A GIS approach to understanding groundwater – surface water interactions in Red Butte Creek, UT

CEE 6440 – Final Project Report

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Introduction

Groundwater – surface water (GW-SW) interactions vary temporally and spatially, significantly influencing the total flow in streams and impacting thermal and chemical processes and transport. A vast majority of research regarding GW-SW interactions and GW recharge focuses on basin-fill aquifers, and gives little attention to mountain systems. It is no surprise that so much emphasis has been placed on determining recharge rates of basin-fill aquifers. The basin-fill aquifers and adjacent mountain systems in Cache Valley, the Lower Bear River, and along the Wasatch Front provide groundwater resources to about 84% of the population in Utah (Anderson et al., 1994). As human population continues to grow, the demand on groundwater resources may not only impact and deplete available groundwater reserves, but surface water flow rates as well (Wahl and Wahl, 1988). An understanding of groundwater recharge is necessary for managers to make informed and effective decisions concerning water usage and future growth.

Several factors determine the amount of precipitation that enters both basin and mountain aquifers. Developing an understanding of these factors is crucial to estimating recharge rates and interactions (Wilson and Guan, 2004; Anderholm, 2000). Watershed characteristics such as precipitation (type and magnitude), interception, evapotranspiration, bedrock percolation (including formation type and faults), watershed and river gradient, soil characteristics, and general differences in flow paths through the mountain block each play a role in the overall mountain block hydrology and groundwater recharge. Many of these characteristics are included in a variety of hydrologic studies and models, however some are often difficult to quantify. Differences in flowpaths (local, intermediate, regional) are dependent upon topographic relief (Tóth, 1963) as well as geology (Spangler et al. 2001). Percolation through bedrock is dependent upon the underlying geology (variable over space) and the type and intensity of precipitation (variable over space and time).

A variety of methods have been established to quantify the recharge to aquifers. In many cases, recharge is simply estimated from fluctuations in water table wells (Mau and Winter, 1997). However, a variety of other methods exist based on different types of data sets, including stream hydrograph separation, the implementation of a water balance, and the use of geochemical tracers. This project focuses on a method developed by Cherkauer and Ansari (2005) that related surface information with groundwater recharge estimates from the streamflow hydrograph separation method. As such, their method and assumptions will be described in order to better justify the approach used throughout the remainder of this paper.

Background

The method of streamflow hydrograph separation stems from the generally accepted idea that baseflow measurements can be used as to represent GW recharge rates (Halford and Mayer, 2000). This assumption originates from a simplified groundwater balance of a small watershed, later described by Cherkauer and Ansari (2005) as:

$$I + GW_{in} = Q_{bf} + GW_{out} + ET + NP + \frac{\Delta S}{t}$$

Where I is infiltration into the system, GW_{in} is groundwater influx to the watershed through aquifers, Q_{bf} is groundwater discharge to stream baseflow, GW_{out} is groundwater efflux from the watershed through aquifers, ET is evapotranspiration losses from the watershed, NP is net pumpage of groundwater into or out of the watershed, and $\Delta S/t$ is the rate of change of groundwater storage with respect to time (Cherkauer and Ansari, 2005).

If watersheds can be selected where $GW_{in} = GW_{out} = NP = \Delta S/t = 0$, and if recharge is defined as net groundwater recharge (I – ET), then the previous equation simplifies to:

$$Recharge = Net\ Recharge = Q_{bf} = Stream\ Baseflow$$

This simplified model assumes that groundwater and surface water divides coincide, that there is no human transport of water into or out of the watershed, and that groundwater storages do not significantly change year to year. The model also suggests interflow to be a negligible component of streamflow and assumes that the hydrograph can be separated into direct surface runoff and groundwater discharge (Kulandaiswamy and Seethareman, 1969). Therefore, watersheds with significant surface water storage (lakes, reservoirs, wetlands) must be avoided to meet this assumption. Lastly, the stream hydrograph separation method for determining groundwater recharge requires small-scale temporal resolution flow measurements, most often provided by the U.S. Geological Survey (USGS) or constructed through field observations at independent sites.

