The Response of Different Soil Types to Precipitation Events over Contrasting Soil Moisture Conditions

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Introduction

The water cycle is constantly exchanging mass between the atmosphere, the earth and the oceans; and it is this persistent cycle of moisture that gives opportunity for life to exist on nearly every reach of this planet. Life is influenced by the quality and quantity of the water they are able to consume; therefore it is paramount that consumed water be available in potable and in sufficient amounts. It is vital that there is an in-depth, scientific understanding of where this water travels, what is comes in contact with, and time scales for which it exists in specific reservoirs. Although the largest volume of water exists in the oceans and the most dynamic reservoirs remain in the atmosphere; the most influential interaction interface of the water cycle occurs in soils, or the vadose zone. The purpose of my project is to quantify the amount of water stored in the vadose zone of a given watershed, and how ambient soil moisture conditions influence the infiltration and storage of incident precipitation.

Runoff from various land surfaces is controlled by a number of factors (Ford et al 2011). One of the most influential is soil moisture content. As a soil's water content increases towards saturation, the amount of water it can hold consequentially decreases in response. The ability for a soil to absorb and/or store water depends on specific geomorphological characteristics of the soil such as: mineral composition, porosity, intrinsic permeability, soil depth, grain size, and so on. Based on these characteristics, soils are divided into specific classes or "orders." Since soil orders across the country have already been mapped, it would be beneficial to understand how these different soils respond to given treatments of precipitation, in order to better forecast quantities of runoff following predictable precipitation events.

Developing a water budget over a given watershed requires several pieces of information, but the most crucial data sets include: files from the National Hydrography Data Set, a map and profile information of soils across the catchment areas, and local measurements from studied watershed that reflect local inputs, outputs, and soil moisture measurements within the watershed. The latter set of data was the most difficult to locate because of the lack of high quality, yet spatially intense soil moisture measurement locations. The most promising locations to find complete soil moisture data sets are at Long Term Ecological Research Sites across the US. These experimental sites generate a plethora of data from energy and hydrological budgets, to environmental chemical analyses, to local plant and animal population studies.

To compare soils of different characteristics, two separate study locations were selected based primarily on the existence of an extensive soil moisture data sets, one being the Harvard Forest LTR in north central MA (Boose 2011, Hadley 2009), and the other as Coweeta LTR in far southwestern NC (Laseter et al 2010, Knoepp 2011). Each site is similar in vegetation cover and mean annual precipitation with Coweeta receiving slightly more precipitation on average. The sites differ, in areas other than soil type, in that the Harvard LTER has gently sloping topography and a groundwater table fairly near the surface (<1m) and covers an area approximately 0.5 km^2. While the Coweeta site is about 0.12 km^2 and overlays steep, rugged terrain.

Data Processing

To begin analysis, individual watershed polygon shape files were obtained from NHDPlus online database. In addition to catchment outlines, the corresponding streamline feature class and elevation raster data set were downloaded and added the workspace. Additionally a soil type .kml file for each catchment was downloaded using a Google Earth Soil Survey Browser developed at the UC Davis Soil Resource Laboratory. The .kml file was then transformed into a feature class and displayed in ArcMAP. Before analysis and comparison between each data layer can proceed, it is essential to ensure each layer is projected in the same coordinates system to ensure specific features match up correctly. Each layer was transformed to be projected in the North America Albers Equal Area Conic projection to ensure area is conserved. In order to isolate the specific catchment of interest I selected the catchment from the attribute table and exported the information into a new feature class. The intersect tool was them implemented to connect several feature classes including: catchment, streamlines, and soil polygons to isolate each within the study watershed. This was especially crucial for the soil polygons, which overlap multiple catchments. After this was preformed, values representing the area of each soil class covering the watershed were established (Figure 1).

