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# An analysis of the relationship between snowpack and groundwater across Utah watersheds.

Samuel Wright
*University of Louisville*

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# AN ANALYSIS OF THE RELATIONSHIP BETWEEN SNOWPACK AND GROUNDWATER ACROSS UTAH WATERSHEDS

By

Sam Wright

B.A., Centre College, 2013

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A Thesis Approved On

April 21, 2017

By the following Thesis Committee:

____________________________________

C. Andrew Day

____________________________________

Keith Mountain

____________________________________

Mark French

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# ABSTRACT

# AN ANALYSIS OF THE RELATIONSHIP BETWEEN SNOWPACK AND GROUNDWATER ACROSS UTAH WATERSHEDS

Sam Wright

April 21, 2017

This thesis examined what type of relationship existed between snow water equivalence (SWE) volume and groundwater elevation within six sub-watersheds in Utah. Data was gathered on SWE from seventeen SNOTEL sites and groundwater elevation data was gathered from six continuously monitored groundwater wells. This data was gathered for January through May for 2011, 2013, and 2014 in order to represent the water conditions that were above average, below average, and average respectively. Using MLR formulas the total SWE for each sub-watershed was determined for each year/month. Afterwards a correlation analysis was performed to determine if any association existed between SWE volume and groundwater elevation. It was determined that there were strong negative correlations between SWE volume and groundwater elevation in April and May and that a decrease in SWE volume across one month would result in an increase of groundwater elevation for the subsequent month

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# 1.0 INTRODUCTION

Access to drinkable water has been a concern for arid areas located in the western U. S. since these areas were first settled. Although there are several large surface freshwater sources across this region, the Colorado River serves as a prime example, many communities in the western U. S. have come to rely on groundwater as their primary source for water (Maupin et al. 2014). This heavy reliance on groundwater means that understanding how groundwater sources are replenished is a top priority.

A major factor that researchers have studied in the past concerning groundwater recharge and availability has been the volume of snow melt that an area receives (Hood and Hayashi. 2014). Previous studies have investigated how water produced from melting snow replenished water resources in local watersheds (Safeeq et al. 2013; Hood and Hayashi. 2014), but there has been little research into the relationship between groundwater levels and the volume of snow melt

This thesis research will investigate the exact nature of the relationship between the volume of snowmelt and groundwater elevation within six sub-watersheds located in Utah, a low population state that receives the majority of its precipitation in the form of snowfall during the winter months. I hypothesize that a decrease in snow water equivalence across one month will correlate with an increase in groundwater elevation for the subsequent month as a result of the meltwater entering the aquifer systems of these watersheds

# 2.0 LITERATURE REVIEW

## 2.1 Snowpack Measurement

Snowpack depth as well as other attributes of snowpack such as snow water equivalent (SWE) and total snow cover have been measured in the past by the Natural Resource Conservation Service (NRCS). Multiple factors play a part in determining the state of snowpack including changing temperature and average annual precipitation which can greatly alter how much snowpack is present (Luce, et al. 2014). Understanding the changes to the state of snowpack over any period of time can help us understand subsequent impacts on the surrounding environment, including hydrology. Multiple methods have been developed in order to try and predict snowpack development as the need for accurate measurement has grown due to the western US receiving 50-70% of annual precipitation as snowfall making the region reliant on snowpack as a water source (Harshburger et al. 2010).

Remote sensing driven methods have arisen primarily to study snowpack depth, temperature and snow cover with some measure of success (Sokol, et al. 2003). Studying the temperature of a snowpack, in particular, is crucial to understanding the potential effects of climate change and variability on any future amount of SWE availability (Sokol, et al. 2003). An example of this involves the application of airborne sensors to create digital elevation models (DEMs) of the study area during periods of snow cover versus no snow cover and creating a difference digital elevation model (dDEM) by subtracting the DEM representing the snow cover from the DEM representing the area during the period of no snow cover (Nolan, et al. 2015). This imagery may then be compared to the SWE or snowpack depth data gathered terrestrially to study spatial changes in these key snowpack variables. Other techniques are currently under development, including measuring the reflectance of microwaves from the surface of snowpack’s to estimate key snowpack characteristics over larger areas (Sokol, et al. 2003). The SWE can also been determined from remote sensing methods, although typically at poor surface resolutions (Harshburger et al. 2010).

Modeling snowpack variables is a common practice that involves gathering data from terrestrial sites including the SNOTEL (Snow Telemetry) network and meteorological stations to create predictive models that show the likely current and future state of snowpack area (Avanzi et al. 2014). Modeling the possible changes of snowpack can highlight the significance and impact of temperature change, snow accumulation and melt over time. However, these methods require continuous data from numerous and reliable sites within the study area (McCreight and Small 2014). A further problem with the use of models is the large number currently available and the different parameters that are required for calibration. For example, two modeling systems may measure the same variable but use different parameters in producing their results (McCreight and Small 2014). One way that this can be accounted for is by using multiple methods to model the results in order to gain a range of outputs that may then be compared.

Two models, known as the Jonas and Sturm density models, have been used in this fashion to compare SNOTEL data regarding snow pack depth and SWE. Researchers were able to use these models to find correlations between the two variables, whilst comparing model error and at the same time create a new model in order to try and construct a more effective model for estimating SWE and snowpack density. The models for this particular study worked by collecting data on snow pack depth (depth level, date, time, and place) for a predetermined period of time. After collecting this data for two observed years (2011 and 2012) the resultant graphs according to depth level and time were used to predict snow pack density and a third model was created to account for errors present in the Sturm and Jonas models. Crucially, the Sturm model was developed for North America and applied separately for different snow classes (alpine, maritime, taiga, etc.) while the Jonas model was developed for different geographic regions of Switzerland which did not take into account the day or month of the year.

When using the Sturm model, it was discovered that the estimated snow pack density was 50% greater than what was later observed. When using the Jonas model, it was found that the estimated SWE was 50% greater than what was later observed (McCreight and Small 2014). Also, modeled snow pack density decreased over time each month, but the observed snow pack density would increase. These errors in estimated snow pack density would also cause errors in estimated SWE to occur. These errors and how they differ from model to model were found to result from two different sources: how the estimated snow pack density was calculated and the scale of the time period studied.

For the scale of time studied there are significant differences on a seasonal and monthly basis. When observed seasonally, each model performs well in 2011 and roughly matches the observed snow pack density. In 2012, the Sturm model begins to overestimate the density of the snow pack and when the time scale is reduced to a monthly observational period the Jonas model begins to underestimate the density of the snow pack. These over and under estimations in snow pack density would then cause a similar error to occur in the prediction of SWE volume making it significantly greater or less than the observed amount (McCreight and Small 2014).

The method of calculating the snow pack density for each method differs in what density is a function of (shares a mathematical relationship with), however each uses similar variables such as air temperature and total winter precipitation. For the Jonas model density is a function of depth, for the Sturm model density is a function of both depth and day of the year (McCreight and Small 2014). This resulted in the Sturm model being the least accurate of the models studied as its equation depended heavily on the day of the year.

To compensate for the errors found in these two models a third model was developed using the Jonas model as a starting point as it proved more accurate than the Sturm model. This model used three different predictive variables in its equation: the average of the snow depth time series, the positive values of the snow depth time series, and the negative values of the snow depth time series (McCreight and Small 2014). These variables were chosen in order to correct the problem of correlation between snow depth and density over different timescales. Using the new model, it was discovered that the modeled SWE was only 20% higher than what was later observed. Although this new model proved more accurate than the Jonas and Sturm models, this increased accuracy was observed at the daily timescale (McCreight and Small 2014.). This shows that no one model will be completely without error.

SNOTEL stations have provided the primary source of snowpack data for numerous studies across the US due to the number of attributes observed on a continuous basis. These autonomous stations have been in operation since the 1960’s to record snowpack depth, precipitation, temperature, and SWE. The only real weakness of the SNOTEL network is that virtually all of them are located in the western United States, limiting any studies that wish to use this dataset to that specific region (Avanzi et al. 2014).

As SNOTEL sites are spaced out over large areas, interpolation of the data gathered by these sites is often performed using techniques such as IDW (Inverse Distance Weighting) to interpolate the SWE values of a region (Fassnacht, et al. 2003). Another way to interpolate SWE across an area is to use MLR (Multiple Linear Regression) equations to determine the effect of topographic surface variables on SWE distribution within a snowpack. In one study researchers gathered DEM files on the Big Wood river basin in south-central Idaho and determined the snow-covered points in the study area to determine the snowline elevation. A series of topographically related independent variables (based on elevation, slope, and aspect) were used in the resulting MLR equations to successfully interpolate SWE values above the snowline in order to determine how the SWE could affect the river basin (Harshburger et al. 2010).

## 2.2 Groundwater

Groundwater has been the primary source of water for many communities across the western US who lack reliable access to clean surface water resources. In 2010 alone the state of Utah withdrew 1030 million gallons of groundwater per day with the total water withdrawn from all freshwater sources equaling 4140 million gallons per day. This means that groundwater sources make up about 1/4th of the freshwater supply in Utah

(Maupin et al. 2014). Understanding how groundwater availability can change either due to human activity or fluctuations in the controlling environmental variables is important as this can greatly affect those living in these areas that experience such changes or fluctuations. The USGS duly operates a series of groundwater wells that measure the elevation of groundwater above sea level. However, the majority of these wells do not record groundwater elevation continuously on a daily to monthly basis making reliable groundwater observation in many areas impossible where there are no continuously monitored well sites.

The focus on hydroclimatic variables and their effect on groundwater arises from a variety of factors that can cause groundwater to fluctuate, including air temperature, precipitation and streamflow (Allen, et al. 2010). The most common way to measure for this involves analyzing the water levels at several wells within a study area in combination with these hydroclimatic variables (Dudley and Hodgkins 2013). Any significant changes in groundwater levels in any of the wells would then be compared to the hydroclimatic data gathered in order to test for any significant correlation. For these studies, anywhere from 5 to 100 wells can be used as multiple data points are needed to provide an accurate description of groundwater elevation as a function of seasonal climatic/usage changes (Allen et al. 2014)

Factors other than climatic variables can also have an effect on the state of groundwater and its sources. One factor is the aquifer geology, for example sandstone, limestone, gravel, etc., and how easily water can enter and flow within the aquifer system, a function of permeability and porosity (Allen, et al. 2010). Any surrounding geological features that have a low permeability and or porosity, such as shale, must also be taken into account as this can direct the flow of runoff away or towards the aquifer. Elevation can also affect how groundwater availability for a location. Higher elevations tend to experience higher levels of groundwater recharge either due to being the first area to receive precipitation or due to lower surface evapotranspiration rates at these locations (Smerdon et al. 2009).

## 2.3 Connections between snowmelt and groundwater recharge

One of the primary reasons groundwater is closely monitored is to better understand how it replaces water lost from human usage. Multiple factors have been studied including the effects that different components of the hydrological cycle have on snowpack such as precipitation. Also studied is the impact snowpack may have on any nearby groundwater reservoirs (Allen, et al. 2010). It is commonly believed that high amounts of snowfall will cause the groundwater elevation to subsequently rise following a melt event with the resulting runoff entering the adjacent groundwater aquifer.

Modeling has again been used to study the potential relationship between groundwater recharge and snowmelt. In one such case, researchers used an SDTI (Spatially Distributed Temperature Index) model in comparison to a GWLF (Generalized Watershed Loading Function) model to study how SWE and groundwater varies spatially across a watershed. These two models examined air temperature and snowfall respectively within six watersheds located in the Catskills mountain range that are major suppliers for water reservoirs used by New York City (Schneiderman et al. 2013). It was determined that a higher spatial variability of SWE occurs in the later snow season due to higher elevation snow persisting longer, usually into the spring. This resulted in more melt water being available in the spring within a particular watershed causing a predicted rise in groundwater.

Another example of models being used to study these two factors can be seen in a project performed at Yoho National Park in Canada. There, researchers gathered a variety of data (temperature, humidity, snow depth, precipitation, etc.) to create a model simulating snowmelt in order to predict snowmelt for an inaccessible area of the park (Hood and Hayashi 2014). This model showed that from April to late September as the amount of water entering the local aquifer kept rising the amount of SWE for the area's watershed would decrease. This suggests a correlation between SWE and groundwater

Snowmelt has been shown to have a significant effect on watershed hydrology during the late winter and early spring periods of the year (Safeeq et al. 2013). Snowmelt has also impacted groundwater levels suggesting that the same link between snowpack and streamflow also exists for groundwater (Allen, et al. 2010). The sensitivity of a watershed to the level of snowpack has been examined in many cases. Many watersheds, such as those in the Cordillera region of Canada, show significant sensitivity to changing snowpack levels at certain times of the year, in particular winter and spring before the onset of snowmelt recharge (Allen, et al. 2010). Temperature changes of only a few degrees can cause the accumulation of snowpack to drastically decrease and can greatly affect the recharge rates of regional groundwater aquifers (Rasouli et al. 2015).

