PALEOCLIMATIC INDICATORS OF SURFACE WATER RESOURCES IN THE CHUSKA MOUNTAINS, NAVAJO NATION

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EXECUTIVE SUMMARY

- Declining snow water equivalent is impacting water resources in northeastern Arizona, a condition that is expect to be exacerbated in a warming and drying future.
- Water availability is a critical issue for the Navajo Nation in the coming decades. Navajo tribal members who use the lakes along the crest of the Chuska Mountains for stock, wildlife, and recreation report declining lake levels and diminished surface water availability.
- Projections of rising temperatures and possible precipitation declines in the southwestern United States suggest that diminished surface water resources in the Chuska Mountains may continue in the future.
- Instrumental records of climate and of surface waters in the Chuska Mountains are acutely limited. The Navajo Nation began recording snow depth and snow water equivalent in 1985. At the time of this study, no lake level records existed for the Chuskas.
- This study is a collaborative effort with the aim of co-producing knowledge about the long-term variability of snow water equivalent and surface waters in the Chuska Mountains of the Navajo Nation. It is the result of collective efforts of the Navajo Nation Department of Water Resources Water Management Branch and the University of Arizona. The goal was to produce management relevant science products for the modern and paleo periods.
- The study represents the first attempt to place current snow water equivalent conditions in the context of the last 400 years. The results of this study provide the first ever lake area estimation for three primary lakes in the Chuska range. Methods are replicable and expandable so that Navajo water managers can continue Chuska water resources monitoring and supplement new efforts to quantify water resources in the Chuska Mountains.
- The methods were to 1) use regional precipitation sensitive tree-ring chronologies in a stepwise multiple linear regression model to produce snow water equivalent estimates back in time, 2) characterize decadal-length variability in snow water equivalent in terms of periods of low snowpack, 3) leverage existing remote sensing resources to generate satellite-based estimates of water cover for specified basins.
- The regression model shows that snowpack in the Chuskas can be successfully reconstructed using tree-rings. The most severe low snowpack period in the reconstruction was in 1954-1961. When compared to local knowledge, this study agrees with observations. This is the first 30-year long record of lake area for three large lakes in the Chuska Mountains. Lake area shows seasonal and interannual variability in surface water. Precipitation and temperature show a potential influence on this variability, as well as the apparent downward trend in surface waters over the last 30 years.
- Together with the Navajo Nation Water Management Branch, we took an interactive approach to knowledge production that was guided by the Navajo Nation, that was driven by their management needs, and intended to inform Navajo planning for regional water sustainability in times of drought and in the face of projected warming. These relationships are critical to forging integrated science-water management partnerships with the Navajo Nation in the future.

INTRODUCTION

Recent decades are characterized by declining snow water equivalent (SWE) in snowpack of northeastern Arizona and climate projections indicate that reduction of late-winter and spring snowpack will reduce water supply (3rd National Climate Assessment 2014). Snowpack in the Chuska Mountains feeds lakes, streams, and springs that support community farms. Depressions at the crest of the Chuskas collect snowmelt, providing water for Navajo stock animals, wildlife, and fish. Long-term records of water resources for the Navajo Nation are acutely limited, and without this knowledge of the natural variability of water resources in the Chuska Mountains, anticipating water availability in a culturally important region near the Navajo Nation's most populated and economically productive areas is difficult. At the onset of this project, no comprehensive records existed for the lakes in the Chuskas, and snow records were just reaching 30 years in length.

In light of declining snowpack, drying lakes, and a lack of up-to-date scientific knowledge of this problem, this study aims to gain current insight into the relationship between snowpack and Chuska surface waters, as well as gain long-term quantitative information about the hydroclimatic variability of this system. Tree-ring reconstructions can be useful for evaluating the natural history of a local area on a long-term basis and provide deeper quantitative context on the natural variability inherent to the place. Paleo records of drought, used in conjunction with model projections of climate change, can inform adaptation strategies and water management plans in the context of future drought conditions.

This study was designed to meet the expressed needs of the Navajo Nation Department of Water Resources, Water Management Branch (WMB). It was part of a collaborative arrangement with Navajo Nation water resource managers to produce management relevant science products for the modern and paleo periods, and was guided by a partnership with WMB and researchers in the School of Geography and Development and Laboratory of Tree-Ring Research. Together, we identified concerns and potential research avenues. This work provides insights into the drying surface waters of the Chuskas that may impact agricultural activities in the Chuska Mountains and in community farms downstream (e.g. Ganado, Cornfields, Kinlichee, Chinle, Many Farms, etc.). Results from this study are available to the Navajo Nation and can be used for future evaluation of snowpack variability. This information may also support local knowledge. As of 2016, the Navajo Nation Water Management Branch (WMB) is beginning a lake capacity monitoring program, which may be supplemented with satellite-derived lake area monitoring. This study also dovetails with ongoing climate research and partnerships between the University of Arizona and the Navajo Nation.

BACKGROUND

Observed declines in snowpack in the Navajo region are attributed to rising temperatures and the increased thermal effects of dust transported and deposited on the snow surface (Redsteer et al., 2013). Lower SWE leads to less water volume in the snowpack, and therefore less water runoff and storage in that year (Melillo et al., 2014). Mellilo et al., (2014) report that projections of future SWE suggest surface water from runoff in the southwestern United States will decrease in the future. At the same time, tribal members report that surface waters supporting agricultural practices and community resources have begun to go dry from extended drought. These trends mean understanding snowpack and the water it provides is critical for future water security in the Chuska Mountains.

A small number of previous studies have examined the role of climate variability on snowpack patterns in the Chuskas, but the ability of this work to examine the most extreme recent snowpack trends was limited by short instrumental records. For instance, Rachel Novak (2007) considered the variability and change in climate in the Chuskas. She used 25 existing tree-ring chronologies from the southern Colorado plateau and four corners (Dean and Robinson, 1978) to show that the region has experienced decade or longer droughts in the paleo record, and that the 20th century droughts do not rank among the most locally severe. However, this work was nearly a decade ago and consequently 1. misses the most recent 10-15 years of snow decline and drought in the region, and 2. the Chuska snow records were too short at that time to be used in statistical analysis. Lani Tsinnajinnie (2011) evaluated Navajo snow course and snowpack data in 2011. Her analysis was very useful in the exploratory stages of this project and in determining the climatological pattern of snow accumulation in the region. Her analysis was also limited by the short duration of the records at the time.

DATA AND METHODS

Study Area

The Chuska Mountains are an 80 km-long mountain range straddling Northeastern Arizona and northwestern New Mexico. The mountains stand tall above the surrounding plateaus, valleys, mesas and buttes of the Navajo Nation semi-arid lands. The western gradually sloped Chuska Mountains with steep eastern cliffs create a gradual elevational change from the highest, steepest points at the eastern most rim to lower elevations in the west. The crest of these mountains is relatively flat, allowing for the accumulation of surface waters in lakes and ponds, and flow into streams and springs. Reaching an elevation of almost 3,050 m (10,000 ft) they are considered vital native headwaters on the Navajo Nation (Harshbarger and Repenning, 1954; Garfin et al, 2007). Predominantly sandstone mixed with basaltic layers facilitates the vertical and lateral movement of surficial and subsurface water to streams, base flow, and groundwater aquifers (Wright, 1964).

The Chuska Mountains lie at the transition zone between winter-dominated weather systems and summer-dominated monsoonal precipitation. Here, there is a bimodal precipitation regime where most of the precipitation received is during the summer months of July and August, and during winter months of December through March. This results in summer precipitation patterns with the distinct timing of onset of monsoonal rain with high intensity convective events and winter snow accumulation at high elevations. Average annual precipitation on the Chuska Mountains ranges from 0.93 in/yr to 2.46 in/yr, but up to 4 in/yr in both winter (January-March) and summer (July-August) seasons. Annual mean temperatures range between 44° C and 49° C. From a seasonal perspective, interannual variability is a key characteristic of the Chuska Mountain region, and is punctuated by single-year large departures from mean precipitation values. Greater interannual variability exists in the cool season for both temperature and precipitation rates.

Surface water in the Chuska Mountains is primarily derived from snowpack, though surface water levels in late summer respond to heavy monsoonal events. The Chuskas have been used traditionally as a summer grazing location. Additionally, water resources are diverted off the mountains with small-scale diversions to agricultural farms below. Change in surface waters from one year to the next in the Chuska Mountains is largely documented in local observations. Based on these local observations, and because this is a mountain landscape with two dominant precipitation periods and because of the limited but stated assumptions in scientific literature (Wright, 1964) describing a snow driven hydrologic system, our hypothesis is that the amount of water in these lakes each year is in part controlled by snowpack.

Dendrochronological Analysis

Nearly a century of scientific literature documents the climatic sensitivity of trees in the western U.S. (e.g. Douglass, 1920; Schulman, 1956). Ponderosa pine (*P. ponderosa*), Douglas fir *(P.* menziesii) and Pinon pine *(P.* edulis) are tree species in the American Southwest sensitive to variation in precipitation. Ring-width, or radial growth, variability is controlled by the interannual variability of the tree's most limiting factor (eg. precipitation in this case). The result of this "sensitivity" to the environment around it means that ring widths will be small when the limiting factor is constrained, and wide when the limiting factor is abundant. Dendrochronological methods using sensitive trees can be used to generate reconstructions of hydroclimatic conditions in the southwest that occurred prior to the implementation of instrumental records. These paleorecords are instructive for analyzing when extreme dry or extreme wet periods have occurred, where they have occurred, and the sequence of seasons and years experiencing these extremes (Fritts, 1976).

