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Navajo Nation Snowpack Variability from 1985-2014 and Implications for Water Resources Management

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Abstract: In the arid Southwest, snowpack in mountains plays an essential role in supplying surface water resources. Water managers from the Navajo Nation monitor snowpack at nine snow survey stations located in the Chuska Mountains and Defiance Plateau in northern Arizona and New Mexico. We characterize these snowpack data for the period 1985-2014 and evaluate the efficacy of snowpack data collection efforts. Peak snow water equivalent occurs in early to mid-March depending on elevation. Variability in snowpack levels correlates highly among all sites ($r > 0.64$), but higher elevation sites in the Chuska Mountains correlate more strongly with one another compared to lower elevation sites and vice versa. Northern sites also correlate well with each other. A principal component analysis is used to create a weighted average time series of year-to-year peak snowpack variability. The first principal component showed no trend in increasing or decreasing Navajo Nation snowpack. Results from this research will provide the Navajo Nation Department of Water Resources information to help determine if any snow survey sites in the Chuska Mountains are redundant and can be discontinued to save time and money, while still providing snowpack information needed by the Navajo Nation. This summary of snowpack patterns, variability, and trends in the Chuska Mountains and Defiance Plateau will help the Navajo Nation to understand how snowpack and water resources respond to climate change and climate variability.

Keywords: *mountain hydrology, climate, Southwest*

In the Southwest region of the United States, snowpack is an important indicator of water resource availability. Snowpack annually stores large amounts of water in mountainous regions in the Southwest. Snowpack feeds perennial and ephemeral streams in mountainous watersheds. Snowmelt runoff in headwaters contributes to streamflow in large river basins, such as the San Juan River, Colorado River, and Rio Grande. Thus, monitoring snowpack can be used for the interpretation and prediction of climate and hydrologic conditions in the region. Snow water equivalent (SWE) data manually collected from snow courses and/or automated data from SNOTEL (SNOpack TELemetry) stations are commonly used to study the relationships between snowpack variability and climate. Previous research shows the importance of snowpack data in helping to characterize and further understand regional climate and sensitivity to climate variability. Gutzler (2000) found an inverse relationship between spring snowpack and summer rainfall in the Southwest. Other studies show that snowpack is sensitive to temperature and precipitation variability (Cayan 1996; Scalzitti et al. 2016) and to warming trends (Mote 2006). Observed decreasing trends of snowpack (Kalra et al. 2008) and projections of large snowpack losses (Fyfe et al. 2017) have created a sense of urgency for additional studies and understanding of relationships between climate, snowpack, and streamflow.

Recent studies have focused on the influence of warming and climate variability on streamflow generated from snowmelt runoff. Several tools and methods have been developed to assess impacts of warming climate on streamflow driven by snowmelt (Day 2009). Declines in peak snowpack and sensitivity of snowpack to temperature variability have led to shifts towards earlier snowmelt and snowmelt timing (Clow 2010) for much of the western U.S. With increasing discussion and evidence of climate change, more climate and water resources researchers and professionals are looking for improvements of snowpack data collection and analysis to make these forecasts.

Collecting and storing snowpack data are very crucial for water resources agencies and departments to characterize water resources for the year. The Navajo Nation Department of Water Resources (NNDWR) is responsible for monitoring snowpack and streamflow within the boundaries of the Navajo Nation. The NNDWR collects snowpack data from the Chuska Mountains and Defiance Plateau, which are located primarily in northeastern Arizona and partially in northwestern New Mexico on the Colorado Plateau (Figure 1). The Chuska Mountains are the major mountain range within the boundaries of the Navajo Nation and are the only location of perennial snowfed