In the western United States, significant evidence exists to suggest that there is a strong association between snowpack volume and the recharge rates of both surface and groundwater hydrology. Much of this evidence has come from higher elevation regions of this area such as the Rocky and Sierra Nevada mountains (Godsey, et al. 2014).

Studying how sensitive the recharge rate for groundwater levels from snowpacks is important as it provides the first indication of overall water availability for a groundwater region.

# 3.0 STUDY AREA

Utah, located in the western US, is partially within the Great Basin endorheic watershed and has a mostly arid climate with an annual normal precipitation of 17.6 inches for 1981-2010 (PRISM 2016) leading to a reliance on groundwater reserves for various uses (Table 1). There are multiple sub-watersheds within the Great Basin, six of which will be investigated for SWE and groundwater correlations: Corn Creek, Recapture Creek, Vega Creek-Montezuma Creek, Sugarville-Broad Canyon, Chicken Creek, and Coal Bed Canyon (Figures 1-6). SNOTEL sites and continuously monitored groundwater wells operated by the NRCS and USGS respectively are present within each of these watersheds and will serve as data sources. Another factor considered when choosing these watersheds was the level of groundwater withdrawal for the counties within these watersheds. Utah County has the highest groundwater withdrawal in the state at 164.47 million gallons per day (Table 1), this county is adjacent to Salt Lake County which contains the largest city in the state: Salt Lake City, meaning that the population of this county is likely higher than other more rural areas. Dagget County in Northeastern Utah has the lowest groundwater withdrawal in the state of Utah at .38 million gallons per day (Table 1). San Juan county, in which Recapture Creek, Vega Creek-Montezuma Creek, and Coal Bed Canyon are located has the fourth lowest groundwater withdrawal in the state of Utah with 23.22 million gallons per day, or .4% of the total daily use in the state (Table 1) meaning that human use will have little impact on the groundwater levels in that area.  The Corn Creek and Sugarville-Broad Canyon watersheds are located in Juab and Millard counties both of which have higher withdrawals of groundwater (1% and 8% of the total daily use respectively) (Table1) which means that the impact of human use will be greater on the groundwater levels in these areas.

A final factor to consider is the geology of the watersheds. Many of the SNOTEL sites are located on shale near the Coal Bed Canyon, Recapture Creek, and Vega Creek-Montezuma Creek watersheds, a mineral known to have low hydraulic conductivity, meaning that any meltwater will flow into the nearby valleys and recharge the local aquifers. The Chicken Creek, Corn Creek, and Sugarville-Broad Canyon watersheds all contain high amounts of alluvium which has a high hydraulic conductivity allowing easier groundwater flow (Figures1, 3, and 5).

Much of the geologies of the watersheds rely on the underlying aquifers. The Vega Creek-Montezuma Creek, Recapture Creek, and Coal Bed Canyon watersheds all lie over the Colorado Plateau aquifer which covers 11,000 km$^2$The principal means of discharge is human withdrawal, and is primarily recharged in the Rocky Mountains of Colorado by winter precipitation (Robson and Banta. 1995). The major source of recharge for the aquifer comes in the form of precipitation which occurs mostly in areas of high elevation which then travels to lower altitudes in the form of runoff. This occurs mostly in the Rocky Mountains of Colorado in the form of snow (Robson and Banta. 1995).

The Chicken Creek, Corn Creek, and Sugarville-Broad Canyon watersheds all lie over the Basin and Range aquifer system which covers 322,000 km$^2$. Unlike many aquifers, the principal means of discharge for the Basin and range aquifer is evapotranspiration and there are no major surface water sources where water is discharged (Robson and Banta. 1995). Recharge of the aquifer comes from the mountainous regions near the aquifer where runoff enters the aquifer system.

