UNDERSTANDING TRENDS IN SNOW ACCUMULATION, WATER AVAILABILITY, AND CLIMATE CHANGES USING SNOW TELEMETRY AND STREAMFLOW OBSERVATIONS IN THE MISSOURI RIVER HEADWATERS

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ABSTRACT

The Missouri River headwaters are located in the mountains of southwestern Montana, and serve as a water source for 10 states and approximately 10 million people. A key component of the annual water budget in this headwater region is from snowfall, accounting for around 70% of the total annual flow. The Western U.S. is comprised of semi-arid to arid regions that exhibit a high degree of inter-annual to multi-decadal variability. Changing trends in water availability due to climate change and yearly variations must be understood and quantified for proper allocation and forecasting of water resources. Here we use snow, temperature and precipitation records from the Natural Resource Conservation Service (NRCS) and streamflow records from the U.S. Geological Survey (USGS) in a coupled analysis designed to assess recent changes in these temperature sensitive high alpine headwaters over the last 40 years of record. Snow water equivalence, snow depth, temperature and streamflow are key metrics that are indicative of changes in these headwater regions and are useful in determining the amount, timing and duration of hydrologically important snow-driven events. These data are being examined to determine what role inter annual and decadal drivers such as the El Niño Southern Oscillation (ENSO), the Pacific North American Pattern (PNA), and the Pacific Decadal Oscillation (PDO) play in controlling the amount and timing of water availability in this catchment. Metadata from the weather stations used in this study are being analyzed to determine how changes to the station, such as vegetation growth or equipment updates, could help explain any trends or relationships seen in the data beyond the natural climate variations. (KEYWORDS: SNOTEL, snow hydrology, temporal trends, climate, Missouri)

INTRODUCTION

In the Western United States, where snowfall accounts for as much as 50 – 70% of total annual precipitation, the winter snowpack is a major water resource. (Serreze et al., 2001) Water availability is an important issue for most of the interior west, which is characterized in many parts by an arid to semi arid climate. Currently the Western US uses a large portion of available water so the establishment and quantification of a relationship between water and climate is crucial. (Regonda et al., 2005) To meet the needs of continued development in the west understanding water and snowfall trends is imperative for allocating water resources.

The snow telemetry (SNOTEL) network, which is operated by the Natural Resources Conservation Service (NRCS) and streamgage sites operated by the U.S. Geological Survey (USGS) provide a record for tracking our water resources. The SNOTEL records help monitor important parameters of snow accumulation over the winter and ablation in the spring. SNOTEL has allowed for observations of snow water equivalence (SWE), snow depth, precipitation, and temperature to occur on a daily basis. SNOTEL records in Montana started in the winter of 1963-1964 at Lick Creek in Hyalite Canyon (Farnes, 1969). Streamgage sites give daily observations of discharge flows. A detailed analysis of these long-term records allows for understanding of relationships between snowfall, water abundance and long-term climate patterns. Establishing these relationships would provide an understanding of year-to-year variability and how it is connected to long-term weather patterns to help predict future water availability.

The representativeness of using SNOTEL stations in determining changing trends in snowfall and water availability will be studied. Metadata from SNOTEL stations will be analyzed to determine how changes to the station could explain any trends or relationships seen in the data. These changes include, but are not limited to, changes in site location, vegetation and site sensors. This should differentiate between what may be a change in snowfall and temperature trends and what may be a change in the state of the recording device. While numerous studies have used historical records to investigate trends in water resources they have generally not addressed potential complications that could arise from the associated metadata of the sources.

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STUDY AREA

The Missouri River headwaters are located in the mountains of southwestern Montana, and serve as a water source for the Missouri River basin (Figure 1). The Missouri River basin encompasses 10 states with a population of approximately 10 million people. Landmass in the basin is predominantly used for agriculture, accounting for roughly 40% of wheat, 20% of corn and 30% of cattle produced in the US. (Mehta, 2013) As one of the only mountainous catchment basins feeding to the Mississippi, the Missouri relies heavily on snowfall as a water source.