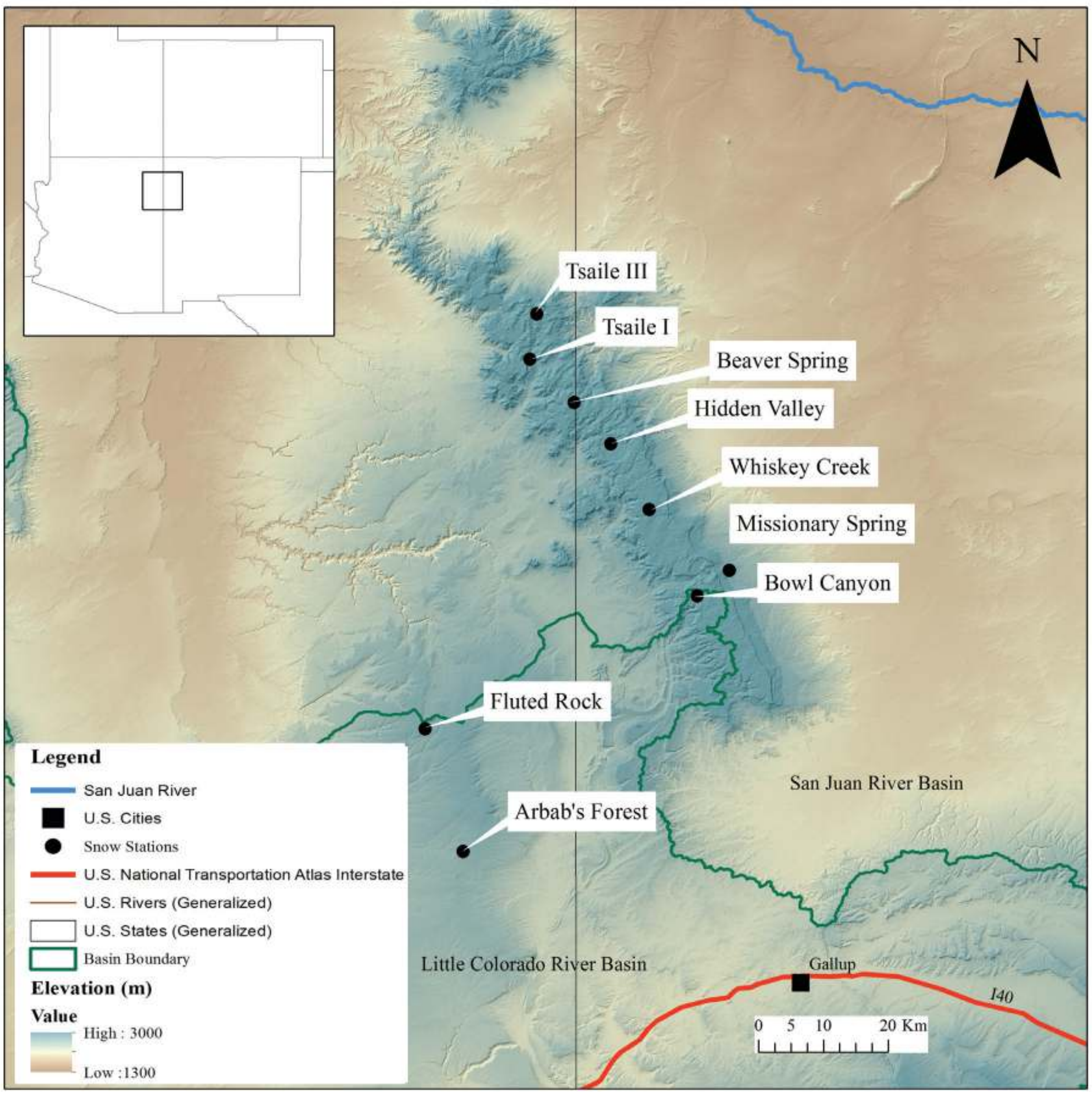

Figure 1. Location map of Navajo Nation snow survey sites. Map colors denote elevation. Black line represents the drainage divide between San Juan and Little Colorado Rivers.

streams completely sourced within Navajo Nation boundaries. Six of the nine stream gages monitored by the NNDWR are in the Chuska Mountains-Defiance Plateau landscape.

Every winter, between December and April, the NNDWR conducts manual snow surveys twice monthly. Collection of snowpack data is an important component of monitoring and managing water resources for the Navajo Nation, but snow surveys are time-consuming and costly. In a time of changing climate and uncertainties about water supply in the arid Southwest, more ways of efficiently collecting and interpreting snowpack data that would help in the forecast of water supplies are needed. A better understanding of data captured by snow survey sites on the Navajo Nation will help the NNDWR make management decisions about snow survey sites that may save time and money for future collection of snowpack data.

We intend to address the need for additional analysis and characterization of snowpack on the Navajo Nation. The overall research question addressed in this paper is "How well is snowpack in the Navajo Nation represented, based on data from individual snow survey sites in the Chuska Mountains and Defiance Plateau?" This question is determined through three sub-questions:

- What is the climatology of snowpack on the Navajo Nation?
- How do snowpack data from the nine survey sites in the Navajo Nation compare with one another?
- Could snowpack data collection efforts be refined with fewer sites and still maintain a quality data standard?

This research may help the Navajo Nation make better predictions of its water supply, as well as provide additional information about the local and regional climate and hydrology.

Background

The Navajo Nation is one of the largest recognized tribes in the United States and has the largest Indian reservation in the country. The Navajo reservation is located in the Four Corners area of the southwestern U.S. and spans parts of Utah, Arizona, and New Mexico with an area of approximately 71,000 km^2. The Navajo Nation has a population of approximately 330,000, over 150,000 of whom live on the reservation (Navajo Epidemiology Center 2013). The primary source of municipal water on the reservation is groundwater (NNDWR 2000). The Coconino, Navajo, Dakota, and San Juan Unit aquifers are the four major aquifers of the Navajo Nation and total about 700 million acre-feet of storage (NNDWR 2000). Surface water sources on the reservation include the Colorado River, Little Colorado River, San Juan River, tributary washes, and other river systems (NNDWR 2000). However, many residents do not have access to a safe source of potable drinking water. In 2009, U.S. legislation was signed to settle Navajo Nation water rights claims to the San Juan River, including authorization for the Navajo-Gallup Water Supply Project that will pump water from the San Juan River to communities on the reservation.

As a sovereign entity, the Navajo Nation manages its own natural resources through the Navajo Nation Division of Natural Resources and the Navajo Nation Environmental Protection Agency (NNDWR 2000). The NNDWR is institutionally within the Navajo Nation Division of Natural Resources. Its Water Management Branch monitors Navajo Nation water resources with networks of monitoring wells, stream gages, weather stations, and snow courses (NNDWR 2000). Data collected by the Water Management Branch play a crucial role in assessing and forecasting water resources for the Navajo Nation. In 2007, a study was conducted to assess the Navajo Nation hydroclimate network, analyzing the accuracy and efficiency of data collected at NNDWR stream gage and weather stations (Garfin et al. 2007). Some of the weather and streamflow data were inconsistent, irregular, or compromised by site conditions because of a shortage of resources to efficiently manage all the data collection stations in the hydroclimate network.

Snowpack data collected by the Navajo Nation are not fully integrated with U.S. national snowpack data collection. The U.S. Natural Resource Conservation Service (NRCS) manages a national network of SNOTEL sites throughout the United States. Two of the NNDWR snow survey sites in the Chuska Mountains are also SNOTEL sites. Besides climate monitoring, the NRCS also uses data collected in the SNOTEL system for water supply forecasting. Simulation models have been developed, or are in the process of being developed, using SNOTEL data to predict water supplies. However, statistical-regression relations based on historical snowpack data have been the more common method of discerning climate trends and forecasting water supplies.

Recent studies have focused on snowpack variability in the Chuska Mountains and nearby regional mountains. Novak (2007) analyzed snowfall in the Chuska Mountains using unpublished NNDWR data for the period 1985-2006 for seven of the nine snow survey sites analyzed here. Novak (2007) created aggregated time series of SWE in the Chuska Mountains for high elevation sites and for low elevation sites. Correlations of SWE with temperature and precipitation were also computed as part of the snowfall analysis of Novak (2007). Comparisons of year-to-year SWE results from the present study with results from Novak (2007) are presented in the Summary and Discussion section below. Jones (2007) analyzed snowpack in the San Juan Mountains and its relationship with streamflow, finding that snowpack in southern, lower elevation basins had earlier snow melt and March 1 SWE values are better to use when correlating snowpack with streamflow for the northwest New Mexico area.

Although land in the Chuska Mountains is managed by the Navajo Forestry Department, many families have homesteads in the Chuska Mountains and Defiance Plateau and rely on land and water resources for ranching and agriculture. If not connected to utility water supply, residents in these local communities rely on water from domestic wells, developed springs, or hauled water from other sources. Navajo Nation chapters (local government subdivisions) that lie within the Chuska Mountains and Defiance Plateau include Crystal, Red Lake, Mexican Springs, Tohatchi, Tsaile/Wheatfields, and Lukachukai. Communities with relatively high populations within these chapters include Tsaile, AZ, Lukachukai, AZ, and Crystal, NM. Window Rock, AZ, the Navajo Nation capital, is approximately 20 miles south of the Chuska Mountains and is within 10 miles east of the Defiance Plateau.