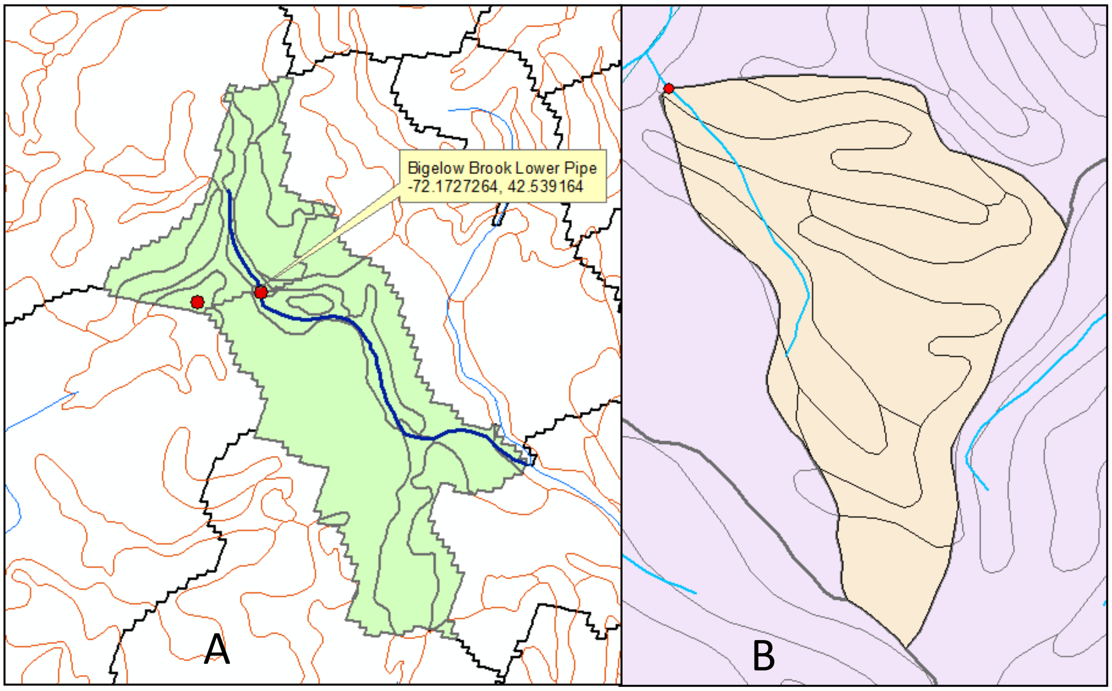

Figure 1: A.) Map display of a selected catchment in Harvard Forest LTER in ArcMap. Grey lines designate catchments, orange lines designate soils, blue lines represent streams. B) A map of a selected catchment in Coweeta LTER in ArcMap. Tan area highlights the catchment studied, with black lines representing the catchment outline and grey lines representing the soil type outline.

Data Analysis and Results:

3.1 Harvard LTER

After dividing up each catchment into their specific spatial distributions of soil types, it appeared the Harvard LTER site was composed primarily of Spodosols and included one unit type of Inceptisols. Spodosols are a well-developed, well-drained, coarse-loamy soil that is primarily identified by significant leaching of Fe and Al from upper organic rich layers to lower horizons. Inceptisols are geomorphically young soils that form on hill slopes, are more course-grained and drain well also (Fuss, et al 2010). To determine how soil moisture is affected by rainfall, soil moisture was plotted against precipitation amounts over time (Figure 2).

