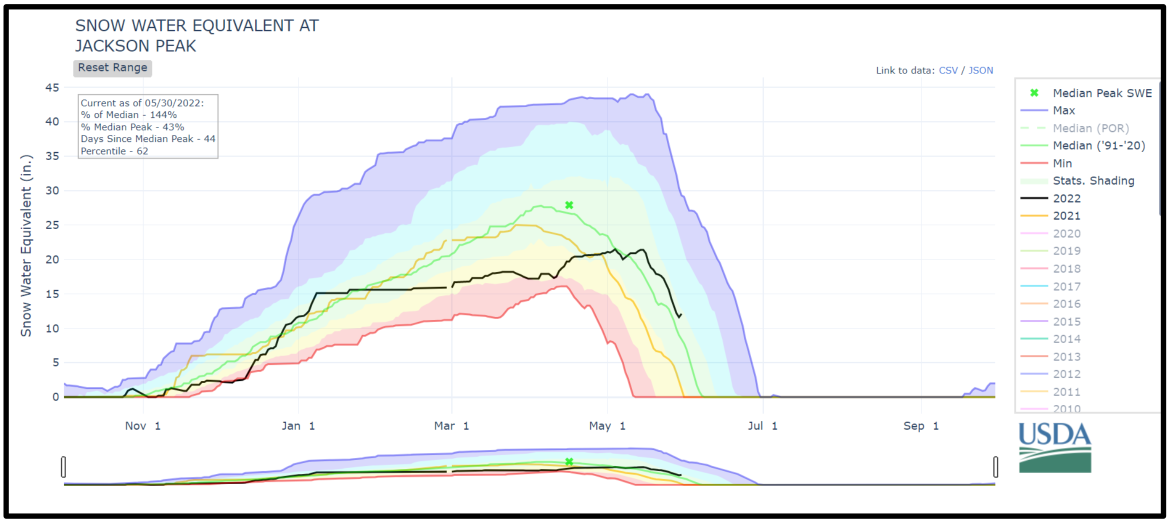
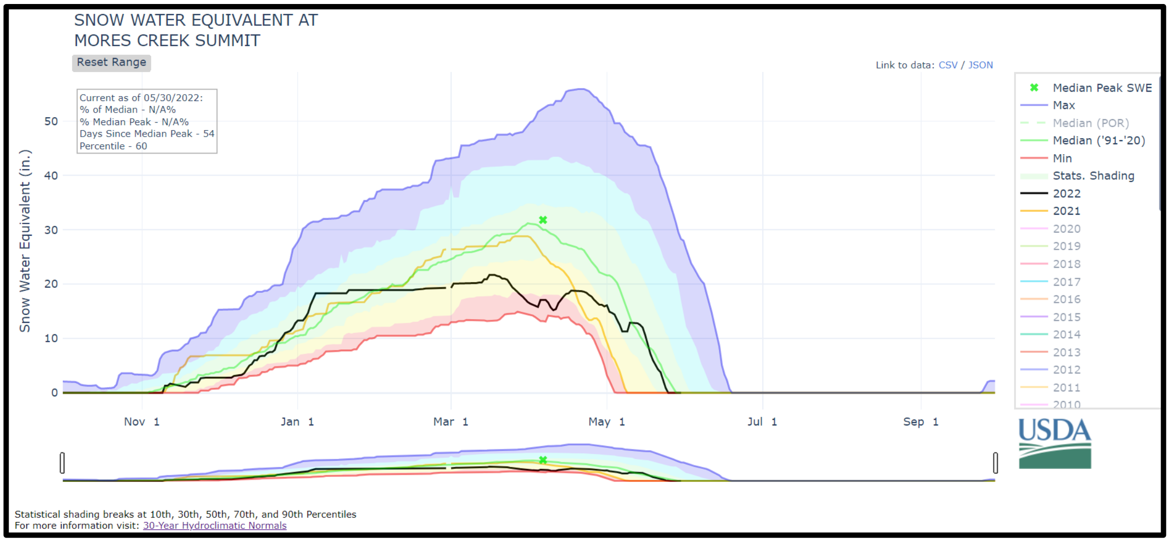


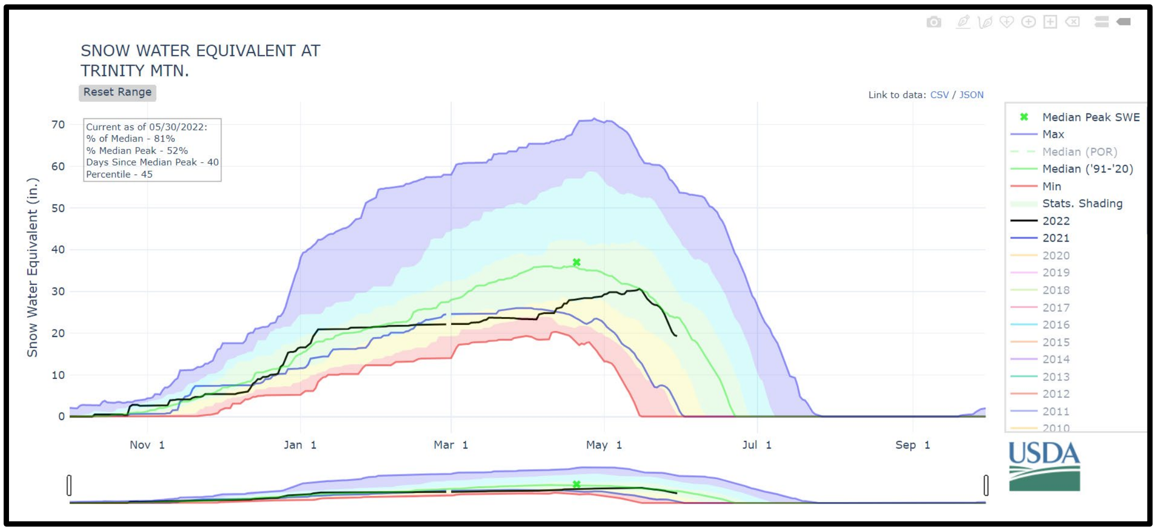
Figure 2.6 Jackson Peak SNOTEL Station: Max, Median and Min. 2010 to 2022



Current as of 05/30/2022:
% of Median - N/A%
% Median Peak - N/A%
Days Since Median Peak - 54
Percentile - 60

Statistical shading breaks at 10th, 30th, 50th, 70th, and 90th Percentiles
For more information visit: 30-Year Hydroclimatic Normals

Figure 2.7 Mores Creek Summit SNOTEL Station: Max, Median and Min. 2010 to 2022



Current as of 05/30/2022:
% of Median - 81%
% Median Peak - 52%
Days Since Median Peak - 40
Percentile - 45

Figure 2.8 Trinity Mtn. SNOTEL Station: Max, Median and Min. 2010 to 2022

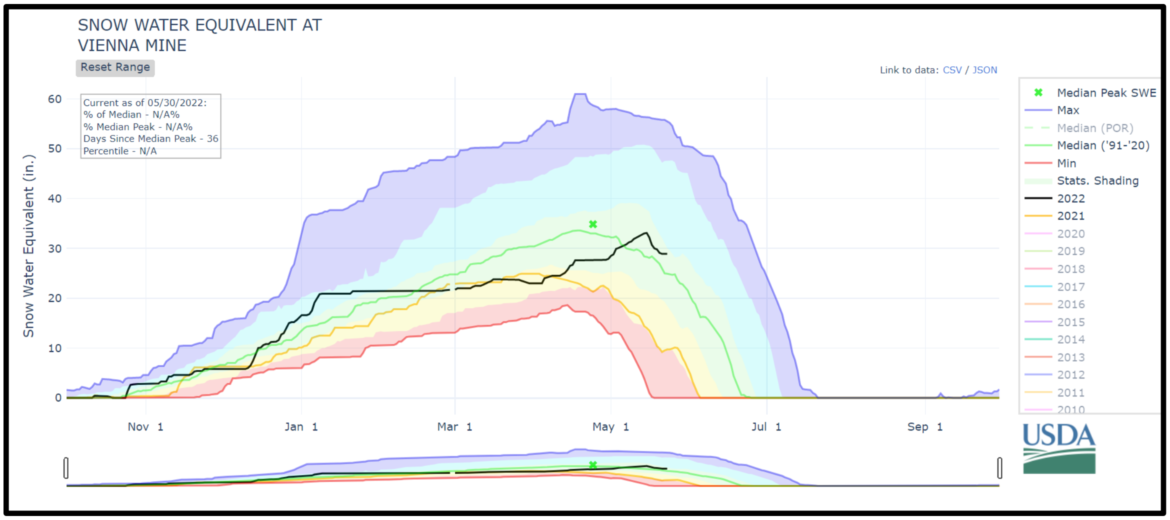


Figure 2.9 Vienna Mine SNOTEL Station; Max, Median and Min. 2010 to 2022

As supplemental information to understand how SNOTEL stations collect data, Figure 2.10 shows the Graham Guard SNOTEL station, which includes a ground truth marker, wind sensor, temperature sensor, snow depth sensor, solar radiation sensor, snow pillow, radio antena, equipment shelter that includes a data logger, and precipitation gauge. Furthermore, and as supplemental information, Figure 2.11 shows historical maximum SWE from 1980 to 2020.

Figure 2.10 Photo of Graham Guard SNOTEL Station. Courtesy of USDA

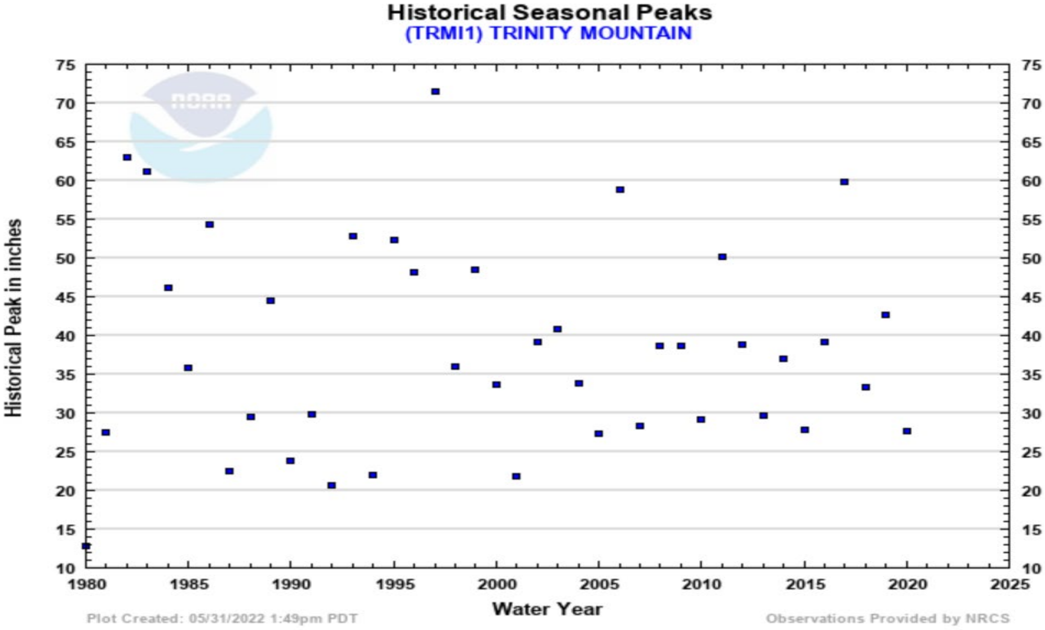


Figure 2.11 Historical Season SWE Peaks for Trinity Mountain Station 1980-2022

Figure 2.12 illustrates historical dam storage values in the Boise area, collected on the first day of April in each year. Storage values from all three dams that feed into the Boise River come from Arrowrock Dam, Anderson Ranch Dam, and Lucky Peak Dam. The colored band represents values within the 60th percentile occurrence probability, including values for the focus value for the 2021 reservoir storage of the Boise River watershed. All of the dots represent each year's reservoir storage levels. The values for the three dams were used to determine the cumulative available water storage for the Boise River watershed from 1982 to 2021, and were collected from the Bureau of Reclamation website [4]. The 2021 storage value was 606,167.92 acre-ft which corresponds to an occurrence probability of 61%, or a 39% exceedance probability. These values are not the lowest in the period from 1982 to 2021. These values are in some way indicative of the reservoir storage values, but are not as low as drought predictions might initially suggest. With such a high occurrence probability, it is unlikely that dam storage was solely the main contributing factor of the 2021 drought. The values of reservoir storage for the Boise River watershed in the period of 1995 to 2000 were below 300,000 acre-ft, which, for the period of 1982 to 2021, were the lowest.

