Colorado Water Conservation Board (CWCB) Completion Report – Evaluating the Time Series Discontinuity of the NRCS Snow Telemetry (SNOTEL) Temperature Data across Colorado

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1. Overview of the Issue

The Natural Resources Conservation Service (NRCS), formerly the Soil Conservation Service (SCS), established monthly manual snowpack measurements called snow courses across the Western United States (U.S.) in the 1930s. Snow water equivalent (SWE), snow depth and density were measured at the snow courses, typically on the first of the month over the winter (from February through May in Colorado). The SWE data were used to forecast seasonal runoff volumes across mountain rivers. In the late 1970s, these snow courses were complemented by automated snow telemetry (SNOTEL) stations that provide daily, and even sub-daily, measurements of SWE and cumulative precipitation. A decade later temperature measurements were added to the SNOTEL stations. Temperature was measured using a YSI temperature sensor located at or near the SNOTEL datalogging hut. In the late 1990s to mid-2000s, a change occurred whereby i) the sensor was changed from a (standard) YSI to a YSI Extended Range sensor <*ysi.com*>, ii) the radiation shield was changed, iii) the voltage to temperature algorithm was changed, and iv) the sensor location was changed so that all are now at the same relative position, on a cross-arm off the tower opposite the snow pillow and snow depth sensor (Julander *et al*., 2007). Unfortunately the first temperature configuration was only maintained concurrent with the new configuration at a few sites in Idaho. This temperature sensor change has yielded an "artificial amplification" of warming at many of the SNOTEL stations (Oyler *et al*., 2015).

Globally there has been a focus on warming and it relation to elevation (e.g., Pepin and Lundquist, 2008; Rangwala and Miller, 2012; Pepin *et al*., 2015). Across the Western US, the SNOTEL network has been used to assess climate change. In Colorado, SNOTEL stations have been used to identify changes to the snowpack (e.g., Harpold *et al*., 2012) and warming in the mountains (e.g., Clow, 2010). However, SNOTEL-based temperature changes are partly an artifact of the sensor changes (Oyler *et al*., 2015). In Colorado, the sensor change occurred between 2004 and 2006 <*wcc.nrcs.usda.gov*>. This focus of this project is to evaluate the discontinuity of the temperature time series at the SNOTEL stations across the state of Colorado.

2. Existing Homogenization of the Temperature Dataset

Oyler *et al*. (2015) provide corrections to the daily minimum and maximum SNOTEL dataset (482 stations) based on comparisons to the U.S. Historical Climatology Network (USHCN, see Menne *et al*., 2009) dataset (320 stations) over the period from 1991 to 2012. Trends were computed by Oyler *et al*. (2015) using an ordinary least squares linear regression to time series of annual temperature anomalies, and showed a substantial bias, especially for minimum temperature across the Southern Rocky Mountains of Colorado (Oyler *et al*., 2015 Figures 2e, 2f, S3e, and S3f) . As well, data from the old sensors and new sensors that were operated concurrently at four sites in Idaho from 1999 to 2001 were compared to explore the apparent cold temperature bias for old sensor (data from Phil Morrisey, hydrologist, USDA NRCS shown in Figure S4 of Oyler *et al*., 2015).

3. *Approaches to Evaluating the Data*

While the adjusted SNOTEL temperature dataset, homogenized using the USHCN data, appear reasonable (e.g., Oyler et al., 2015 Figure 3 and 4), trends over a similar time period (1989 to 2008) from an elevational gradient in the Front Range in Colorado are not as consistent (McGuire *et al*., 2012). In relatively flat terrain, such as the Eastern Plains of Colorado (Pielke *et al*., 2002) and the Northern Great Plains (Fassnacht *et al*., 2016), temperatures (and other climatic trends) are often different, even over short distances. It is unclear how useful it is to provide homogenization of the SNOTEL temperature dataset using lower elevation USHCN stations. As such, three adjusted datasets were evaluated using two approaches.