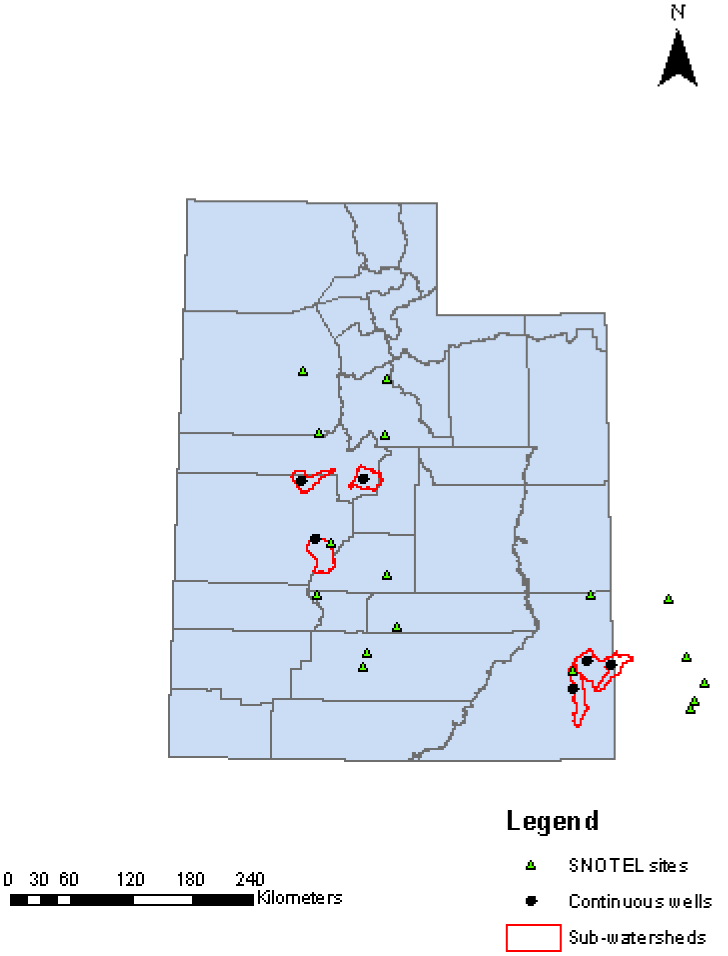


**Figure 1**

SNOTEL sites and Well sites

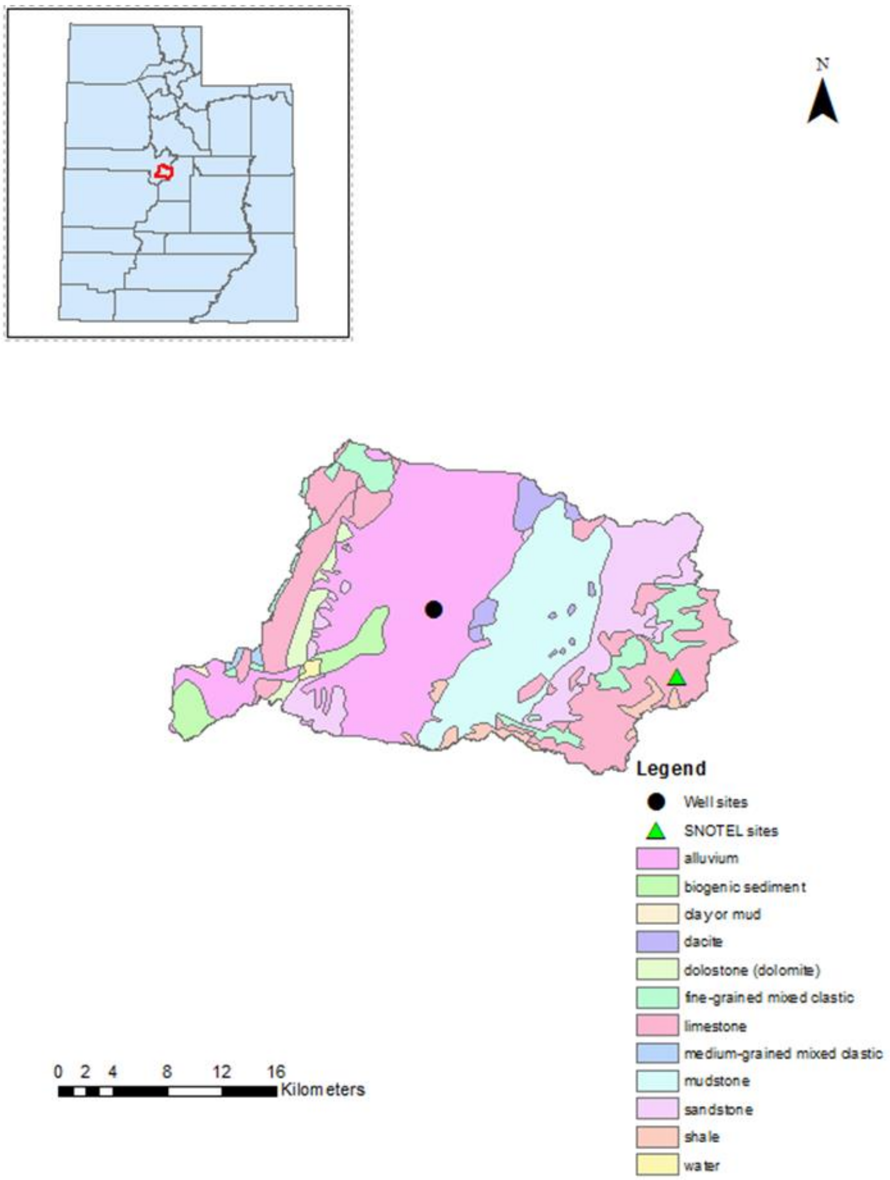


**Figure 2**

Geology of Chicken Creek Watershed

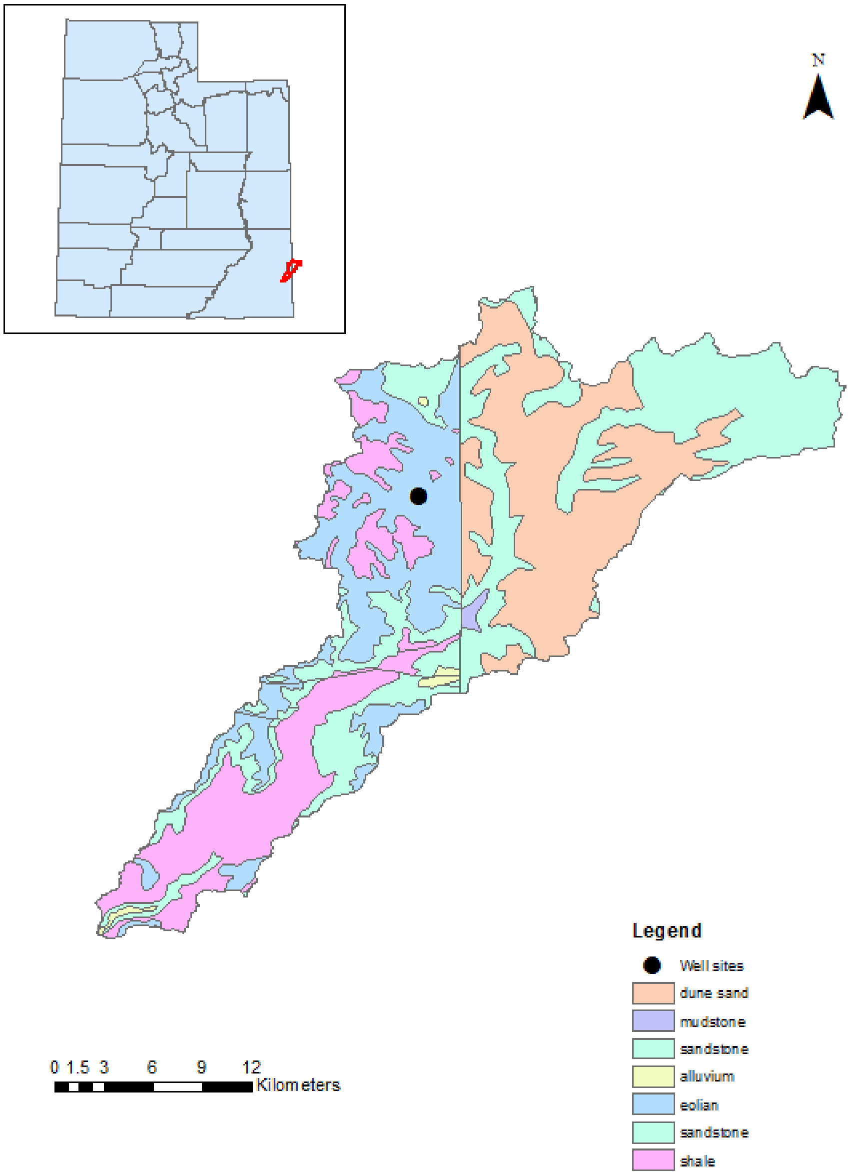


**Figure 3**

Geology of Coal Bed Canyon watershed

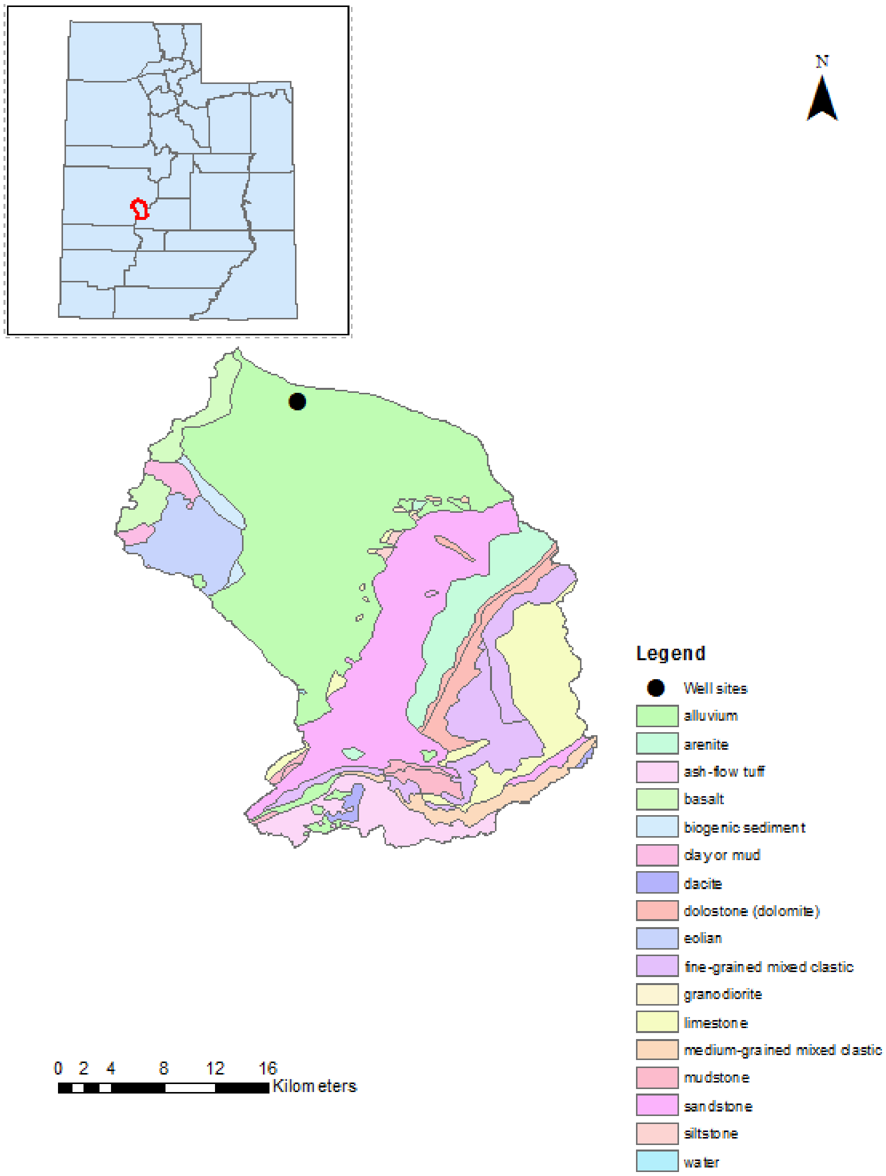


**Figure 4**

Geology of Corn Creek watershed

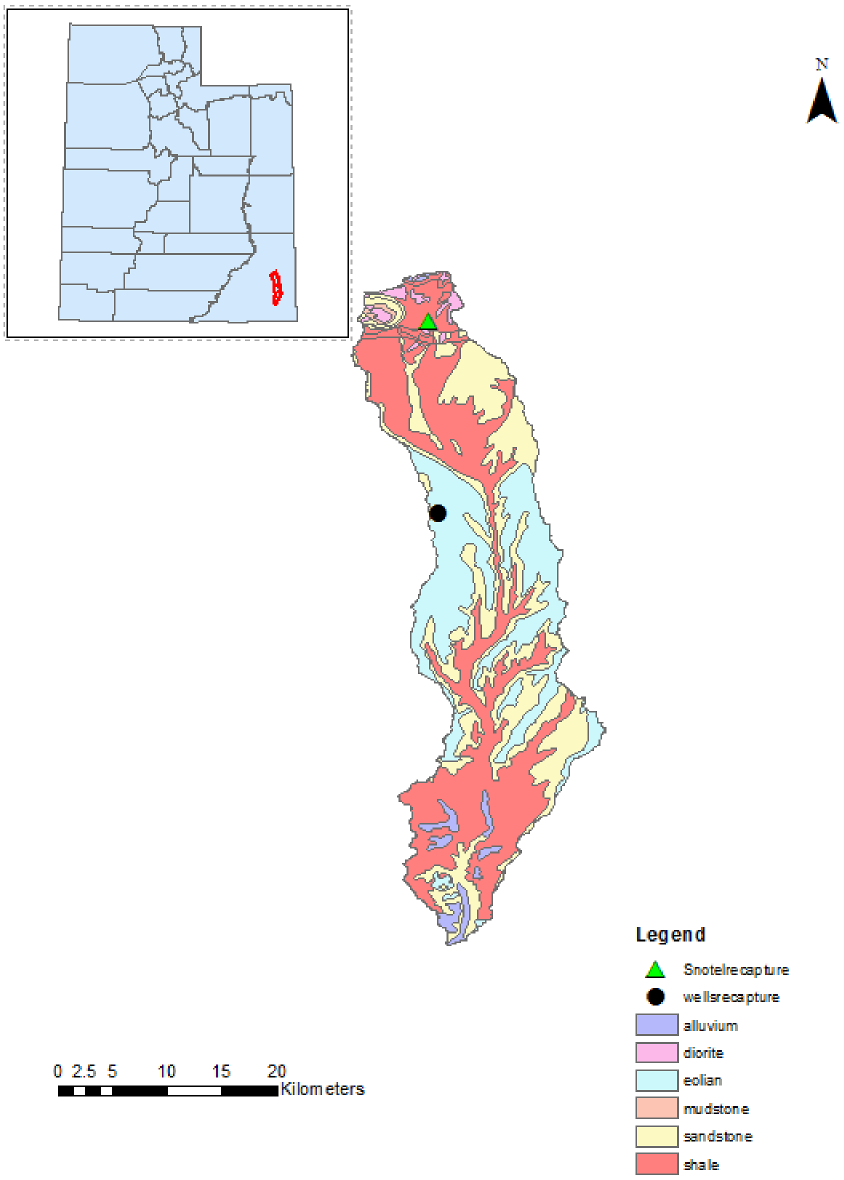


**Figure 5**

Geology of Recapture Creek Watershed

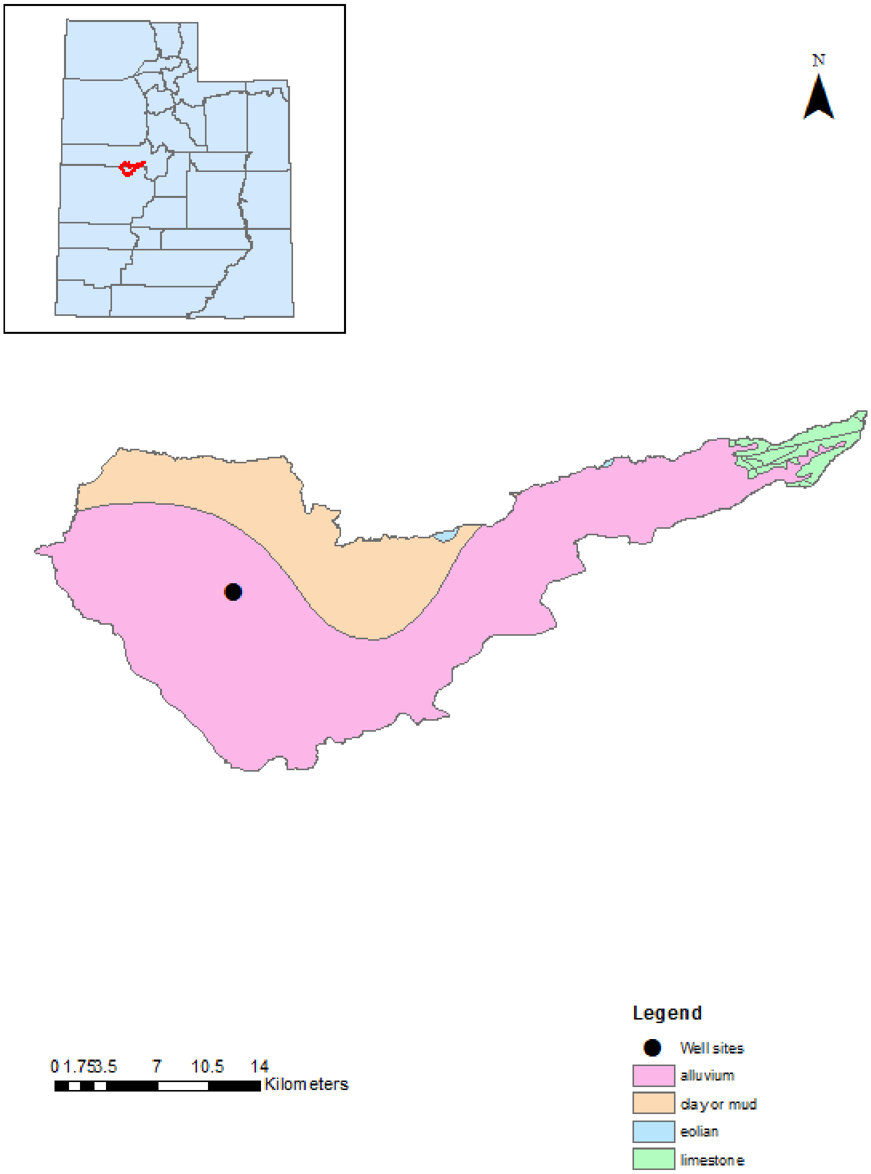


**Figure 6**

Geology of Sugarville-Broad Canyon watershed

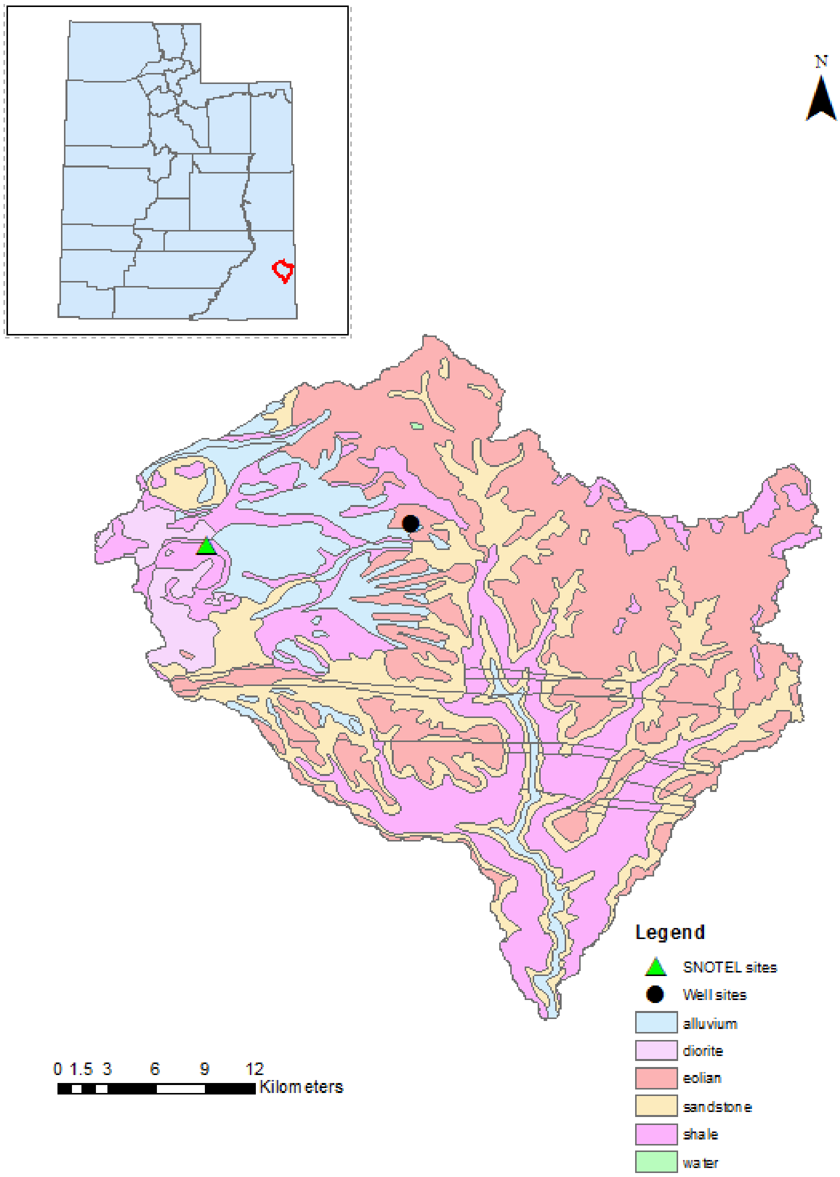


**Figure 7**

Geology of Vega Creek-Montezuma Creek watershed

Table 1.