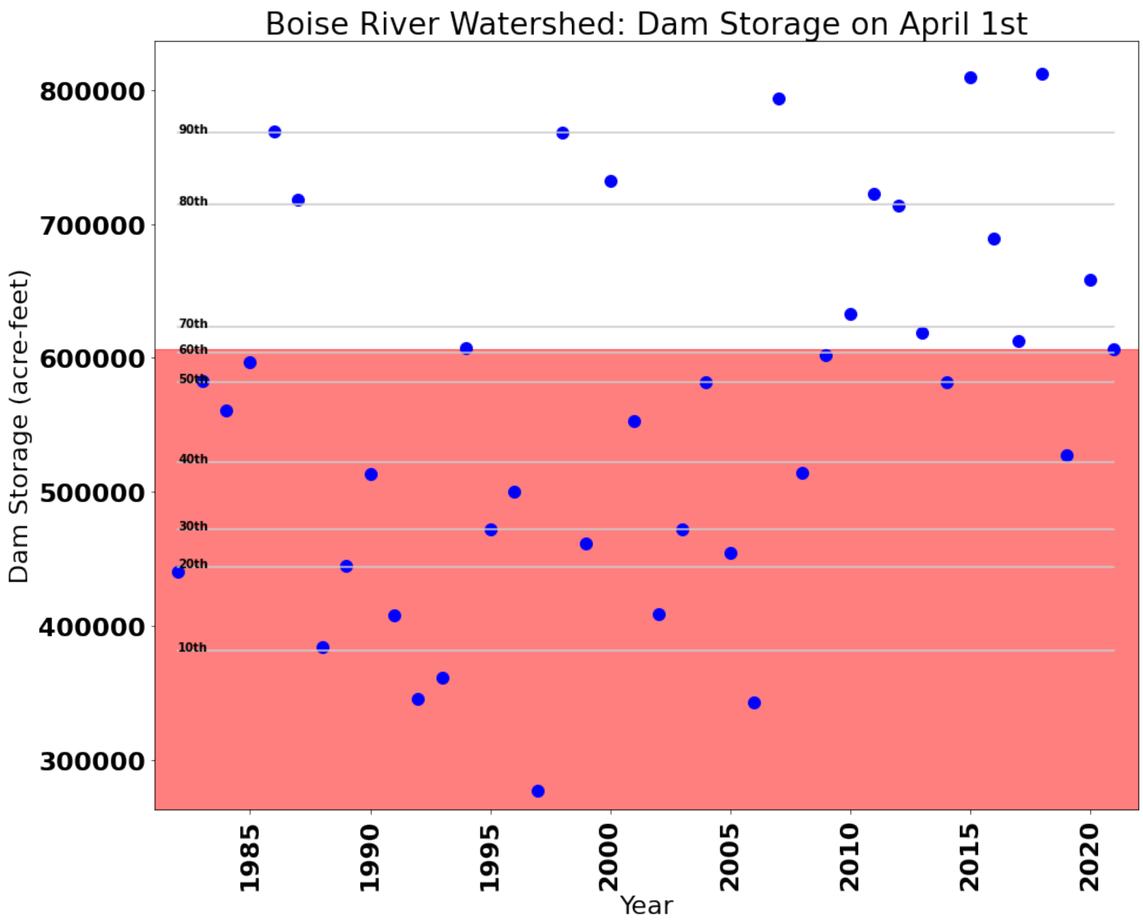


Figure 2.12 April 1st Cumulative Dam Storage in the Boise River Watershed

Figure 2.13 presents atmospheric storage values, i.e., spring precipitation, for the period of 1982 to 2021. Atmospheric storage values for Boise, Idaho usually range between 11 and 12 inches annually [7]. PRISM daily precipitation data was collected by entering relevant regions and variables in the Climate Engine website relating to the Boise area [6]. In order to collect precipitation data for the Boise River watershed, data for April, May, and June for each of the 40 years was averaged from the three sub-catchments which contribute to the Boise River. These sub-catchments include the Boise Mores, South Fork Boise, and Lower Boise catchments.

From the collected precipitation data, I isolated the precipitation measured in the months of April, May, and June for the period of analysis to determine an average of spring precipitation. Visual analysis of the historical precipitation data is presented in Figure 2.13. The value seen in the year of 2021 indicates an occurrence probability that is about 5% (95% exceedance probability). Historically, 2002 was the only year with a lower spring precipitation than 2021. This indicates a rarity potential for this kind of value for the Boise River watershed area.

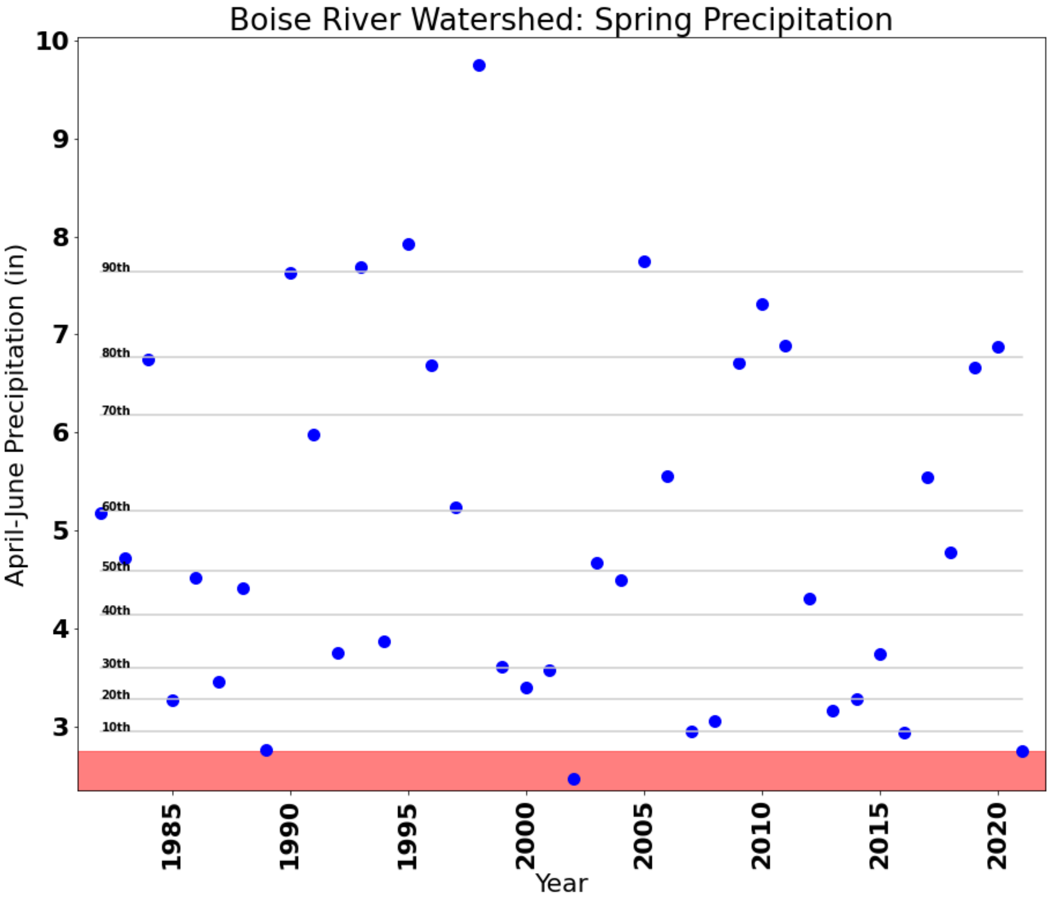


Figure 2.13 Spring (April-May-June) Precipitation in the Boise River Watershed

The data presented in Figure 2.14, below, shows the daily precipitation amounts in 2021. The spring season usually brings heavy precipitation to the Treasure Valley (i.e., high atmospheric storage; also see Figure 2.15), however the year 2021 was too low in the spring precipitation.

Monthly Boise River Watershed Precipitation

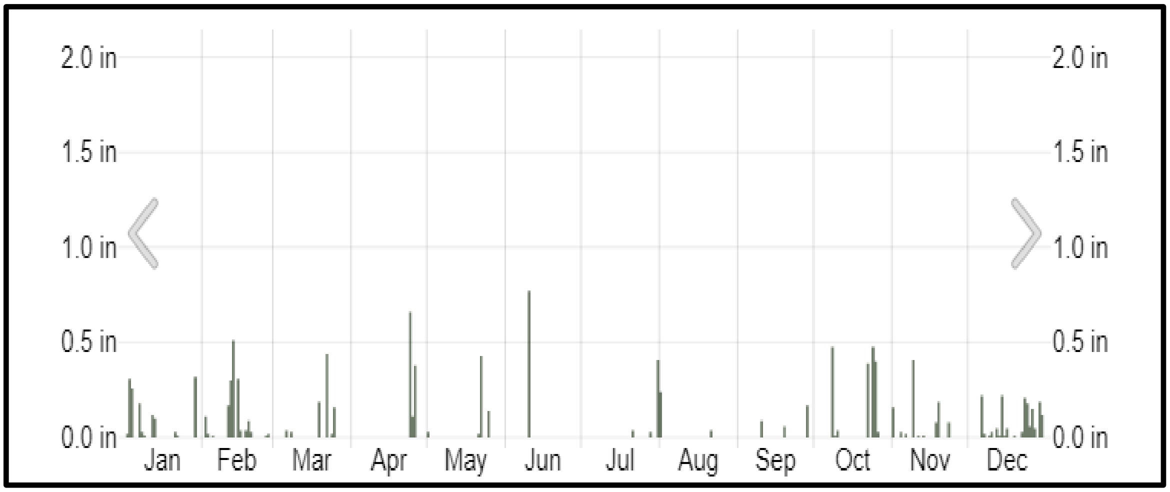


Figure 2.14 2021 Boise River Watershed Daily Precipitation

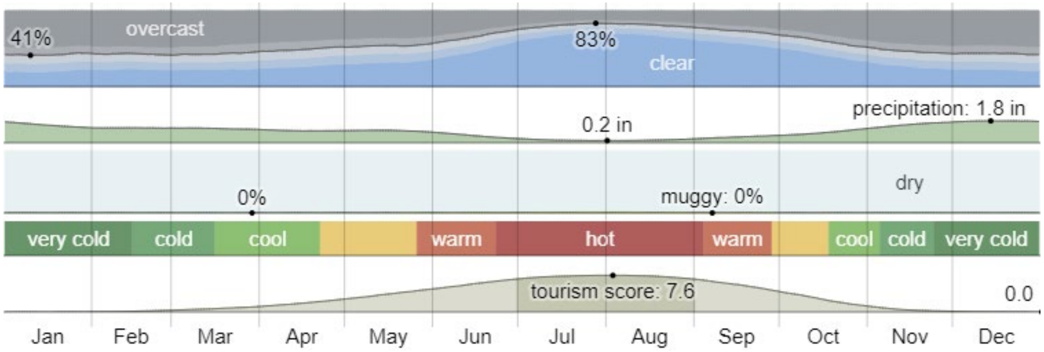


Figure 2.15. Historical weather in Boise, Idaho. Courtesy of Weatherspark

I now turn my attention to analysis of the 2021 Boise drought drivers in a bivariate context. Figure 2.16, below, shows a bivariate analysis SWE and dam storage for 2021 and how that compares to the historical record. In this graph, the region with a worse bivariate condition compared to 2021 is shaded with a red color. Here, worse is defined with an "AND" scenario [28], in which both SWE and dam storage should have lower values compared to that of 2021 (i.e., P(SWE<SWE_2021 ∧ Dam Storage<Dam Storage_2021)).. The year of 2021 is located in the lower left quarter of the graph, marking itself low in comparison with other years in the 40 years studied. In fact, there are only six other years that fall below 2021 in terms of bivariate SWE and dam storage levels. This puts 2021 at the 18th percentile for combined SWE and dam storage values.

