RESPONSE OF STREAMFLOW AND SPRING DISCHARGE FROM PRECIPITATION RECHARGE EVENTS IN ICEHOUSE CANYON WATERSHED, EASTERN SAN GABRIEL MOUNTAINS, CALIFORNIA

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SIGNATURE PAGE

THESIS: RESPONSE OF STREAMFLOW AND SPRING DISCHARGE FROM PRECIPITATION RECHARGE EVENTS IN ICEHOUSE CANYON WATERSHED, EASTERN SAN GABRIEL MOUNTAINS, CA

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ABSTRACT

Icehouse Canyon watershed lies in the eastern San Gabriel Mountains of Southern California within a natural region of Angeles National Forest. Icehouse Creek is an important tributary of the San Antonio watershed that provides drinking water supplies to residents of Mount Baldy Village and the city of Upland. Surface flow in the creek during dry periods is controlled by discharge from landslide and alluvial deposits in addition to deep-seated fractures and fault zones in crystalline rock. We utilized a velocity flow probe, V-notch weirs, and pressure transducers to measure streamflow in Icehouse Creek and discharge from associated perennial springs at approximately bi-weekly intervals between June 2014 and January 2018. Pressure transducers were installed at selected gauging stations in order to obtain a continuous record of surface flow over long periods of time. Coincident with the discharge study, we have monitored precipitation at 5 rain gauges located between 4,600 and 6,200 ft elevation beginning December 2014. Our general objective was to record the watershed's response to precipitation recharge events.

Distribution and magnitudes of storm events occurring within Icehouse Canyon watershed varied from year to year. The highest monthly precipitation values were recorded during the months of December 2016 and January 2017. On an annual basis, the highest precipitation value of 36.2 in occurred in 2017. Spatial flow variations observed along Icehouse Creek may be governed by factors such as surrounding surface and subsurface geology. Stations that recorded the highest streamflow values displayed significant bedrock exposure, causing groundwater to rise to the surface at those specific locations. Examination of hydraulic responses occurred through analysis of the composite charts comparing precipitation and streamflow data. The results revealed that Icehouse

Creek responded rapidly (<1 week) after the occurrence of noteworthy storms producing more than 2 inches of precipitation. In contrast, the springs generally responded significantly slower to major storm events. Results from the isotopic analysis revealed strong similarity between the spring samples and the precipitation samples collected in Icehouse Canyon. The isotopic results suggested that groundwater discharging at the spring locations may be derived from local meteoric water following recent storm events. Calculated groundwater ages from the tritium data ranged between 20 to 30 years for Spring #2 and East Cabin Spring. These results are important because they show non-zero values suggesting that mixing may be occurring between local meteoric water and older groundwater from deep fractures in the bedrock. Noticeable spatial and temporal variations were detected in water quality for the creek and spring locations. Overall, the water quality for the samples collected were determined to be in excellent condition based on current federal regulations.

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INTRODUCTION

Purpose and Objectives

The purpose of this research study was to accomplish two primary goals: (1) to quantify the hydraulic response of a mountain watershed following precipitation recharge events (2) to constrain potential sources of water for naturally occurring springs that supply groundwater to Icehouse Creek. In addition, a general objective (3) was to gain more practical knowledge of the available water resources located within Icehouse Canyon watershed. Initially, one important goal of this research study was to observe the transition from a severe 3-year drought period into a predicted strong El Nino year, which should have produced significant storm events, but did not meet expectations. Instead, the observational period captured continued drought conditions for two additional years. This particular observational period may be considered significant due to unprecedented drought conditions recently impacting the state of California. The third year of this study captured an unexpected wet period and its outcomes.

To accomplish these research goals, various field methods were utilized throughout the data collection phase of the project. Manual flow measurements were performed using instruments such as a current meter and v-notch weirs. Spring discharge was monitored at two separate gauging stations by installing pressure transducers. Precipitation was manually measured following storm events using several rain gauges installed at different elevations within the watershed area. The locations of springs were determined using a handheld GPS unit and a detailed hydrogeologic map was developed using ArcGIS software. Finally, water samples were collected at spring locations to determine basic water quality parameters, measure tritium concentrations, and to analyze stable water isotopes.

Project Location and Background

The study area for this research project is located in the eastern San Gabriel Mountains of Southern California within a watershed of the Angeles National Forest known as Icehouse Canyon. This canyon is situated north-east of Mt. Baldy Village, where a small community of locals live and where many visitors stop to dine and rest after exploring the outdoors. Upon arriving at the parking lot near the canyon entrance, visitors will find a detailed map created by the U.S. Forest Service located at the trailhead. This map of the local region shows Icehouse Canyon Trail running parallel to Icehouse Creek, which spans a total distance of approximately 4.4 miles, beginning in Icehouse Trailhead near the parking lot and ending at Icehouse Saddle (Robinson, 1977). Figure 1 displays a satellite image from Google earth (2018) showing the general location of the study area. The box outlined in red provides a closer view of the study area and the targeted canyon for investigation. Figure 2 presents a Google earth satellite image illustrating the delineation of Icehouse Canyon watershed outlined in blue. The watershed area and perimeter were estimated using the measuring tool in Google earth Pro (2015), which yielded 8.47 mi for the perimeter and 4.44 mi² for the watershed area. Furthermore, the main trail in Icehouse Canyon passes through steep and rugged terrain, which gradually increases in elevation from 4,920 ft to approximately 7,580 ft at Icehouse Saddle. The surrounding peaks that delineate the watershed include: Ontario Peak (~8,700 ft), Bighorn Peak (~8,400 ft), Timber Mountain (~8,300 ft), Telegraph Peak (~8,900 ft), and Thunder Mountain (~8,500 ft). This forested region of the Cucamonga

Wilderness is home to a variety of wildlife including deer, black bear, mountain lions, bob cats, big horn sheep, and coyotes.

In addition, the study area is filled with remains from pre-existing buildings that provide valuable clues about the history of Icehouse Canyon. For instance, in 1921 a building known as the Icehouse Canyon Resort was built by a land owner named Roy Chapman (Robinson, 1977). This particular building was once located near the entrance of Icehouse Canyon Trail, however, today only two stone pillars that supported a large wooden sign still remain standing. The interior space of this building was frequently used for filming movies and TV shows for nearly fifty years (Robinson, 1977). It is also believed that around 1858 people from the city of Los Angeles were supplied with ice cream made from blocks of ice cut from the mountains of San Antonio, which may explain the origin of the name "Icehouse Canyon".

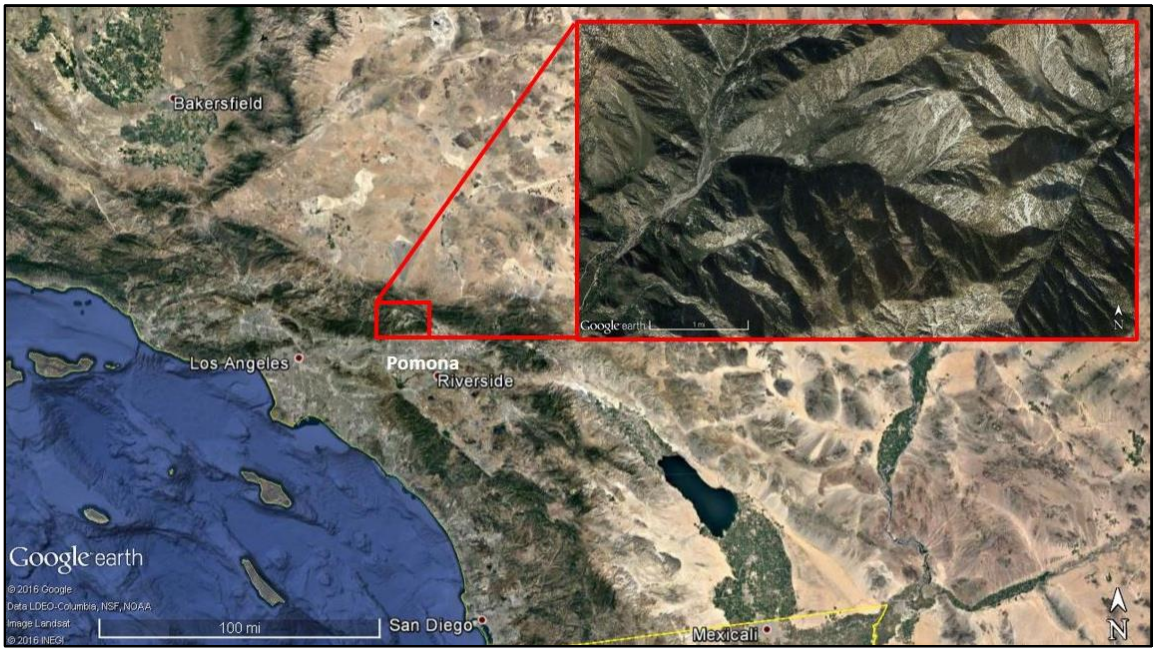


Figure 1. Satellite image from Google earth (2018) displaying the general location of the study area.

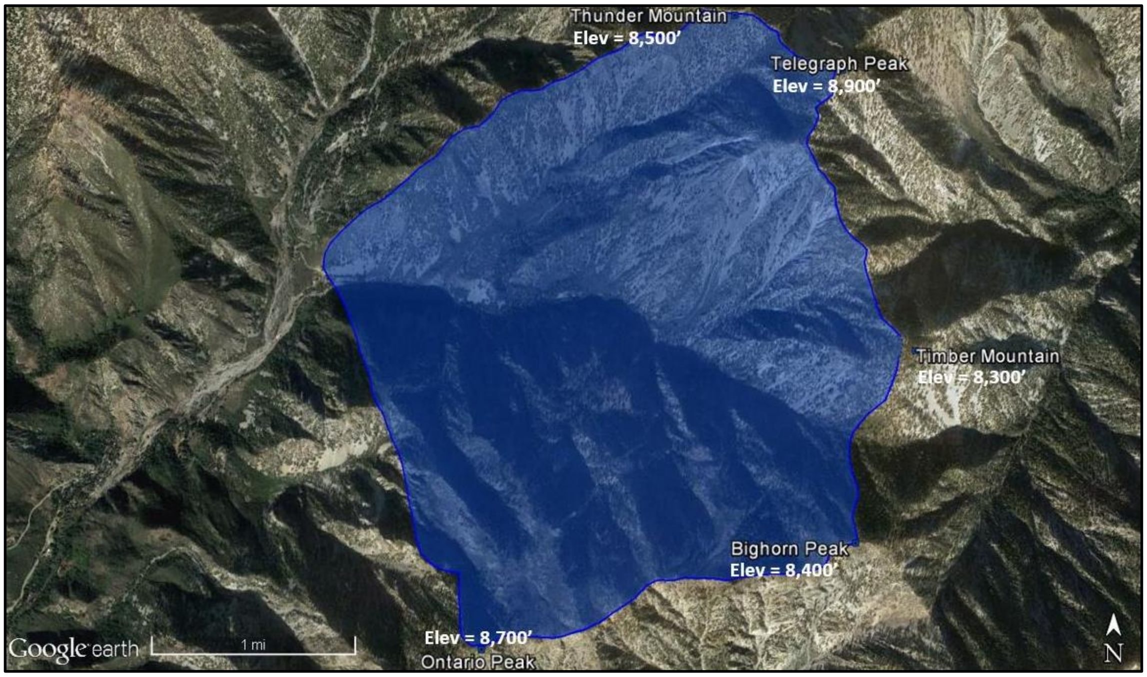


Figure 2. Google earth (2018) satellite image illustrating the delineation of Icehouse Canyon Watershed area in blue.

Previous Work

Research studies have been conducted within Icehouse Canyon watershed over the past 23 years. An undergraduate student from the Pomona College Geology Department completed a research study in Icehouse Canyon that investigated the seasonal influences on stream chemistry and potential evidence for mining activity in the past (Cunningham, 1992). His research goals included the following: to observe seasonal fluctuations in stream chemistry, to discover significant levels of metal content in the stream discharge that would suggest mining activity, and to verify the surface geology within the surrounding study area. Three sites were selected along a mile section of Icehouse Creek for sample collection and field measurements. At approximately bi-weekly intervals, Cunningham collected water samples and measured water quality parameters including: temperature, pH, and oxidation reduction potential. Cunningham also performed chemical analysis at the Pomona College laboratory to measure chloride, chromium, copper, cyanide, iron, total dissolved solids, and total hardness. The final test results from the water samples revealed no evidence of mining activity within the watershed area. In addition, seasonal variations in stream chemistry were detected over the observational period which were attributed to multiple factors including storm events.

Melissa L. Pratt, an undergraduate Geology student from Cal Poly Pomona, completed a research study that investigated the hydrogeology of Icehouse Canyon watershed (Pratt, 1995). The primary goals of this research project included the following: monitoring streamflow during two consecutive years, identifying gaining and losing segments along Icehouse Creek, performing geologic mapping of the study area, and completing a water budget analysis for the watershed. Because Icehouse Creek is an important tributary to the San Antonio watershed, Pratt assumed that significant water contributions may be derived from this tributary. Three field methods were utilized during the observational period in order to determine streamflow and spring discharge within the watershed. These methods included the stick method, current meter method, and bucket catch method. The hydrologic data collected over the two-year period revealed that losing and gaining segments along Icehouse Creek are influenced by spring and tributary contributions, locations of alluvium widening, and bedrock exposure causing groundwater to rise to the surface. Results from the water budget analysis estimated that approximately 30% of the total water found in San Antonio Creek is contributed by Icehouse Canyon watershed, which is a significant amount. Pratt's investigation provided new scientific knowledge regarding water resources and a better understanding of the hydrogeology in Icehouse Canyon watershed.

Another study was completed in Icehouse Canyon by Lauren R. Carey, an undergraduate Geology student at Cal Poly Pomona (Carrey, 2009). She discussed baseflow recession values in comparison to surrounding drainage basins, and examines the hydraulic conductivity of landslide material from an important aquifer located within the study area. The main objective of this research project was to monitor discharge at different spring locations within the watershed in order to record the effects in streamflow along Icehouse Creek, which allowed baseflow recession values to be determined. In addition, properties of the landslide material such as hydraulic conductivity was also evaluated to acquire more information about the aquifer properties and associated springs. Similar field methods were utilized in this study including the bucket-catch method and velocity-area method to estimate spring discharge and streamflow values. The results suggest that baseflow recession values for various gauging stations remain relatively constant over time with minor variation due to factors such as geology, vegetation, topography, and precipitation recharge events. Carey's analysis revealed an inverse relationship between precipitation and baseflow recession values in Icehouse Canyon, suggesting that recharge events may have an influence on the rate of drainage. Furthermore, Carey estimated a relatively high value for hydraulic conductivity of the landslide material, which indicates that the aquifer is capable of transmitting and storing significant quantities of groundwater. This may explain the resiliency of perennial springs within the watershed that are responsible for sustaining surface flow in Icehouse Creek throughout the year.

A Geological Society of America field guide was created by several authors containing information regarding the hydrogeologic characteristics of Icehouse Canyon

(Nourse et al., 2010). Figure 3 presents a hydrogeologic map of the study area developed in Arc Map by Dr. Jonathan A. Nourse, professor of Geological Sciences at Cal Poly Pomona, from several years of detailed fieldwork observations (Nourse and Miranda, 2017). The hydrogeologic map shows various surface geological units including the following: Holocene alluvium (Qa), well-consolidated Quaternary landslide (Qls), poorly consolidated Holocene talus deposit (Qt), and nonporous crystalline bedrock (b). These geological units especially the Quaternary deposits have a major influence on the surface flow regulation of Icehouse Creek and associated tributaries supplied by natural springs. The Qls and Qt units in particular behave like sponges by absorbing rainfall and snowmelt during winter and spring months, then gradually releasing the stored groundwater to drainages such as Icehouse Creek during the summer and fall dry seasons (Nourse et al. 2010, Nourse and Miranda, 2017).

The hydrogeologic map also displays specific locations of gauging stations along Icehouse Creek with asterisk symbols and the locations of perennial springs using solid red circles. It appears that many of the perennial springs discharge near contact points between nonporous bedrock units and highly porous surface deposits. These springs (Spring #1, Spring #2, and Spring #3) correspond to locations where bedrock units act as barriers, which tend to force groundwater within the sediments to rise up to the surface (Nourse et al. 2010). Field observations indicate that a steep south facing wall of Icehouse Canyon prevents direct sunlight from reaching lower areas of the Canyon during the months of December and January, which tends to preserve ice and snow for longer periods of time due to less sun exposure. One reason for continuous flow in Icehouse Creek is the persistence of snow on the south facing slope of the canyon that gradually melts during the months of April through July, which then feeds the springs during the dry season period (Nourse et al. 2010).

In addition, some research studies conducted near the area of interest examined the impact of environmental factors on water resources. For instance, Susan Perez completed a thesis project at Cal Poly Pomona that investigated the impacts of soil, bedrock, vegetation, and solar energy input on baseflow recession at two adjacent watersheds in the eastern San Gabriel mountains (Perez, 2015). Multiple geologic maps of the study area were analyzed utilizing geographic information system tools to compare and contrast the various features of two neighboring watersheds. The research findings from this project revealed that spatial variations in surface geology, vegetation, and sunlight exposure were significant for both watersheds, which may explain the differences in baseflow recession rates and evapotranspiration.

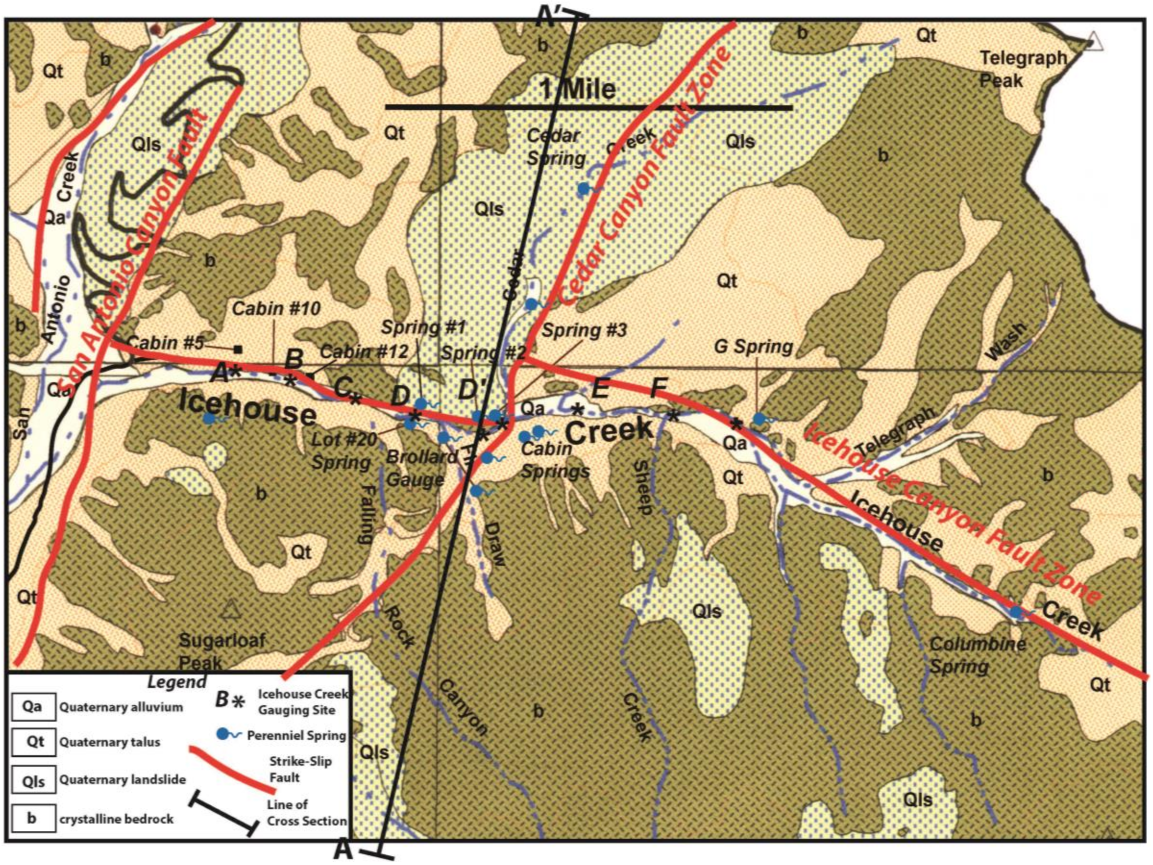


Figure 3. Hydrogeology map of the study area showing surface geology and specific locations of various gauging stations from previous work performed along Icehouse Creek (Nourse et al. 2010, Nourse and Miranda, 2017).

Paula Soto, an undergraduate student from the Geology Department at Cal Poly Pomona completed a research study involving two springs from Icehouse Canyon watershed (Soto, 2015). Discharge was measured at Spring #1 and Spring #2 using a flow meter and the bucket-catch method during the project duration. Water samples were collected for selected spring locations to analyze water isotopes including Oxygen 18 and Deuterium as well as tritium for age dating. Isotope analysis was performed to asses potential mixing between deeper older groundwater and shallower younger groundwater. One objective of this research study was to monitor the effects of extended drought conditions on local water resources. A second objective was to improve the understanding of water quantity and quality in the study area, in order to benefit those that utilize the resource.

Presently, there are certain knowledge gaps that exist for Icehouse Canyon watershed, which will be addressed with this current research study. For instance, there is no precipitation data available for the canyon itself and little is known regarding the sources of groundwater discharging at the selected spring locations. In order to address these knowledge gaps, this research study will examine the following areas: a detailed distribution of precipitation within Icehouse Canyon watershed, the relation of specific storm events to discharge in Icehouse Creek and four perennial springs, and the delineation of specific groundwater sources that contribute to spring discharge. Focusing research efforts in these specific areas will help narrow the existing knowledge gap in Icehouse Canyon watershed.

Research Objectives

This research study has 3 main research objectives: (1) to quantify the hydraulic response of a mountain watershed following precipitation recharge events (2) to constrain potential sources of water for naturally occurring springs that supply groundwater to Icehouse Creek and (3) to gain more practical knowledge of the available water resources located within Icehouse Canyon watershed. These specific research objectives will address knowledge gaps in previous studies, such as precipitation data for storm events within the watershed and determination of sources for groundwater discharging at selected spring locations. I will utilize various field methods and isotopic analyses to obtain data that will narrow the knowledge gaps.

METHODS

Gauging Stations

Data collection in the field occurred at various locations within the watershed area. Figure 4 displays a satellite image from Google earth (2018) showing the selected gauging stations with red, yellow, and blue circular icons. The red circular icons identify locations for gauging stations along Icehouse Creek, and yellow icons represent locations for perennial springs that supply water to the stream. These specific gauging stations include the following: A, B, C, Broullard, D', Spring #1, Spring #2, East Cabin Spring, and Cedar Glen Spring. The blue circular icons represent locations of five all-weather rain gauges installed at various elevations. These rain gauges were labeled with the following names: Confluence, Cabin 5, Cabin 34, Chapman, and Cedar Glen. Sections below provide descriptions of various methods used.