Sixty-eight long-term SNOTEL stations across Colorado were examined for the period from 1991 through 2015. SWE and precipitation data through 2013 were obtained from Fassnacht and Records (2015). The SNOTEL temperature data and the remaining years of SWE and precipitation data were retrieved from the NRCS <*wcc.nrcs.usda.gov*>. The temperature datasets were adjusted using i) the best-fit curve for the Morrisey data (Figure S4 of Oyler *et al*., 2015), ii) the Oyler *et al*. (2015) adjustments to individual SNOTEL stations, and iii) nearby USHCN and other independent stations. Although it has been shown that climatic trends from adjacent stations can vary in magnitude and direction (e.g., Pielke *et al*., 2002; Fassnacht *et al*., 2016), the comparison to other stations (iii) facilitated evaluation of local trends and patterns. Throughout these analyses, the temperature time series after the sensor change (~2004 to 2006) was used as representative, and the pre-change data were adjusted (Domonkos, 2016).

The first analysis approach was to investigate trends in the various datasets through the non-parametric trend analysis using the Mann-Kendall test for significance (Mann, 1945; Kendall and Gibbons, 1990) and the Theil-Sen's slope for the rate of change (Theil, 1950; Sen, 1968). A variety of trend analyses were performed. Initially the trends for the original dataset were computed for the entire time series, for the data before the sensor change, and for the data after the sensor change (Table 1). Trends were also computed for the entire period of record for the three adjusted datasets.

Table 1. Temperature datasets and time periods used in the a) trend analysis, and b) calibration and evaluation of the SWE modeling.

dataset	a) trend analysis time period		b) SWE modeling
	start	end	
original entire	1991	2015	N/A
original pre-sensor change	1991	2004 to 2006	evaluation
original post-sensor change	2004 to 2006	2015	calibration
H1: Morrisey concurrent data	1991	2015	evaluation (pre change only)
H2: Oyler adjustment	1991	2015	evaluation (pre change only)
H3: USHCN adjacent station(s)	1991	2015	evaluation (pre change only)

The impact of the inhomogeneity of the SNOTEL temperature datasets have been evaluated for climate change analysis (Oyler *et al*., 2015; Rangwala *et al*., 2015) and this current study investigated this in detail across the state of Colorado. Further, a second analysis approach was used to evaluate the implications on modeling SWE. A modified version of the Snowmelt Runoff Model (SRM) formulation (Martinec *et al*., 2008) was developed by Kampf and Richer (2014) that uses precipitation and temperature to model snow accumulation and melt, based solely on a temperature threshold for precipitation to fall as snow (T_s) and a melt coefficient (α), respectively. SWE is modeled for each year at each SNOTEL station and the two model parameters, T_s and α, are calibrated using the post-sensor change period of record. The calibrated model is then evaluated for the pre-sensor change period of record using the original and three adjusted datasets (Table 1).

4. Results

There are differences in the trends for the various periods of record (Table 1 original) with greater variations for minimum (Figure 1b) than maximum (Figure 1a) temperatures.