Tree-ring chronologies were collected and developed from moisture-sensitive trees, *P. ponderosa, Ps. menziesii,* and *P. edulis,* at 14 sites in the Chuska Range and near the San Francisco Peaks (Figure 1). The Chuska Range climate chronologies were new collections as part of Chris Guiterman's 2015 "Climate Sensitivities of Navajo Forestlands" CLIMAS Climate and Society Fellows project. To supplement the chronology pool of potential predictors sampled from the Chuska Mountains, we sampled tree-cores from five sites in the San Francisco Peaks to update existing chronologies in the area so the records cover the most recent drought and have the most overlap with the snow records. Five sites located in the San Francisco Peaks were selected based upon existing collections that demonstrated a significant relationship ($p < 0.01$) with potential snow records, and feasibility of collection. Original collections updated for this study are San Francisco Peaks, Slate Mountain, Robinson Mountain, Sunset Crater, and Dry Creek (Salzer and Kipfmeuler, 2004; Sheppard et al, 2005; Meko and Hirschboeck, 2008). Two cores per tree were removed using Haglof increment borers. For every site, a location was recorded using GPS.

Each core was mounted, sanded and visually crossdated with cores following standard dendrochonological practices (Speer, 2010; Stokes and Smiley, 1996). Crossdating and measurement accuracy were verified using COFECHA (Holmes 1983; Grissino-Mayer 2001). Each individual series was detrended in the dplR program using a modified negative exponential curve (frequency response 0.50) or cubic smoothing spline interactive detrending (Bunn, 2008). Signal strength was assessed using effective chronology signal (reff) and expressed population signal (EPS) using the arbitrary 0.85 EPS threshold for statistically acceptable chronologies to be used in climate reconstruction. Robust bi-weight averaging of detrended indices resulted in developed site chronologies (Cook et al., 1990).

The Navajo Nation Water Management Branch provided snowcourse data for eight Chuska sites where they have been collecting snow depth and snow water equivalent for thirty years (1985-2015). In addition to Navajo snowcourse data, we obtained SNOTEL data from the Natural Resources Conservation Service (NRCS) for Navajo Whiskey Creek and Beaver Spring stations in the Chuskas. We obtained SNOTEL data for 18 snowcourse and SNOTEL stations along the Mogollon Rim, San Francisco Peak and Grand Canyon areas (Figure 2). Average winter storm tracks over northeastern Arizona provide a climatological link between the San Francisco Peaks, Mogollon Rim and Chuska Mountains. Lani Tsinnijinnie (2011) found strong correlations between MaxSWE (March) at 26 snow measurement stations in the Chuska Mountains and San Francisco Peaks. Leveraging the strong relationship with Mogollon rim snow records and shorter Chuska records, I chose to identify and use a single SWE record to represent Chuska snow. Selection critera excluded potential surrogates if they were very short and if they had several years with zero values. To ensure that the selected snow site is as representative of Chuska snow as possible, each potential site was correlated with each Chuska snow site, and the average of these correlations was taken. Based on these selection criteria, Williams Ski Run Snowcourse (WSR; 1965-2015) had highest correlation (($R^2 = 0.81$) and was determined the most appropriate surrogate for Navajo snow.

I used stepwise multiple linear regression and leave-one-out validation to develop a reconstruction model for WSR MaxSWE. Of the pool of 14 tree-ring predictor chronologies, 3 predictors (SSR, OCW and STC) contributed to the model. Runs anaylsis was used to isolate multi-year periods of severely low snowpack in the Chuska Mountains (Faulstich et al., 2013). Following Faulstich et al. (2013) runs periods were identified based upon a threshold of at least two consecutive years below the reconstruction mean, total number of consecutive years below this threshold, magnitude (cumulative deficit), and intensity (magnitude divided by duration). Scores in each category were summed to ascertain the most severe periods, and then ranked.

Lake Area Estimation

The Normalized Difference Water Index (NDWI) is used in remote sensing applications to monitor changes in water content in water basins. NDWI is calculated using the green and near infrared (NIR) reflectance wavelengths recorded in satellite imagery (McFeeters, 1996)

$$NDWI = (Xgreen - Xnir)/(Xgreen + Xnir)$$

A 32-day composite calculated NDWI dataset is accessible through Google Earth Engine (GEE; Gao, 1996). GEE is a Python-driven remote sensing analysis tool and satellite imagery clearinghouse available to scientists and researchers. Off-site storage and computational resources make intensive calculations of NDWI possible for low-budget researchers and water managers. GEE scripts facilitate storage, replicability, and the sharing of lake area calculations with the Navajo Nation Water Management Branch. With GEE scripts in hand, Navajo managers may continue to monitor water resources each year using the same methodology as that used in this study thereby ensuring an uninterrupted dataset.

Landsat images are generated from space-based multiband sensors (EMT+) acquired every 16 days at a 30-meter resolution. I used three Landsat datasets, Landsat 5 (1984-1998), Landsat 7 (1999-2012), and Landsat 8 (2013-2016) for full coverage of the period of available data. I delineated polygons around three primary lakes in the Chuska Mountains and overlaid pixels classified NDWI. NDWI pixels within each lake polygon were then counted. Percent NDWI, the lake area index, was calculated by dividing the NDWI pixels by the total number of pixels within the basin polygon. Results were compared with agricultural reports of estimates for Whiskey Lake, lake perimeter ground-truth with Navajo WMB staff, and pilot data using a modified NDWI method. This method is scalable and can used for surface waters over 30 sq meters throughout the Chuska Mountains. NDWI index values were compared to gridded monthly mean temperature (1895-2015) and summer precipitation (1895-2015) PRISM time series obtained from the PRISM Oregon State PRISM Climate Group (Oregon State University, http://prism.oregonstate.edu, created October 2016).

RESULTS AND DISCUSSION

Snowpack Reconstruction

We sampled 219 cores from 137 trees from Sunset Crater National Monument, Robinson Mountain, Slate Mountain, San Francisco Peak, and Dry Creek near Sedona. These chronologies boosted the number of predictors longer than 400 years, and with a statically significant ($p < 0.05$) relationship to Chuska snow for use in the reconstruction. The reconstruction calibration period is 1967-2014 and the reconstruction period is 1694-2014. Model predictors are *P. ponderosa, P. menziesii* and *P. edulis* collected at Small Twin Canyon, Spider Rock, and Oak Creek Wash, respectively. The regression model explains 52% of the variance in the calibration period, demonstrating skill in the model (Figure 3). Residuals are normally distributed, and all assumptions were met. RE and $RMSE_v$ validation statistics show that this model skillfully estimates MaxSWE during the validation period (Table 2). The snowpack reconstruction illuminates patterns of low MaxSWE and high MaxSWE at decadal to century scales (Figure 4).

Runs analysis highlights the frequency of low snowpack and reveals periods of extremely low snowpack in the Chuska range (Table 3). The most severe low snowpack period was in 1954-1961. The top ten lowest snowpack periods cluster in the mid- to late-1700’s, mid- to late-1800’s, and after about 1950. The longest run of low snowpack was at the beginning of the 20th century (1893-1905). The most recent drought (since 2000) does not rank among the top 5 lowest snowpack periods in the record. When compared to local knowledge, this study agrees with observations presented in Redsteer (2011) and in Novak (2007), both studies using local knowledge to study climate on the Navajo Nation. Consultants in these studies state: "In the 1950's there was blowing sand and dust [suggesting drought]"; "1950-1951 there was a drought that required moving livestock or selling it"; "…from ~1999-present (2007) there has been very little snow to fill the reservoir, so h/ has not planted... [and despite water management improvements] there is still not enough water to farm."

Lake Area Estimations

NDWI images estimating lake area from year to year (1984-2016) were successfully generated. This is the first 30-year long record of lake area for three large lakes in the Chuska Mountains - Toadlena Lake, Long Lake, and Whiskey Lake (Figure 5). NDWI images show seasonal and interannual variability in each basin. Time series have also been generated for the period 1986-2016. During the first two years of service for Landsat 5 (1984 and 1985) some images resulted in zero NDWI indexed images and were unusable. For this reason, these "roll up" years were excluded from the final time series. This method for estimating lake area is replicable at different scales and can be used to estimate surface waters over 30 sq meters throughout the Chuska Mountains. Additionally, this approach to surface water monitoring is transferrable with a minimal amount of training to the Navajo Nation Water Management Branch, providing a baseline for ongoing water monitoring.

Changes in water levels in each lake basin are observable in the NDWI images (Figure 6). The time series results were also evaluated qualitatively and quantitatively. There is a notable change in variance in the time series for each lake (Figure 7). Crimmins et al., (2013) analyzed drought for the Navajo Nation using a 24-mo Standardized Precipitation Index (SPI). One finding from that work was evidence of rapid swings between intense drought and periods of unusual wetness since 1990. Prior to that there were more years with precipitation closer to average. Characteristics in the lake area time series may support this finding. The range in variance at each lake increases beginning around 1990-1995 and may similarly indicate a climatic shift in extremes, though this hypothesis requires further investigation.
An apparent downward trend in Chuska surface water also shows that, at the beginning of the period, lake area estimates are above average. At the end of the period they are below average. It should be noted, however, that these records are short and this trend could be part of long-term variability indistinguishable over the short duration.