Overall, SWE and reservoir storage seem connected and go hand-in-hand. Wet years provide a higher storage in each of these two components. However, dam storage is controllable by humans, while snow storage is not, and farmers may decide to bank their share of a year's water share for a future year. This brings a level of resilience to the farmers that if a future year's water provision is low, they can use their banked water. This happened in 2021, when farmers used the majority of their banked water from previous years to compensate for the low streamflows in the Boise River induced by a dry spring. However, the downside is that if several dry years occur successively, farmers may run out of banked storages.

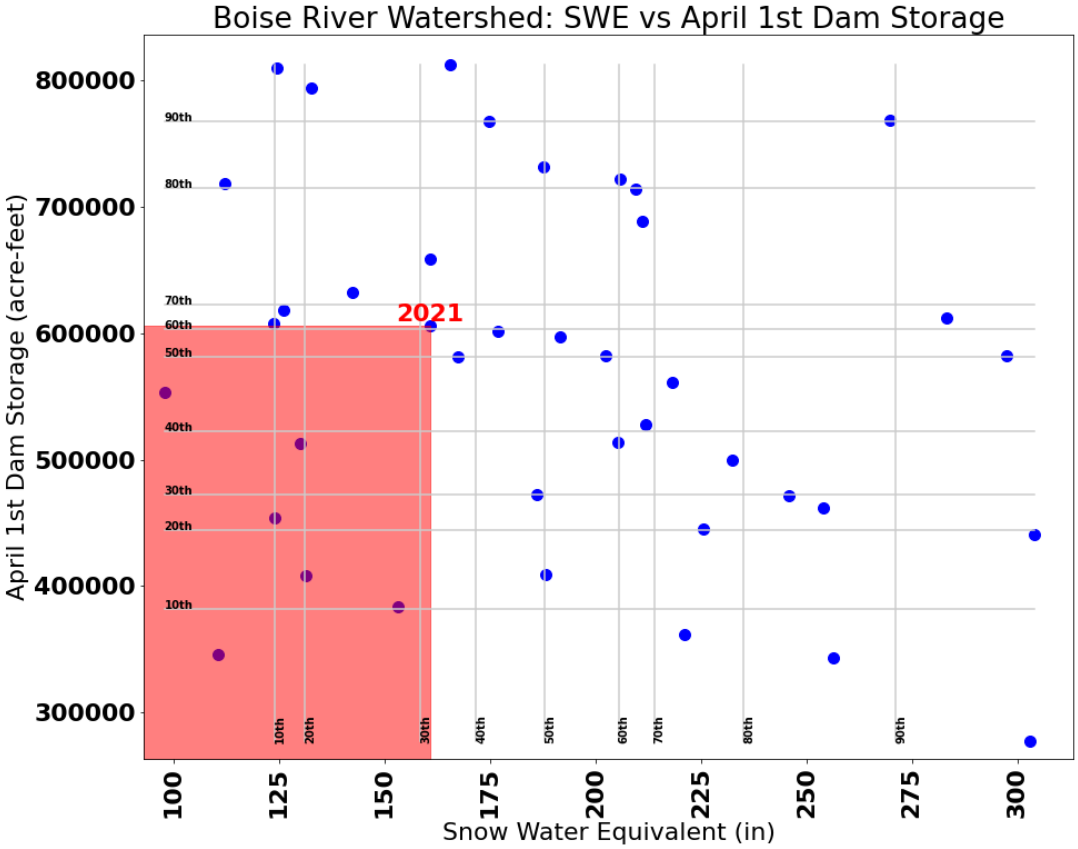


Figure 2.16 Boise River Watershed: SWE vs April 1st Dam Storage

Figure 2.17, below, displays a historical record of bivariate SWE and spring precipitation for the Boise River watershed, and clearly shows the year 2021 alone on the bottom left corner. Indeed, 2021 is the worst on record in terms of combined precipitation and SWE occurrences in the 40 year period studied. This is extremely significant in terms of finding the root causes of the 2021 drought. This chart helps explain why the 2021 drought turned out to be so acute. Farmers decide the extent of cultivated land in late winter and early spring, when spring precipitation data is uncertain, and they do so mainly based on dam and snowpack storages. Hence, droughts that are triggered by low spring precipitation can have a double whammy effect, if farmers cultivate their land to the full extent, since it will cause low water availability combined with high water demand.

These two variables (SWE and spring precipitation) shown in Figure 2.16, combined, carried a huge impact on the resulting drought. The SWE, although pretty low, was itself not at an alarming level. However, combined with precipitation, resulted in a very impactful driver for the drought. An important takeaway for farmers, in terms of future preparedness, would be to look more closely at the monitoring SNOTEL stations in combination with predicted precipitation levels. The National Oceanic and Atmospheric Administration provides short-term (less than 10 days or so) to mid-term (seasonal) prediction of precipitation and temperature. This would give farmers a better understanding of "what's coming" for the remainder of the growing/maturing season. It is noteworthy that precipitation predictions at the seasonal scale are very uncertain, and mostly qualitative. It might even be helpful to create an app, free to all, that could use this multivariate analysis in a way that's beneficial to farmers and water resource engineers.

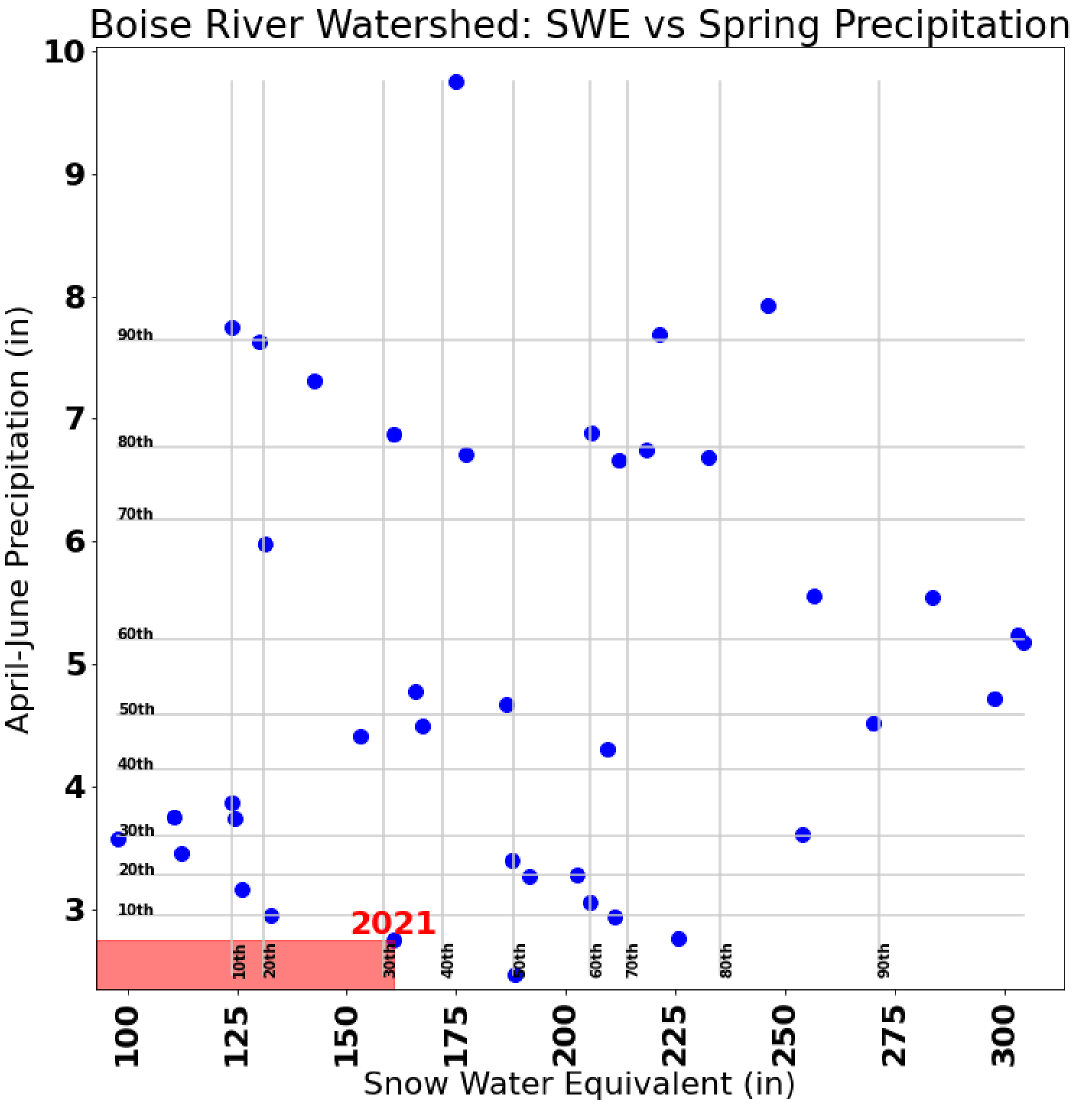


Figure 2.17 Boise River Watershed: SWE vs Spring Precipitation

Figure 2.18 signifies the occurrence and historic place of 2021 in terms of combined spring precipitation and dam storage values. As can be seen in Figure 2.18, below, only the year 2002 had a lower level than 2021 in the 40 years studied. Even if the year starts off with average dam storage levels, if there is not sufficient spring precipitation, then the stored water will get consumed at a faster rate without replenishment. In 2021, farmers took their allotted, as well as their banked, water for their crops, leaving reservoirs at low levels, and this resulted in the irrigation supply being cut off one whole month earlier than normal. This 30 day water deficit is a clear indication of the 2021 severe drought in Boise River watershed.