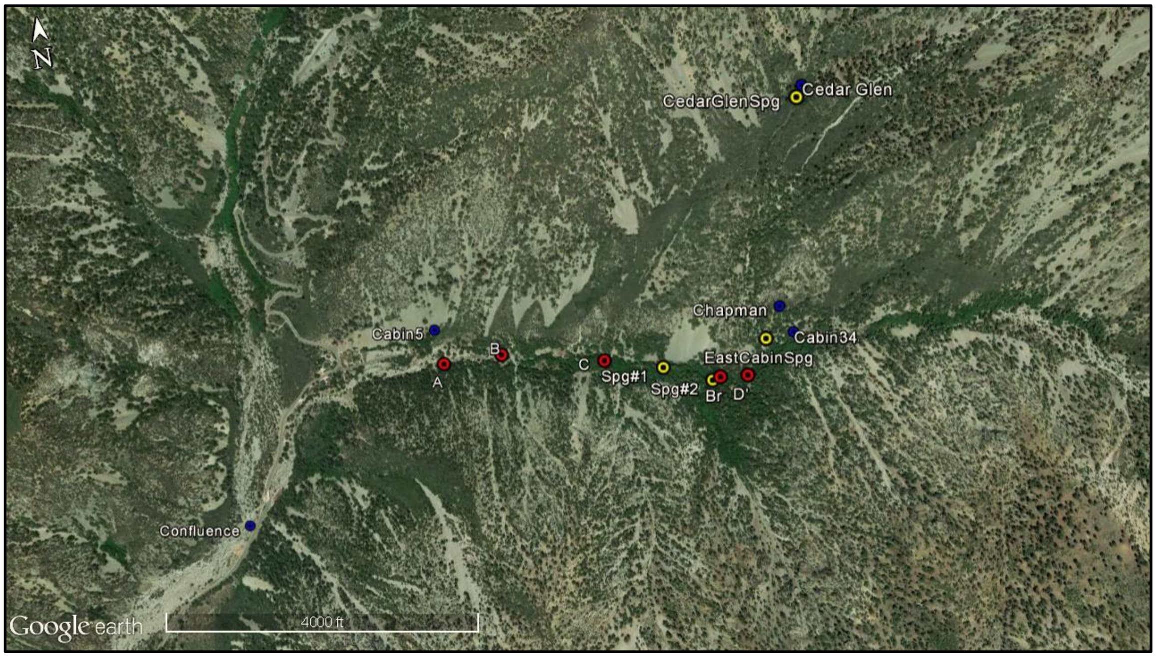


Figure 4. Satellite image from Google earth (2018) showing selected gauging stations within Icehouse Canyon watershed. Blue circles represent locations of rain gauges, red circles indicate creek flow stations, and yellow circles show spring locations.

Bucket Catch Technique

Various methods were utilized in this research study to determine streamflow in Icehouse Creek and discharge for perennial springs located within the canyon. These field methods include the following: 1) bucket catch method, 2) velocity-area method, 3) triangular v-notch weir method, and 4) the application of pressure transducers. The bucket catch method in particular was applied to areas of low to moderate flow conditions such as Spring #2 and East Cabin Spring gauging stations where the majority of surface flow could be captured with a container of appropriate size and shape. Three pitchers of different sizes (0.25 gal, 0.5 gal, 1 gal) made from clear plastic material were used to capture spring water. The amount of spring water captured with the containers was estimated as a percentage of total discharge and taken into account in the final calculation step. Moreover, the bucket catch method involved a simple procedure of measuring the amount of time (using a stopwatch) required to fill a container of known volume. Five consecutive measurements were recorded in a field notebook, and the average value was used to determine spring discharge. The discharge value was initially calculated in units of cubic feet per second using the equation below then converted into units of gallons per minute.

$$Q = \text{Volume/Time} \qquad \textbf{(Equation 1)}$$

Figure 5. Capturing spring discharge using a measuring cup and stopwatch to record elapsed time.

Velocity-Area Method

The velocity-area method was applied primarily along the main channel of Icehouse Creek for low to moderate flow conditions. The procedure for this particular method involved a detailed survey of the cross-sectional area of the main stream channel and measuring average stream velocity using a portable flow probe. For each gauging station located along Icehouse Creek (A, B, C, Broullard, and D') the width and depth of the channel were measured in units of centimeters using stainless steel rulers of different lengths. To account for a non-uniform stream bed, the depth was measured at multiple points across the main channel and an average depth was computed. After determining the dimensions of the cross-sectional area, the average stream velocity was measured by moving a flow probe slowly and smoothly throughout the cross-sectional area of the stream channel until an average velocity reading stabilized in the display screen of the instrument. Additionally, the portable flow probe used in this study is manufactured by Global Water, Inc. and is capable of measuring the average stream velocity to an accuracy of +/- 0.1 feet per second (Global Water, 2009). Streamflow values using this particular method can be determined by using the equation below where cross-sectional area (A) of the stream channel is multiplied by the average stream velocity (V).

$$Q = \mathrm{A} \bullet \mathrm{V} \qquad \textbf{(Equation 2)}$$

The streamflow for gauging stations along Icehouse Creek was first calculated in units of cubic feet per second (ft^3/sec), then converted into units of gallons per minute (gal/min).

Figure 6. Measuring average stream velocity at the Broullard gauging station using a Global Water digital flow probe.

Thin Plate 90° V-notch Weirs

The third method implemented in this research project to determine discharge values involves the use of thin plate 90° V-notch weirs. These V-notch weirs were constructed from sheets of clear acrylic material with various dimensions depending on the width and depth of the stream channel where gauging stations were selected. The V-notch opening placed at the center of the weir was made with a central angle equal to approximately 90°. To properly install the weir plate, it was inserted into the streambed and balanced vertically and horizontally using a level bubble instrument. The sides of the weirs were then covered with soil and streambed material to prevent any water from leaking. Weir plates were installed at three different spring locations including Spring #1, East Cabin Spring, and Cedar Spring in order to obtain flow measurements efficiently and accurately. Figure 7 shows a photograph of one V-notch weir installed at the Spring #1 gauging station. According to the U.S. Geological Survey (1982), the proper field procedure for this method involves the measurement of vertical distance from the bottom of the notch to the surface water level; this measurement is typically made at a location slightly upstream from the weir plate to avoid any influence from drawdown caused by the opening (Measurement of Stage, USGS). In this research project, a clear ruler was attached to the side of the weir to perform the required measurement. The vertical distance value is commonly represented by the variable h, which is also referred to as the static head of the weir (Fetter, 2001). Furthermore, once the head value is measured, then spring discharge was calculated using the following empirical equation

$$Q = 2.5h^{2.5} \qquad \textbf{(Equation 3)}$$

where Q = discharge in cubic feet per second, and h = static head above the weir crest in units of feet (Fetter, 2001). The overall goal from implementing this particular field method was to obtain more accurate values of discharge in order to improve the level of confidence in the hydrologic data.

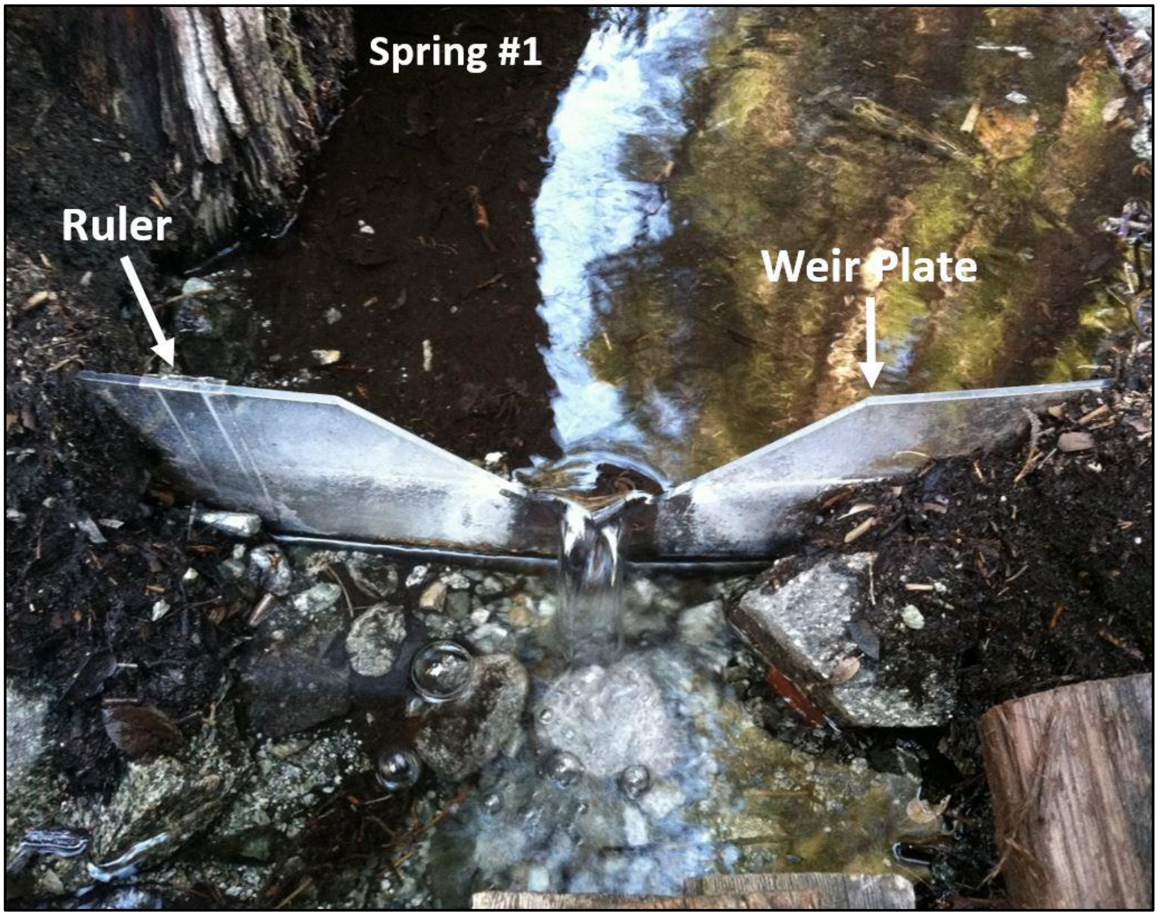


Figure 7. Photograph of a thin plate 90° V-notch weir installed at the Spring #1 gauging station.

Pressure Transducers

During the observational period of this research project, two AquiStar PT2X Smart Sensors manufactured by Instrumentation Northwest Inc. were used for water level data collection. The Smart Sensors were installed at selected spring locations including East Cabin Spring and Cedar Spring to monitor water temperature and pressure in real-time. These pressure transducers are integrated dataloggers designed with built-in pressure and temperature sensors. They have the capability of measuring fluid pressure in units of pounds per square inch (psi), temperature in degrees Celsius, and actual time. The data collected in the field utilizing these sensors can be viewed and exported into an Excel workbook using the provided control software from the manufacturer called Aqua4Plus. Figure 9 is a diagram illustrating how the pressure sensor communicates with a laptop computer in order to view and download the collected field data. The pressure transducers were preprogrammed to record one measurement at one hour intervals for several consecutive weeks. The overall goal was to record data at the selected spring locations in order to observe the long-term variations in water pressure and temperature. Figure 8 is a photograph showing the current experimental setup at the East Cabin Spring gauging station.

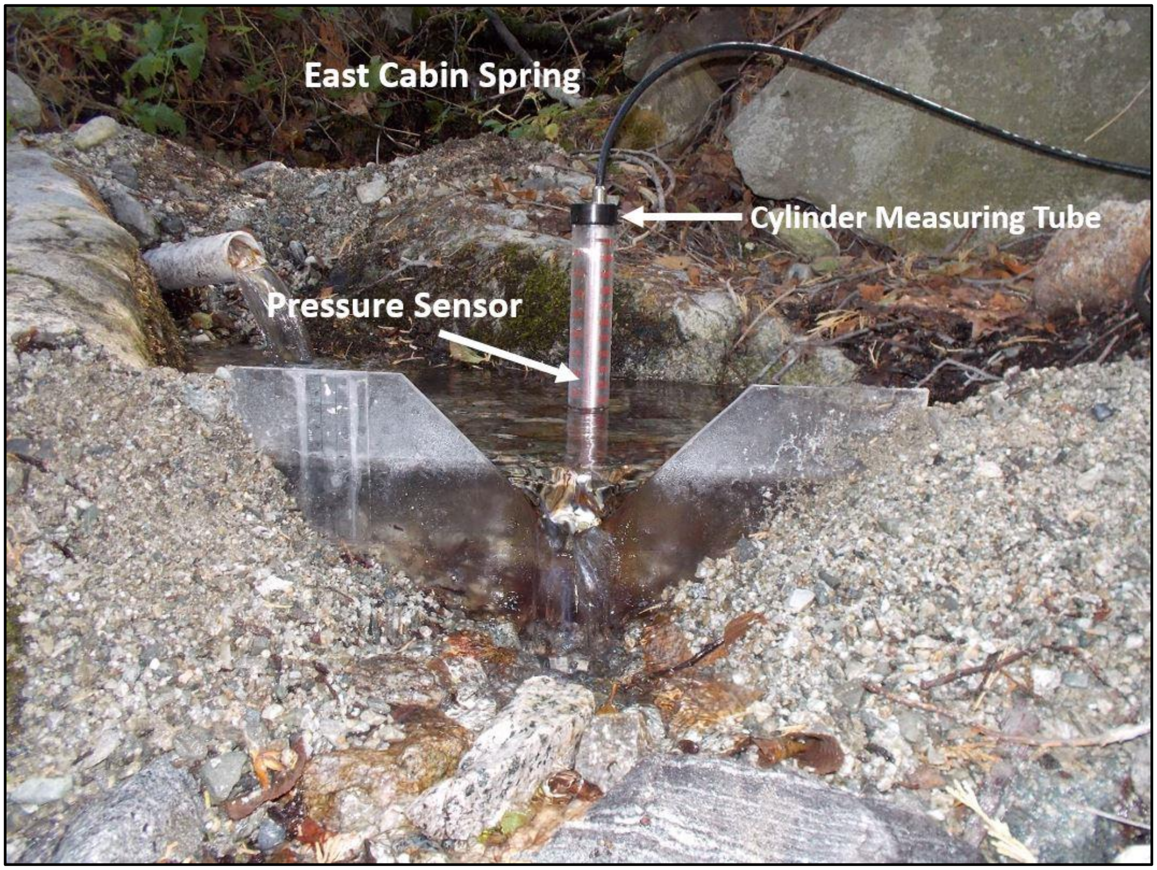


Figure 8. Pressure transducer placed inside a clear cylinder measuring tube to record water level pressure on an hourly basis.

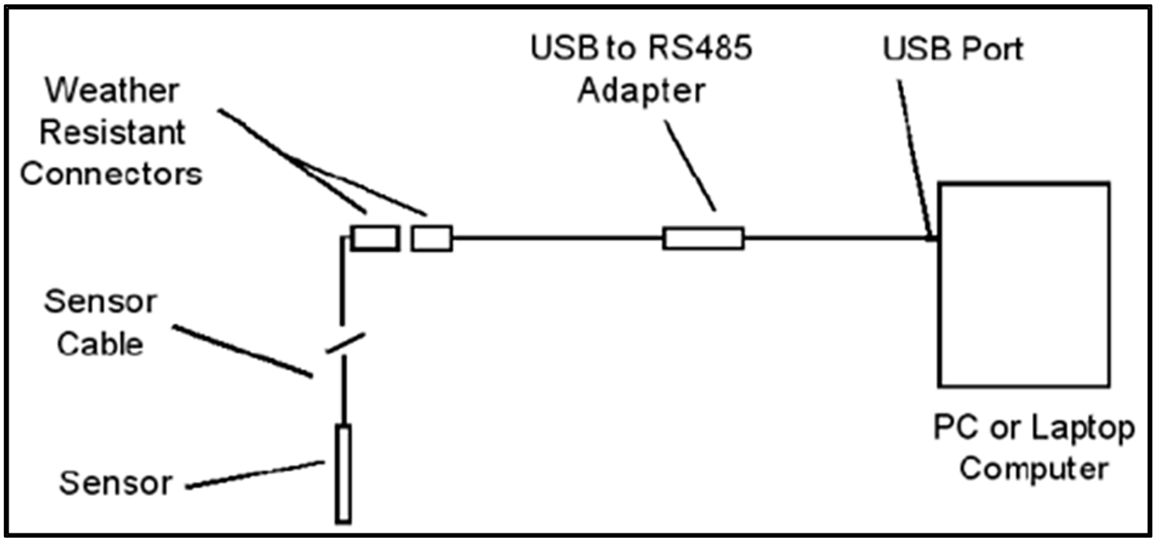


Figure 9. Diagram illustrating how the PT2X Smart Sensor communicates with a laptop computer (Instrumentation Northwest Inc., 2013).

Stage-Discharge Relation

The U.S. Geological Survey (1982) is able to obtain a continuous record of discharge in real-time for various stream gauging stations around the nation by implementing the stage-discharge relation method. This method involves the following steps: obtaining a continuous record of stage (elevation of water surface above a datum) for a specific gauging station, measuring discharge periodically at this gauging station, establishing and maintaining a relationship between stage and discharge, and applying this relationship to the stage record (USGS Water Science School, 2016). For the East Cabin Spring and Cedar Spring gauging stations, water level pressure data recorded with the pressure transducers were converted into stage values using the hydrostatic equation. In addition, the spring discharge at these gauging stations were measured periodically using the V-notch weirs. From this information, it was possible to plot stage versus discharge, which is also referred to as a rating curve. Rating curves show the relationship between stage and discharge in graphical form and are useful for determining discharge values for any corresponding stage measurement. This method allows a continuous record of discharge to be obtained through the application of a rating curve. Furthermore, obtaining a continuous record of spring discharge for these gauging stations can be useful for observing seasonal and diurnal variations, which is beneficial for water resources management.

Precipitation Measurements

Storm events occurring within Icehouse Canyon watershed were documented by measuring and recording the amount of precipitation produced from each storm event using several rain gauges. Five all-weather rain gauges manufactured by Productive Alternatives were installed between 4,600 and 6,300 ft in elevation within the watershed area. The installation locations for these rain gauges were carefully selected in open areas to prevent tree branches or large bushes from interfering with the capture of precipitation during storm events. Figure 10 is a photograph showing one of the rain gauges installed near the Cabin 5 location. The components of each rain gauge instrument consist of a funnel for capturing rainfall, an inner tube for measuring inches of water, and an outer tube for overflow water. By obtaining long-term precipitation records, the orographic effect (i.e. the variation in precipitation with increasing elevation) in Icehouse Canyon may be determined. Additionally, the orographic trend can then be extrapolated in a linear fashion to higher elevations in order to estimate average annual precipitation for Icehouse Canyon watershed (Nourse et al., 2010). Ultimately, the average annual precipitation of the study area is important for developing water budget analysis and water resources management.

Figure 10. Photograph of an all-weather rain gauge installed at the Cabin 5 location.

Stable Water Isotopes Measurements

Water samples were collected from the spring locations and two rain gauges to perform an analysis of stable water isotopes including $\delta^{2}H$ (deuterium) and $\delta^{18}O$. The water samples were collected using 1,000 ml narrow mouth plastic bottles and analyzed at the UC Riverside Isotope Laboratory within the Department of Environmental Sciences. Figure 11 is a photograph showing the laboratory equipment used for completing the analysis, a triple isotope water analyzer model number TIWA-45-EP manufactured by Los Gatos Research. These specific water isotopes were selected for analysis in order to gain a better understanding of the type of water sources discharging at the spring locations in Icehouse Canyon such as deep groundwater or shallow groundwater sources.

Figure 11. Laboratory equipment used to measure isotopic ratios of stable Hydrogen and Oxygen isotopes located within the Environmental Sciences Department at UC Riverside.

Tritium Analyses for Groundwater Age Dating

Water samples were collected from two spring locations in Icehouse Canyon to analyze tritium concentrations. The water samples from Spring #2 and East Cabin Spring were collected using 1,000 ml narrow mouth plastic bottles. These samples were analyzed on May 12, 2016 at the Environmental Isotopic Laboratory within the Geosciences Department at the University of Arizona. The research objective for this specific method was to estimate the age of groundwater discharging from these spring locations in order to distinguish between different type of water sources and potential mixing between younger shallow groundwater and older deeper groundwater.

Water Quality Parameters

Various water quality parameters were measured periodically at each monitoring station utilizing a portable field instrument. These parameters include the following: temperature, pH, conductivity, total dissolved solids, and salinity. The field instrument used is manufactured by Oakton Instruments and labeled the Waterproof Multiparameter PCS Testr 35 model number WD-35425-10. Instrument calibration with three different pH solutions (4, 7, and 10) was performed before each data collection session in order to maintain accurate measurements in the field. The procedure for measuring the various parameters required inserting the instrument sensor 1 inch below the water surface for approximately 2 minutes until the LCD screen stabilized with one value. After stabilization was reached, the values were recorded in a field notebook. This procedure was repeated for each water quality parameter until all five parameters were measured. Moreover, there were three primary research objectives associated with this particular method. First, to compare the water quality of the springs with Icehouse Creek in order to examine any similarities or differences. Secondly, to detect any potential sources of contamination from nearly cabin shelters or past mining activities. Finally, to gain a better understanding of the quality of water resources in the Icehouse Canyon watershed.

Figure 12. Waterproof Multiparameter PCS Testr 35 manufactured by Oakton Instruments (http://www.4oakton.com). This field instrument was used to measure various water quality parameters at each gauging station.

HYDROLOGIC RESULTS

Over the course of the project duration beginning on June 2014 and ending on March 2018, various types of hydrologic data were collected and analyzed for the study area. Figure 4 presents a satellite image showing the gauging stations where this data was collected within the watershed. The results gathered from this data collection effort provided the following graphs and charts: precipitation hyetographs, stream hydrographs, spring hydrographs, rating curves, stable water isotope graph, and water quality graphs. Climatic conditions under which the data collection phase occurred included an extended drought period during the first two years followed by a few significant recharge events that triggered noticeable hydraulic responses.