Apparent trends in the lake time series are curious, and they may have a relationship to climate. Snow is expected to be an important source of runoff in the Chuska Mountains based upon previous studies in the region, and based upon the theoretical understanding of snow-driven hydrology in mountain environments in the western US. Lake area trends were compared to trends in temperature, snowpack, and summer rains. There were no apparent trends in the snow records or summer rain records over the common period. However, lake area and temperature trends, negative trend and positive trend respectively, were evident (Figure 8). Some statistical methods can give misleading results if there are trends like these in the data. For example, correlations between all three lakes and snow/climate data including trends show the lakes having very high correlations with temperature, and modest to no correlation with snow and summer precipitation. After removing the trend in both the lake data and temperature data, different relationships emerge (Table 4). Similarly, linear regression can be used to find the influence of each climate variable (snow, temperature, summer precipitation) on changes in lake levels. Linear regression analysis in this application reveals similar differences before and after removing the trends in the data (Table 4). This observed statistical behavior suggests a more complex underlying phenomena driving lake level change in the Chuskas.

Small variability early in the record that gets larger over time suggests nonlinear relationships in the lake area data. For this reason, we also looked at individual extreme years (the largest lake area and the smallest) to see if these extreme years can be explained as a function of climate variable combinations. Of the top 10 driest years in the lake record, 4-6 of them are also the hottest years in the period. Of the top 3 driest lake-years (2003, 2004, and 2014) 2 of the 3 are also the hottest in the period. The driest year for Toadlena and Whiskey lakes was 2014 when temperature was hottest, rain was least, and snowpack was smallest. These results imply an important role for temperature in lake level decline over that last 30 years. Griffin and Anchukaitis (2015) recently reported that California experienced its longest and most severe dry period, from 2012 to 2014. This drought is more severe than any other dry period in a 1,200-year long paleo record obtained from the North American Drought Atlas and Blue oak tree-ring chronologies (Griffin and Anchukaitis, 2015). This is an important finding because it demonstrates that, while we have been searching for analogues for future drought, this period in California appears to have no exact analogue. Furthermore, while the cause of the California drought is a combination of precipitation deficit and high temperature, temperature appears to be the most important factor since higher temperatures increase evaporative loss from soil and exacerbate already dry conditions.

Vapor pressure deficit (VPD) is the difference between the maximum amount of water the atmosphere can hold at an air temperature, and the actual amount of water in the air. It is an important concept because it represents a driving force for evaporation from the land to the atmosphere. Higher temperatures increase the VPD, and therefore increase evaporation on the lakes. The results of this study suggest that the upward trend in temperature and the downward trend in lake area are related. In the context of temperature changes projected into the future using climate models, there is general consensus that it is going to get warmer in the southwestern U.S. exacerbating dry periods in the Chuskas (Garfin et al., 2013). Given that we may not see much change in future water entering the surface waters from precipitation, but that we may see a greater withdrawal from surface waters because of higher VPD in a warmer atmosphere, this is a cautionary tale that the surface waters of the Chuskas may continue to dry.

Notes from the field - Partnership with Navajo Nation Department of Water Resources, Water Management Branch

This study was conducted in partnership with the Navajo Nation Department of Water Resources Water Management Branch (WMB). They maintain water sovereignty, economic growth and health in a context of drought and variable water supplies. They manage water resources in the Chuska Mountains where snowpack and runoff impact agricultural activities for community farms and water for livestock. I visited the WMB several times over the course of this study. Most recently, I spent two days with staff assessing the progress of the research and evaluating early results and products (Appendix A). Together, we were able to identify the confluence of WMB projects and my work. For example, Teresa Showa, WMB principle hydrologist, launched a storage capacity quantification campaign for major reservoirs in eastern Navajo Nation and the Chuska Mountains in 2016. Results from this study provide useful baseline data for her new monitoring program. We also traveled in to the Chuska Mountains to GPS ground-truth lake perimeter with preliminary results. In November 2017, I was honored to present the results of this study to the Navajo Nation Division of Natural Resources (NNDNR), and more broadly to tribal community members in attendance, at the NNDNR Summit near Flagstaff, Arizona.

This study has laid the groundwork for further community engagement and has spawned nascent collaborations with other early career researchers working in the Chuska Mountains. Our goal is to continue collaborative efforts between Navajo Nation land managers and researchers across multiple institutions in an effort to answer key management questions about this special region of the Navajo Nation.

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FIGURES

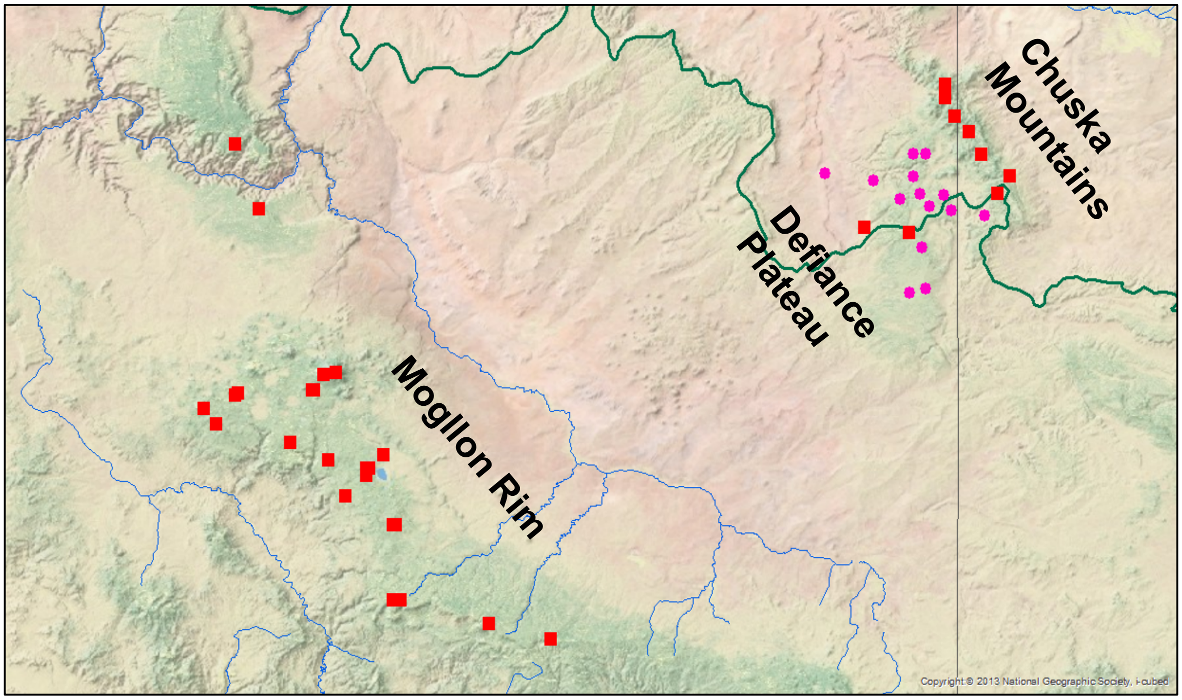


Figure 1: Location of snow sites (red squares) and tree-ring sites (pink circles) used in this study.

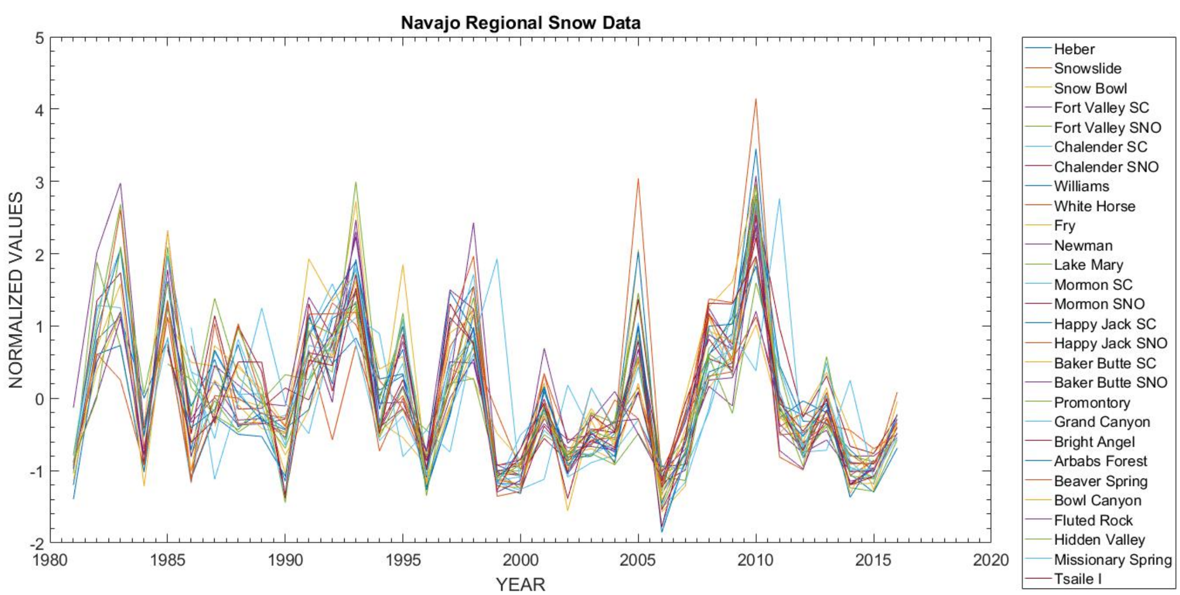


Figure 2: Monthly SWE from 26 snow measurement stations in Chuska Mountains and Mogollon Rim, Arizona. The longest, most representative record was selected as the predictand for MaxSWE (March) using correlation analysis.