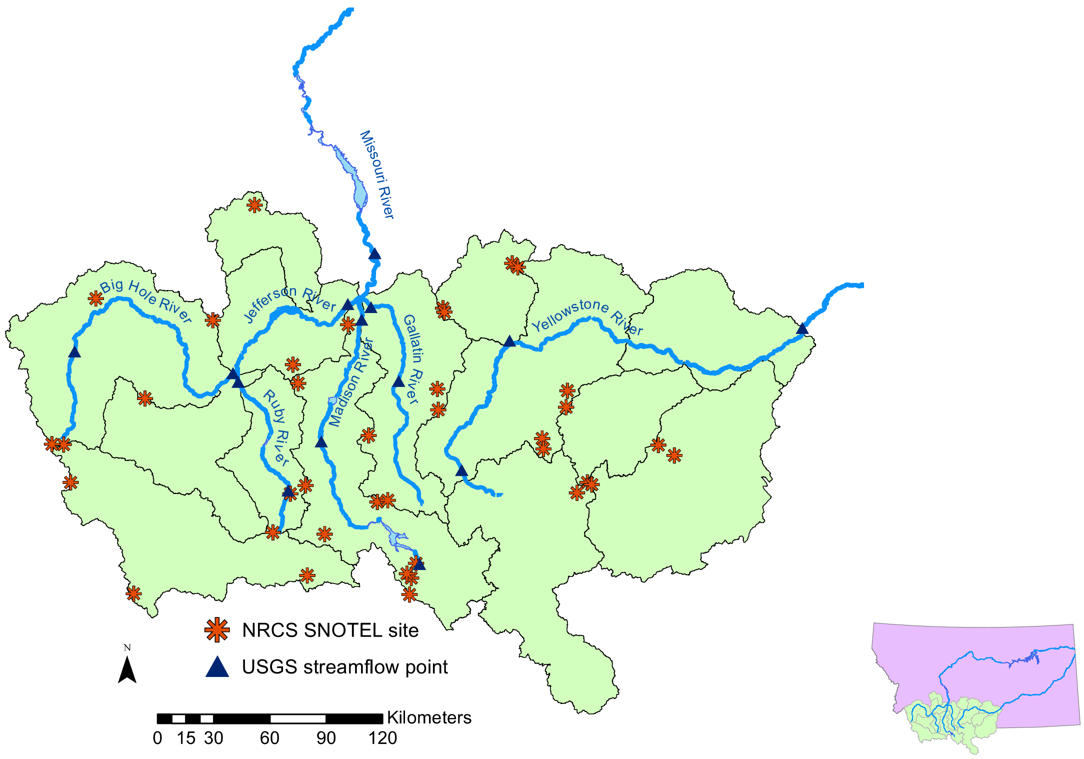

Figure 1. Missouri River headwaters

This study will concentrate on the Missouri River headwaters in southwestern Montana. The Jefferson, Madison and Gallatin Rivers are the three main waterways that comprise the headwaters. The Madison, and Gallatin Rivers originate near the Montana, Wyoming and Idaho border and run north through southwestern Montana to their confluence near Three Forks, Montana. The Jefferson is formed at the confluence of the Big Hole and Ruby rivers and flows to the northeast to join the Madison and Gallatin near Three Forks. The Missouri River source is the confluence of the Jefferson, Madison and Gallatin rivers. The Upper Yellowstone River can also be considered part of this headwater system. The Upper Yellowstone originates in the very southern section of Yellowstone National Park. The Yellowstone flows north through the park to Livingston, Montana where it turns, travels eastward through Montana and joins the Missouri River just inside North Dakota.

To take advantage of all possible pieces of information on snowpack and temperatures every NRCS SNOTEL site in the headwater region will be used for the study. USGS streamgage sites were chosen from the USGS Hydro-Climatic Data Network. These are sites that have met criteria developed by the USGS to represent natural flows. The natural state conditions that exist at these locations allow the streamflows to be deemed as climate sensitive rather than influenced by human factors. Sub basins in the study area generally have around 4 SNOTEL sites draining to one streamgage site. Each location in the SNOTEL network usually has two stations, one station representing low elevations and one representing high elevations.