Groundwater use in Utah by county, 2000. (millions of gallons per day (mgal/d))

(Utah water science center 2013)

| County | Public Supply | Industrial | Thermoelectric | Mining | Agriculture | Irrigation | Livestock | Total use |
|---|---|---|---|---|---|---|---|---|
| Total | 364.27 | 34.3 | 13.07 | 8.6 | 116.11 | 468.87 | 7.22 | 1012.44 |
| Utah | 86.11 | 13.63 | 0 | 0.31 | 12.56 | 50.77 | 1.09 | 164.47 |
| Iron | 9.37 | 1.56 | 0 | 0 | 0 | 123.69 | 0.1 | 134.72 |
| Salt Lake | 77.45 | 11.44 | 0 | 0.85 | 0.17 | 6.83 | 0.02 | 96.76 |
| Millard | 4.72 | 0 | 2.62 | 0.91 | 0 | 85.04 | 0.84 | 94.13 |
| Box Elder | 13.84 | 1.37 | 0 | 0 | 6.85 | 48.21 | 0.51 | 70.78 |
| Beaver | 2.16 | 1.82 | 0.16 | 0.01 | 1.94 | 48.21 | 0.99 | 55.29 |
| Cache | 32.65 | 1.21 | 0 | 0 | 7.23 | 9.73 | 0.57 | 51.39 |
| Uintah | 7.46 | 0 | 9.64 | 3.94 | 27.19 | 0.89 | 0.01 | 49.13 |
| Weber | 29.09 | 0 | 0 | 0.02 | 1.62 | 7.14 | 0.42 | 38.29 |
| Wayne | 0.56 | 0 | 0 | 0 | 32.15 | 3.12 | 0.08 | 35.91 |
| Davis | 24.2 | 1.45 | 0 | 0.29 | 0 | 9.46 | 0.07 | 35.47 |
| Toole | 7.15 | 1.21 | 0 | 0.02 | 0 | 22.92 | 0.13 | 31.43 |
| Juab | 5.67 | 0 | 0 | 0.18 | 0 | 25.33 | 0.13 | 31.31 |
| Washington | 21.92 | 0 | 0 | 0.14 | 0 | 6.92 | 0.01 | 28.99 |
| Sevier | 5.64 | 0 | 0 | 0.09 | 11.19 | 7.05 | 0.42 | 24.39 |
| Sanpete | 3.97 | 0.47 | 0 | 0 | 4.03 | 5.18 | 0.81 | 14.46 |
| Summit | 10.25 | 0.01 | 0 | 0 | 2.53 | 0.45 | 0.21 | 13.45 |
| Wasatch | 2.91 | 0 | 0 | 0 | 3.39 | 0.89 | 0.04 | 7.23 |
| Piute | 0.94 | 0 | 0 | 0 | 3.27 | 1.78 | 0.05 | 6.04 |
| Garfield | 1.56 | 0 | 0 | 0.01 | 1.89 | 0.89 | 0.03 | 4.38 |
| Carbon | 3.19 | 0.03 | 0.61 | 0.06 | 0 | 0.09 | 0.03 | 4.01 |
| Duchesne | 2.81 | 0.03 | 0 | 0.21 | 0 | 0.89 | 0.05 | 3.99 |
| Grand | 3.28 | 0 | 0 | 0 | 0 | 0.45 | 0 | 3.73 |
| Kane | 2.4 | 0 | 0 | 0 | 0.1 | 0.89 | 0.02 | 3.41 |
| Rich | 1.32 | 0 | 0 | 0 | 0 | 0.89 | 0.39 | 2.6 |
| San Juan | 0.92 | 0.07 | 0 | 0.63 | 0 | 0.89 | 0.03 | 2.54 |
| Emery | 1.03 | 0 | 0.04 | 0.86 | 0 | 0.09 | 0.01 | 2.03 |
| Morgan | 1.41 | 0 | 0 | 0.07 | 0 | 0.09 | 0.16 | 1.73 |
| Dagget | 0.29 | 0 | 0 | 0 | 0 | 0.09 | 0 | 0.38 |

## 4.0 DATA AND METHODS

### 4.1 Data collection

Groundwater elevation data were taken from a series of continuously monitored wells operated by the USGS (Table 2). These well sites are located in six separate sub-watersheds: Chicken Creek, Vega Creek-Montezuma Creek, Sugarville-Broad Canyon, Corn Creek, Recapture Creek, and Coal Bed Canyon (Refer to table 2 for location), and provide daily monitoring of groundwater elevation since 1970. In figure 8 an example of the change that groundwater elevation can experience is shown.

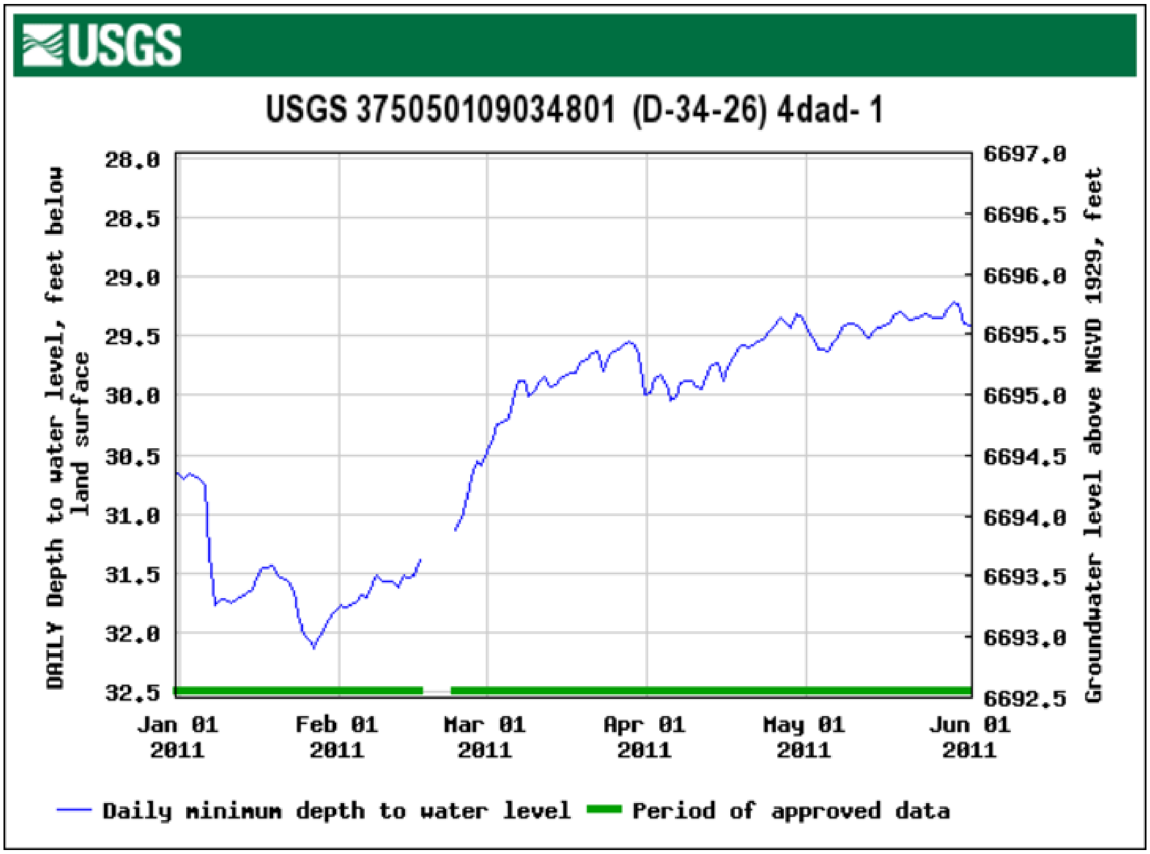


**Figure 8** Example of groundwater elevation change at one studied well site

The SWE data was obtained through 17 SNOTEL sites operated by the NRCS (Natural Resource Conservation Service), (Table 3). These SNOTEL sites were chosen according to two factors: availability of data for the three proposed study years and proximity to one of the 6 sub-watersheds. Each of these sites is located in or near one of the 6 sub-watersheds and possess continuously monitored data regarding the area's snowpack for the past several decades on a monthly basis.

The SWE and groundwater data were collected for three years which represent average water year precipitation (2014), below average (2013), and above average conditions (2011). The months during which data was gathered included January through May on the first of each month, which covers the mid-winter build-up to late spring melt of the snowpack.

## Table 2

## Continuously monitored Groundwater Well Sites

| Well Number | Latitude | Longitude | Elevation (m) | Sub-Watershed (sq.km) | Mean Slope(Deg) |
|---|---|---|---|---|---|
| 385844112245801 | 38.97 | -112.41 | 1446 | Corn Creek (653.68) | 11.13 |
| 373830109283201 | 37.64 | -109.47 | 1890 | Recapture Creek (536.93) | 7.27 |
| 375243109191301 | 37.87 | -109.32 | 2108 | Vega Creek-Montezuma Creek (738.19) | 6.68 |
| 393020112362201 | 39.50 | -112.60 | 1411 | Sugarville-Broad Canyon (431.61) | 1.38 |
| 393143111523301 | 39.52 | -111.87 | 1586 | Chicken Creek (475.13) | 11.50 |
| 375050109034801 | 37.84 | -109.06 | 2050 | Coal Bed Canyon (450.61) | 5.83 |

## Table 3

## SNOTEL Sites

| Site name | Site number | Elevation (m) | Lat | Long |
|---|---|---|---|---|
| **Black Flat U.M Ck** | **348** | **2884** | **38.66** | **-111.58** |
| **Camp Jackson** | **383** | **2733** | **37.80** | **-109.48** |
| **Clayton Springs** | **983** | **3063** | **37.96** | **-111.81** |
| **Columbine Pass** | **409** | **2865** | **38.41** | **-108.38** |
| **Donkey Reservoir** | **452** | **2847** | **38.20** | **-111.46** |
| **Kimberly Mine** | **557** | **2783** | **38.48** | **-112.38** |
| **Lasal Mountain** | **69** | **2913** | **38.46** | **-109.26** |
| **Lone Cone** | **589** | **2962** | **37.90** | **-108.20** |
| **Mancos** | **905** | **3048** | **37.43** | **-108.16** |
| **Mining Fork** | **631** | **2506** | **40.48** | **-112.60** |
| **Payson R.S.** | **686** | **2459** | **39.91** | **-111.61** |
| **Pine Creek** | **694** | **2679** | **38.95** | **-112.23** |
| **Scotch Creek** | **739** | **2774** | **37.65** | **-108.00** |
| **Sharkstooth** | **1060** | **3267** | **37.50** | **-108.11** |
| **Timpanogos Divide** | **820** | **2481** | **40.417** | **-111.60** |
| **Vernon Creek** | **844** | **2256** | **39.93** | **-112.40** |
| **Widtsoe #3** | **865** | **2938** | **37.83** | **-111.86** |

**Table 4**

**Number of SNOTEL and well sites within 30 Km to Sub-Watersheds**

| Sub-Watershed | Number of Well sites | Number of SNOTEL sites |
|---|---|---|
| Chicken Creek | 1 | 5 |
| Coal Bed Canyon | 3 | 2 |
| Corn Creek | 2 | 2 |
| Recapture Creek | 2 | 2 |
| Sugarville Broad Canyon | 1 | 1 |
| Vega Creek-Montezuma Creek | 3 | 2 |

Table 4 displays the well sites and SNOTEL sites in and around the sub-watersheds studied. As several of the sub-watersheds were very close to each other the well sites for each sub-watershed are within 30 Km to another watershed. Also, several SNOTEL sites, several of which do not register as being within 30 Km, in Colorado were used as one sub-watershed (Coal Bed Canyon) does partially extend into Colorado. Satellite derived imagery will also be used in the form of digital elevation models (DEMs) for each of the watersheds. Each DEM will have a spatial resolution of approximately 30 $m^2$ originating from 2011 at the earliest available time. These files will be gathered from the national mapper operated by the United States Geological Survey (USGS).