With an increasing amount of residents relying on groundwater, it is crucial that water resource managers have adequate information regarding GW recharge. Cherkauer and Ansari's method was designed to be used as a first approach to understanding recharge rates based on available surface information. They developed a simplified conceptual model (Figure 1), where the watershed is represented as a rectangle with the horizontal length being the length of the main channel (L_c), the width being the drainage area/L_c, and the average length of the surface flow path (L_f) to the channel being half the width. Watersheds were assumed to be internally homogenous with each physical property (elevation, slope, effective soil conductivity, etc.) represented as the mean value of the entire drainage area. As precipitation falls within the watershed, water flows toward the main channel. Along the flow path, some of the water infiltrates and enters the river as baseflow, while the remainder of the water enters as surface runoff. The entire drainage area acts as a recharge area, and the stream is considered the only point of groundwater discharge. The physical characteristics of the watershed determine the partitioning of precipitation to either groundwater or runoff (Cherkauer and Ansari, 2005).

They point out that the developed model is highly simplified and does not account for spatial heterogeneity in physical properties. It does not account for antecedent soil moisture or other discharge points other than the stream. The model also assumes precipitation is uniform across the watershed and that it occurs with uniform intensity.

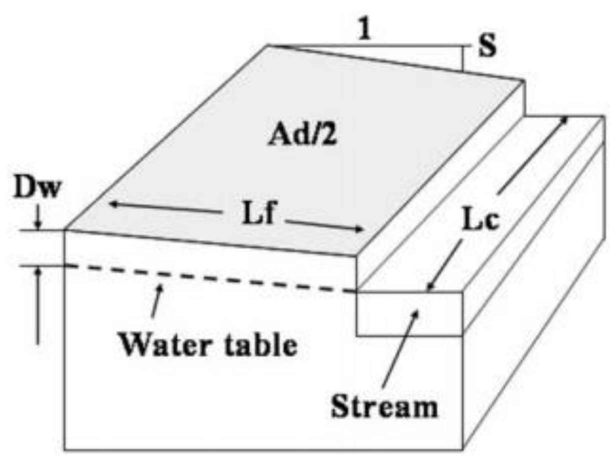

Figure 1. Conceptualized geometric dimension of study watershed. Half of the watershed of drainage area Ad is shown; other half is mirror image. Lc is length of main channel. Lf, length of overland flow, is Ad/(2 Lc), S is average surface slope toward stream, and Dw is the average depth to the water table. Figure from Cherkauer and Ansari (2005).

Objectives

This project aims to address the following:

1) Demonstrate how GW-SW interactions on Red Butte Creek vary over space and time.
2) Perform streamflow hydrograph separation and compare to precipitation estimates.
3) Determine the applicability of Cherkauer and Ansari's method in estimating groundwater recharge based on topography, hydrogeology, land cover, precipitation and other watershed characteristics.
4) Compare surface characteristics from watersheds delineated at various pour points distributed longitudinally throughout the watershed.
5) Discuss additional surface information that could be considered to improve Cherkauer and Ansari's method to be more applicable for Red Butte Creek.

Methods

A variety of methods were applied in order to address the aforementioned objectives. Following a brief site description of the Red Butte Creek study area, the methods will be described in the order of the objective which they fulfill.

Site Description

Red Butte Creek (RBC) drains a small watershed located at the northeast end of the Salt Lake valley (Figure 2). This small, second order stream flows southwest through quartzite, limestone and sandstone before entering the valley by the University of Utah (Ehleringer et al., 1992; Mast and Clow, 2000). The creek quickly transitions from a relatively pristine watershed to a highly urbanized area as it flows from the headwaters and drains into the Jordan River. Much of the upper watershed has limited public access as the area is managed as a Research Natural Area. Within the research area is a single impoundment, Red Butte Reservoir. Originally constructed by the U.S. Army, the reservoir is managed by the Central Utah Water Conservancy district as habitat for a refuge population of the endangered June sucker (*Chasmistes liorus*). The reservoir generally maintains a constant level, only decreasing storage to be able to capture and mitigate spring runoff events. A single USGS gage measures flow above the reservoir (Site 10172200). The stream at the USGS station drains 18.8 square kilometers.