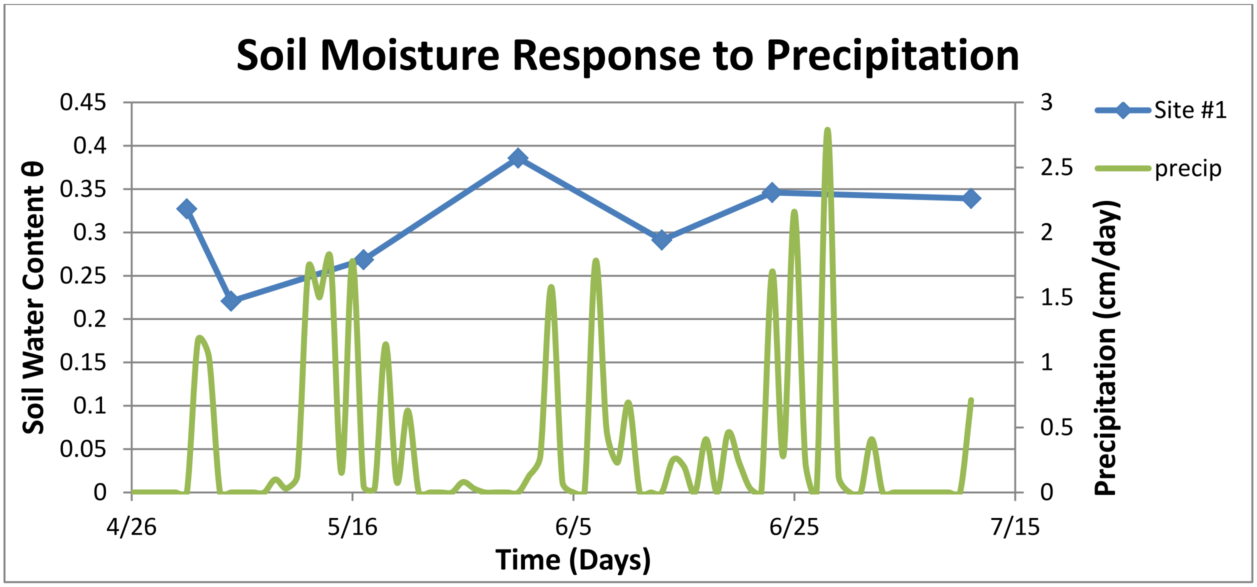

Figure 2: Soil Water Content values (θ) from a single sensors is plotted over time, as well as precipitation amounts during the same time periods in the Prospect Hill catchment basin of the Harvard Forest LTER in north central MA.

A delayed temporal pattern can be distinguished between the rainfall and the soil moisture trends. After a precipitation event, the soil takes about 1 day for the water content levels in the soil to rise; which they will continue to do following the end of the rainfall. Figure 3 displays the hydrograph that records all water leaving the catchment through stream flow.

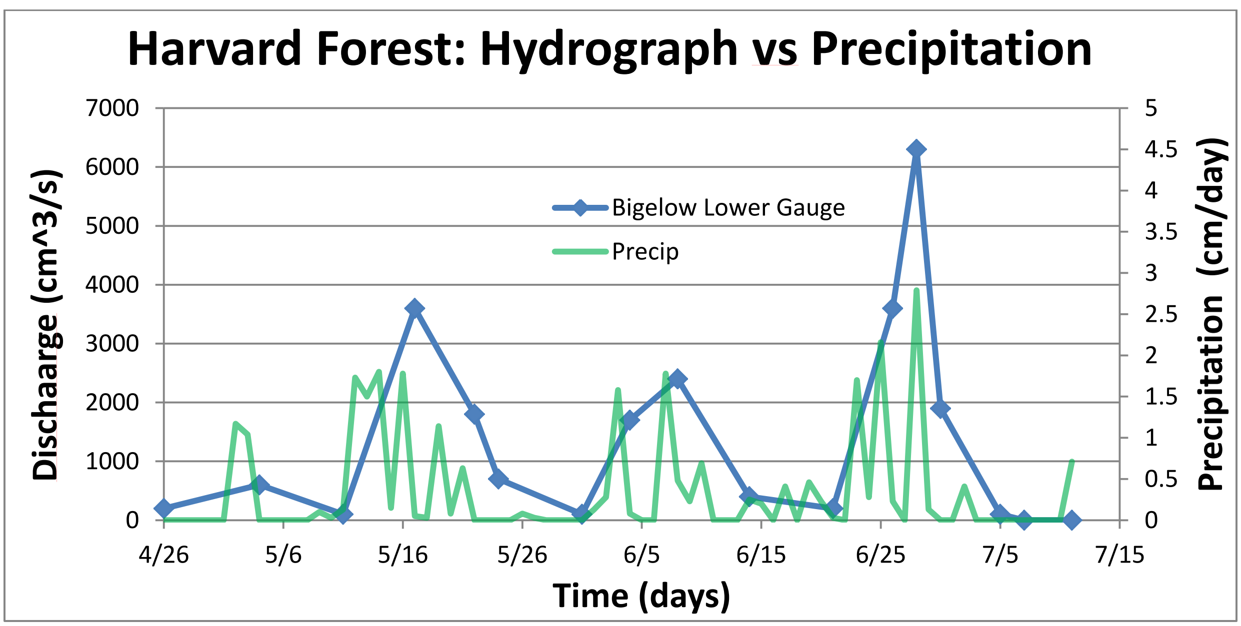

Figure 2: Daily stream discharge rates and precipitation amounts are displayed over time in the Prospect Hill catchment basin of the Harvard Forest LTER in north central MA. Stream discharge rates reflect the stream at the base of the basin.