Data and Methods

The NNDWR has nine active snow survey sites in the Chuska Mountains and Defiance Plateau (Figure 1) that range in elevation between 2338-2813 m (Table 1). Six sites (Tsaile III, Tsaile I

Table 1. Navajo Nation snow survey site information.

Site Name	Established	Elevation (m)	Basin	# Years Missing	Station Type/s
Arbab's Forest	1/31/00	2338	Little Colorado	0	snow course
Beaver Spring	9/1/85	2813	San Juan River	8	snow course, SNOTEL
Bowl Canyon	10/3/85	2731	Little Colorado	1	snow course
Fluted Rock	10/20/84	2429	Little Colorado	0	snow course
Hidden Valley	9/11/85	2473	San Juan River	2	snow course
Missionary Spring	10/17/90	2393	San Juan River	6	snow course
Tsaile I	11/29/84	2496	San Juan River	2	snow course
Tsaile III	10/17/90	2758	San Juan River	3	snow course
Whiskey Creek	10/31/84	2761	San Juan River	0	snow course, SNOTEL

Beaver Springs, Hidden Valley, Whiskey Creek, and Missionary Springs) are located within the San Juan River Basin. Three sites (Bowl Canyon, Fluted Rock, and Arbab's Forest) are in the Little Colorado River drainage. Fluted Rock and Arbab's Forest are on the Defiance Plateau and the rest of the sites are in the Chuska Mountains. The Whiskey Creek and Beaver Springs snow survey sites include snow courses and active SNOTEL sites. Snow survey samples are collected by NNDWR hydrologic technicians according to NRCS sampling techniques. Snow survey sampling is typically conducted twice per month between late December and early April. Data provided by the NNDWR for this research include snow depth, SWE, and snow density from the nine sites over the 30-year period 1985-2014, as well as basic snow course information.

SWE, the amount of water contained in the snowpack, is the parameter used to characterize for snowpack in this study. It is listed as "water content" in NNDWR snow survey sampling field notes. SWE used for this analysis is measured from snow courses at the snow survey sites established by the NNDWR because these have a longer history than the two active SNOTEL sites. Snow depth and snow density are measured at aerial markers that form an established transect for each snow course. SWE is calculated from the snow depth and snow density at each marker and an average SWE from each marker is used as the representative SWE for the snow course.

Climatology of snowpack on the Navajo Nation is characterized by seasonal cycle, time of maximum SWE, and year-to-year variability. Comparison of snowpack data from Navajo Nation snow survey sites is made using principal component analysis. The minimums, maximums, quartiles, medians, and means of each sample date (January 1, January 15, February 1, February 15, March 1, March 15, and April 1) for the 1985-2014 period of record were calculated for each snow survey site to characterize the climatological seasonal cycle of snowpack in the Chuska Mountains. Two March SWE measurements (March 1 and March 15) for every year were averaged for each site, and are used to represent maximum seasonal snowpack accumulation at the sites. If one of the March sample date measurements was missing, an average for that year was not calculated and was left blank. A year-to-year correlation table (Table 2) for March SWE was created using the correlation function in Microsoft Excel. Missing data were filled from average normalized anomalies. Normalized anomalies of real data were calculated by:

$$anomaly_{x,t} = \frac{y_{x,t} - \mu_x}{\sigma_x} \qquad \text{(Equation 1)}$$

where $anomaly_{x,t}$ is the normalized anomaly for a snow survey site x, at year t; $y_{x,t}$ is the March SWE from x at year t; μ_x is the mean March SWE for all years at x; and σ_x is the standard deviation of March SWE for all years at x. The normalized anomalies for missing data were calculated by taking the average normalized anomalies of all sites with non-missing data for the year with missing data. Missing SWE values were then estimated and filled by:

$$y^*_{x,t} = anomaly_{x,t} * \sigma_x + \mu_x \qquad \text{(Equation 2)}$$

where $y^*_{x,t}$ is the estimated SWE for year t with a missing sample at site x (Table 2).

A year-to-year correlation table (Table 3) for a complete time series of March average SWE (1985-2014) measurements between snow survey sites in the Chuska Mountains and Defiance Plateau was created using the estimated March SWE data in Table 2. The correlation coefficients generated in the year-to-year correlation table were used to assess the relationships between each of the snow survey sites.

A two-tailed t-test was used to determine whether the year-to-year correlation coefficients are large enough to be statistically different from zero at 1% and 5% levels based on 30 years of snowpack data, assuming 1 degree of freedom per year. For alpha = 5%, correlation coefficients of 0.36 or above are needed for the relationship of the snow survey sites to be statistically significant relative to a null hypothesis of zero correlation. For alpha = 1%, correlation coefficients of 0.46 or above are needed for statistical significance.

The correlation matrix of March SWE for the nine NNDWR sites (Table 3) was passed as input into MATLAB to perform an eigenanalysis (Von Storch and Zwiers 2002). Eigenanalysis is used to analyze the similarities and differences between snowpack variations at the Chuska Mountain sites.

Table 2. March snow water equivalent (SWE) and principal component time series for snow survey sites (filled data in bold).