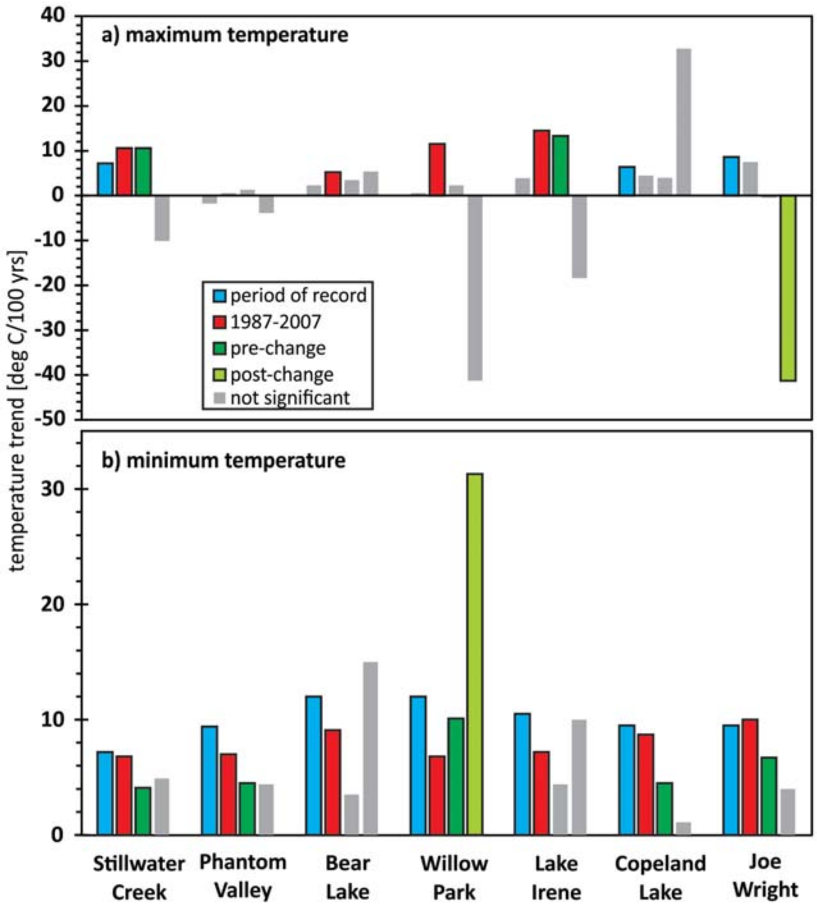

Figure 1. Northern Colorado examples of trends over the entire period of record (original dataset), pre-sensor change, post-sensor change, and the period of record used by Clow (2010).

From the Morrisey data (Oyler *et al*., 2015 Figure S4), an equation was derived as follows to adjust the daily minimum and maximum temperature:

$$T_{adjusted} = 5.30x10^{-7}\ T_{old}^{4} + 3.72Ex10^{-5}\ T_{old}^{3} - 2.16x10^{-3}\ T_{old}^{2} - 7.32x10^{-2}\ T_{old} + 1.37 \quad (1),$$

where $T_{adjusted}$ is the revised temperature and T_{old} is the existing temperature. This equation was applied to the pre-sensor change dataset. It can be seen that the annual minimum temperature tends to be cooler in the pre-sensor situation (Figures 1b and 2). The adjustments has less of an impact on maximum temperatures. The Oyler *et al*. (2015) homogenization with the USHCN stations yields more of a trend, but is still not significant (Figure 2).

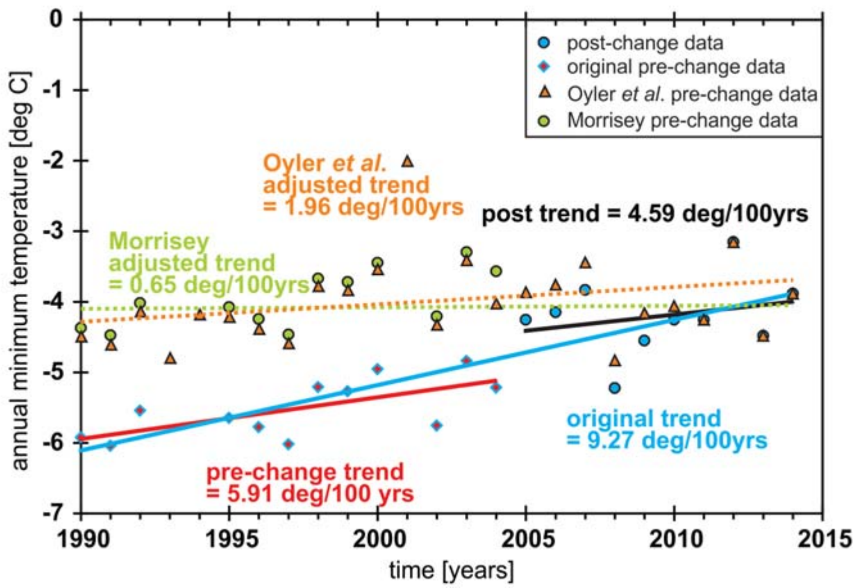

Figure 2. Plot of mean annual minimum temperature for the Joe Wright NRCS SNOTEL station. Trend lines were fit to the data according to the different time periods. Dotted lines represent no statistical significance. Two adjustments were applied to the data (the Morrisey concurrent sensor curve and the Oyler et al. UCHCN homogenization).

From the original dataset, a majority of the annual trends were warming temperatures (Table 2). This was especially true for the average and minimum temperatures where 67 of the 68 stations (except Arrow) were warming significantly. More of the maximum temperatures were warming (51 stations) than cooling (17 stations), but fewer trends were significant. When the Morrisey concurrent sensor curve adjustment was applied, few stations were significantly warming and the average rate of warming was at a lower rate. From the original dataset, the greatest computed warming was 27.8 and 22.1 degrees per century for maximum and minimum temperatures, respectively, while it was 23.7 and 12.0 degrees per century for the adjusted dataset. Similar results were found using the Oyler *et al*. (2015) adjustment. Overall the trends tend to be smaller and fewer are significant with the adjusted data compared to the original dataset (Figure 3).