Note that as the soil moisture profile reaches saturation during the precipitation event on 6/25, the amount of runoff increases compared to similar precipitation events earlier in the summer.

To determine effective water input into the streams, a conceptual model of effective water input was implemented as described by Equation 1.

$$W_{eff} = W - ET + \Delta Sc + \Delta D + \Delta\theta \qquad \text{Eq 1)}$$

W_{eff} = Effective water input
Q_{ef} = Volume event flow
W = Total Water input
ET = Evapotranspiration
ΔSc = Vegetative Storage
ΔD = Depression Storage
$\Delta\theta$ = Vadose zone storage
$Q_{ef} = W_{eff}$

Values for ET and ΔSc are generally assumed to be magnitudes smaller than other terms in the equation and are considered to be 0 in this case. Although for short term events ET remains small, if a study is examined over longer time periods ET will become substantial. ΔD is very difficult to measure in nature, but for this study it should remain fairly low as a result of the topographic relief at each location, decreasing the ability of water to pond upon the soil surface.

Using this equation an estimated budget was created to quantify the % of precipitation that is stored by the soils during the study period. Table 1 displays the budget for the Harvard LTER from 4/26/06 through 7/11/06.

	Totals	
Discharge:	7979.04	m^3
Δ Soil Moisture	1226.77	m^3
Precip:	0.2671	m
Basin Area:	511,000.0	m^2
Basin Input:	136,488.1	m^3
D = P - dSw	= 7979	m^3
Total	+135,261.3	m^3

Table 1: Totals reflect the summed amount of water input, output, or change in volume of each relative category. The equation represents the amount of discharge expected if all rainfall that is not stored in soils results in stream flow or Weff, effective water input.

The total at the bottom of the table indicates the difference between precipitation and the change in volume of water storage in the soils. This value should be near the discharge value at the top of the table if given assumptions are valid. Unfortunately, this number is 2 magnitudes larger than the measured discharge, suggesting that either earlier assumptions are incorrect or the incoming water is being transferred out or stored in another area not measured within this study (possibly influx to water table.) Figure 3 also sheds some light on other issues plaguing this study.