AF	BS	BC	FR	HV	MS	T I	T III	WC	PC1	PC2
0.066	**0.296**	0.258	0.095	**0.228**	**0.121**	0.197	**0.266**	0.279	0.119	0.017
0.005	**0.168**	0.131	0.010	**0.107**	**0.027**	0.117	0.203	0.157	-0.176	-0.010
0.020	**0.212**	0.213	0.027	0.133	**0.053**	0.131	0.174	0.218	-0.090	0.008
0.061	0.291	0.269	0.121	0.204	**0.129**	0.225	0.296	0.271	0.139	0.013
0.013	0.258	0.169	0.046	0.175	**0.068**	0.141	0.208	0.265	-0.035	0.027
0.048	0.116	0.161	0.081	0.113	**0.034**	0.065	0.149	0.133	-0.189	-0.101
0.036	0.281	0.260	0.122	0.239	0.076	0.204	0.246	0.304	0.108	0.043
0.058	0.255	0.217	0.119	0.230	0.114	0.201	0.262	0.226	0.077	-0.020
0.069	0.420	0.377	0.150	0.342	0.193	0.269	0.386	0.396	0.390	0.109
0.019	0.215	0.236	0.038	0.151	0.061	0.157	0.225	0.222	-0.042	0.027
0	0.339	0.304	0.043	0.292	0.043	0.260	0.325	0.314	0.165	0.175
0.005	0.132	0.099	0.010	0.023	0.010	0.022	0.154	0.136	-0.292	-0.063
0.079	0.340	0.326	0.135	0.271	0.268	0.239	0.290	0.358	0.285	-0.002
0.130	0.320	0.293	0.196	0.310	0.171	**0.263**	**0.336**	0.307	0.292	-0.023
0	**0.088**	**0.095**	0.000	0.013	0.000	0.022	0.062	0.027	-0.388	-0.118
0	0.146	0.157	0.000	0.090	0.003	0.067	0.182	0.164	-0.216	-0.004
0.086	**0.302**	0.246	0.132	0.197	0.152	0.193	0.246	0.245	0.114	-0.045
0.010	**0.119**	0.103	0.015	0.066	0.014	0.047	0.086	0.072	-0.311	-0.097
0.013	0.182	0.189	0.055	0.171	0.083	0.137	0.240	0.224	-0.053	0.001
0.036	0.197	0.171	0.089	0.145	0.104	0.154	0.220	0.216	-0.042	-0.047
0.015	0.331	0.329	0.050	0.253	0.047	0.192	0.300	0.340	0.142	0.151
0.023	0.057	0.046	0.020	0.032	0.028	0.032	0.047	0.053	-0.380	-0.163
0.037	0.169	0.165	0.071	0.130	0.047	0.123	0.180	0.216	-0.107	-0.041
0.097	0.372	0.338	0.178	0.321	0.194	0.206	0.295	0.370	0.308	0.016
0.018	**0.250**	0.251	0.056	0.220	0.052	**0.159**	**0.228**	0.310	0.034	0.071
0.187	0.470	0.405	0.211	0.403	0.253	0.387	0.434	0.443	0.584	0.057
0.014	**0.210**	0.199	0.027	0.157	0.023	0.165	0.231	0.212	-0.069	0.042
0.008	0.170	0.175	0.005	0.131	0.010	0.099	0.183	0.194	-0.159	0.015
0.043	0.239	0.211	0.077	0.206	0.064	0.234	0.295	0.240	0.054	0.036
0	0.084	0.076	0.003	0.011	0	0.028	0.119	0.094	-0.351	-0.090

Table 3. Year-to-year March snow water equivalent (SWE) correlation matrix with filled data. Rows and columns labeled as principal components or PCs are derived from eigenvector analysis of the site time series (see text and Table 4).

	AF	BS	BC	FR	HV	MS	T I	T III	WC	PC1	PC2
Arbab's Forest	1.00	0.71	0.67	0.93	0.73	0.87	0.74	0.67	0.64	0.78	0.16
Beaver Spring	0.71	1.00	0.97	0.80	0.97	0.82	0.94	0.94	0.96	0.98	0.70
Bowl Canyon	0.67	0.97	1.00	0.77	0.96	0.78	0.91	0.93	0.96	0.96	0.72
Fluted Rock	0.93	0.80	0.77	1.00	0.83	0.91	0.81	0.76	0.75	0.87	0.29
Hidden Valley	0.73	0.97	0.96	0.83	1.00	0.80	0.95	0.94	0.95	0.98	0.70
Missionary Spring	0.87	0.82	0.78	0.91	0.80	1.00	0.79	0.75	0.77	0.86	0.30
Tsaile I	0.74	0.94	0.91	0.81	0.95	0.79	1.00	0.96	0.91	0.96	0.66
Tsaile III	0.67	0.94	0.93	0.76	0.94	0.75	0.96	1.00	0.93	0.95	0.69
Whiskey Creek	0.64	0.96	0.96	0.75	0.95	0.77	0.91	0.93	1.00	0.96	0.72
Principal Comp 1	0.78	0.98	0.96	0.87	0.98	0.86	0.96	0.95	0.96	1.00	0.64
Principal Comp 2	0.16	0.70	0.72	0.29	0.70	0.30	0.66	0.69	0.72	0.64	1.00

Eigenvectors were created to show the optimum combination of snow survey sites that accounts for the most total year-to-year variance of March SWE in the Chuska Mountains and Defiance Plateau. Corresponding eigenvalues show the fraction of total year-to-year variance accounted for by each eigenvector. The first and second eigenvectors, which account for most of the year-to-year variance within the network as a whole, were projected into principal component time series that show the year-to-year variations in strength of the eigenvector patterns in each year's March SWE map.

Results

Mean SWE peaks in March for most NNDWR snow survey sites. Mean SWE for each sample date of each site for all years on record was calculated to show the seasonal cycles of snowpack (Figure 2). Arbab's Forest generally has the least snowpack, while Beaver Spring has the most snowpack. Mean SWE at Arbab's Forest peaks in mid-February (at least two weeks earlier than other sites) at 0.058 m. Mean SWE at Beaver Spring peaks in mid-March at 0.25 m. The other seven sites have peak SWE between early and mid-March. The higher peak snowpack values occur mostly in the higher elevation (Figure 3) and northern (Figure 4) sites (Tsaile I, Tsaile III, Beaver Springs, Hidden Valley, Whiskey Creek, and Bowl Canyon) where SWE measurements range from 0.156-0.25 m. Lower peak snowpack measurements occur in the more southern and lower elevation sites (Missionary Springs, Fluted Rock, and Arbab's Forest) where SWE measurements range from 0.058-0.099 m.

The year-to-year correlation matrix (Table 3) shows that the March SWE fluctuations among the sites are all positively and significantly correlated. Two pairs of sites that have the strongest correlations are Beaver Spring and Bowl Canyon and Beaver Spring and Hidden Valley, both pairs with $r^2 = 0.94$. Sites with the weakest correlations include Arbab's Forest and Whiskey Creek ($r^2 = 0.41$), Arbab's Forest and Bowl Canyon ($r^2 = 0.45$), and Arbab's Forest and Tsaile III ($r^2 = 0.45$).