Rain Gauges

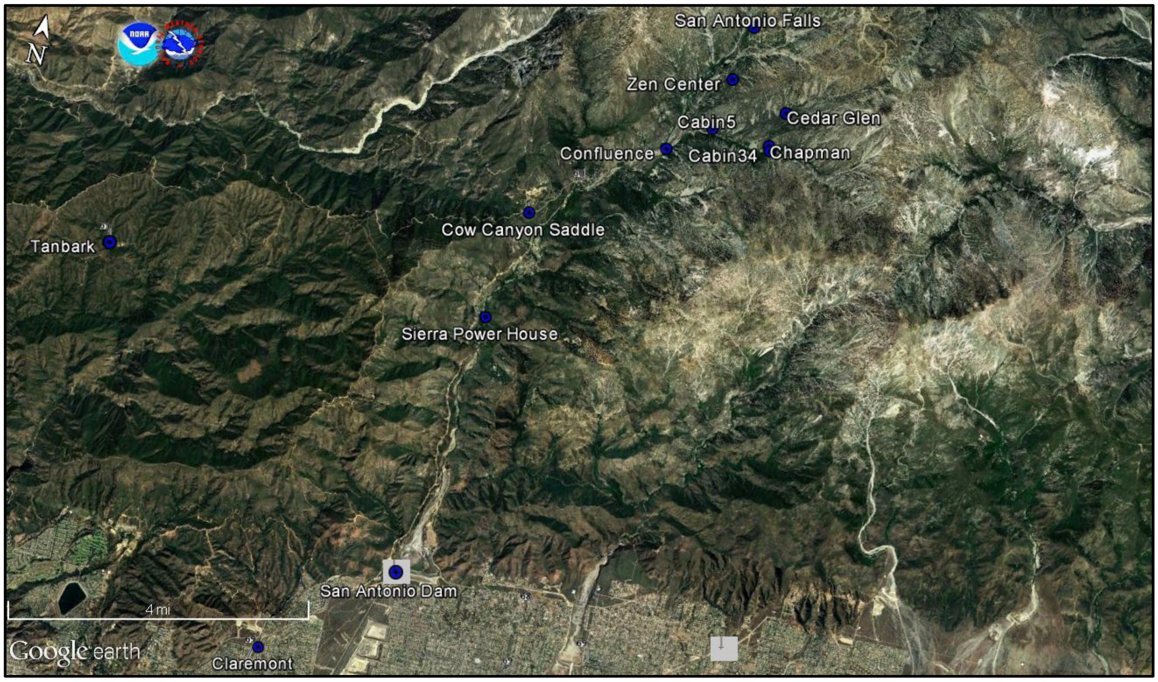
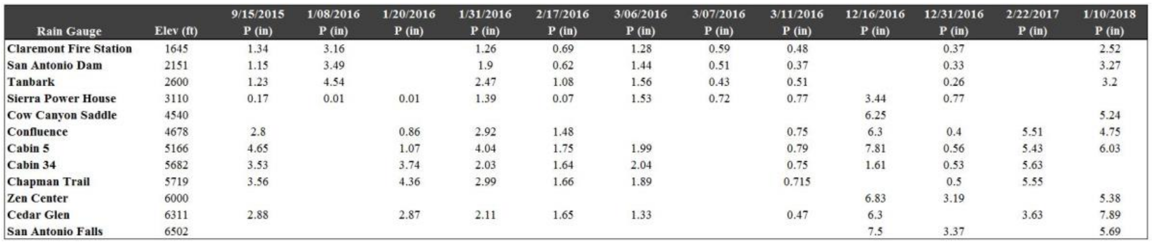


Figure 13. Satellite image from Google earth (2018) showing all the rain gauges utilized in this research study. Precipitation data from twelve rain gauges was used for analysis and interpretation.

Precipitation Data

Several major storm events occurred during the project duration that impacted the study area. Table 1 contains precipitation data for some of these noteworthy storm events that resulted in significant streamflow increases for Icehouse Creek. For instance, one major storm event occurred on December 16, 2016 generating 7.81 inches of precipitation for the Cabin 5 rain gauge. A second storm event occurred on February 22, 2017 producing 5.43 inches for the same rain gauge. In addition, on January 10, 2018 a third major storm event yielded a precipitation value of 6.03 inches at Cabin 5. These significant recharge events resulted in noticeable spikes as seen in the hydrographs for the creek monitoring stations.

Table 1. Precipitation data for twelve significant storm events occurring from 2015 to 2018.



Rain Gauge	Elev (ft)	9/15/2015 P (in)	1/08/2016 P (in)	1/20/2016 P (in)	1/31/2016 P (in)	2/17/2016 P (in)	3/06/2016 P (in)	3/07/2016 P (in)	3/11/2016 P (in)	12/16/2016 P (in)	12/31/2016 P (in)	2/22/2017 P (in)	1/10/2018 P (in)
Claremont Fire Station	1645	1.34	3.16		1.26	0.69	1.28	0.59	0.48		0.37		2.52
San Antonio Dam	2151	1.15	3.49		1.9	0.62	1.44	0.51	0.37		0.33		3.27
Tanbark	2600	1.23	4.54		2.47	1.08	1.56	0.43	0.51		0.26		3.2
Sierra Power House	3110	0.17	0.01	0.01	1.39	0.07	1.53	0.72	0.77	3.44	0.77		
Cow Canyon Saddle	4540									6.25			5.24
Confluence	4678	2.8		0.86	2.92	1.48			0.75	6.3	0.4	5.51	4.75
Cabin 5	5166	4.65		1.07	4.04	1.75	1.99		0.79	7.81	0.56	5.43	6.03
Cabin 34	5682	3.53		3.74	2.03	1.64	2.04		0.75	1.61	0.53	5.63	
Chapman Trail	5719	3.56		4.36	2.99	1.66	1.89		0.715		0.5	5.55	
Zen Center	6000									6.83	3.19		5.38
Cedar Glen	6311	2.88		2.87	2.11	1.65	1.33		0.47	6.3		3.63	7.89
San Antonio Falls	6502									7.5	3.37		5.69

Precipitation data derived from two different rain gauges was utilized to develop a hyetograph for a specific area within Icehouse Canyon. The primary rain gauge used was installed at the Cabin 5 location; this particular rain gauge contained a larger and more reliable data set in comparison to other rain gauges placed within the canyon. The secondary rain gauge known as the Sierra Power House station is currently managed by the County of Los Angeles, within the Department of Public Works. Precipitation data from this station was included in order to supplement missing information for months where no data was available from the Icehouse Canyon stations. Figure 14 presents a hyetograph showing the distribution and magnitudes of storm events that occurred during the observation period. According to the hyetograph, the distribution and magnitudes of storm events varied from year to year. The storm events ranged from 0 to 7.81 inches of precipitation and averaged 1.34 inches during the data collection phase. The largest storm events were recorded from December 2016 to February 2017. During this time period, the largest storm event generated 7.81 inches of precipitation. This significant storm event was the largest recorded throughout the project duration, and probably provided substantial recharge water to the local aquifers. In addition, a major storm event on January 10, 2018 generated 6.03 inches of precipitation. This was the third largest storm event recorded during the project duration, and is also significant because it is the first major recharge for the watershed since May of 2017.

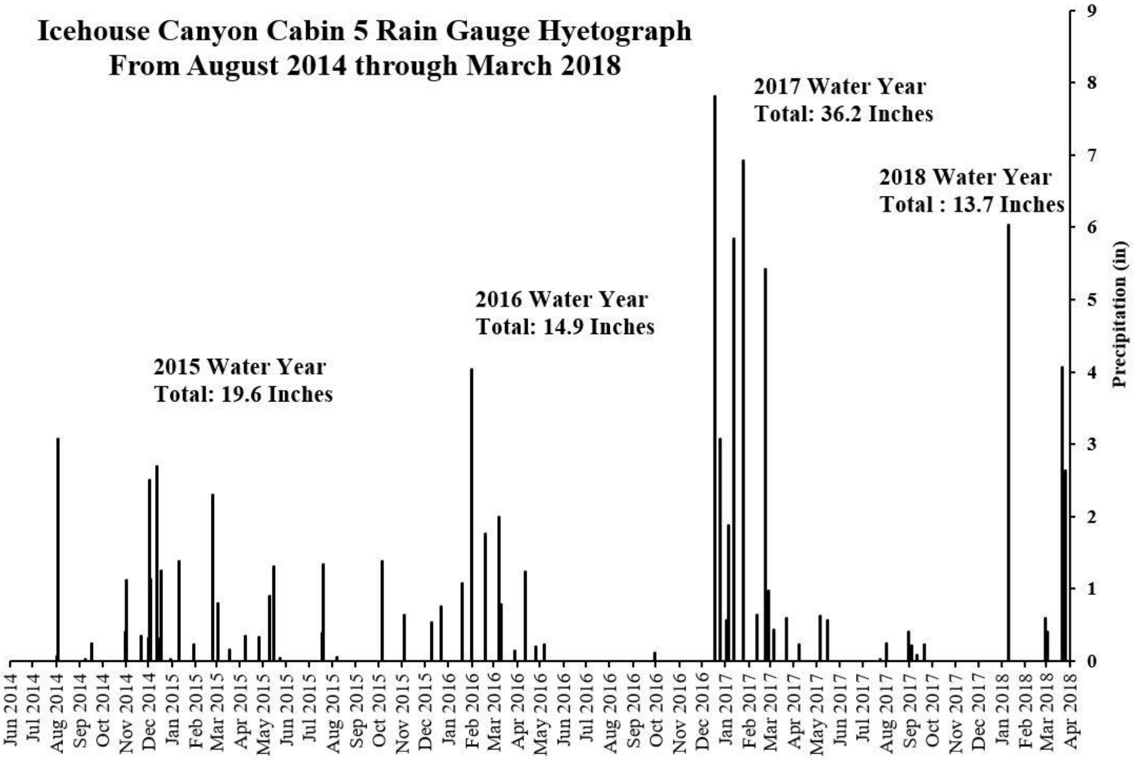


Figure 14. Hyetograph from the Cabin 5 and Sierra Powerhouse rain gauge stations displaying the distribution and magnitude of storm events occurring during the project duration.

Precipitation data obtained from the Cabin 5 rain gauge was analyzed to determine the amount of monthly precipitation collected. Figure 15 is a bar graph displaying the inches of precipitation that were captured with the rain gauge on a monthly basis over the project duration. The monthly precipitation values were placed above each black bar to clearly show the highest and lowest values. According to the results from this graph, the highest precipitation values were observed during the months of December 2016 (10.9 inches) and January 2017 (15.2 inches). In contrast, the lowest precipitation values were observed during the months of August 2015 (0.05 inches) and July 2017 (0.02 inches). These results show that the precipitation values from the 2016-2017 rainy season are significantly higher in comparison to the previous years. It is possible that the Icehouse

Canyon watershed received substantial recharge water from recent historical storm events that may have contributed to the end of a severe 5-year drought period.

In the beginning of 2018, three considerable storm events occurred during the months of January and March. The first noteworthy storm of 2018 was recorded on January 10th producing 6.03 inches of rainfall. On March 21st, a second storm event occurred that generated 4.06 inches of precipitation. Approximately four days later, a third storm was recorded on March 25th that yielded 2.64 inches. Furthermore, these major storm events during the beginning of 2018 likely impacted streamflow in Icehouse Creek and discharge for selected spring locations.

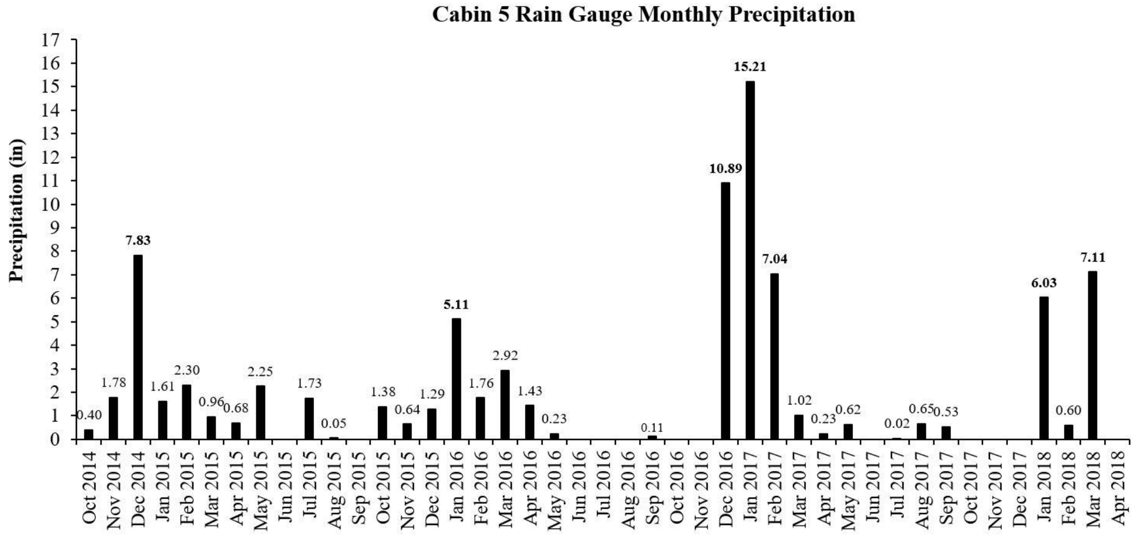


Figure 15. Bar graph displaying the monthly precipitation in units of inches captured with the Cabin 5 rain gauge instrument.

Precipitation data collected from the Cabin 5 rain gauge was also utilized to compare annual precipitation over the observation period. Figure 16 presents a bar graph comparing the annual precipitation beginning in August 2014 and ending in March 2018. In the United States, the term “water year” is defined as a period of 12 months beginning on October 1st of any given year and ending on September 30th of the following year (Fetter, 2001). After careful analysis, the results show that the highest annual precipitation (36.2 inches) occurred in the 2017 water year period. The second highest annual precipitation (19.6 inches) was recorded in the water year of 2015. The high precipitation values observed during the beginning of 2017 strongly suggest that it will surpass the water year of 2016, which should provide substantial recharge water to replenish the Icehouse Canyon watershed aquifers. Furthermore, the least amount of annual precipitation occurred in 2016 during the fifth year of a severe drought in California. This particular year received approximately 21.3 inches less precipitation in comparison to 2017. The annual precipitation for 2018 was not considered as the lowest, because only a few months of data were available for this water year. Moreover, the significant amount of precipitation that the watershed received in the wet season of 2017 contributed to improved conditions and may have even resulted in the full recovery of the watershed from the effects of a historical drought period.

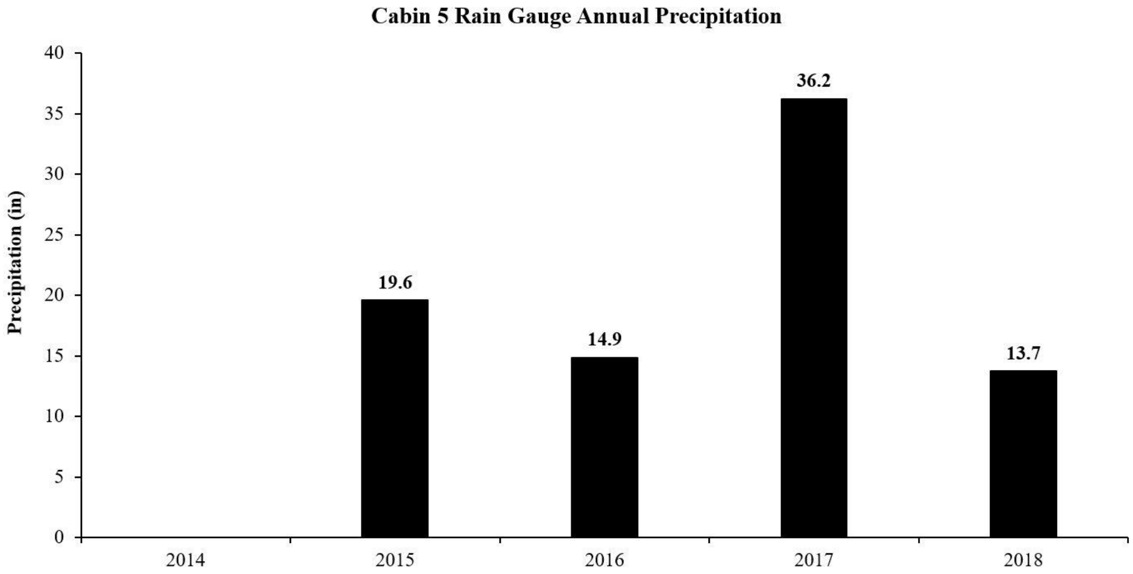


Figure 16. Bar graph showing the annual precipitation in water years for the Cabin 5 all-weather rain gauge until March of 2018.

The precipitation data collected from the Cabin 5 rain gauge was utilized to develop a hyetograph, which displays inches of precipitation over time for each storm event occurring within Icehouse Canyon. The Cabin 5 rain gauge was selected for the main hyetograph because it provided the most complete record of precipitation data. Additionally, the Sierra Power House gauge was also used to provide rainfall data for storm events that were missed. After completing the hyetograph, it was then overlaid with the streamflow hydrographs for each station in order to examine the hydraulic response following precipitation recharge events.

Icehouse Creek Streamflow

Streamflow was determined at selected gauging stations along Icehouse Creek at approximately biweekly intervals during the data collection phase of the project utilizing the velocity-area method. The streamflow records for each gauging station were plotted on the same graph in order to compare and contrast hydraulic response over the observation period. Figure 17 presents five lines in various colors that correspond to specific gauging stations along the Icehouse Creek channel. Collectively, when these runoff hydrographs are plotted in the same graph they appear to follow similar increasing-decreasing flow patterns. For example, the peaks of each hydrograph seem to occur during the month of January in three consecutive years of observation. Typically, the rainy season in Icehouse Canyon begins in December and continues for a few months thereafter, which may explain the consistent occurrence of hydrograph peaks during the specific month of January. In contrast, the lowest streamflow values for each hydrograph were observed during the dry months of July through October. During these dry months, storm events occur less frequently resulting in minor to no hydraulic response in the Icehouse Creek hydrographs.

Although similar increasing-decreasing flow patterns may be observed in the hydrographs, the quantity of water flowing at each gauging station is not necessarily the same along the creek channel. For instance, the highest streamflow values were consistently recorded at stations C and Broullard represented by the grey and yellow lines. In contrast, the lowest streamflow values were recorded at stations A and B represented by the light blue and orange lines. Intermediate of the maximum and minimum flows lies station D’, which is located adjacent to the Spring #1 station. Similar flow patterns were also observed in a previous study (Nourse et al., 2010), which tends to be related to the width of alluvium along the creek channel. Moreover, three gauging stations (C, B, and Broullard) displayed significant streamflow increases on May 20, 2017 due to a minor storm event of 0.56 inches that occurred five days prior. However, this noticeable response may also be an effect of spring snowmelt occurring within the canyon, which would also contribute to the streamflow increase recorded in the hydrograph.

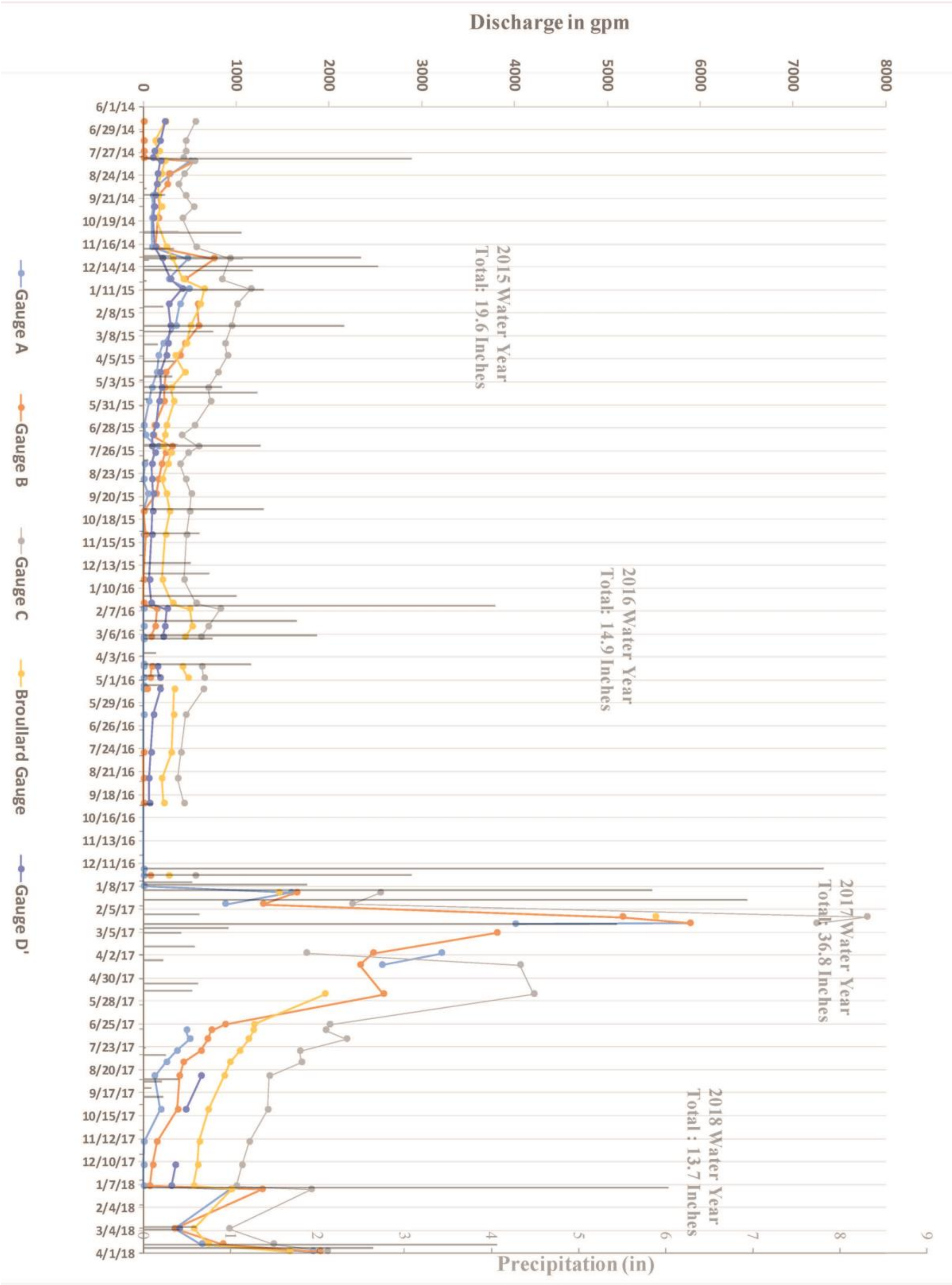


Figure 17. Runoff hydrographs for selected gauging stations along the main channel of Icehouse Creek. The hyetograph for the Cabin 5 rain gauge was superimposed on this chart for hydraulic response analysis.

