STREAM GAUGING, GROUNDWATER MONITORING AND

ISOTOPIC ANALYSIS IN BIG CHICO CREEK, CALIFORNIA

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A Thesis

Presented

to the Faculty of

California State University, Chico

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In Partial Fulfillment

of the Requirement for the Degree

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in

Geosciences

Hydrology/Hydrogeology Option

---

by

Patrick Marcio DeCarvalho

Summer 2012

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# ABSTRACT

STREAM GAUGING, GROUNDWATER MONITORING AND ISOTOPIC ANALYSIS IN BIG CHICO CREEK, CALIFORNIA

by

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Master of Science in Geosciences

Hydrology/Hydrogeology Option

California State University, Chico

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The sources of the water that keep Big Chico Creek flowing during the dry summer months were previously unknown. It was hypothesized that the water flowing in the creek during the summer months was largely contributed by melted snow from the mountains in Butte Meadows. Three study elements were employed to investigate Big Chico Creek between January 30 and August 28, 2011. Stream gauging was performed and the depth of the water table along a portion of Big Chico Creek was monitored, indicating whether the creek was gaining or losing to groundwater. Stream gauging and water table monitoring indicated that baseflow did not contribute to the creek over the course of the study. Additionally, samples of snowmelt, rainwater, spring water, groundwater, and water from Big Chico Creek were collected and subjected to isotopic analysis to deter mine whether Big Chico Creek assumes an isotopically depleted signature consistent with snowmelt. Water from Big Chico Creek did become more depleted over the summer and adopted an isotopic makeup more consistent with that of the snow collected from Butte Meadows. Rainwater sources, water from a natural spring and groundwater sources were relatively enriched compared to Big Chico Creek and snow from Butte Meadows

To determine the relative contributions from the various sources, a variety of statistical applications, such as cross correlation between creek water elevation and the water table elevation, an analysis of variance to establish statistically significant differences in isotope ratios across the different locations and collection dates, a cross-correlation between the creekflow and depletion of $^{18}O$ and $^{2}H$ isotopes, a cross-correlation between isotope ratios of creekwater and snowmelt, rainwater, spring water, and groundwater, and a runs test to determine that the changes in isotope ratios were non-random in nature were performed. Cross-correlation showed strong correlations between the water table elevation at individual monitoring points and the creek elevation, with no lag detected. An analysis of variance revealed that significant differences in $\delta^{18}O$ and $\delta^{2}H$ values did exist between different sample sites, but no significant difference was found between different sampling dates. Cross-correlation found a strong correlation between low creek levels and waters depleted in $^{18}O$ and $^{2}H$ isotopes, while no correlation was seen between the creek and any one particular sampling site. A runs test showed that non-random variation was present in all samples.

Monitoring of creek discharge, groundwater levels in the vicinity of the creek, and isotopic composition of the water all suggest that Big Chico Creek is consistently

losing to groundwater year-round and only maintains flow due to the contribution of snowmelt in the headwaters. Failure to reach statistically significant differences within the analysis of variance may have been due to the evaporative enrichment endemic to the dry summer months, dulling the depleting effect of the melting snow contributing to the creek. Additionally, the early summer months featured higher than average precipitation, further enriching the creek water.

# CHAPTER I

# INTRODUCTION

Perennial streamflow is typically composed of a mixture of groundwater discharge and surface runoff. Traditionally, it has been assumed that perennial streams are fed by groundwater during non-storm periods, allowing year-round flow during dry periods. Identifying the source of water supplying a perennial stream is of great importance. If perennial stream flow is diminished, local effects on plant and wildlife could be drastic. Hydrologic disturbance can alter the variation and distribution of algal biomass and primary consumers (Riseng et al. 2004) and invertebrates (Covich et al. 2003) in perennial streams. Human activity such as land development may interfere with natural recharge areas (Preston et al., 2001; Jacobson, 2011) due to increased imperviousness associated with urbanization, while global warming and diminished snowpack may deprive perennial streams of source water if they are being fed by snowmelt in the warmer, drier months (Brikowski, 2008; Claramonte et al., 2011).

Stable isotopes of water, particularly oxygen-18 ($^{18}O$) and deuterium ($^{2}H$) have been used as a form of tracer with colder, higher elevation water associated with a relative depletion in $^{18}O$ and $^{2}H$ and warmer, lower elevation water associated with a relative enrichment of $^{18}O$ and $^{2}H$. Brock et al. (2007) found that flooding from the nearby rivers drove spring lakewater balances in outer and mid-delta lakes while higher elevation lakes received input primarily from snowmelt. Cui et al. (2009) analyzed precipitation delivered to the upper catchments of the Yangtze River. Rain and fog in an alpine meadow were found to contain fewer heavy isotopes than precipitation at lower elevations. Precipitation at lower elevations came from water that had originally evaporated from the ocean. The contribution from evaporated water to precipitation in the alpine meadow was mainly from sub-alpine valleys.

Isotopes have been used to study how geospatial, temporal and climactic factors affect the water cycle. Vreča et al. (2006) compared isotopic composition of $^{18}O$ and $^{2}H$ in precipitation and found less seasonal variability in isotope composition at coastal stations because of greater temperature variations present inland. Yuan and Miyamoto (2008) compared several portions of the Pecos River and found that river water from the upper valley was depleted in $^{18}O$ and $^{2}H$ while the river water became more enriched further downstream. This was attributed to warmer average climates and heavy isotope enrichment by evaporation. Greater seasonal variability was seen in samples from lower elevations. Jeelani et al. (2010) found precipitation to be depleted in the cooler seasons and the higher elevations in streams and springs of the Himalayas. The isotopic makeup of streams and springs was controlled by the catchment elevations, with depleted water encountered at the higher altitudes. The snowmelt contribution was found to be dominant in May, while baseflow contributions peaked in January. Machavaram et al. (2006) studied a small stream in the Great Plains and found that after storm events, flow was primarily from shallow subsurface flow and runoff, while in headwater locations, flow was primarily from shallow groundwater and pond outflow. Isotopic fingerprints of precipitation and evaporated pond water allowed for separation of event water from older water sources and for hydrograph separation. Yi et al. (2010) found that in the Mackenzie River system of Canada, snowmelt dominated the discharge with mixing of depleted discharge from nearby mountains and enriched water from a lowland catchment. Conditions of low flow contained the most depleted waters, while it was observed that high flow conditions were highly enriched in heavier isotopes. Evaporated waters from surface storage were likely contributors to this flow.

The purpose of this study was to investigate the sources of water to Big Chico Creek, a perennial stream located in Butte and Tehama counties in Northern California, which heads in the Sierra Nevada and flows through the city of Chico (39.73° N, 121.84° W) before reaching the Sacramento River (Figure 1).

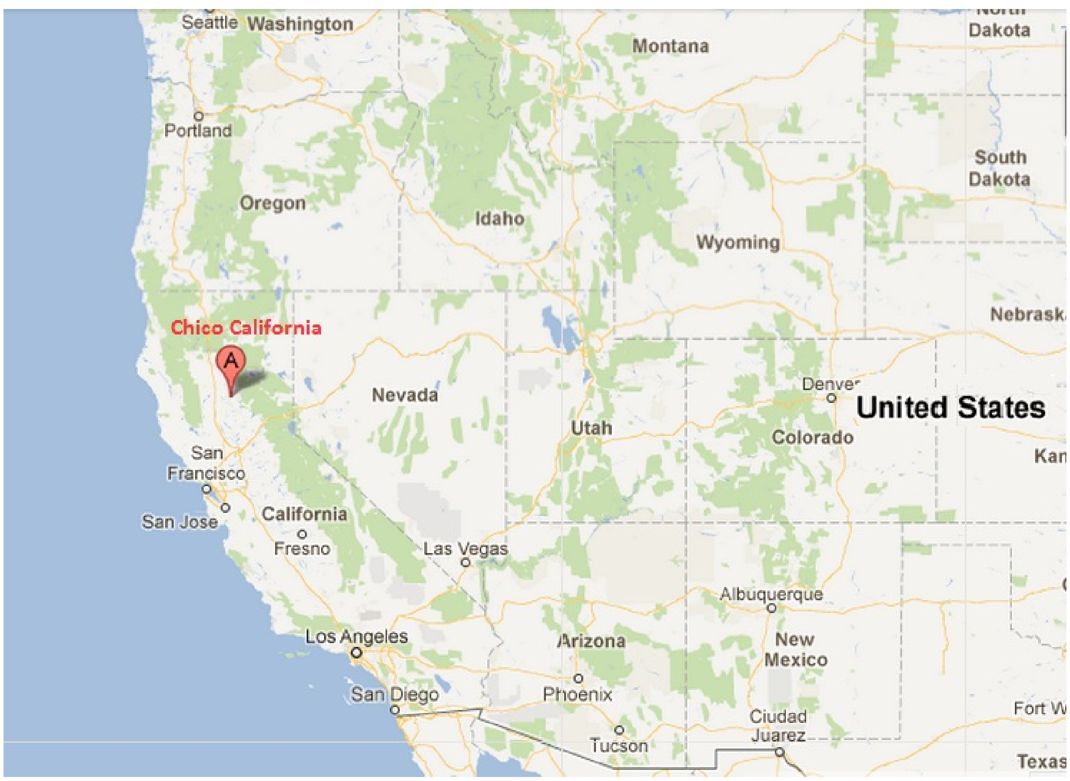


Figure 1. Chico California.

Flow in Big Chico Creek is generally high during the winter and low during the summer. During extremely high flow storm events, Big Chico Creek's flow is partially diverted into the Lindo Channel (Figure 2), which formed as a natural channel across the alluvial fan on which Chico is located. The Lindo Channel runs parallel to Big Chico Creek for approximately seven miles and was the original path of Big Chico Creek. Traditionally, it has been assumed that groundwater feeds Big Chico Creek during dry periods, but several lines of evidence suggest that groundwater may not be the source of the creek's year-round flow. In a monitoring report conducted by the Groundwater Ambient Monitoring Assessment Program, Moran et al. (2003) studied the isotopic makeup of samples taken from monitoring wells along Big Chico Creek. It was found that samples taken in closer proximity to the creek were more isotopically depleted than samples taken from further away. This was interpreted as evidence that Big Chico Creek was largely being fed from snowmelt in the nearby mountains. The study did not take samples over time however, so temporal variations could not be determined. Additionally, a report from the Department of Fish and Game stated that a beaver dam had to be modified after it stopped water flow in Big Chico Creek in 2007and the creek bed downstream of the dam ran dry. After the beaver dam was modified to allow stream flow, Big Chico Creek returned to its previous water level (Department of Fish and Game, 2007). Conditions that could cause Big Chico Creek to lose to groundwater include the permeable fan sediments in the valley and excessive pumping of the Tuscan Aquifer (Butte Country Department of Water and Resource Conservation, 2010).

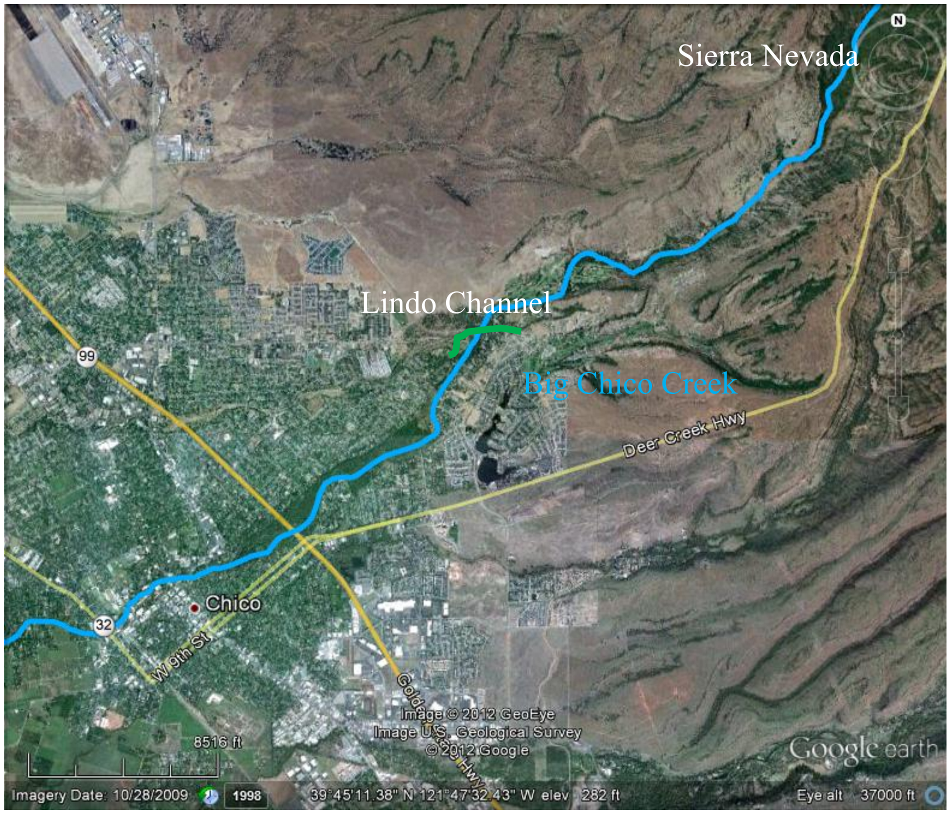


Figure 2. Big Chico Creek and Lindo Channel, Chico California.

It was hypothesized that the water flowing in the creek during the summer months was largely contributed by melted snow from the mountains in Butte Meadows, located in the foothills of the Sierra Nevada (Figure 2). Three study elements were employed to investigate contributions to flow in Big Chico Creek. Stream gauging was performed at three separate locations on two occasions to ascertain whether the creek was gaining or losing to groundwater and the depth of the water table at various distances from Big Chico Creek was monitored every two weeks between January 30$^{th}$ and August 28$^{th}$ 2011. Additionally, samples of snow, rainwater, spring water, groundwater and water from the creek were collected and subjected to isotopic analysis to determine whether the water in Big Chico Creek becomes more isotopically depleted during the dry summer months. In the wet months from January to April, it was expected that the creek would have an isotopic makeup more consistent with rainwater and higher amounts of $^{18}O$ and $^{2}H$ should be found in the water during that time of the year, as suggested by Jeelani et al. (2010). During the dry months, from May to August, as precipitation decreased in both frequency and magnitude, it was expected that the creek would be depleted of heavier isotopes and the dominant source of water would be derived from snowmelt, which would have a lower amounts of $^{18}O$ and $^{2}H$. Additionally, it was hypothesized that, given the permeability of the valley sediments as well as the effects of groundwater pumping, Big Chico Creek would be losing to groundwater during both the rainy winter season and the drier summer.

The results of this study indicated that baseflow from groundwater did not contribute to the creek over the course of the investigation. Stream gauging demonstrated that Big Chico Creek lost significant flow to groundwater while traveling from the foothills of Sierra Nevada to the valley. Monitoring water table depths along Big Chico Creek revealed that over the duration of the study, Big Chico Creek is an influent stream. Cross-correlation analysis showed a strong relation between the elevation of the water table at the individual monitoring points and the creek. Isotopic analysis revealed that water from Big Chico Creek became more depleted over the summer and adopted an isotopic makeup more consistent with that of the snow collected from Butte Meadows. Data from the study, plotted along the global meteoric water line, revealed that the samples fell along the calculated line very closely with higher elevation samples displaying the characteristic depletion and lower elevation samples displaying the characteristic enrichment found on the global meteoric water line. Isotopic analysis revealed that samples from higher elevations did indeed carry greater amounts of $^{18}O$ and $^{2}H$. An analysis of variance revealed that significant differences in $\delta^{18}O$ and $\delta^{2}H$ values did exist between different sample sites, but no significant difference was found between different sampling dates. Cross-correlation between low creek levels and waters depleted in $^{18}O$ and $^{2}H$ isotopes revealed a strong relation, indicating that during low flow the creek was being fed by water from higher elevations. A runs test indicated that non-random variation in $^{18}O$ and $^{2}H$ values over time was present in all samples. Failure to reach statistically significant differences within the analysis of variance may have been due to the evaporative enrichment endemic to the dry summer months, muting the depleting effect of the snowmelt contribution to the creek. Additionally, during the early summer months within the sampling period there was greater than average precipitation, further enriching the creek water with higher $\delta^{18}O$ and $\delta^{2}H$ values.

# CHAPTER II

## BIG CHICO CREEK WATERSHED

### OVERVIEW

Perennial streams are usually assumed to be fed by groundwater, allowing year-round flow during non-storm periods. A study testing this assumption was conducted between January and August, 2011 on Big Chico Creek in the Northern Sacramento Valley (Figure 3). Big Chico Creek is located in Butte and Tehama counties and originates at an elevation of approximately 5,400 feet, on the southern face of Colby Mountain. Big Chico Creek drains an area of approximately 72 $mi^2$ (Figure 3) and flows 44.8 mi before discharging to the Sacramento River. Big Chico Creek is a perennial stream and continues to flow even in the dry hot summers endemic to the area.

The climate within the Big Chico Creek watershed is described as Mediterranean (Critchfield, 1974). During the spring, summer, and even fall, it is not uncommon for the local watersheds to go over six months without rain (National Weather Service, 2011). Summer temperatures in the lower elevations can reach 105° F. Winters are typically mild although freezing temperatures are frequently encountered in the upper portions of the watershed. The bulk of precipitation falls between November and May with average values of 20 in. in the valley and between 70-80 in at higher elevations (Big Chico Creek Watershed Alliance, 2009). Average values between January and April are

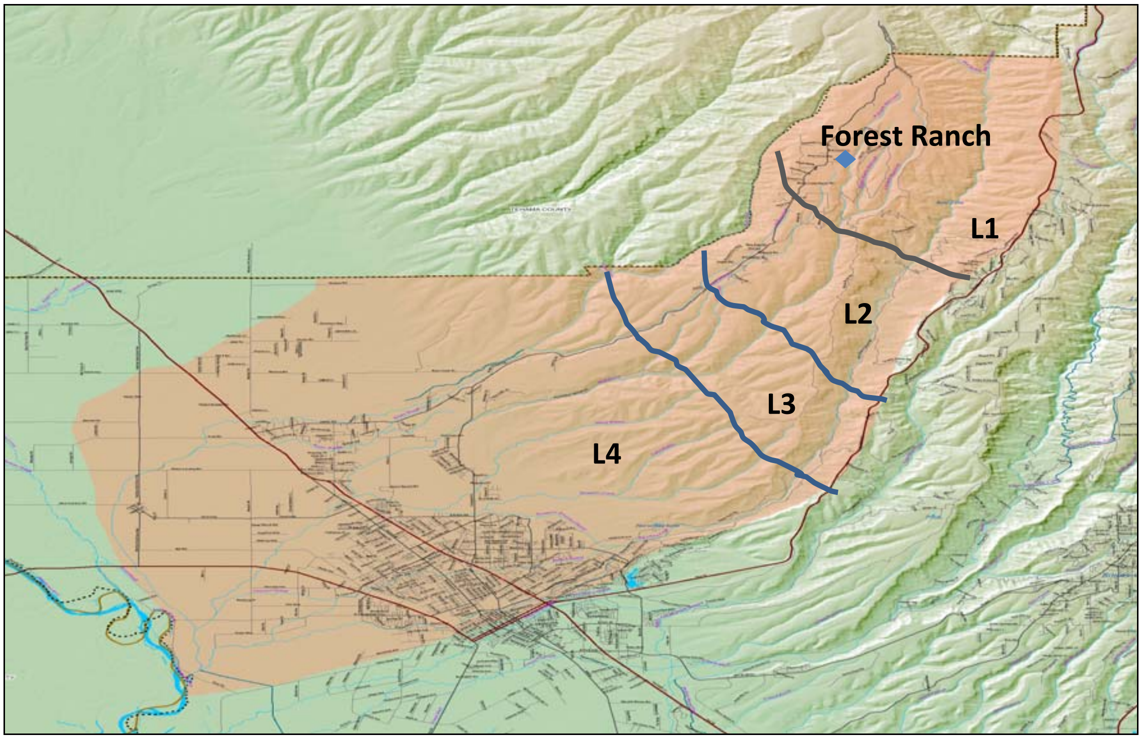


Figure 3. Map of Big Chico Creek watershed in Butte County, California.

Source: Adapted from Butte County Development Services Department, 2005, Big Chico Creek watershed map: Butte County, Oroville, CA.

17.91 in, while between May and August, average precipitation is just 1.72 in (National Weather Service, 2011).

The geology of the Big Chico Creek watershed is dominated by ancient volcanic activity in the Sierra Nevada and Cascade ranges. Big Chico Creek originates in the extrusive igneous rocks of the Tuscan Formation (Figure 4). The Tuscan Formation consists of volcaniclastic fan apron deposits (Critchfield, 1974) and is the most significant geologic formation in Big Chico Creek watershed because it is the most recently deposited (approximately 4 million years ago). The upper reaches of the Big Chico Creek watershed are composed of Tuscan Formation deposits. Further downstream

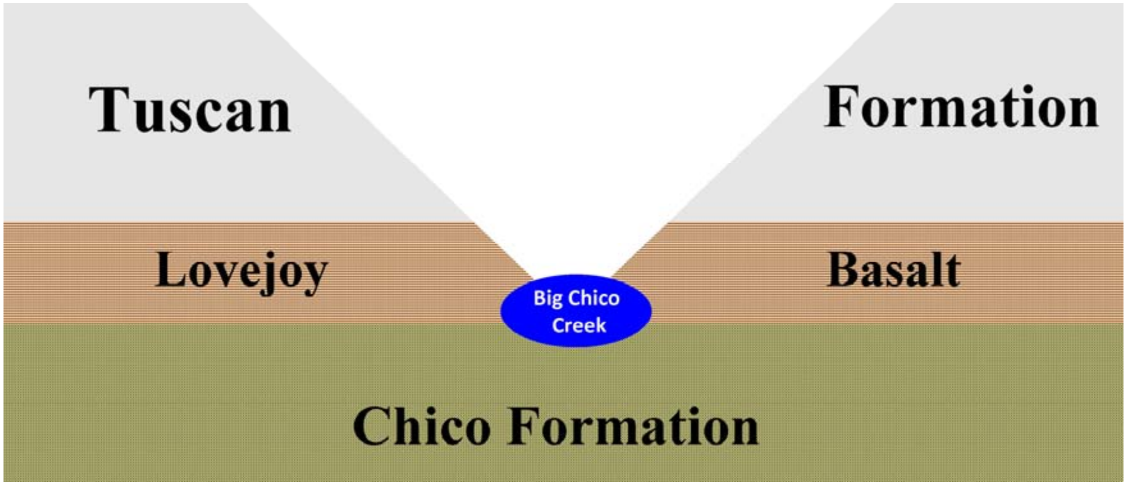


Figure 4. Relative stratigraphic positions of the Tuscan Formation, Lovejoy Basalt and Chico Formation.

Source: Adapted from Guyton, J. W., and DeCourten, F. L., 1978, Introduction to the geology of Bidwell Park: Chico, California, University Foundation, 25 p.

the Lovejoy Basalt, which underlies the Tuscan Formation, is exposed. This formation is approximately 20 million years old and is highly fractured, with large boulders occasionally falling off the cliff faces, depositing basalt fragments into Big Chico Creek. Underlying the Lovejoy Basalt is the Chico Formation, which Big Chico Creek cuts through before entering the Big Chico Creek alluvial fan. The Chico Formation is approximately 75 million years old and is composed of ancient coastal sandstone. The Chico Formation is significantly less resistant than the Tuscan Formation, allowing the creek to meander. Big Chico Creek is continually incising through the different layers, exposing them in the canyon walls.

The soils along Big Chico Creek vary greatly due to differing parent materials and topography present. According to the Big Chico Creek Watershed Alliance (2009), the upper reaches (L1, Figure 3) are characterized by coarse soils. This area supports coniferous trees such as the ponderosa pine, sugar pine, incense cedar, and Douglas fir. The next lower zone (L2, Figure 3) extends to an elevation of about 2,000 feet along Highway 32 below Forest Ranch. The soil in this region is characterized as loamy with a fine clayey to silty texture. Ponderosa pines dominate this area, along with Douglas fir, and black oak. The next lowermost zone (L3, Figure 3) descends to 1,500 feet. The soils in this zone have moderately fine texture. Black oak, grey pine, manzanita, and ponderosa are found here. The lowest zone (L4, Figure 3) includes the foothill region, which extends to Horseshoe Lake in Upper Bidwell Park and is composed of loamy textured soils. These soils support blue and black oak and vast areas of grasslands. The lowermost region of this zone is composed of the Big Chico Creek alluvial fan and Sacramento River flood deposits. Soils in these deposits can be very deep and range from fine to coarse grained, exhibiting both high transmissivity and water holding capacity.

Big Chico Creek flows through a variety of properties, both public and private. The upper and middle portions of Big Chico Creek are rural, with much of the upland portions being found in the Big Chico Creek Ecological Reserve and Bidwell Park. The lower portion runs through the city of Chico before continuing on to privately owned agricultural lands.

Flow rates in Big Chico Creek have been gauged by the United States Geological Survey (USGS) and volunteers from the Big Chico Creek Watershed Alliance. The USGS has extensive hydrological records of flow rates between 1941 to 1986, recorded in Upper Bidwell Park with an upstream watershed area of 72 $mi^2$ (Figure 5). USGS records indicate that over their period of monitoring, Big Chico Creek discharged an average flow of 156 cubic feet per second (cfs) (Figure 6).

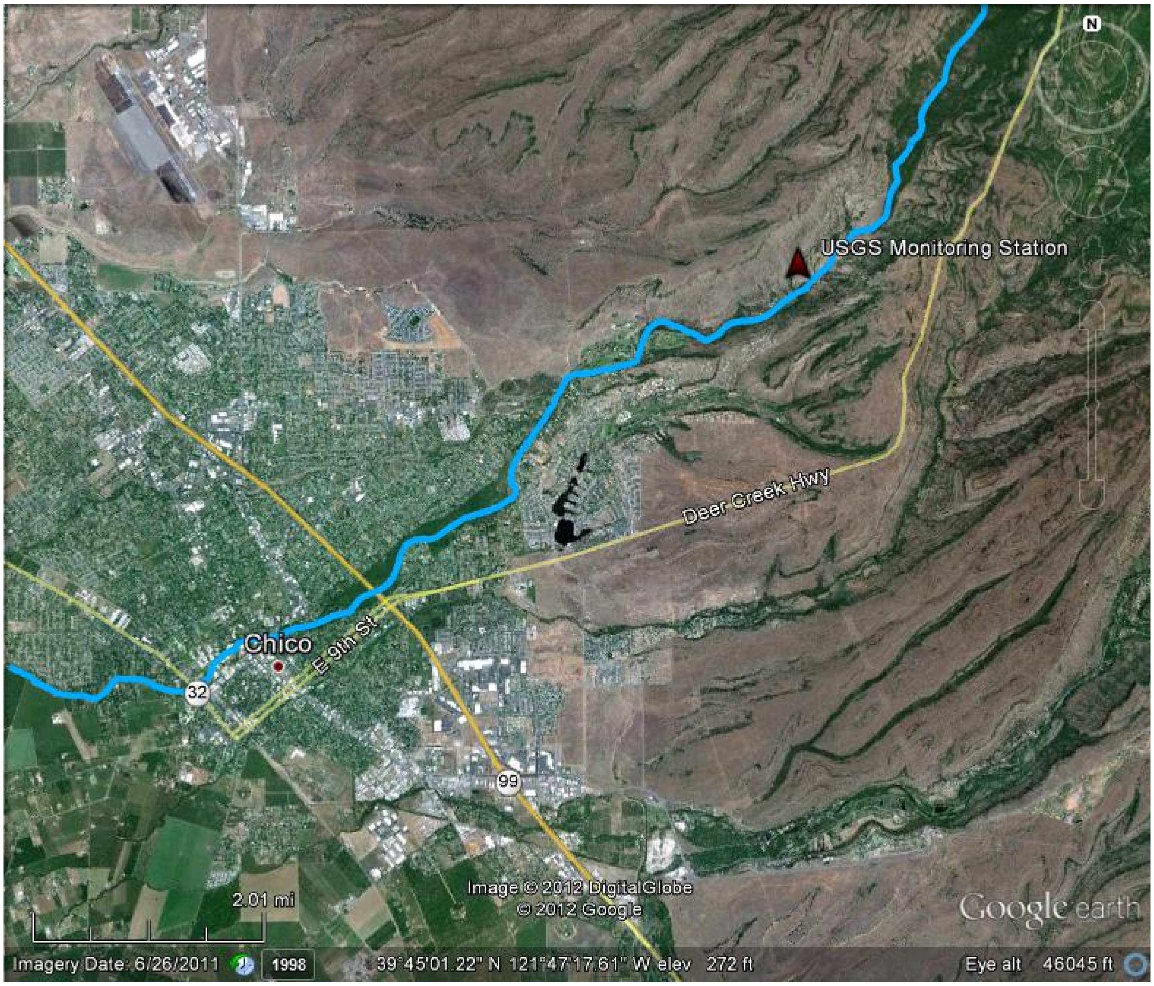


Figure 5. United States Geological Survey gauging station, Chico California.

The Big Chico Creek Watershed Alliance monitored Big Chico Creek between May and October from 2005 to 2010 and during storm events from 2005 through 2010. Using the USGS gauging station, The Big Chico Creek Watershed Alliance found that over the duration of their monitoring,the peak flow encountered was 1199.12 cfs while lowest flow was 13.5 cfs (Figure 7; United States Geological Survey, 2012).

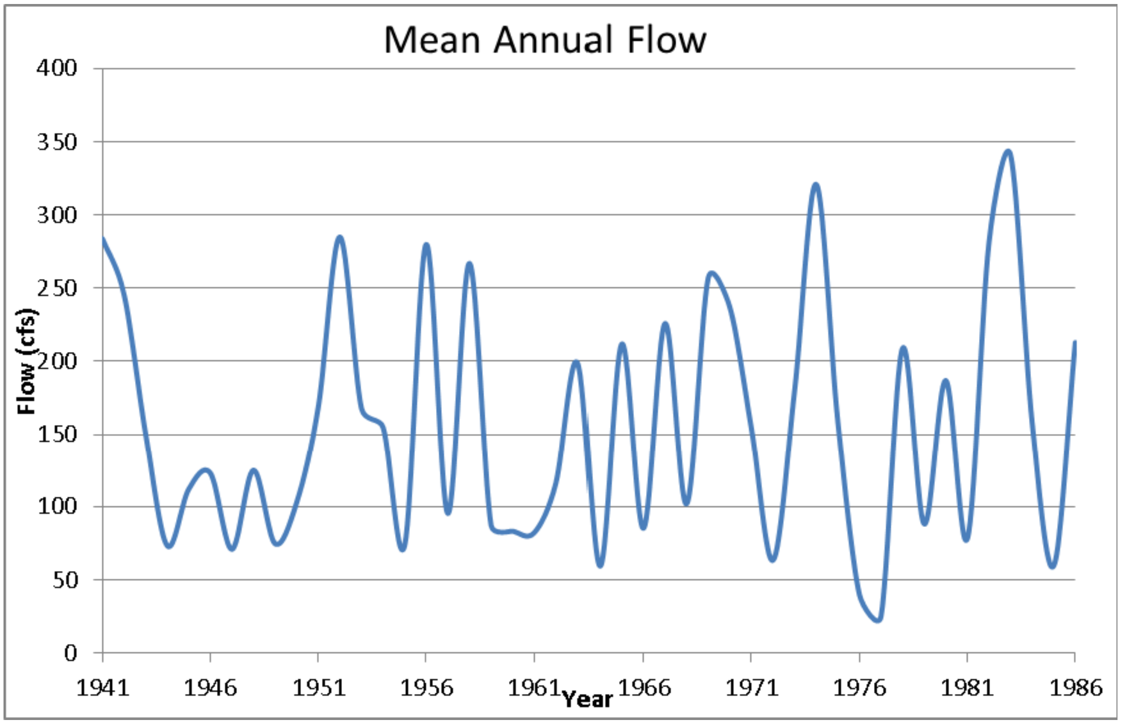


Figure 6. United States Geological Survey streamflow data for Big Chico Creek.

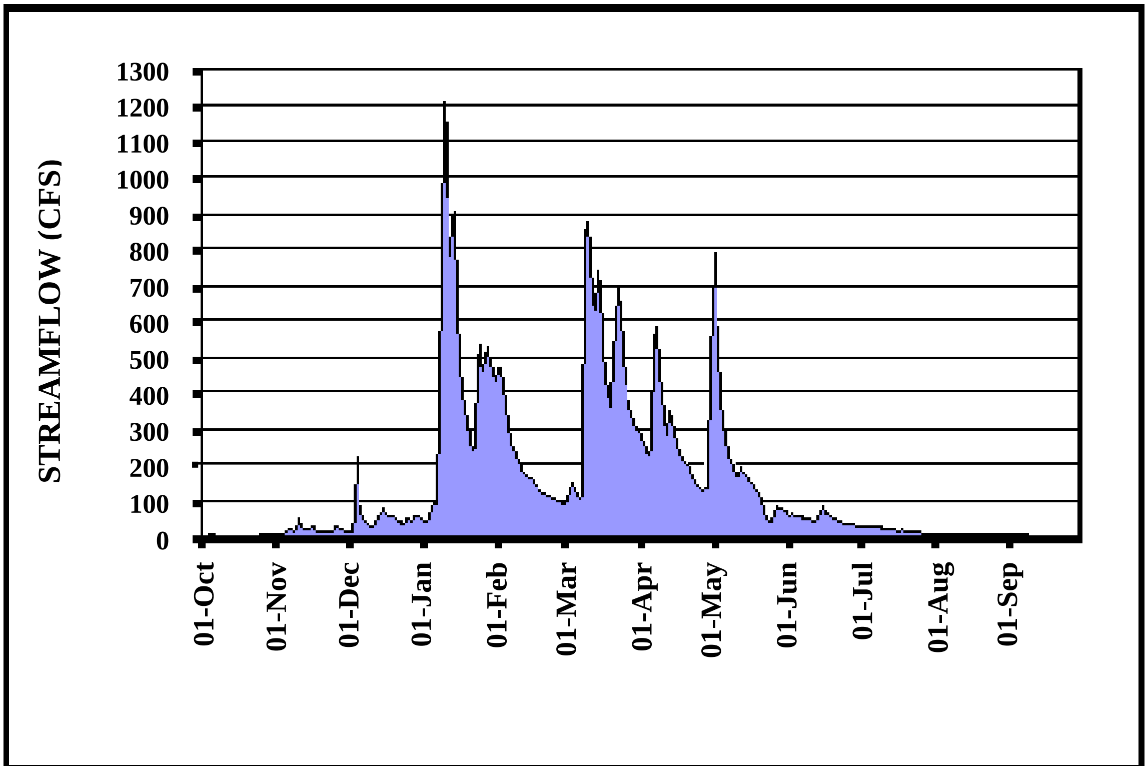


Figure 7. Big Chico Creek hydrograph averaged between 2005-2010.

# CHAPTER III

# METHODS AND RESULTS

The purpose of this study was to investigate the sources of water to Big Chico Creek, a perennial stream located in Butte and Tehama counties. Flow in Big Chico Creek is generally high during the winter and low during the summer. It was hypothesized that the water flowing in the creek during the summer months was largely contributed by melted snow from the foothills of the Sierra Nevada. Three study elements were employed to investigate contributions to flow in Big Chico Creek. To determine the amount of water flowing through Big Chico Creek and to assess how that volume of water varied at various sections of the creek, stream gauging was performed at three separate locations on two occasions to verify that Big Chico Creek loses to groundwater as it travels through the valley. The depth of the water table along Big Chico Creek was also monitored, indicating whether the creek was gaining or losing to groundwater in the vicinity of the CSU Chico campus across the alluvial fan along the valley floor. Additionally, samples of snow, rainwater, spring water, groundwater and water from the creek were collected and subjected to isotopic analysis to determine whether the water in Big Chico Creek becomes more isotopically depleted during the dry summer months, which would indicate that the streamflow was composed largely of snowmelt.

Stream gauging indicated Big Chico Creek loses significant flow to groundwater. On September 25$^{th}$and December 11$^{th}$ 2010, volumetric flows were gauged using the velocity-area method. Stream velocity was measured with a pygmy meter and cross sectional area of the stream was measured, allowing for calculation of discharge. In Upper Bidwell Park (Figure 8) the stream width was 45 feet, depths ranged from 0.25

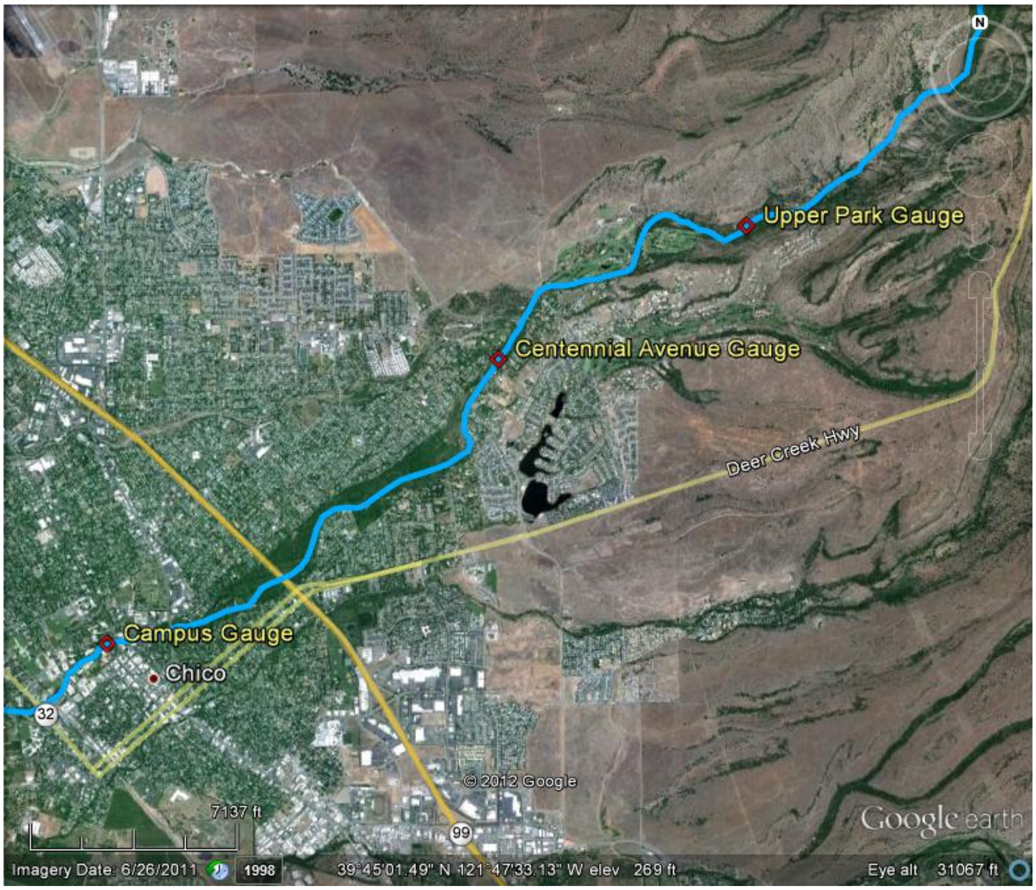


Figure 8. Stream gauging locations in the vicinity of Chico California.

feet to 2.15 feet and velocities ranged from 0.05 to 2.5 ft/s during September; the corresponding flow was calculated to be 90.3cfs. During December, the stream width was 45 feet, depths ranged from 0.3 to 2.15 feet and velocities ranged from 0.1 to 2.5 ft/s; the calculated discharge was 97.3 cfs (Appendix A). Downstream, near the intersection of Centennial Avenue (Figure 8) the stream width was 42 feet, depths ranged from 0.25 feet to 2.25 feet and velocities ranged from 0.05 to 2.5 ft/s during September; the corresponding flow was calculated to be 82.1 cfs. During December, the stream width was 42 feet, depths ranged from 0.3 to 2.3 feet and velocities ranged from 0.3 to 2.6 ft/s; the calculated discharge was 89.2 cfs (Appendix A). At the furthest downstream location, on the California State University Chico campus (Figure 8) the stream width was 28 feet, depths ranged from 0.2 feet to 1.35 feet and velocities ranged from 1.4 to 3.9 ft/s during September; the corresponding flow was calculated to be 66.6 cfs. During December, the stream width was 28 feet, depths ranged from 0.3 to 1.45 feet and velocities ranged from 1.5 to 3.8 ft/s; the calculated discharge was 73.5 cfs (Appendix A). In both September and December, over 23 cfs was lost in the 4.5 miles between the Upper Bidwell Park gauging site and the campus site.

The depth to the water table in wells adjacent to the creek was important to ascertain as another indication of whether the creek was being fed by groundwater or was losing to groundwater. If the water table sits higher than the creek level, it is assumed that groundwater is feeding the creek; conversely, if the water table sits below the creek, it can be assumed that the creek is losing to groundwater. Depth to water level in wells located along Big Chico Creek was monitored every two weeks between January 30$^{th}$ and August 28$^{th}$, 2011. Piezometers installed along the creek on the California State University Chico campus (Figure 9) were gauged with a water level indicator. The water level indicator provided measurements down the nearest 0.01 foot.

Wells along the creek were separated into those on the north bank and the south bank of Big Chico Creek. Wells were then plotted in order of increasing distance

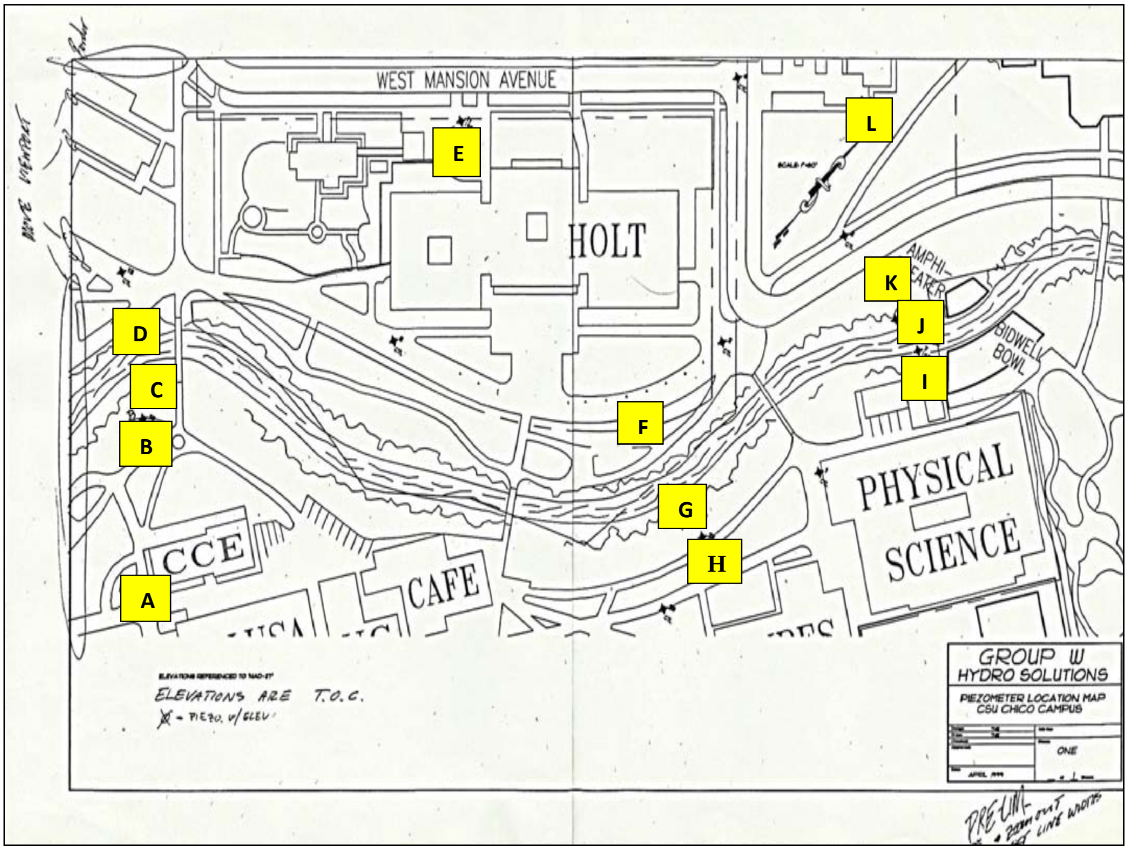


Figure 9. Map of piezometers on California State University Chico campus.

Source: Adapted from Brown, David, n.d., Piezometer location map CSU Chico campus: California State University, Chico. Used with permission.

from the creek. Using a 0.151% grade (United States Geological Survey, 2012), creek water surface elevations were calculated relative to their distance from the stilling well (Figure 9, location I), which provided a reference elevation for the water level in the creek, in the direction parallel to the river at points along Big Chico Creek. This allowed for comparisons between wells found downstream from the stilling well and the elevation of the creek at those particular distances from the stilling well. Away from the creek, the water table consistently dropped in a roughly linear fashion on both the north and south banks (Appendix B). While both the elevation of the creek and water table were subject to fluctuations dependent on storm events, the creek consistently had the highest water elevation. The water table decreased with increasing perpendicular distance from Big Chico Creek (Figures 10 and 11), representing the north and south banks of Big Chico Creek). Groundwater levels, as measured at location L, did not follow the trend present at

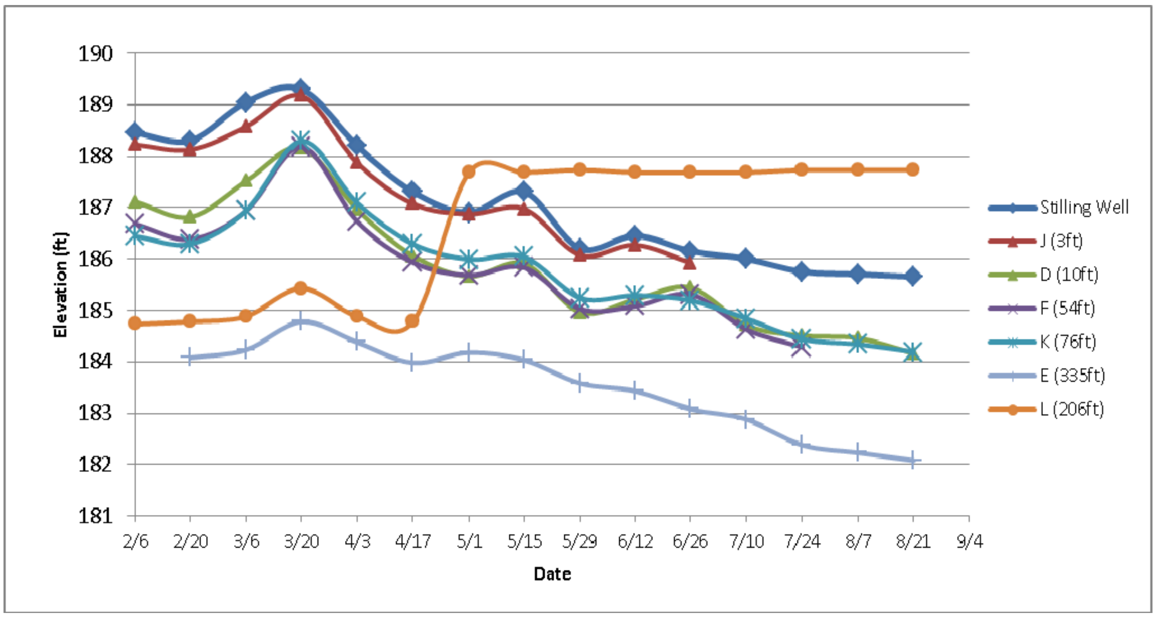


Figure 10. Groundwater elevation variation by date of north creek bank.

all other locations. Over the course of the study, it was observed that the area surrounding location L was very wet, with water noticeably present at the grounds surface. This is believed to be due to a broken water pipe, which flooded the local area.

Because the creek appeared to be consistently losing to groundwater and yet continued to flow year-round, samples of snow, rain, spring water, groundwater, and water from the creek were collected and subjected to isotopic analysis to determine the source of the water in Big Chico Creek. Distinguishing the source of the water present in rain, snow, soils, groundwater and streams using stable isotopes of water, particularly $^{18}O$

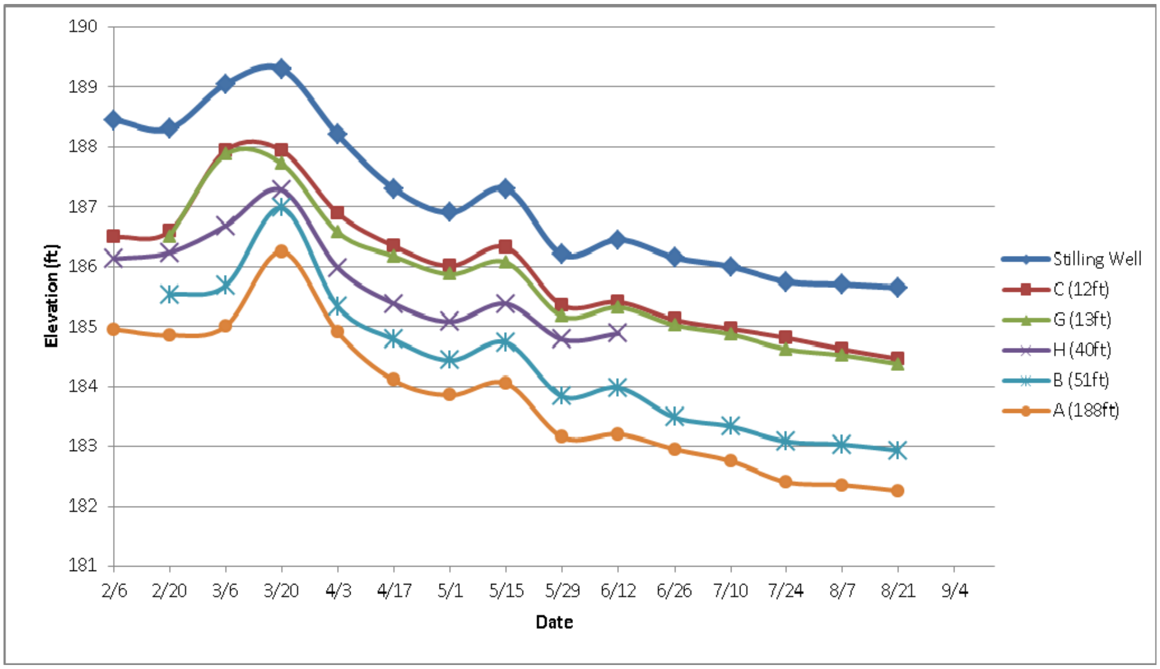


Figure 11. Groundwater elevation variation by date of south creek bank.

and $^2H$, is made possible by the process of fractionation (Faure and Mensing, 2005). Water molecules consist of several stable isotopes with $^{18}O$ making up only 0.2% of the world's oxygen and $^2H$ making up 0.015% of naturally occurring hydrogen. All molecules have the same kinetic energy at a specific temperature. Through conservation of kinetic energy, molecules with greater mass travel at lower velocities.

$$(½)m_{heavy}v^2_{heavy} = (½)m_{light}v^2_{light}$$

$$V_{light} > V_{heavy}$$

The difference in mass of water molecules and the corresponding difference in velocities cause higher mass numbers to be associated with correspondingly lower vapor pressures (Faure and Mensing, 2005). Heavier isotopes are thus more inclined to exist in a liquid state while lighter isotopes prefer a gaseous state, although the difference is small enough to dictate reporting numbers as a per-mil (one-tenth of a percent) value. As clouds move to higher elevations and cooler temperatures, they begin to precipitate. As this precipitation of water occurs, the clouds lose heavy isotopes first. As precipitation continues, the ratio of heavy to light isotopes changes as the clouds continue to lose water. The depletion of $^{18}O$ and $^{2}H$ is generally described using a Rayleigh distillation. This exponential function describes the progressive division of heavy isotopes into the water reservoir as it decreases in mass.

$$R = R_o f^{(a-1)}$$

where $R_o$ is the initial isotope ratio, $R$ is the final ratio, $f$ is the residual component, and α is the equilibrium fractionation factor (Faure and Mensing, 2005). Isotopically lighter water molecules containing $^{16}O$ and $^{1}H$ will evaporate slightly more easily than the isotopically heavier water molecules containing $^{18}O$ and $^{2}H$. During the course of fractionation, clouds become enriched with $^{16}O$ and $^{1}H$ as they are the first to vaporize, while the bulk of the water remaining in liquid form becomes enriched in $^{18}O$ and $^{2}H$ (Brock et al. 2007). A geospatial gradient is thus created in which the isotopic ratio of water delivered to the land surface varies, with the gradient depending on the rate at which the water was precipitated. With higher temperatures, the precipitation of water enriched in $^{18}O$ and $^{2}H$ is greater. If precipitation occurs under freezing conditions, $^{16}O$ and $^{1}H$ are much more common (Jeelani et al., 2010). The fractionation of hydrogen and oxygen thus allows water to be traced back to source because the isotopic makeup acts as a sort of fingerprint.

The standard to which water is compared is the Vienna Standard Mean Ocean Water (VSMOW). The values for VSMOW are m $^{18}O/^{16}O$ = 2005.20+/- 0.4 ppm and $^{2}H/H$ =155.76 +/- 0.1 ppm. Isotopic ratios are measured in terms of their ratio to this standard and reported as delta values $\delta^{18}O$ (for stable ratio of oxygen) and $\delta^{2}H$ (for stable ratio of hydrogen) (Gat and Gonfiantini, 1981). Delta is defined as

$$\delta = ((R_{sample}/R_{standard})-1)*1000$$

$$R_{oxygen} = {}^{18}O/{}^{16}O$$

$$R_{hydrogen}= {}^{2}H/H$$

The δ value of O and H can be positive, negative or zero. A positive δ value indicates that the sample has a higher $^{18}O/^{16}O$ or $^{2}H/H$ ratio than the standard and may be considered enriched with respect to the $^{18}O$ or $^{2}H$ isotopes. A negative value indicates that the sample has a lower ratio than the standard and may be considered depleted in $^{18}O$ or $^{2}H$ isotopes.

To determine the source of water in Big Chico Creek, samples of water were collected for isotopic analysis every two weeks between January 30th and August 28th 2011. This time frame captured both the wettest and driest times of the year. Snowmelt was collected as permissible by season from Butte Meadows between January 30th and May 8th 2011, at an elevation of 4721 feet above sea level (Figure 12, location S). Samples were taken from 3 inches below the snow surface to avoid freeze/thaw effects (Ingraham and Taylor, 1989). Rainwater was collected as permitted from two locations. The first was collected within the Big Chico Creek Ecological Reserve at an altitude of 1831 feet above sea level, but still below the snow line (Figure 12, location R1). The valley sample was collected in Chico at 1550 Springfield Drive, representing lower altitudes, with an altitude of 230 feet above sea level (Figure 12, location R2). Samples were collected immediately following any major precipitation event. Very light or very brief precipitation events were not collected. Fractionation of the rainwater samples was avoided by their immediate collection.

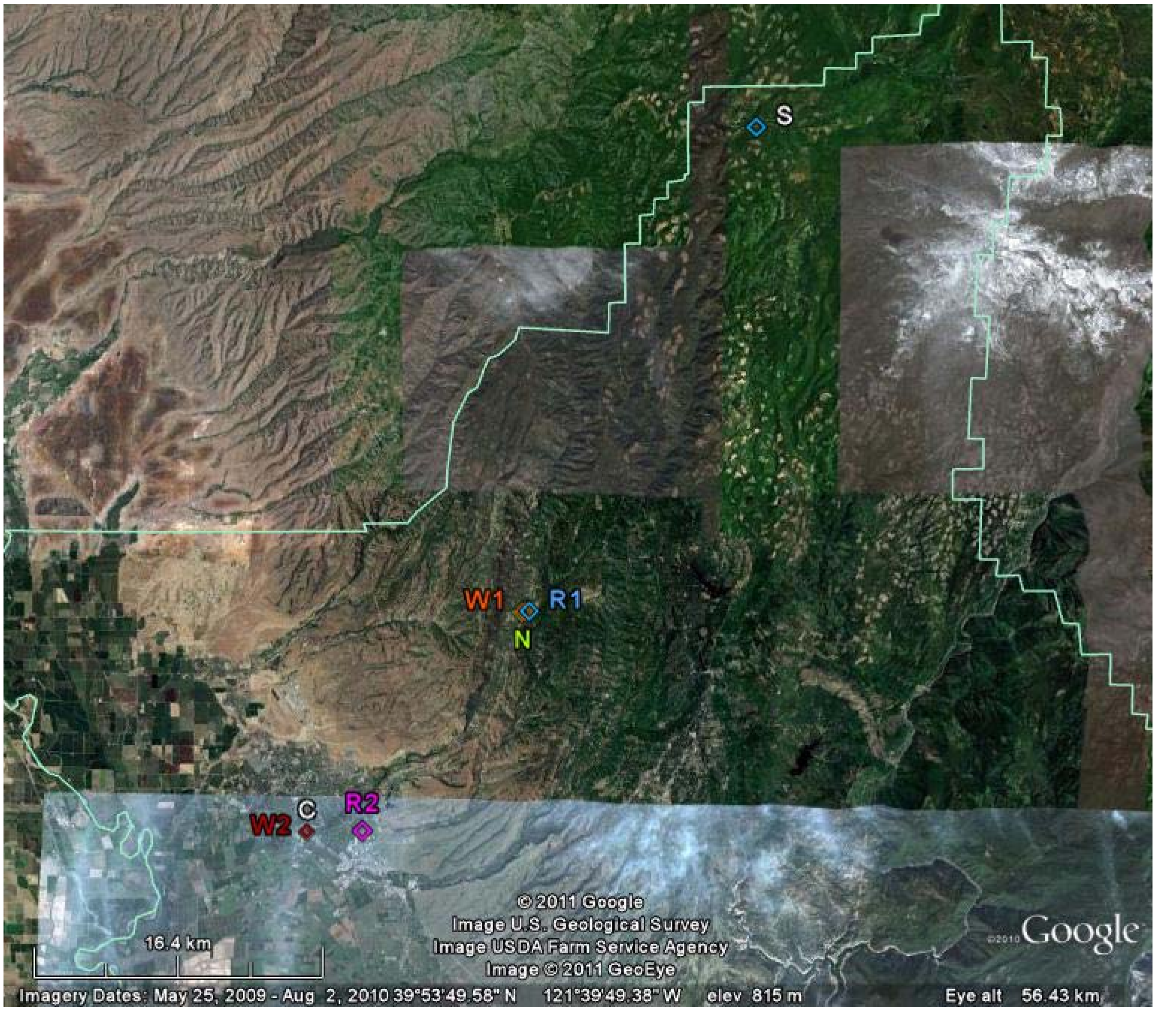


Figure 12. Sampling site locations.

S represents snow captured in Butte Meadows, R1 represents the rain collector in Big Chico Creek Ecological Reserve, R2 represents the rain collector in the valley, N represents the natural spring, W1 represents the well in Big Chico Creek Ecological Reserve, W2 represents the well adjacent to Big Chico Creek, and C represents Big Chico Creek.

Groundwater and creek water samples were collected from springs, wells and the creek itself. Springwater was collected every two weeks from Big Chico Creek Ecological Reserve between January 30th and May 8th 2011, at an elevation of 1570 feet above sea level (Figure 12, location N). The natural spring is located on the contact between the Chico Formation and the Tuscan Formation. Samples were taken directly from the spring and captured directly into National Scientific C4010-1W sample vials. These vials have a pocketed lid making it possible to eliminate headspace above the water, to eliminate the possibility of fractionation after samples were collected.

Groundwater was collected every two weeks from two shallow wells at two different locations. The first sampling location was in the Big Chico Creek Ecological Reserve at an elevation of 1650 feet above sea level (Figure 12, location W1). This well has a depth of 6 feet. Samples were collected using PVC bailers, which were tied to a piece of fishing line and lowered into the water column. Once lowered, the bailers use a simple ball valve to seal at the bottom to pull up the sample from the groundwater table. Wells were emptied three times prior to sample collection to ensure fresh groundwater in the well. Separate bailers were used at the separate wells. Bailers were dried in the two weeks between sample collection, eliminating any water residue and the possibility of contamination of samples. Samples were transferred immediately from the bailer to the C4010-1W sample vials. Groundwater samples were also taken from a piezometer on the university campus at an elevation of 198 feet above sea level. Labeled piezometer F (Figure 9), this well has a depth of 18 feet. This piezometer was chosen to reflect the groundwater isotopic makeup in the vicinity of Big Chico Creek, with a distance of 54 feet from the creek bank.

Creek water was collected every two weeks from Big Chico Creek on the California State University Chico campus, at an elevation of 197 feet above sea level (Figure 12, location C). Samples were collected from the middle of the stream at a distance of 3 feet from the south bank. Samples were collected directly from the creek and captured directly in the National Scientific C4010-1W sample vials.

All snowmelt, rainwater, spring, groundwater and creek water samples were sent to the University of California, Davis for analysis at the stable isotope facility. Analysis was performed via laser water isotope analyzer. Isotopes of both $^{18}O$ and $^{2}H$ were analyzed; precision for water samples at natural abundance is ≤0.3 permil for $^{18}O$ and ≤0.8 permil for $^{2}H$. Final $^{18}O/^{16}O$ and $^{2}H/H$ values were reported relative to VSMOW.

The isotopic analysis indicates that snowmelt, rainwater, spring water, groundwater and creek water have distinctive signatures based on their location and date of collection (Figures 13 and 14). Snowmelt was the most isotopically depleted sample source, which would be expected given its high altitude (Figures 13 and 14). The $\delta^{18}O$ averaged -12.93 and had a standard deviation of 1.119. The $\delta^{2}H$ values had an average of -82.2 and standard deviation of 8.45 (Table 1). Rainwater values exhibited a similar pattern. Rainwater $\delta^{18}O$ and $\delta^{2}H$ values varied greatly during the course of the study, but rainwater collected at the higher elevation in the Big Chico Creek Ecological Reserve was consistently more depleted in $^{18}O$ and $^{2}H$ than rainwater collected in the valley (Table 2). The $\delta^{18}O$ values averaged -7.71 and had a standard deviation of 2.54. The $\delta^{2}H$ values had an average of -48.8 and standard deviation of 15.11. The natural spring became increasingly enriched over the course of the study (Table 3). The $\delta^{18}O$ values averaged -7.65 and had a standard deviation of 2.403. The $\delta^{2}H$ values had an average of -55.2 and standard deviation of 8.573. Groundwater from the two wells analyzed showed fluctuations but no obvious trends (Tables 4 and 5). The $\delta^{18}O$ values from the Big Chico

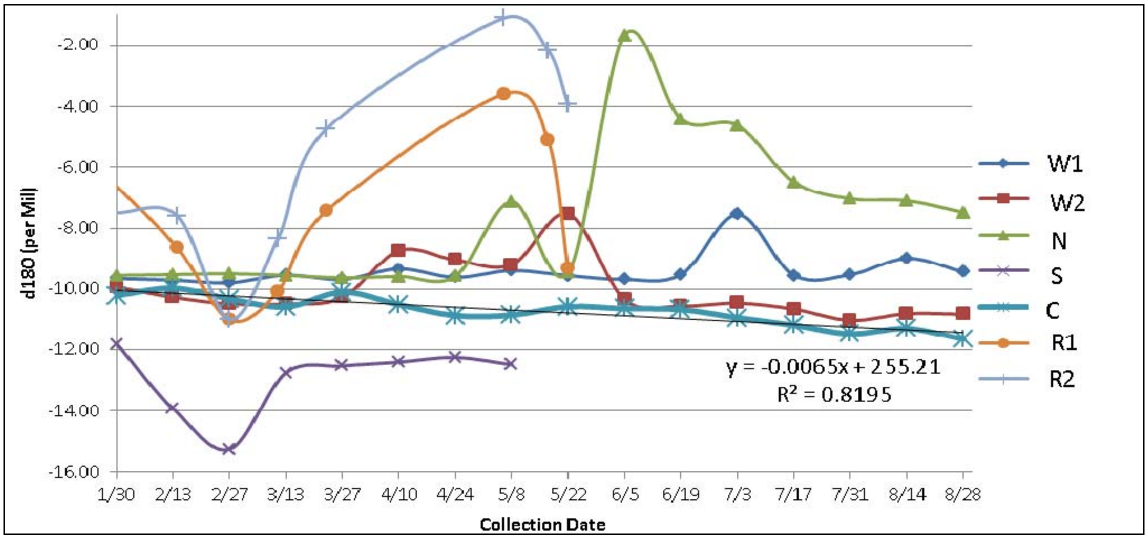


Figure 13. Sample $\delta^{18}O$ values by date.

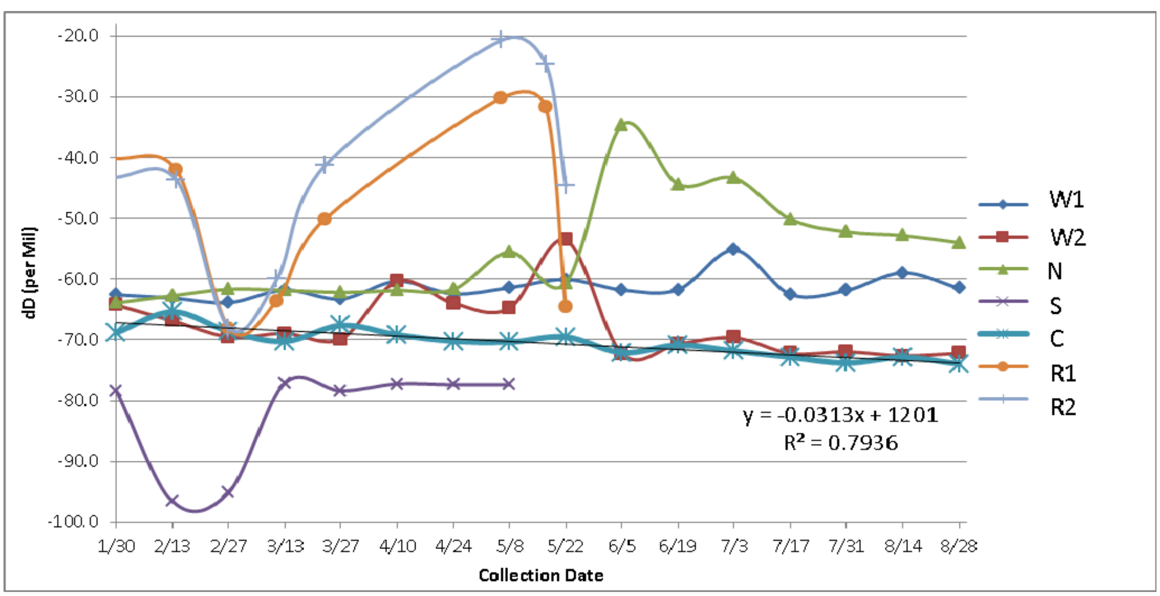


Figure 14. Sample $\delta^{2}H$ values by date.

TABLE 1. SNOW $\delta^{18}O$ AND $\delta^{2}H$ VALUES

| VSMOW $\delta^{18}O$ | VSMOW $\delta^{2}H$ | Date |
|---|---|---|
| -11.81 | -78.4 | 30-January |
| -13.92 | -96.6 | 13-February |
| -15.25 | -95.1 | 27-February |
| -12.75 | -77.1 | 13-March |
| -12.52 | -78.4 | 27-March |
| -12.40 | -77.2 | 10-April |
| -12.25 | -77.4 | 24-April |
| -12.48 | -77.4 | 8-May |

TABLE 2. RAINWATER $\delta^{18}O$ AND $\delta^{2}H$ VALUES

| VSMOW $\delta^{18}O$ | VSMOW $\delta^{2}H$ | Date |
|---|---|---|
| -6.50 | -40.1 | 29-January |
| -8.63 | -42.1 | 14-February |
| -11.00 | -68.0 | 27-February |
| -10.08 | -63.6 | 11-March |
| -7.44 | -50.1 | 23-March |
| -3.59 | -30.2 | 6-May |
| -5.13 | -31.8 | 17-May |
| -9.33 | -64.7 | 22-May |

Creek Ecological Reserve averaged -9.4 and had a standard deviation of 0.530. The $\delta^{2}H$ values had an average of -61.4 and standard deviation of 2.061. The $\delta^{18}O$ values from groundwater near the California State University campus averaged -10.04 and had a standard deviation of 0.940. The $\delta^{2}H$ values had an average of -67.7 and standard deviation of 5.259.

Plots of the $\delta^{18}O$ and $\delta^{2}H$ values from creekwater collected from Big Chico Creek on the California State University Chico campus indicate that Big Chico Creek

TABLE 3. NATURAL SPRING $\delta^{18}O$ AND $\delta^{2}H$ VALUES

| VSMOW $\delta^{18}O$ | VSMOW $\delta^{2}H$ | Date |
|---|---|---|
| -9.56 | -63.9 | 30-January |
| -9.53 | -62.7 | 13-February |
| -9.50 | -61.7 | 27-February |
| -9.56 | -61.8 | 13-March |
| -9.64 | -62.2 | 27-March |
| -9.59 | -61.9 | 10-April |
| -9.58 | -61.7 | 24-April |
| -7.14 | -55.6 | 8-May |
| -9.45 | -60.6 | 22-May |
| -1.66 | -34.7 | 5-June |
| -4.43 | -44.4 | 19-June |
| -4.63 | -43.4 | 3-July |
| -6.49 | -50.1 | 17-July |
| -7.04 | -52.2 | 31-July |
| -7.10 | -52.8 | 14-August |
| -7.49 | -54.0 | 28-August |

becomes more isotopically depleted with time (Figures 13 and 14; Table 6), suggesting snowmelt is the dominant contributor to streamflow. The $\delta^{18}O$ values averaged -10.74 and had a standard deviation of 0.481. The $\delta^{2}H$ values had an average of -70.5 and standard deviation of 2.33.

A linear regression of Big Chico Creek $\delta^{18}O$ values yielded a slope of -0.0065 and an $r^2$ of 0.8195 while $\delta^{2}H$ values yielded a slope of -0.0313 and an $r^2$ of 0.7936. These negative slope values indicate greater depletion of $^{18}O$ and $^{2}H$ over time. This is because during precipitation, initial rainfall is enriched in $^{18}O$ and as $^{2}H$ when compared to later precipitation. As a result, the precipitation becomes isotopically lighter as the rain continues, in a phenomenon known as the rainout effect (Faure and Mensing, 2005). This is also associated with increases in altitude. The center of a large land mass has precipitation that is depleted in $^{18}O$ and $^{2}H$, in a trend called the continental effect (Faure

TABLE 4. GROUNDWATER FROM BIG CHICO CREEK ECOLOGICAL RESERVE $\delta^{18}O$ AND $\delta^{2}H$ VALUES

| VSMOW $\delta^{18}O$ | VSMOW $\delta^{2}H$ | Date |
|---|---|---|
| -9.66 | -62.6 | 30-January |
| -9.72 | -63.1 | 13-February |
| -9.80 | -63.9 | 27-February |
| -9.55 | -61.8 | 13-March |
| -9.69 | -63.3 | 27-March |
| -9.34 | -60.3 | 10-April |
| -9.63 | -62.4 | 24-April |
| -9.40 | -61.4 | 8-May |
| -9.57 | -60.1 | 22-May |
| -9.70 | -61.8 | 5-June |
| -9.53 | -61.7 | 19-June |
| -7.56 | -55.2 | 3-July |
| -9.56 | -62.5 | 17-July |
| -9.53 | -61.8 | 31-July |
| -8.99 | -58.9 | 14-August |
| -9.44 | -61.5 | 28-August |

TABLE 5. GROUNDWATER FROM CALIFORNIA STATE UNIVERSITY CHICO CAMPUS $\delta^{18}O$ AND $\delta^{2}H$ VALUES

| VSMOW $\delta^{18}O$ | VSMOW $\delta^{2}H$ | Date |
|---|---|---|
| -9.93 | -64.3 | 30-January |
| -10.27 | -66.8 | 13-February |
| -10.49 | -69.5 | 27-February |
| -10.49 | -68.9 | 13-March |
| -10.28 | -69.8 | 27-March |
| -8.73 | -60.4 | 10-April |
| -9.04 | -64.0 | 24-April |
| -9.20 | -64.8 | 8-May |
| -7.54 | -53.5 | 22-May |
| -10.35 | -72.3 | 5-June |
| -10.56 | -70.7 | 19-June |
| -10.46 | -69.6 | 3-July |
| -10.66 | -72.2 | 17-July |
| -11.02 | -72.0 | 31-July |
| -10.80 | -72.6 | 14-August |
| -10.82 | -72.2 | 28-August |

TABLE 6. BIG CHICO CREEK $\delta^{18}O$ AND $\delta^{2}H$ VALUES

| VSMOW $\delta^{18}O$ | VSMOW $\delta^{2}H$ | Date |
|---|---|---|
| -10.21 | -68.8 | 30-January |
| -9.97 | -65.4 | 13-February |
| -10.32 | -68.6 | 27-February |
| -10.58 | -70.2 | 13-March |
| -10.10 | -67.6 | 27-March |
| -10.51 | -69.2 | 10-April |
| -10.86 | -70.2 | 24-April |
| -10.85 | -70.4 | 8-May |
| -10.57 | -69.5 | 22-May |
| -10.64 | -72.1 | 5-June |
| -10.67 | -70.9 | 19-June |
| -10.93 | -71.8 | 3-July |
| -11.18 | -72.8 | 17-July |
| -11.46 | -73.8 | 31-July |
| -11.29 | -72.8 | 14-August |
| -11.65 | -73.9 | 28-August |

and Mensing 2005). Isotopically enriched rain condenses and falls from a cloud of decreasing mass, with the residual vapor becoming isotopically depleted when compared to earlier rains from the same cloud. The continental effect and rainout effect can be seen in the global meteoric water line.

The values of $\delta^{18}O$ and $\delta^{2}H$ from all collected water samples were plotted for comparison to the global meteoric water line, in which delta values of precipitation from sites around the world form a linear data array, represented by a straight line and governed by the equation.

$$\delta^{2}H=7.96x\ \delta^{18}O+8.86$$

This graphical representation of the data shows the relative enrichment and depletion of the samples, as $\delta^{18}O$ and $\delta^{2}H$ values become increasingly negative with greater distance from the equator while less negative values are associated with warmer climates and lower elevations (Faure and Mensing, 2005).

The distribution of the samples varied greatly because they were collected over different seasons and greatly varying atmospheric conditions (Figure 15). A plot generated using average values of the samples indicated that snowmelt had the most negative $\delta^{18}O$ and $\delta^{2}H$ values while Big Chico Creek had the second most negative $\delta^{18}O$ and $\delta^{2}H$ values (Figure 16). All other water samples had more positive $\delta^{18}O$ and $\delta^{2}H$ values than Big Chico Creek. This indicates again that Big Chico Creek has an isotopic signature more consistent with snowmelt.

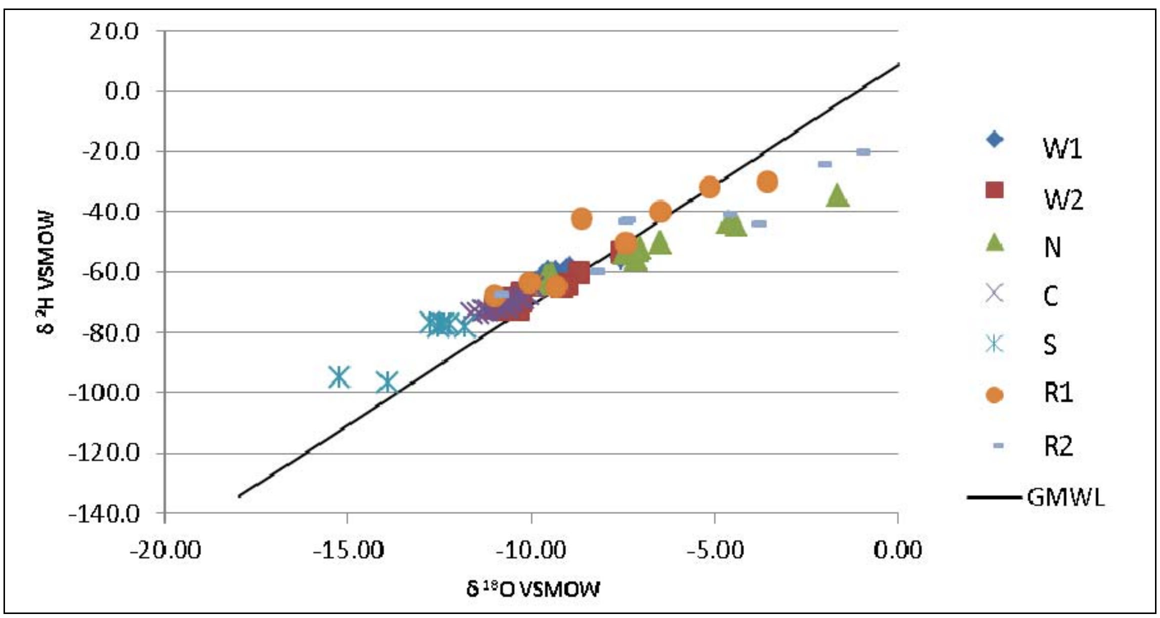


Figure 15. Global meteoric water line and samples.

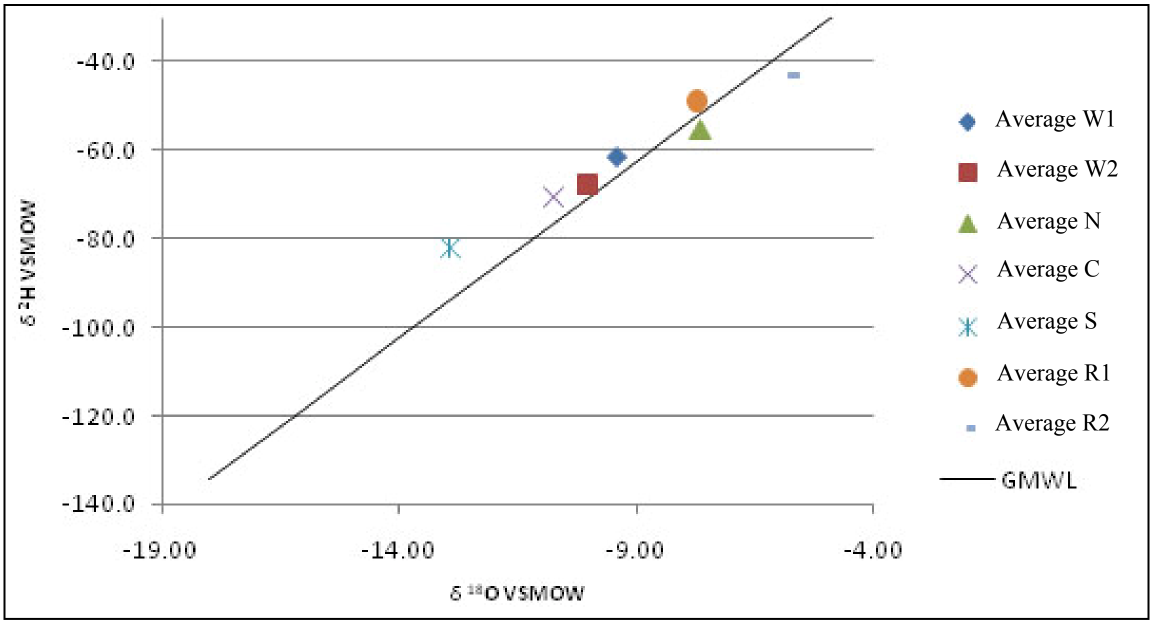


Figure 16. Global meteoric water line and average of samples.

# CHAPTER IV

## ANALYSIS AND INTERPRETATION

Stream gauging, groundwater level monitoring and stable isotope analysis all suggest that Big Chico Creek derives its flow from precipitation during storm periods and from snowmelt runoff during dry summer periods. To determine the relative contributions from the various sources through time and space, a variety of statistical applications, such as cross-correlation between the creek water elevation and the water table elevation, an analysis of variance to establish statistically significant differences in isotope ratios across the different locations and collection dates, a cross-correlation between the creekflow and depletion of $^{18}O$ and $^{2}H$ isotopes, a cross correlation between isotope ratios of creekwater and snowmelt, rainwater, springwater, and groundwater, and a runs test to determine that the changes in isotope ratios were non-random in nature were performed.

Both stream gauging and groundwater monitoring suggest that the creek loses to groundwater both during the wet winter and the dry summer periods. Cross-correlation between creek elevation and water table elevation at individual wells revealed high correlation coefficients (Figures 17 and 18). This strong correlation suggests that changes in creek elevation have a direct impact on the groundwater elevation along the creek, as the groundwater elevation was consistently below the creek elevation. Over the course of monitoring, very little lag was witnessed, with water table depth profiles mirroring that of

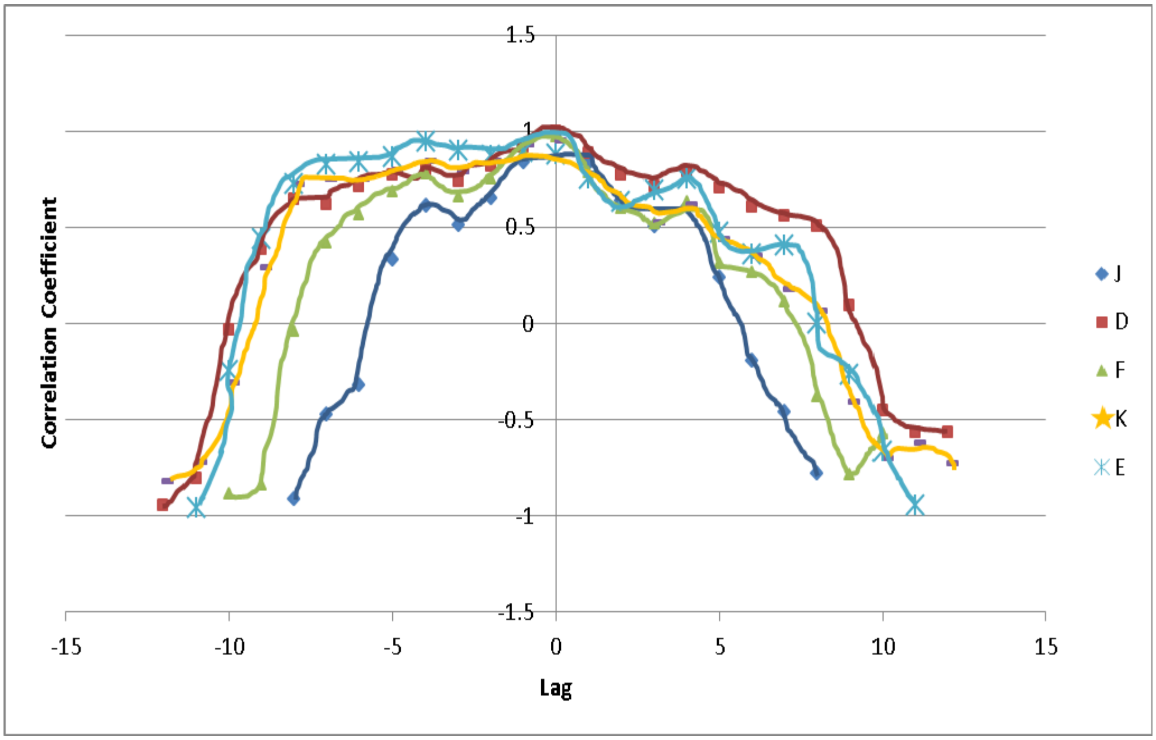


Figure 17. Cross-correlation between creek elevation and water table along the north bank.

the creeks almost identically. On both the north and south banks, a lag of 0 always produced the highest correlation coefficient (Figures 17 and 18). There appears to be a rapid response between water levels in the creek and the water table elevation. This may be attributed to sediment adjacent to the creek having a high hydraulic diffusivity, although this was not investigated during the course of the study.

A two-way analysis of variance was used to determine the significance of different isotopic ratios in the collected samples of water from snowmelt, rainwater, a natural spring, groundwater and water from Big Chico Creek to identify any significant differences between the different locations and collection dates. The first factor analyzed was the difference occurring between samples of water from snowmelt, rainwater, a

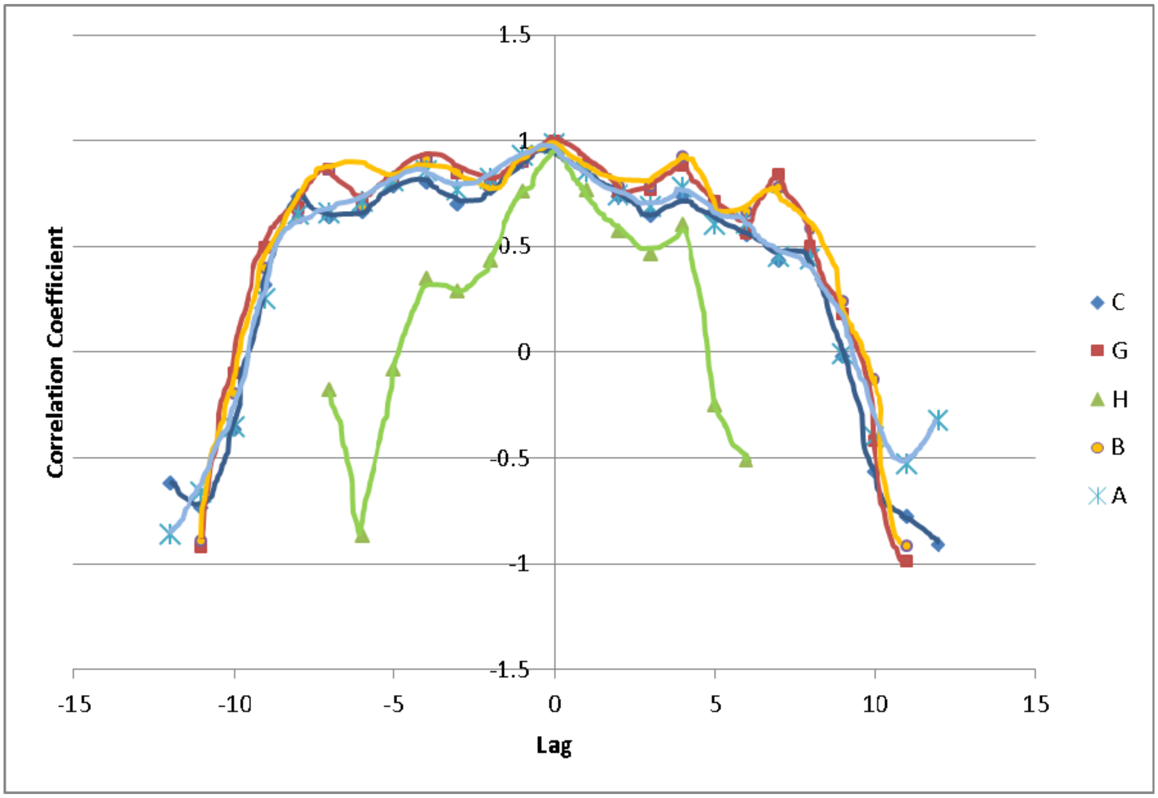


Figure 18. Cross-correlation between creek elevation and water table along the south bank.

natural spring, groundwater and creek water from Big Chico Creek. Samples from the same collection date were compared against other samples also collected on that date to determine whether significant differences existed between the individual samples collected from different sites, thus establishing spatial variability in isotopic composition. The second factor analyzed was the differences present within each of the samples of water from different collection dates, between January 30th and August 28th to establish temporal variability and verify whether Big Chico Creek was becoming more depleted in $^{18}O$ and $^{2}H$ isotopes.

The analysis of variance indicated that while there were significant differences between the samples collected from different locations, there were no temporal significant differences within the samples collected on different dates (Appendix C). Analyzing $\delta^{18}O$ with an $\alpha$ of 0.05, significant differences were found between the different locations ($p = 9.79 \times 10^{-7}$, $F = 14.47$, $F_{crit} = 2.81$), but not the different dates ($p = 0.761$, $F = 0.71$, $F_{crit} = 1.89$). Analyzing $\delta^{2}H$ with an $\alpha$ of 0.05, significant differences were again found between the different locations ($p = 2.58 \times 10^{-9}$, $F = 23.55$, $F_{crit} = 2.81$), but not the different dates ($p = 0.929$, $F = 0.49$, $F_{crit} = 1.89$). This suggests that the samples of snowmelt, rainwater, a natural spring, groundwater and creek water from Big Chico Creek were significantly different from one another, but did not exhibit significant temporal variation in depletion of $^{18}O$ and $^{2}H$ over the duration of the study.

A cross-correlation was employed to identify a physical relationship between Big Chico Creek depth (and indirectly volume) and depletion of $^{18}O$ and $^{2}H$ isotopes in Big Chico Creek water. Cross-correlation of $\delta^{18}O$ yielded a moderate correlation ($r = 0.769$), while maximum correlation was found with a lag of 1 ($r = 0.835$), with a lag period representing a time period of two weeks (Figure 19). Cross-correlation of $\delta^{2}H$ yielded a slightly weaker correlation ($r = 0.739$), while maximum correlation was found with a lag of 1 ($r = 0.837$) (Figure 20). These results indicate that with decreasing depth and the diminished volume of water flow associated with dry periods, there is a corresponding increase in the depletion of $^{18}O$ and $^{2}H$ isotopes. The $\delta^{18}O$ and $\delta^{2}H$ values become more negative as less water flows in the creek. This supports the theory that Big Chico Creek is fed by snowmelt, which has the most negative $\delta^{18}O$ and $\delta^{2}H$ values collected, during the dry summer months. The significance of this finding is magnified when one considers that during the dry summer months, it is likely that Big Chico Creek's $\delta^{18}O$ and $\delta^{2}H$ values were made more positive due to evaporative enrichment.

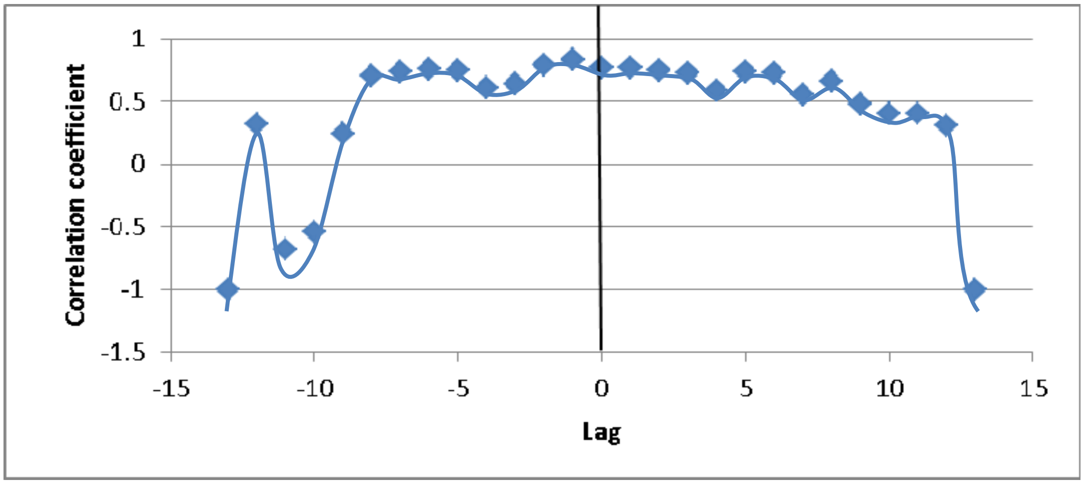


Figure 19. Cross-correlation of $\delta^{18}O$ and depth of Big Chico Creek.

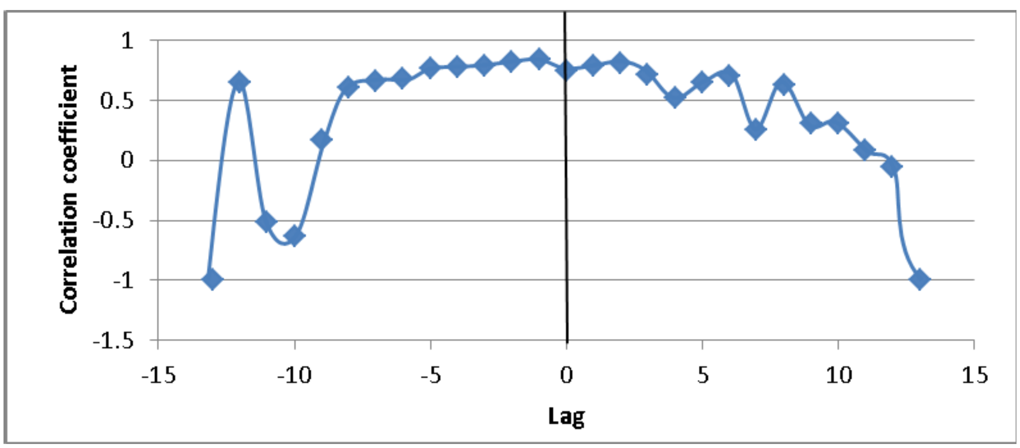


Figure 20. Cross-correlation of $\delta^{2}H$ and depth of Big Chico Creek.

Cross-correlations were also performed to explore the relationship between creek water $\delta^{18}O$ and $\delta^{2}H$ values and the $\delta^{18}O$ and $\delta^{2}H$ values from samples of snowmelt, rainwater, natural spring water and groundwater that were collected. A strong correlation between creek isotope ratios and the ratios from any of the other sample sources may suggest that the creek is being fed by that source. Correlations, as well as lag were calculated for all samples (Figures 21 and 22). The cross correlation indicated that no one source seemed to have any dominant contribution to the creek. Cross-correlation of $\delta^{18}O$ values between Big Chico Creek and the snow collected from Butte Meadows yielded a weak negative correlation (*r* = -0.339), while maximum correlation was found with a lag of 5 (*r* = 0.999). Cross-correlation of $\delta^{2}H$ values yielded a moderate negative correlation (*r* = -0.713), while maximum correlation was found with a lag of 5 (*r* = 0.981). Cross-correlation of $\delta^{18}O$ values between Big Chico Creek and the rainwater collected in the Big Chico Creek Ecological Reserve yielded a weak negative correlation (*r* = -0.141), while maximum correlation was found with a lag of 4 (*r* = 0.985). Cross-correlation of $\delta^{2}H$ values yielded a weak positive correlation (*r* = 0.185), while maximum correlation was found with a lag of 4 (*r* = 0.879). Cross-correlation of $\delta^{18}O$ values between Big Chico Creek and the rainwater collected in the valley yielded a weak negative correlation (*r* = -0.479), while maximum correlation was found with a lag of 4 (*r* = 0.985). Cross-correlation of $\delta^{2}H$ values yielded no correlation (*r* = -0.067), while maximum correlation was found with a lag of 4 (*r* = 0.829). Cross-correlation of $\delta^{18}O$ values between Big Chico Creek and the natural spring yielded a weak negative correlation (*r* = -0.424), while maximum correlation was found with a lag of 1 (*r* = 0.739). Cross-correlation of $\delta^{2}H$ values yielded a mild negative correlation (*r* = -0.662), while maximum correlation was found with a lag of 8 (r = 0.546). Cross-correlation of $\delta^{18}O$ values between Big Chico Creek and the well located in Big Chico Creek Ecological Reserve yielded a weak negative correlation (*r* = -0.359), while maximum

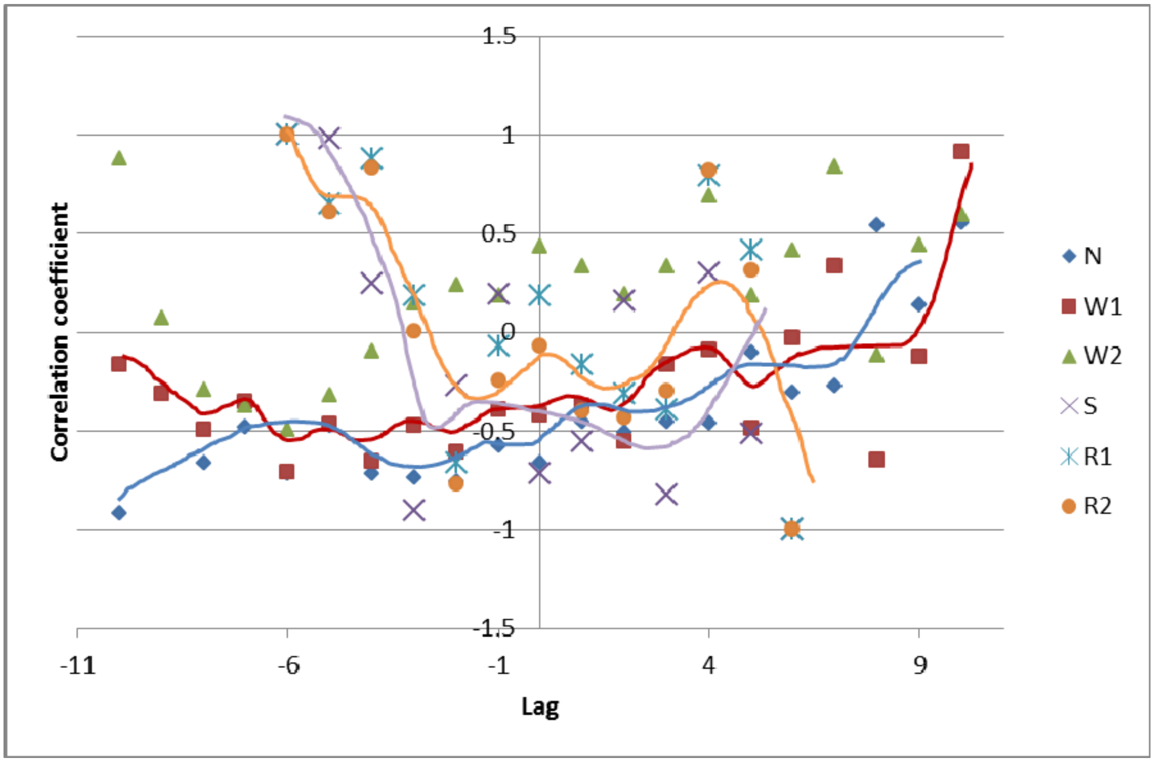


Figure 21. Cross-correlation between Big Chico Creek $\delta^{18}O$ values and natural spring (N), groundwater in Big Chico Creek Ecological Reserve (W1), groundwater on California State University Chico campus (W2), snowmelt (S), rainwater from Big Chico Creek Ecological Reserve (R1) and rainwater from the valley (R2) $\delta^{18}O$ values.

correlation was found with a lag of 10 ($r$ = 0.755). Cross-correlation of $\delta^2H$ values yielded a weak negative correlation ($r$ = -0.417), while maximum correlation was found with a lag of 10 ($r$ = 0.912). Cross-correlation of $\delta^{18}O$ values between Big Chico Creek and the well located on the university campus yielded a weak positive correlation ($r$ = 0.233), while maximum correlation was found with a lag of 10 ($r$ = 0.858). Cross-correlation of $\delta^2H$ values yielded a weak positive correlation ($r$ = 0.434), while maximum correlation was found with a lag of 7 ($r$ = 0.840). These results show that the creek's isotope ratios do not follow the isotope ratios of the snowmelt, rainwater, natural spring or groundwater very closely. One very strong relationship existed however, between the

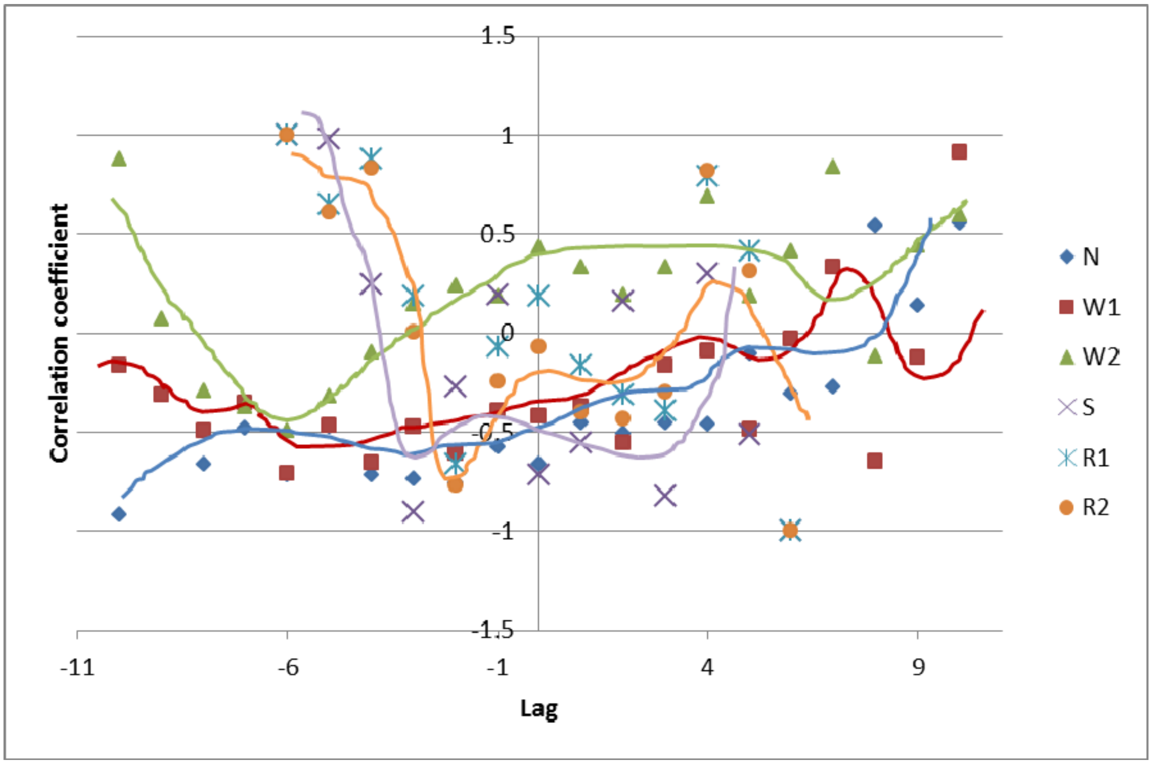


Figure 22. Cross-correlation between Big Chico Creek $\delta^2$H values and natural spring (N), groundwater in Big Chico Creek Ecological Reserve (W1), groundwater on California State University Chico campus (W2), snowmelt (S), rainwater from Big Chico Creek Ecological Reserve (R1) and rainwater from the valley (R2) $\delta^2$H values.

creek's isotope ratios and the snowmelt's isotope ratios when lag was investigated. A lag of 5, a time period of 10 weeks, produced a correlation coefficient of 0.98 and 0.9 for $\delta^{18}$O and $\delta^2$H, respectively. This may suggest that the snowmelt influences the isotope ratios of Big Chico Creek, but that it takes a long period of time to travel from the Sierra Nevada to the valley stretches of Big Chico Creek.

A runs test, which allows calculating the possibility that a sequence of values was generated by a random process, was performed for both $\delta^{18}$O and $\delta^2$H values from collected snowmelt, rain water, natural spring, groundwater and creekwater samples to determine whether or not the results were random in nature. A run is a sequence of data having the same characteristics, such as an increase in values. This run is preceded and followed by data with a different characteristic. If the number of runs is higher or lower than expected, the set of data is non-random. Analysis of $\delta^{18}O$ values indicated non-random variation at a 5% level of confidence in all water samples collected over the course of the study. Additionally, analysis of $\delta^{2}H$ values indicated non-random variation at a 5% level of confidence in all water samples collected over the duration of the study (Appendix C).

# CHAPTER V

# SUMMARY AND RECOMMENDATIONS

The original hypothesis of this study conjectured that water in Big Chico Creek was primarily driven by snowmelt during the dry summer months. Three means of investigation were employed in this seven-month study. Stream gauging was performed to determine if Big Chico Creek loses a significant volume of water between different gauging locations. Groundwater monitoring was also performed to record the depth of the water table at multiple piezometers at varying distances from Big Chico Creek. Water samples were collected for analysis of stable water isotopes. Samples of snowmelt, rainwater, spring water, groundwater, and water from Big Chico Creek were collected and sent to the UC Davis stable isotope facility for analysis.

Stream gauging indicated that in both September and December 2010, over 23 cfs were lost in the 4.5 miles between the upper park gauging site and the campus gauging site, suggesting that the majority of the creek may be influent. Discharges calculated at Upper Bidwell Park, the intersection of Centennial Avenue, and on the California State University Chico campus established that when traveling along the creek from higher to lower elevations, the creek loses to groundwater. Groundwater monitoring revealed that over the course of the study and in the area monitored, Big Chico Creek is an influent stream. From early February to late August, the creek was always at higher elevation than the surrounding water table. Cross-correlation indicated that there was a strong correlation with the water table as monitored at the piezometers and the stage of the creek. No lag was observed but this may be attributed to the fact that measurements were made at two week intervals. Such long sample periods likely failed to provide sufficient resolution to observe lag time between creek levels and water table levels.

The primary significance of these findings is that, in the area observed, Big Chico Creek is not being maintained by baseflow discharge. Because the area observed was limited in size, a larger network of piezometer would need to be employed to make additional conclusions; recommendation for future studies would be to employ a much larger network of piezometers along the length of the creek to determine whether Big Chico Creek may be an effluent stream in another area. While Big Chico Creek may indeed be an influent stream in the entire valley before eventually meeting the Sacramento River, it is possible that groundwater may be recharging the creek in the foothills.

Isotopic analysis yielded a number of findings. Big Chico Creek did indeed become more isotopically depleted over the course of the study, supporting the hypothesis that highly depleted snowmelt plays a significant role in maintaining the perennial nature of the creek. An analysis of variance showed, however, that while there were statistically significant differences between the samples collected from different locations, there was no statistically significant difference between samples collected on different dates. This suggests that the trend of increasingly negative $\delta^{18}O$ and $\delta^{2}H$ values in the stream was not statistically significant. A likely cause of this failure to reach significant levels may be attributed to the high rainfall encountered over the course of the study, with heavy precipitation occurring well into June of 2011. While precipitation values for 2011 are in line with average recorded precipitation, the distribution of the rainfall was more widespread. In 2011, precipitation between January and April totaled 12.86 in, while between May and August, precipitation totaled 5.88 inches (National Weather Service, 2011). With precipitation values tending to be relatively enriched compared to the snowmelt, creekwater, spring and groundwater values, it is likely that the unusually heavy rainfall in the summer months had an enriching effect, dulling the depleting effect of the melting snow contributing to the creek.

The findings of this study were consistent with the principles of isotope hydrology, as samples from higher elevations were more depleted in heavier isotopes. The statistically significant differences between the $\delta^{18}O$ and $\delta^{2}H$ values from different sample sites fall in line with what would be expected, given their geographic locations. Snowmelt had the most depleted $\delta^{18}O$ and $\delta^{2}H$ values observed, which is consistent with the fact that it was collected at the highest elevation. Rainwater samples collected from the Big Chico Creek Ecological Reserve and the valley were significantly more enriched in heavier isotopes than the snowmelt, as they were collected at lower altitudes. Rainwater collected from the higher altitudes of Big Chico Creek Ecological Reserve was consistently more depleted in heavier isotopes than those from the valley. Water collected from the natural spring in Big Chico Creek Ecological Reserve had similar $\delta^{18}O$ and $\delta^{2}H$ values until early June, at which point, the water became more enriched. This may indicate the spring water has a residence time of several months, with the enrichment spike in rainfall manifesting itself in the spring discharge several months later. Groundwater collected from piezometer F on the California State University Chico campus yielded $\delta^{18}O$ and $\delta^{2}H$ values which closely mirrored those of Big Chico Creek except during the period of enriched rainfall, at which time, the groundwater became more enriched in $^{18}O$ and $^{2}H$ than that of Big Chico Creek. This would suggest that the infiltration from rainwater is mixing with the more depleted water from the creek. Groundwater collected from Big Chico Creek Ecological Reserve had relatively stable $\delta^{18}O$ and $\delta^{2}H$ values over the course of the study. Creekwater, being a mixture of snowmelt, rainwater, and spring water, had the least fluctuation in $\delta^{18}O$ and $\delta^{2}H$ values. Cross-correlations employed to examine the relationships that may be present indicated that a strong correlation existed between creek flow and isotopic depletion. With decreasing flow in Big Chico Creek, $\delta^{18}O$ and $\delta^{2}H$ values decreased. This supports the hypothesis that the water in the creek is provided by snowmelt in summer months, when the flow of the creek is at its lowest. The runs test performed showed non-random variation present across all sample locations.

The findings of this study indicate that Big Chico Creek is fed primarily by snowmelt. Big Chico Creek appears to lose to groundwater year-round and becomes more depleted in $^{18}O$ and $^{2}H$ during the dry summer months. The significance of these findings is enhanced when one considers that during the dry summer months, the vapor pressure deficit in the region is very high. This increases the rate of evaporative enrichment in surface waters. It is likely that Big Chico Creek's $\delta^{18}O$ and $\delta^{2}H$ values are increased due to this evaporative enrichment. When comparing the $\delta^{18}O$ and $\delta^{2}H$ values of the creek with those of the other sample sites, no one sample site was found to have a strong correlation with the creek. This is likely due to the fact that the creek is so well mixed with water from so many different sources that no one source ever truly dominates, and thus no strong correlation with any one source exists. However, if the dominant source of water in the creek is snowmelt, climate change could have a significant impact. Climate change models have projected that the snowpack in the Sierra Nevada could be greatly diminished in the future (Butte Country Department of Water and Resource Conservation, 2010). One implication of this reduction in snowpack is that Big Chico Creek may lose its perennial nature and dry out during summer months.

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APPENDIX A

# STREAM GAUGING DATA

Big Chico Creek Volumetric Flowrate
Location: Bidwell Park Upper Area
Date: 9/26/2010

Total Stream Width= 45ft Broken into 15, 3 ft segments

All units in feet

| Depths | Velocities | Segment | Seg. Length | Tot. Length | (D1+D2)/2 | Seg. Area | Seg. Vel. | Seg. Q |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 1 | 3 | 3 | 0.475 | 1.425 | 0.95 | 1.35375 |
| 0.95 | 1.9 | 2 | 3 | 6 | 1.025 | 3.075 | 1.6 | 4.92 |
| 1.1 | 1.3 | 3 | 3 | 9 | 1.25 | 3.75 | 1.5 | 5.625 |
| 1.4 | 1.7 | 4 | 3 | 12 | 1.6 | 4.8 | 2 | 9.6 |
| 1.8 | 2.3 | 5 | 3 | 15 | 1.675 | 5.025 | 2.4 | 12.06 |
| 1.55 | 2.5 | 6 | 3 | 18 | 1.575 | 4.725 | 2.35 | 11.10375 |
| 1.6 | 2.2 | 7 | 3 | 21 | 1.7 | 5.1 | 2.3 | 11.73 |
| 1.8 | 2.4 | 8 | 3 | 24 | 1.975 | 5.925 | 2.15 | 12.73875 |
| 2.15 | 1.9 | 9 | 3 | 27 | 2.075 | 6.225 | 1.5 | 9.3375 |
| 2 | 1.1 | 10 | 3 | 30 | 1.925 | 5.775 | 1 | 5.775 |
| 1.85 | 0.9 | 11 | 3 | 33 | 1.7 | 5.1 | 0.75 | 3.825 |
| 1.55 | 0.6 | 12 | 3 | 36 | 1.25 | 3.75 | 0.45 | 1.6875 |
| 0.95 | 0.3 | 13 | 3 | 39 | 0.7 | 2.1 | 0.225 | 0.4725 |
| 0.45 | 0.15 | 14 | 3 | 42 | 0.35 | 1.05 | 0.1 | 0.105 |
| 0.25 | 0.05 | 15 | 3 | 45 | 0.125 | 0.375 | 0.025 | 0.009375 |
| 0 | 0 | | | | | | | |

| Total Q |
|---|
| 90.33375 $ft^3/s$ |

Big Chico Creek Volumetric Flowrate
Location: Bidwell Park Upper Area
Date: 12/11/2010
Total Stream Width= 45ft Broken into 15, 3 ft segments

All units in feet

| Depths | Velocities | Segment | Seg. Lengt | Tot. Lengt | (D1+D2)/2 | Seg. Area | Seg. Vel. | Seg. Q |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 1 | 3 | 3 | 0.475 | 1.425 | 1 | 1.425 |
| 0.95 | 2 | 2 | 3 | 6 | 1.1 | 3.3 | 1.75 | 5.775 |
| 1.25 | 1.5 | 3 | 3 | 9 | 1.45 | 4.35 | 1.65 | 7.1775 |
| 1.65 | 1.8 | 4 | 3 | 12 | 1.775 | 5.325 | 1.95 | 10.38375 |
| 1.9 | 2.1 | 5 | 3 | 15 | 1.7 | 5.1 | 2.3 | 11.73 |
| 1.5 | 2.5 | 6 | 3 | 18 | 1.625 | 4.875 | 2.5 | 12.1875 |
| 1.75 | 2.5 | 7 | 3 | 21 | 1.85 | 5.55 | 2.4 | 13.32 |
| 1.95 | 2.3 | 8 | 3 | 24 | 2 | 6 | 2.05 | 12.3 |
| 2.05 | 1.8 | 9 | 3 | 27 | 1.975 | 5.925 | 1.5 | 8.8875 |
| 1.9 | 1.2 | 10 | 3 | 30 | 2.025 | 6.075 | 1.1 | 6.6825 |
| 2.15 | 1 | 11 | 3 | 33 | 1.9 | 5.7 | 0.85 | 4.845 |
| 1.65 | 0.7 | 12 | 3 | 36 | 1.375 | 4.125 | 0.45 | 1.85625 |
| 1.1 | 0.2 | 13 | 3 | 39 | 0.8 | 2.4 | 0.225 | 0.54 |
| 0.5 | 0.25 | 14 | 3 | 42 | 0.4 | 1.2 | 0.175 | 0.21 |
| 0.3 | 0.1 | 15 | 3 | 45 | 0.15 | 0.45 | 0.05 | 0.0225 |
| 0 | 0 | | | | | | | |

Total Q
97.32 $ft^3/s$

Big Chico Creek Volumetric Flowrate
Location: Near Centennial Ave.
Date: 9/26/2010
Total Stream Width= 42 ft Broken into 14, 3 ft segments

All units in feet

| Depths | Velocities | Segment | Seg. Length | Tot. Length | (D1+D2)/2 | Seg. Area | Seg. Vel. | Seg. Q |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 1 | 3 | 3 | 0.45 | 1.35 | 0.35 | 0.4725 |
| 0.9 | 0.7 | 2 | 3 | 6 | 1 | 3 | 0.9 | 2.7 |
| 1.1 | 1.1 | 3 | 3 | 9 | 1.3 | 3.9 | 1.45 | 5.655 |
| 1.5 | 1.8 | 4 | 3 | 12 | 1.625 | 4.875 | 2.05 | 9.99375 |
| 1.75 | 2.3 | 5 | 3 | 15 | 1.65 | 4.95 | 2.3 | 11.385 |
| 1.55 | 2.3 | 6 | 3 | 18 | 1.575 | 4.725 | 2.35 | 11.10375 |
| 1.6 | 2.4 | 7 | 3 | 21 | 1.625 | 4.875 | 2.45 | 11.94375 |
| 1.65 | 2.5 | 8 | 3 | 24 | 1.95 | 5.85 | 2.15 | 12.5775 |
| 2.25 | 1.8 | 9 | 3 | 27 | 2.075 | 6.225 | 1.45 | 9.02625 |
| 1.9 | 1.1 | 10 | 3 | 30 | 1.775 | 5.325 | 0.85 | 4.52625 |
| 1.65 | 0.6 | 11 | 3 | 33 | 1.425 | 4.275 | 0.45 | 1.92375 |
| 1.2 | 0.3 | 12 | 3 | 36 | 0.925 | 2.775 | 0.225 | 0.624375 |
| 0.65 | 0.15 | 13 | 3 | 39 | 0.45 | 1.35 | 0.1 | 0.135 |
| 0.25 | 0.05 | 14 | 3 | 42 | 0.125 | 0.375 | 0.025 | 0.009375 |
| 0 | 0 | | | | | | | |

Total Q
82.07625 $ft^3/s$

Big Chico Creek Volumetric Flowrate
Location: Near Centennial Ave.
Date: 12/11/2010
Total Stream Width= 42 ft Broken into 14, 3 ft segments

All units in feet

| Depths | Velocities | Segment | Seg. Lengt | Tot. Lengt | (D1+D2)/2 | Seg. Area | Seg. Vel. | Seg. Q |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 1 | 3 | 3 | 0.55 | 1.65 | 0.35 | 0.5775 |
| 1.1 | 0.7 | 2 | 3 | 6 | 1.2 | 3.6 | 0.9 | 3.24 |
| 1.3 | 1.1 | 3 | 3 | 9 | 1.45 | 4.35 | 1.45 | 6.3075 |
| 1.6 | 1.8 | 4 | 3 | 12 | 1.75 | 5.25 | 2.05 | 10.7625 |
| 1.9 | 2.3 | 5 | 3 | 15 | 1.775 | 5.325 | 2.45 | 13.04625 |
| 1.65 | 2.6 | 6 | 3 | 18 | 1.675 | 5.025 | 2.5 | 12.5625 |
| 1.7 | 2.4 | 7 | 3 | 21 | 1.675 | 5.025 | 2.5 | 12.5625 |
| 1.65 | 2.6 | 8 | 3 | 24 | 1.975 | 5.925 | 2.2 | 13.035 |
| 2.3 | 1.8 | 9 | 3 | 27 | 2.175 | 6.525 | 1.45 | 9.46125 |
| 2.05 | 1.1 | 10 | 3 | 30 | 1.875 | 5.625 | 0.85 | 4.78125 |
| 1.7 | 0.6 | 11 | 3 | 33 | 1.5 | 4.5 | 0.45 | 2.025 |
| 1.3 | 0.3 | 12 | 3 | 36 | 1 | 3 | 0.225 | 0.675 |
| 0.7 | 0.15 | 13 | 3 | 39 | 0.5 | 1.5 | 0.1 | 0.15 |
| 0.3 | 0.05 | 14 | 3 | 42 | 0.15 | 0.45 | 0.025 | 0.01125 |
| 0 | 0 | | | | | | | |

| Total Q |
|---|
| 89.1975 $ft^3/s$ |

Big Chico Creek Volumetric Flowrate
Location: CSU Chico Campus
Date: 9/25/2010
Total Stream Width= 28ft Broken into 14, 2 ft segments

All units in feet

| Depths | Velocities | Segment | Seg. Lengt | Tot. Length | (D1+D2)/2 | Seg. Area | Seg. Vel. | Seg. Q |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 1 | 2 | 2 | 0.1 | 0.2 | 1.025 | 0.205 |
| 0.2 | 2.05 | 2 | 2 | 4 | 0.275 | 0.55 | 2.275 | 1.25125 |
| 0.35 | 2.5 | 3 | 2 | 6 | 0.375 | 0.75 | 2.85 | 2.1375 |
| 0.4 | 3.2 | 4 | 2 | 8 | 0.475 | 0.95 | 3.2 | 3.04 |
| 0.55 | 3.2 | 5 | 2 | 10 | 0.625 | 1.25 | 3.45 | 4.3125 |
| 0.7 | 3.7 | 6 | 2 | 12 | 0.825 | 1.65 | 3.8 | 6.27 |
| 0.95 | 3.9 | 7 | 2 | 14 | 1.075 | 2.15 | 3.8 | 8.17 |
| 1.2 | 3.7 | 8 | 2 | 16 | 1.225 | 2.45 | 3.5 | 8.575 |
| 1.25 | 3.3 | 9 | 2 | 18 | 1.3 | 2.6 | 3.25 | 8.45 |
| 1.35 | 3.2 | 10 | 2 | 20 | 1.375 | 2.75 | 3 | 8.25 |
| 1.4 | 2.8 | 11 | 2 | 22 | 1.3 | 2.6 | 2.5 | 6.5 |
| 1.2 | 2.2 | 12 | 2 | 24 | 1.1 | 2.2 | 2.55 | 5.61 |
| 1 | 2.9 | 13 | 2 | 26 | 0.8 | 1.6 | 2.15 | 3.44 |
| 0.6 | 1.4 | 14 | 2 | 28 | 0.3 | 0.6 | 0.7 | 0.42 |
| 0 | 0 | | | | | | | |

| Total Q |
|---|
| 66.63125 $ft^3/s$ |

Big Chico Creek Volumetric Flowrate
Location: CSU Chico Campus
Date: 12/11/2010
Total Stream Width= 28ft Broken into 14, 2 ft segments

All units in feet

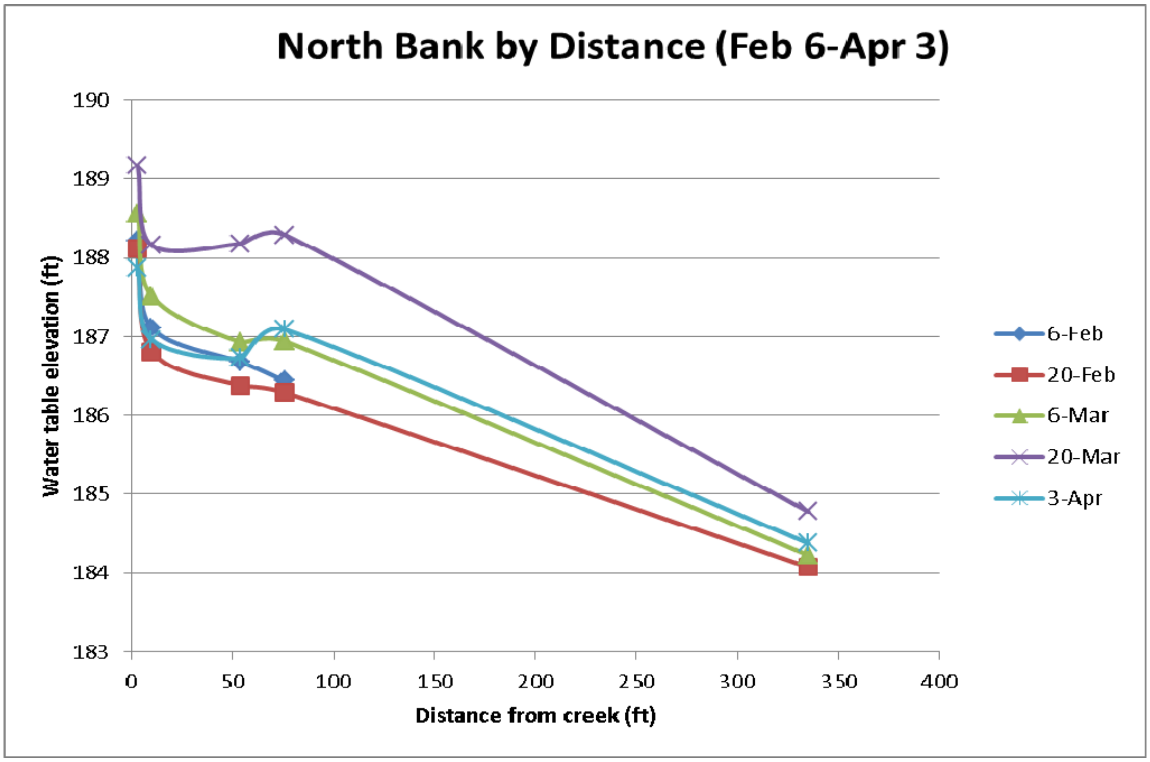
| Depths | Velocities | Segment | Seg. Lengt | Tot. Lengt | (D1+D2)/2 | Seg. Area | Seg. Vel. | Seg. Q |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 1 | 2 | 2 | 0.15 | 0.3 | 1.05 | 0.315 |
| 0.3 | 2.1 | 2 | 2 | 4 | 0.375 | 0.75 | 2.35 | 1.7625 |
| 0.45 | 2.6 | 3 | 2 | 6 | 0.45 | 0.9 | 2.9 | 2.61 |
| 0.45 | 3.2 | 4 | 2 | 8 | 0.525 | 1.05 | 3.25 | 3.4125 |
| 0.6 | 3.3 | 5 | 2 | 10 | 0.675 | 1.35 | 3.45 | 4.6575 |
| 0.75 | 3.6 | 6 | 2 | 12 | 0.875 | 1.75 | 3.7 | 6.475 |
| 1 | 3.8 | 7 | 2 | 14 | 1.15 | 2.3 | 3.75 | 8.625 |
| 1.3 | 3.7 | 8 | 2 | 16 | 1.35 | 2.7 | 3.5 | 9.45 |
| 1.4 | 3.3 | 9 | 2 | 18 | 1.425 | 2.85 | 3.3 | 9.405 |
| 1.45 | 3.3 | 10 | 2 | 20 | 1.425 | 2.85 | 3.1 | 8.835 |
| 1.4 | 2.9 | 11 | 2 | 22 | 1.35 | 2.7 | 2.55 | 6.885 |
| 1.3 | 2.2 | 12 | 2 | 24 | 1.2 | 2.4 | 2.6 | 6.24 |
| 1.1 | 3 | 13 | 2 | 26 | 0.95 | 1.9 | 2.25 | 4.275 |
| 0.8 | 1.5 | 14 | 2 | 28 | 0.4 | 0.8 | 0.75 | 0.6 |
| 0 | 0 | | | | | | | |

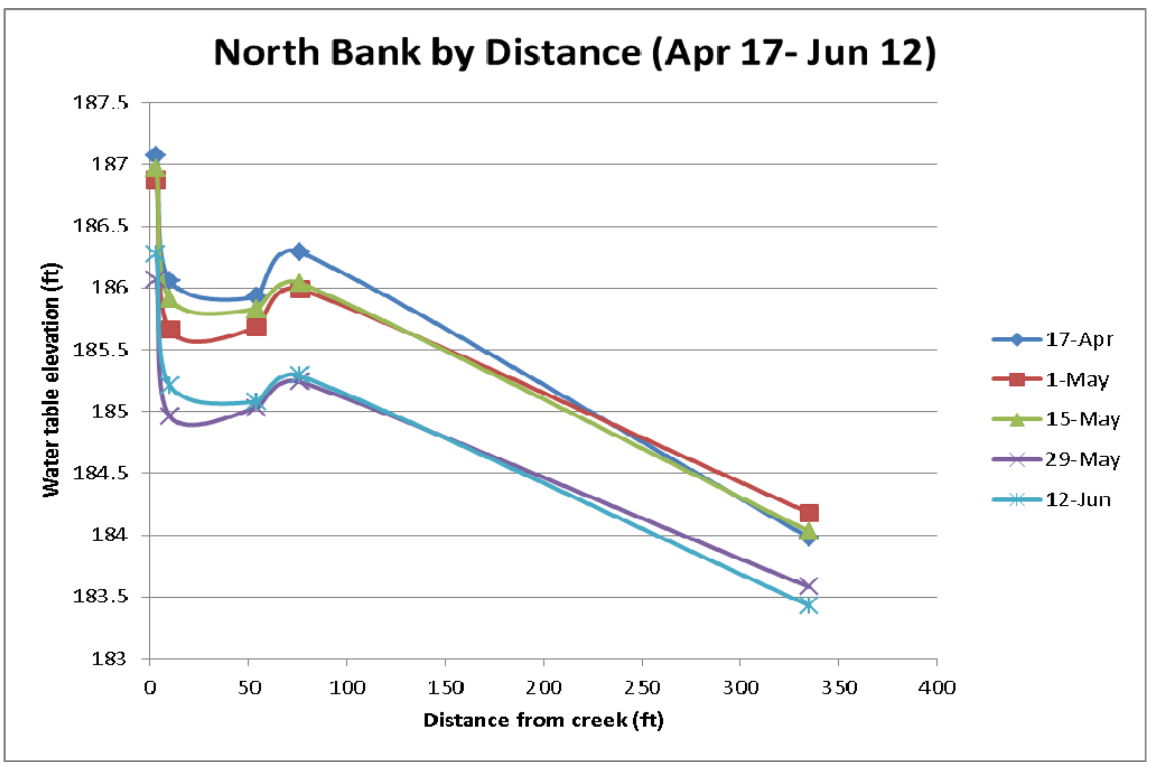
| Total Q |
|---|
| 73.5475 $ft^3/s$ |

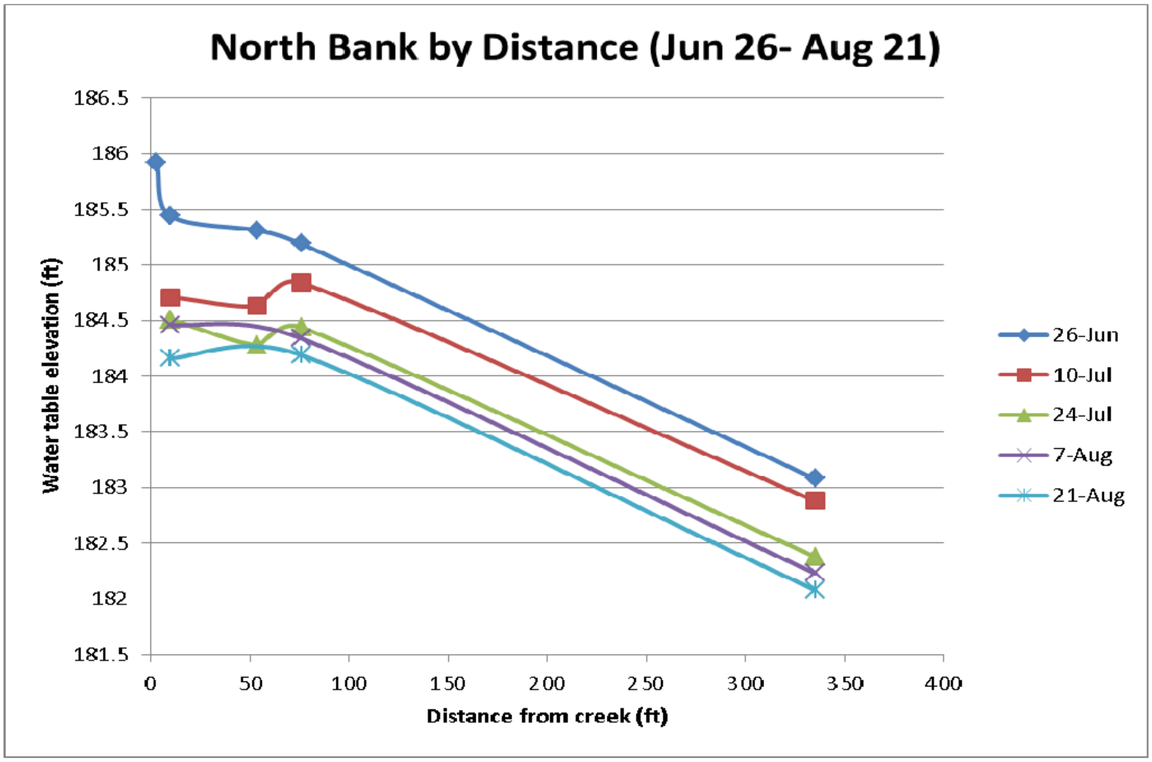
APPENDIX B

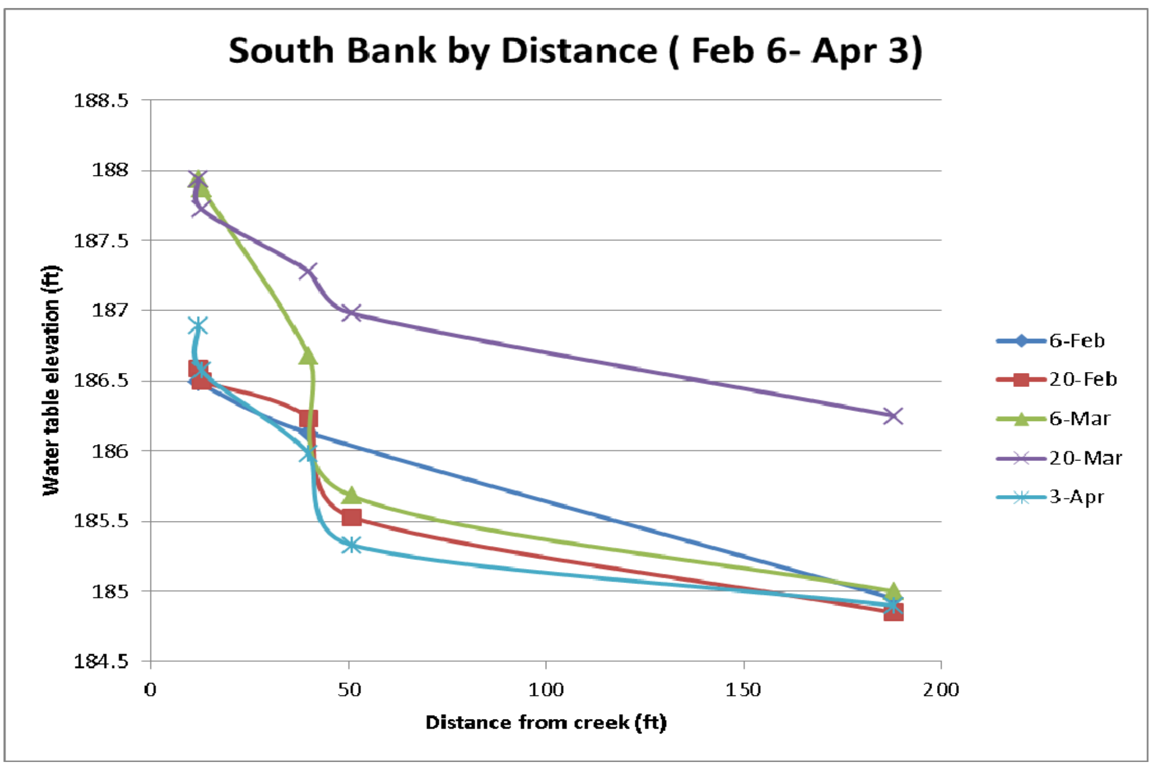
GROUNDWATER MONITORING
AND WELL DATA

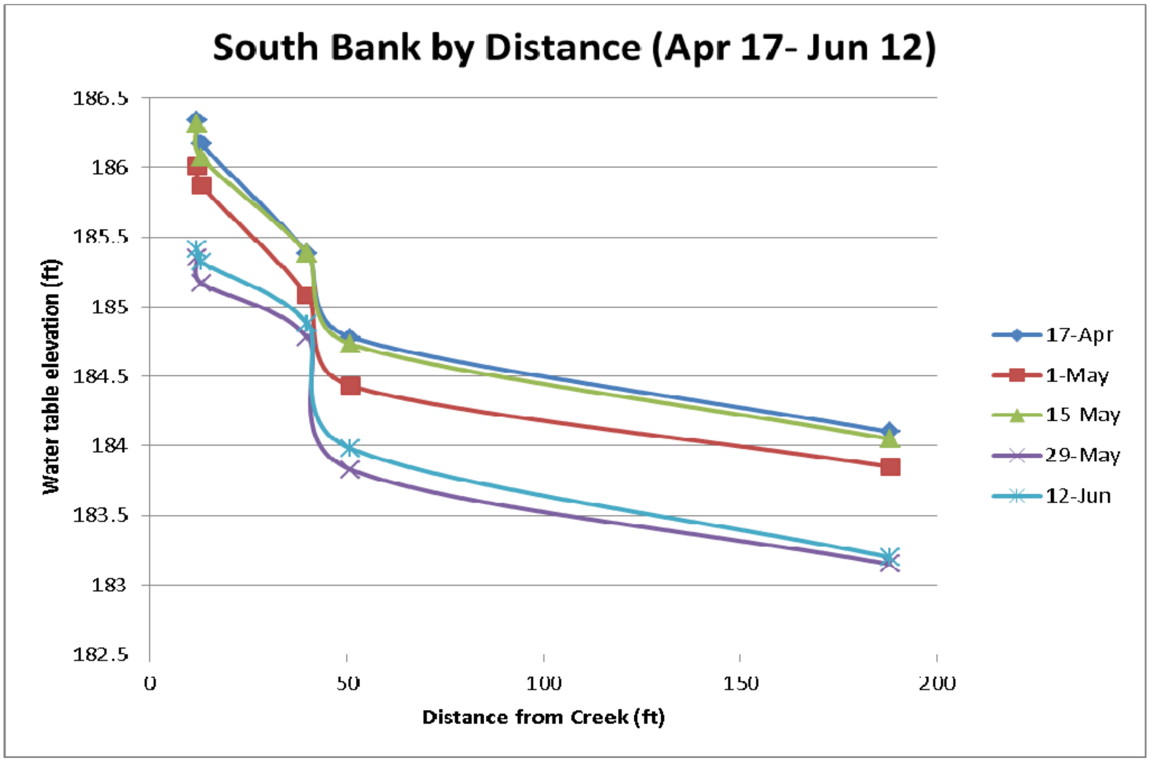
| Depth to water surface in feet | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | Well I | Well J | Well K | Well L | Well E | Well D | Well C | Well B | Well A | Well G | Well H | Well F |
| 2/6/2011 | 8.65 | 2.8 | 12.6 | 13.4 | N/A | 9.7 | 4.05 | N/A | 10.1 | N/A | 10.4 | 11.2 |
| 2/20/2011 | 8.8 | 2.9 | 12.75 | 13.35 | 12.4 | 10 | 3.95 | 9.7 | 10.2 | 6.25 | 10.7 | 11.5 |
| 3/6/2011 | 8.05 | 2.45 | 12.1 | 13.25 | 12.25 | 9.3 | 3.2 | 9.55 | 10.05 | 5.3 | 10.45 | 10.95 |
| 3/20/2011 | 7.8 | 1.85 | 10.75 | 12.7 | 11.7 | 8.65 | 2.6 | 8.55 | 8.8 | 4.75 | 9.55 | 9.7 |
| 4/3/2011 | 8.9 | 3.15 | 11.95 | 13.25 | 12.1 | 9.85 | 3.95 | 10.1 | 10.15 | 6.2 | 11.15 | 11.15 |
| 4/17/2011 | 9.8 | 3.95 | 12.75 | 13.35 | 12.5 | 10.75 | 4.8 | 10.65 | 10.95 | 7 | 11.75 | 11.95 |
| 5/1/2011 | 10.2 | 4.15 | 13.05 | 10.45 | 12.3 | 11.15 | 5.1 | 11 | 11.2 | 7.3 | 12.05 | 12.2 |
| 5/15/2011 | 9.8 | 4.05 | 13 | 10.45 | 12.45 | 10.9 | 4.8 | 10.7 | 11 | 7.1 | 11.75 | 12.05 |
| 5/29/2011 | 10.9 | 4.95 | 13.8 | 10.4 | 12.9 | 11.85 | 5.6 | 11.6 | 11.9 | 8 | 12.35 | 12.85 |
| 6/12/2011 | 10.65 | 4.75 | 13.75 | 10.45 | 13.05 | 11.6 | 5.55 | 11.45 | 11.85 | 7.85 | 12.25 | 12.8 |
| 6/26/2011 | 10.95 | 5.1 | 13.85 | 10.45 | 13.4 | 11.95 | 5.65 | 11.75 | 12.1 | 8.15 | Dry | 13.1 |
| 7/10/2011 | 11.1 | Dry | 14.2 | 10.45 | 13.6 | 12.1 | 5.8 | 11.9 | 12.3 | 8.3 | Dry | 13.25 |
| 7/24/2011 | 11.35 | Dry | 14.6 | 10.4 | 14.1 | 12.3 | 6.05 | 12.15 | 12.65 | 8.55 | Dry | 13.6 |
| 8/7/2011 | 11.4 | Dry | 14.7 | 10.4 | 14.25 | 12.35 | 6.15 | 12.2 | 12.7 | 8.65 | Dry | Dry |
| 8/21/2011 | 11.45 | Dry | 14.85 | 10.4 | 14.4 | 12.65 | 6.2 | 12.3 | 12.8 | 8.8 | Dry | Dry |

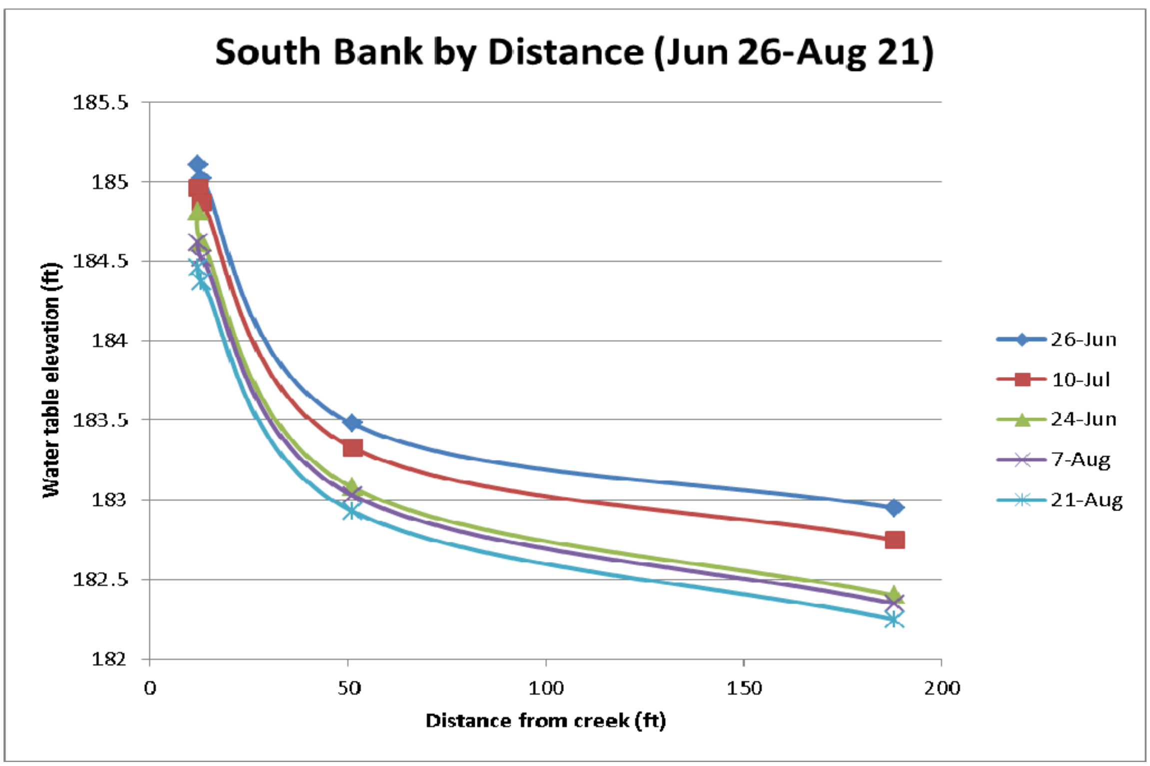

North Bank by Distance (Feb 6-Apr 3)
Water table elevation (ft)
Distance from creek (ft)
6-Feb
20-Feb
6-Mar
20-Mar
3-Apr


North Bank by Distance (Apr 17- Jun 12)
Water table elevation (ft)
Distance from creek (ft)
17-Apr
1-May
15-May
29-May
12-Jun


North Bank by Distance (Jun 26- Aug 21)
Water table elevation (ft)
Distance from creek (ft)
186.5
186
185.5
185
184.5
184
183.5
183
182.5
182
181.5
0
50
100
150
200
250
300
350
400
26-Jun
10-Jul
24-Jul
7-Aug
21-Aug


South Bank by Distance ( Feb 6- Apr 3)
Water table elevation (ft)
Distance from creek (ft)
188.5
188
187.5
187
186.5
186
185.5
185
184.5
0
50
100
150
200
6-Feb
20-Feb
6-Mar
20-Mar
3-Apr


South Bank by Distance (Apr 17- Jun 12)
186.5
186
185.5
185
184.5
184
183.5
183
182.5
Water table elevation (ft)
0
50
100
150
200
Distance from Creek (ft)
17-Apr
1-May
15 May
29-May
12-Jun


South Bank by Distance (Jun 26-Aug 21)
185.5
185
184.5
184
183.5
183
182.5
182
Water table elevation (ft)
0
50
100
150
200
Distance from creek (ft)
26-Jun
10-Jul
24-Jun
7-Aug
21-Aug

APPENDIX C

ISOTOPE DATA

| **Well BCCER** | | |
|---|---|---|
| VSMOW | VSMOW | |
| $\delta^2H$ | $\delta^{18}O$ | Date |
| -62.6 | -9.66 | 30-Jan |
| -63.1 | -9.72 | 13-Feb |
| -63.9 | -9.80 | 27-Feb |
| -61.8 | -9.55 | 13-Mar |
| -63.3 | -9.69 | 27-Mar |
| -60.3 | -9.34 | 10-Apr |
| -62.4 | -9.63 | 24-Apr |
| -61.4 | -9.40 | 8-May |
| -60.1 | -9.57 | 22-May |
| -61.8 | -9.70 | 5-Jun |
| -61.7 | -9.53 | 19-Jun |
| -55.2 | -7.56 | 3-Jul |
| -62.5 | -9.56 | 17-Jul |
| -61.8 | -9.53 | 31-Jul |
| -58.9 | -8.99 | 14-Aug |
| -61.5 | -9.44 | 28-Aug |

| **Well Creek** | | |
|---|---|---|
| VSMOW | VSMOW | |
| $\delta^2H$ | $\delta^{18}O$ | Date |
| -64.3 | -9.93 | 30-Jan |
| -66.8 | -10.27 | 13-Feb |
| -69.5 | -10.49 | 27-Feb |
| -68.9 | -10.49 | 13-Mar |
| -69.8 | -10.28 | 27-Mar |
| -60.4 | -8.73 | 10-Apr |
| -64.0 | -9.04 | 24-Apr |
| -64.8 | -9.20 | 8-May |
| -53.5 | -7.54 | 22-May |
| -72.3 | -10.35 | 5-Jun |
| -70.7 | -10.56 | 19-Jun |
| -69.6 | -10.46 | 3-Jul |
| -72.2 | -10.66 | 17-Jul |
| -72.0 | -11.02 | 31-Jul |
| -72.6 | -10.80 | 14-Aug |
| -72.2 | -10.82 | 28-Aug |

| **Natural Spring** | | |
|---|---|---|
| VSMOW | VSMOW | |
| $\delta^2H$ | $\delta^{18}O$ | Date |
| -63.9 | -9.56 | 30-Jan |
| -62.7 | -9.53 | 13-Feb |
| -61.7 | -9.50 | 27-Feb |
| -61.8 | -9.56 | 13-Mar |
| -62.2 | -9.64 | 27-Mar |
| -61.9 | -9.59 | 10-Apr |
| -61.7 | -9.58 | 24-Apr |
| -55.6 | -7.14 | 8-May |
| -60.6 | -9.45 | 22-May |
| -34.7 | -1.66 | 5-Jun |
| -44.4 | -4.43 | 19-Jun |
| -43.4 | -4.63 | 3-Jul |
| -50.1 | -6.49 | 17-Jul |
| -52.2 | -7.04 | 31-Jul |
| -52.8 | -7.10 | 14-Aug |
| -54.0 | -7.49 | 28-Aug |

| **Big Chico Creek** | | |
|---|---|---|
| VSMOW | VSMOW | |
| $\delta^2H$ | $\delta^{18}O$ | Date |
| -68.8 | -10.21 | 30-Jan |
| -65.4 | -9.97 | 13-Feb |
| -68.6 | -10.32 | 27-Feb |
| -70.2 | -10.58 | 13-Mar |
| -67.6 | -10.10 | 27-Mar |
| -69.2 | -10.51 | 10-Apr |
| -70.2 | -10.86 | 24-Apr |
| -70.4 | -10.85 | 8-May |
| -69.5 | -10.57 | 22-May |
| -72.1 | -10.64 | 5-Jun |
| -70.9 | -10.67 | 19-Jun |
| -71.8 | -10.93 | 3-Jul |
| -72.8 | -11.18 | 17-Jul |
| -73.8 | -11.46 | 31-Jul |
| -72.8 | -11.29 | 14-Aug |
| -73.9 | -11.65 | 28-Aug |

| Rain BCCER | | |
|---|---|---|
| VSMOW | VSMOW | |
| $\delta^2H$ | $\delta^{18}O$ | Date |
| -40.1 | -6.50 | 29-Jan |
| -42.1 | -8.63 | 14-Feb |
| -68.0 | -11.00 | 27-Feb |
| -63.6 | -10.08 | 11-Mar |
| -50.1 | -7.44 | 23-Mar |
| -30.2 | -3.59 | 6-May |
| -31.8 | -5.13 | 17-May |
| -64.7 | -9.33 | 22-May |

| Rain Chico Valley | | |
|---|---|---|
| VSMOW | VSMOW | |
| $\delta^2H$ | $\delta^{18}O$ | Date |
| -43.2 | -7.51 | 29-Jan |
| -43.7 | -7.60 | 14-Feb |
| -68.0 | -10.98 | 27-Feb |
| -60.0 | -8.35 | 11-Mar |
| -41.3 | -4.75 | 23-Mar |
| -20.7 | -1.11 | 6-May |
| -24.6 | -2.17 | 17-May |
| -44.6 | -3.93 | 22-May |

| Snowmelt | | |
|---|---|---|
| VSMOW | VSMOW | |
| $\delta^2H$ | $\delta^{18}O$ | Date |
| -78.4 | -11.81 | 30-Jan |
| -96.6 | -13.92 | 13-Feb |
| -95.1 | -15.25 | 27-Feb |
| -77.1 | -12.75 | 13-Mar |
| -78.4 | -12.52 | 27-Mar |
| -77.2 | -12.40 | 10-Apr |
| -77.4 | -12.25 | 24-Apr |
| -77.4 | -12.48 | 8-May |

# TWO WAY ANALYSIS OF VARIANCE

| | W $\delta^2H$ | W2 $\delta^2H$ | N $\delta^2H$ | C $\delta^2H$ |
|---|---|---|---|---|
| 30-Jan | -62.6 | -64.3 | -63.9 | -68.8 |
| 13-Feb | -63.1 | -66.8 | -62.7 | -65.4 |
| 27-Feb | -63.9 | -69.5 | -61.7 | -68.6 |
| 13-Mar | -61.8 | -68.9 | -61.8 | -70.2 |
| 27-Mar | -63.3 | -69.8 | -62.2 | -67.6 |
| 10-Apr | -60.3 | -60.4 | -61.9 | -69.2 |
| 24-Apr | -62.4 | -64.0 | -61.7 | -70.8 |
| 8-May | -61.4 | -64.8 | -55.6 | -70.4 |
| 22-May | -60.1 | -53.5 | -60.6 | -69.5 |
| 5-Jun | -61.8 | -72.3 | -34.7 | -72.1 |
| 19-Jun | -61.7 | -70.7 | -44.4 | -70.9 |
| 3-Jul | -55.2 | -69.6 | -43.4 | -71.8 |
| 17-Jul | -62.5 | -72.2 | -50.1 | -72.8 |
| 31-Jul | -61.8 | -72.0 | -52.2 | -73.8 |
| 14-Aug | -58.9 | -72.6 | -52.8 | -72.8 |
| 28-Aug | -61.5 | -72.2 | -54.0 | -73.9 |

Anova: Two-Factor Without Replication

| SUMMARY | Count | Sum | Average | Variance |
|---|---|---|---|---|
| 40573 | 4 | -259.552 | -64.888 | 7.295449 |
| 40587 | 4 | -258.046 | -64.5116 | 3.782702 |
| 40601 | 4 | -263.613 | -65.9032 | 14.07169 |
| 40615 | 4 | -262.797 | -65.6992 | 20.34188 |
| 40629 | 4 | -262.882 | -65.7204 | 13.01638 |
| 40643 | 4 | -251.719 | -62.9298 | 17.72251 |
| 40657 | 4 | -258.877 | -64.7194 | 17.38082 |
| 40671 | 4 | -252.097 | -63.0242 | 38.37204 |
| 40685 | 4 | -243.741 | -60.9353 | 43.0437 |
| 40699 | 4 | -240.791 | -60.1977 | 313.4916 |
| 40713 | 4 | -247.668 | -61.9169 | 154.7306 |
| 40727 | 4 | -240.066 | -60.0165 | 177.1986 |
| 40741 | 4 | -257.696 | -64.424 | 113.1729 |
| 40755 | 4 | -259.777 | -64.9441 | 99.679 |
| 40769 | 4 | -257.229 | -64.3073 | 100.7387 |
| 40783 | 4 | -261.589 | -65.3973 | 88.32355 |
| | | | | |
| W d 2H | 16 | -982.325 | -61.3953 | 4.246688 |
| W2 d 2H | 16 | -1083.57 | -67.7228 | 27.66629 |
| N d 2H | 16 | -883.655 | -55.2284 | 73.50017 |
| C d 2H | 16 | -1128.59 | -70.5372 | 5.46843 |

ANOVA

| | Source of Variation | SS | df | MS | F | P-value | F crit |
|---|---|---|---|---|---|---|---|
| Date | Rows | 236.2553 | 15 | 15.75035 | 0.496693 | 0.929661 | 1.894875 |
| Sample Site | Columns | 2240.118 | 3 | 746.7061 | 23.54766 | 2.58E-09 | 2.811544 |
| | Error | 1426.968 | 45 | 31.71041 | | | |
| | | | | | | | |
| | Total | 3903.342 | 63 | | | | |

| | W $\delta^{18}O$ | W2 $\delta^{18}O$ | N $\delta^{18}O$ | C $\delta^{18}O$ |
|---|---|---|---|---|
| 30-Jan | -9.66 | -9.93 | -9.56 | -10.21 |
| 13-Feb | -9.72 | -10.27 | -9.53 | -9.97 |
| 27-Feb | -9.80 | -10.49 | -9.50 | -10.32 |
| 13-Mar | -9.55 | -10.49 | -9.56 | -10.58 |
| 27-Mar | -9.69 | -10.28 | -9.64 | -10.10 |
| 10-Apr | -9.34 | -8.73 | -9.59 | -10.51 |
| 24-Apr | -9.63 | -9.04 | -9.58 | -10.86 |
| 8-May | -9.40 | -9.20 | -7.14 | -10.85 |
| 22-May | -9.57 | -7.54 | -9.45 | -10.57 |
| 5-Jun | -9.70 | -10.35 | -1.66 | -10.64 |
| 19-Jun | -9.53 | -10.56 | -4.43 | -10.67 |
| 3-Jul | -7.56 | -10.46 | -4.63 | -10.93 |
| 17-Jul | -9.56 | -10.66 | -6.49 | -11.18 |
| 31-Jul | -9.53 | -11.02 | -7.04 | -11.46 |
| 14-Aug | -8.99 | -10.80 | -7.10 | -11.29 |
| 28-Aug | -9.44 | -10.82 | -7.49 | -11.65 |

Anova: Two-Factor Without Replication

| SUMMARY | Count | Sum | Average | Variance |
|---|---|---|---|---|
| 40573 | 4 | -39.3654 | -9.84135 | 0.085775 |
| 40587 | 4 | -39.4909 | -9.87272 | 0.1034 |
| 40601 | 4 | -40.1113 | -10.0278 | 0.207339 |
| 40615 | 4 | -40.1832 | -10.0458 | 0.321657 |
| 40629 | 4 | -39.7135 | -9.92838 | 0.09707 |
| 40643 | 4 | -38.1719 | -9.54298 | 0.541596 |
| 40657 | 4 | -39.1124 | -9.77811 | 0.595569 |
| 40671 | 4 | -36.584 | -9.146 | 2.32611 |
| 40685 | 4 | -37.1311 | -9.28277 | 1.603368 |
| 40699 | 4 | -32.3448 | -8.08621 | 18.49063 |
| 40713 | 4 | -35.1808 | -8.79519 | 8.751327 |
| 40727 | 4 | -33.5893 | -8.39733 | 8.518608 |
| 40741 | 4 | -37.8766 | -9.46915 | 4.40816 |
| 40755 | 4 | -39.0546 | -9.76366 | 3.98156 |
| 40769 | 4 | -38.1825 | -9.54563 | 3.629627 |
| 40783 | 4 | -39.4027 | -9.85069 | 3.3022 |
| | | | | |
| W d 2H | 16 | -150.658 | -9.41611 | 0.281163 |
| W2 d 2H | 16 | -160.643 | -10.0402 | 0.883903 |
| N d 2H | 16 | -122.403 | -7.65017 | 5.774919 |
| C d 2H | 16 | -171.792 | -10.737 | 0.231713 |

ANOVA

| | Source of Variation | SS | df | MS | F | P-value | F crit |
|---|---|---|---|---|---|---|---|
| Date | Rows | 20.59834 | 15 | 1.373223 | 0.710474 | 0.760804 | 1.894875 |
| Sample Site | Columns | 83.91485 | 3 | 27.97162 | 14.47188 | 9.79E-07 | 2.811544 |
| | Error | 86.97713 | 45 | 1.932825 | | | |
| | | | | | | | |
| | Total | 191.4903 | 63 | | | | |

**Runs Test**

| | W $\delta^2$H | | W2 $\delta^2$H | |
|---|---|---|---|---|
| 30-Jan | -62.6 | | -64.3 | |
| 13-Feb | -63.1 | | -66.8 | |
| 27-Feb | -63.9 | - | -69.5 | - |
| 13-Mar | -61.8 | + | -68.9 | + |
| 27-Mar | -63.3 | - | -69.8 | - |
| 10-Apr | -60.3 | + | -60.4 | + |
| 24-Apr | -62.4 | - | -64.0 | |
| 8-May | -61.4 | | -64.8 | - |
| 22-May | -60.1 | + | -53.5 | + |
| 5-Jun | -61.8 | - | -72.3 | - |
| 19-Jun | -61.7 | | -70.7 | |
| 3-Jul | -55.2 | + | -69.6 | + |
| 17-Jul | -62.5 | - | -72.2 | - |
| 31-Jul | -61.8 | | -72.0 | + |
| 14-Aug | -58.9 | + | -72.6 | - |
| 28-Aug | -61.5 | - | -72.2 | + |

| | | | |
|---|---|---|---|
| $\mu$ | 11 runs | $\mu$ | 12 runs |
| + | 5 | + | 6 |
| - | 6 | - | 6 |
| $\mu$ bar | 5.454545 | $\mu$ bar | 6 |
| $\sigma^2$ | 2.429752 | $\sigma^2$ | 2.7272727 |
| z | 3.557592 | z | 3.6331804 |
| $\alpha = 0.05$ | | $\alpha = 0.05$ | |
| critical region is 1.96, -1.96 | | critical region is 1.96, -1.96 | |
| Critical value exceeded | | Critical value exceeded | |
| Non-random | | Non-random | |

**Runs Test**

| | N $\delta^2$H | | S $\delta^2$H | |
|---|---|---|---|---|
| 30-Jan | -63.9 | | -78.4 | |
| 13-Feb | -62.7 | | -96.6 | - |
| 27-Feb | -61.7 | + | -95.1 | |
| 13-Mar | -61.8 | | -77.1 | + |
| 27-Mar | -62.2 | - | -78.4 | - |
| 10-Apr | -61.9 | | -77.2 | + |
| 24-Apr | -61.7 | | -77.4 | |
| 8-May | -55.6 | + | -77.4 | - |
| 22-May | -60.6 | - | | |
| 5-Jun | -34.7 | + | | |
| 19-Jun | -44.4 | - | | |
| 3-Jul | -43.4 | + | | |
| 17-Jul | -50.1 | | | |
| 31-Jul | -52.2 | | | |
| 14-Aug | -52.8 | | | |
| 28-Aug | -54.0 | - | | |

| | | | |
|---|---|---|---|
| $\mu$ | 8 runs | $\mu$ | 5 runs |
| + | 4 | + | 2 |
| - | 4 | - | 3 |
| $\mu$ bar | 4 | $\mu$ bar | 2.4 |
| $\sigma^2$ | 1.71 | $\sigma^2$ | 0.84 |
| z | 3.06 | z | 2.837 |
| $\alpha$ = 0.05 | | $\alpha$ = 0.05 | |
| critical region is 1.96, -1.96 | | critical region is 1.96, -1.96 | |
| Critical value exceeded | | Critical value exceeded | |
| Non-random | | Non-random | |

**Runs Test**

| | C $\delta^2$H | | R2 $\delta^2$H | | R2 $\delta^2$H | |
|---|---|---|---|---|---|---|
| 30-Jan | -68.8 | | -40.1 | | -43.2 | |
| 13-Feb | -65.4 | + | -42.1 | | -43.7 | |
| 27-Feb | -68.6 | | -68.0 | - | -68.0 | - |
| 13-Mar | -70.2 | - | -63.6 | | -60.0 | |
| 27-Mar | -67.6 | + | -50.1 | | -41.3 | |
| 10-Apr | -69.2 | | -30.2 | + | -20.7 | + |
| 24-Apr | -70.8 | - | -31.8 | | -24.6 | |
| 8-May | -70.4 | | -64.7 | - | -44.6 | - |
| 22-May | -69.5 | + | | | | |
| 5-Jun | -72.1 | - | | | | |
| 19-Jun | -70.9 | + | | | | |
| 3-Jul | -71.8 | | | | | |
| 17-Jul | -72.8 | | | | | |
| 31-Jul | -73.8 | - | | | | |
| 14-Aug | -72.8 | + | | | | |
| 28-Aug | -73.9 | - | | | | |

| | | | | | |
|---|---|---|---|---|---|
| μ | 10 runs | μ | 3 runs | μ | 3runs |
| + | 5 | + | 1 | + | 1 |
| - | 5 | - | 2 | - | 2 |
| μ bar | 5 | μ bar | 1.333333 | μ bar | 1.333333 |
| $\sigma^2$ | 2.222222 | $\sigma^2$ | 0.222222 | $\sigma^2$ | 0.222222 |
| z | 3.354102 | z | 18.38478 | z | 18.38478 |
| α = 0.05 | | α = 0.05 | | α = 0.05 | |
| critical region is 1.96, -1.96 | | critical region is 1.96, -1.96 | | critical region is 1.96, -1.96 | |
| Critical value exceeded | | Critical value exceeded | | Critical value exceeded | |
| Non-random | | Non-random | | Non-random | |

**Runs Test**

| | W $\delta^{18}O$ | | W2 $\delta^{18}O$ | |
|---|---|---|---|---|
| 30-Jan | -9.66 | | -9.93 | |
| 13-Feb | -9.72 | | -10.27 | |
| 27-Feb | -9.80 | - | -10.49 | |
| 13-Mar | -9.55 | + | -10.49 | - |
| 27-Mar | -9.69 | - | -10.28 | |
| 10-Apr | -9.34 | + | -8.73 | + |
| 24-Apr | -9.63 | - | -9.04 | |
| 8-May | -9.40 | | -9.20 | - |
| 22-May | -9.57 | + | -7.54 | + |
| 5-Jun | -9.70 | - | -10.35 | |
| 19-Jun | -9.53 | | -10.56 | - |
| 3-Jul | -7.56 | + | -10.46 | + |
| 17-Jul | -9.56 | - | -10.66 | |
| 31-Jul | -9.53 | | -11.02 | - |
| 14-Aug | -8.99 | + | -10.80 | + |
| 28-Aug | -9.44 | - | -10.82 | - |

| | | | |
|---|---|---|---|
| $\mu$ | 11 runs | $\mu$ | 9 runs |
| + | 5 | + | 4 |
| - | 6 | - | 5 |
| $\mu$ bar | 5.454545 | $\mu$ bar | 4.444444 |
| $\sigma^2$ | 2.429752 | $\sigma^2$ | 1.91358 |
| z | 3.557592 | z | 3.293199 |
| $\alpha = 0.05$ | | $\alpha = 0.05$ | |
| critical region is 1.96, -1.96 | | critical region is 1.96, -1.96 | |
| Critical value exceeded | | Critical value exceeded | |
| Non-random | | Non-random | |

**Runs Test**

| | N $\delta^{18}O$ | | S $\delta^{18}O$ | |
|---|---|---|---|---|
| 30-Jan | -9.56 | | -11.81 | |
| 13-Feb | -9.53 | | -13.92 | |
| 27-Feb | -9.50 | + | -15.25 | - |
| 13-Mar | -9.56 | | -12.75 | |
| 27-Mar | -9.64 | - | -12.52 | |
| 10-Apr | -9.59 | | -12.40 | |
| 24-Apr | -9.58 | | -12.25 | + |
| 8-May | -7.14 | + | -12.48 | - |
| 22-May | -9.45 | - | | |
| 5-Jun | -1.66 | + | | |
| 19-Jun | -4.43 | | | |
| 3-Jul | -4.63 | | | |
| 17-Jul | -6.49 | | | |
| 31-Jul | -7.04 | | | |
| 14-Aug | -7.10 | | | |
| 28-Aug | -7.49 | - | | |

| | | | |
|---|---|---|---|
| $\mu$ | 6 runs | $\mu$ | 3 runs |
| + | 3 | + | 1 |
| - | 3 | - | 2 |
| $\mu$ bar | 3 | $\mu$ bar | 1.333333 |
| $\sigma^2$ | 1.2 | $\sigma^2$ | 0.222222 |
| z | 2.738613 | z | 3.535534 |

$\alpha$ = 0.05
critical region is 1.96, -1.96

Critical value exceeded
Non-random

$\alpha$ = 0.05
critical region is 1.96, -1.96

Critical value exceeded
Non-random

**Runs Test**

| | C $\delta^{18}O$ | | R2 $\delta^{18}O$ | | R2 $\delta^{18}O$ | |
|---|---|---|---|---|---|---|
| 30-Jan | -10.21 | | -6.50 | | -7.51 | |
| 13-Feb | -9.97 | + | -8.63 | | -7.60 | |
| 27-Feb | -10.32 | | -11.00 | - | -10.98 | - |
| 13-Mar | -10.58 | - | -10.08 | | -8.35 | |
| 27-Mar | -10.10 | + | -7.44 | | -4.75 | |
| 10-Apr | -10.51 | | -3.59 | + | -1.11 | + |
| 24-Apr | -10.86 | - | -5.13 | | -2.17 | |
| 8-May | -10.85 | | -9.33 | - | -3.93 | - |
| 22-May | -10.57 | + | | | | |
| 5-Jun | -10.64 | | | | | |
| 19-Jun | -10.67 | | | | | |
| 3-Jul | -10.93 | | | | | |
| 17-Jul | -11.18 | | | | | |
| 31-Jul | -11.46 | - | | | | |
| 14-Aug | -11.29 | + | | | | |
| 28-Aug | -11.65 | - | | | | |

| | | | | | |
|---|---|---|---|---|---|
| $\mu$ | 8 runs | $\mu$ | 3 runs | $\mu$ | 3runs |
| + | 4 | + | 1 | + | 1 |
| - | 4 | - | 2 | - | 2 |
| $\mu$ bar | 4 | $\mu$ bar | 1.333333 | $\mu$ bar | 1.333333 |
| $\sigma^2$ | 1.714 | $\sigma^2$ | 0.222222 | $\sigma^2$ | 0.222222 |
| z | 3.055 | z | 18.38478 | z | 18.38478 |
| $\alpha = 0.05$ | | $\alpha = 0.05$ | | $\alpha = 0.05$ | |
| critical region is 1.96, -1.96 | | critical region is 1.96, -1.96 | | critical region is 1.96, -1.96 | |
| Critical value exceeded | | Critical value exceeded | | Critical value exceeded | |
| Non-random | | Non-random | | Non-random | |

**Correlation between creek elevation and isotopic depletion**

| | Creek Elevation | VSMOW Creek $\delta^{2}H$ | $\delta^{18}O$ |
|---|---|---|---|
| 2/6/2011 | 188.45 | -68.8 | -10.21 |
| 2/20/2011 | 188.3 | -65.4 | -9.97 |
| 3/6/2011 | 189.05 | -68.6 | -10.32 |
| 3/20/2011 | 189.3 | -70.2 | -10.58 |
| 4/3/2011 | 188.2 | -67.6 | -10.10 |
| 4/17/2011 | 187.3 | -69.2 | -10.51 |
| 5/1/2011 | 186.9 | -70.2 | -10.86 |
| 5/15/2011 | 187.3 | -70.4 | -10.85 |
| 5/29/2011 | 186.2 | -69.5 | -10.57 |
| 6/12/2011 | 186.45 | -72.1 | -10.64 |
| 6/26/2011 | 186.15 | -70.9 | -10.67 |
| 7/10/2011 | 186 | -71.8 | -10.93 |
| 7/24/2011 | 185.75 | -72.8 | -11.18 |
| 8/7/2011 | 185.7 | -73.8 | -11.46 |
| 8/21/2011 | 185.65 | -72.8 | -11.29 |
| | | -73.9 | -11.65 |

| Cross correlation $^{2}H$ | | Positive lag | Negative lag | Cross correlation $^{18}O$ | | Positive lag | Negative lag |
|---|---|---|---|---|---|---|---|
| 0.739825 | | 0 | | 0.768681 | | 0 | |
| 0.791397 | 0.8369822 | 1 | -1 | 0.766068 | 0.834658 | 1 | -1 |
| 0.810915 | 0.8361243 | 2 | -2 | 0.81522 | 0.79205 | 2 | -2 |
| 0.714368 | 0.7871189 | 3 | -3 | 0.779112 | 0.641218 | 3 | -3 |
| 0.517273 | 0.7766187 | 4 | -4 | 0.584879 | 0.609819 | 4 | -4 |
| 0.647841 | 0.8341739 | 5 | -5 | 0.741265 | 0.77878 | 5 | -5 |
| 0.730577 | 0.6761835 | 6 | -6 | 0.778919 | 0.843679 | 6 | -6 |
| 0.255325 | 0.6749874 | 7 | -7 | 0.550222 | 0.910683 | 7 | -7 |
| 0.627959 | 0.6066708 | 8 | -8 | 0.661733 | 0.700806 | 8 | -8 |
| 0.307486 | 0.1701868 | 9 | -9 | 0.483893 | 0.239159 | 9 | -9 |
| 0.305164 | -0.634837 | 10 | -10 | 0.401667 | -<br>0.539541 | 10 | -10 |
| 0.084208 | -0.518953 | 11 | -11 | 0.408865 | -<br>0.681476 | 11 | -11 |
| -0.05375 | 0.6484457 | 12 | -12 | 0.303405 | 0.312404 | 12 | -12 |
| -1 | -1 | 13 | -13 | -1 | -1 | 13 | -13 |

**Cross correlation between natural spring and Big Chico Creek**

| VSMOW Spring | | VSMOW Creek | | | | |
|---|---|---|---|---|---|---|
| $\delta^{2}$H | | $\delta^{2}$H | Cross correlation $^{2}$H | | Positive lag | Negative lag |
| -63.9 | 30-Jan | -68.8 | -0.66185 | | 0 | |
| -62.7 | 13-Feb | -65.4 | -0.45521 | -0.57627 | 1 | -1 |
| -61.7 | 27-Feb | -68.6 | -0.50597 | -0.75676 | 2 | -2 |
| -61.8 | 13-Mar | -70.2 | -0.45308 | -0.73532 | 3 | -3 |
| -62.2 | 27-Mar | -67.6 | -0.46061 | -0.71382 | 4 | -4 |
| -61.9 | 10-Apr | -69.2 | -0.10124 | -0.47588 | 5 | -5 |
| -61.7 | 24-Apr | -70.2 | -0.30737 | -0.71726 | 6 | -6 |
| -55.6 | 8-May | -70.4 | -0.26932 | -0.48188 | 7 | -7 |
| -60.6 | 22-May | -69.5 | 0.545586 | -0.65808 | 8 | -8 |
| -34.7 | 5-Jun | -72.1 | 0.138474 | -0.30749 | 9 | -9 |
| -44.4 | 19-Jun | -70.9 | 0.555939 | -0.91796 | 10 | -10 |
| -43.4 | 3-Jul | -71.8 | 0.090814 | -0.90258 | 11 | -11 |
| -50.1 | 17-Jul | -72.8 | -0.34867 | -0.04116 | 12 | -12 |
| -52.2 | 31-Jul | -73.8 | -1 | 1 | 13 | -13 |
| -52.8 | 14-Aug | -72.8 | | | | |
| -54.0 | 28-Aug | -73.9 | | | | |

| VSMOW Spring | | VSMOW Creek | | | | |
|---|---|---|---|---|---|---|
| $\delta^{18}$O | | $\delta^{18}$O | Cross correlation $^{2}$H | | Positive lag | Negative lag |
| -9.56 | 30-Jan | -10.21 | -0.42417 | | 0 | |
| -9.53 | 13-Feb | -9.97 | -0.34428 | -0.45963 | 1 | -1 |
| -9.50 | 27-Feb | -10.32 | -0.48484 | -0.65523 | 2 | -2 |
| -9.56 | 13-Mar | -10.58 | -0.62653 | -0.73152 | 3 | -3 |
| -9.64 | 27-Mar | -10.10 | -0.7042 | -0.74104 | 4 | -4 |
| -9.59 | 10-Apr | -10.51 | -0.13667 | -0.52721 | 5 | -5 |
| -9.58 | 24-Apr | -10.86 | -0.18435 | -0.65238 | 6 | -6 |
| -7.14 | 8-May | -10.85 | -0.03661 | -0.3921 | 7 | -7 |
| -9.45 | 22-May | -10.57 | 0.33126 | 0.713703 | 8 | -8 |
| -1.66 | 5-Jun | -10.64 | 0.382621 | 0.739706 | 9 | -9 |
| -4.43 | 19-Jun | -10.67 | 0.535622 | 0.255905 | 10 | -10 |
| -4.63 | 3-Jul | -10.93 | 0.374111 | -0.70309 | 11 | -11 |
| -6.49 | 17-Jul | -11.18 | -0.12055 | -0.37957 | 12 | -12 |
| -7.04 | 31-Jul | -11.46 | -1 | 1 | 13 | -13 |
| -7.10 | 14-Aug | -11.29 | | | | |
| -7.49 | 28-Aug | -11.65 | | | | |

**Cross correlation between BCCER Well and Big Chico Creek**

| Well BCCER VSMOW $\delta^2H$ | | VSMOW Creek $\delta^2H$ | Cross correlation $^2H$ | | Positive lag | Negative lag |
|---|---|---|---|---|---|---|
| -62.6 | 30-Jan | -68.8 | -0.41678 | | 0 | |
| -63.1 | 13-Feb | -65.4 | -0.37136 | -0.39513 | 1 | -1 |
| -63.9 | 27-Feb | -68.6 | -0.55195 | -0.60773 | 2 | -2 |
| -61.8 | 13-Mar | -70.2 | -0.1654 | -0.47116 | 3 | -3 |
| -63.3 | 27-Mar | -67.6 | -0.09272 | -0.65503 | 4 | -4 |
| -60.3 | 10-Apr | -69.2 | -0.48396 | -0.46281 | 5 | -5 |
| -62.4 | 24-Apr | -70.2 | -0.02756 | -0.71064 | 6 | -6 |
| -61.4 | 8-May | -70.4 | 0.334424 | -0.35246 | 7 | -7 |
| -60.1 | 22-May | -69.5 | -0.64619 | -0.49456 | 8 | -8 |
| -61.8 | 5-Jun | -72.1 | -0.12102 | -0.31044 | 9 | -9 |
| -61.7 | 19-Jun | -70.9 | 0.912606 | -0.16419 | 10 | -10 |
| -55.2 | 3-Jul | -71.8 | -0.55234 | 0.585425 | 11 | -11 |
| -62.5 | 17-Jul | -72.8 | -0.28639 | -0.09603 | 12 | -12 |
| -61.8 | 31-Jul | -73.8 | 1 | -1 | 13 | -13 |
| -58.9 | 14-Aug | -72.8 | | | | |
| -61.5 | 28-Aug | -73.9 | | | | |

| Well BCCER VSMOW $\delta^{18}O$ | | VSMOW Creek $\delta^{18}O$ | Cross correlation $^2H$ | | Positive lag | Negative lag |
|---|---|---|---|---|---|---|
| -9.66 | 30-Jan | -10.21 | -0.35942 | | 0 | |
| -9.72 | 13-Feb | -9.97 | -0.2417 | -0.37519 | 1 | -1 |
| -9.80 | 27-Feb | -10.32 | -0.24444 | -0.60446 | 2 | -2 |
| -9.55 | 13-Mar | -10.58 | -0.13439 | -0.43063 | 3 | -3 |
| -9.69 | 27-Mar | -10.10 | -0.44613 | -0.11124 | 4 | -4 |
| -9.34 | 10-Apr | -10.51 | -0.52857 | -0.05911 | 5 | -5 |
| -9.63 | 24-Apr | -10.86 | -0.07318 | -0.56662 | 6 | -6 |
| -9.40 | 8-May | -10.85 | 0.249091 | -0.58644 | 7 | -7 |
| -9.57 | 22-May | -10.57 | -0.55311 | -0.70823 | 8 | -8 |
| -9.70 | 5-Jun | -10.64 | -0.20963 | -0.43885 | 9 | -9 |
| -9.53 | 19-Jun | -10.67 | 0.755112 | -0.30364 | 10 | -10 |
| -7.56 | 3-Jul | -10.93 | -0.08355 | 0.344688 | 11 | -11 |
| -9.56 | 17-Jul | -11.18 | -0.71043 | 0.262262 | 12 | -12 |
| -9.53 | 31-Jul | -11.46 | 1 | -1 | 13 | -13 |
| -8.99 | 14-Aug | -11.29 | | | | |
| -9.44 | 28-Aug | -11.65 | | | | |

**Cross correlation between Well adjacent to BCC and Big Chico Creek**

Well Big Chico Creek

| VSMOW $\delta^{18}O$ | | VSMOW Creek $\delta^{18}O$ |
|---|---|---|
| -9.93 | 30-Jan | -10.21 |
| -10.27 | 13-Feb | -9.97 |
| -10.49 | 27-Feb | -10.32 |
| -10.49 | 13-Mar | -10.58 |
| -10.28 | 27-Mar | -10.10 |
| -8.73 | 10-Apr | -10.51 |
| -9.04 | 24-Apr | -10.86 |
| -9.20 | 8-May | -10.85 |
| -7.54 | 22-May | -10.57 |
| -10.35 | 5-Jun | -10.64 |
| -10.56 | 19-Jun | -10.67 |
| -10.46 | 3-Jul | -10.93 |
| -10.66 | 17-Jul | -11.18 |
| -11.02 | 31-Jul | -11.46 |
| -10.80 | 14-Aug | -11.29 |
| -10.82 | 28-Aug | -11.65 |

| Cross correlation $^{2}H$ | | Positive lag | Negative lag |
|---|---|---|---|
| 0.233224 | | 0 | |
| 0.170625 | 0.168837 | 1 | -1 |
| 0.064995 | 0.214177 | 2 | -2 |
| 0.319857 | 0.172882 | 3 | -3 |
| 0.731085 | -0.04431 | 4 | -4 |
| 0.385646 | -0.51799 | 5 | -5 |
| 0.552492 | -0.77379 | 6 | -6 |
| 0.753935 | -0.88623 | 7 | -7 |
| 0.311554 | -0.72947 | 8 | -8 |
| 0.038206 | -0.22343 | 9 | -9 |
| 0.784815 | 0.858423 | 10 | -10 |
| 0.418541 | 0.942508 | 11 | -11 |
| -0.75265 | 0.503386 | 12 | -12 |
| 1 | -1 | 13 | -13 |

Well Big Chico Creek

| VSMOW $\delta^{2}H$ | | VSMOW Creek $\delta^{2}H$ |
|---|---|---|
| -64.3 | 30-Jan | -68.8 |
| -66.8 | 13-Feb | -65.4 |
| -69.5 | 27-Feb | -68.6 |
| -68.9 | 13-Mar | -70.2 |
| -69.8 | 27-Mar | -67.6 |
| -60.4 | 10-Apr | -69.2 |
| -64.0 | 24-Apr | -70.2 |
| -64.8 | 8-May | -70.4 |
| -53.5 | 22-May | -69.5 |
| -72.3 | 5-Jun | -72.1 |
| -70.7 | 19-Jun | -70.9 |
| -69.6 | 3-Jul | -71.8 |
| -72.2 | 17-Jul | -72.8 |
| -72.0 | 31-Jul | -73.8 |
| -72.6 | 14-Aug | -72.8 |
| -72.2 | 28-Aug | -73.9 |

| Cross correlation $^{2}H$ | | Positive lag | Negative lag |
|---|---|---|---|
| 0.433482 | | 0 | |
| 0.330868 | 0.185877 | 1 | -1 |
| 0.190539 | 0.237239 | 2 | -2 |
| 0.331257 | 0.143039 | 3 | -3 |
| 0.693678 | -0.09705 | 4 | -4 |
| 0.188082 | -0.31531 | 5 | -5 |
| 0.412787 | -0.49242 | 6 | -6 |
| 0.840155 | -0.36858 | 7 | -7 |
| -0.11707 | -0.28826 | 8 | -8 |
| 0.44176 | 0.072689 | 9 | -9 |
| 0.599006 | 0.882181 | 10 | -10 |
| -0.08785 | 0.909552 | 11 | -11 |
| 0.778124 | -0.00326 | 12 | -12 |
| -1 | -1 | 13 | -13 |

**Cross correlation between snowmelt and Big Chico Creek**

| Snow VSMOW δ$^{2}$H | | VSMOW Creek δ$^{2}$H | Cross correlation $^{2}$H | | Positive lag | Negative lag |
|---|---|---|---|---|---|---|
| -78.4 | 30-Jan | -68.8 | -0.71258 | | 0 | |
| -96.6 | 13-Feb | -65.4 | -0.55574 | 0.19301 | 1 | -1 |
| -95.1 | 27-Feb | -68.6 | 0.161542 | -0.27151 | 2 | -2 |
| -77.1 | 13-Mar | -70.2 | -0.81933 | -0.90399 | 3 | -3 |
| -78.4 | 27-Mar | -67.6 | 0.301346 | 0.24991 | 4 | -4 |
| -77.2 | 10-Apr | -69.2 | -0.51449 | 0.981295 | 5 | -5 |
| -77.4 | 24-Apr | -70.2 | -1 | 1 | 6 | -6 |
| -77.4 | 8-May | -70.4 | | | | |

| VSMOW Snow δ$^{18}$O | | VSMOW Creek δ$^{18}$O | Cross correlation $^{2}$H | | Positive lag | Negative lag |
|---|---|---|---|---|---|---|
| -11.81 | 30-Jan | -10.21 | -0.33913 | | 0 | |
| -13.92 | 13-Feb | -9.97 | -0.65053 | 0.106584 | 1 | -1 |
| -15.25 | 27-Feb | -10.32 | -0.19181 | -0.54278 | 2 | -2 |
| -12.75 | 13-Mar | -10.58 | -0.61237 | -0.48135 | 3 | -3 |
| -12.52 | 27-Mar | -10.10 | 0.106606 | 0.670975 | 4 | -4 |
| -12.40 | 10-Apr | -10.51 | 0.999429 | 0.906074 | 5 | -5 |
| -12.25 | 24-Apr | -10.86 | -1 | -1 | 6 | -6 |
| -12.48 | 8-May | -10.85 | | | | |

**Cross correlation between rain collected at BCCER and Big Chico Creek**

| Rain BCCER VSMOW δ$^{2}$H | | VSMOW Creek δ$^{2}$H | Cross correlation $^{2}$H | | Positive lag | Negative lag |
|---|---|---|---|---|---|---|
| -40.1 | 30-Jan | -68.8 | 0.184521 | | 0 | |
| -42.1 | 13-Feb | -65.4 | -0.16478 | -0.07002 | 1 | -1 |
| -68.0 | 27-Feb | -68.6 | -0.31206 | -0.6595 | 2 | -2 |
| -63.6 | 13-Mar | -70.2 | -0.38935 | 0.185315 | 3 | -3 |
| -50.1 | 27-Mar | -67.6 | 0.794225 | 0.879773 | 4 | -4 |
| -30.2 | 10-Apr | -69.2 | 0.416096 | 0.649608 | 5 | -5 |
| -31.8 | 24-Apr | -70.2 | -1 | 1 | 6 | -6 |
| -64.7 | 8-May | -70.4 | | | | |

| Rain BCCER VSMOW δ$^{18}$O | | VSMOW Creek δ$^{18}$O | Cross correlation $^{2}$H | | Positive lag | Negative lag |
|---|---|---|---|---|---|---|
| -6.50 | 30-Jan | -10.21 | -0.14083 | | 0 | |
| -8.63 | 13-Feb | -9.97 | -0.01285 | -0.48632 | 1 | -1 |
| -11.00 | 27-Feb | -10.32 | -0.40252 | -0.64681 | 2 | -2 |
| -10.08 | 13-Mar | -10.58 | -0.56523 | -0.03704 | 3 | -3 |
| -7.44 | 27-Mar | -10.10 | 0.847809 | 0.985089 | 4 | -4 |
| -3.59 | 10-Apr | -10.51 | 0.539218 | 0.826287 | 5 | -5 |
| -5.13 | 24-Apr | -10.86 | -1 | -1 | 6 | -6 |
| -9.33 | 8-May | -10.85 | | | | |

**Cross correlation between rain collected in valley and Big Chico Creek**

| Rain Valley VSMOW $\delta^2H$ | | VSMOW Creek $\delta^2H$ | Cross correlation $^2H$ | | Positive lag | Negative lag |
|---|---|---|---|---|---|---|
| -43.2 | 30-Jan | -68.8 | -0.06743 | | 0 | |
| -43.7 | 13-Feb | -65.4 | -0.39871 | -0.24734 | 1 | -1 |
| -68.0 | 27-Feb | -68.6 | -0.43097 | -0.77016 | 2 | -2 |
| -60.0 | 13-Mar | -70.2 | -0.29706 | 0.003231 | 3 | -3 |
| -41.3 | 27-Mar | -67.6 | 0.821081 | 0.829637 | 4 | -4 |
| -20.7 | 10-Apr | -69.2 | 0.310641 | 0.612547 | 5 | -5 |
| -24.6 | 24-Apr | -70.2 | -1 | 1 | 6 | -6 |
| -44.6 | 8-May | -70.4 | | | | |

| Rain Valley VSMOW $\delta^{18}O$ | | VSMOW Creek $\delta^{18}O$ | Cross correlation $^2H$ | | Positive lag | Negative lag |
|---|---|---|---|---|---|---|
| -7.51 | 30-Jan | -10.21 | -0.47945 | | 0 | |
| -7.60 | 13-Feb | -9.97 | -0.43586 | -0.64175 | 1 | -1 |
| -10.98 | 27-Feb | -10.32 | -0.5336 | -0.87586 | 2 | -2 |
| -8.35 | 13-Mar | -10.58 | -0.45205 | -0.28853 | 3 | -3 |
| -4.75 | 27-Mar | -10.10 | 0.56777 | 0.688529 | 4 | -4 |
| -1.11 | 10-Apr | -10.51 | 0.434781 | 0.480552 | 5 | -5 |
| -2.17 | 24-Apr | -10.86 | -1 | -1 | 6 | -6 |
| -3.93 | 8-May | -10.85 | | | | |