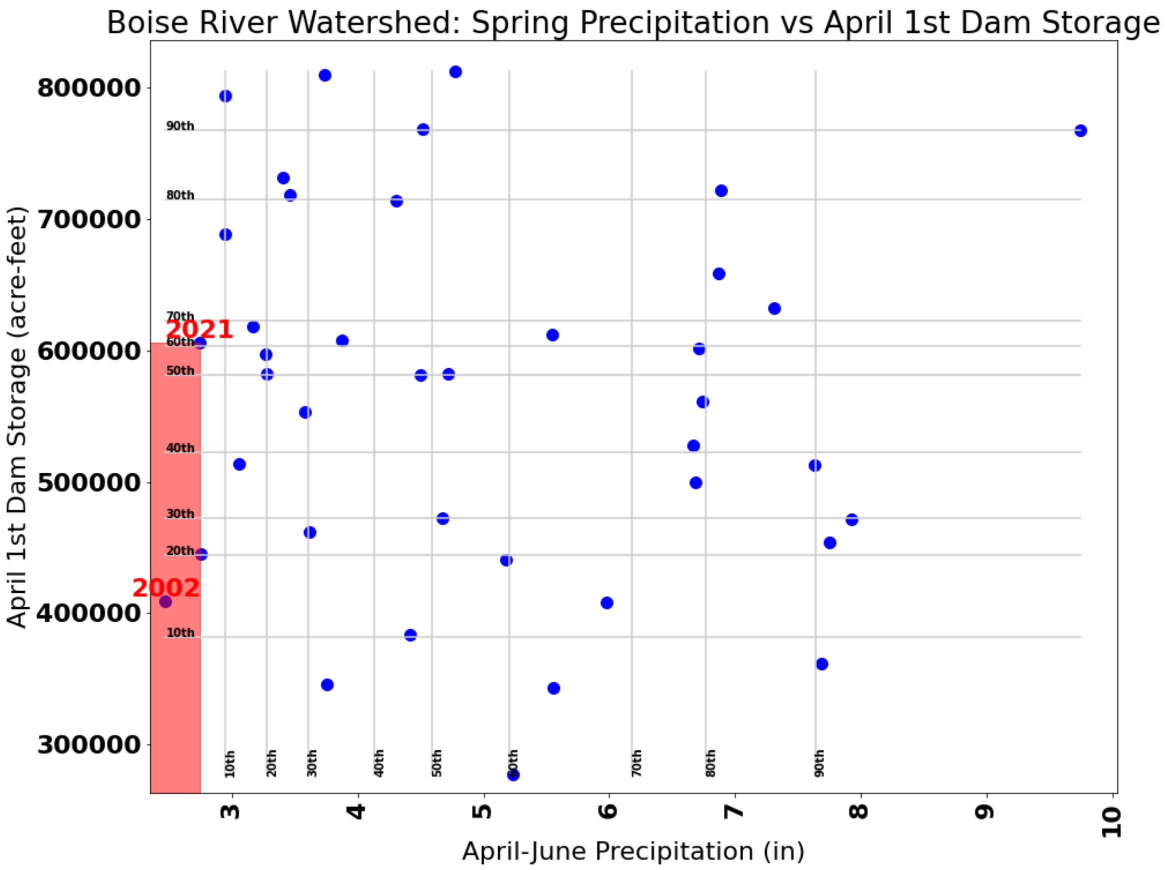


Figure 2.18 Boise River Watershed: Spring Precipitation Vs April 1st Dam Storage

A univariate analysis of drought proves to be insufficient when looking at the 2021 Boise drought, as well as many other cases shown in the literature. Specifically, if dam storage levels were used in isolation, 2021 would not be in bad shape. In fact, the year started in a good status with more than normal storage. The fact that lack of precipitation caused large withdrawal of water from dams, and their subsequent dropdown to lower than normal levels, is key in giving way to a massive drought in Boise in 2021. In other words, a 60% occurrence probably for the reservoir storage (Arrowrock, Anderson Ranch, and Lucky Peak combined) for the year 2021 in the Boise area alone is not a reason to sound the alarm of a possible drought. However, when combined with the lack of precipitation, the picture becomes more clear. Boise was using the same amount of water without replenishing its water "bank". Looking at the many drivers is crucial for the ability to monitor and analyze droughts. For this reason, a trivariate analysis was performed in this research.

A trivariate analysis was proven to be a useful tool in order to determine how the precipitation, SWE, and dam storage levels resulted in the 2021 drought. Figure 2.19, below, can be read easily if it was imagined as the inside corner of a simple cardboard box. The left edge of the "bottom" wall of the box would indicate SWE, ranging from lowest to highest in terms of left and right. On the right edge of that same "bottom," the dam storage levels are measured; again, leftward values are lowest, and right hand values are highest. Finally, the "back" wall of the box indicates precipitation, indicating values with the lower side of the wall as smaller values and the higher end of the wall with higher values. Once this can be imagined, then the dots can be visualized in a 3D sense. With this in mind, the orange marker, indicating the year 2021, can be visualized as indicating a low SWE and precipitation values, yet slightly above the median for dam storage levels.

As can be seen in Figure 2.19, 2021 was indeed located toward the lower section of the “box corner”, placing 2021 in the worst case scenario in a trivariate space in the historical record. This means that there was no other year on record that had lower dam storage AND lower SWE and lower spring precipitation than 2021. As stated before, the two variables of precipitation and SWE had the highest impact on the drought occurrence and severity. They together failed to replenish reservoir levels, and ultimately led to lack of water for farmers' crops. In addition to the SWE levels being low, a warm El Nino springtime caused snow to melt off at a faster rate than normal, resulting in very little snowpack being available for the rest of the season, when it would normally be used.

Figure 2.18 depicts the status of SWE, dam storage, and spring precipitation for a period of 40 years, ranging from 1982 to 2021. The resulting combined graphical representation gives a detailed analysis of the overall reach of these three variables. The purple markers demonstrate the 1980s through the mid-90s, the green markers represent mid-90s to early 2000’s, and lastly the yellow markers represent the 2010 to 2021 years. The 2021 value of the dam storage was reasonable and while the SWE value was on the low side, it was still within a reasonable range from normal. However, the precipitation that the Boise River watershed received in 2021 was significantly lower than usual, with an occurrence probability of only 5%. In this case, because the dam storage was not outside of its usual range, we can infer that the driving factor of the 2021 drought in the Boise River watershed was the low precipitation received and, to a lesser extent, the moderately low SWE value.

Through analysis of the historical values, it is evident that low precipitation is not always the driving factor that leads to drought. In 1987, the available dam storage was high (with an occurrence probability of 81%), and the precipitation received by the Boise River watershed was moderately low (with an occurrence probability of 25%). In the same year, the available SWE was very low (with an occurrence probability of 6%). In this case, the very low value of SWE is likely one driving factor that caused the drought in combination with the low precipitation. In 2006, both the precipitation and available SWE were fairly high (with occurrence probabilities of 64% and 86% respectively), but the available dam storage that year was very low (with an occurrence probability of only 7%). In 2006, the extremely low dam storage was the driving factor that led to the drought [20].

From the analysis of the historical data, it is clear that if one out of the three factors goes awry in the available dam storage, SWE, and precipitation, there is a good chance that a drought will ensue. However, if two (or more) of the factors have below average values, it becomes highly likely that it will result in a drought. Closer monitoring of these factors can provide a good indication of whether a drought is about to occur. In the case of Boise in 2021, the drought was outpacing the needs of the community. According to a local news outlet, KTVB, many sectors like farming and homes had their irrigation water cut off early, with the reason being the severe lack of water in the reservoirs to meet the demands of the residents and farmers [1].

Based on this research, the trivariate analysis represents a more realistic description of whether or not a drought will be observed, and if it does occur, how it will progress and terminate. The severe 2021 Boise drought was difficult to predict since it was mainly driven by precipitation, which is difficult to predict. Monitoring and prediction efforts need to be strengthened if we want to be prepared for the next major drought year. By looking at the historical data and extrapolating into the future, we can make educated assumptions of potential drought years.

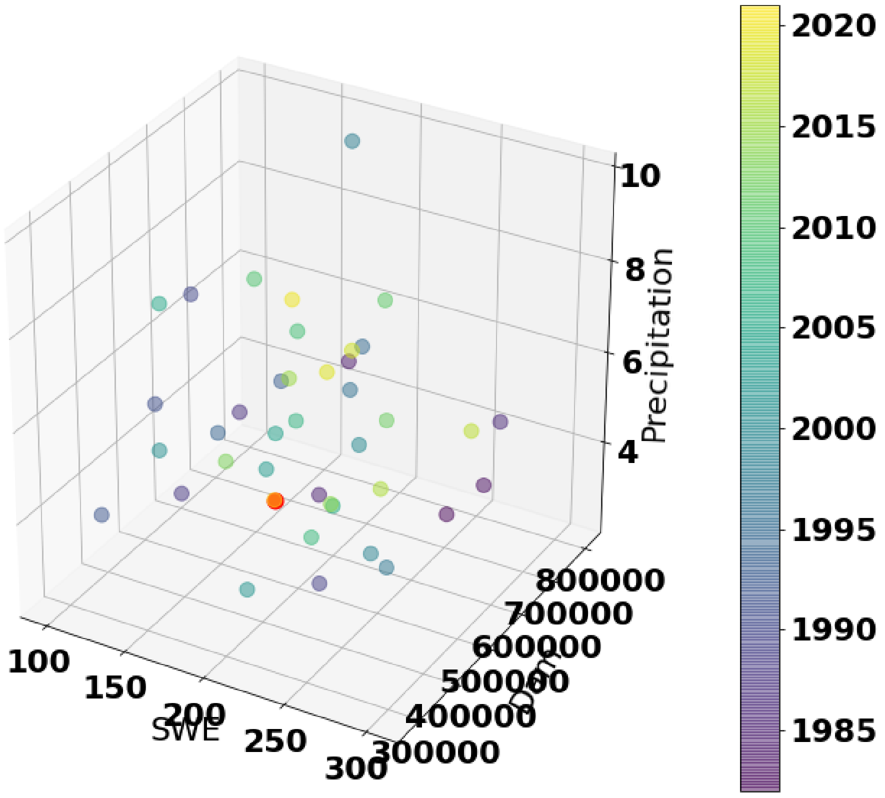
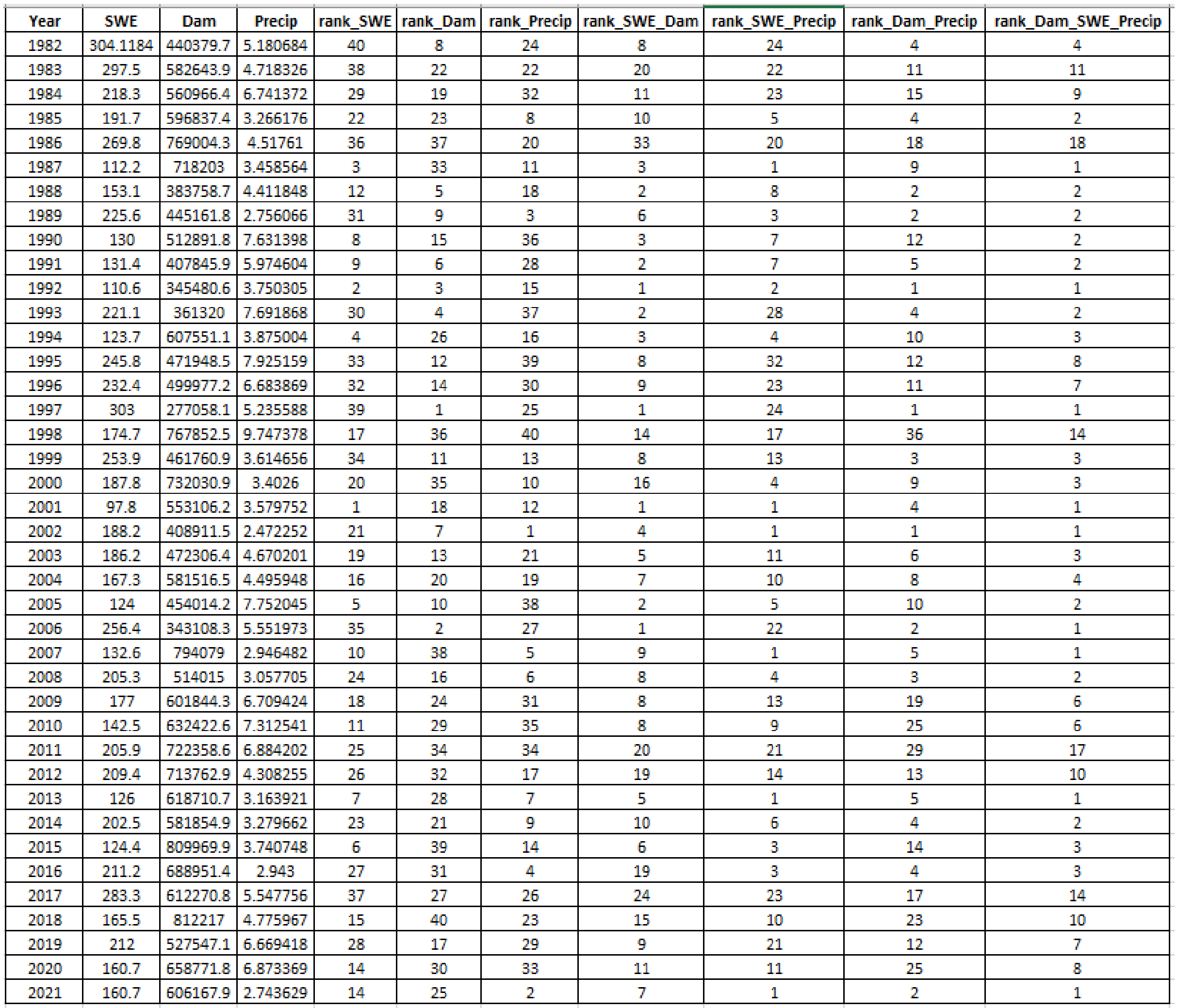


Figure 2.19 Trivariate Analysis: Precipitation, SWE, and Dam Storage (Years 1982 - 2021)