By plotting streamflow hydrographs and hyetographs in conjunction, the hydraulic response for each gauging station may be determined through analyzing the increase of stream discharge following the occurrence of storm events. Figure 18 shows the streamflow hydrograph for gauging station A overlaid by the Cabin 5 rainfall hyetograph. The black bars on the x-axis represent the inches of precipitation for individual storm events and the open circle markers depict individual streamflow values. This graph for station A reveals five distinct hydraulic responses consisting of minor (1-30% increase), intermediate (31%-60% increase), and major (> 60% increase) creek discharge increases over the observation period. The first major response occurred on January 16, 2017 following a storm event that produced 5.84 inches of precipitation. This response resulted in a significant streamflow increase, however, the percentage increase could not be calculated because the previous measurement was zero. The second major response occurred on February 22, 2017 after a recharge event of 5.43 inches of precipitation. This substantial storm event resulted in a streamflow increase of approximately 724%. Furthermore, the first major storm event recorded on August 3, 2014 yielded 3.08 inches of rainfall, which resulted in a streamflow increase of 505 gal/min. Prior to this storm, the observed surface flow at Station A was zero. Overall, there was one minor, two intermediate, and two major hydraulic responses that were recorded for this specific station.

In the beginning of the year 2018, three storm events occurred during the months of January and March that significantly impacted streamflow conditions in Icehouse Creek. For example, on January 13th a hydraulic response of 1,279 gal/min was recorded at gauging station B, which represents a significant streamflow increase of 1,868%. The storm event triggering this response occurred three days prior and produced 6.03 inches of precipitation. In addition, on March 30th a second hydraulic response of 1,820 gal/min was observed at gauging station A, increasing the streamflow at that particular location by 190%. The storm that contributed to this response occurred five days prior and yielded 2.64 inches of rainfall.

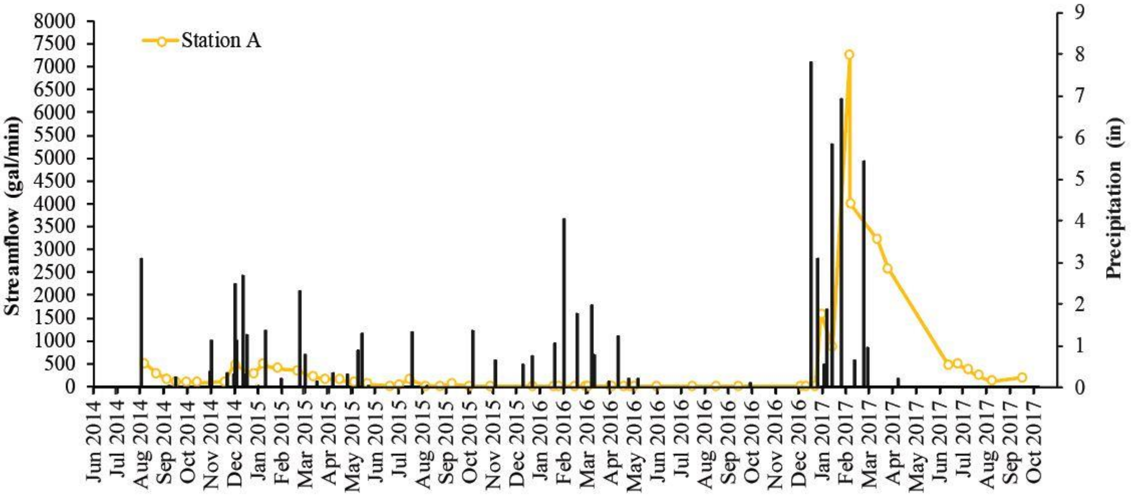


Figure 18. Streamflow hydrograph for gauging station A along the Icehouse Creek channel overlaid by a hyetograph from the Cabin 5 rainfall data.

The hydraulic response recorded at station B was analyzed using a similar approach. Figure 19 presents a runoff hydrograph overlaid by a precipitation hyetograph for station B. After completing a careful analysis of the graph, the results reveal that a total of seven hydraulic responses occurred over the observation period. This is two more responses in comparison to the station A location. The most significant response at this station of 7,391 gal/min occurred on February 15, 2017 possibly from a minor storm event of 0.64 in. This caused the streamflow to significantly increase by 476%. It is unclear if the response was triggered by this minor storm event or by a combination of several storms that accumulated water storage in the aquifer over time. The more likely explanation is a cumulative effect from several storms or snow melt contribution from previous storm events. In addition, a second major response occurred on January 16, 2017 yielding a streamflow value of 1,646 gal/min, which caused an increase by 2,073%. For this particular response, the nearest storm event of January 12, 2017 produced 5.84 inches of rainfall. Moreover, a noteworthy storm occurred during the summer month of August in 2014 that recorded 3.08 inches. Prior to this storm, the surface runoff in the creek channel was observed to be zero. The resulting hydraulic response from this summer storm caused the streamflow to rise from zero to 551 gal/min. This is represented on the hydrograph as the first circular marker.

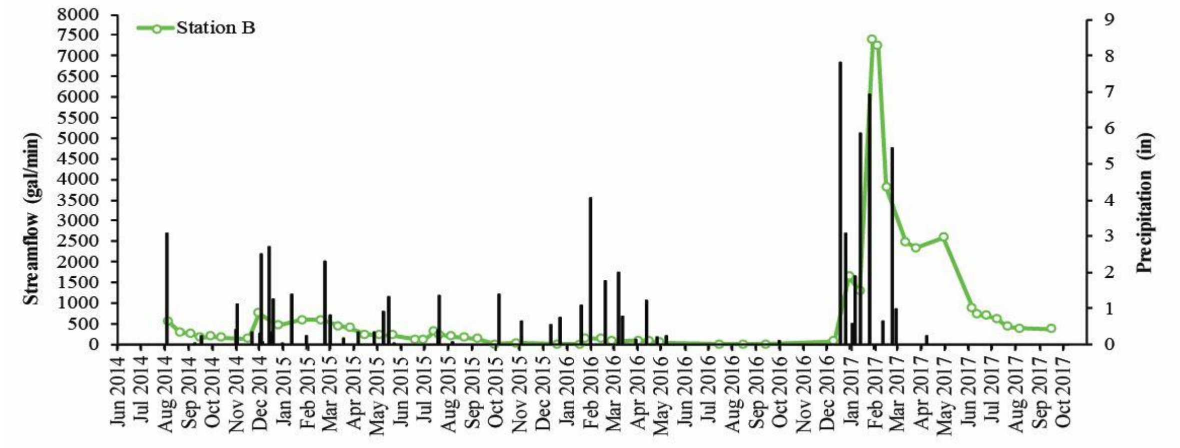


Figure 19. Runoff hydrograph and Cabin 5 precipitation hyetograph for gauging station B showing the hydraulic response following storm events in Icehouse Canyon.

For gauging station C, the hydraulic response was examined using the graph below containing the most complete Icehouse Creek streamflow record for the research study. Figure 20 shows a unique hydrograph for station C displayed in light blue color on the same graph as the primary hyetograph created for the Cabin 5 rain gauge. The results from this graph reveal eight distinct hydraulic responses during the observation period.

These responses consist of various magnitudes including minor, intermediate, and major. The highest response of 7,391 gal/min occurred on February 15, 2017 following a minor storm event that produced 0.64 inches of precipitation. As a result, the streamflow at this particular station experienced an increase of 229% from the previous observation. A second significant response of 1,803 gal/min occurred on January 13, 2018 from a storm that generated 6.03 inches of rainfall. This response resulted after several consecutive months of little to no precipitation recharge in the canyon. In addition, the summer storm from August 3 of 2014 triggered a minor response that increased the streamflow by 24%. This is a significant difference in comparison to the responses recorded at Stations A and B from the same storm event. Furthermore, it is also important to note that most of the major hydraulic responses occurred during the rainy season of 2017, when historical storm events were observed.

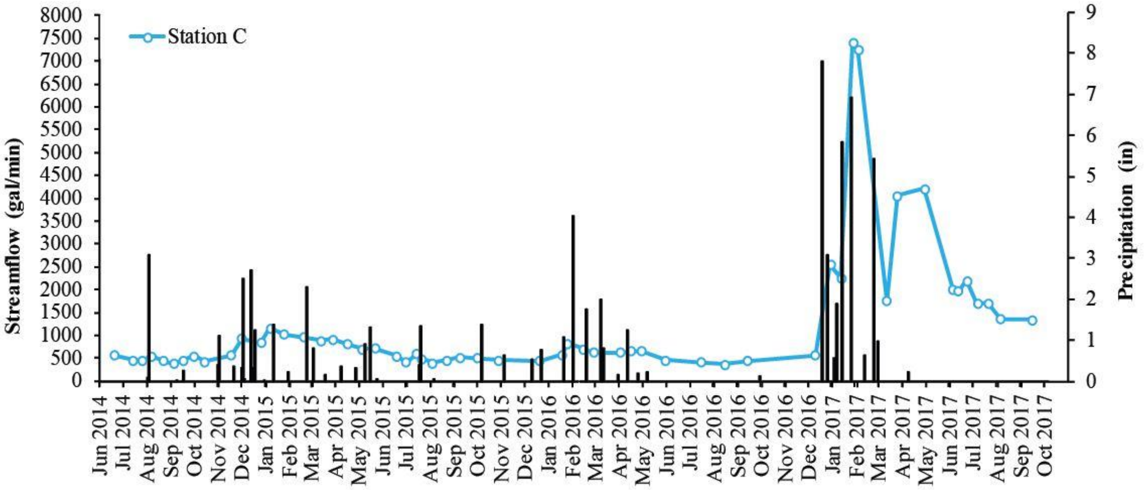


Figure 20. Runoff hydrograph overlaid by a precipitation hyetograph for gauging station C.

The gauging station Broullard along Icehouse Creek appears to be responding more frequently to precipitation recharge events, however, majority of the responses that occurred before December 2016 were minor. Figure 21 presents a streamflow hydrograph for station Broullard showing the response to recharge events in Icehouse Canyon over the project duration. The results from this hydrograph indicate that a total of eleven hydraulic responses occurred. This is the most responses observed in comparison to the other gauging stations along Icehouse Creek. After careful analysis, it appears that the most significant response occurred on February 15, 2017 when a streamflow value of 5,516 gal/min was observed. As a result from this hydraulic response, the streamflow experienced a significant increase of 279%. The summer storm event from August 3, 2014 resulted in a flow rate of 231 gal/min, which represents a minor increase of 36%. This specific response is similar to the recorded observation at Station C for the same summer storm. Moreover, the presence of bedrock at this station may have a strong influence on the frequent hydraulic responses observed after the occurrence of recharge events.

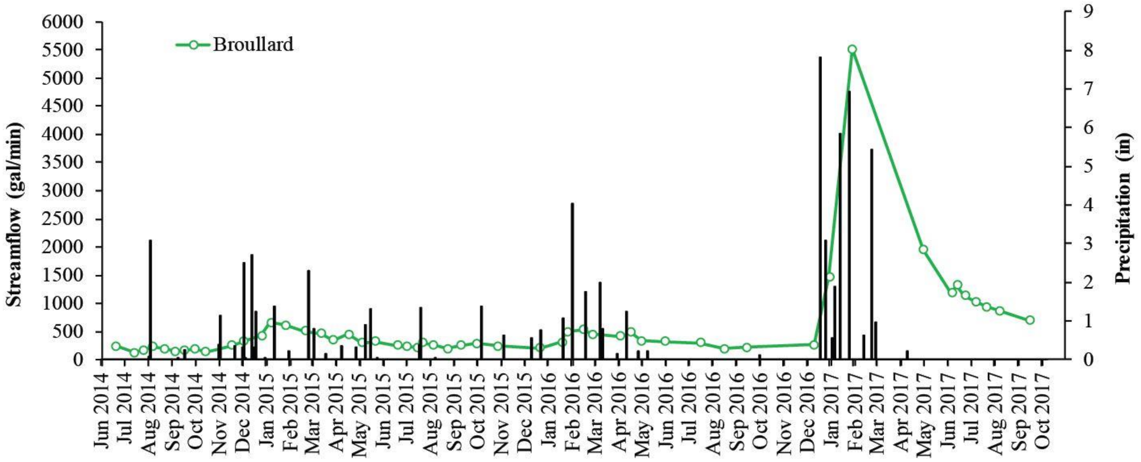


Figure 21. Streamflow hydrograph for station Broullard showing the response from precipitation recharge events in Icehouse Canyon.

Streamflow data was collected at gauging station D’ beginning in June 2014 and ending in September 2016, with additional intermittent measurements performed during late 2017. Figure 22 presents a hydrograph for station D’ plotted in conjunction with the Cabin 5 hyetograph to show hydraulic responses following precipitation recharge events. The results from this hydrograph reveal a total of nine hydraulic responses also consisting of various magnitudes including minor, intermediate, and major. The first major response occurred on August 7, 2014 when the streamflow value was recorded at 182 gal/min due to a storm event that produced 3.08 inches of precipitation four days prior. As a consequence, the streamflow at station D’ increased by approximately 51%. A second major response recorded on February 5, 2016 yielded 254 gal/min, which represents 199% increase in streamflow. The closest storm event to this hydraulic response occurred five days prior and produced 4.04 inches of precipitation. Furthermore, the highest streamflow during the observation period occurred on August 28, 2017 with a value of 623 gal/min. However, the percent increase was misleading due to a large data gap between the last observation and this streamflow value.

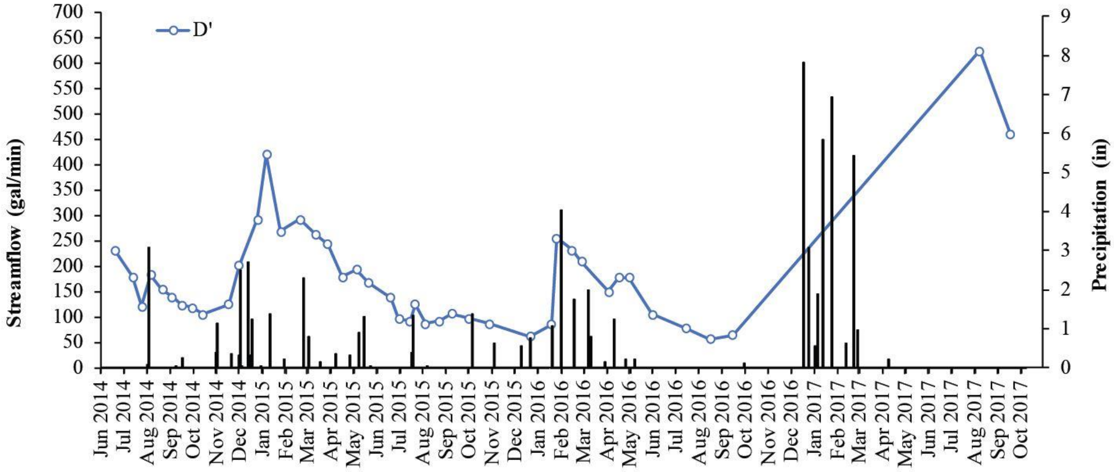


Figure 22. Hydrograph for station D’ plotted in conjunction with the Cabin 5 hyetograph to show hydraulic responses from recharge events.

Icehouse Canyon Spring Discharge

The hydrologic data collected for the selected perennial springs in Icehouse Canyon displayed on Figure 4 was plotted on the same graph to compare hydraulic response following storm events and to evaluate water resource potential. Figure 23 displays five spring hydrographs overlaid by a hyetograph developed from the Cabin 5 precipitation data. The results from these hydrographs show that two specific springs responded substantially to precipitation recharge events that occurred during the 2017 rainy season, although the response was noticeably delayed in comparison to the creek stations. For example, Spring #1 and Cedar Spring produced significant groundwater discharge approximately 4-6 weeks following the storm events that occurred during the months of January and February of 2017. In contrast, Spring #2 and East Cabin Spring only displayed a minor hydraulic response. The noticeable differences in hydraulic response for the spring locations suggest that more than one type of source may exist.

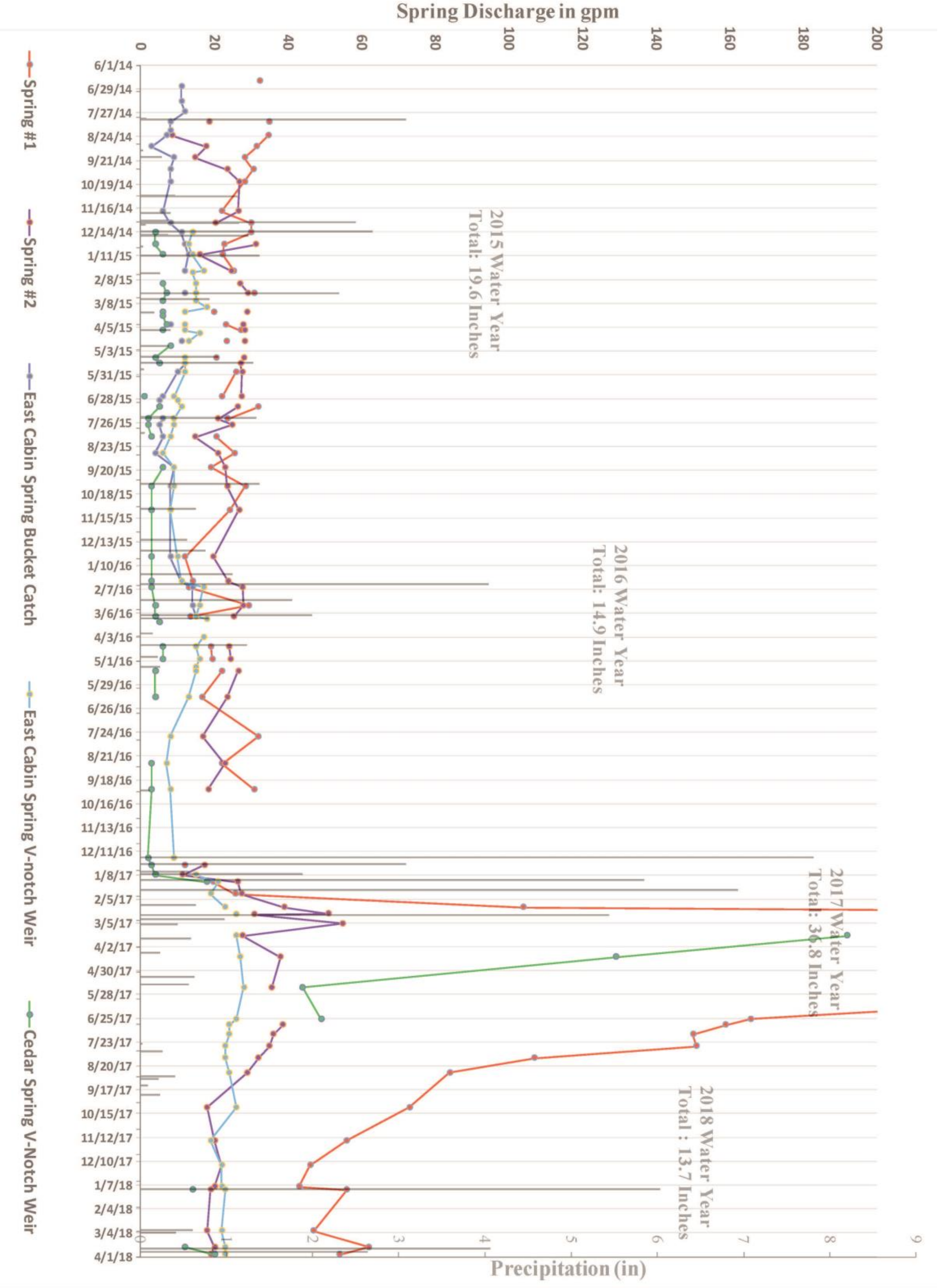


Figure 23. Spring hydrographs overlaid over the main hyetograph to compare hydraulic response and water resource potential.

In the first few months of 2018, two major storm events occurred in January and March that affected discharge at some of the spring locations. For instance, on January 13th a hydraulic response of 56 gal/min was recorded for Spring #1, which represents a 30% increase in discharge. The storm event triggering this response occurred threes day prior and produced 6.03 inches of precipitation. Similarly, on March 21st a second hydraulic response of 62 gal/min was observed at the Spring #1 gauging station, resulting in a 32% discharge increase. The storm event contributing to this specific response was recorded on the same date and yielded 4.06 inches of rainfall.

The four perennial springs in Icehouse Canyon selected for this research study appear to be responding differently in comparison to the hydraulic behavior observed at Icehouse Creek. Figure 24 shows a discharge hydrograph for Spring #1 that displays the hydraulic response after the occurrence of recharge events within the canyon. During the observational period, only one major hydraulic response was recorded for this gauging station. This response occurred on February 15, 2017 following a minor storm event of 0.64 inches. As a result, the spring discharge increased by approximately 305%. In addition, several significant recharge events occurred prior to this minor storm event, which may have provided substantial replenishment to the surrounding aquifers. Furthermore, the results for Spring #1 did not show any noticeable responses to minor precipitation recharge events that occurred during the severe drought period. It is possible that local aquifers may have experienced significant depletion during the drought period, which allowed sufficient storage space for major recharge events before a hydraulic response was initiated.

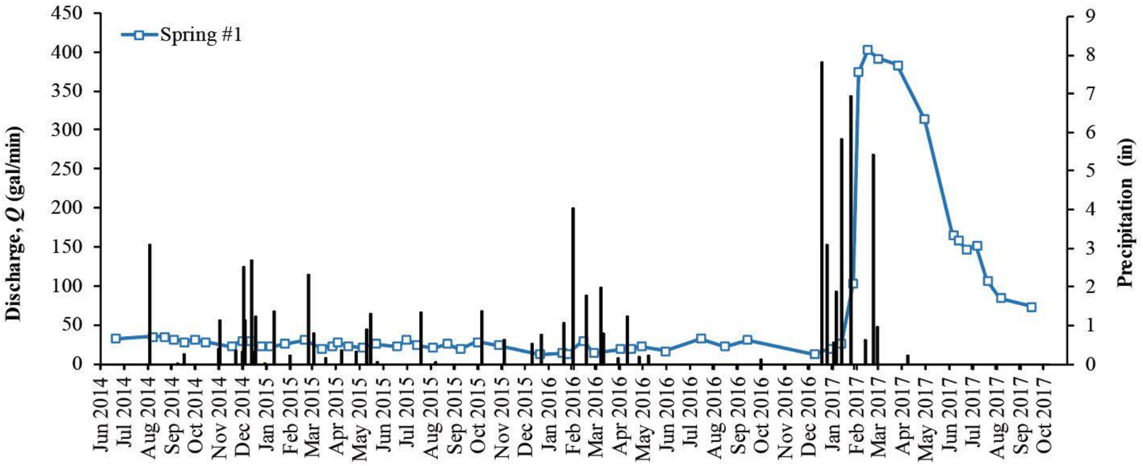


Figure 24. Spring #1 hydrograph showing the hydraulic responses following storm events in Icehouse Canyon.