### 4.2 Data analysis

After the data has been gathered, the SWE depths from each SNOTEL site will be interpolated across each watershed using Multiple Linear Regression (MLR) in order to run a correlation analysis between the SWE volume and groundwater elevation at each corresponding groundwater well. The MLR is an extension of bivariate linear regression to include multiple explanatory or independent variables to predict the value of a single dependent variable (Helsel and Hirsch 2002). The first step will determine the latitude and longitude, elevation, slope (steepness), and aspect (slope direction) for each DEM cell for each watershed to be entered as the independent variables during the MLR analysis to predict the dependent variable, in this case SWE depth. These variables are significant to this study as they represent locational/physical surface characteristics that can have a substantial effect on the properties of the snowpack across the six sub-watersheds.

These variables also have a minimal chance of cross-correlating with each other which is a major assumption of MLR in that all the independent variables are truly independent. Other variables that can strongly affect SWE such as temperature (air or soil), precipitation, or land cover were not included in this study for this reason and to reduce the chance of any of the resulting MLR models ‘over-fitting’. As a secondary check, a correlation matrix will test for any statistically significant association between the independent variables described above. Any variables found to have a significant association will be subsequently removed from the MLR analysis should they be selected together in any of the resulting models. An example of one of these formulas would be:

$$78.538 + (\text{Elevation} * -.024)$$

For this formula 78.538 would represent the y intercept for the line of regression and the -.024 would represent the slope of that line.

Using procedures similar to Harshburger et al. (2010), MLR formulas will be generated and validated for the SWE interpolation procedure to determine the monthly SWE depth for the aforementioned months and years across the six sub-watersheds. These MLR formulas will be produced monthly (one formula for January 2011, one formula for February 2011, etc.) The stepwise procedure will be employed in which each independent variable is tested during the procedure with insignificant explanatory variables excluded from the MLR model altogether. At this stage, the validity of each MLR formula will be examined. This will be performed using a split-sample procedure in which a random sample of the SNOTEL gages is used to predict the SWE depth observations of the remaining gages. The resulting residuals will provide the root mean square error (RMSE) and mean absolute error (MAE) which, along with the resulting variance explained produced by the MLR models (R2), may be used to validate the overall model outputs for each month/year.

The formulas produced by the MLR models will be entered in to the raster calculator tool within ArcGIS software in order to produce multiple raster's displaying SWE data for each month for each pixel within the six sub-watersheds. In some cases, negative values may be produced where ArcMap underestimates SWE at lower elevations due to a lack of SNOTEL sites at these locations. These negative values will be removed by extracting values greater than and including zero from each watershed raster.

After interpolating the SWE depths and removing the negative values, the interpolated SWE raster's will be converted to volumes in cubic meters. To do this the sum of the values, which represents the total watershed SWE in millimeters, will be taken from the raster's classification statistics and converted to meters using the following equation: mm/1000. The resulting number will then be multiplied by the projected raster pixel resolution in square meters to give the watershed SWE volume for each month/year.

Finally, a correlation analysis will determine whether an association exists between the groundwater well elevation and watershed SWE volume across the six sub watersheds. A correlation analysis measures the strength and direction of association between two or more variables, although it does not provide evidence for causality between the variables (Helsel and Hirsch 2002). The association is shown in numerical form as a coefficient between -1.00 and 1.00, with values closer to 1.00 indicating a stronger positive association between the two variables and values closer to -1.00 indicating a stronger negative association.

# 5.0 RESULTS

## 5.1 MLR Validations

Using MLR, the independent variables were determined for January, February, March, April, and May of the three years studied. In addition to elevation, slope, and aspect; longitude and latitude were also included as independent variables. Once these key independent variables were determined they were used to create the relevant MLR formulas along with the Root Mean Square Error (RMSE) and Mean Absolute Error (MAE), both of which act as measures of error between the predicted and observed values.

Table 5 shows which independent variables were necessary for the MLR formulas for each month. The R-Square value indicates the variance explained by the MLR formulas. The RMSE and MAE are also shown in order to show how far the observed results deviate from the predicted results. Of the independent variables used for the MLR formulas slope was used the most occurring in eight of the formulas. This was followed by latitude which was used in five, elevation which was used in four, and finally both longitude and aspect which were both only found in one formula.

**Table 5**

**MLR Validation Results**

| Year | Month | I Variable | R-Square | RMSE(mm) | MAE(mm) |
|---|---|---|---|---|---|
| 2011 | January | Elevation | 0.632 | 16.00 | 3.81 |
| | February | Elevation | 0.684 | 32.51 | 7.87 |
| | March | Elevation | 0.656 | 22.09 | 5.33 |
| | April | Latitude | 0.797 | 2.54 | .50 |
| | May | Latitude | 0.868 | 42.67 | 10.41 |
| 2013 | January | Latitude | 0.546 | 22.35 | 5.33 |
| | February | Slope | 0.553 | 69.34 | 16.76 |
| | March | Slope | 0.694 | 66.54 | 16.25 |
| | April | Slope | 0.569 | 1.77 | .50 |
| | May | Slope and Longitude | 0.807 | .76 | .25 |
| 2014 | January | Elevation | 0.714 | 58.67 | 14.22 |
| | February | Slope and Aspect | 0.808 | 69.59 | 17.01 |
| | March | Slope | 0.519 | 3.04 | .76 |
| | April | Latitude and Slope | 0.701 | 9.65 | 2.28 |
| | May | Latitude and Slope | 0.834 | 34.29 | 8.38 |

The results of the MLR validation show that 2011 generated the most robust model of SWE based on the predicted and observed values. The average RMSE and MAE values for 2011 (23.16mm and 5.58mm respectively) were lower than for either 2013 (32.15mm and 7.82mm respectively) or 2014 (35.05mm and 8.53mm respectively). The average R-square for 2011 is also the highest out of the three years (.727). In total, the R-squared values for each month are all above .5 suggesting that these MLR formulas can adequately explain the variance in the observed SWE data. In each of the three years May has the highest R-square value for that particular year suggesting that the MLR formulas for May in all three years produce predicted results that most closely follow the observed results. The MLR results are generally comparable to Harshburger et al. (2010) who used similar procedures in interpolating SWE across watersheds.

Before running the MLR, a correlation matrix was also generated to check if any statistically significant correlation existed between any of the independent variables that were used together in any of the MLR formulas. The results of this analysis are available in table 6 below.

**Table 6**

**Independent variables correlation matrix**

| I Variable | Latitude | Longitude | Elevation | Slope | Aspect |
|---|---|---|---|---|---|
| Latitude | 1.00 | -0.645 | -0.848 | 0.203 | 0.075 |
| Longitude | -0.645 | 1.00 | 0.528 | -0.216 | 0.003 |
| Elevation | -0.848 | 0.528 | 1.00 | -0.204 | -0.04 |
| Slope | 0.203 | -0.216 | -0.204 | 1.00 | 0.593 |
| Aspect | 0.075 | 0.003 | -0.04 | 0.593 | 1.00 |

As seen in table 6 each of the five independent variables used were compared to one another using bivariate Pearson correlation analysis to detect if any significant correlations existed between the independent variables. The biggest concern was whether any of the independent variables that were used together in any of the MLR formulas would display a statistically significant correlation at the 0.01 level of significance. This is known as multicollinearity, a phenomenon where two predicating (independent) variables have significant correlation with one another which can artificially increase the variance explained by the MLR model. None of the independent variables used in the MLR formulas display a significant correlation at the 0.01 level showing that multicollinearity was not a factor in the MLR outcomes.

## 5.2 SWE and Groundwater Correlations

Figures 9-111 show the volume of SWE for each of the six sub-watersheds for the five months studied for 2011, 2013, and 2014 interpolated from the MLR formulas. The values for the observed SWE volume are displayed on a log base 10 scale due to the wide range of SWE volumes that were generated. This caused several of the smaller values to not appear on their respective graphs when using the original volume scale.

In 2011, the SWE volume for each watershed is significantly higher than the other two years, in particular the months of February and March which have total volumes of 6022907208$m^3$ and 6093111736$m^3$ respectively. The year of 2011 was above average for winter precipitation which would explain the greater SWE volume for all months in that year.