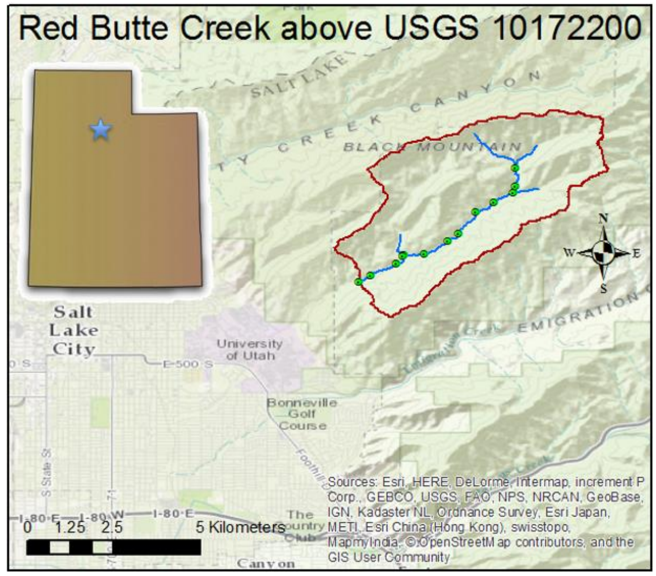

Figure 2. Site map of Red Butte Creek watershed (delineated above USGS 10172200). Green circles indicate various differential gaging locations. State of Utah given for reference of approximate location of study site.

Variability in GW-SW interactions

Areas of interest in regards to GW-SW interactions were determined from data collected during a seepage study that began in the summer of 2014 and is continuing through 2016. Differential gaging at various sites over different seasons helped identify areas of net change in streamflow and were identified as a gaining or a losing system. As there appears to be some discrepancy in the literature, for this paper this is to be interpreted as gaining surface water from groundwater or losing surface water to groundwater. Net gains or losses were determined by subtracting an upstream stream discharge measurement from a downstream measurement and accounting for any tributaries. At each discharge site, GPS coordinates were recorded and used to create a point shapefile. Sections between differential gaging sites were identified as either gaining, losing, or neither based on previous data.

Streamflow Hydrograph Separation and Precipitation

Graphical hydrograph separation relies solely upon stream discharge records. Different procedures of graphical hydrograph separation are outlined well in the literature (Miller et al., 2014; Kao et al., 2012; Yeh et al., 2007; Cherkauer and Ansari, 2005; Chen and Lee, 2003; Mau and Winter, 1997). Chen and Lee (2003) suggest that graphical methods may be more suitable for estimating groundwater recharge in mountain regions than in plain regions due to the difference in water-flow characteristics. While a variety of software exist, the Web Hydrograph Analysis Tool (WHAT) from Purdue University was used for this project for simplicity and availability. Baseflow estimates were obtained for the past 10 calendar years (2005-2014) for daily flow from the USGS gaging station on RBC (station 10172200). Filter parameters for the recursive digital filter were left as default values for perennial streams with porous aquifers.

Annual precipitation values for the past 10 years were obtained using PRISM data from Oregon State University. The annual data downloads as a 4 km raster for the contiguous United States. The PRISM data was clipped to the RBC drainage area.

Using the total flow, baseflow, and precipitation estimates, a variety of ratios were calculated including the runoff ratio (P/Q), baseflow index, or BFI, (R/Q), and recharge over precipitation (R/P) used by Cherkauer and Ansari.

Estimating Groundwater Recharge

In order to match Cherkauer and Ansari's method, a variety of topography, hydrogeology, and land cover data needed to be acquired from GIS servers (Table 1). The data were imported and clipped to a buffered watershed polygon using the Extract by Mask tool. Descriptions of the data were determined using either the Zonal Statistics as Table tool, calculating statistics or summarizing a single column in the layer's attribute table.

Table 1. Topography, hydrogeology, and land cover data collected from different GIS servers to be used in estimating groundwater recharge.

GIS Server	Layer	Data
Elevation	NED30m	Area, Slope
Landscape1	USA_NHD_HighRes	Length of Channel
Landscape2	USA_Soils_Water_Table_Depth	Depth to water table
Landscape2	USA_NLCD_2006	Land cover (percentages)
Landscape5	USA_Soils_Hydrologic_Group	Effective hydraulic conductivity

Values were further manipulated in Excel to ensure unit agreement and form. Afterwards, the values were input into Cherkauer and Ansari's regression equation and compared to R/P values determined earlier.

Comparison of Subwatershed Characteristics

This step will essentially repeat all of the watershed delineation, clipping and summarizing of data that was just described. Due to the high number of repetitions, this portion of the project was automated using Python.