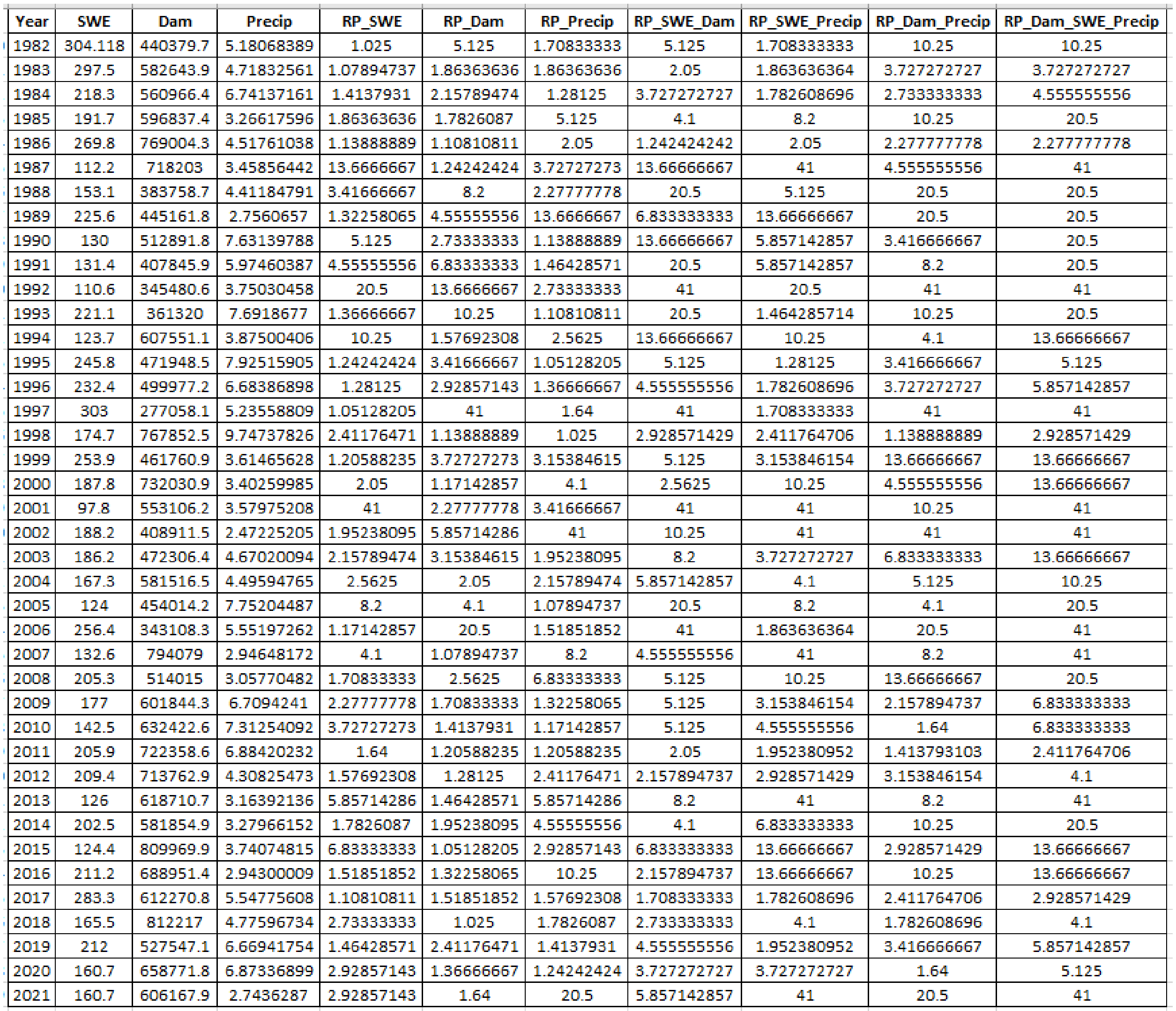
Tables 2.2 and 2.3 present historical values of April 1st dam storage and SWE for each year, as well as spring precipitation for the Boise River watershed, as well as their associated univariate, bivariate and trivariate ranks (Table 2.2) and return periods (Tables 2.3). In Table 2.2 rank 1 refers to the worst case, for example lowest spring precipitation on record. Ranking in a univariate case is quite simple and intuitive. For example, if a year observed the lowest precipitation on record, it is assigned a rank of 1. In a multivariate case, however, it is not as straightforward. For a year to get a rank of 2 for precipitation and SWE, for example, there needs to be another year that is worse both in terms of precipitation and SWE (i.e., lower precipitation and lower SWE). A similar definition applies to a trivariate ranking. Multivariate ranks are, therefore, not unique. As visible in Table 2.2, there are 9 years with a rank of 1 in the trivariate space. This is because there was no other year that could supersede these years in all three variables (worse precipitation AND worse SWE AND worse dam storage). There are statistical methods to break these non-uniqueness, which I will not pursue in this research due to time limitations. These ranks are then translated to exceedance probabilities (rank/(N+1) in which N is the number of observations, here 40), and are then translated to return period levels (RP = 1/exceedance probability, where RP stands for return period). Return period levels for univariate, bivariate, and trivariate cases are presented in Table 2.3. Note that here the maximum return period can be only 41 years since I am using an empirical approach to calculate return period levels. If I were to fit distributions (such as GEV for univariate cases), I would probably better sample the tails, which would have resulted in different (probably larger) return period levels for extreme cases. But that would introduce a level of uncertainty, for which reason I would refrain from it. I note that provided results are for understanding purposes and operational planning needs to explore more robust statistical methods, such as more robust distribution tail analysis.

Table 2.2 Historical April 1st dam storage and SWE for each year, as well as spring precipitation for the Boise River Watershed and their uni, bi, and trivariate ranks (rank 1: worst)



Year	SWE	Dam	Precip	rank_SWE	rank_Dam	rank_Precip	rank_SWE_Dam	rank_SWE_Precip	rank_Dam_Precip	rank_Dam_SWE_Precip
1982	304.1184	440379.7	5.180684	40	8	24	8	24	4	4
1983	297.5	582643.9	4.718326	38	22	22	20	22	11	11
1984	218.3	560966.4	6.741372	29	19	32	11	23	15	9
1985	191.7	596837.4	3.266176	22	23	8	10	5	4	2
1986	269.8	769004.3	4.51761	36	37	20	33	20	18	18
1987	112.2	718203	3.458564	3	33	11	3	1	9	1
1988	153.1	383758.7	4.411848	12	5	18	2	8	2	2
1989	225.6	445161.8	2.756066	31	9	3	6	3	2	2
1990	130	512891.8	7.631398	8	15	36	3	7	12	2
1991	131.4	407845.9	5.974604	9	6	28	2	7	5	2
1992	110.6	345480.6	3.750305	2	3	15	1	2	1	1
1993	221.1	361320	7.691868	30	4	37	2	28	4	2
1994	123.7	607551.1	3.875004	4	26	16	3	4	10	3
1995	245.8	471948.5	7.925159	33	12	39	8	32	12	8
1996	232.4	499977.2	6.683869	32	14	30	9	23	11	7
1997	303	277058.1	5.235588	39	1	25	1	24	1	1
1998	174.7	767852.5	9.747378	17	36	40	14	17	36	14
1999	253.9	461760.9	3.614656	34	11	13	8	13	3	3
2000	187.8	732030.9	3.4026	20	35	10	16	4	9	3
2001	97.8	553106.2	3.579752	1	18	12	1	1	4	1
2002	188.2	408911.5	2.472252	21	7	1	4	1	1	1
2003	186.2	472306.4	4.670201	19	13	21	5	11	6	3
2004	167.3	581516.5	4.495948	16	20	19	7	10	8	4
2005	124	454014.2	7.752045	5	10	38	2	5	10	2
2006	256.4	343108.3	5.551973	35	2	27	1	22	2	1
2007	132.6	794079	2.946482	10	38	5	9	1	5	1
2008	205.3	514015	3.057705	24	16	6	8	4	3	2
2009	177	601844.3	6.709424	18	24	31	8	13	19	6
2010	142.5	632422.6	7.312541	11	29	35	8	9	25	6
2011	205.9	722358.6	6.884202	25	34	34	20	21	29	17
2012	209.4	713762.9	4.308255	26	32	17	19	14	13	10
2013	126	618710.7	3.163921	7	28	7	5	1	5	1
2014	202.5	581854.9	3.279662	23	21	9	10	6	4	2
2015	124.4	809969.9	3.740748	6	39	14	6	3	14	3
2016	211.2	688951.4	2.943	27	31	4	19	3	4	3
2017	283.3	612270.8	5.547756	37	27	26	24	23	17	14
2018	165.5	812217	4.775967	15	40	23	15	10	23	10
2019	212	527547.1	6.669418	28	17	29	9	21	12	7
2020	160.7	658771.8	6.873369	14	30	33	11	11	25	8
2021	160.7	606167.9	2.743629	14	25	2	7	1	2	1

Table 2.3 Historical April 1st dam storage and SWE for each year, as well as spring precipitation for the Boise River Watershed and their uni, bi, and trivariate return periods (year)



Year	SWE	Dam	Precip	RP_SWE	RP_Dam	RP_Precip	RP_SWE_Dam	RP_SWE_Precip	RP_Dam_Precip	RP_Dam_SWE_Precip
1982	304.118	440379.7	5.18068389	1.025	5.125	1.70833333	5.125	1.708333333	10.25	10.25
1983	297.5	582643.9	4.71832561	1.07894737	1.86363636	1.86363636	2.05	1.863636364	3.727272727	3.727272727
1984	218.3	560966.4	6.74137161	1.4137931	2.15789474	1.28125	3.727272727	1.782608696	2.733333333	4.555555556
1985	191.7	596837.4	3.26617596	1.86363636	1.7826087	5.125	4.1	8.2	10.25	20.5
1986	269.8	769004.3	4.51761038	1.13888889	1.10810811	2.05	1.242424242	2.05	2.277777778	2.277777778
1987	112.2	718203	3.45856442	13.6666667	1.24242424	3.72727273	13.66666667	41	4.555555556	41
1988	153.1	383758.7	4.41184791	3.41666667	8.2	2.27777778	20.5	5.125	20.5	20.5
1989	225.6	445161.8	2.7560657	1.32258065	4.55555556	13.6666667	6.833333333	13.66666667	20.5	20.5
1990	130	512891.8	7.63139788	5.125	2.73333333	1.13888889	13.66666667	5.857142857	3.416666667	20.5
1991	131.4	407845.9	5.97460387	4.55555556	6.83333333	1.46428571	20.5	5.857142857	8.2	20.5
1992	110.6	345480.6	3.75030458	20.5	13.6666667	2.73333333	41	20.5	41	41
1993	221.1	361320	7.6918677	1.36666667	10.25	1.10810811	20.5	1.464285714	10.25	20.5
1994	123.7	607551.1	3.87500406	10.25	1.57692308	2.5625	13.66666667	10.25	4.1	13.66666667
1995	245.8	471948.5	7.92515905	1.24242424	3.41666667	1.05128205	5.125	1.28125	3.416666667	5.125
1996	232.4	499977.2	6.68386898	1.28125	2.92857143	1.36666667	4.555555556	1.782608696	3.727272727	5.857142857
1997	303	277058.1	5.23558809	1.05128205	41	1.64	41	1.708333333	41	41
1998	174.7	767852.5	9.74737826	2.41176471	1.13888889	1.025	2.928571429	2.411764706	1.138888889	2.928571429
1999	253.9	461760.9	3.61465628	1.20588235	3.72727273	3.15384615	5.125	3.153846154	13.66666667	13.66666667
2000	187.8	732030.9	3.40259985	2.05	1.17142857	4.1	2.5625	10.25	4.555555556	13.66666667
2001	97.8	553106.2	3.57975208	41	2.27777778	3.41666667	41	41	10.25	41
2002	188.2	408911.5	2.47225205	1.95238095	5.85714286	41	10.25	41	41	41
2003	186.2	472306.4	4.67020094	2.15789474	3.15384615	1.95238095	8.2	3.727272727	6.833333333	13.66666667
2004	167.3	581516.5	4.49594765	2.5625	2.05	2.15789474	5.857142857	4.1	5.125	10.25
2005	124	454014.2	7.75204487	8.2	4.1	1.07894737	20.5	8.2	4.1	20.5
2006	256.4	343108.3	5.55197262	1.17142857	20.5	1.51851852	41	1.863636364	20.5	41
2007	132.6	794079	2.94648172	4.1	1.07894737	8.2	4.555555556	41	8.2	41
2008	205.3	514015	3.05770482	1.70833333	2.5625	6.83333333	5.125	10.25	13.66666667	20.5
2009	177	601844.3	6.7094241	2.27777778	1.70833333	1.32258065	5.125	3.153846154	2.157894737	6.833333333
2010	142.5	632422.6	7.31254092	3.72727273	1.4137931	1.17142857	5.125	4.555555556	1.64	6.833333333
2011	205.9	722358.6	6.88420232	1.64	1.20588235	1.20588235	2.05	1.952380952	1.413793103	2.411764706
2012	209.4	713762.9	4.30825473	1.57692308	1.28125	2.41176471	2.157894737	2.928571429	3.153846154	4.1
2013	126	618710.7	3.16392136	5.85714286	1.46428571	5.85714286	8.2	41	8.2	41
2014	202.5	581854.9	3.27966152	1.7826087	1.95238095	4.55555556	4.1	6.833333333	10.25	20.5
2015	124.4	809969.9	3.74074815	6.83333333	1.05128205	2.92857143	6.833333333	13.66666667	2.928571429	13.66666667
2016	211.2	688951.4	2.94300009	1.51851852	1.32258065	10.25	2.157894737	13.66666667	10.25	13.66666667
2017	283.3	612270.8	5.54775608	1.10810811	1.51851852	1.57692308	1.708333333	1.782608696	2.411764706	2.928571429
2018	165.5	812217	4.77596734	2.73333333	1.025	1.7826087	2.733333333	4.1	1.782608696	4.1
2019	212	527547.1	6.66941754	1.46428571	2.41176471	1.4137931	4.555555556	1.952380952	3.416666667	5.857142857
2020	160.7	658771.8	6.87336899	2.92857143	1.36666667	1.24242424	3.727272727	3.727272727	1.64	5.125
2021	160.7	606167.9	2.7436287	2.92857143	1.64	20.5	5.857142857	41	20.5	41