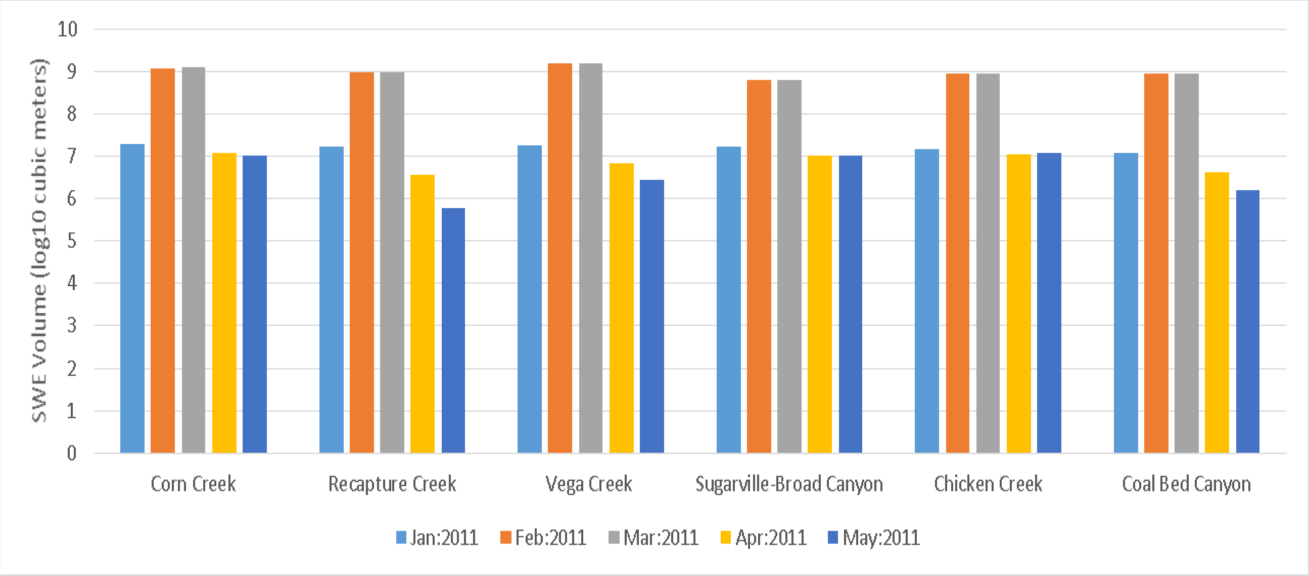


**Figure 9** SWE volumes in each sub-watershed for the five months studied in 2011

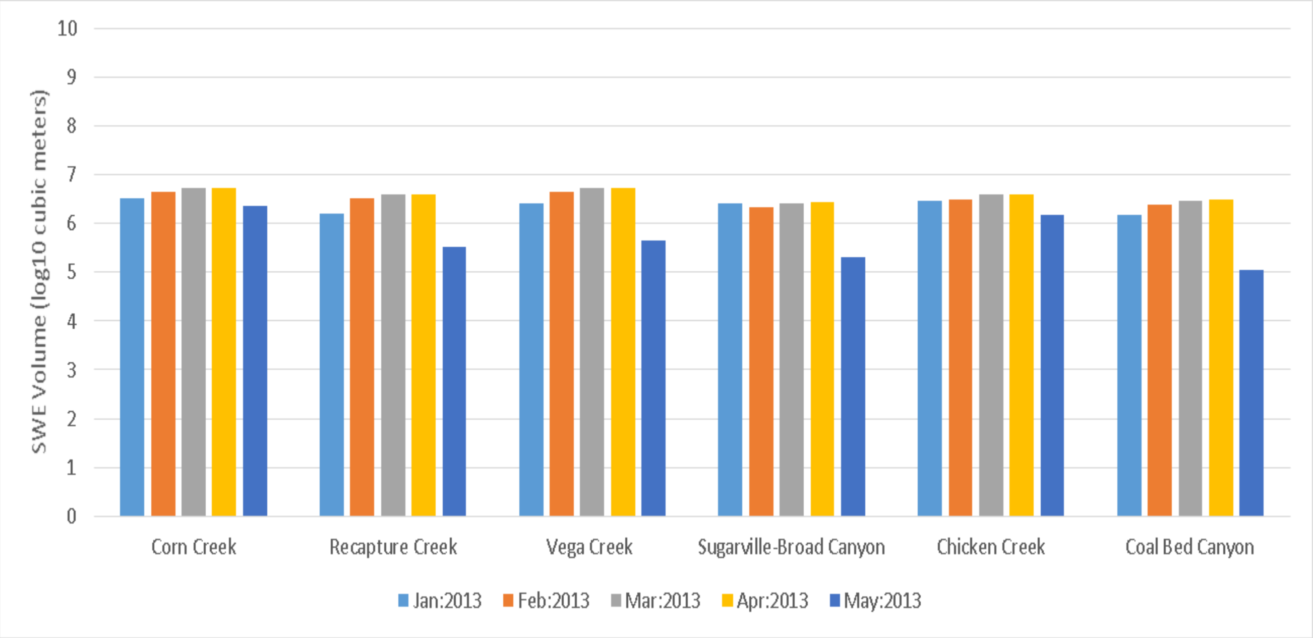


**Figure 10** SWE volumes in each sub-watershed for the five months studied in 2013

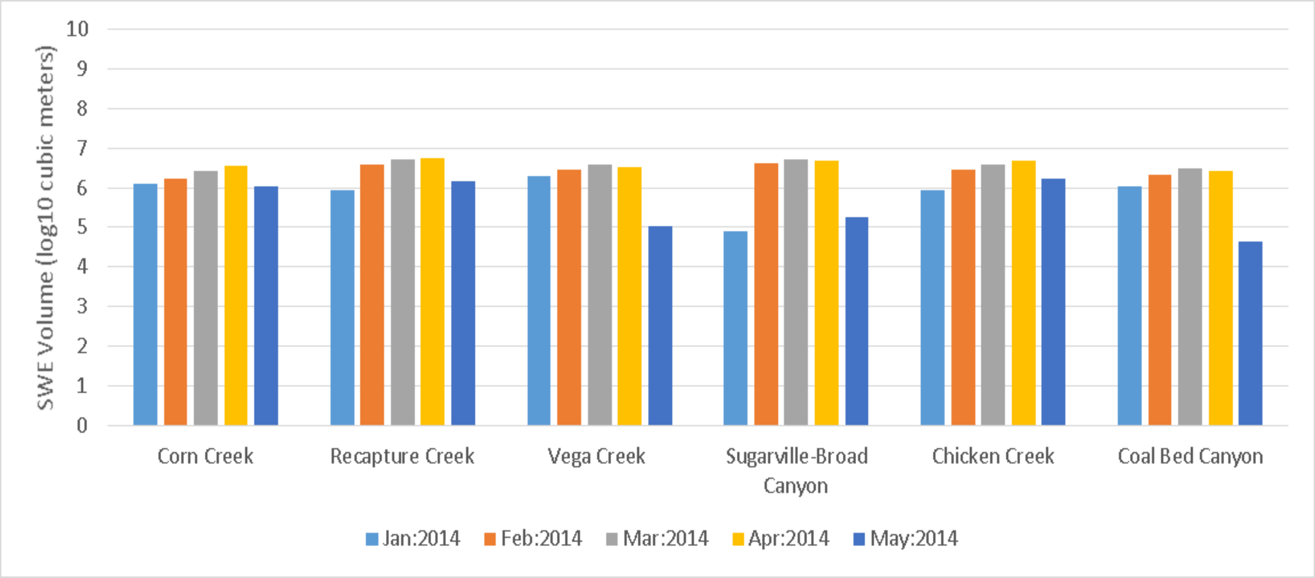
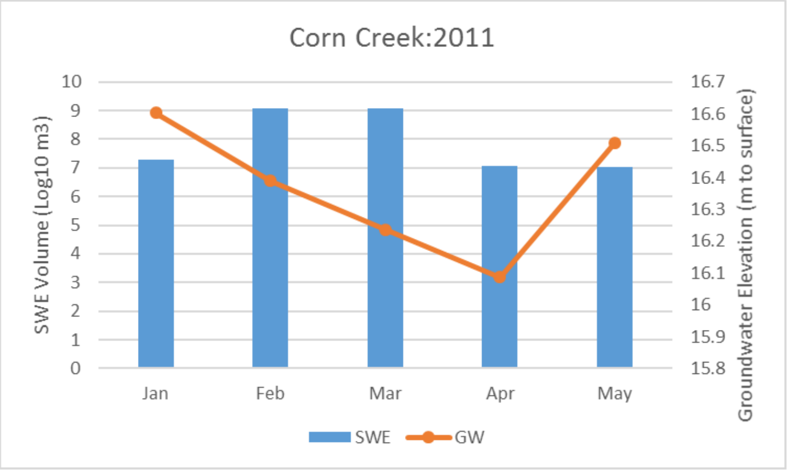


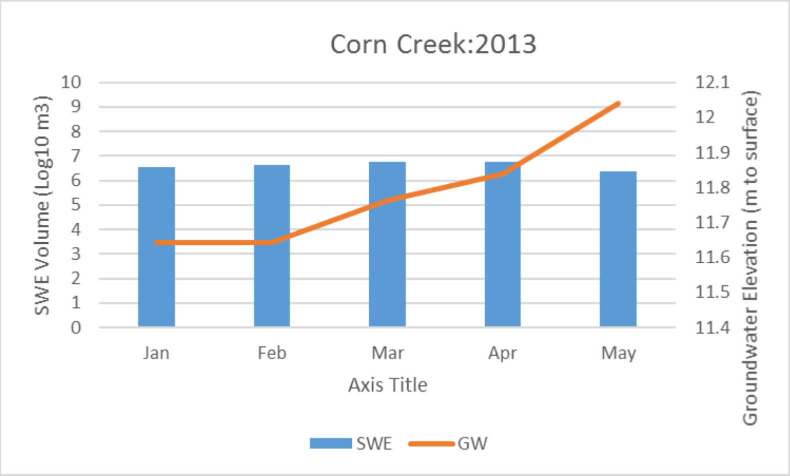
**Figure 11** SWE volumes in each sub-watershed for the five months studied in 2014

The SWE volumes for both 2013 and 2014 follow a rising trend from January to April before falling in May. The only time this did not occur was in 2013 for the Sugarville-Broad Canyon watershed where the SWE volume fell from January to February by 17%. There are no other decreases at any other sub-watershed from January to February for 2011, 2013, or 2014. This suggests that this is unique to this sub-watershed for this period and may be a result of unique weather rather than a reoccurring phenomenon.

The decrease in SWE volume from April to May is present at all sub-watersheds and months except for two: Sugarville-Broad Canyon and Chicken Creek during 2011. Both sub-watersheds experience an increase in SWE volume from April to May with Sugarville-Broad Canyon increasing by 3% and Chicken Creek increasing by 3%. Both sub-watersheds are close to one another and a third sub-watershed: Corn Creek. Although Corn Creek does experience a drop in SWE volume from April to May the decrease in volume is much smaller than what is found in the other three sub-watersheds of Vega Creek, Recapture Creek, and Coal Bed Canyon. This similarity in values may be a result of Sugarville-Broad Canyon, Chicken Creek, and Corn Creek residing in the Great Basin region of Utah as opposed to the Colorado Plateau where the other three reside and which is higher in elevation. The noted drops in SWE volume in May are expected. It was hypothesized at the beginning of this study that there would be a drop in SWE volume across one month. The next step was to determine if a correlation existed between the SWE volume and the groundwater elevation for each month.

To best display the groundwater elevation in relation to SWE volume per month in each individual sub-watershed, the groundwater data and SWE data were plotted together for each sub-watershed for each month examined (Figures 12-17). The groundwater elevation was portrayed in terms of meters to surface and the SWE volume was portrayed in base 10 similar to figures 9, 10, and 11. These plots were created for the purpose of comparing the groundwater elevation to the SWE volume.





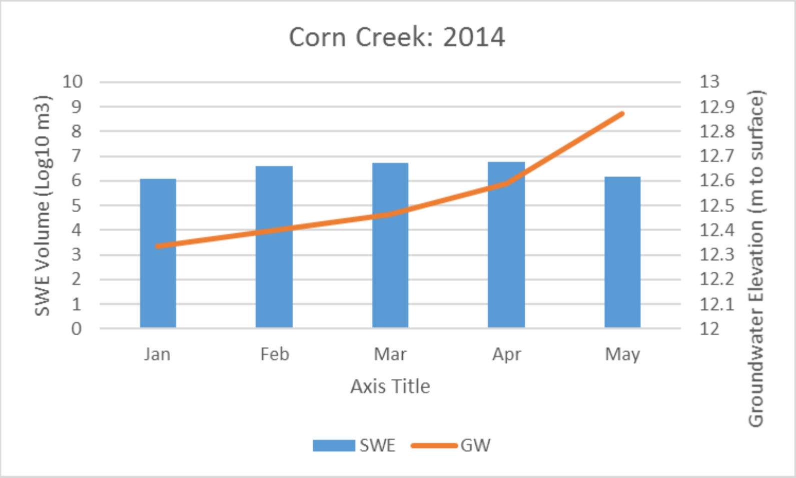


**Figure 12** SWE volumes and groundwater elevation for the five months studied in Corn Creek for 2011, 2013, and 2014

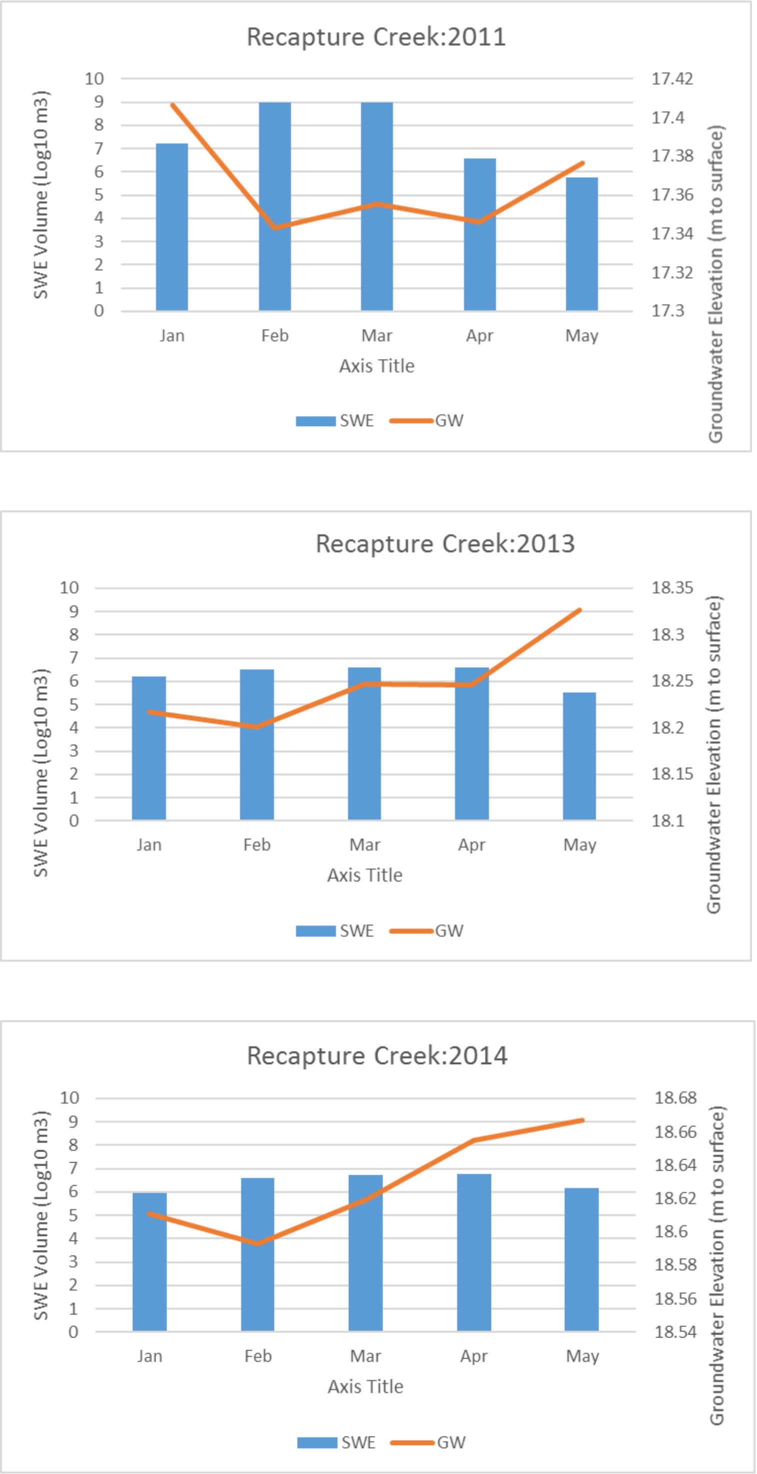


**Figure 13** SWE volumes and groundwater elevation for the five months studied in Recapture Creek for 2011, 2013, and 2014