The results from the Spring #2 hydrograph reveal a more complicated responsiveness to precipitation recharge events. During the project duration, three major (>60% increase) hydraulic responses were observed. The first major response occurred on September 5, 2014 without the occurrence of any storm events during this time. Spring discharge for this response was determined to be 18 gal/min, which represents a 108% increase from the previous value. Additionally, another major response occurred on January 16, 2017 after the occurrence of a significant recharge event that produced 5.84 inches of precipitation. The spring discharge increased to 26 gal/min, which was one of the greatest percent increases (132%) recorded during the data collection period. A third major hydraulic response was observed on March 6, 2017 following a small storm event of 0.43 inches of rainfall. This resulted in a 78% increase in spring discharge. Moreover, the observance of multiple hydraulic responses may indicate that this particular spring is more sensitive to precipitation recharge events. With regards to water resources, the results suggest that availability of spring water will increase soon after a storm event occurs at this specific spring location. This water supply information is particularly beneficial for cabin owners that rely on the spring water for consumption and other uses.

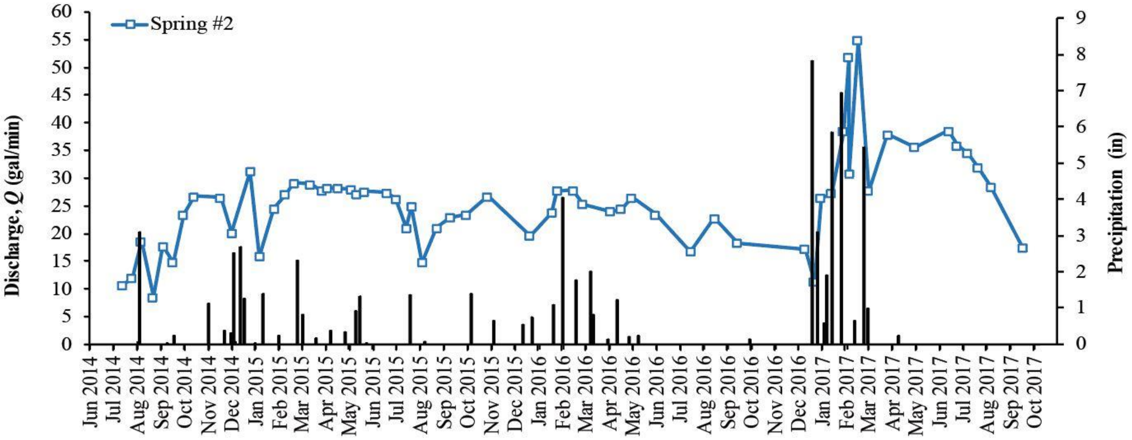


Figure 25. Spring #2 hydrograph displaying discharge over time overlaid by the main precipitation hyetograph.

Since we are interested in improving our understanding of water resources in Icehouse Canyon watershed, the major hydraulic responses become particularly important because they indicate when more freshwater is available for use. Figure 26 shows the results for the East Cabin Spring station. For this spring, the first major hydraulic response occurred on January 16, 2017 with a calculated discharge value of 21 gal/min. The storm event that most likely caused this response produced 5.84 inches of precipitation. Additionally, the second major hydraulic response occurred on February 23, 2017 with a recorded discharge value of 26 gal/min, one of the highest during the observation period. Similarly, the storm event that caused this response yielded a significant amount of precipitation (5.43 inches). Both major hydraulic responses occurred during the winter of 2017 and were the result of substantial replenishment following significant recharge events. However, the observed discharge fluctuations prior to the rainy season of 2017 are difficult to correlate to specific storm events due to high variation.

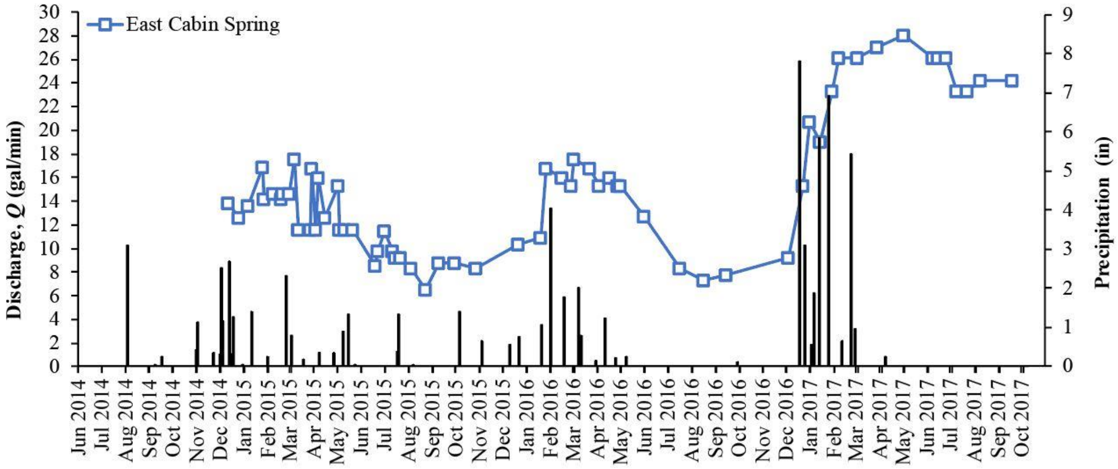


Figure 26. East Cabin Spring hydrograph displaying spring discharge from December 2014 to October 2017.

The hydrograph for the Cedar Glen Spring station revealed a similar response behavior as the Spring #1 results. For example, only one major response was recorded for this spring. The hydraulic response occurred on February 15, 2017 with a recorded discharge value of approximately 259 gal/min. This noticeable response resulted in a discharge increase of 1,335%, the highest increase recorded during the observation period. It is unclear which precipitation recharge event was responsible for this response or if many recharge events contributed to the response. The closest storm event to the response occurred on February 2, 2017, which was 13 days prior to the recorded response.

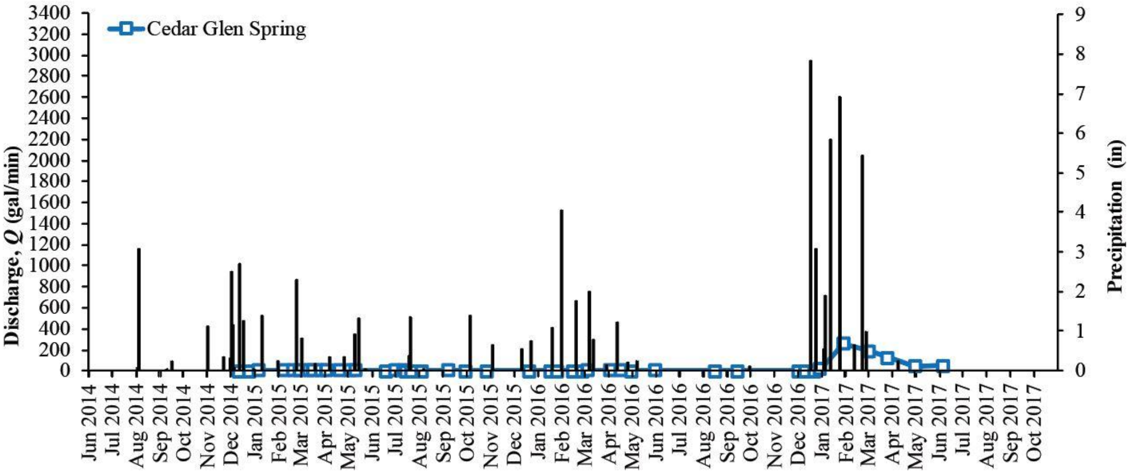


Figure 27. Runoff hydrograph for Cedar Glen Spring gauging station overlaid by the Cabin 5 rain gauge hyetograph.

Rating Curves

Stage and discharge were measured periodically at the East Cabin Spring and Cedar Glen Spring gauging stations. Discharge values at these monitoring stations were determined using thin plate V-notch weirs and stage was measured directly using a clear plastic graduated cylinder. Stage was also calculated using the pressure transducer measurements and the hydrostatic equation. These measurements were performed on the same day in order to establish a relationship between stage and discharge at these particular gauging stations. The objective of this method was to obtain a continuous record of discharge by measuring water level pressure in real-time with the pressure transducers. This method may provide valuable information regarding seasonal and long-term variations in spring discharge patterns.

The rating curve for the East Cabin Spring station does not show an overall positive correlation between discharge and stage. However, the data points appear to display two distinct trends that may take the form of a power function. One set of data points plots slightly higher than the other, but with a similar trend showing an increase in stage as the discharge increases. A trendline was added to determine the equation of the rating curve, which yielded an *r* squared value of approximately 2%. This *r* squared value is significantly low indicating that the rating curve does not fit the data well. Figure 28 (b) presents the rating curve for the Cedar Glen Spring station. Similarly, the data points for this station appear to be plotting as two distinct curves, one set slightly higher than the other. These two patterns reveal a positive correlation between discharge and stage, resulting in an overall rating curve that resemble a power function in form. Furthermore, the r squared value for this particular trendline is slightly higher at approximately 9% indicating a better fit.

The rating curves for both gauging stations revealed similar patterns, but different overall curves. Ultimately, these rating curves may not be useful for determining future discharge values because the curves do not fit the data well enough. Potential sources of error that may have contributed to these results include the following: insufficient variation of actual discharge over long periods of time, continuous fluctuation of water level when performing weir measurements, horizontal eye level required to properly read weir, weirs not designed as sharp crested, and zero point on the weir was probably not calibrated correctly to the pressure transducer zero point.

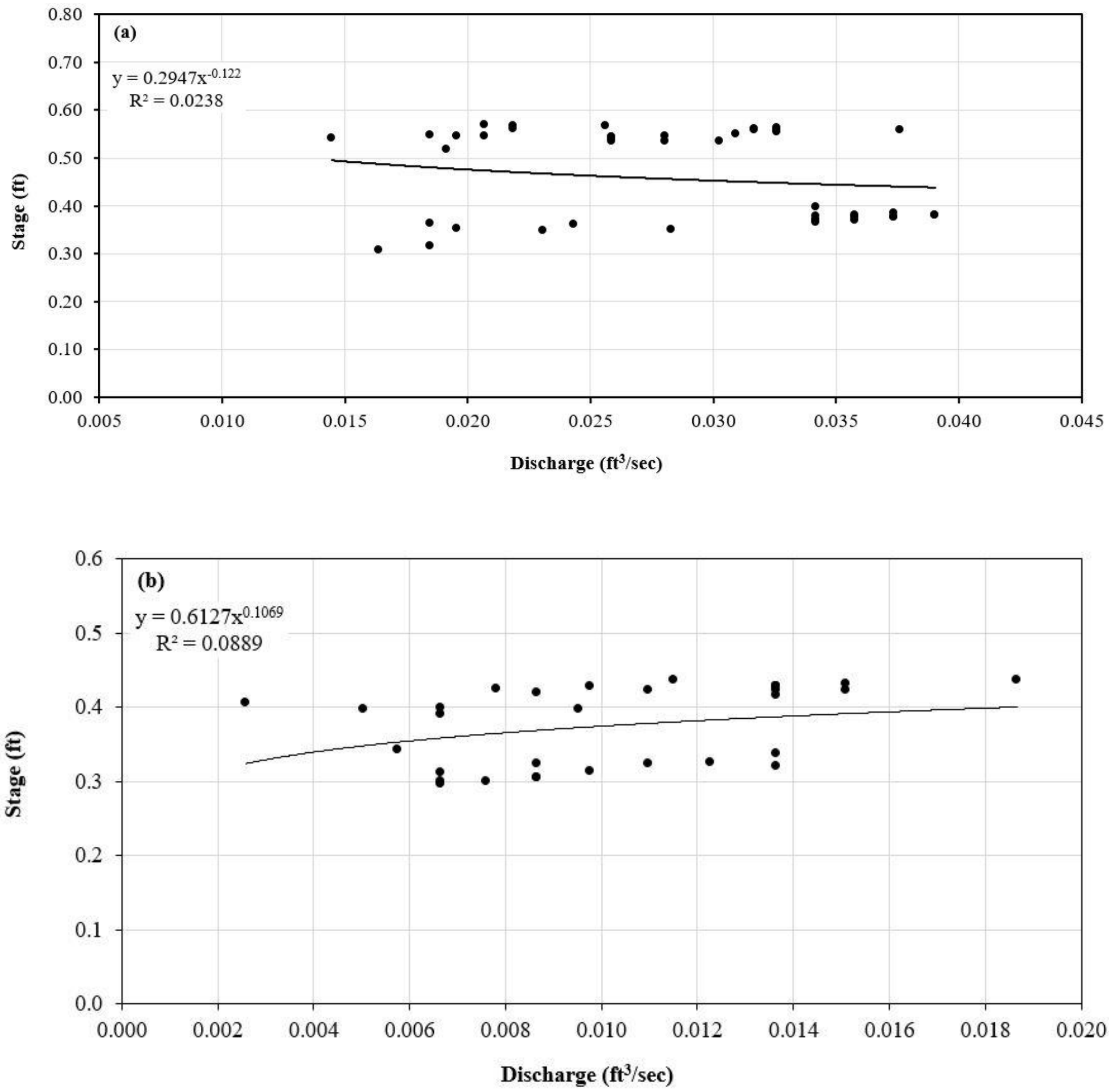


Figure 28. Stage-discharge relation derived from the v-notch weir and pressure transducer data for: **(a)** the East Cabin Spring gauging station; **(b)** and the Cedar Glen Spring gauging station.

Stable Water Isotope Data

Water samples were collected from the spring stations and two rain gauges to perform an analysis of stable water isotopes including δ^{2}H (deuterium) and δ^{18}O. The water samples were collected using 1,000 ml narrow mouth plastic bottles and analyzed at the UC Riverside Isotope Laboratory within the Department of Environmental Sciences. The following instrument was used for completing the analysis, a triple isotope water analyzer model number TIWA-45-EP manufactured by Los Gatos Research. These specific water isotopes were selected for analysis in order to gain a better understanding of the type of groundwater sources discharging at the spring locations.

The results from the spring samples were plotted along with the precipitation samples to examine any similarities or differences. Figure 29 presents a plot of Deuterium versus Oxygen 18 showing the similarities in isotopic signature between the different types of water samples. The isotopic results reveal significant similarity between the spring samples and the precipitation samples. For example, the four spring samples plotted nearly on the local meteoric water line (LMWL) represented by the solid black line. To determine the LMWL, a total of six precipitation samples were used from different research studies. Two of the samples were collected from Icehouse Canyon for this study, one sample from Cow Canyon Saddle by Logan Wicks in 2014, and three samples from Thomson Creek by Jazmin Gonzales in 2013. The LMWL indicates the specific areas on the graph where precipitation water is expected to plot for that particular region. According to the graph, all the spring samples collected from Icehouse Canyon appear to plot within a narrow range of $\delta^{18}O$ and $\delta^{2}H$ (deuterium) values, which also tend to fall close in proximity to the local meteoric water line. Similarly, the spring samples from Wick’s study represented by gold circles also plot close to the meteoric water line.

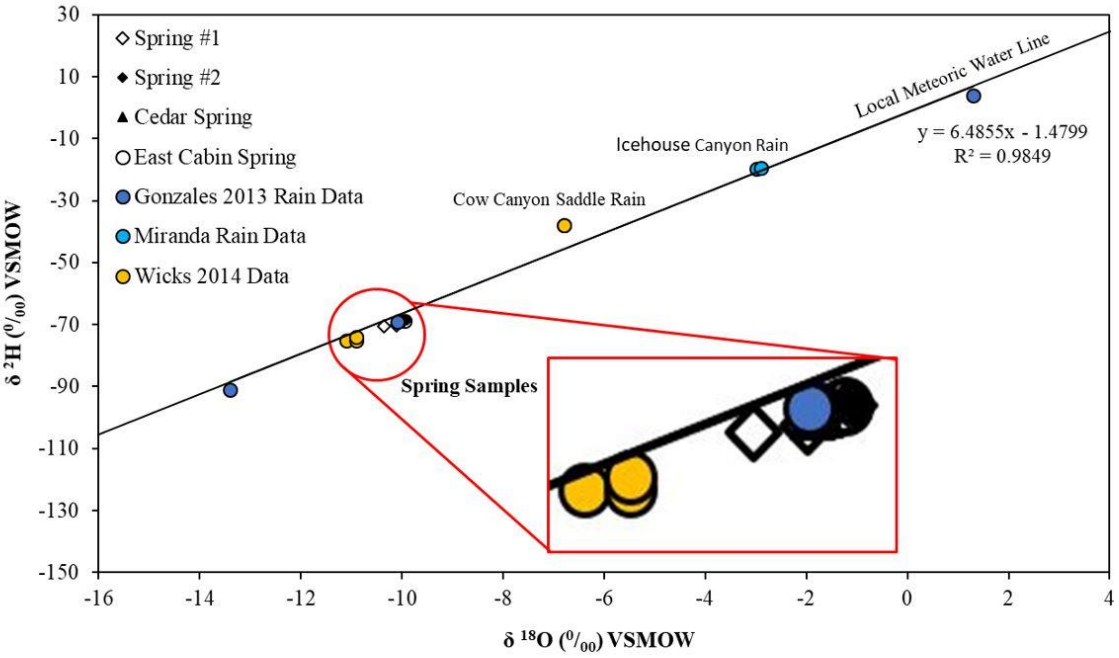


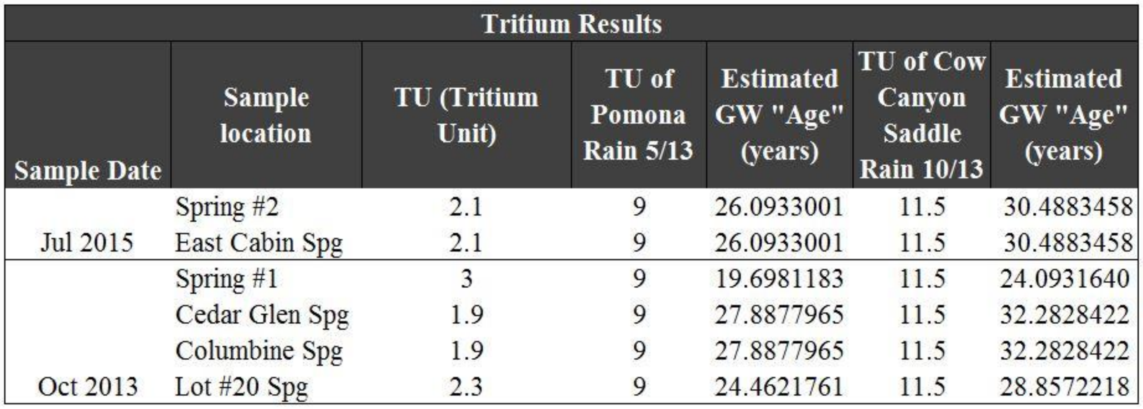
Figure 29. Plot of deuterium versus Oxygen 18 for precipitation and spring samples collected in Icehouse Canyon. Data sources from Gonzales 2013 and Wicks 2014 thesis reports.

Tritium Analysis

Results from the tritium analysis for Spring #2 and East Cabin Spring samples were used to calculate the relative age of these groundwater sources. Table 2 contains the tritium data and calculated groundwater ages for the two spring samples. This table also presents relevant tritium data for Icehouse Canyon spring samples collected by Wicks in 2014. According to the results, Spring #2 and East Cabin Spring yielded similar approximate ages ranging from 26.1 to 30.4 years. These results are similar to the previous study conducted by Wicks. For instance, Spring #1 ranged from 19.7 to 24.1 years and Cedar Glen Spring ranged from 27.9 to 32.2 years. The tritium results from these four different spring locations in Icehouse Canyon revealed groundwater ages of non-zero, which may indicate more than one type of source. In addition, the range of ages were calculated using equation 4, where the tritium units for the spring samples (TU_{sample}) and rain samples (TU_{rain}) were applied for estimating groundwater ages. The estimated age is reported as a range because two different TU values are used for rain samples. The calculated age is ultimately dependent on the particular value used for modern rain.

$$\text{Groundwater Age} = \ln\left(TU_{sample}/TU_{rain}\right) \bullet -17.93$$ **(Equation 4)**

Table 2. Tritium data for spring samples collected in Icehouse Canyon during July 2015 and October 2013.



Tritium Results						
Sample Date	**Sample location**	**TU (Tritium Unit)**	**TU of Pomona Rain 5/13**	**Estimated GW "Age" (years)**	**TU of Cow Canyon Saddle Rain 10/13**	**Estimated GW "Age" (years)**
Jul 2015	Spring #2	2.1	9	26.0933001	11.5	30.4883458
	East Cabin Spg	2.1	9	26.0933001	11.5	30.4883458
Oct 2013	Spring #1	3	9	19.6981183	11.5	24.0931640
	Cedar Glen Spg	1.9	9	27.8877965	11.5	32.2828422
	Columbine Spg	1.9	9	27.8877965	11.5	32.2828422
	Lot #20 Spg	2.3	9	24.4621761	11.5	28.8572218

Water Quality

Basic water quality parameters were measured over the project duration at the Icehouse Creek and spring stations using a multi-parameter field instrument manufactured by Oakton. These water quality parameters included the following: temperature, pH, conductivity, total dissolved solids, and salinity. Obtaining information regarding water quality at the source is important especially for water resources studies. The objective of this project task was to record basic water quality parameters in order to observe any spatial or temporal variations that may be occurring at the selected gauging stations. Additionally, another research objective was to compare water quality from the creek stations with the spring locations to examine any potential contamination from human activities.

Water temperature was measured on eight separate occasions at selected gauging stations along Icehouse Creek and different spring locations. Figure 30 (a) shows the change in water temperature over time at the various creek stations. The results from this graph reveal noticeable temperature variations over the observation period. For example, water temperatures decreased in the months of November, October, and January. Then water temperatures increased during the summer months of July, August, and September. Moreover, the results from this graph also show minor changes at the different creek stations indicating minor spatial variation. In contrast, the temperature results for the spring stations display less temporal variation. Figure 30 (b) presents the change in water temperature for the four spring locations selected for this study. According to this graph, the water temperature at the spring locations show minor change over time indicating minor temporal variation. For the spring locations, the water temperature appears to remain relatively stable over the observation period due to vegetation cover that limits sun exposure.