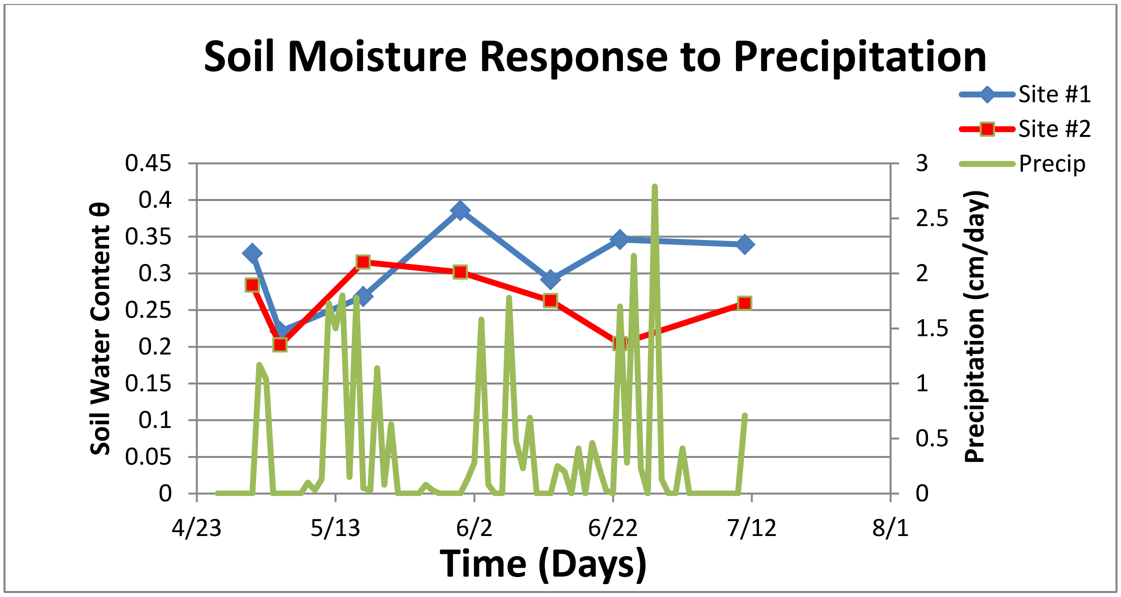

Figure 3: Soil Water Content values (θ) from two separate sensors are plotted over time, as well as precipitation amounts during the same time periods in the Prospect Hill catchment basin of the Harvard Forest LTER in north central MA.

Soil moisture values of two separate sensors within close spatial range of each other are plotted with precipitation amounts over time. The assumption that one soil moisture measurement could use as an approximation for soil moisture over the entire catchment is proven invalid here as the two sensors vary considerably at the end of the measurement period, even while being in close proximity to each other. This strenghtens the point that soils and precipitation can be extremely heterogeneous, even on the small catchment scale focus for this study.

3.2 Coweeta LTER

Similar comparative studies were done with the data sampled from the Coweeta LTER compared to the analysis done with the soil moisture, precipitation, and stream gauge information from the Harvard LTER. NDHPlus and soil .kml data sets were downloaded into ArcMap and isolated to determine percent soil cover type for each series of soil. The main soil order at this site is Ultisols. These are typically deep, well developed soils with a light brown to reddish hued horizons that are indicative of strong weathering. Much of the Ca, Mg, and K are leached from these soils resulting in developed clay horizons. The Coweeta LTER data sets differ from the Harvard data sets by being much more temporally complete. Daily water content, stream gauge, and precipitation data are available, making this analysis more precise. Figure 4 displays soil water content measurements from two sensors within the catchment.