Results

Variability in GW-SW interactions

Analysis of the differential gaging data (not included in this report as it is not relevant to the scope and purpose of a GIS project) indicated that the majority of the watershed was gaining groundwater from diffuse sources (green points indicate the downstream end of a gaining section) with the exception of a single losing section (red point) near the outlet of the watershed (Figure 3). Some reaches (grey points) in the watershed were inconsistent, or were within measurement error and could not be definitively labeled as a gaining or losing section.

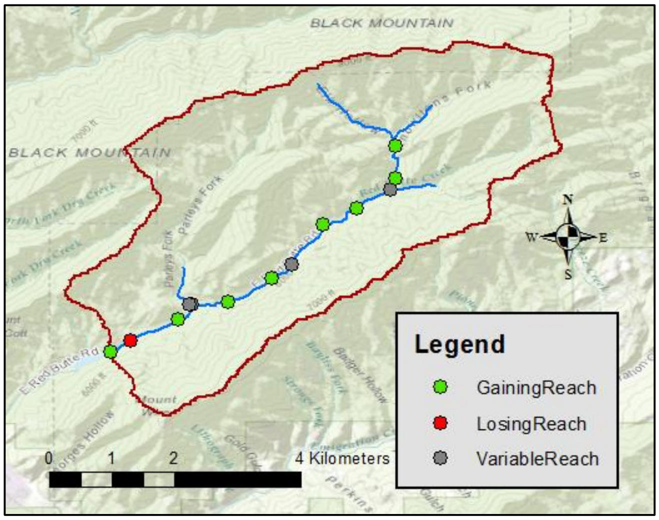

Figure 3. Gaining and losing sections of the river are indicated by green and red points, respectively, at the downstream end of the reach. Grey points indicate reaches with inconsistent data or differences in data were within measurement error.

Streamflow Hydrograph Separation and Precipitation

Using the WHAT, streamflow hydrograph separation was quickly performed for the past 10 years of data (Figure 4). The output was downloaded as a CSV for further analysis, and for closer investigation of individual years of data (Figure 5).

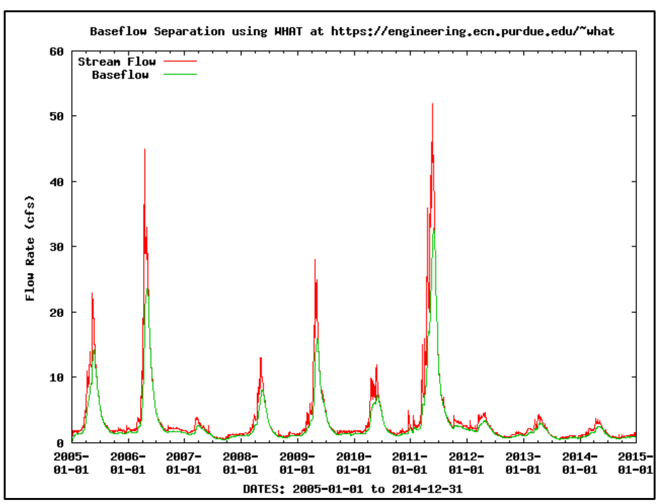

Figure 4. Results from the baseflow separation using WHAT. Red indicates total flow while green represents an estimate of baseflow.

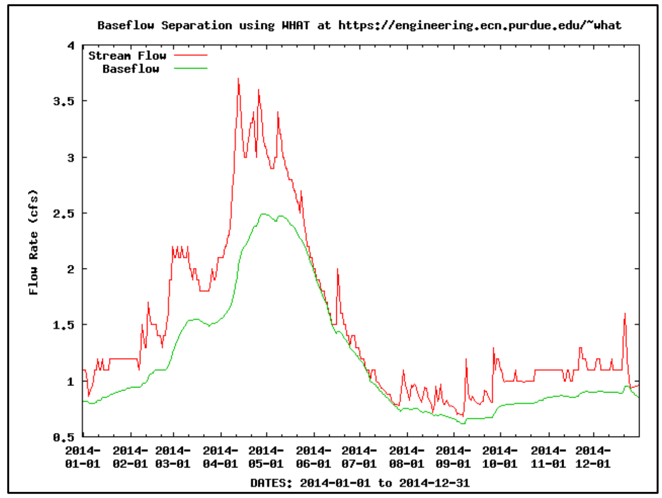

Figure 5. Results from the baseflow separation using WHAT for the 2014 calendar year. Red represents total flow while green represents an estimate of baseflow.