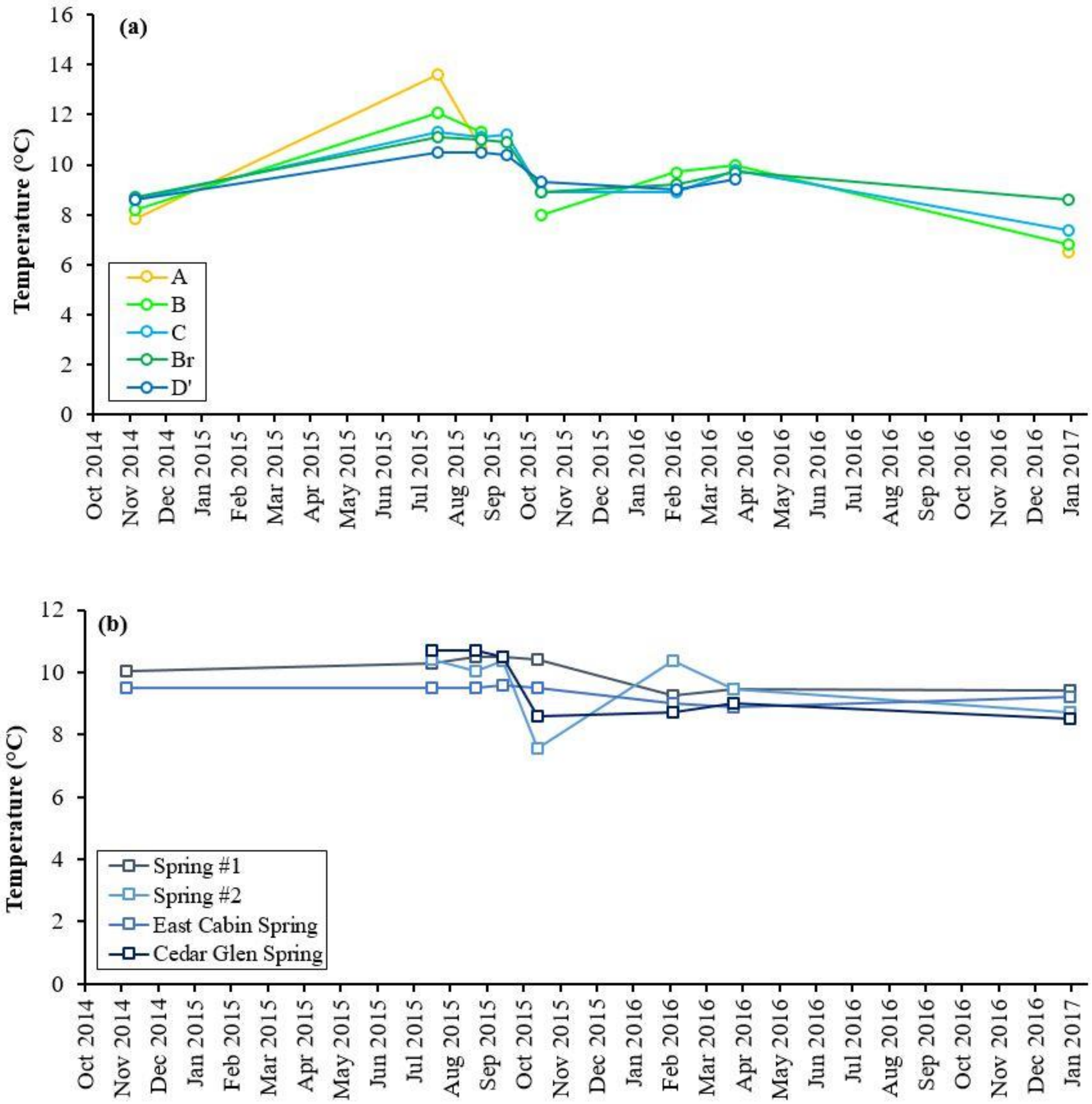


Figure 30. Scatter plots illustrating the change in water temperature at the creek stations **(a)** and spring stations **(b)** over time.

The pH of water samples from the monitoring stations was measured using the Oakton field instrument on eight different data collection sessions. Measuring pH is an important water quality indicator for aquatic organisms and provides useful information regarding natural water chemistry. Figure 31 (a) presents a scatter plot showing the variation in pH along the Icehouse Creek stations during the data collection phase. The results from this graph reveal minor spatial variation, however, there is noticeable temporal variation that occurred during the month of September 2015 where the pH appears to decrease. Additionally, one particular measurement recorded on August 2015 yielded a pH value at the freshwater limit of 9.0 established by the U.S. Environmental Protection Agency (EPA). Figure 31 (b) presents a scatter plot displaying the pH results for various spring locations within Icehouse Canyon. In contrast to the previous results, this graph shows minor spatial and temporal variation in pH. All four spring monitoring stations reveal relatively constant pH values of approximately 8 during the observation period. Furthermore, one particular measurement also yielded a value above the EPA recommended water quality criteria. For example, the pH value on November 6, 2015 was 9.7, which is slightly above the recommended freshwater limit. Overall, the spring waters appear to be more pH stable over time in comparison to the creek water.

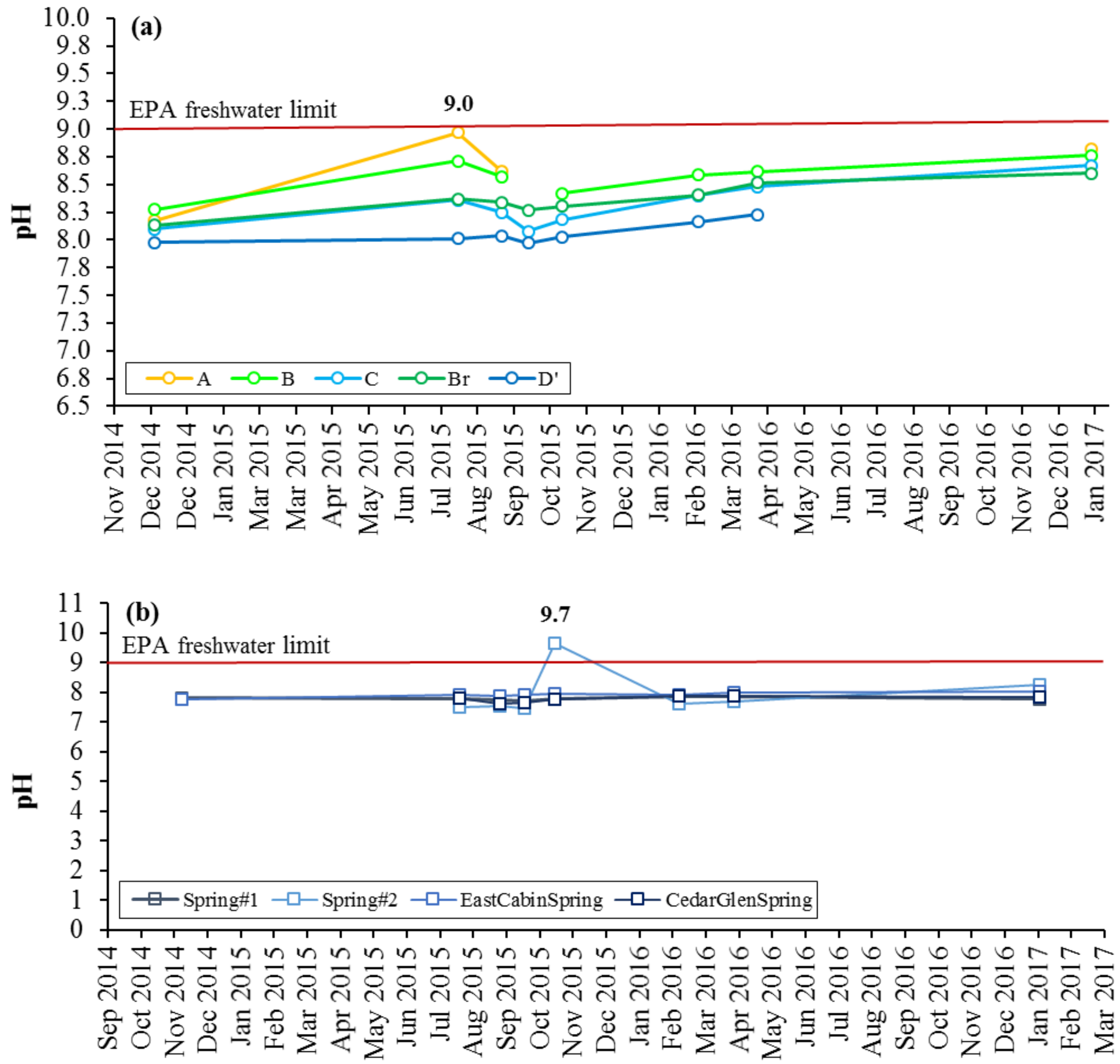
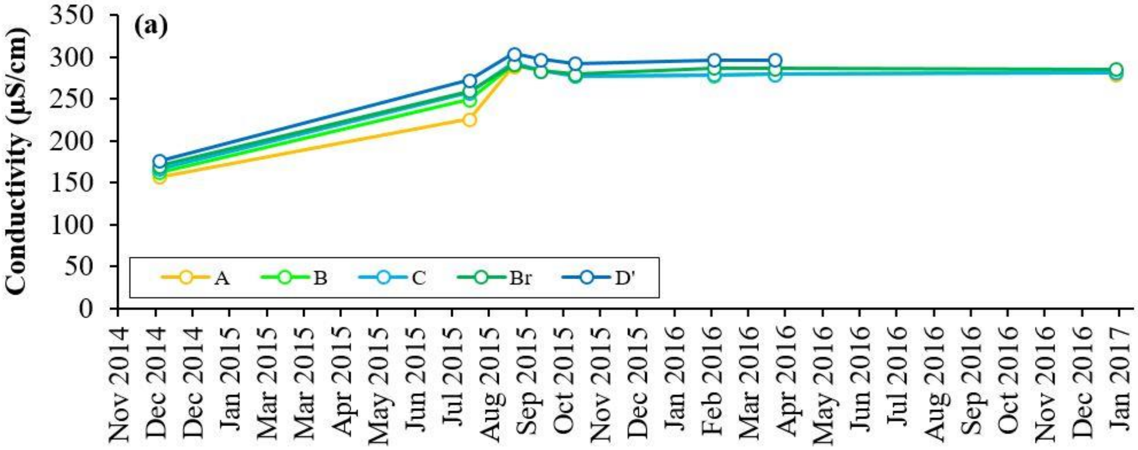


Figure 31. Scatter plots showing the spatial and temporal variation in pH for the creek **(a)** and spring gauging stations **(b).** The national recommended water quality criteria for pH established by the U.S. Environmental Protection Agency is highlighted in red.

Conductivity of water samples was measured at selected monitoring stations during the data collection phase of the research project utilizing the Oakton multi-parameter field instrument. The measurement of conductivity determines the ability of a water sample to transmit an electrical current (U.S. EPA, 2017). This specific parameter is beneficial beacause it can indicate the presence of water contaminants when significantly high values in conductivity are detected. Some parts of Icehouse Canyon contain private cabins that are located close to gauging stations, therefore, it is important to monitor conductivity in order to detect potential contamination events from human activity.

The conductivity at each monitoring station was measured on eight separate occasions and then graphed using scatter plots to examine the spatial and temporal variation. Figure 32 (a) presents the change in water conductivity over time for the Icehouse Creek monitoring stations. The results from this graph reveal a noticeable increase in conductivity from all the stations on September 17, 2015. However, this increase may not be an indicator of water contamination because the signal is not substantially higher than the previous measurement. Figure 32 (b) presents the change in conductivity over time for the Icehouse spring stations. Similarly, the results from this graph show a noticeable increase in conductivity during the middle of September 2015. As a result, the signal may be a natural response caused by an increase in dissolved solids derived from the surrounding rock material instead of an indicator of contamination. Moreover, the range in conductivity for all the stations was 157 to 331 µS/cm. According to the U.S. Environmental Protection Agency, the typical range for freshwater rivers in the United States falls between 50 to 1,500 µS/cm (U.S. EPA, 2017). Therefore, the conductivity range observed for the Icehouse monitoring stations falls within the natural range of freshwater rivers in the United States indicating no effect from contamination.



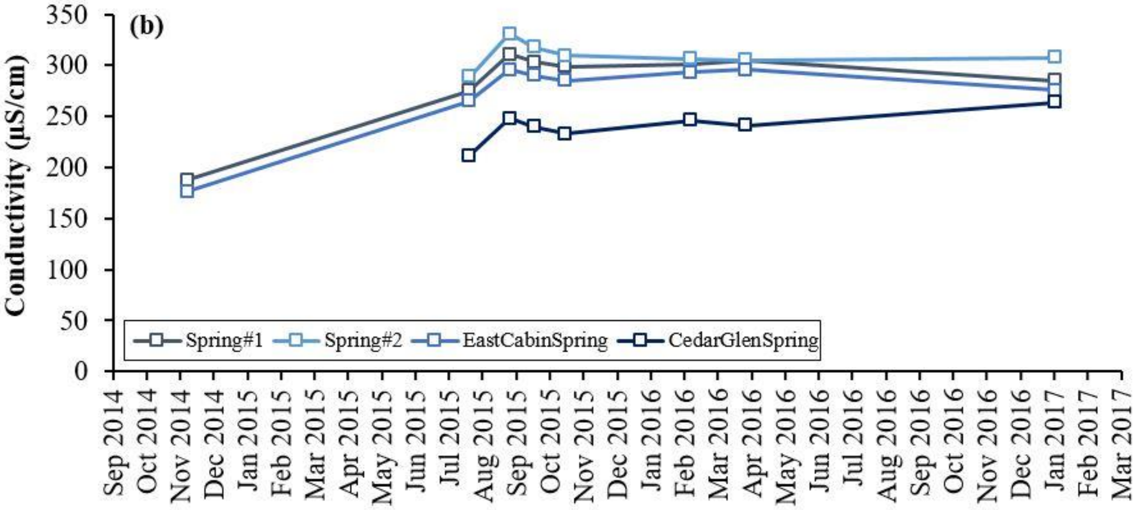


Figure 32. Scatter plots illustrating the change in electrical conductivity at the creek **(a)** and spring **(b)** stations over the observation period.

Total dissolved solids (TDS) was measured at selected gauging stations in Icehouse Canyon on seven different fieldwork sessions. This water quality parameter was monitored in order to examine the concentration of dissolved material within the water for safety determination. The U.S. Environmental Protection Agency has established a secondary maximum contaminant level (SMCL) for total dissolved solids at 500 mg/L

(U.S. EPA, 2017). This secondary drinking water standard is not enforceable, but is used as a guideline for aesthetic purposes such as color, taste, and odor. Figures 33 (a) and (b) show the TDS levels for the creek and spring stations at seven different time periods during the research project. According to the results, the TDS ranges from 155 to 234.5 mg/L and the overall average value is approximately 200 mg/L. These values are less than half the concentration recommended by the EPA, which indicates that the water can be potentially used for human consumption and other purposes.

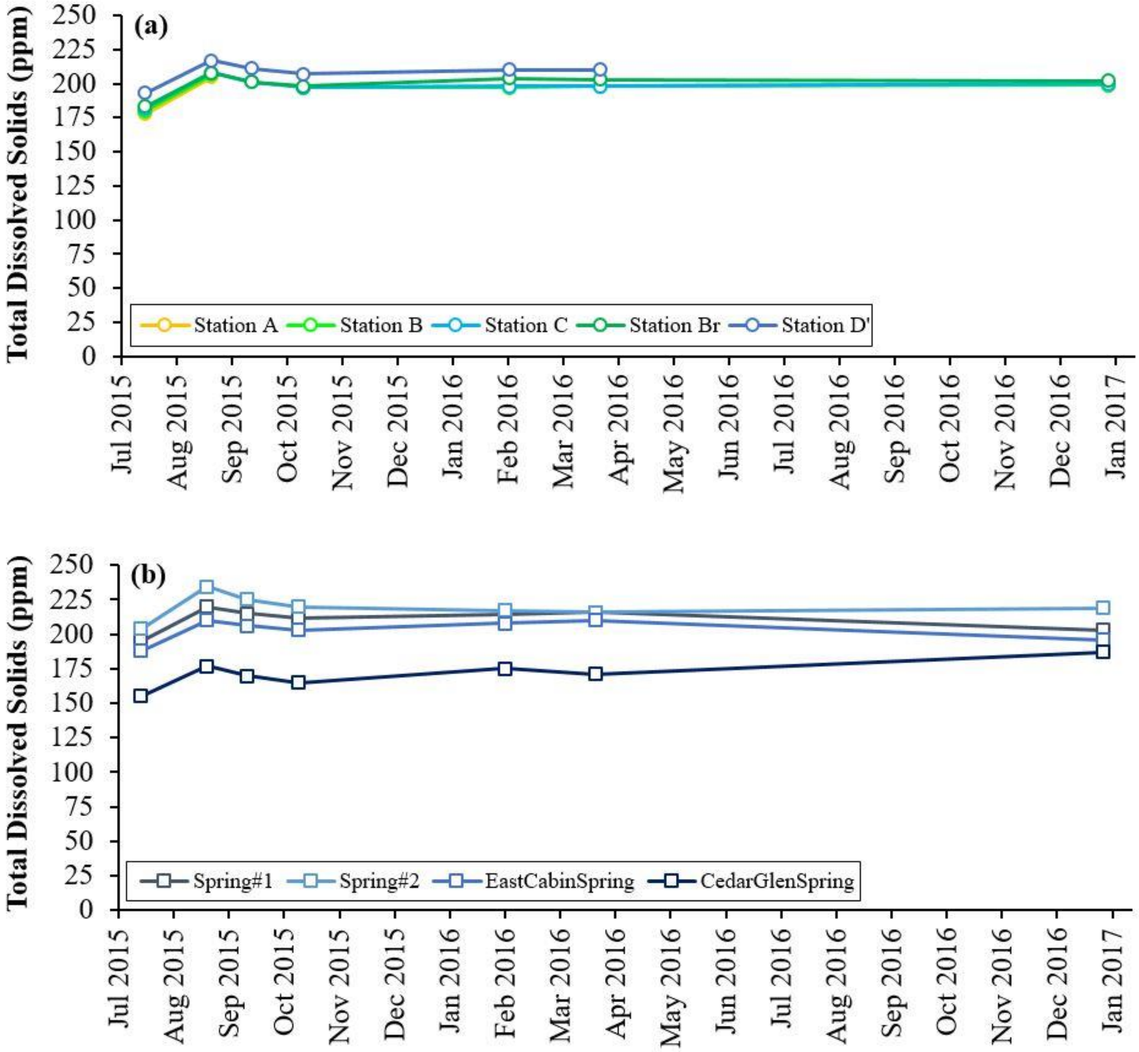


Figure 33. Scatter plots displaying the total dissolved solids at each creek station **(a)** and spring station **(b)** in Icehouse Canyon.

Salinity concentrations of the water samples were measured multiple times at the creek and spring stations using the Oakton field instrument to evaluate dissolved salt content in the water. Figure 34 (a) illustrates the change in salinity at the Icehouse creek stations over time. The creek stations display noticeable variation in salinity especially station D’ where the concentrations are consistently higher in comparison to the other stations. Figure 34 (b) shows the change in salinity over time for the selected spring stations in Icehouse Canyon. These spring stations reveal significantly less spatial and temporal variation in comparison to the creek stations. The salinity ranged from 98.8 to 134.5 ppm for all the gauging stations with an overall average value of 120.3 ppm. This salinity range falls well below the freshwater limit of less than 1,000 ppm established by the U.S. Geological Survey, suggesting that the water quality in terms of salinity is in excellent condition.

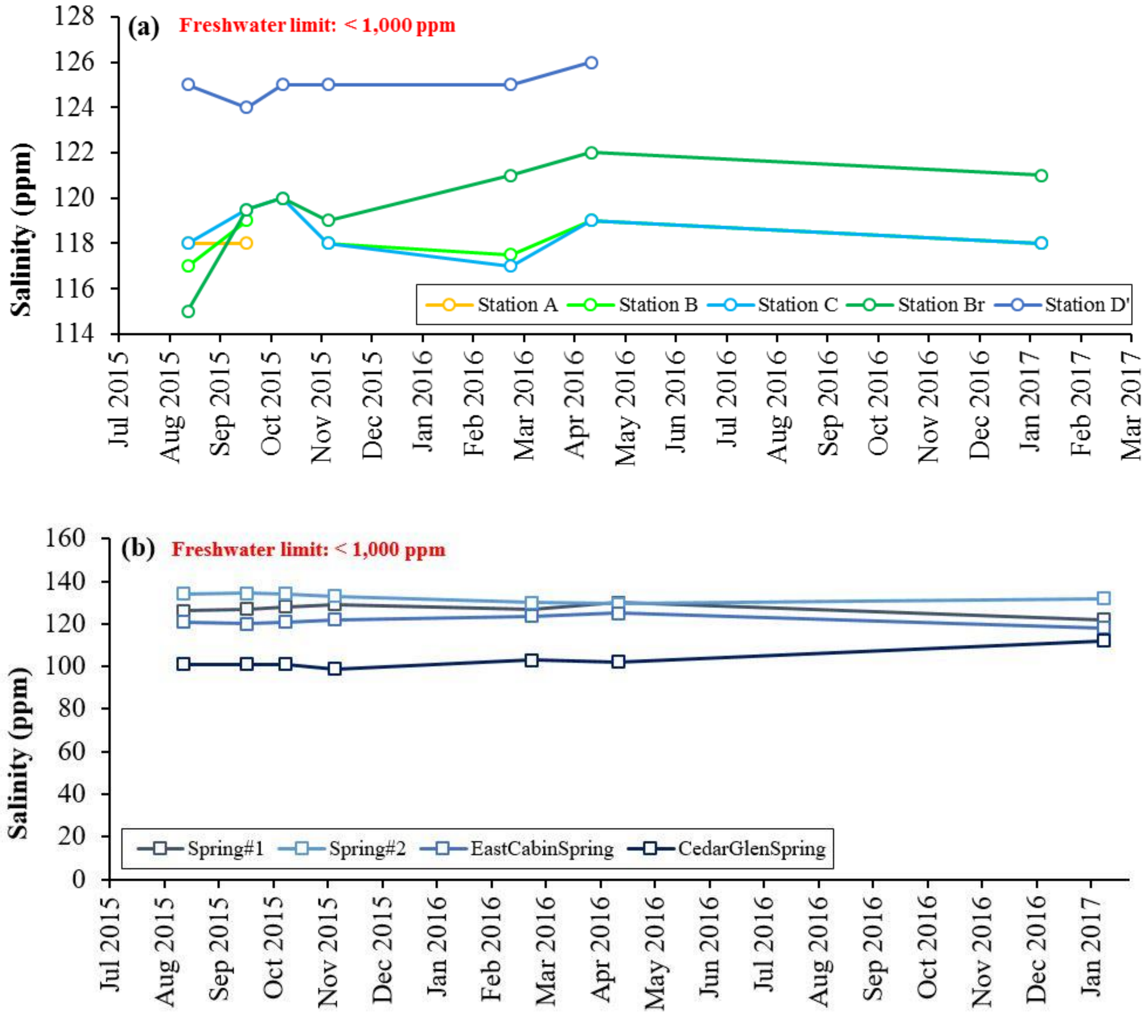


Figure 34. Graphs displaying the salinity concentrations in parts per million at the selected creek stations **(a)** and spring stations **(b)** for water quality determination.