The 2021 Boise drought was somewhat unpredictable, since it was mainly driven by a lack of spring precipitation. Predicting precipitation, SWE, and dam storage levels are key for the preparedness of areas prone to droughts. In the case of Boise, the results show a clear picture of the climate and variables which are changing.

2.6 Future Projection of Drought Likelihood in the Boise River Watershed

Historical analysis of droughts provides invaluable information of the occurred disasters and provides a baseline for developing future management scenarios. Another tool that is available to scientists about what can be expected to happen in the future is General Circulation Models (a.k.a. Global Climate Models; GCM) that can project future climates given various emission and development scenarios. GCMs are numerical representations of elements that contribute to and control climate of the Earth, including Ocean, Atmosphere, Sea-Ice, and Land-Atmosphere interactions. One set of scenarios that drive GCM simulations is the RCP (representative concentration pathway) values. The RCP values reflect the amount of "Radiative Forcing" or climate forcing which differentiates the amount of sunlight absorbed and sunlight reflected into space [35]. This value takes into consideration many variables like economics, green gas emissions, fossil fuel rate of use, population, etc.

Researchers have formulated a range of RCP values, with some of the most common including the RCP values of 4.5 and 8.5. The RCP of 8.5 typically refers to a "business as usual" scenario, which according to some scientific papers, is considered to be "the worst case scenario" [35], where as a whole, adequate actions are not taken to address some of the many changes occurring with the natural world due to human-induced greenhouse gasses emissions. In this scenario, things like coal consumption, polluting our water bodies, greenhouse gas emissions, and more, stay on a constant path of rising trend. RCP 4.5 refers to a scenario where many of the offenders, like the greenhouse gasses and coal combustion, are reduced greatly – although not as much as more aggressive scenarios like RCP 2.5. Implementations like carbon capturing, lower emissions, change in energy systems, or even forest land expansion are adopted in RCP 4.5 [35]. Furthermore, various modeling groups across the globe developed models in an attempt to model the Earth's climate. These models can use similar modules in their structure, but they generally differ in spatiotemporal scales of process representations in their structure, as well as the type of processes to include or exclude. Figures 2.20 and 2.21 present a multi-model ensemble of projected annual precipitation for Boise, Idaho, using models from Coupled Model Intercomparison Project, Phase 5 (CMIP5) unders scenarios RCP 8.5 and RCP 4.5 scenarios, respectively. Under the high emission scenario (RCP 8.5; Figure 2.19), the annual precipitation in Boise, Idaho is expected to increase slightly (~1 inch increase) by the end of the century. This is mainly due to an increase in evaporation rates from the oceans as well as higher atmospheric capacity to hold water in a warmer climate, which results in an expected increase in severity of precipitation events. Importantly, a warming climate also changes the atmospheric circulation patterns that bring moisture to any location on Earth, resulting in the projected changes in annual precipitation in Boise, Idaho. Expected increase in annual precipitation in Boise, Idaho, under RCP 4.5 scenario, however, is much less notable. In fact, the increase in annual precipitation is marginal under a medium emission scenario (Figure 2.21).

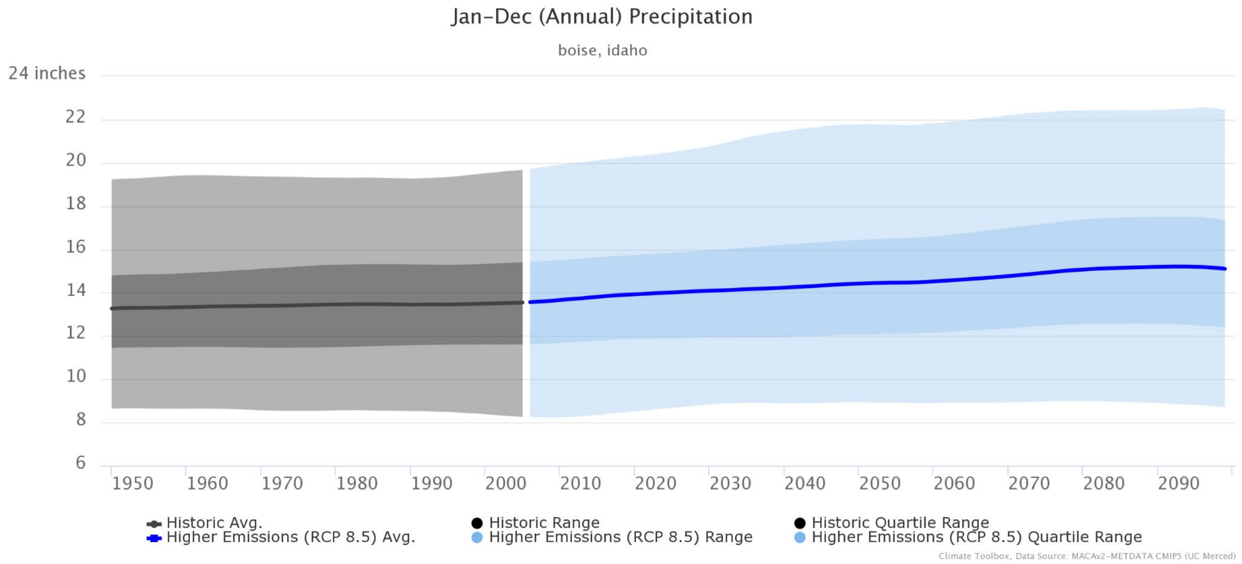


Figure 2.20 Projected annual precipitation for Boise, Idaho, using CMIP5 models with an RCP 8.5 scenario.

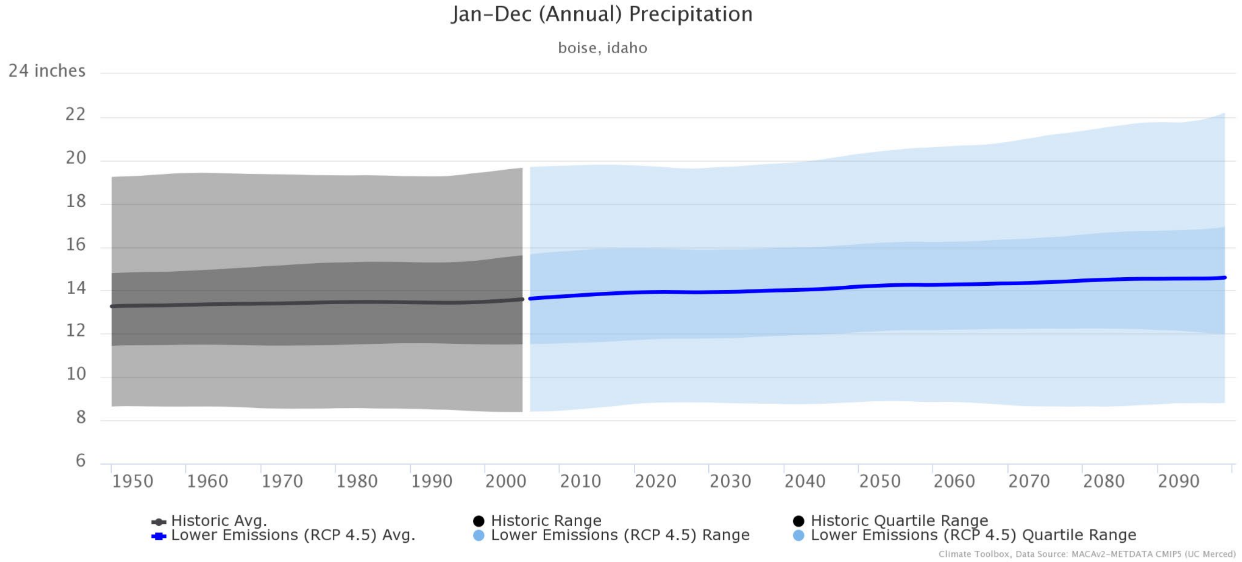
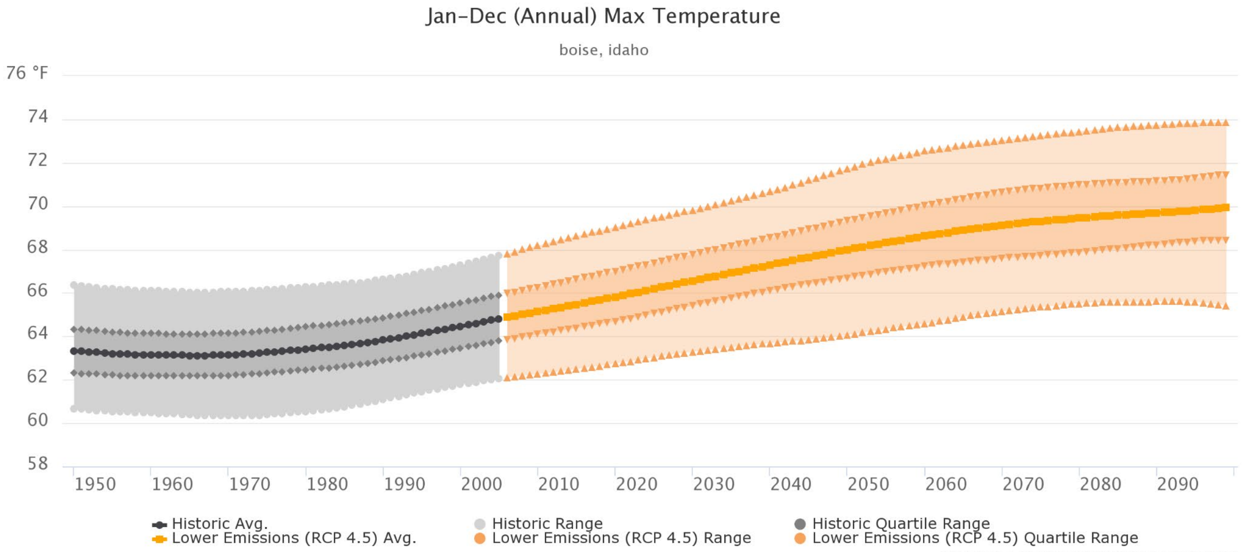


Figure 2.21 Projected annual precipitation for Boise, Idaho, using CMIP5 models with an RCP 4.5 scenario.