Annual precipitation data were obtained as PRISM coverages (Figure 6) and summarized using the Zonal Statistics as Table tool to get a total depth of precipitation in mm/year for each of the 10 years of interest. The tabulated results were compared to total and baseflow values from the WHAT baseflow separation. Results are given in Table 2.

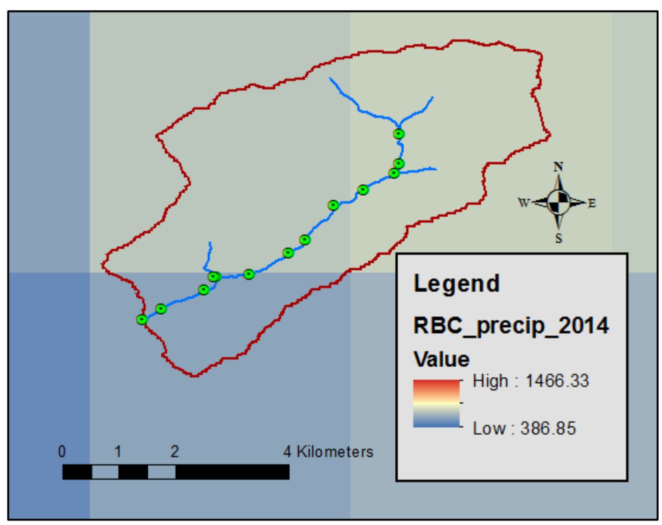

Figure 6. PRISM annual precipitation totals (mm/year) for 2014.

Table 2. Average daily flow, baseflow and annual precipitation values. From these, annual runoff ratios, baseflow indices, and R/P values were determined (after flow and precipitation were converted to volumes)

Year	Mean Daily Flow, Q (cfs)	Mean Daily Baseflow, R (cfs)	Annual Precip, P (ft)	Runoff Ratio (P/Q)	BaseFlow Index (R/Q)	Recharge/ Precip (R/P)
2005	4.6	3.6	2.8	3.84	0.78	0.20
2006	6.4	5.0	2.8	2.80	0.77	0.28
2007	1.5	1.2	2.0	8.51	0.81	0.09
2008	2.8	2.2	2.2	4.88	0.79	0.16
2009	4.6	3.6	2.6	3.62	0.77	0.21
2010	3.2	2.5	2.9	5.84	0.79	0.13
2011	9.8	7.6	2.8	1.85	0.77	0.42
2012	2.0	1.6	1.9	6.11	0.81	0.13
2013	1.6	1.3	1.9	7.63	0.80	0.11
2014	1.5	1.2	2.3	10.12	0.80	0.08
Mean	3.8	3.0	2.4	5.5	0.8	0.2
St.Dev	2.67	2.03	0.40	2.64	0.02	0.10

A runoff ratio, baseflow index (BFI), and recharge vs. precipitation ratio were determined for each of the ten years. An average value and standard deviation were also calculated for use in the estimation of groundwater recharge calculations later and for convenience in understanding the system's hydrology.

Estimating Groundwater Recharge

A variety of layers were collected and clipped to the watershed boundary of interest (Figure 7). These layers were summarized and data were manipulated to obtain the parameters in the same units as previously used by Cherkauer and Ansari (Table 3) and used in the regression equation they developed:

$$\frac{R}{P} = 0.0085\left(\frac{K_v}{SD^{0.3}}\right) - 4.18\left(\frac{D_W}{L_f}\right) + 0.0025(N) + 0.022$$

Where R/P is recharge/precipitation, Kv is effective hydraulic conductivity, S is average hillslope, Dw is average depth to the water table, Lf is length of flowpath to the channel, D is the percentage of area that is developed, and N is the natural percentage.

Table 3. Parameters for estimating groundwater recharge following the method developed by Cherkauer and Ansari (2005).

	Watershed	Red Butte Creek above USGS 10172200
Hydrogeology	Hydraulic Conductivity(m/d)	0.10
	Depth to Water Table (m)	0.61
Land Cover	Natural (%)	100
	Developed (%)	0
	Agriculture (%)	0
Topography	Drainage Area (km^2)	18.8
	Length of Channel (km)	8.81
	Slope (m/m)	0.511

For calculation purposes, D was set to 0.001 to avoid dividing by zero since the RBC watershed shows no portion of developed land cover.