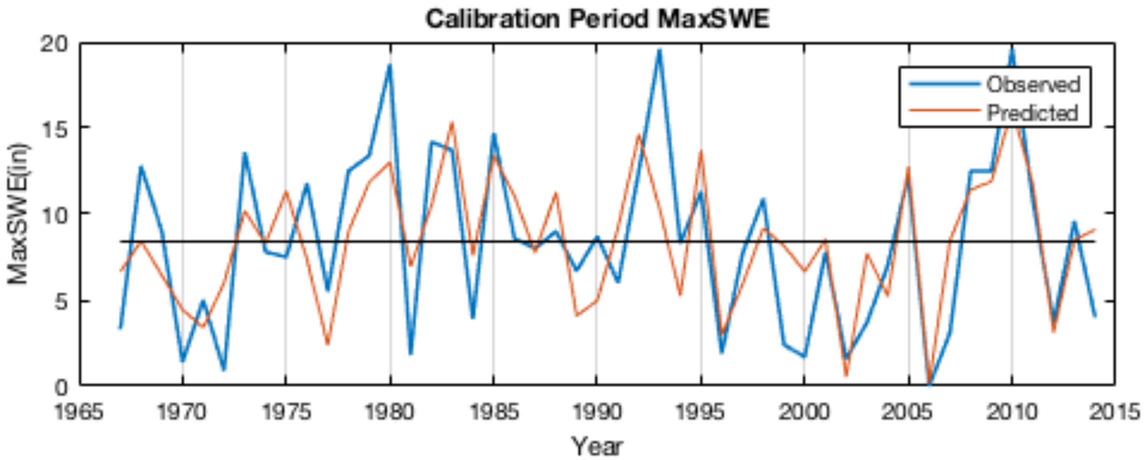


Figure 3: Calibration time series for observed MaxSWE at Williams Ski Run (blue) and predicted MaxSWE (orange) based upon stepwise regression model.

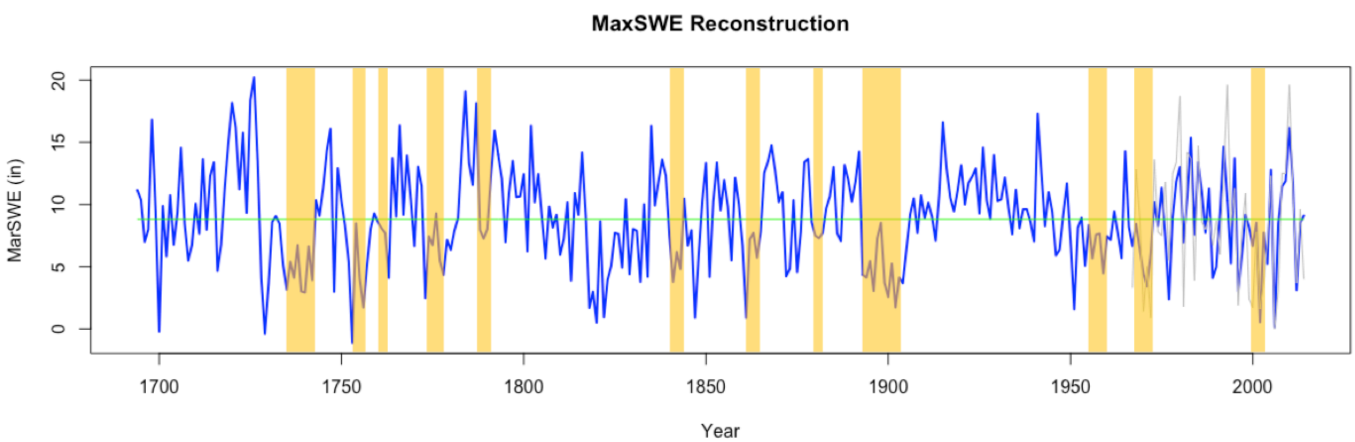


Figure 4: MaxSWE (March) reconstruction (1694-2014 AD). The blue line is estimated MaxSWE for each year. The green line is the long-term reconstructed mean. Orange bars highlight the top ten most severe low-snowpack periods in the reconstruction found using runs analysis.

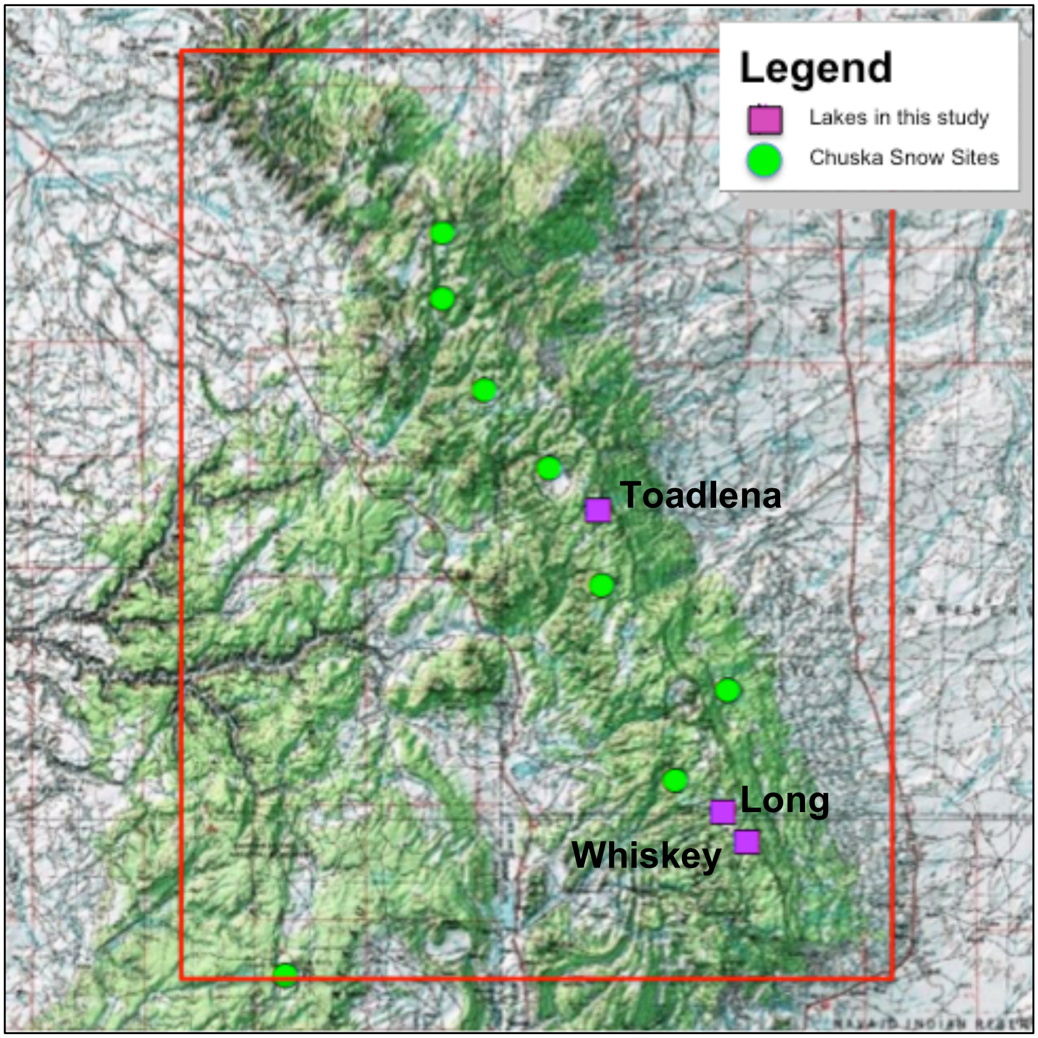


Figure 5: Location of lakes examined in this study (purple squares) and Navajo snow sites (green circles).