Table 2. Average (and count out of 68 in parentheses) of trends in degrees per century for annual maximum, average and minimum temperatures for the original dataset versus the adjustment using the Morrisey concurrent sensor curve (equation 1), separated significant and non-significant increasing and decreasing trends.

		maximum		average		minimum	
dataset	direction	signif.	non signif.	signif.	non signif.	signif.	non signif.
original	decreasing	-7.5 (7)	-2.0 (10)	N/A (0)	-1.9 (1)	N/A (0)	-3.7 (1)
	increasing	7.4 (30)	1.4 (21)	9.3 (67)	N/A (0)	12.3 (66)	4.2 (1)
	total	4.6 (37)	0.3 (31)	9.3 (67)	-1.9 (1)	12.3 (66)	0.2 (2)
Morrisey adjustment	decreasing	-6.8 (13)	-1.5 (22)	-5.5 (1)	-0.4 (2)	-9.0 (1)	-2.9 (1)
	increasing	6.9 (17)	1.7 (16)	4.4 (51)	1.5 (14)	5.4 (59)	2.1 (7)
	total	1.0 (30)	-0.2 (38)	4.2 (52)	1.2 (16)	5.2 (60)	1.5 (8)

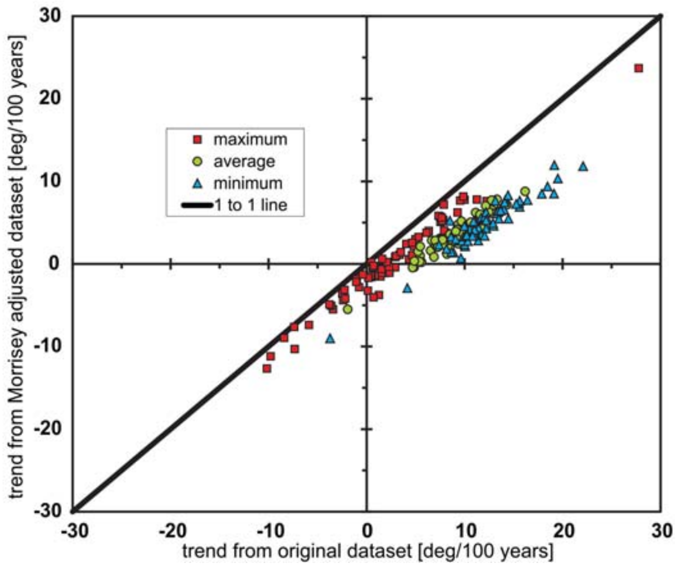

Figure 3. Comparison of trends from the original datasets versus those computed from the data adjusted using the the Morrisey concurrent sensor curve.

While the adjustment of the data using the Morrisey concurrent sensor curve yields computed trends that are more closely aligned with those observed elsewhere, some of the adjustments may be unnecessarily inflating the temperatures. Thus, the Morrisey concurrent sensor curve adjustment is not applicable for all stations, since not all pre-change sensors were in the same location at the data collection hut. *In situ* observations have noted the possibility of preferential cold air drainage at night about the hut which would yield colder minimum temperatures (Domonkos, 2016). At many sites, there have also been changes in the canopy, either by possible encroachment (e.g., Fassnacht and Hultstrand, 2015a; 2015b) or conversely due to beetle kill. It should be noted that the NCRS snow survey has made an effort to minimize canopy changes, especially encroachment, but for safety reasons some dead trees have been removed. For example, around 2009, the Arrow site was completely cleared by a private land owner due to beetle kill. Therefore, it is recommended that hemispherical canopy closure photographs be taken at each SNOTEL station on a regular basis. It may be possible to use high resolution imagery to examine canopy changes over the past decade.

Similar to Figure 3, the Oyler *et al*. (2015) adjustment using the USHCN stations appears to yield good results at numerous stations, but not all. Thus, for a few SNOTEL stations, trends and SWE modeling are being evaluated for the two adjustment methods, as well as using nearby meteorological stations (Table 1) from the USHCN and other sources (e.g., USGS Loch Vale used by Clow, 2010 or Niwot LTER stations used McGuire et al., 2012). Most USHCN stations are located at lower elevations than the SNOTEL stations, but some are at similar elevations (e.g., Fassnacht *et al*., 2013). Results from these comparisons are pending.

SWE was calibrated using the post-sensor change data, and then evaluated using the other datasets (Table 1). The model works reasonably well (T_s = 5.35 C, α = 3.05mm/C), capturing the general shape for a low and high snow year (Figure 4). In this example, using the temperature adjusted by the Morrisey concurrent sensor curve yielded the best results. It should be noted that the calibration parameters varied depending on the SWE data used with the optimization statistics, specifically the entire year of daily data, March through Mary of daily data, or just peak SWE. For Joe Wright, peak SWE was modeled best when calibrated but next best with the Morrisey concurrent sensor curve adjustment (Figure 5).

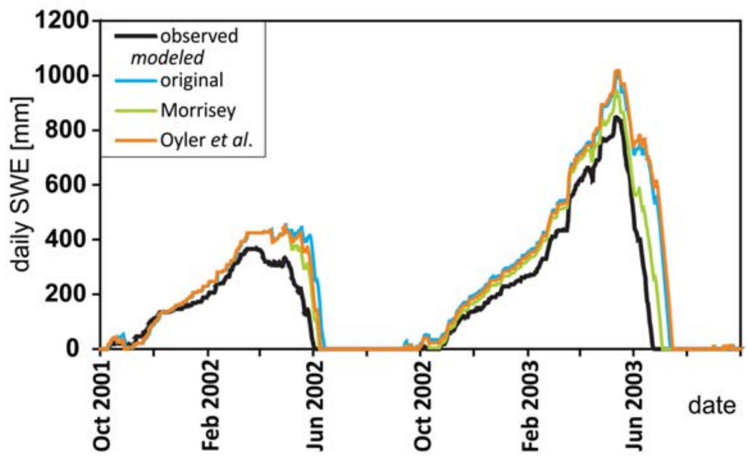

Figure 4. Sample observed and modeled SWE using the original, Morrisey concurrent sensor curve, and Oyler et al. adjustments for the Joe Wright SNOTEL station for low (2002) and high (2003) snow years.

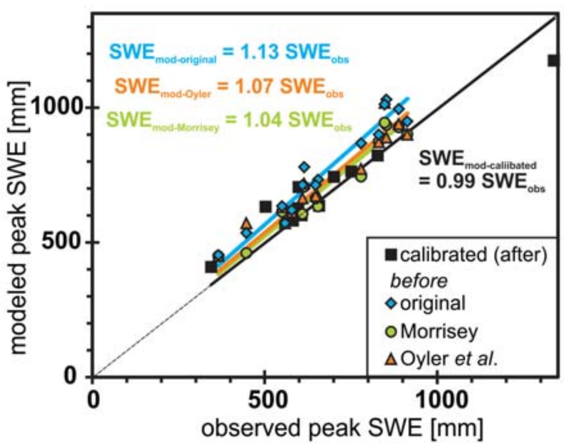

Figure 5. Modeled versus observed peak SWE at the Joe Wright station based on calibrated (post-sensor change data) and evaluated using the original, Morrisey concurrent sensor curve and Oyler et al. adjustments. The equations are the best fit lines through the origin showing that the calibration is almost a 1:1 fit.

The modeling peak SWE for the Joe Wright station performed well for all datasets (Figure 5), but this is not the case for time periods compared (e.g., daily SWE for the entire year), nor for all stations (Figure 6). Modeling the daily SWE for March through May period (Figure 6b) is important to estimate peak SWE, and the timing of peak SWE. While that SWE modeled used herein is a simple model, it does illustrate an additional use of the SNOTEL data. Non-stationarity must be considered in such modeling exercises (Fassnacht and Records, 2015).