DISCUSSION

Precipitation Variations

Noteworthy Storms and Their Geographic Variability

The distribution and magnitudes of storm events occurring in Icehouse Canyon varied from one year to another. The highest monthly precipitation values were observed during the months of December 2016 and January 2017. In contrast, the lowest precipitation values occurred during the months of August 2015 and September 2016 during severe drought conditions. Historical precipitation data is available in areas outside the Icehouse Canyon watershed, however, there is no historical record for the study area itself. As a result, it becomes challenging to explain and fully understand the storm event behavior in Icehouse Canyon long term. Since storm events provide recharge water to the local mountain aquifers, it is important to continue monitoring the amount of precipitation that the canyon receives on an annual basis. This will provide the historical precipitation records necessary to better explain and understand the storm events. Figure 14 presents a satellite image showing the geographic distribution of all the rain gauges used for this study. Each rain gauge station is located at a specific elevation, which may have influenced the variability in precipitation capture for various storm events. For instance, the rain gauges in Icehouse Canyon and Mid Fork Lyttle Creek located east of the study area are distinct because they consistently recorded higher precipitation values for various storms.

Orographic Effect

The orographic effect in Icehouse Canyon was examined using precipitation data from five rain gauges installed at various elevations within the study area and other several rain gauges from low and high elevations located in the eastern San Gabriel Mountains. The precipitation data from storm events of different intensities and time periods was plotted against rain gauge elevation to examine the large-scale orographic effect, or the change in precipitation capture with change in elevation. A total of eleven storm events were examined to determine the presence of any orographic effect occurring within Icehouse Canyon and the surrounding region. Figure 35 displays precipitation data and elevation for twelve rain gauges in order to examine any potential orographic effect for large storm events. The results from this graph revealed that eight storm events out of eleven demonstrated an overall positive correlation between elevation and precipitation capture. Many of the rain gauges installed at higher elevations generally recorded greater precipitation values, which may suggest a potential orographic effect. Furthermore, the majority of storm events exhibited a consistent increasing-decreasing pattern indicating that other factors may also be influencing the amount of precipitation captured by rain gauges aside from elevation alone. Installing a rain gauge at a higher elevation within the canyon does not necessarily result in higher precipitation capture. Other environmental variables such as sunlight exposure, surrounding vegetation, geography, and wind conditions may also play a significant role impacting orographic effect.

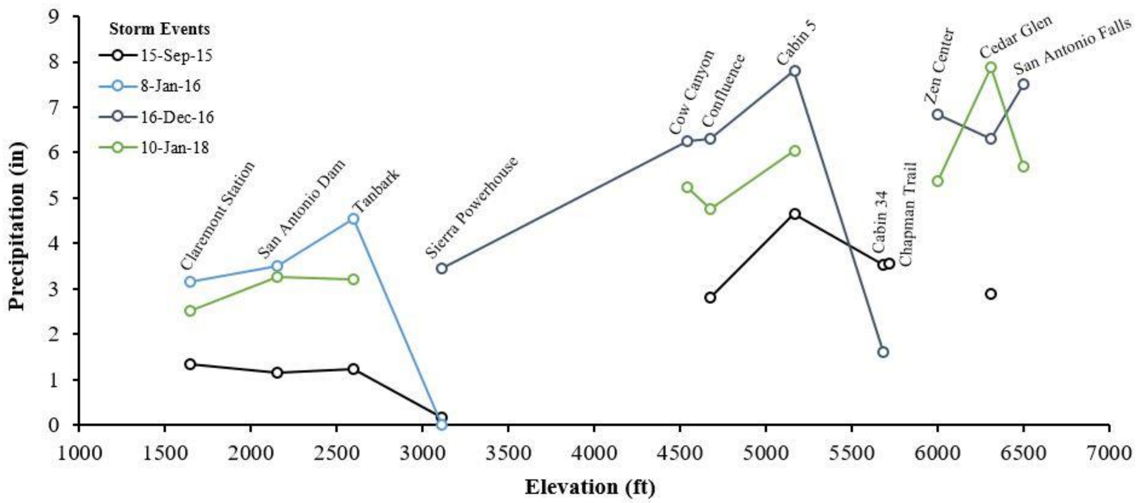


Figure 35. Graph comparing precipitation and elevation data for twelve rain gauges to examine a potential orographic effect for larger storm events.

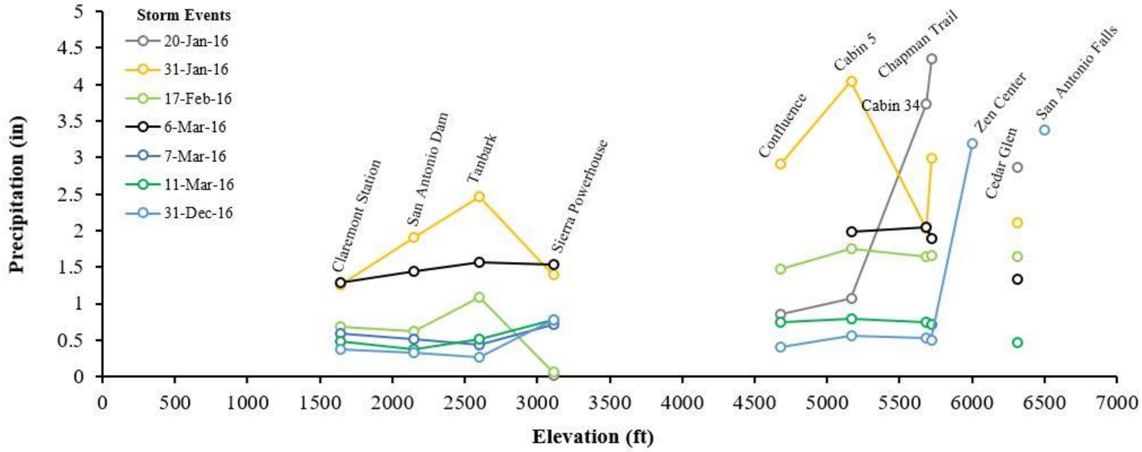


Figure 36. Graph comparing precipitation data and elevation for twelve rain gauges to determine orographic effects for smaller storm events.

Upstream to Downstream Flow Variations

The nonuniform streamflow behavior observed along Icehouse Creek may be the result of influences from factors such as surface and subsurface geology in the surrounding area. At the stations with the highest streamflow, there is significant bedrock exposure, which may be forcing groundwater to rise to the surface resulting in more runoff at those specific stations. Moreover, the lowest streamflow values were consistently observed at stations A and B. At these particular locations there may be thicker layers of alluvium material, which allows streamflow to infiltrate beneath the surface resulting in loss of water. This distinct flow pattern was also noted by a previous study where gaining and losing segments along the Icehouse Creek channel were observed consistently (Nourse et al., 2010). In this previous study, the flow variations were attributed to geologic factors. Furthermore, the surface and subsurface geology of the study area are important factors that influence the surface flow behavior along Icehouse Creek. However, further research is necessary to obtain more information about the subsurface geology at each gauging station in order to gain a better understanding of the streamflow behavior. Geophysical methods such as seismic and electrical resistivity can provide valuable information related to subsurface geology including structure and layer thickness.

Icehouse Creek Response to Precipitation Recharge

The number of hydraulic responses at each gauging station along Icehouse Creek varied during the observation period. Stations with the most frequent hydraulic responses following recharge events included station C, Broullard, and D’. These three stations exhibited more sensitivity to recharge events possibly as a result of the surrounding geologic conditions. For instance, these three stations are located in areas of the canyon where more bedrock exposure is present. The presence of bedrock allows minimal infiltration and less water loss, which ultimately results in higher streamflow values displayed in the hydrograph as peaks. These peak values are interpreted as part of the hydraulic response after the occurrence of storm events. The surrounding geology may explain why certain stations are experiencing more frequent hydraulic responses. In addition, the composite charts allowed individual storm events to be compared with streamflow responses at each of the five gauging stations along Icehouse Creek. The results revealed that the creek experienced a rapid response (<1 week) following noteworthy storms greater than 2 inches.

Icehouse Canyon Springs

The distinct differences in hydraulic response for the spring locations suggest that deeper groundwater sources may be supplying two of the springs, while shallow groundwater may be supplying the more responsive springs. Moreover, the results from these spring hydrographs were evaluated to determine the best option for long-term water resource utilization. After analyzing the results, it appears that Spring #1 would be the most reliable source of freshwater for long-term use. This particular spring produced the highest average discharge value of 70 gal/min over the observation period. In addition, Spring #1 also yielded the highest minimum value of 12 gal/min and highest maximum value of 403 gal/min, suggesting that it is the most reliable source of freshwater over long periods of time. The aquifer supplying Spring #1 may be capable of storing and transmitting larger quantities of groundwater for longer periods of time, which would explain the consistency in spring discharge. Additionally, analysis from the hyetograph-hydrograph charts revealed that springs generally responded slower to major storm events in comparison to creek gauging stations. Spring discharge was only affected slightly by precipitation recharge events under drought conditions. During the year of 2016-2017, a delayed response (~1-2 months) was observed between storm events in mid December and resulting increases in spring discharge.

The cross-section through Icehouse Canyon in Figure 37 illustrates a subsurface model showing different types of aquifers and possible flow paths for groundwater discharging at the spring locations. This interpretation of the subsurface hydrogeology shows that Spring #2 discharges groundwater from two primary sources including an unconfined aquifer composed of landslide material and bedrock fractures associated with local fault zones. Following a major storm event, water can infiltrate through the unconfined aquifer of landslide material with high hydraulic conductivity, which tends to initiate a hydraulic response at the spring locations on a time scale of weeks. In contrast, the creek stations responded rapidly within days because overland flow that reaches the stream channel does pass through these aquifer flow paths. In addition, storm water can also percolate through fractures in bedrock and use fault zones as conduits to discharge at spring locations. The hydraulic conductivity and porosity tends to be significantly lower for fractured bedrock in this longer flow path, which results in a greater residence time for groundwater. The tritium analyses reveal that groundwater discharging at Spring #2 contains an older component, which is probably related to this deeper longer flow path. Overall, it is likely that all the spring locations are receiving groundwater contributions from Cedar Canyon and Icehouse Canyon faults. The landslide aquifer in Cedar Canyon provides a significant additional source of groundwater for Spring #1 and Spring #2.

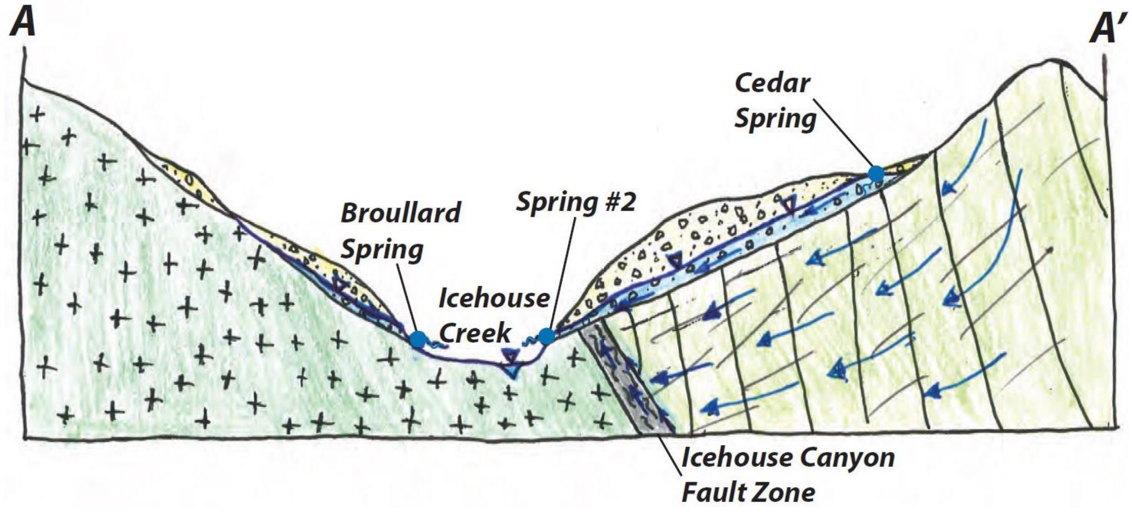
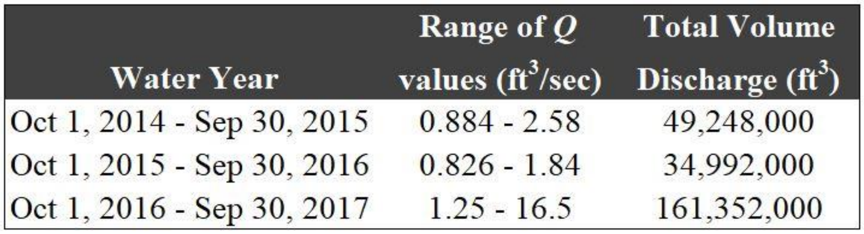


Figure 37. Cross-section traversing Icehouse Canyon (view to the west) showing the hydrogeologic connections near Cedar Canyon landslide and the Spring #2 location (Soto, 2015).

Water Quantity

The complete hydrograph for gauging station C was utilized to determine the total volume discharging from Icehouse Canyon for three different water years. To determine the total volume of water discharging at station C for various water years, the area beneath the hydrograph was divided into squares of equal volume. The total number of squares for each water year were then multiplied by the value 2,592,000 ft^3, which represents the volume of one full square. Appendix 4 provides more details for this particular method of estimating water quantity. Table 3 contains water quantity information relating to volumetric flow through gauging station C between 2014 and 2017. According to the calculations, the highest value for total volume occurred during the water year of 2017. In contrast, the lowest volume was calculated for water year 2016 during drought conditions.

Table 3. Volumetric flow through gauging station C for water years 2014 - 2017.



Water Year	Range of Q values (ft^3/sec)	Total Volume Discharge (ft^3)
Oct 1, 2014 - Sep 30, 2015	0.884 - 2.58	49,248,000
Oct 1, 2015 - Sep 30, 2016	0.826 - 1.84	34,992,000
Oct 1, 2016 - Sep 30, 2017	1.25 - 16.5	161,352,000

Stable Water Isotope Data

The results from the isotopic analysis performed at UC Riverside revealed a high level of similarity between the spring samples and the precipitation samples collected in Icehouse Canyon. Both types of water samples plotted on or near the local meteoric water line. For instance, the two precipitation samples yielded an average value of -2.95 per mil for $\delta^{18}O$ and plotted directly on the LMWL. The spring samples yielded a more depleted average value of -10.06 per mil for $\delta^{18}O$, but also plotted nearly on the line. These isotopic results strongly suggest that groundwater discharging from the spring locations has undergone little fractionation due to factors such as evaporation, freezing, or mixing with metamorphic water, which indicates that the source may originate from local meteoric water produced by storm events within Icehouse Canyon. Additionally, the strong similarity in isotope signature between the two types of water samples also suggests that there is no mixing occurring with other water sources such as deep brine water. The lack of deviation from the LMWL indicates no mixing trend.

Tritium Ages

The calculated groundwater ages of 26.1 to 30.4 years for Spring #2, East Cabin Spring and two other springs are significant because they are non-zero values. This suggest that the meteoric source water discharging at these spring locations may be mixing with an older component of groundwater probably from deep fractures in the crystalline bedrock. Figure 38 shows a potential flow path for this older groundwater source. Storm water can percolate downwards through fractures in the bedrock material and then flow upwards toward a spring discharge point through conduits in fault zones. The deeper groundwater source most likely originated from older precipitation recharge water that entered the network of fractures beneath the surface. Overall, the tritium results provide a line of evidence for spring discharge fed by groundwater sources found in deep fault zones within the canyon. The range of groundwater ages for these specific springs indicate that a partial amount is not derived from modern meteoric water.

Water Quality

The basic water quality parameters measured at the Icehouse Canyon gauging stations included: temperature, pH, conductivity, total dissolved solids, and salinity. Some noticeable differences were detected in spatial and temporal variation. However, the overall water quality for the creek and spring samples was determined to be in excellent condition. There was no presence of contamination from human activities such as previous mining projects or other human causes. The overall quality of the freshwater sources in Icehouse Canyon suggest that it may be used for human consumption or other purposes, however, further examination is required in order to be more certain. As precipitation infiltrates through the soil and rock layers, it undergoes a natural purification process which tends to remove some contaminants dissolved in the water. The water discharging at the spring locations, which also supplies Icehouse Creek, ends up as a high-quality resource that must be protected.

CONCLUSIONS

The hydraulic response of Icehouse Canyon's watershed to precipitation recharge events was observed for a period of over 3 years during drought and non-drought conditions in southern California. Various field methods were utilized to collect sufficient hydrologic data in order to analyze the watershed's response in great detail. Below is a summary of key findings associated with the 3 research questions discussed earlier:

A. Rainfall Variations

(1) Distribution and magnitudes of storm events occurring within Icehouse Canyon watershed varied from year to year. The highest monthly precipitation values were recorded during the months of December 2016 and January 2017. Highest water year precipitation occurred in 2017 with 36.2 inches.

(2) Rain gauge stations installed at different elevations documented the variability in precipitation capture. The rain gauges in Icehouse Canyon and Mid Fork Lytle Creek were significant because they consistently recorded higher precipitation values than other areas of San Gabriel Mountains.

(3) Eight storm events out of eleven demonstrated an overall positive correlation between elevation and precipitation capture. Many of the rain gauges installed at higher elevations generally recorded greater precipitation values, which suggested a potential orographic effect.

B. Discharge Variations

(1) The spatial flow variations observed along Icehouse Creek is influenced by factors including surface and subsurface bedrock geology of the study area. Stations that recorded the highest streamflow values displayed significant bedrock

exposure, which may be causing groundwater to rise to the surface at those specific locations. The lowest streamflow values were consistently observed at stations A and B. These locations displayed wider and probably thicker layers of alluvium material, which allows surface flow to infiltrate beneath the streambed resulting in loss of water. Ultimately, the surface and subsurface geology of the study area are important factors governing the spatial flow variations along Icehouse Creek.

(2) Gauging stations along the creek with the most frequent hydraulic responses occurred at stations C, Broullard, and D'. These stations exhibited more sensitivity to precipitation recharge events most likely from effects of surrounding geologic conditions. Examination of hydraulic responses was made possible through the composite charts comparing precipitation and streamflow data. The results revealed that Icehouse Creek responded rapidly (<1 week) after the occurrence of noteworthy storms producing more than 2 inches of precipitation.

(3) Distinct variations in hydraulic response for the spring locations suggest that deeper groundwater sources may be supplying two of the spring locations, while shallow groundwater may be contributing to the more responsive springs. The analysis from the composite charts revealed that all the springs generally responded significantly slower to major storm events in comparison to Icehouse Creek. It is likely that all the spring stations are receiving delayed groundwater contributions from the Cedar Canyon and Icehouse Canyon faults. The Cedar Canyon landslide is probably providing an additional source of groundwater for Spring #1 and Spring #2.

C. Water Quantity

The volume calculations for gauging station C revealed that the highest value of 161,352,000 ft^3 occurred during the water year of 2017. In contrast, the lowest volume of 34,992,000 ft^3 was calculated for water year 2016 during drought conditions.

D. Isotopic Information

(1) Oxygen and hydrogen isotopic analysis revealed strong similarity between the spring samples and the precipitation samples collected in Icehouse Canyon. The isotopic results suggest that groundwater discharging at the spring locations has experienced little fractionation with respect to local meteoric water, indicating that the source may be derived from local meteoric water following storm events. In addition, the strong similarity in isotopic signature between the two types of water samples also suggest that there may be little to no mixing occurring with other water sources.

(2) Calculated groundwater ages from the tritium data ranged between 26.1 to 30.4 years for Spring #2 and East Cabin Spring. These results are important because they show non-zero values suggesting that mixing may be occurring between local meteoric water and older groundwater derived from deep fractures in the bedrock.

(3) Noticeable spatial and temporal variations were detected in water quality for the creek and spring locations. The overall water quality for the samples collected were determined to be in excellent condition based on current federal regulations. There was no detection of water contamination from human activities including

previous mining projects or other human causes. The high quality of freshwater sources in Icehouse Canyon suggest that it may be used for human consumption and other beneficial purposes, however, further testing is recommended.

The freshwater supplies derived from this watershed contribute to drinking water sources for residents of Mount Baldy Village and the city of Upland. This water source also supports the wildlife and vegetation within the watershed area. Consequently, proper management and planning of this limited water resource is essential for long-term sustainability. Although important knowledge was acquired through this research study, further research is necessary in order to determine long-term trends in streamflow and spring discharge especially during drought conditions. As the human population continues to grow, greater demands will be placed on limited fresh water supplies. Therefore, it is crucial to continuously monitor water quantity and quality data not only in Icehouse Canyon but also in other watershed systems throughout California.