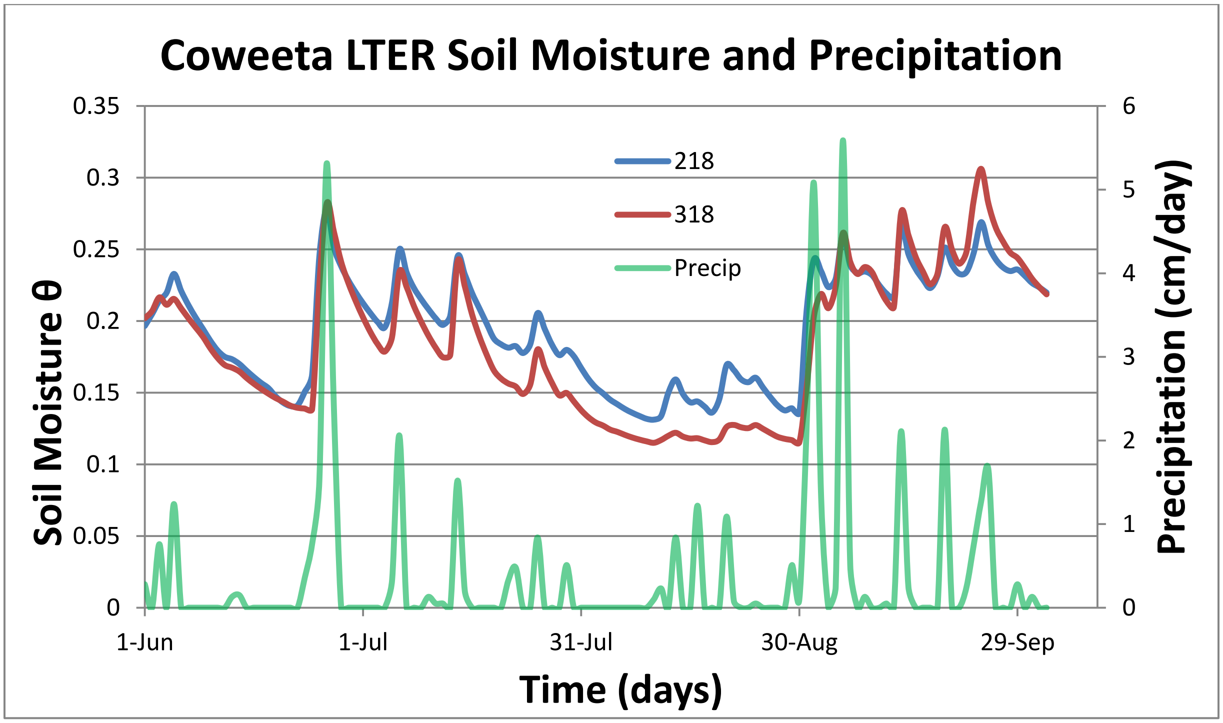

Figure 4: Daily soil Water Content values (θ) from two sensors plotted over time, as well as daily precipitation totals during the same time periods from the Watershed 18 catchment basin of the Coweeta LTER in southwestern NC.

This graph displays the quick reaction of water content (WC) to incident precipitation, with peaks in both values accurately aligned in time. Figure 5 displays the volume of water stored in the top 30cm of the catchment's vadose zone. This total over time was established by finding the average WC between the two studied sensors and then multiplying the volume of soil in the catchment by the water content.

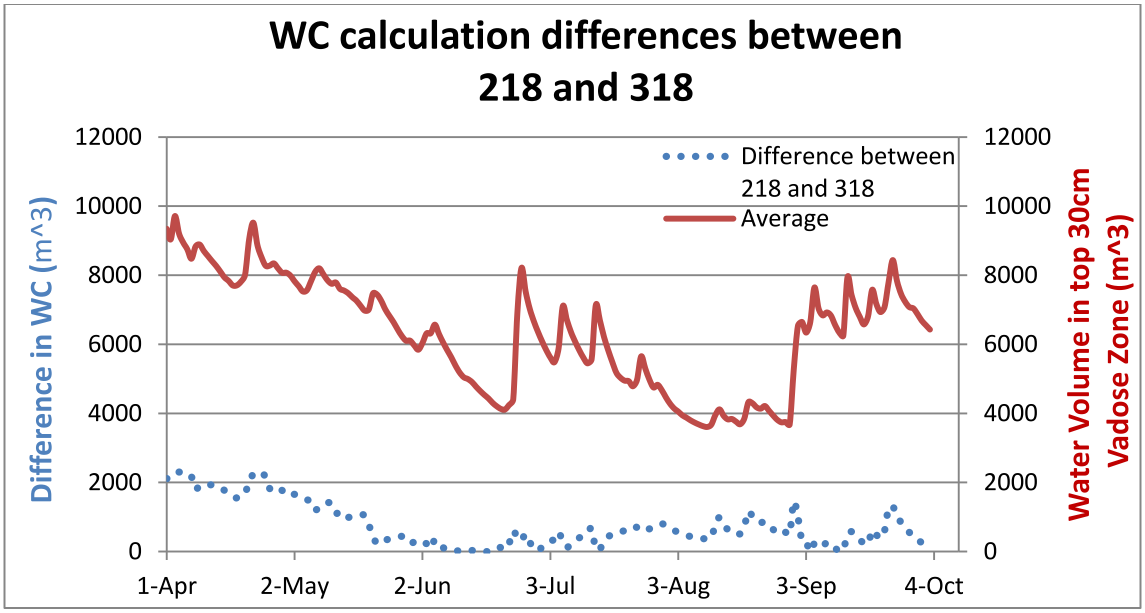

Figure 7: The red line represents the average volume of water (m^3)in the top 30cm of the vadose zone over a time in Watershed 18 of the Coweeta LTER in NC. The dotted blue line represents the difference in water content between the two moisture sensors that were averaged to create the solid red line.

The dotted blue line represents the difference between the two water content measurements that were averaged to create the mean volume of water in the vadose zone over time for the watershed. It is interesting to note that the two sensors were similar in measurements during the time periods in which the least amount of water was contained in the vadose (the drier periods, June thru July) and had the largest difference in measurement during times when the soils held the larger volumes of water (April thru May). These differences could be caused by elevation differences between sensors which may cause the sensor at higher elevations to receive more precipitation due to orographic lifting.