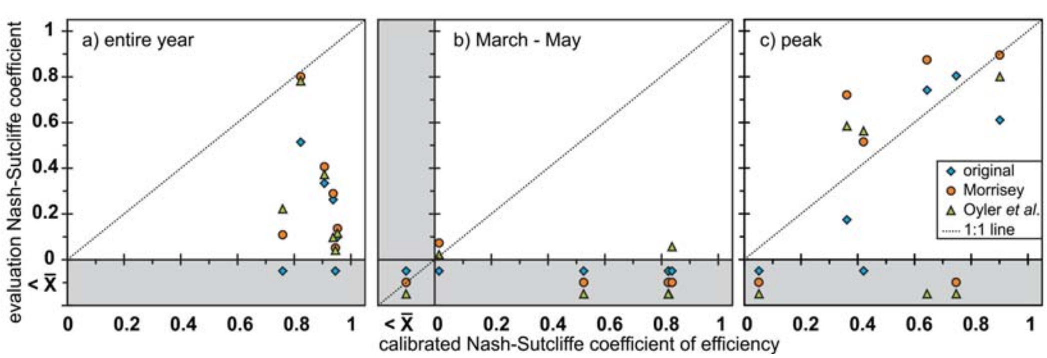

Figure 6. Modeled SWE comparison of Nash-Sutcliffe coefficient of efficiency (NSCE) for Northern Colorado stations shown in Figure 1 for a) daily SWE for the entire year, b) March - May, and c) peak SWE. When the NSCE value is less than zero (grey area), the mean is better.

5.   Ongoing Work

The results presented herein are mostly from the M.S. research undertaken by Chenchen Ma, under the supervision of Professors Steven Fassnacht and Stephanie Kampf. She will likely defend her thesis in the spring of 2017, at which time more results will become available (see Table 1). A journal manuscript will be prepared based this work and will be submitted in fall 2017. Her research will thoroughly assess the feasibility of adjusting the pre-sensor change temperature dataset for the Colorado SNOTEL stations. At that time the most useful adjustment for each station, where feasible, will be applied to the temperature dataset. Such data will be available in the public domain by the end of 2017 through the library at Colorado State University <*lib.colostate.edu*>. Other online portals will also be explored.

6.   Uses of the Adjusted Dataset

While the SNOTEL temperature dataset has problems, it has been used to drive and evaluate a variety of models, including hydrological and climate. Recently, the data have been combined with SWE data to estimate melt rates across the Southern Rocky Mountains (Figure 7 from Weber, 2016). It is anticipated that further adjustment to improve the continuity of the temperature dataset will enable numerous other applications.

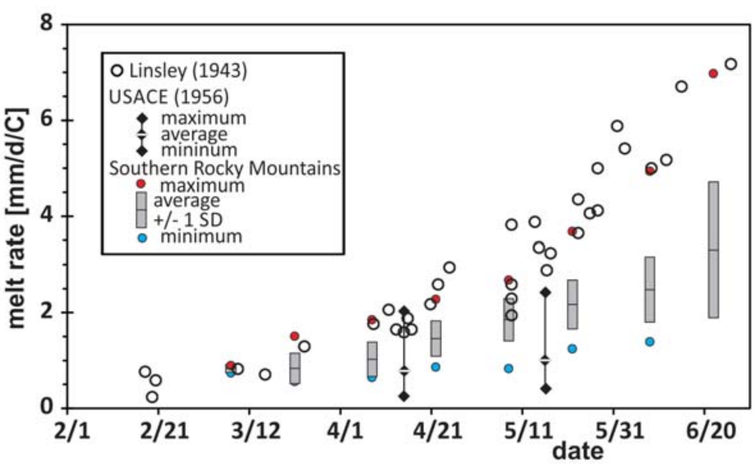

Figure 7. Snowmelt rates as a function of time of year for three different studies (Linsley, 1943; U.S. Army Corps of Engineers, 1956; Weber, 2016). The Southern Rocky Mountain data are for nine half-month periods and summarize four (early July) to 75 (early May) stations (from Weber, 2016).

It is very unlikely that the non-extended range YSI sensors will be installed at their pre-sensor change location and operated concurrently with the new sensor (Domonkos, 2016). There are also some issues with the current calibration of the extended-range YSI sensors, but those are being explored by the NRCS (Domonkos, 2016). The quality control of the daily temperature data from the hourly data also illustrates some anomalous spikes which may not be obvious from the daily data (Landers, 2016). It is thus recommended that the hourly, or historically three-hour, data be quality-controlled and adjusted to improve the continuity of the pre-sensor change temperature time series. This will be explored as part of this current research.

7.   Existing Products from the Work

The honors undergraduate thesis was written in part based on this research (Weber, 2016), and a manuscript is in preparation. The M.S. research is ongoing and results have been presented at the American Geophysical Union Hydrology Days Conference (Ma *et al*., 2016) and to the NRCS Colorado Snow Survey office (Domonkos, 2016; Landers, 2016).

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