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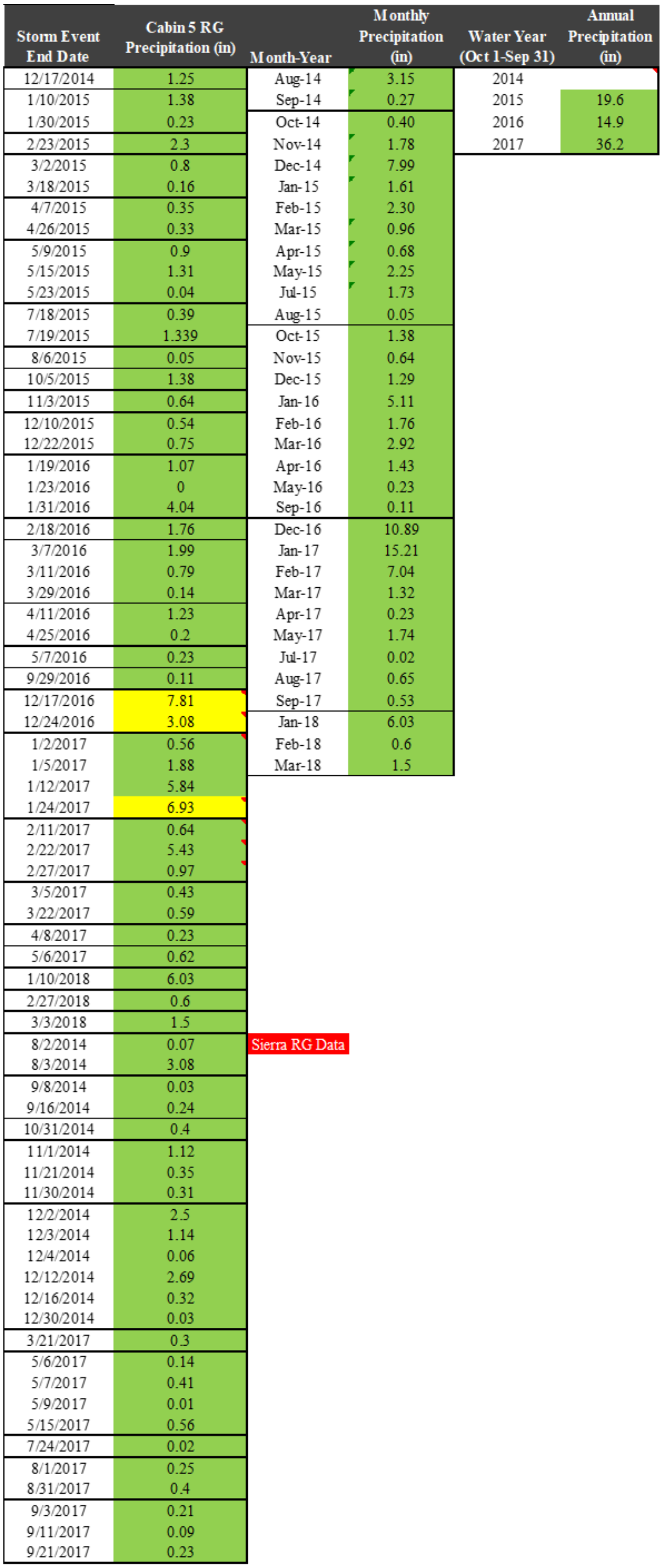
APPENDIX 1: Table of Rain Data (2014-2018)



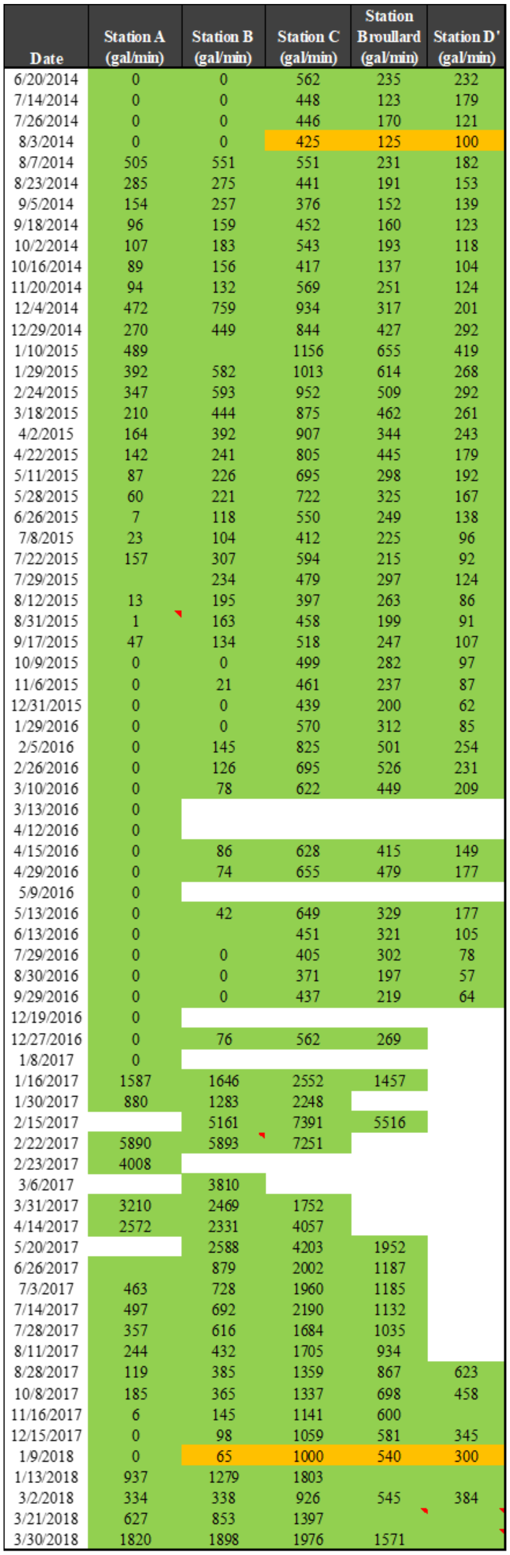
Storm Event End Date	Cabin 5 RG Precipitation (in)
12/17/2014	1.25
1/10/2015	1.38
1/30/2015	0.23
2/23/2015	2.3
3/2/2015	0.8
3/18/2015	0.16
4/7/2015	0.35
4/26/2015	0.33
5/9/2015	0.9
5/15/2015	1.31
5/23/2015	0.04
7/18/2015	0.39
7/19/2015	1.339
8/6/2015	0.05
10/5/2015	1.38
11/3/2015	0.64
12/10/2015	0.54
12/22/2015	0.75
1/19/2016	1.07
1/23/2016	0
1/31/2016	4.04
2/18/2016	1.76
3/7/2016	1.99
3/11/2016	0.79
3/29/2016	0.14
4/11/2016	1.23
4/25/2016	0.2
5/7/2016	0.23
9/29/2016	0.11
12/17/2016	7.81
12/24/2016	3.08
1/2/2017	0.56
1/5/2017	1.88
1/12/2017	5.84
1/24/2017	6.93
2/11/2017	0.64
2/22/2017	5.43
2/27/2017	0.97
3/5/2017	0.43
3/22/2017	0.59
4/8/2017	0.23
5/6/2017	0.62
1/10/2018	6.03
2/27/2018	0.6
3/3/2018	1.5
8/2/2014	0.07
8/3/2014	3.08
9/8/2014	0.03
9/16/2014	0.24
10/31/2014	0.4
11/1/2014	1.12
11/21/2014	0.35
11/30/2014	0.31
12/2/2014	2.5
12/3/2014	1.14
12/4/2014	0.06
12/12/2014	2.69
12/16/2014	0.32
12/30/2014	0.03
3/21/2017	0.3
5/6/2017	0.14
5/7/2017	0.41
5/9/2017	0.01
5/15/2017	0.56
7/24/2017	0.02
8/1/2017	0.25
8/31/2017	0.4
9/3/2017	0.21
9/11/2017	0.09
9/21/2017	0.23

Sierra RG Data

Month-Year	Monthly Precipitation (in)
Aug-14	3.15
Sep-14	0.27
Oct-14	0.40
Nov-14	1.78
Dec-14	7.99
Jan-15	1.61
Feb-15	2.30
Mar-15	0.96
Apr-15	0.68
May-15	2.25
Jul-15	1.73
Aug-15	0.05
Oct-15	1.38
Nov-15	0.64
Dec-15	1.29
Jan-16	5.11
Feb-16	1.76
Mar-16	2.92
Apr-16	1.43
May-16	0.23
Sep-16	0.11
Dec-16	10.89
Jan-17	15.21
Feb-17	7.04
Mar-17	1.32
Apr-17	0.23
May-17	1.74
Jul-17	0.02
Aug-17	0.65
Sep-17	0.53
Jan-18	6.03
Feb-18	0.6
Mar-18	1.5

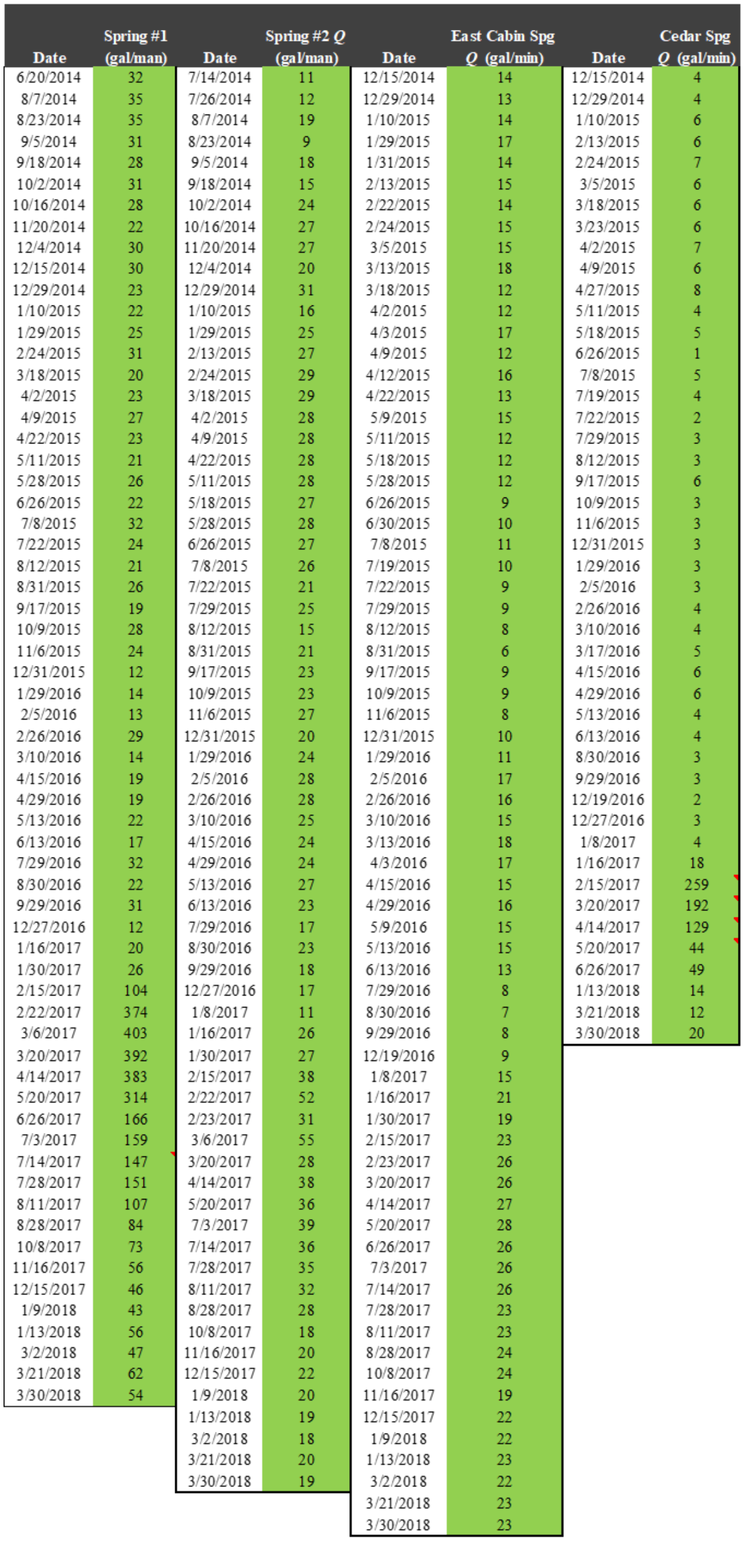
Water Year (Oct 1-Sep 31)	Annual Precipitation (in)
2014	
2015	19.6
2016	14.9
2017	36.2

APPENDIX 2: Table of Icehouse Creek Discharge Data



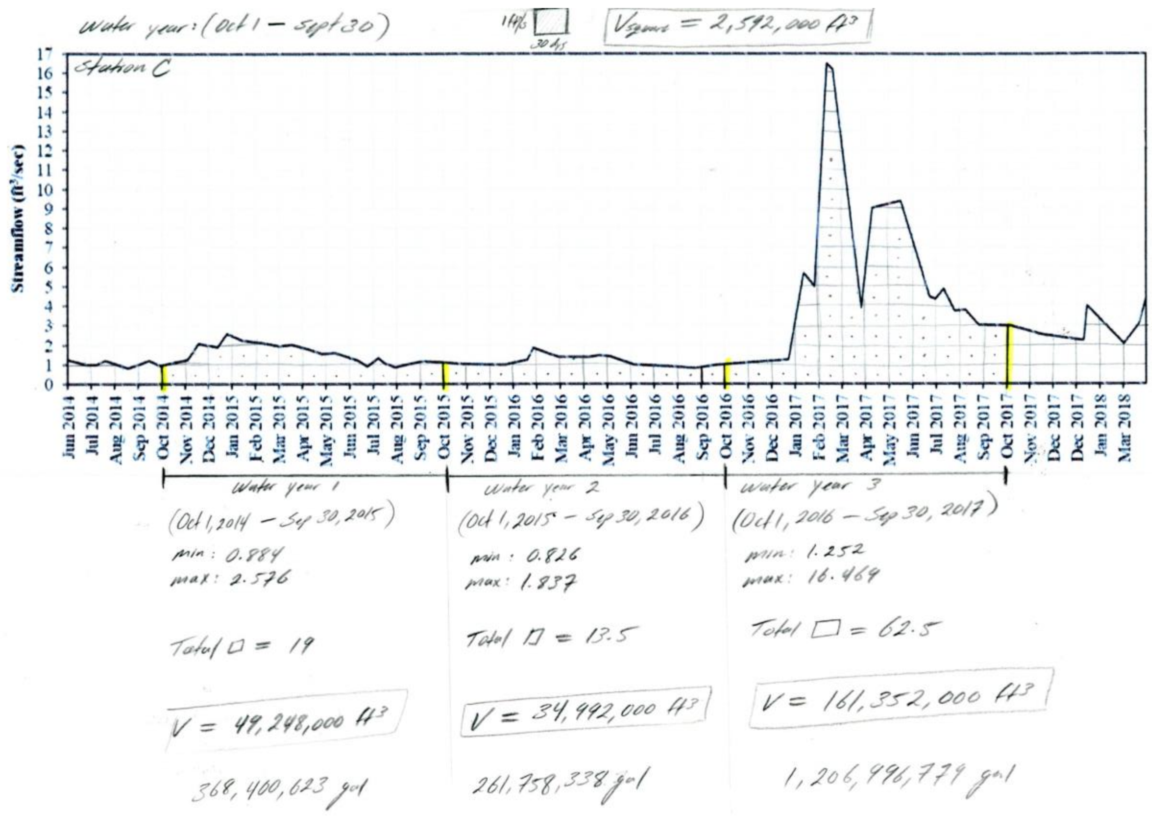
Date	Station A (gal/min)	Station B (gal/min)	Station C (gal/min)	Station Broullard (gal/min)	Station D' (gal/min)
6/20/2014	0	0	562	235	232
7/14/2014	0	0	448	123	179
7/26/2014	0	0	446	170	121
8/3/2014	0	0	425	125	100
8/7/2014	505	551	551	231	182
8/23/2014	285	275	441	191	153
9/5/2014	154	257	376	152	139
9/18/2014	96	159	452	160	123
10/2/2014	107	183	543	193	118
10/16/2014	89	156	417	137	104
11/20/2014	94	132	569	251	124
12/4/2014	472	759	934	317	201
12/29/2014	270	449	844	427	292
1/10/2015	489		1156	655	419
1/29/2015	392	582	1013	614	268
2/24/2015	347	593	952	509	292
3/18/2015	210	444	875	462	261
4/2/2015	164	392	907	344	243
4/22/2015	142	241	805	445	179
5/11/2015	87	226	695	298	192
5/28/2015	60	221	722	325	167
6/26/2015	7	118	550	249	138
7/8/2015	23	104	412	225	96
7/22/2015	157	307	594	215	92
7/29/2015		234	479	297	124
8/12/2015	13	195	397	263	86
8/31/2015	1	163	458	199	91
9/17/2015	47	134	518	247	107
10/9/2015	0	0	499	282	97
11/6/2015	0	21	461	237	87
12/31/2015	0	0	439	200	62
1/29/2016	0	0	570	312	85
2/5/2016	0	145	825	501	254
2/26/2016	0	126	695	526	231
3/10/2016	0	78	622	449	209
3/13/2016	0				
4/12/2016	0				
4/15/2016	0	86	628	415	149
4/29/2016	0	74	655	479	177
5/9/2016	0				
5/13/2016	0	42	649	329	177
6/13/2016	0		451	321	105
7/29/2016	0	0	405	302	78
8/30/2016	0	0	371	197	57
9/29/2016	0	0	437	219	64
12/19/2016	0				
12/27/2016	0	76	562	269	
1/8/2017	0				
1/16/2017	1587	1646	2552	1457	
1/30/2017	880	1283	2248		
2/15/2017		5161	7391	5516	
2/22/2017	5890	5893	7251		
2/23/2017	4008				
3/6/2017		3810			
3/31/2017	3210	2469	1752		
4/14/2017	2572	2331	4057		
5/20/2017		2588	4203	1952	
6/26/2017		879	2002	1187	
7/3/2017	463	728	1960	1185	
7/14/2017	497	692	2190	1132	
7/28/2017	357	616	1684	1035	
8/11/2017	244	432	1705	934	
8/28/2017	119	385	1359	867	623
10/8/2017	185	365	1337	698	458
11/16/2017	6	145	1141	600	
12/15/2017	0	98	1059	581	345
1/9/2018	0	65	1000	540	300
1/13/2018	937	1279	1803		
3/2/2018	334	338	926	545	384
3/21/2018	627	853	1397		
3/30/2018	1820	1898	1976	1571	

APPENDIX 3: Table of Spring Discharge Data



Date	Spring #1 (gal/man)	Date	Spring #2 *Q* (gal/man)	Date	East Cabin Spg *Q* (gal/min)	Date	Cedar Spg *Q* (gal/min)
6/20/2014	32	7/14/2014	11	12/15/2014	14	12/15/2014	4
8/7/2014	35	7/26/2014	12	12/29/2014	13	12/29/2014	4
8/23/2014	35	8/7/2014	19	1/10/2015	14	1/10/2015	6
9/5/2014	31	8/23/2014	9	1/29/2015	17	2/13/2015	6
9/18/2014	28	9/5/2014	18	1/31/2015	14	2/24/2015	7
10/2/2014	31	9/18/2014	15	2/13/2015	15	3/5/2015	6
10/16/2014	28	10/2/2014	24	2/22/2015	14	3/18/2015	6
11/20/2014	22	10/16/2014	27	2/24/2015	15	3/23/2015	6
12/4/2014	30	11/20/2014	27	3/5/2015	15	4/2/2015	7
12/15/2014	30	12/4/2014	20	3/13/2015	18	4/9/2015	6
12/29/2014	23	12/29/2014	31	3/18/2015	12	4/27/2015	8
1/10/2015	22	1/10/2015	16	4/2/2015	12	5/11/2015	4
1/29/2015	25	1/29/2015	25	4/3/2015	17	5/18/2015	5
2/24/2015	31	2/13/2015	27	4/9/2015	12	6/26/2015	1
3/18/2015	20	2/24/2015	29	4/12/2015	16	7/8/2015	5
4/2/2015	23	3/18/2015	29	4/22/2015	13	7/19/2015	4
4/9/2015	27	4/2/2015	28	5/9/2015	15	7/22/2015	2
4/22/2015	23	4/9/2015	28	5/11/2015	12	7/29/2015	3
5/11/2015	21	4/22/2015	28	5/18/2015	12	8/12/2015	3
5/28/2015	26	5/11/2015	28	5/28/2015	12	9/17/2015	6
6/26/2015	22	5/18/2015	27	6/26/2015	9	10/9/2015	3
7/8/2015	32	5/28/2015	28	6/30/2015	10	11/6/2015	3
7/22/2015	24	6/26/2015	27	7/8/2015	11	12/31/2015	3
8/12/2015	21	7/8/2015	26	7/19/2015	10	1/29/2016	3
8/31/2015	26	7/22/2015	21	7/22/2015	9	2/5/2016	3
9/17/2015	19	7/29/2015	25	7/29/2015	9	2/26/2016	4
10/9/2015	28	8/12/2015	15	8/12/2015	8	3/10/2016	4
11/6/2015	24	8/31/2015	21	8/31/2015	6	3/17/2016	5
12/31/2015	12	9/17/2015	23	9/17/2015	9	4/15/2016	6
1/29/2016	14	10/9/2015	23	10/9/2015	9	4/29/2016	6
2/5/2016	13	11/6/2015	27	11/6/2015	8	5/13/2016	4
2/26/2016	29	12/31/2015	20	12/31/2015	10	6/13/2016	4
3/10/2016	14	1/29/2016	24	1/29/2016	11	8/30/2016	3
4/15/2016	19	2/5/2016	28	2/5/2016	17	9/29/2016	3
4/29/2016	19	2/26/2016	28	2/26/2016	16	12/19/2016	2
5/13/2016	22	3/10/2016	25	3/10/2016	15	12/27/2016	3
6/13/2016	17	4/15/2016	24	3/13/2016	18	1/8/2017	4
7/29/2016	32	4/29/2016	24	4/3/2016	17	1/16/2017	18
8/30/2016	22	5/13/2016	27	4/15/2016	15	2/15/2017	259
9/29/2016	31	6/13/2016	23	4/29/2016	16	3/20/2017	192
12/27/2016	12	7/29/2016	17	5/9/2016	15	4/14/2017	129
1/16/2017	20	8/30/2016	23	5/13/2016	15	5/20/2017	44
1/30/2017	26	9/29/2016	18	6/13/2016	13	6/26/2017	49
2/15/2017	104	12/27/2016	17	7/29/2016	8	1/13/2018	14
2/22/2017	374	1/8/2017	11	8/30/2016	7	3/21/2018	12
3/6/2017	403	1/16/2017	26	9/29/2016	8	3/30/2018	20
3/20/2017	392	1/30/2017	27	12/19/2016	9		
4/14/2017	383	2/15/2017	38	1/8/2017	15		
5/20/2017	314	2/22/2017	52	1/16/2017	21		
6/26/2017	166	2/23/2017	31	1/30/2017	19		
7/3/2017	159	3/6/2017	55	2/15/2017	23		
7/14/2017	147	3/20/2017	28	2/23/2017	26		
7/28/2017	151	4/14/2017	38	3/20/2017	26		
8/11/2017	107	5/20/2017	36	4/14/2017	27		
8/28/2017	84	7/3/2017	39	5/20/2017	28		
10/8/2017	73	7/14/2017	36	6/26/2017	26		
11/16/2017	56	7/28/2017	35	7/3/2017	26		
12/15/2017	46	8/11/2017	32	7/14/2017	26		
1/9/2018	43	8/28/2017	28	7/28/2017	23		
1/13/2018	56	10/8/2017	18	8/11/2017	23		
3/2/2018	47	11/16/2017	20	8/28/2017	24		
3/21/2018	62	12/15/2017	22	10/8/2017	24		
3/30/2018	54	1/9/2018	20	11/16/2017	19		
		1/13/2018	19	12/15/2017	22		
		3/2/2018	18	1/9/2018	22		
		3/21/2018	20	1/13/2018	23		
		3/30/2018	19	3/2/2018	22		
				3/21/2018	23		
				3/30/2018	23		

APPENDIX 4: Water Quantity Estimation



$V_{square} = 2,592,000$ ft³

water year 1

(Oct 1, 2014 – Sep 30, 2015)

min: 0.884
max: 2.576

Total □ = 19

$V = 49,248,000$ ft³

368,400,623 gal

water year 2

(Oct 1, 2015 – Sep 30, 2016)

min: 0.826
max: 1.837

Total □ = 13.5

$V = 34,992,000$ ft³

261,758,338 gal

water year 3

(Oct 1, 2016 – Sep 30, 2017)

min: 1.252
max: 16.469

Total □ = 62.5

$V = 161,352,000$ ft³

1,206,996,779 gal