Discussion

Although more questions have been asked than addressed during this study, there are valuable points and credible ideas explaining the trends put forth regarding the soil moisture response to precipitation. Figure 7 displays the most prominent explanation for the incorrect water budgets for each catchment.

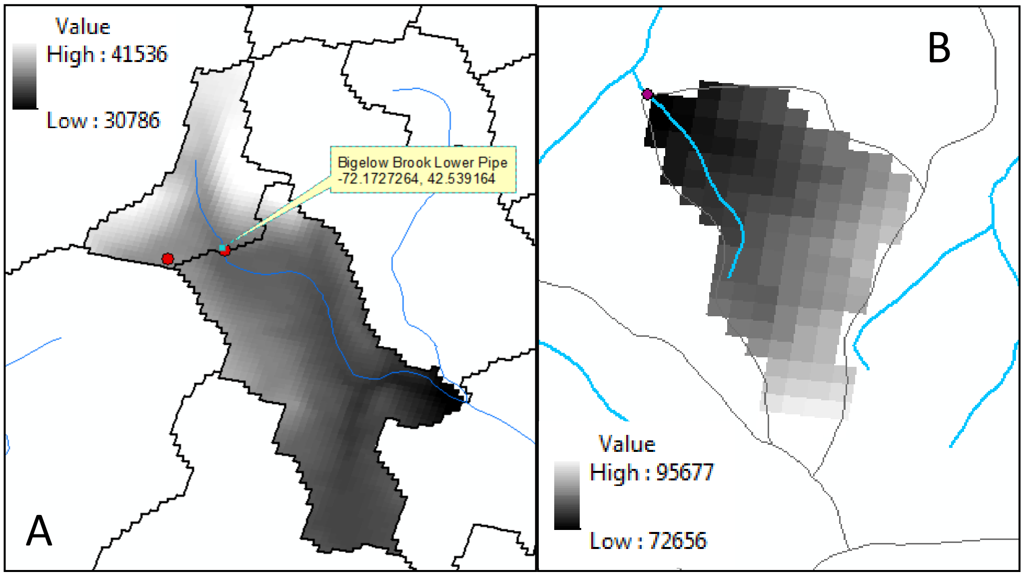

Figure 8: Elevation raster data is displayed over each of the catchments A) Harvard Forest LTER and B) Coweeta LTER. Additional dimensions include area and elevation difference across each basin: 0.511 km^2, 108m; and 0.123km^2, 230m for Harvard LTER and Coweeta LTER respectively.

Due to the less extreme elevation changing in the Harvard LTER, it exhibits more of a rolling hillside; the lack of discharge compared to output could be explained as precipitation has less of a tendency to run-off the soils due to the low hill slope aspect. Conversely, the budget in Coweeta shown in Table 2 shows that the stream output is 2 magnitudes greater than input. The steep slopes of this catchment could intersect the water table which will yield perennial springs. A rough calculation to assume base flow over the study period was done, but the amount does not make up for the excess amount of discharge reported.

Although explanations given may provide some answers to clarify why the hydrologic budgets are many orders off, the one true validation to this study is that several other factors need to be considered when constructing a hydrologic budget. The largest oversight could be not considering evapotranspiration. While in the short term this is not a large value, over time this avenue for moisture output can add up substantially. Also a change in the volume of water stored in the vadose zone below depths studied (30cm) could account for a miscalculation. Infiltration could be affected by changes in hydraulic conductivity, with intense rainfall resulting in low conductivities and light, gradual rainfall of the same amount may penetrate the soil surface, due to a high conductivity, purely as a result of application rate.

Conclusion:

In addition to considering other natural phenomena, increased density and quality of soil moisture measurements will increase the accuracy of the calculated budget. LTER sites have some of the most extensive networks of soil moisture probes available, yet even these sites do not offer the quantity of measurements needed to accurately address the heterogeneities in soils over large tracts of land. This hammers the idea home that while having extensive and detailed information about vadose zone variables in space and time would provide unimaginable results for hydrologic budgeting; it is a far much more involved process that is not feasible at this moment in time. The convoluted nature of soil response to precipitation is clearly affected by far more than ambient soil moisture and soil type. Further considerations of the other aforementioned inputs and outputs must be considered to create of better picture of flow through this portion of the Earth’s hydrologic cycle.

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