Once all the parameters were included, R/P was calculated to be -2.11 cm/cm. The average R/P for the last 10 years was previously determined to be 0.2 cm/cm.

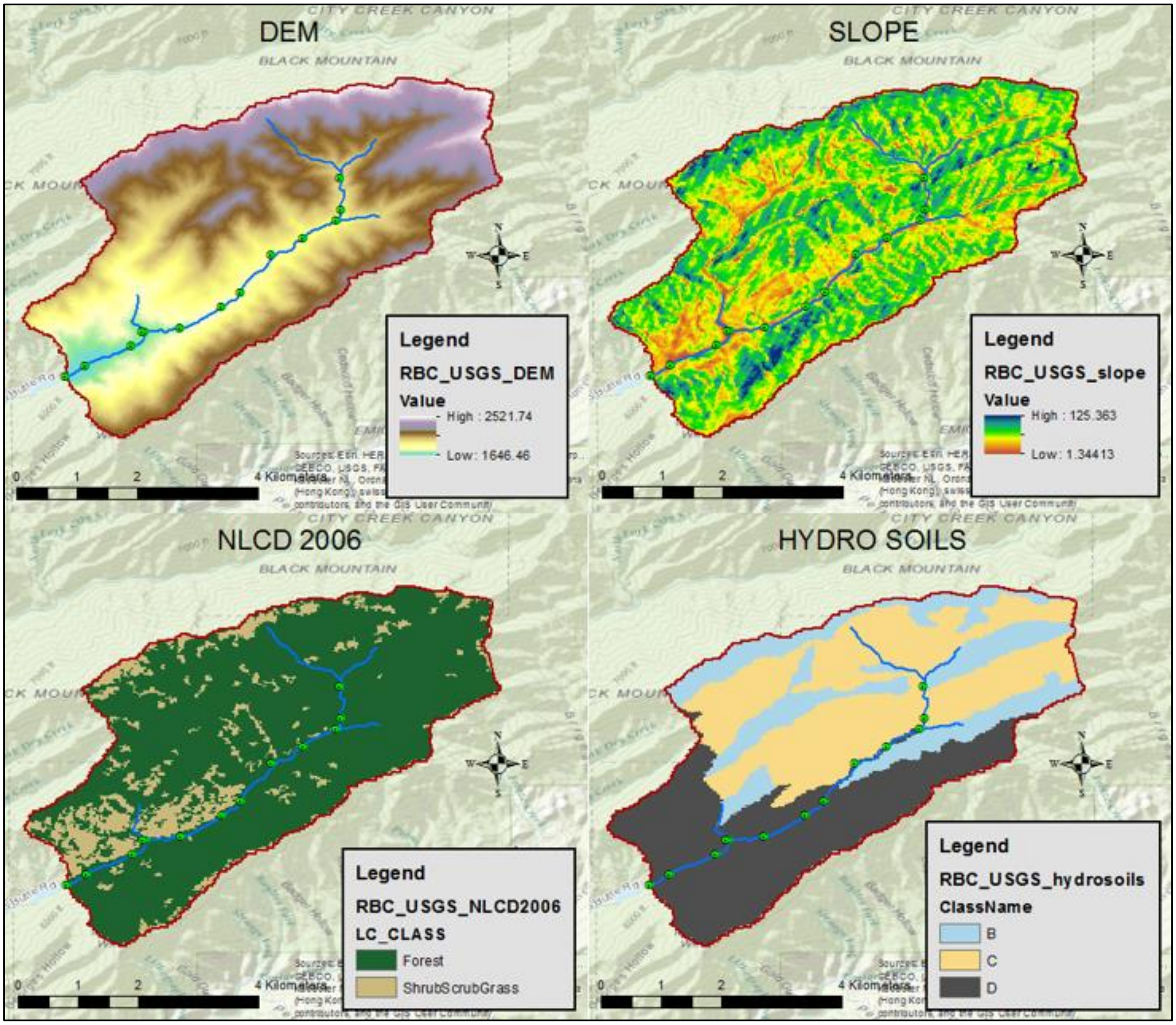

Figure 7. Layers from GIS servers that have been clipped to the Red Butte Creek watershed above USGS 10172200. Each dataset was summarized and manipulated to determine the parameters listed in Table 3.

Comparison of Subwatersheds

Unfortunately this objective was not successfully completed. Code was successfully completed that could delineate watersheds using a point shapefile as a series of pour points. Basins were stored in a file geodatabase as a multipolygon, however when trying to loop through the basin shapefile with the Zonal Statistics as Table tool, only three rows were being read in. As I am a novice with Python, a significant amount of time went into researching and debugging the code. More time was spent on this process that it would have required to run each subwatershed manually. In the end no results are prepared to show in this report.

Discussion

Variability in GW-SW interactions

An in-depth analysis and discussion of the differential gaging results does not fit in the scope or purpose of this paper. The sole purpose of this objective was to be able to demonstrate that GW-SW interactions are variable over space and time within our watershed of interest. Having shown this, we can focus later efforts into describing why this may be occurring.

Streamflow Hydrograph Separation and Precipitation

Red Butte Creek is clearly not a high volume stream, with annual average daily flow at 3.8 cfs, with the highest average at 9.8 cfs in 2011, the same year where a significant amount of flooding occurred across the Wasatch Front.

The watershed has a fairly high runoff ratio, suggesting a significant amount of precipitation is being absorbed by the soils and eventually lost to evapotranspiration. Variability in the runoff ratio could likely be due to antecedent conditions. In 2014, P/Q was significantly higher than other years, but the amount of precipitation was below average. However, the two previous years had the lowest precipitation for the last 10 years. The drought stricken soils were able to adsorb the majority of the precipitation and little made it into the aquifer (R/P = 0.08 for that year, much less than average).

The average R/P suggests that of all of the precipitation that falls throughout the year, 20% eventually enters the aquifer as recharge. The average BFI was 0.80, which could be an artifact of the WHAT baseflow separation parameters. The input average BFI into the web tool was 0.80. A better knowledge of similar systems in the area would allow for a better estimate of BFI, which would in turn affect the R/P estimates.

Estimating Groundwater Recharge

When Cherkauer and Ansari developed their method of estimating groundwater recharge, they assumed that the form of their regression equation would hold across any watershed and that just the coefficients would need to be adjusted. Unfortunately, the time available in the class did not permit for a regression analysis between the variability in R/P and surface characteristics. By simply using their equation and plugging in values from RBC, the estimate for R/P was off by over 1200%. Moving forward, the R/P calculations will be performed for 34 years (1981-Present) as this is the range of recent PRISM data that is considered more accurate. With a better distribution of R/P values, I will perform a non-linear regression analysis to alter the coefficients of the equation before moving forward with attempting to improve their method.

Comparison of Subwatersheds

As mentioned, there are no results yet for this objective. A vast amount of time was spent trying to automate the entire process. In the end, it turned out to be a bigger bite than I could chew. However, I intend to investigate changes in channel slope, fault lines, changes in geology, soil and vegetation as potential indicators of what is driving the variability in GW-SW interactions and what dictates a specific reach to be gaining or losing. Being able to identify areas that are correlated with gains or losses to groundwater would help identify areas of throughout a watershed. Whether it is for construction projects or the development of a source protection plan for a drinking water source, being able to readily identify high risk areas would be very useful.

Potential Improvements and Considerations

Following the regression analysis and correlation of surface characteristics with gaining and losing reaches, I intend to improve upon Cherkauer and Ansari's previous methodology by adding a few terms to the equation. Two specific terms to be considered along the Wasatch Front that might make the method more applicable would be a description of karst features and density of faults and fractures. Fracture flow and macropores have been shown to have a large effect on the groundwater hydrology in local watersheds (Spangler et al. 2001).

I would also propose that if a watershed was gaged at two locations, and if the R/P relationship held for each of the locations, then the relationship could be applied at any point between the two gages. As the watershed incrementally changes moving downstream, shifting from a more pristine to urban environment, changes in the R/P ratio would indicate potential gaining or losing sections without having to collect extensive differential gaging data.

Conclusion

Understanding groundwater-surface water interactions and the surface characteristics that correlate with gaining and losing sections has significant impact for water managers and others in decision making situations. Previously, a method was developed that would allow managers to get a reliable first estimate of groundwater recharge. However, the method remained to be tested on a western karst watershed. Application of the method on Red Butte Creek revealed data regarding runoff ratios, and recharge to precipitation ratios. Further investigation of the method will determine if the regression equation will stand on its own or if further adjustments will be necessary to improve the applicability of the method in local watersheds.

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