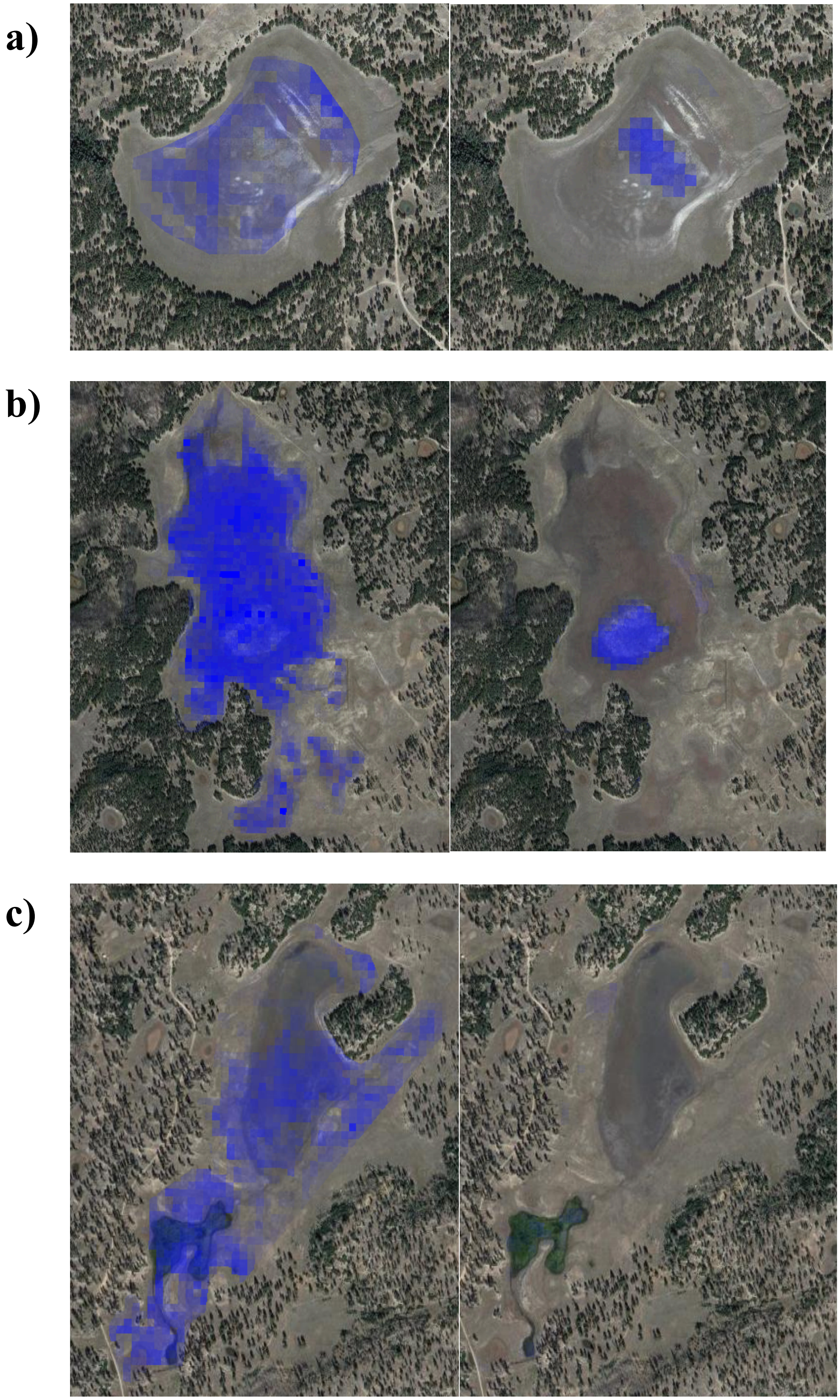


Figure 6: Landsat-derived NDWI images taken from Google Earth Engine, a) Toadlena Lake, b) Long Lake, and c) Whiskey Lake. Each pair of images shows water coverage in June 1986 (left column) and June 2015 (right column). Blue represents water in the basin.

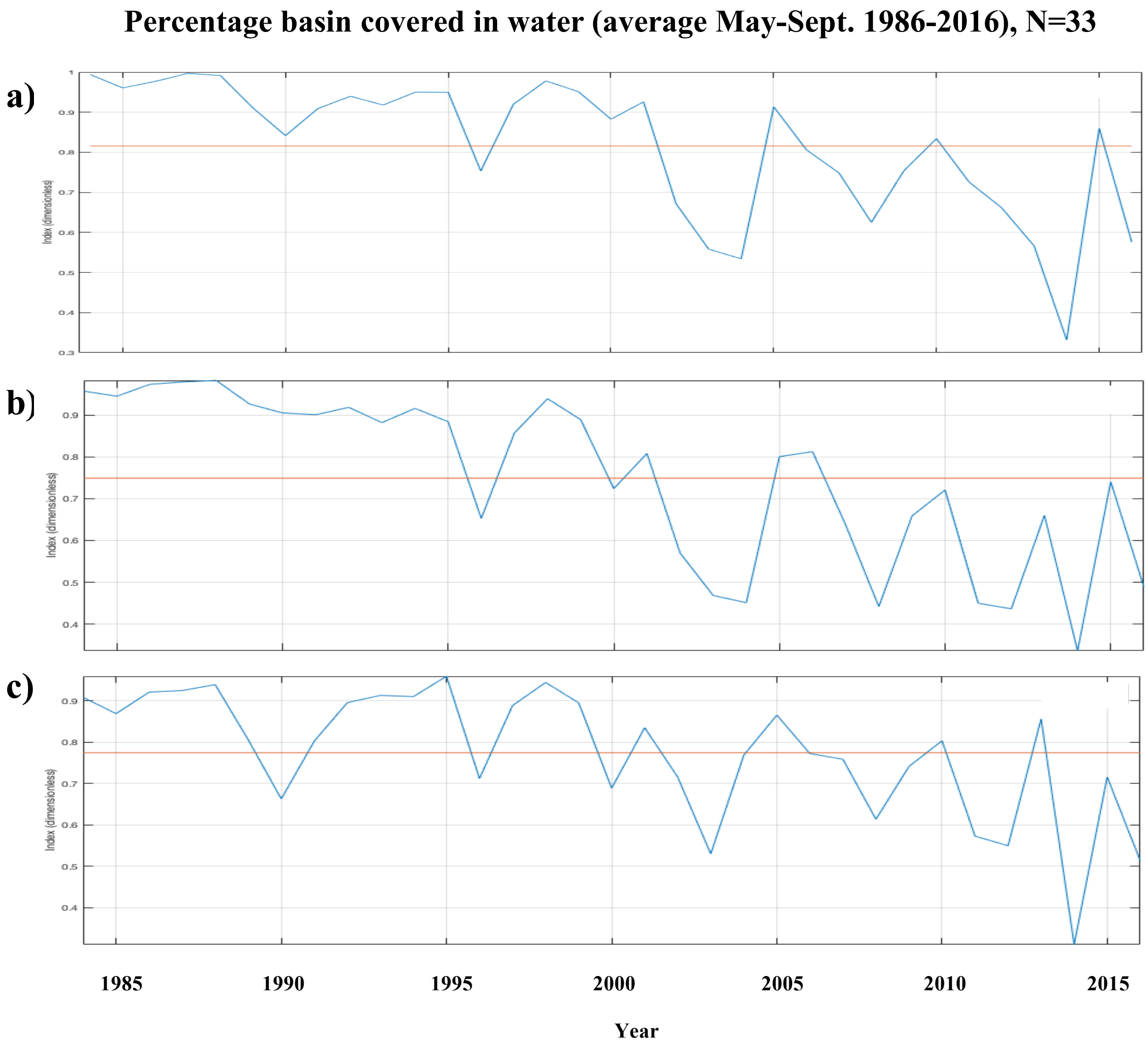
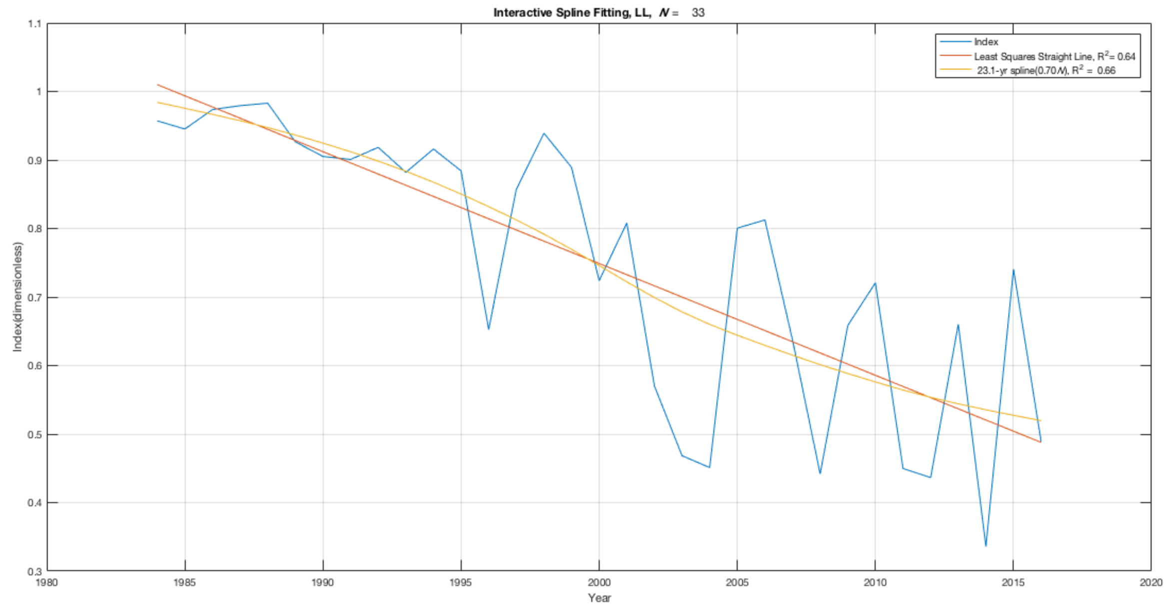


Figure 7: Landsat-derived NDWI time series for proportion of basin covered by water extracted from Google Earth Engine (1984-2015). a) Toadlena Lake, b) Long Lake, and c) Whiskey Lake. The blue line is annual average of basin coverage (May-Sept), orange line is long-term average.



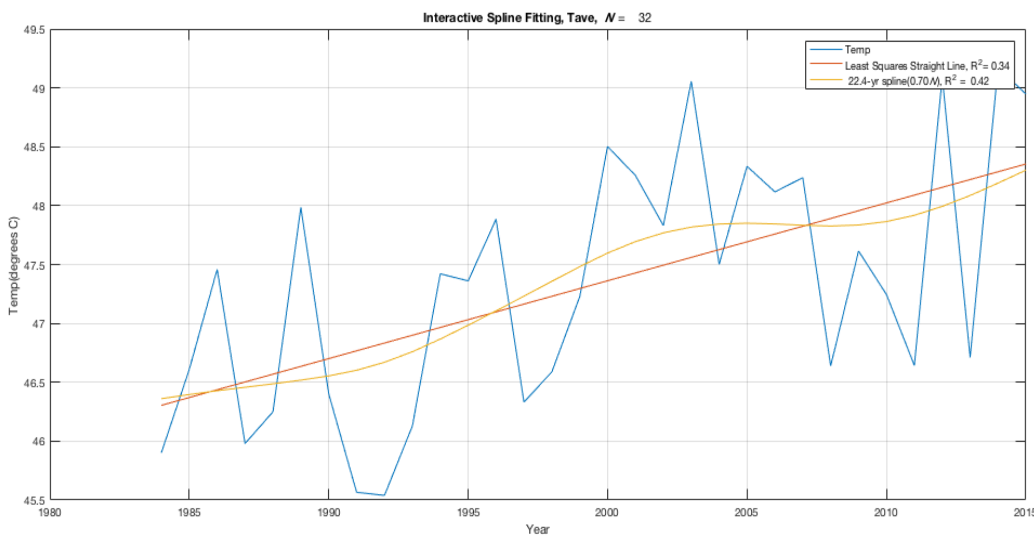


Figure 8: Trends in lake area for Long Lake (top) and in mean temperature (PRISM; bottom) for the Chuska range. Two detrending filters are overlaid on the time series (blue) and their corresponding coefficients of determination indicated within the plot.

TABLES

Table 1: Correlations of Willams Ski Run snowcourse (WSR) and 8 Navajo Chuska based snow sites. Correlations of WSR with the average of all Navajo snow sites show a strong and significant relationship.

	NNBS	NNBC	NNHV	NNTI	NNTIII	NNBC	NNAF	Ave Correlation
WSR	0.85	0.81	0.75	0.87	0.85	0.80	0.66	0.81

Table 2: Calibration and validation statistics for the MaxSWE reconstruction model. Measures of calibration (Adjusted Explained Variance, Standard Error of the Estimate) and validation (Reduction of Error, Root Mean Square Error of the Validation) demonstrate a robust MaxSWE estimation. The reconstruction model explains 52% of the total variation about the mean of the observed snow record.

Statistic	Calibration	Validation
Adj Expl Var. (R^2_a)	0.52	
Reduction of Error (RE)		0.47
Std Error of Estimate	3.5074	
$RMSE_v$		3.6416

Table 3: Runs analysis results. Runs were classified based upon a threshold of at least two consecutive years below the reconstruction mean. Duration (number of consecutive years), magnitude (cumulative deficit), and intensity (magnitude divided by duration) were summed to ascertain the most severe low snowpack periods, and then ranked (Faulstich et al., 2013).

Runs Analysis Scores	Ranked Low Snowpack	Low Snowpack period
86.5	1	1954-1961
86	2	1777-1781
79	3	1966-1972
76.5	4	1879-1882
73	5	1893-1905
72.5	6	1999-2004
71.5	7	1733-1742
71.5	8	1760-1763
68.5	9	1860-1865
67.5	10	1788-1790
66.5	11	1751-1758
64.5	12	1818-1827
61.5	13	1829-1832
60.5	14	1707-1709
53.5	15	1840-1843
53.5	16	1939-1940
51.5	17	1845-1848
49.5	18	1696-1698
47.5	19	1886-1887
47.5	20	1950-1952

Table 4: Effects of trended series verus detrended series on correlation and linear regression statistics.

	Correlation		Variance Explained	
	Before Detrending	**After Detrending**	**Before Detrending**	**After Detrending**
Whiskey	Significant correlation with temperature: .57. Insignificant correlation with snow. No correlation with July-Aug rain.	Significant correlation with temperature: -.37. Correlation with snow: .43.	29% var explained (R2) by temperature	26% var explained (R2) by snow and summer rain
Long	Significant correlation with temperature: .48. No correlation with snow or Jul-Aug rain.	**No** correlation with temperature. Significant correlation with Jul-Aug rain: .38.	27% var explained (R2) by temperature	22% var explained (R2) by snow and summer rain
Toadlena	Significant correlation with temperature: .55. No correlation with snow or Jul-Aug rain.	**No** correlation with temperature or snow or rain.	22% var explained (R2) by temperature	17% var explained (R2) by snow and summer rain

Appendix A

PROJECT REPORT

Surface Water Resources and Paleoclimatic Records in the Chuska Mountains

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Long-term Objectives:

Long-term environmental records obtained using environmental proxies can be useful in planning and decision-making contexts provided that the information is salient, credible and legitimate to those who will use it. A collaborative relationship between the researcher and Navajo Nation Department of Water Resources should pivot on ensuring the science generated through this process meets the above criteria as best as is possible. However, it should be noted that science cannot answer all questions and so we have worked together to minimize the gap between NWMB questions and scientific information that address those questions. Research that evaluates use-inspired science shows that iterative, continual discussion between researcher and stakeholder is most effective in making science information useful.

In November 2016 we explored research questions together. From this meeting, the following objectives were established:

- Estimate snowpack beyond historical records
- Identify periods of below-average snowpack
- Estimate surface water runoff and seasonal storage in historical record
- Evaluate the relationship between surface water and snowpack levels

Goal of the study:

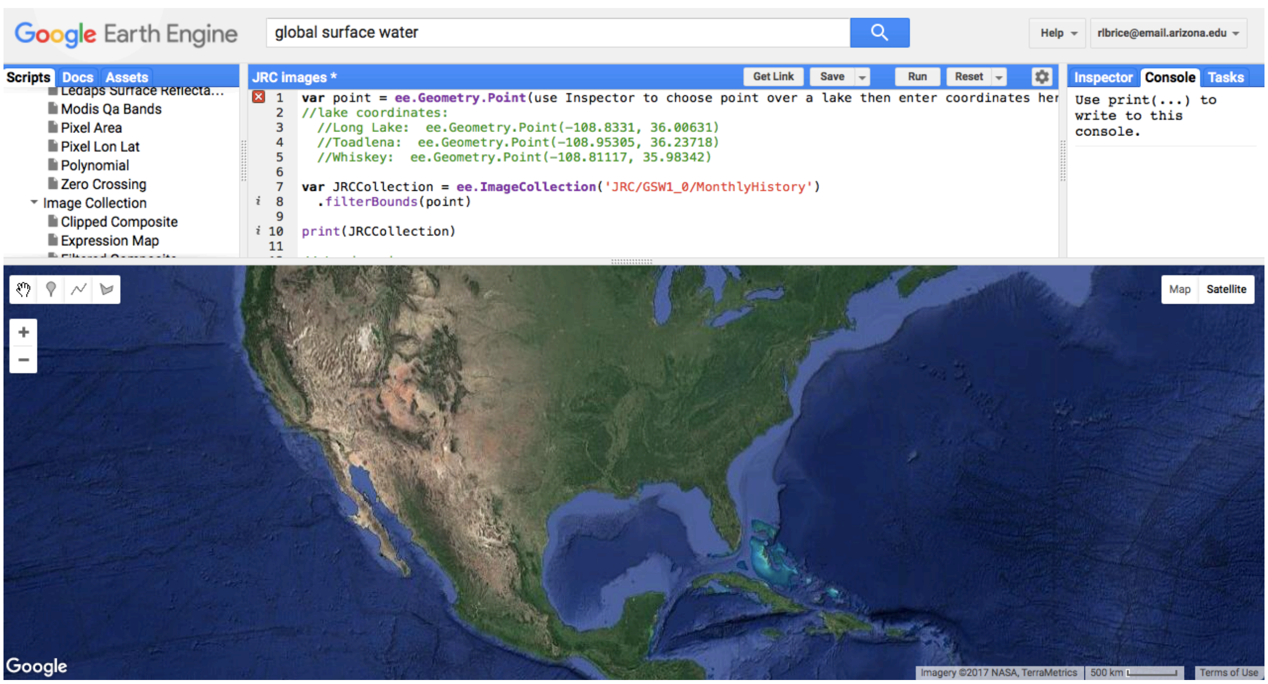
Can we characterize long-term tribal surface water resources, particularly in times of drought, for Navajo Nation water management planning in a culturally important region near their most populated and economically productive areas? To determine the relationship between cool-season precipitation and surface water, we designed a project with two distinct goals to produce long-term records and provide empirical analysis of chuska hydroclimatic variability:

1. Generate a long-term lake area estimation for primary lakes in the Chuska Mountains using satellite imagery.
2. Use tree rings to reconstruct local snowpack in the Chuska Mountains.

Data and Methods

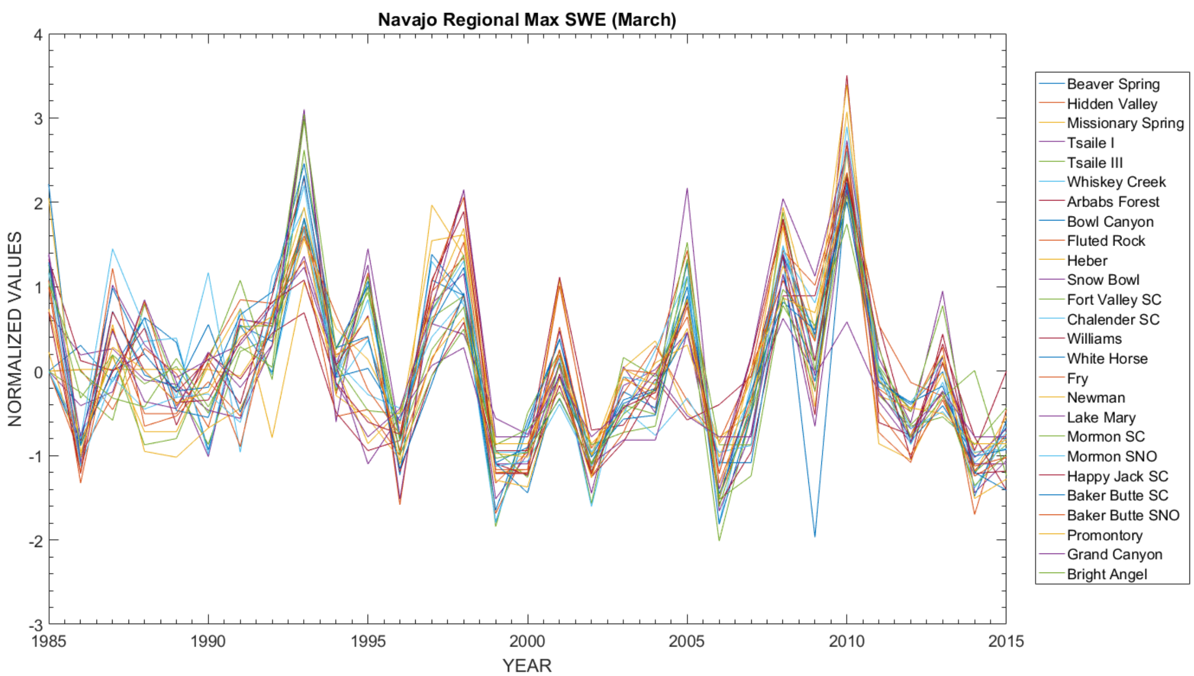
This study uses observed or observation-based data to examine the relationship between cool-season precipitation and surface water in the Chuska Mountains in the historical record and prior to the historical record.

Data used for the lake level estimation:
The JRC dataset by Pekel et al (2016) is a global dataset containing maps of the location and temporal distribution of surface water from 1984 to 2015. These maps are generated using over 3 million scenes from Landsat 5, 7 and 8. Each pixel was individually classified into water / non-water using a remote sensing expert system and the results were collated into a monthly history for the entire time period. The data are accessible through Google Earth Engine, a Python driven remote sensing tool.



For this initial study, polygons were delineated around Toadlena, Whiskey and Long lakes based upon the greatest extent of water coverage in the entire period. Pixels within each polygon that contained water in the months of May to October were counted, and then converted to area in acres.

Data used for the reconstruction:
Snow Water Equivalent for 26 snow monitoring stations in the Chuska Mountains and Mogollon Rim (longest record, 1947-2015) were evaluated for usefulness in a reconstruction model. Chuska snow records have a strong and significant relationship ($p < 0.01$) with tree rings, but are only 30 years in length. The strength of the relationship between all snow sites allows us to use a longer record from the San Francisco Peaks as a surrogate for Chuska snow records. This longer record is expected to improve statistical rigor in the model and should improve observation-proxy calibration.

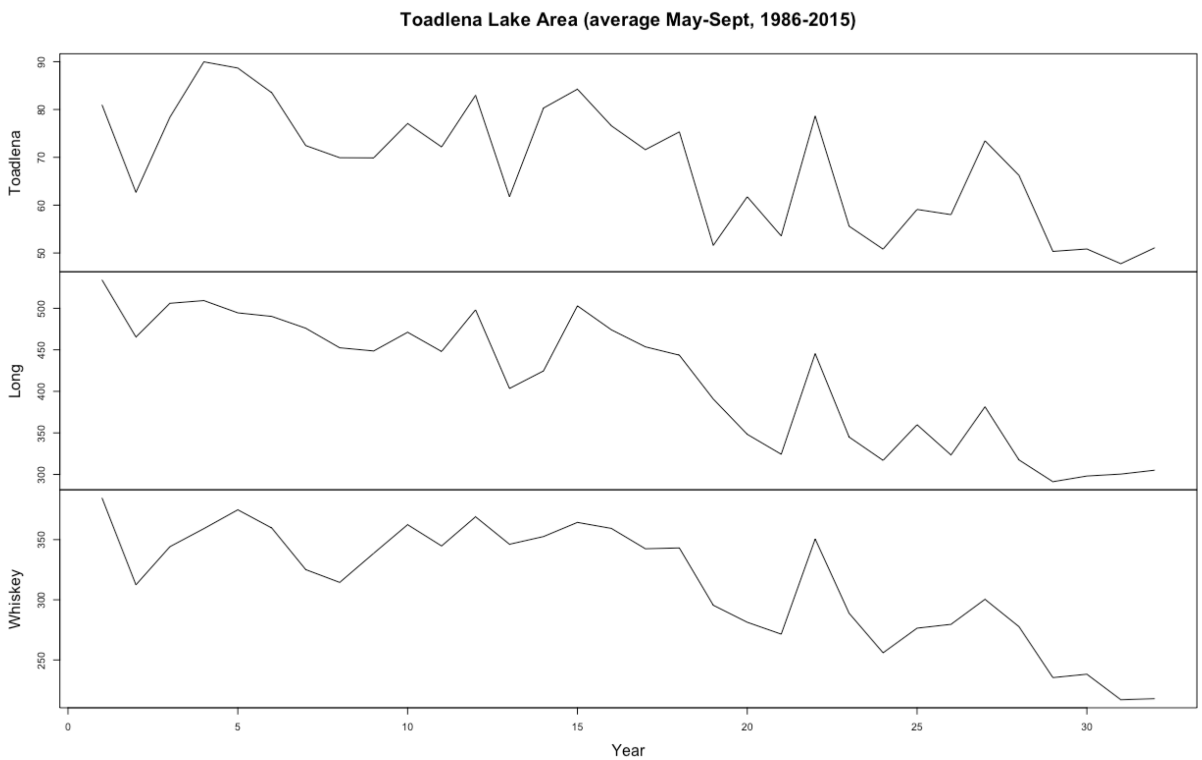


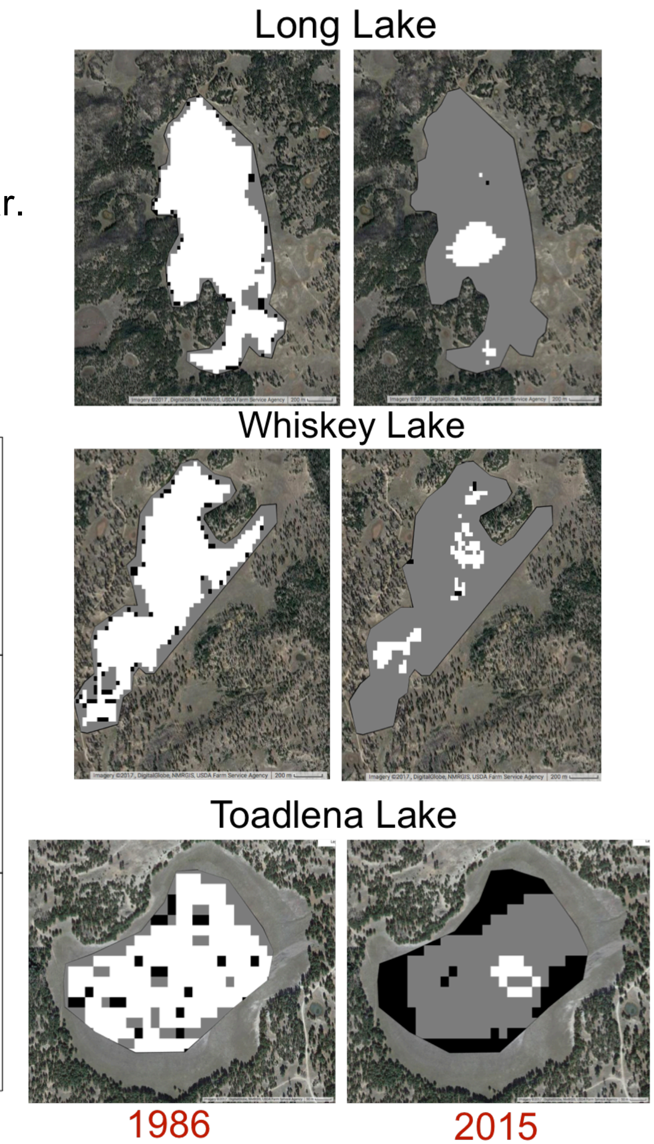
Twenty tree-ring chronologies collected in the Chuska range and on the Defiance Plateau were used based upon their statistically significant ($p < 0.05$) relationship to SWE. These chronologies are collections from Navajo CFI plots and will be replaced with collections from 17 climate sensitive sites in order to both lengthen the record and improve the snow signal derived from the trees.

The statistical contributions of these potential predictors to the variability of SWE were estimated using multiple linear regression.

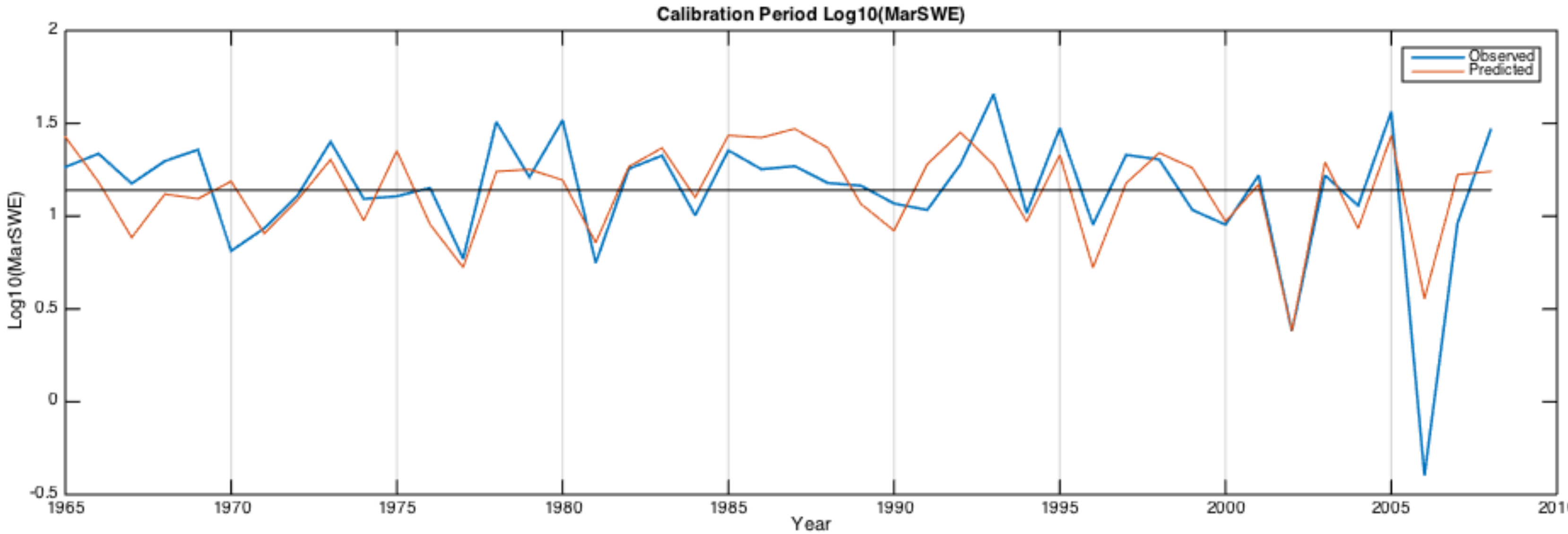
Initial findings – Lake Area

This is a 30-year record of average (May-Sept) seasonal lake area change from 1984-2015 for three primary lakes in the Chuska Mountains. The time series represents the average value for each year. The image comparisons to the right are an example of output from the satellite imagery, and allow for visual comparison in the month of May betwen 1986 (wet year) and 2015 (dry year).





Initial findings – Snowpack Reconstruction

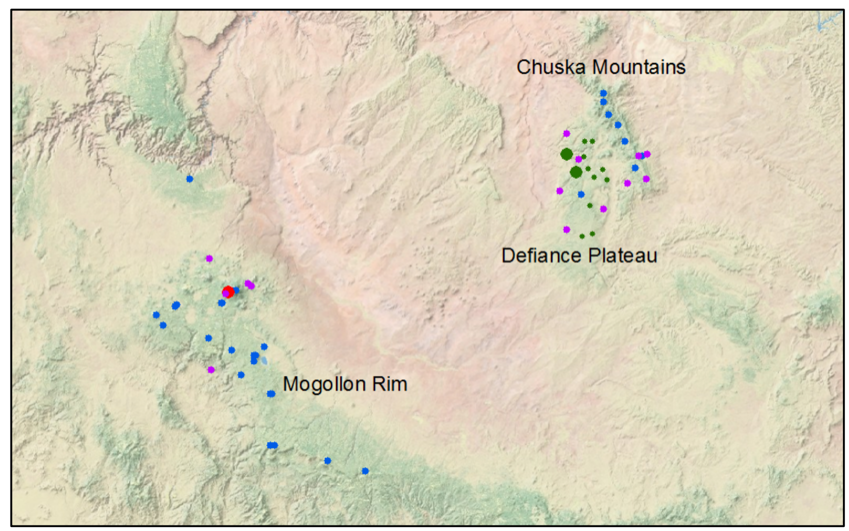


<u>Cal/Val statistics</u>

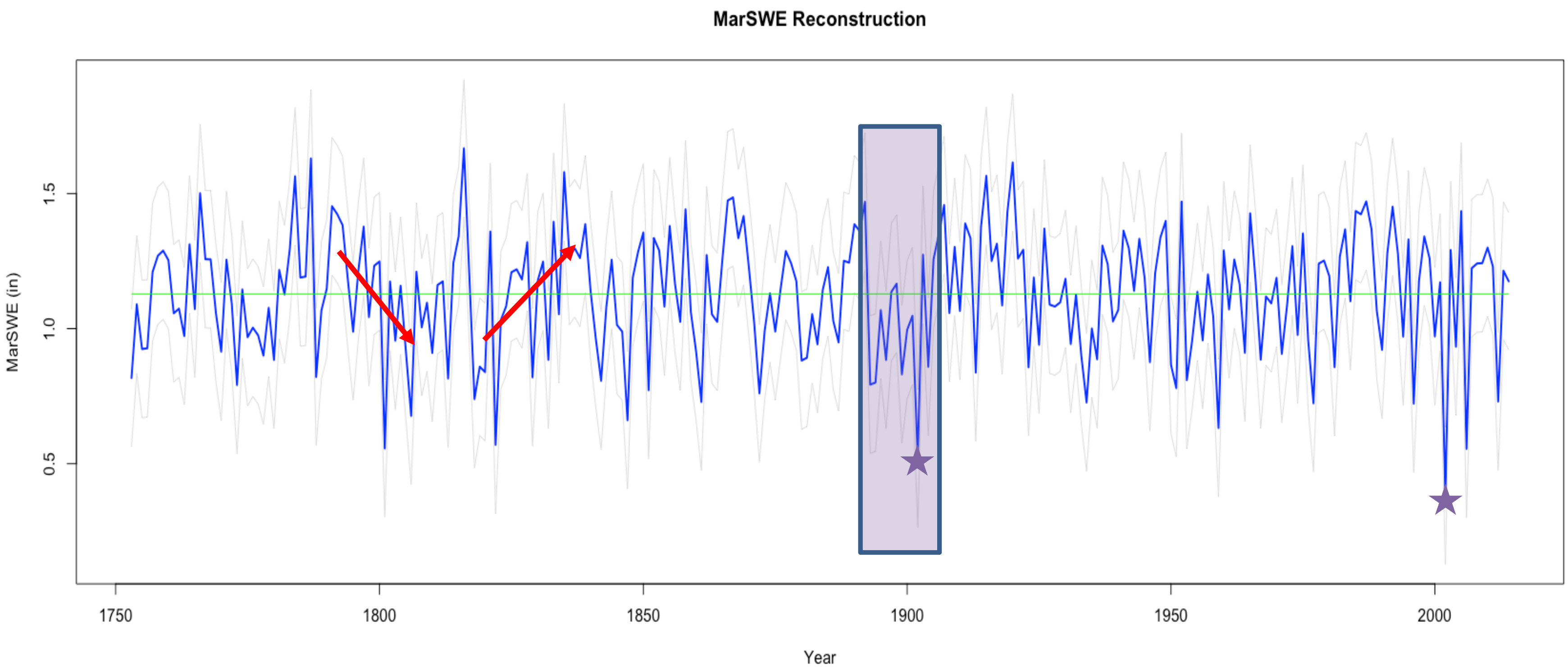
R_{2adj} = 0.51
RE = 0.42
$RMSE_v$ = 02545
Predictors: Spider rock PSME, CFI
636

Above: Calibration time series for observed MarSWE (blue) and predicted MarSWE (orange) and calibration/validation statistics for the model.

Right: Map showing the locations of snow (blue), existing tree-ring collections (green), and new climate tree-ring collections (purple).



The calibration period for this reconstruction is 1965-2015 and the reconstruction period is 1752-2015. The model predictors are Spider Rock and Chuska Forest Inventory Plot 636 located near the center of the Defiance Plateau. The regression model explains 51% of the variance in the calibration period, demonstrating skill in the model.



Above: MarSWE reconstruction (1752-2015). The blue line is the estimated MarSWE value for each year. The grey lines are the upper and lower 95% confidence intervals. The orange line is the long-term mean. The red arrow show decades of downward or upward trends that hold potential for further analysis. Similarly, the purple box shows and extended period of below average snowpack levels. The purple stars highlight years of extremely low snowpack. This preliminary reconstruction demonstrates the type of data and analyses that can be used from tree-ring reconstructions.

Next Steps:

1. Validate lake area estimations through ground-truthing, comparisons to historical documents, and other records for known lakes.

2. Finish tree-ring climate sites chronology development and reconstruction revision.

3. Expand the lake level estimations for other lakes, or all lakes in the Chuskas.

4. Analyses with reconstruction record and with lake level estimations (see examples here).