RESEARCH OBJECTIVES

1. Is there a relationship between snowfall, water availability and climatic trends in the SNOTEL records in the Upper Missouri River basin? What are the larger implications for areas whose water supply relies on the upper Missouri River basin?

2. Are there any patterns (i.e. inter annual or decadal) that could be taken account of and planned for into the future?

3. How does the use of metadata from SNOTEL sites improve our understanding and quantification of these observed trends?

These objectives are designed to give a better understanding of the water budget in high alpine catchments in the interior western US. Understanding the strength of the relationship between snowfall and water availability is important knowledge for places where snowfall makes up a large percentage of the total water budget. The Missouri River headwaters are the focus of the study in order to explore this relationship specifically in high alpine headwater environments. Also, the region has a high density of SNOTEL sites.

Relating the high interannual variability in water availability to decadal weather patterns helps to determine some of the drivers of the variability. Exploring the strength of the link between certain predominant decadal weather patterns and yearly variability would help forecast water resources through the duration and to the extent that decadal weather patterns can be predicted.

SNOTEL data have been used in previous studies to associate snow depths, rainfall, and temperature to climate variability and change. These studies have mostly taken place on a large scale such as the western US (e.g. Serreze et al., 1999, Mote et al., 2001). In particular, Serreze et al. (1999) discusses SNOTEL records for eight regions encompassing the entire western US. The eight regions were studied and compiled to make generalizations about the widespread study area. For pragmatic reasons, large-scale studies often do not use, or even interrogate the metadata available for the sites. These metadata can be critical as they may in some cases explain the observed changes in the measured parameters. There are many factors that could interfere with the reliability of the historical SNOTEL record. Changes in the location of the sensor or growth or destruction of the surrounding vegetation could all have lasting effects on the record produced by this station and could easily be overlooked in larger scale studies.

Pederson (2011) investigated the Northwestern portion of Montana and Southern Canadian Rockies in his recent paper and this study will work closely with his to help extend the study area. Linking independent small-scale studies based in western Montana helps generate a greater understanding of the trends affecting the state. The two study areas contain important headwaters and ecosystems. Individual studies in both these areas would provide important information on the health of their resources. Also, if similar results are found it gives both studies an additional level of validity. This study will allow for compatibility between the two by using similar metrics.

METHODS

SNOTEL and streamgage records are being used to assess the relationship between snowfall, temperatures and streamflow as well as the impact of climate variability and change on water resources in the upper Missouri River basin. Analysis of the SNOTEL record is currently underway. A list of metrics, which characterizes important events of the snow year, has been developed. The statistical program R has been used to query the daily historical SNOTEL and streamgage data and calculate these specified metrics. By developing code, data from multiple stations can be obtained very efficiently and at no extra cost.

For each SNOTEL site these metrics have been collected from the historical record:

- -Peak SWE, date of peak SWE and the date when SWE drops below 90% of maximum
- -Maximum snow depth, date of maximum snow depth and the date when snow depth drops below 90% of maximum
- -April 1st SWE and snow depth
- -Dates when snow depth is more than 10cm and less than 10cm

As well as the following precipitation metrics:
- April 1st year to date precipitation
- Total water year precipitation

Temperature records, also from SNOTEL data, will be analyzed:
- Maximum, minimum and average temperatures
- Maximums, minimums and averages for three month partitions
- Number of days with an average temperature below freezing
- Number of days with an average temperature above freezing

For streamflow the following metrics will be recorded from USGS streamgage sites:
- Total discharge
- Maximum streamflow and date of maximum streamflow
- Minimum streamflow and date of minimum streamflow
- Average daily streamflow
- Dates when 5, 10, 25, 50, 75, 90, 95% of the discharge for the year has passed the streamgage
- Duration of stream flows within the top 10% of all streamflow
- Dates with streamflows greater than 75% of all flows
- Median of dates with streamflows in the top 1% of all flows
- Discharge of streamflows in the top 1% of all flows

These metrics are similar to those of Pederson's (2011) study in the northern portion of the state, allowing the data collected to match data that has already been analyzed. Because snow telemetry requires measurements to be remotely sensed collected measurements must be viewed and used with expert judgment regarding the accurateness.

Statistical Analysis

R is also being used in the statistical analysis of the collected data. Models are used to explore key relationships in the data. These key relationships have been identified as trends in maximum snow water equivalence over time, trends in maximum, minimum and average temperature over time, relationship between maximum snow water equivalent and streamflow and trends in timing of snow melt runoff over time. R squared values will be calculated to quantify the strength for many of the relationships. Matching the data to specific weather patterns is another important part of the statistical analysis. The interannual variability will also be quantified using standard deviation.

Metadata Study

The metadata from SNOTEL sites are being analyzed in order to assess factors that could contribute to any systematic errors in the long-term record. This is being accomplished by inspecting the metadata, comparing horizon diagrams, which are canopy images showing the vegetation that could potentially be interfering with recording sensors at the site, and through graphical tools such as double mass curves which can show points in time when trends seen in the record have been altered.

Lucas Zukiewicz and Brian Domonkos from the snow survey program with the NRCS office in Bozeman are assisting in the search for metadata and for horizon diagrams taken at the sites. Their office has hard copies of all recorded changes to the station as well as the horizon diagrams taken throughout the lifetime of the SNOTEL sites in the Missouri River headwaters. The horizon diagrams available from the NRCS office have been documented. Many sites had diagrams taken in the late 60's and early 70's. No diagrams have been taken since the initial round so new diagrams will be taken at some of the sites. The comparison of how the percentage of open sky has changed over the last 40 years will be incorporated in models when looking at overall trends, yearly variation and reported and discussed as a potential source of error when examining SNOTEL data over the course of many years.

RESULTS

Exploratory plots and statistics are being used to explore the stated objectives. Time series plots have been developed to show the historical record (Figures 2 and 3).

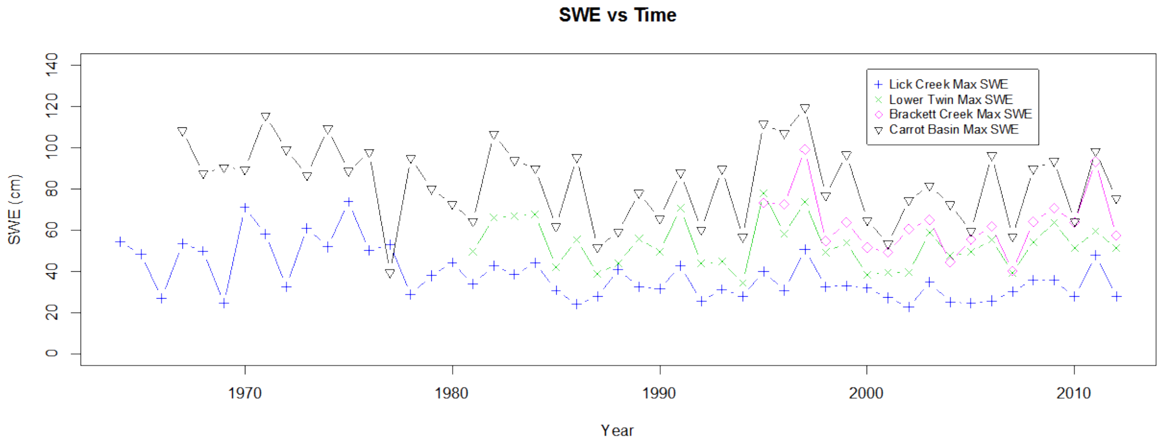

Figure 2. Time series of snow water equivalence over the duration of the SNOTEL record for 4 stations

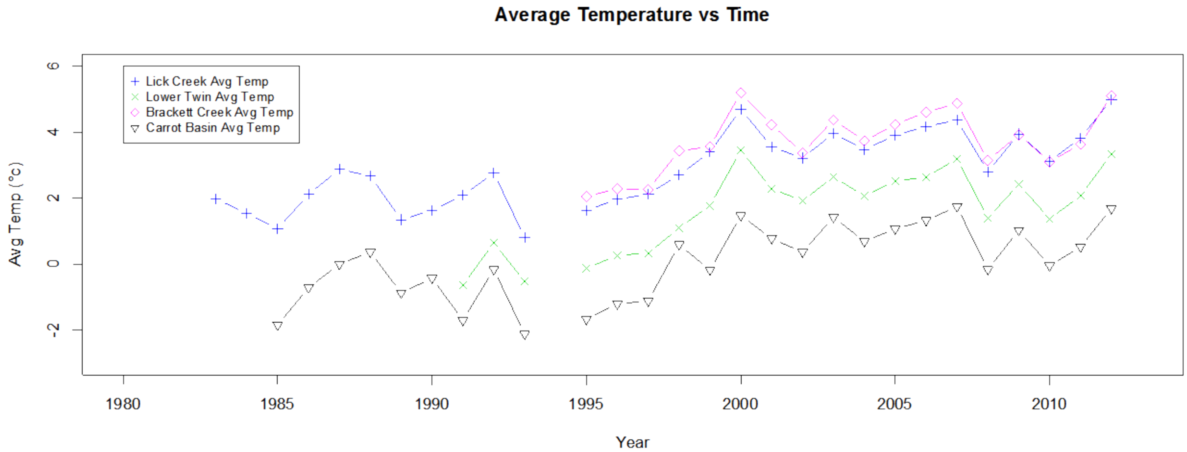

Figure 3. Time series of temperature over the duration of the SNOTEL record for 4 stations

There is a strong correlation between maximum snow water equivalence and total streamflow. As an example, in the Shields River Valley, the developed model incorporated the streamgage at the outlet of the catchment as the response and the four SNOTEL stations in the valley as the explanatory variables (Figure 4). The strength of the maximum SWE and total streamflow relationship can be quantified with an R-squared value of 0.95.

As this thesis is concluded, more results will be reported when they are available. At this point, however, many results have yet to be established.

CONCLUSIONS

The study area is a high alpine fragile headwaters system the results for this small area can give an indication as to whether these types of high alpine areas show similar trends as the rest of the west or if these areas show different types of relationships between snowfall, temperature and streamflow. They might have a different level of dependency on snowmelt, show a different level of temperature sensitivity or show more or less interannual variability.

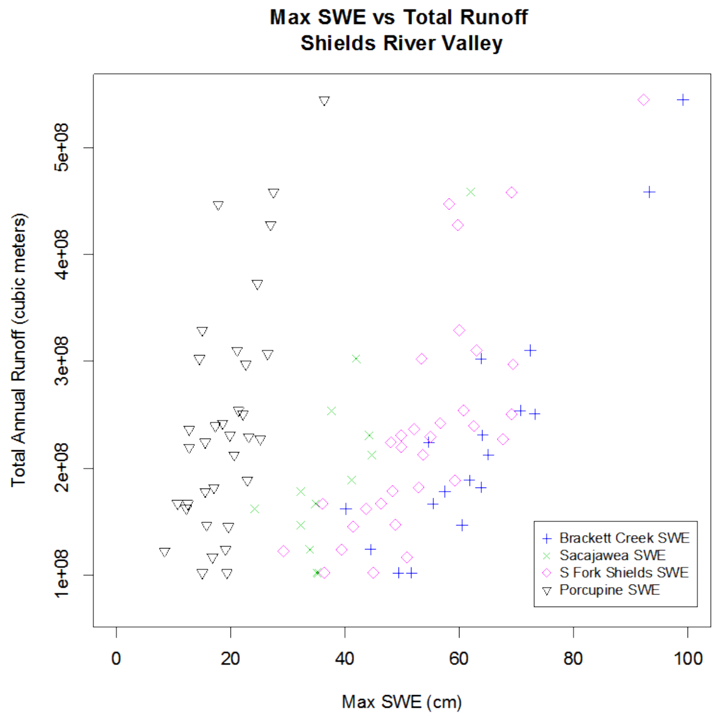

Figure 4. Scatter plot of Max SWE, measured by the four SNOTEL sites, and total annual runoff, measured by the Shields River streamgage, in the Shields River Valley

Documenting the representativeness of the historical SNOTEL record and determining how integral the metadata was in confirming or refuting the results will be an important product of the study. Establishing the importance of the metadata analysis will help establish a standard for other studies of this nature.

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