Water availability, however, is not only governed by precipitation amounts. Temperature trends also help determine water availability in the future through controlling the evaporation and transpiration amounts. Higher temperatures increase evapotranspiration and induce dryness on land. Under both medium (RCP 4.5) and high (RCP 8.5) emission scenarios, CMIP5 models project an increase in temperature in Boise, Idaho by the end of the century. However, the increase in annual Max Temperature under RCP 8.5 is roughly twice as much as that of RCP 4.5 (10 degF vs 5 degF increase in 2100 compared to present day).



Climate Toolbox, Data Source: MACAv2-METDATA CMIP5 (UC Merced)

Figure 2.22 Projected annual Max temperature for Boise, Idaho, using CMIP5 models with an RCP 4.5 scenario.

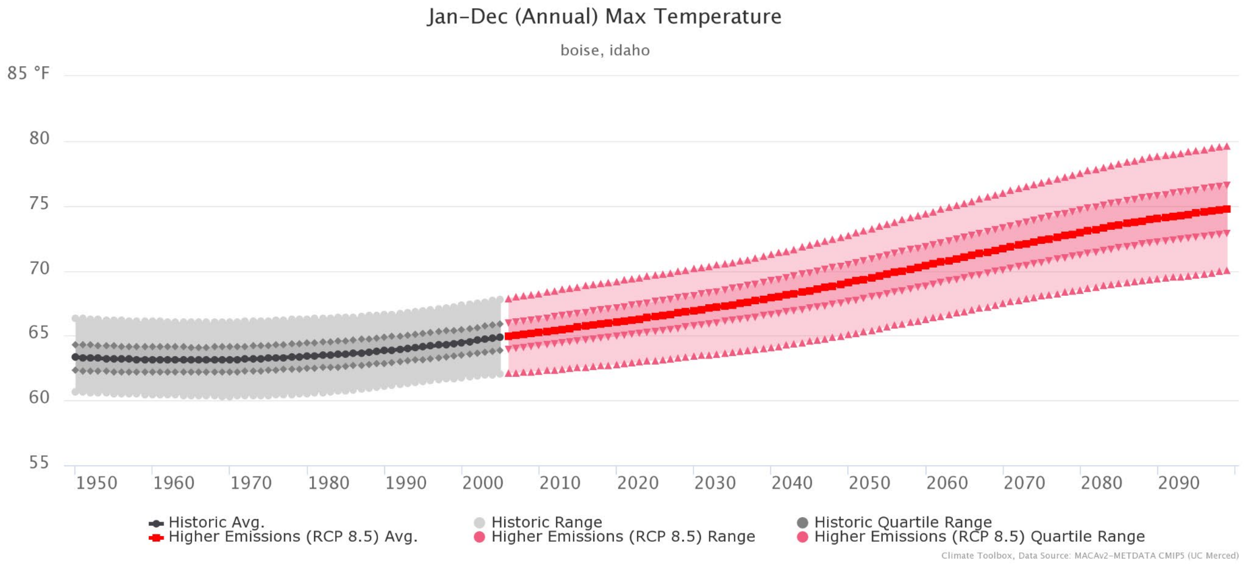
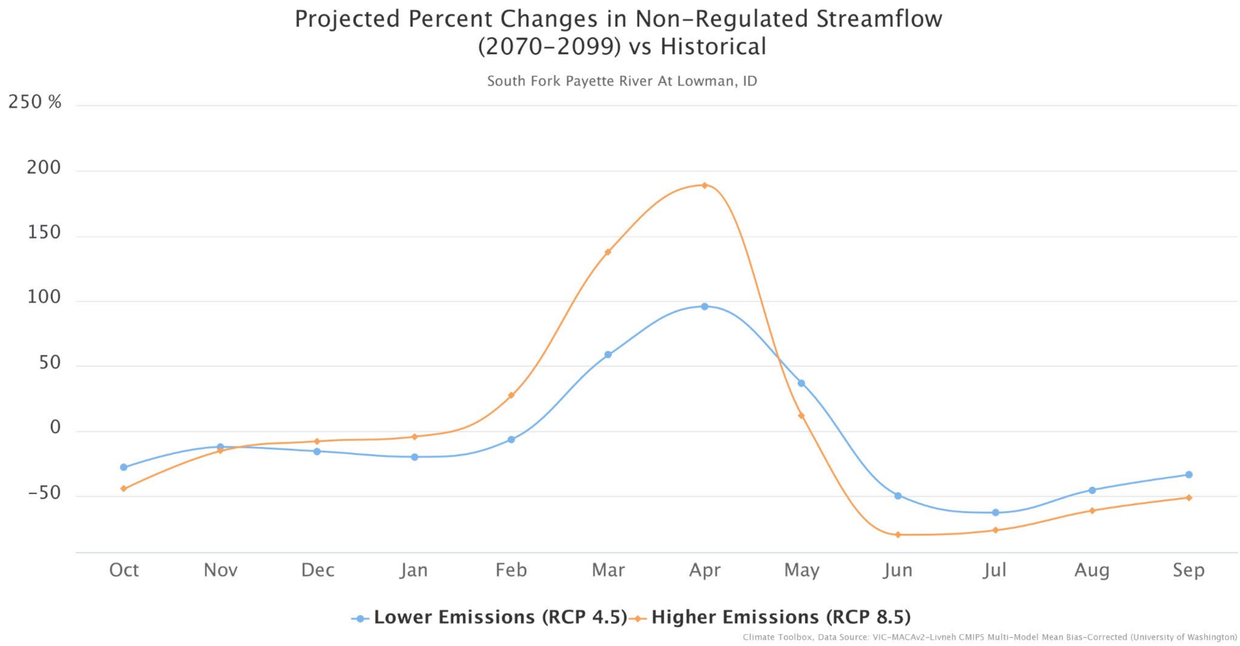


Figure 2.23 Projected annual Max temperature for Boise, Idaho, using CMIP5 models with an RCP 8.5 scenario.

Marginal projected increase in precipitation can arguably be counteracted by significant increase in temperature and consequently evaporative demand to potentially increase drought severity by the end of the century in the Boise area, specifically under the high emission scenario (RCP 8.5). For example, projected streamflow changes in South Fork Payette River in Lowman, Idaho – that has similar climate, land cover and topographical characteristics to headwater streams of the Boise River – point to an increase in February through March streamflows (when streamflow is high and can potentially be at the flooding level), and a decrease in other months (when streamflow is low) compared to the historical record. This causes significant management challenges since streamflows cluster in wet months, and there likely will be a mismatch between the timing of water availability and demand.



Climate Toolbox, Data Source: VIC-MACAv2-Livneh CMIP5 Multi-Model Mean Bias-Corrected (University of Washington)

Figure 2.24 Projected changes (2070-2099 compared to historical) in monthly streamflow in South Fork Payette River in Lowman, Idaho, using CMIP5 models with RCP 4.5 and RCP 8.5 scenarios.

Importantly, spring precipitation that is arguably the main reason for the 2021 Boise drought is also expected to change in the future under various emission scenarios. Figures 2.25 and 2.26 show trends in projected April through June precipitation in Boise, Idaho, under RCP 4.5 and RCP 8.5 scenarios, respectively, using four models randomly selected from the suite of CMIP5 models. Spring precipitation in Boise is expected to marginally increase under medium emission scenario (Figure 2.25), whereas it is projected to marginally decrease (3 of the 4 explored models) under a high emission scenario (Figure 2.26). This finding is specifically alarming given a higher emission and warmer scenario, which increases water demand, is also projected to concur with lower spring precipitation. This setting (low water availability and high demand) is similar to what happened in 2021.

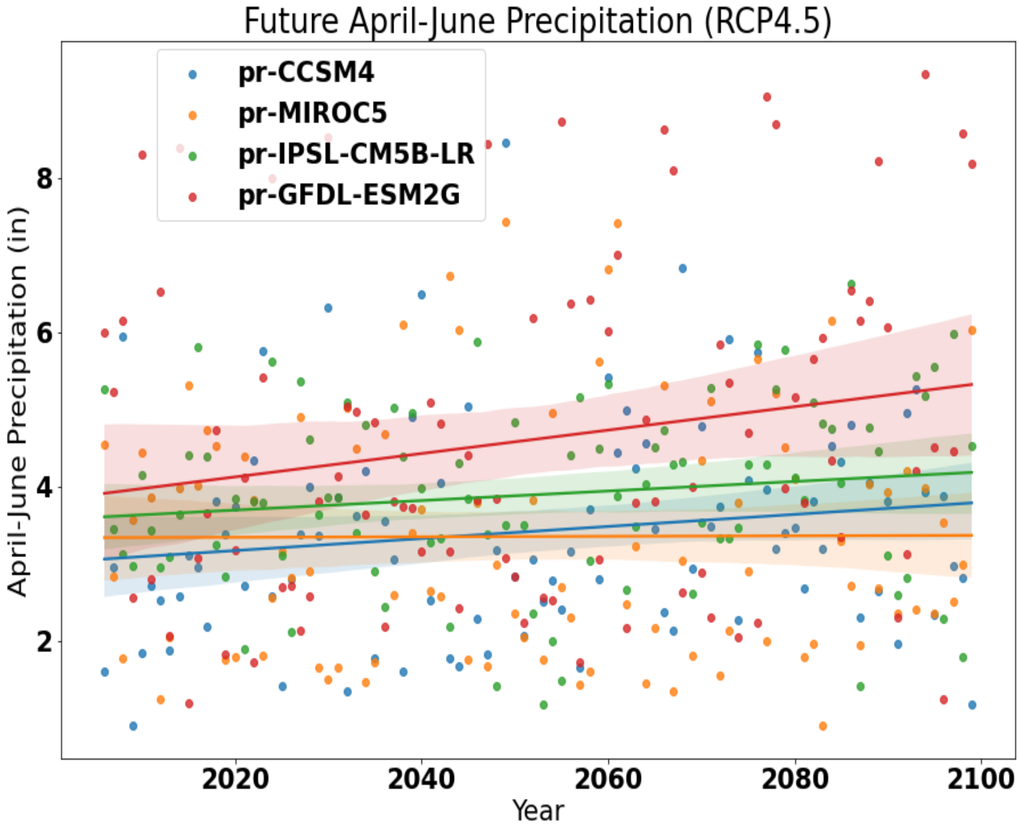


Figure 2.25 Trends in projected April-June Precipitation in Boise, Idaho under RCP 4.5

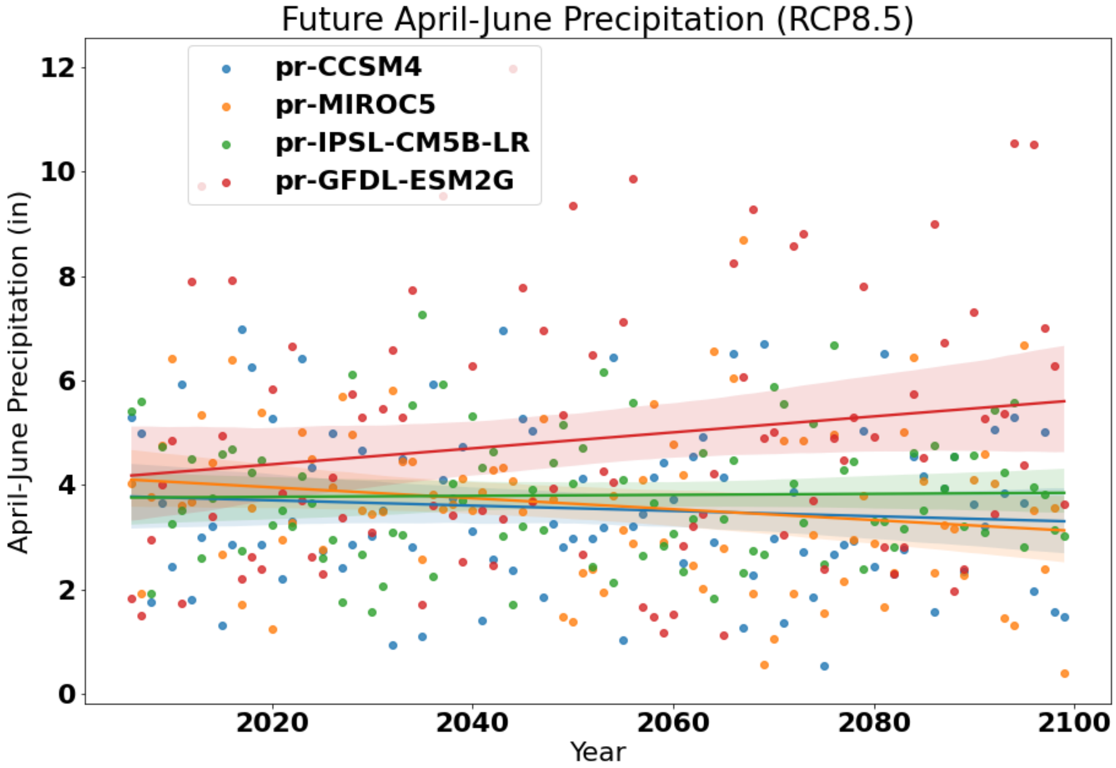


Figure 2.26 Trends in projected April-June Precipitation under RCP 8.5

CHAPTER THREE: DISCUSSION

The 2021 drought proved to be very hard on farmers and their crops, leading to distress and crop failures. The combined effect of the main drivers analyzed in this study are key for understanding why the drought was so impactful to the farming community in the Treasure Valley area. After analyzing the possible causes, this study determined that the main factors that lead to the drought were low precipitation (main) and low snowpack (secondary), combined with "business as usual" practiced by water consumers, such as farmers, that induced high water demand. The combined effect from low precipitation and taking more water than actually available for the year (e.g., through using banked water in dams from previous years) intensified the effects of the drought. Reservoir levels were actually higher than normal in the early spring of 2021, which probably impacted the drought conditions negatively by giving the farmers a sense of security to cultivate their land to the fullest extent. But then when the inflow to the reservoirs dropped due to low spring precipitation, dams were not able to fully support the downstream water demand.. The drought was indeed unpredictable, but just like any issue, there are steps that can be taken for the readiness of the parties involved. In this case, Boise was not ready for the type of damage that the drought of 2021 caused to the crops. Many farmers lost money and gains.

The Boise River watershed is located in the northwestern part of the United States, in the southwest corner of the state of Idaho. It covers most of Ada and Canyon Counties, and also parts of Gem, Boise, Payette, Elmore, and Malheur Counties. The main cities which use the watershed include Idaho’s capital, Boise, as well as Nampa, Caldwell, and Eagle, and some smaller communities. Water is an important resource for these areas due to Idaho’s economy, which heavily relies on agriculture, and more specifically, crop production.

As mentioned above, the drought was caused by several factors, one of which was low precipitation. But it was not simply “little rain”; this term is used to describe a wider span of time and types of precipitation. The low precipitation was seen in the spring months, April, May, and June of 2021, which put 2021 as the second lowest spring precipitation in the historical record. These spring months are specifically critical to farmers, since this is the time when crops are typically planted and seedlings are in need of an adequate water supply. Since an average amount of precipitation was not available in the spring, farmers had to start using canal water earlier than normal, which would later contribute to the low supply of water.

Water stored and available for agriculture use include water levels in reservoirs as well as snowpack. The reservoir levels were somewhat normal from the start of the 2021 year, as well as in the spring of 2021, which indicates that the reservoir levels alone were not a contributing factor to the drought. The reservoir levels were seen at approximately the 60th percentile mark, which means it was slightly above to the median level. Indeed, 24 years out of the 40 years recorded in this study observed lower dam storage than 2021. But the year of 2021 saw a relatively low combined snowpack and reservoir storage - in fact, sitting at the 17th percentile of historical record. Snowpack, a natural source of water storage, was an important contributing factor to the 2021 drought. This is because snowpack levels were relatively low – at the 34th percentile, meaning that in the 40 year period of analysis, 63% of years received higher amounts of snowpack than the year 2021. Low precipitation in 2020, especially in the form of snowfall during the late fall and winter months, created a lower than average amount of snowpack accumulation at the start of 2021. This carried on into the spring months of 2021, which also saw low spring precipitation.

This combination of somewhat low SWE and very low precipitation were a major driving force of the 2021 drought. Together, their forces combined to create the sudden, sharp reduction in available water with detrimental effects. This can be thought of as money in a person's possession. The SWE could be what the person has in the savings account (in this case, we'll say he has saved $1,000), and the precipitation is what he receives from his paycheck (in this case, we'll say he receives paychecks totalling $1,000 per month). If he is going to be spending $2,500 in the coming month, but only has $1,000 in savings and $1,000 from his paycheck, he will come up $500 short and will have to stop spending sooner than anticipated.

The joint dam storage levels and precipitation were also strikingly low (2nd worst on record), driven by very low precipitation. The dam storage levels, at approximately the 60th percentile, seemed to be at a normal level, but with the severe lack of spring precipitation and high agricultural water demand, the water ran out quickly. This can be understood as a marathon runner's experience; let's say that normally the runner carries a filled up 1 liter water bottle when she starts her marathon. Along the way, she is accustomed to grabbing drinks of water from volunteers along the path to keep herself hydrated. But in the current marathon she has just started, the organizers could not find enough volunteers to pass out water bottles to runners AND failed to notify participants. So the runner drinks from her water bottle until it is empty, and finds herself thirsting for more but there seem to be hardly any volunteers. The runner, as well as all the other participants, have to leave the race unfinished or face collapsing due to severe dehydration. This analogy shows the experience farmers faced in the 2021 drought.

The results of this study matter because in the overall scheme of farming production, they can be used as a cautionary tale for future crop production. In addition, this study shows the three main drought drivers – precipitation, SWE, and reservoir levels – have to be studied as a whole. They always go hand-in-hand in mountainous watersheds, and to ignore one will give an incomplete picture of drought, similar to what was experienced in 2021. The results of this study help find the main reason why irrigation was cut abruptly in 2021, leaving farmers unable to complete their watering season: there was not enough surplus water in the dams from the previous year that could offset the severe lack of spring precipitation and low SWE. Farmers and other communities can use this multivariate approach for future assessment of potential droughts.

The limitations of this study include the fact that I only focused on three variables (SWE, precipitation, reservoir levels), but if more variables were to be included, then other factors could be identified (e.g., soil moisture, temperature, etc.). The three factors studied here were selected because they seem to be most impactful and relevant to drought events in the Boise area, but upon further investigation, additional variables could be identified and predictions could be refined and improved. Another limitation in the study is the time period. I could have alternatively chosen a time period of 100 years to compare 2021 to a wider historical sample, but due to ever changing weather conditions, I identified 1982 through 2021 as most relevant for this study. Furthermore, snowpack data do not extend back to 100 years ago, and the Anderson Ranch dam was operationally available only since the 1950s. Similarly, when there are cases studying over 100 years of data, accuracy may sometimes be inconsistent or missing.

Following this study, some practical actions that could be taken could be the implementation of pamphlets given to local farmers, showing an app that corresponds to the information gathered by this study. The app would go on explaining how multiple variables need to be considered when farmers are planning their growing season, and have a drought monitor gauge that gathers real time data from relevant websites to give farmers an instant multivariate analysis as to the drought outlook for the year. If the app users want more information about specific topics or details relating to the gauge's indicator, there could be links to the databases used for the gauge's reading, such as Idaho Drought Monitor, SNOTEL, drought.gov, and NRCS.usda.gov. Another action to implement would be a government funded research project that includes more variables such as humidity, soil types, weather change, and a comprehensive analysis of water demand resulting from the recent years' dramatic increase of human population in the Boise area.

CHAPTER FOUR: SUMMARY AND CONCLUSION

The climate cycles are changing. In many cases, many of the processes become more stochastic in nature. The results of this paper led to a compilation of data and probability analysis that showed the possible reasons why Boise experienced a drought in the year 2021. Drought predictions have become ever more difficult due to anthropogenically driven stochasticity and trends that are imposed on various processes that govern drought onset, evolution and termination [23]. Precipitation, streamflow, and snowmelt are no longer expected to be stationary, because the rate at which a lot of these variables are changing makes the issue more complex and harder to predict [23]. Furthermore, droughts are due to a complex combination of these factors, making it even harder to predict. One might wonder why these conditions are becoming more difficult to predict; perhaps the answer lies in human inputs. Things like greenhouse gas emissions that trap heat are a good example of human contribution to the strength of natural disasters like droughts.

We know that generally, resources are limited, and water is one of the most important resources for the economic development of a community. However, the quantity of water a particular area will receive each year is becoming increasingly difficult to predict and plan for. By looking at enough data, weather patterns can more accurately be predicted, such as amount and frequency of precipitation, and will hopefully assist in creating a fairly accurate water budget. More importantly, this information helps plan for drought and mitigate some of its negative impacts.

Research questions that were considered for this study included:

1. Where, historically, does the 2021 Boise drought rank in terms of snow, dam storage, and spring precipitation?
2. Which driver contributed most to the multivariate drought of 2021 in the context of natural built systems?

These questions helped to determine which routes of research were necessary for this study. Many residents and farmers felt shock among other things, and were left wondering, how the seemingly sudden drought could have happened.

Question 1 gave specific direction on where to look for more information. I knew that I would need to locate data on SWE, dam storage levels, and precipitation, so I scoured databases from government, local, and other environmental organizations. I pinpointed the specific data from the 1982 through 2021 time period and collected everything into charts and tables for further analysis.

After the undertaking of data collection, I was able to focus on Question 2. I compared historical numbers to individual data points, as univariate analyses, and in combinations, as bivariate analyses. Finally, I used data from all three variables in a trivariate analysis, which was very concise and conclusive to answering the research questions.

This study found that spring precipitation values for 2021 were close to a historic low in the 40 years study period (ranked 2nd worst on record). In addition, SWE values were found at a slightly low value, but without being alarming. Since approximately one third of the years studied, such as 2002, 2005, and 2010, had lower SWE than 2021, this year was not a historical record by itself. Lastly, the three reservoirs that regulate the Boise

River (Arrowrock, Anderson Ranch, and Lucky Peak dams) had slightly above average combined water levels. In comparison, most of the years from the 1990s through 2010 had values below 2021's.

After analyzing the bivariate analyses, the duo of spring precipitation and SWE showed 2021 as having the record low of the two combined. Another bivariate analysis was of spring precipitation and dam storage combined. This showed that only the year of 2002 was lower than 2021, almost setting another record low, mainly due to the precipitation side of the equation. In addition, the combination of SWE and dam storage showed the values were on the lower end yet not record setting. When using the three bivariate analyses, this year was ranked as (1) lowest in spring precipitation-SWE, (2) second lowest in spring precipitation-dam storage, and (3) sixth lowest in SWE-dam storage.

Finally, the trivariate analysis was conducted and showed that the historical drought was due mainly to the combined effect of low SWE and extremely low precipitation levels. When stacked against the 40 years, 2021 showed to be the worst in terms of a trivariate analysis, meaning there was no other year on record with worse spring precipitation AND SWE AND dam storage than those of 2021. This study also revealed that reservoir values are mainly indicative of an ever changing input and output situation, and the driver that contributed most to the 2021 drought was precipitation, and exacerbated by somewhat low SWE.

For future work on Boise droughts, I would recommend a frequent data collection and analysis on the three variables identified (precipitation, SWE, and dam storage levels), in combination with frequent updates given to water consumers, specifically farmers. I would recommend an app to create this information flow, that could also give information on crop needs, in relation to plant species and their specific water requirements. In addition, I would recommend to city officials to modify water regulations to better protect the dramatically increasing urban population from sudden, unexpected water shortage.

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