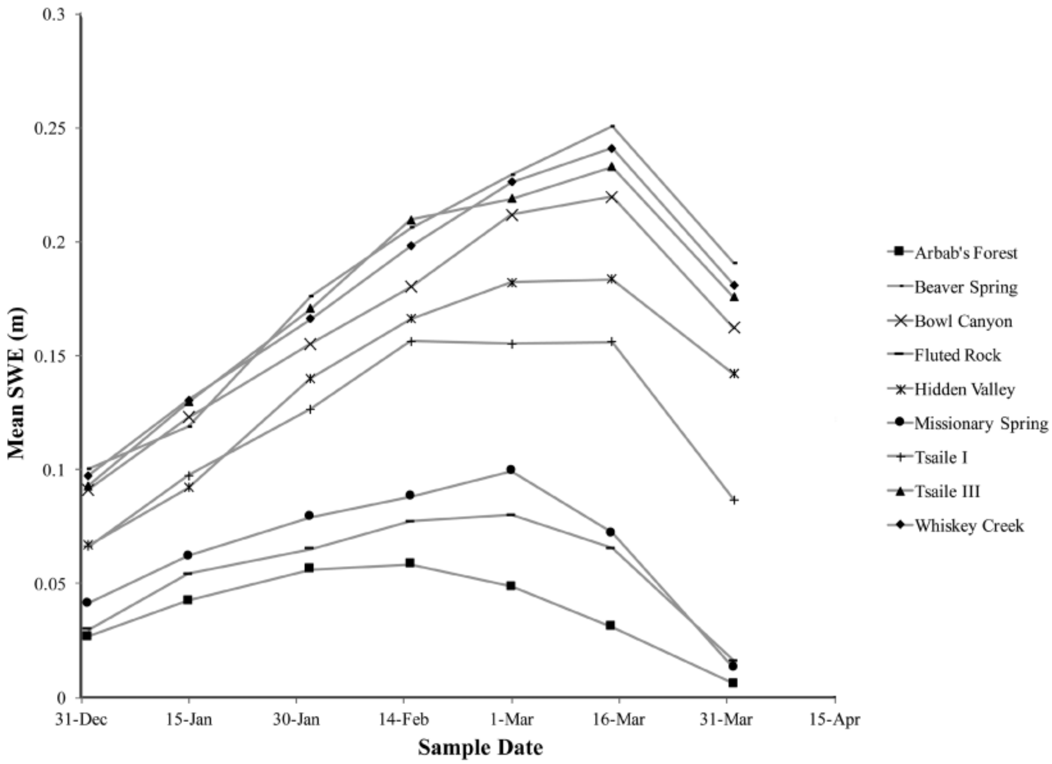

Figure 2. Climatological mean snow water equivalent (SWE) at each site, illustrating the seasonal cycle of snowpack for Navajo Nation snow survey sites.

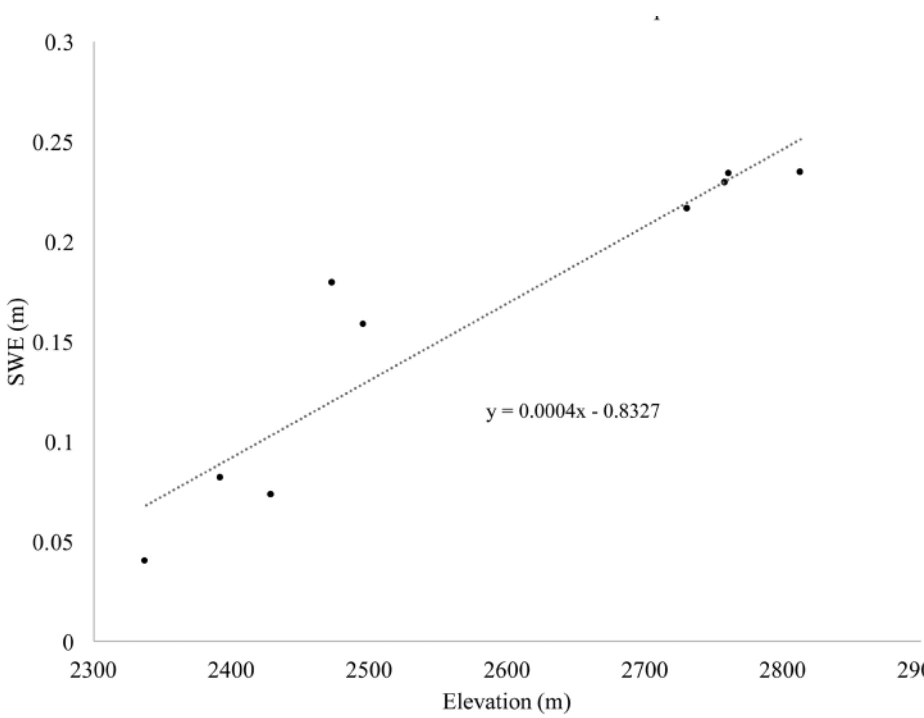

Figure 3. Navajo Nation March snow water equivalent (SWE) as a function of snow station elevation. Linear regression indicates that March SWE increases by 4 cm per 100 m in elevation.

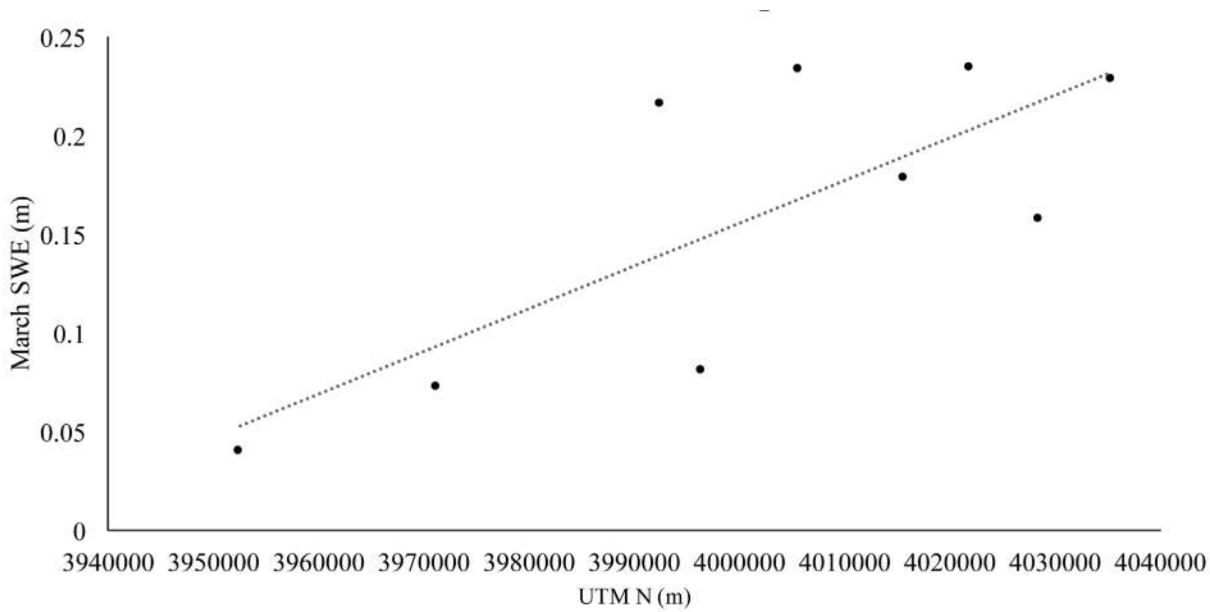

Figure 4. Plot of Navajo Nation snow survey site UTM northing coordinates and March snow water equivalent (SWE).

High elevation sites correlate well. Northern sites (Tsaile III, Tsaile I, Beaver Spring, Hidden Valley, and Whiskey Creek), which are all high elevation sites and nearby to one another, correlate well. Southern sites (Missionary Spring, Bowl Canyon, Fluted Rock, and Arbab's Forest) do not correlate as well with each other as do the northern sites, likely due to the southern sites being further away from one another and having more variation in altitude.

A corresponding set of eigenvectors and eigenvalues was created for the nine Chuska Mountain sites based on the matrix of March SWE year-to-year correlations. The principal component analysis reduced the dimensionality (found patterns that optimally described the year-to-year variability in less than nine individual time series) of the nine Chuska Mountains and Defiance Plateau snow survey sites. Nine eigenvectors of the correlation matrix were created that completely account for the total year-to-year variability at all sites. The first eigenvector, associated with the first eigenvalue, is a pattern that explains the most year-to-year variance of the nine snow survey sites. The second eigenvector, associated with the second eigenvalue, is orthogonal to the first eigenvector and explains the most remaining year-to-year variance of the snow survey network sites. The first two eigenvectors in this analysis together account for 95% of the total year-to-year variance. Subsequent eigenvectors, together accounting for just 5% of the variance, were not considered. Table 4 shows the first and second eigenvectors and their associated vector weights and eigenvalues.

The first eigenvalue accounts for 86% of the total year-to-year variance of March SWE in the Chuska Mountains and Defiance Plateau. Thus, the pattern of the first eigenvector signifies the optimized or "primary" mode of year-to-year variability. In this first eigenvector, all sites have positive coefficients, representing positive correlations between year-to-year March SWE fluctuations at each pair of sites. The coefficients of the first eigenvector are relatively evenly weighted, ranging from 0.2927 for Arbab's Forest to 0.3503 for Hidden Valley. Therefore, the eigenanalysis suggests that, to a first approximation, March SWE rises and fall together at all nine sites.

The second eigenvector accounts for 9% of the total March SWE variance in the Chuska Mountains. By construction, this eigenvector must be spatially orthogonal to the first eigenvector, so the out-of-phase structure of this vector, with three sites exhibiting large negative coefficients

Table 4. First and second eigenvectors, eigenvalues, and associated percent variances.

Site	Vector Weight	
	1	2
Arbab's Forest	0.2927	-0.5883
Beaver Spring	0.3477	0.2261
Bowl Canyon	0.3417	0.2408
Fluted Rock	0.3212	-0.4384
Hidden Valley	0.3503	0.1523
Missionary Spring	0.3167	-0.4107
Tsaile I	0.3439	0.1369
Tsaile III	0.3393	0.2655
Whiskey Creek	0.3424	0.2676
Eigenvalue	7.7537	0.8322
Percent Variance	86.1522	9.2467

and the other six sites exhibiting modest positive coefficients, is built into the analysis. The three sites with the large negative coefficients are all located near the southern end of the network of sites, and are the three lowest-elevation sites (less than 8000 feet, as documented in Table 1). Additionally, the snowpack fluctuations at these three sites are more strongly correlated with each other than with the higher elevation sites to the north (Table 3). We interpret the second eigenvector as mostly representing variability of SWE at the southern end of the Chuska Mountains and not correlated with the snowpack in the rest of the range.

The first and second eigenvectors were projected back onto the year-to-year variability time series of March snowpack anomalies to compute the corresponding principal-component time series. Missing March average SWE values were filled in using average normalized anomalies of all the NNDWR sites with actual data for March of that year. Figure 5 shows the first principal component (PC1) time series for March SWE. This time series shows times of high and low snowpack accumulation in the entire Chuska Mountains and Defiance Plateau region. Each PC1 point in the time series can be interpreted as an optimally weighted average of March SWE over the entire network of sites. The second principal component (PC2) time series, projected from the second eigenvector (Figure 5), shows a different aspect of year-to-year March SWE variability associated with the low-elevation southern sites that project strongly onto the second eigenvector.

The principal component analysis reduces the amount of uncorrelated "noise" associated with the compilation of every site's time series of March snowpack year-to-year variability. The set of nine time series, representing year-to-year variability of the nine NNDWR sites, is reduced to two representative time series. The PC1 time series illustrates the first or "primary" mode of year-to-year variability of March snowpack in the Chuska Mountains and Defiance Plateau, showing the years of high snowpack in 1993, 1997, 1998, 2008, and 2010, and years of low snowpack in 1996, 1999, 2002, 2006, and 2014. The PC2 time series shows the second mode of year-to-year variability of March snowpack in the Chuska Mountains and Defiance Plateau, representing most of the residual year-to-year variance.

The PC1 time series was correlated with the nine NNDWR snow survey sites and the five regional SNOTEL sites to compare the weighted composite average with the individual sites. The correlation map of the PC1 time series for March SWE (Figure 6) shows that the principal component analysis effectively synthesizes the correlations of individual NNDWR sites. The PC1 correlation map shows very strong correlation with all of the snow survey sites, especially with those in the higher elevations of the Chuska Mountains, where snowpack is most variable.

Summary and Discussion

Climatological means for each snow survey site in the Chuska Mountains and Defiance Plateau were calculated for the years 1985-2014. Snow survey sites in lower elevations showed peak snowpack accumulation in early March (snow measurements conducted from February 26 to March 1). Snow survey sites in higher elevations showed peak snowpack accumulation in mid-March. Therefore, a March index was developed based on the average of both yearly March observation dates. March

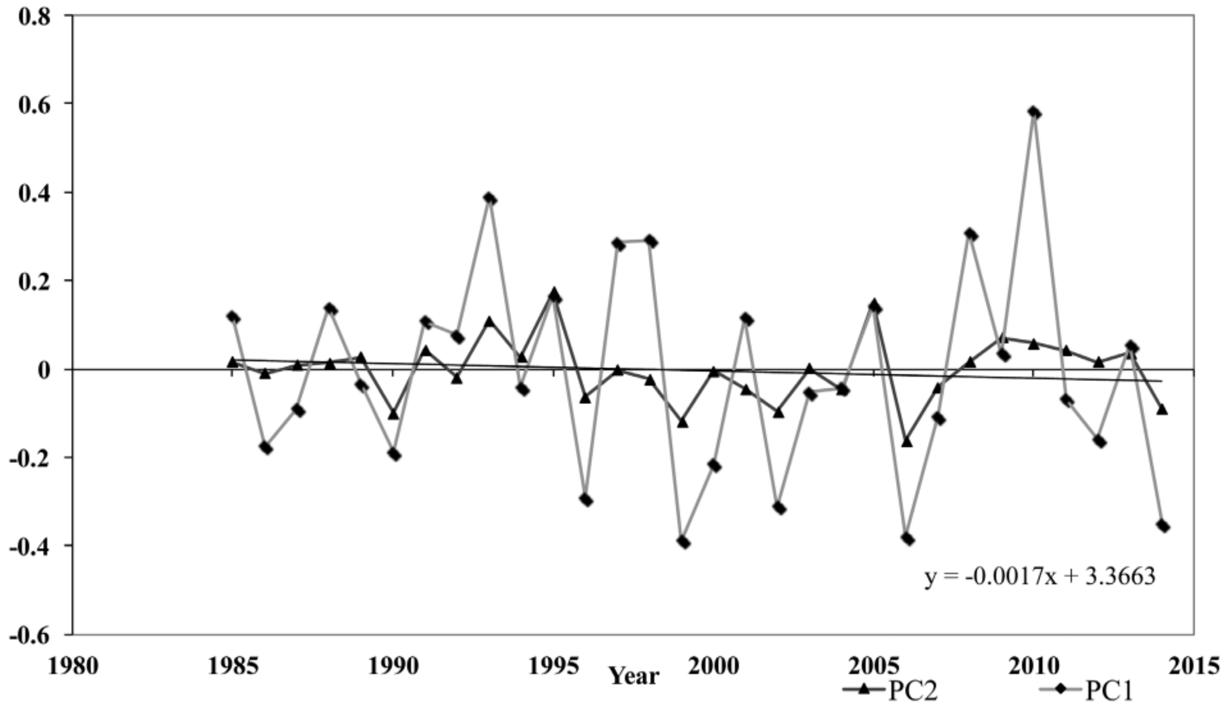

Figure 5. Weighted March Index (1985-2014). Time series of PC1 and PC2 of March SWE in the Chuska Mountains and Defiance Plateau. Dashed line and regression equation in lower right describe a linear trend fit to the PC1 time series.

SWE increases with both elevation and latitude for snow survey sites in the Chuska Mountains, as seen in Figures 3 and 4. Generally, most mountains in the western U.S. have peak snowpack accumulation somewhat later, in early April (Bohr and Aguado 2001). The earlier peak snow accumulation in the Chuska Mountains and Defiance Plateau is likely due to the warmer temperatures associated with the more southern latitude snow survey stations. Though altitudes of the NNDWR snow survey sites are generally at higher elevations than other snow survey stations in the western U.S., Harpold et al. (2012) and Ralph et al. (2014) found timing of peak snowpack to vary by region and latitude in western mountains. Within the NNDWR network, earlier peak snow accumulation dates are associated with sites being at lower elevations.

Year-to-year snowpack anomalies in the Chuska Mountains and Defiance Plateau are generally highly correlated among all snow survey sites; each of the snow survey sites correlated positively with every other site with R values of 0.6 or greater. Snow water equivalencies at sites in lower elevations and sites in higher elevations vary somewhat more from each other. Of the higher elevation sites, Hidden Valley explains the most year-to-year variance of the overall snowpack time series and Whiskey Creek carries the least weight in the eigenvector that describes coherent year-to-year variability throughout the nine-site network. A second mode of variability was primarily associated with lower elevation snowpack sites at the southern end of the Chuska Mountains, accounting for nearly 10% of total SWE variability that is uncorrelated with the principal range-wide, year-to-year fluctuations.

The PC1 time series is also used as a weighted composite average of SWE representing the Chuska Mountains and Defiance Plateau. This series (Figure 5) shows multi-year trends. A linear fit to the PC1 time series shows a slight decline of March snowpack from 1985 to 2014 that cannot be confirmed because the decreasing trend is statistically insignificant. Novak (2007) also found trends of declining SWE in both aggregated SWE time series of five high elevation (>2440m) and two low elevation (<2440m) Chuska Mountain snow survey sites for the 1985-2006 period. The 2006 snow year, the final year in the time series available to Novak (2007), was one of the lowest

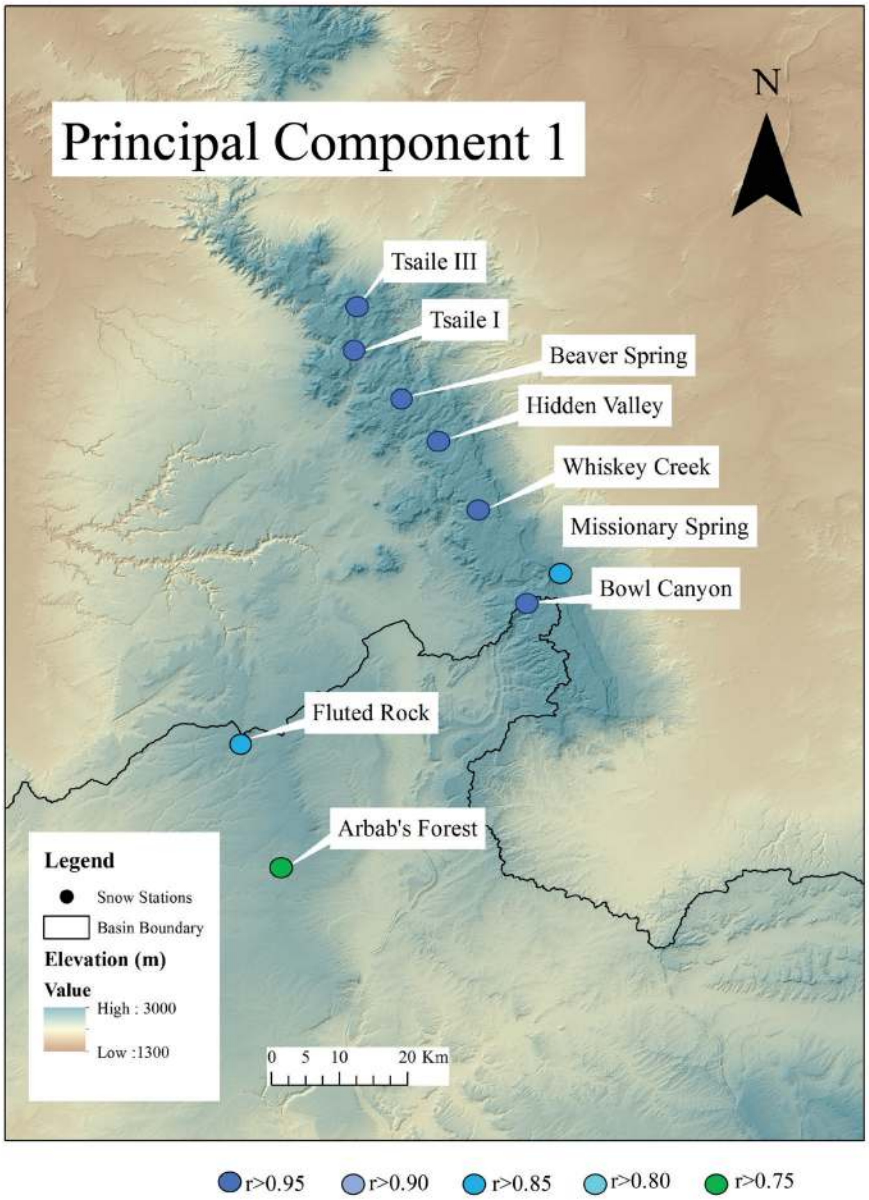

Figure 6. Year-to-year correlation map of March SWE for Principal Component 1.

years on record for SWE in the Chuska Mountains. Years of relatively high snowpack following the 2006 snow year changed the overall snowpack trend based on snow survey record between 2006 and 2014. Because of the length of the NNDWR snowpack record, multiple years of relatively high or relatively low snowpack within a short time span (~5 years) could still greatly influence the snowpack trend. The snowpack record length for the Chuska Mountains studied for this research is thirty years (1985-2014) but still ends on an unusually dry year. Thirty years is the standard length of time required to calculate a climate "normal" that can be used to describe climate in a particular area based on a climatic element such as temperature or SWE. An average over a thirty-year period of record is typically long enough to accurately represent climate because it spans several episodes of short term weather variations and anomalies. However, the year-to-year variability and short term fluctuations of SWE observed in the Chuska Mountains (likely due to natural short term weather patterns such as the El Niño/Southern Oscillation cycle) can influence trend estimation. Thus, the linear trend fitted for the 1985-2014 record may not entirely reflect the actual long term trend in climate in the Chuska Mountains. If a longer period of record of snowpack were available, short term weather variations and long term climate trends could be more easily differentiated from one another.

The NNDWR faces challenges of collecting snow survey data with minimal funding and staff. If the NNDWR needs to eliminate any of its snow survey sites in the Chuska Mountains or Defiance Plateau, removing a snow survey site from pairs of stations that are very strongly correlated with one another is most likely to maintain the most accurate representation of snowpack in the Chuska Mountains and Defiance Plateau. The NNDWR should initially consider discontinuing sites from pairs with highest correlation ($r = 0.97$) seen in Table 4. In particularly dire conditions, high elevation and low elevation sites from each of the two different watersheds and sites that represent the two different modes of year-to-year variability need to be kept. The recommended sites to keep (at a minimum) include: Bowl Canyon as a high elevation site in the Little Colorado River watershed; Fluted Rock or Arbab's Forest as a low elevation site in the Little Colorado River watershed and as a site from the second mode of variability; Missionary Spring as a low elevation site in the San Juan River watershed; and at least one of the remaining five sites (Tsaile III, Tsaile I, Beaver Spring, Hidden Valley, and Whiskey Creek). From the eigenvector analysis, the Hidden Valley site carries the most weight from the first mode of year-to-year variability out of all the Chuska Mountain sites. It is recommended that Hidden Valley be kept in the NNDWR snow course network as a high elevation site in the San Juan River watershed that represents the first mode of year-to-year variability in the eigenvector analysis. The Whiskey Creek snow course is also recommended to be continued because it has one of the longest, most continuous snow data records of all the NNDWR sites. Additionally, continuing the Whiskey Creek snow course is important for comparing and validating snowpack data collected by the SNOTEL station.

Eliminating any of the snow courses from the NNDWR network would result in a loss of resolution of the snowpack data. Loss of a data collection site is a loss of data. Correlations based on historical data may unexpectedly change in a time of uncertain climate change and reducing sites could still lead to a loss of coverage of snowpack variability. Further studies may show different types of importance any of the sites have that is not yet known, due to limited research on responses of surface water and groundwater to snowpack variability, or due to climate uncertainty. For example, if further research is completed on the relationship between snowpack and snowmelt runoff in the Chuska Mountains, results may reveal high correlation between certain snow survey sites and stream gages. Also, the thirty-year period of record may be too short to show any sensitivity of snowpack to long-term climate trends. Different areas of the Chuska Mountains and Defiance Plateau may show a variation of responses to climate variability that is not shown in this study, so any truncation of snow data collection would result in some loss of sensitivity in future climatic analyses.

The NNDWR can use the information provided in this study as a basis for future studies, projects, and decisions on their snow course network. This study provided a basic characterization of snowpack in the Navajo Nation. Further understanding of the seasonal cycle and variability of snowpack can help the NNDWR in forecasting snowmelt runoff and surface water resources for the Navajo Nation through additional studies involving correlation of snowpack and stream discharge in the Chuska Mountains. The correlation and "weighting" of NNDWR snow survey sites with one another may help the NNDWR prioritize snow survey sites and determine which, if any, snow courses can be discontinued. However, it is advisable that the NNDWR retain the current snow survey and SNOTEL sites to maintain resolution of data. Also, merging of NNDWR snow survey data with national networks of data, such as the NRCS SNOTEL network, may provide a better understanding of snowpack patterns from a larger regional perspective.

Amid growing concern over climate change, it is important for the Navajo Nation and other tribes to continue to monitor and collect meteorological, climatic, and hydrologic data to better understand how climate change and climate variability influence their water resources. In the Chuska Mountains and the Defiance Plateau, snowpack provides runoff to streams and recharge to groundwater and springs which are all economically, culturally, ecologically, and hydrologically important. Local communities rely on springs and groundwater as one of their sources of drinking water. Streams in the Chuska Mountains provide water for agriculture and ecosystems. Snowmelt provides water for ponds and lakes used for recreation and livestock. Snowmelt is also important for providing soil moisture for vegetation. Results will help the NNDWR relay information to communities that rely on snowpack and water resources in the Chuska Mountains. The NNDWR has built a solid foundation in the collection of data in their streamflow, precipitation, and snowpack records. Further and continued analyses of hydroclimatic data will help the Navajo Nation and local communities in the Chuska Mountains and Defiance Plateau to better plan and manage for any changes in water resources in the near or distant future.

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