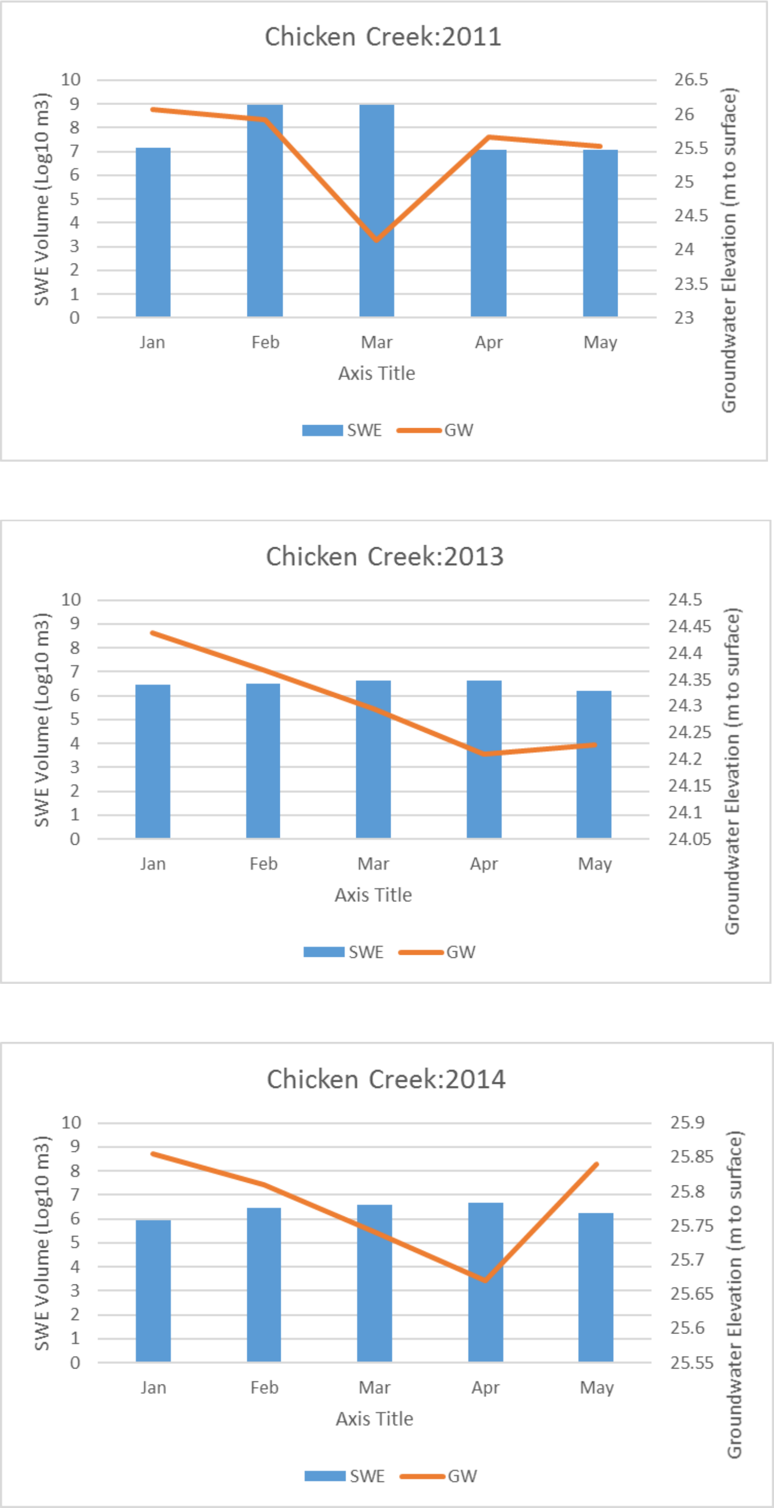
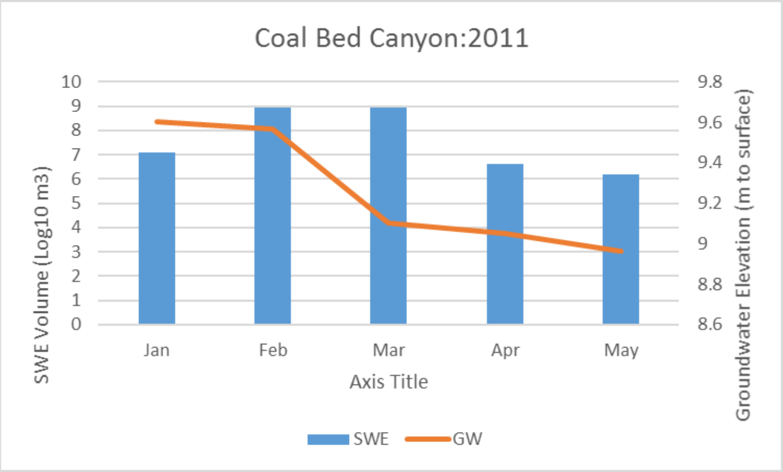
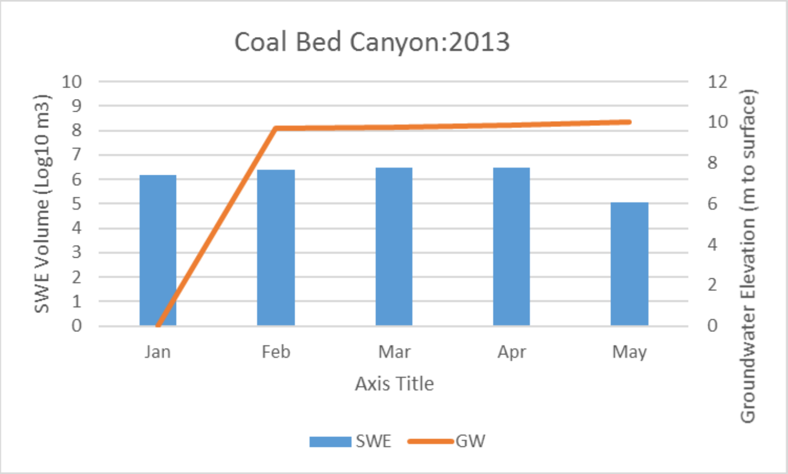


**Figure 14** SWE volumes and groundwater elevation for the five months studied in Chicken Creek for 2011, 2013, and 2014





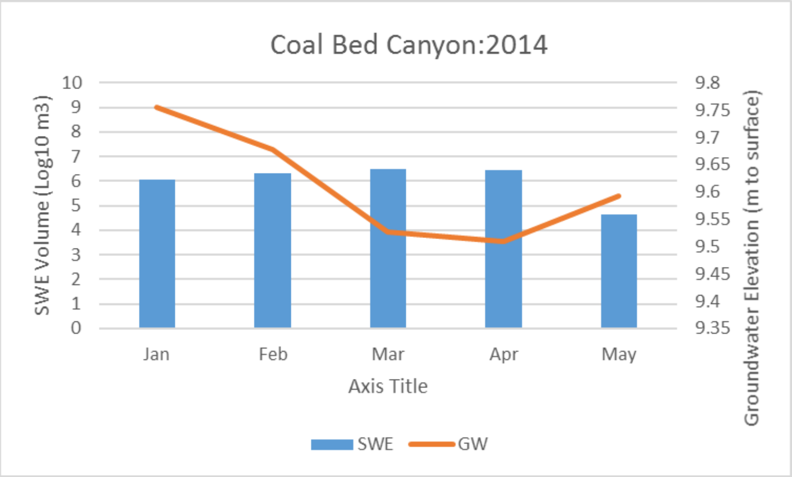


**Figure 15** SWE volumes and groundwater elevation for the five months studied in Coal Bed Canyon for 2011, 2013, and 2014

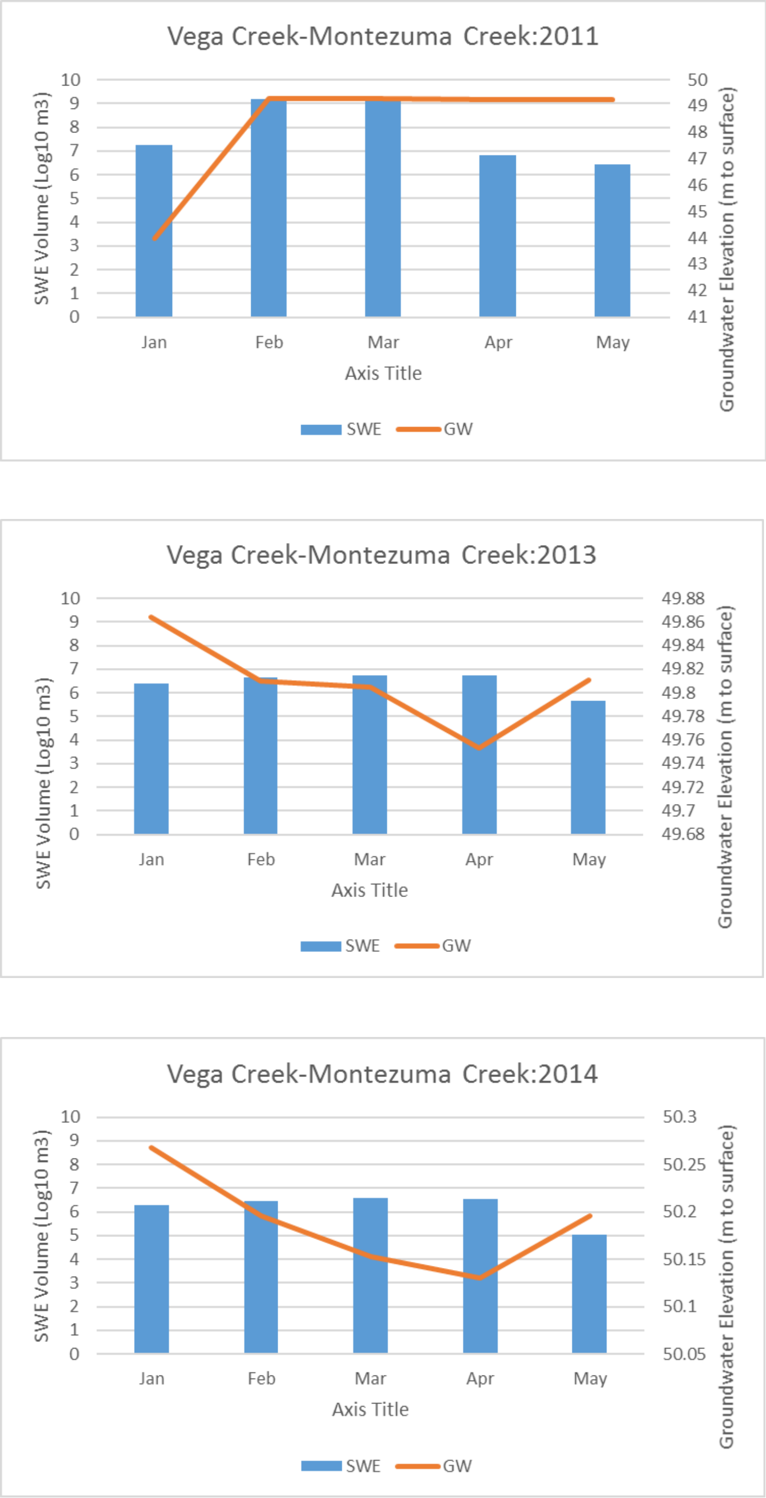
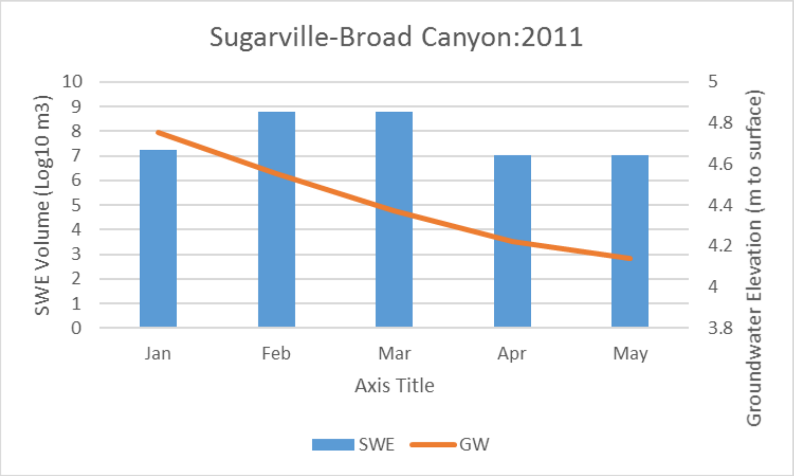
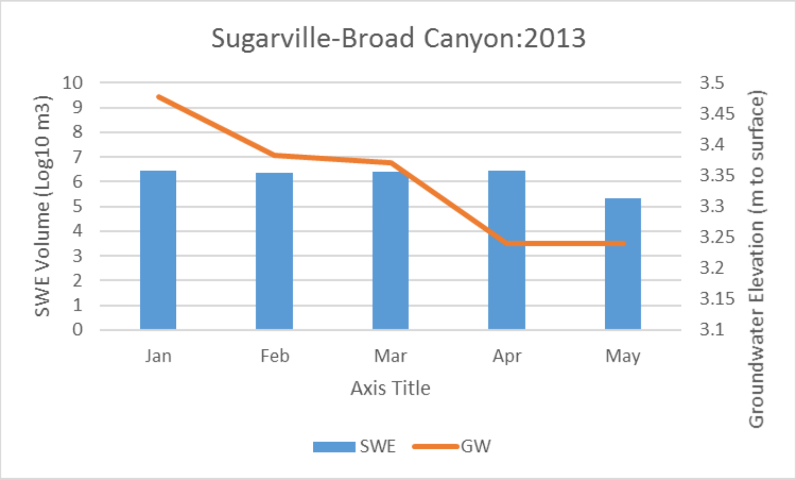


**Figure 16** SWE volumes and groundwater elevation for the five months studied in Vega Creek-Montezuma Creek for 2011, 2013, and 2014





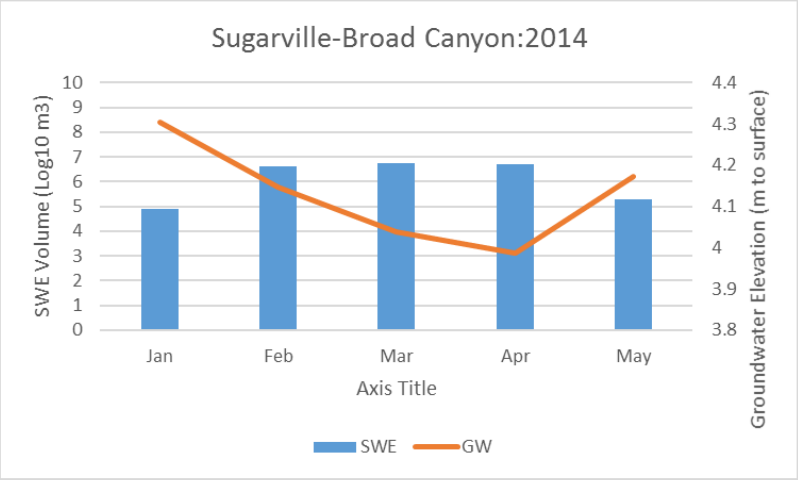


**Figure 17** SWE volumes and groundwater elevation for the five months studied in Sugarville-Broad Canyon for 2011, 2013, and 2014

In Figures 12 through 17, a line portraying groundwater elevation decreasing corresponds to the depth in meters from the surface to the water table also decreasing as the water table rises. An increase in this line indicates that the water table is falling. All the watersheds experience decreasing groundwater elevation in terms of meters to the surface at different times. All sub-watersheds also experience an increase in groundwater elevation for May of 2014 indicating that the water table is falling in this period. In all but two of these sub-watersheds (Recapture Creek and Corn Creek) this phenomenon occurs after a long period of decreasing elevation meaning that for the rest of the study period the water table is rising. The two watersheds that experience falling water tables for this period experience similar trends for 2013 but also experience decreasing groundwater elevation for 2011 until May at which point the elevation increases. This increase in May also corresponds with a decrease in SWE volume and could represent less water entering the local aquifer system.

Comparing the groundwater elevation to the SWE volume for the same period is crucial to understanding the relationship between these two variables. In figure 13 for Recapture Creek:2011 when the SWE volume increases from January to February the groundwater elevation decreases at the same time. This suggests that as the snow melts more water is entering the aquifer system causing the depth to the water table to decrease. This can also be seen in figure 15 for Coal Bed Canyon for2011 as the depth to the water table decreases the six months studied. It is important to note that figures 12 through 17 do not account for the potential lag between SWE and groundwater elevation in order to account for the amount of time it potentially takes for SWE to enter the aquifer system. As such the SWE in April would be compared to the groundwater elevation in May. This is important as figures 12 through 17 commonly show a sharp increase in groundwater elevation in May.

The SWE volumes along with the groundwater elevation for each watershed were analyzed using bivariate Pearson correlation to determine which months, if any, displayed significant correlations between SWE volume and groundwater volume. A bivariate Pearson correlation works by comparing a pair of variables, in this case groundwater elevation and SWE volume, and producing a correlation coefficient measuring the strength and direction of a linear relationship between that pair of variables. The coefficient produced ranges from -1.00 to 1.00 representing decreasing and increasing linear relationships between the two variables respectively. In this case, a positive correlation would represent SWE volume increasing at the same time as groundwater elevation while a negative correlation would represent either SWE volume or groundwater elevation decreasing while the other rises. A correlation of 0.00 would show that there is no noticeable relationship between the two variables. Sig values representing whether the correlation between the two variables are statistically significant were also produced, a value of less than 0.05 would represent a significant correlation.

Two correlations were performed: monthly (e.g. January SWE volume compared to January groundwater elevation) and on a lagged monthly basis (e.g. January SWE volume compared to February Groundwater elevation). The lagged monthly basis correlation was performed to account for the amount of time snowmelt could take to enter the groundwater zone as this could vary for a variety of factors including changing temperatures and aquifer geology (Allen, Whitfield, and Werner 2010). Both of these correlations are available in tables 8 and 9 respectively with correlations statistically significant at the 0.01 level of significance highlighted.

## Table 7

## Monthly Correlation analysis results

| | JanSWE/JanGW | FebSWE/FebGW | MarSWE/MarGW | AprSWE/AprGW | MaySWE/MayGW |
|---|---|---|---|---|---|
| 2011Pearson | -0.357 | 0.459 | 0.457 | -0.859* | -0.91* |
| 2011Sig Value | 0.488 | 0.36 | 0.362 | 0.028* | 0.012* |
| 2013Pearson | 0.408 | 0.114 | 0.078 | 0.104 | -0.584 |
| 2013Sig Value | 0.422 | 0.829 | 0.884 | 0.844 | 0.224 |
| 2014Pearson | 0.634 | 0.162 | 0.137 | -0.459 | -0.837* |
| 2014Sig Value | 0.176 | 0.759 | 0.796 | 0.36 | 0.023* |

* Significant correlation

## Table 8

## Lagged Correlation analysis results

| | JanSWE/FebGW | FebSWE/MarGW | MarSWE/AprGW | AprSWE/MayGW | MaySWE/JunGW |
|---|---|---|---|---|---|
| 2011Pearson | -0.361 | 0.458 | 0.457 | -0.859* | -0.91* |
| 2011Sig Value | 0.482 | 0.361 | 0.362 | 0.028* | 0.012* |
| 2013Pearson | -0.728 | 0.109 | 0.083 | 0.104 | -0.608 |
| 2013Sig Value | 0.101 | 0.837 | 0.876 | 0.844 | 0.2 |
| 2014Pearson | 0.634 | 0.162 | 0.137 | -0.459 | -0.873* |
| 2014Sig Value | 0.176 | 0.76 | 0.796 | 0.36 | 0.023* |

* Significant correlation

In both tables 7 and 8 the only statistically significant values occur in the later months of April and May. The lack of statistically significant values in earlier months is likely due to a lack of snowmelt during these earlier months which caused the groundwater elevation and SWE volume to not experience any significant changes.

Significant values also occur in both tables for the same period as well. On table 8 there are three months that have statistically significant values: April 2011, May 2011, and May 2014. These same three months would also be statistically significant in table 9 with the same Pearson and Sig values. In all three cases the Pearson correlation coefficient exceeds .8 and are negative in association. This means that as the value of one variable increases the value of another decreases. Figure 10 shows that there is a drop in SWE volume from April to May in every sub-watershed for the year of 2014 and Figure 8 shows that there is a similar drop in the same period for three of the sub-watersheds. These results are expected as Figures 8 and 10 show that SWE volume is decreasing while the statistically significant negative correlations in table 8 show that as the SWE volume decreases in one month the groundwater elevation increases

## 6.0 CONCLUSIONS

The purpose of this study was to investigate the relationship between the volume of snowmelt and groundwater elevation within six sub-watersheds in the state of Utah. Data was collected from these six sub-watersheds for five months (January-May) for three years (2011, 2013, and 2014). The data collected allowed the groundwater elevation and snow water equivalent volume to be correlated and analyzed to determine if any relationship existed between those two variables. Determining that a relationship does exist between these two variables can best determine when groundwater sources are replenished for water resource planning purposes.

The SWE volumes and groundwater elevations at each sub-watershed do show statistically significant correlations. In April and May of 2011 there are strong correlations as well as in May of 2014. These correlations are all negative and occur only in these months. This means that while one variable is decreasing another is increasing, in this case it is the amount of SWE volume decreasing corresponding with an increase in groundwater elevation.

The initial hypothesis of this study was that a decrease in SWE volume across one month would share a correlation with an increase in groundwater elevation for the subsequent month because of the meltwater entering the aquifer systems of the sub-watersheds. However; this study does not account for human use of groundwater. If there was heavy usage by any human population within the six sub-watersheds studied it could have had a slight effect on the correlation results. A future study could, therefore, investigate if any correlations existed between that amount of water used by humans in each sub-watershed and the groundwater elevation.

The strong negative correlation that occurs in the later months of this study show that the decrease of SWE and increase of groundwater elevation occur during the same period which starts in April/May. It can be determined that a negative relationship exists between SWE volume and groundwater elevation within these six sub-watersheds and that there is more water entering the aquifer system during April and May suggesting that these two months are when groundwater sources are being replenished. What this means is that the areas in and around the Great Basin region can better predict the quantity of groundwater available which is vital information as it provides roughly 1/4th of Utah’s freshwater supply (Maupin et al. 2014).

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# CURRICULUM VITA

NAME: Samuel Thomas Wright

ADDRESS: 1436 Christy Avenue
Louisville, KY 40204

DOB: Huntington, West Virginia – August 24, 1990

EDUCATION
& TRAINING: B.A., History
Centre College
2009-2013

AWARDS: Eagle scout rank
Troop 30, Louisville
2008

PROFESSIONAL SOCIETIES:

PUBLICATIONS:

NATIONAL MEETING PRESENTATION:

REFEREED JOURNALS:

BOOKS AND SYMPOSIA:

INVITED PRESENTATIONS: