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Assessment of the Navajo Nation Hydroclimate Network

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Assessment of the Navajo Nation Hydroclimate Network: Executive Summary

During 2007, investigators from Arizona's three state universities undertook an investigation of Navajo Nation's hydroclimate network. The project, funded by the newly-formed Arizona Water Institute (AWI), was requested by the Navajo Nation Department of Water Resources (NNDWR) to follow up on a 2003 Technical Memorandum, which, among its many conclusions, stated that NNDWR needed to reduce its network in order to facilitate data collection, reduction, and quality control commensurate with its human resources. The overarching goal of the project is to provide science-based advice to improve data collection and processing in support of climate, drought, and hydrologic analyses, while reducing the manpower required to manage the network. In consultation with NNDWR, the AWI project team visited data collection stations, interviewed staff, analyzed NNDWR hydroclimate data, evaluated instrumentation and data communication needs, identified potential improvements, and determined options for reducing overall network size – while filling in key data gaps. At NNDWR's request, the AWI project team convened a workshop to explore possibilities for NNDWR to achieve its goals through collaboration and exchange of data with outside agencies.

Based on its investigations, the AWI project team recommends the following key strategies:

1. Develop a master plan for NNDWR data use. Well-articulated needs and uses for hydrologic, climate, and weather data will guide optimization of station locations, and will create a basis for identifying needs for collaboration and opportunities to leverage data and hydroclimate monitoring to mutual advantage. Master planning is especially important, because *in most cases data continuity and data quality cannot be used to guide selection of existing gages* for future use; thus, needs will drive key selection criteria.
2. Enhance data communication. Automating data collection, adding telecommunications, and locating automated stations where telecommunications are easily accessed will reduce visits to stations, alert staff to equipment malfunction, and facilitate data sharing – which can shift the burden of data reduction and quality control to collaborators. Moreover, data communicated through data-sharing networks, such as MesoWest or AHIS, will improve real-time data visualization and reduce the burden of metadata management.
3. Leverage existing data collection networks, in order to reduce resources devoted to manual data collection. While this may require some initial effort to establish procedures and routines for acquiring electronic data, leveraging data from other networks may obviate the need for much of the existing rain can network – which requires substantial investment of time and human resources.

4. Fill in gaps in the NNDWR automated weather station network. Station density analysis suggests 6 accessible locations with nearby telecommuncations. For precipitation, NNDWR can fill in gaps with inexpensive automatic-logging precipitation gauges that can provide digital data at daily or sub-daily time scales.
5. Augment rain can observations by enlisting cooperative observers. We recommend (a) daily data collection (for which procedures are less confusing than those required for monthly collection), and (b) making sure that the cooperators' rain cans or weather stations are located near telecommunications, so values can be phoned in (or input via Internet) directly to the National Weather Service, who will take on responsibility for data reduction and quality control.
6. Do not remove stream gages, but shift streamflow data collection emphasis from time consuming sheet-recorded chart digitizing to efforts that improve data quality and usability, such as, gage maintenance, regular calibration, and timely and consistent data collection and communication.

Key Science Findings

Our data analyses and interviews led us to the following conclusions and recommendations:

- Confirmation that hydroclimate data prior to 2001 are hampered by irregular data collection, many missing streamflow and manual precipitation gauge data, over-written automated weather station data, and an imposing backlog of undigitized data. Thus, for practical purposes, these data cannot be used. Data collected subsequent to 2001 have a lower incidence of missing data, but they are still influenced by in-channel vegetation and sedimentation (streamflow data), lack correspondence with calendar months (rain can data), and data overwriting combined with a lack of instrument calibration (automated weather station data). NNDWR data *can provide some baseline information that augments data from other agencies, if aggregated to coarse time scales* (seasonal, annual). These records are not of sufficient length for determining average values ("climatology"), trends, or variability.
- Rain can data are only usable when aggregated to seasonal or annual time scales, due to incompatibility in monthly data collection timing. *These data may be valuable for drought and climate monitoring*, *but only with considerable effort* to reconcile time frames, account for missing data, and aggregate spatial data; our analyses show that rain can precipitation data are valuable for improving the spatial robustness of measured precipitation in the region – but their value is undermined by the missing data and lack of calendar month correspondence issues. Rain can data and nearby National Weather Service cooperative observations show poor correspondence, that may be due to site factors and/or data quality. *The rain can data collection effort provides a low return on investment of time and human resources.* By leveraging data from other networks, rain can sites can be reduced to as few as 47 locations. *The burden of rain can data collection, reduction and quality*

control could be further reduced, if NNDWR enlists cooperators in locations near telecommunications; some Chapter Houses, schools, and Diné College are likely locations. Moreover, the **Northern Arizona Mesonet**, an effort embraced by the National Weather Service, and with high probability of expansion within Navajo Nation, can provide real-time data to supplement existing automated weather station data and reduce rain can stations.

- *Streamflow data quality is compromised by site factors*, such as vegetation encroachment in stream channels, sedimentation in stilling wells, sediment aggradation in stream channels, as well as sporadic data collection. *Data analysis indicates robust stage-discharge relationships only for Kinlichee Creek and Tsaile Creek*.
- More efficient, reliable and adequate data collection, processing, archiving, and dissemination may be accomplished through *ongoing and improved training of Navajo Nation Department of Water Resources technicians*, and further investment in human resources when possible. Based on our assessment, key training needs include: stream gage maintenance, data processing, weather station calibration, and data uses. A new AWI project can address some of these needs. Calibration requirements for the various sensors vary from 6 months to every two years. Options include purchase of calibration equipment from the vendor or sending sensors to the vendors for calibration. Either option would require investments of financial and human resources. Establishing a calibration schedule, timing of which depends on the individual sensor, would improve data quality and reliability.

Workshop Recommendations

Most participants in the October 9, 2007 Navajo Nation Hydroclimate Workshop enthusiastically embraced data sharing with Navajo Nation and others in the region. Participants' key recommendations include the following:

- *Lack of automated data collection and electronic data communication* are the key barriers to Navajo Nation hydroclimatic data network enhancement and data exchange. Workshop participants recommended that Navajo Nation *select a few existing sites for automation, making use of Internet connectivity to facilitate data communication.* The aforementioned may require moving existing automated stations to locations with nearby Internet connectivity.
- NNDWR can *leverage resources, such as innovative pilot projects* (e.g., Northern Arizona Mesonet), to expand or enhance parts of the regional hydroclimatic observation network.
- Some Navajo Nation sites can be incorporated into the National Weather Service Cooperative Observer Network. Sites will need to be selected carefully. Navajo Nation may need to invest manpower, and perhaps upgraded equipment, in order to participate.

Key Strategy Options

Based on our investigations, the best science-based options for reducing manpower needs, while maintaining data quality and sufficient hydroclimate network spatial coverage, include:

1. Develop a strategy and plan for the network so the monitoring stations are located for the purpose(s) of the network, which may include flood warning, severe storm warning, water resource monitoring, drought planning, or agricultural or rangeland monitoring. These purposes are not mutually exclusive, though planning for the highest temporal and spatial resolution allows the network to meet the maximum number of needs. Real-time data, that inform NWS for storm watches and warnings, are equally viable for agricultural needs, floodplain management, and climate analyses. Including other networks in the plan can maximize resources.
2. Use the current weather station network along with the other weather networks operating on the Nation, and automate as many stations as possible to get real-time data and then work to fill in gaps that currently exist, based on the density analysis. To minimize the cost of communications or telemetry, some stations can be moved to locations near institutions with computer resources and Internet access, such as colleges, high schools, or Navajo government facilities. The period of record with good digital data is not sufficiently long to preclude moving a station. Relatively short distance station moves will not adversely impact the spatial distribution. Climate data are used extensively in schools for teaching both science and mathematics as the students have a sense of ownership of the data and they can visualize the concepts since the data represent real conditions.
3. Significantly reduce the rain can network as it currently exists, in favor of Cooperators in the NWS system, which eliminates all manpower requirement for collection, digitizing, QA/QC and data reduction, and provides daily data with more utility and potentially an improvement in spatial coverage. The daily temperature and precipitation data collected at a COOP site can be used by the surrounding community to characterize their climate for purposes of farming or ranching, including calculation of heating and cooling degree days, growing season length, evaporative demand for water and irrigation scheduling. If more Chapters had COOP stations (whether through Chapter Houses or through reliable individual cooperators), the overall distribution on the Navajo Nation would be better than the current network, with less manpower required of the NNDWR.
4. Alternatively, or in conjunction with number 3 above, substantially reduce or eliminate the current rain can network and use the precipitation data from other networks, and fill in the gaps with inexpensive automatic logging precipitation gauges that can provide digital data at daily or sub-daily time scales. Remote locations or large gaps in the spatial coverage can be filled by logging gauges that can be downloaded at any time. They do not provide real-time data, but the data can be integrated with all the other data for climatological or case study research.

Disclaimer

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Introduction

Drought, during much of the past decade in the United States Southwest, has raised societal awareness of the risks associated with reduced water. Concern, created by uncertainty regarding water availability, has prompted unprecedented action by local governments and education of the local population. As a reflection of the region, the protection and management of the water resources of Navajo Nation – established in 1868, and the largest Indian reservation in the United States – is crucial for the welfare of its people. Drought-related sand dune incursions put many of the Navajo population centers at risk, and Navajo Nation farmers and livestock producers have been dramatically impacted by the recent periods of drought. Leaders of Navajo Nation have recognized the importance of hydroclimatic monitoring for public safety and for triggering drought action (NNDWR, 2002). As of Fall 2006, Navajo Nation Department of Water Resources (NNDWR) operated 209 hydroclimate gages in several environmental networks. The networks include stream gages, automated weather stations, snow surveys, and recording and non-recording precipitation gauges. The data from these networks are critical to Navajo Nation resource and drought planning, its economy, and to those regional groups with whom they may wish to partner in data sharing.

The NNDWR has collected hydroclimate data on the reservation since 1984. Despite the size and topographic complexity of the Nation, two characteristics that warrant a well-integrated high density network, the NNDWR data collection effort has lacked continuous and reliable funding. NNDWR has determined that hydroclimate network data collection and processing require more than twice the available manpower (WMI-Memo, 2003). Much of the work load is the result of long travel distances between stations, and labor-intensive equipment. In response to this manpower analysis, many gages and observation stations have been shut down – but without strategic guidance on the quality, reliability, and monitoring value of the remaining stations.

In January 2007, a team comprised of researchers from the University of Arizona, Arizona State University, Northern Arizona University, and NNDWR, and funded by the Arizona Water Institute (AWI), began a thorough and systematic analysis of the current NNDWR instrumentation network. The overarching objectives of the project are to:

a) determine the utility of archived hydroclimate data, record continuity, and record-keeping methods in support of drought and hydrologic analysis and long-term impact assessment, and
b) advise Navajo Nation on how the network should evolve to provide the highest quality information that describes the climatic and hydrologic conditions across Navajo Nation.

In addition to NNDWR, many government agencies and private companies collect data on and around Navajo Nation to meet specific narrow programmatic objectives, with no integration of the networks. Coordination of the various data sources would greatly enhance knowledge of Navajo Nation hydroclimatic conditions, improving local and statewide drought forecasting and response and sharpening local hazard forecasting. As such, a secondary task of the AWI project is to assess the feasibility of establishing a community data network, integrating NNDWR and other regional network data, in order to improve drought and flood monitoring and planning, and agricultural and livestock management.

This document reports on data analyses and recommendations related to the aforementioned project tasks. The report is organized as follows: Section 1 describes the physical setting and distribution of various hydroclimate data stations in the region; Section 2 describes analysis of the NNDWR precipitation gauge network; Section 3 describes analysis of the NNDWR automated weather station instrumentation and calibration; Section 4 describes analysis of enhancements to the density of the NNDWR automated weather station network; Section 5 describes the Northern Arizona Mesonet (a supplemental source of data for the NNDWR and other users); Section 6 describes analysis of NNDWR's stream gauge network; Section 7 describes the results of a workshop to explore regional hydroclimatic data collection efforts and potential partnerships; Section 8 synthesizes the key recommendations from the aforementioned studies. Several appendices provide ancillary materials, including comprehensive analyses, references, and items pertaining to the workshop.

Section 1. Physical Setting and Hydroclimatic Data Networks in the Region of Navajo Nation.

Since its establishment in 1868, the Navajo Reservation has been expanded through a series of executive orders to become the largest Indian reservation in the United States. Physically larger than 10 of the 50 states of the United States, the Navajo Nation encompasses more than 27,000 square miles, stretching from the four corners region (intersection of Arizona, Colorado, New Mexico, Utah) across the Colorado Plateau.

The complex topography of Navajo Nation is characterized by arid deserts at elevations as low as 5,500 feet and alpine forests at elevations as high as 10,500 feet. The three most prominent landforms are the Chuska Mountains (> 9,000 feet) in the east-central portion of the Navajo Nation along the Arizona-New Mexico border, the Defiance Uplift (7,000-8,000 feet) just to the southwest of the Chuska Mountains, and Black Mesa (7,000-8,000 feet) in the west-central portion of the Navajo Nation. To the east of the Chuska Mountains is the San Juan Basin (5,900 feet), and to the west and south of Black Mesa is the Black Mesa-Holbrook Basin complex.

The climate of the Navajo Nation is arid to semi-arid, as most areas receive less than 10 inches of precipitation annually. The region largely falls between the more northerly track of wintertime mid-latitude storm systems from the Pacific Ocean and the more southerly location of abundant summertime moisture for generating convective precipitation. The Navajo Nation is subject to extreme seasonal temperatures, with rather cold winters and hot summers. The annual average temperature across the Navajo Nation ranges from about 40^{o}F to about 55^{o}F, with differences driven by elevation and latitude. The Colorado Plateau, on which the Navajo Nation is situated, is drained by the Colorado River and its tributaries, the Green, San Juan, and Little Colorado Rivers.

The average population density of the Navajo Nation is about 6 people per square mile, less than one-tenth that of the United States as a whole, and the density is much less in many portions of the region. As a result, population centers are generally widespread and there is a very limited roadway infrastructure in many areas of the Navajo Nation, particularly the areas of higher elevation and complex topography. Limited vehicular access and the sheer size of the Navajo Nation present a stiff challenge for operating an extensive environmental monitoring network.

The Navajo Nation Department of Water Resources (NNDWR) has collected hydroclimate data on the reservation since 1984 and now operates 209 hydroclimate gages (late 2006) in several environmental networks. The networks include stream gages, automated weather stations, snow surveys, and recording and non-recording precipitation gages. In addition to NNDWR, additional agencies of the Navajo Nation, United States federal, state, and local government agencies, other tribal governments, and private companies collect data on and around the Navajo Nation.

The design of an environmental network focuses on a station/gage density that is necessary to represent the spatial variability in the targeted element of the environment. However, working against that idea are the physiographic challenges of the geographic area – size, accessibility, terrain complexity - and the available resources, financial and manpower, required to combat those challenges. Given the physiography of the Navajo Nation, NNDWR's operation of over 200 hydroclimate gages is remarkable. Equally impressive is the 24-year rate of growth of nearly 9 stations per year. The result is a present density of one gage, measuring some aspect of the hydroclimate, per 129 square miles (see Section 2 for comments on the spatial distribution of these stations).

Figures 1.1 and 1.2 provide an overview of Navajo Nation's hydroclimate network. The figures are designed to show the spatial distribution of stations recording data for various parameters. Details are reported in Sections 2-6, below. This report does not examine snow course data, which are reported to the USDA-Natural Resources Conservation Service, and which are recorded following USDA-NRCS protocols. In the figures, *SOD* refers to Navajo Nation Safety of Dams Branch; *Coops* refers to the NOAA-National Weather Service Cooperative Observer Network (unless labeled in the legend as "current," some of these stations are no longer active). *ALERT* stream gages are operated by Arizona county flood control districts. *NAU Wx* refers to Northern Arizona Mesonet stations (Section 5).

The aforementioned figures show the strong concentration in the central part of Navajo Nation (Chuska Mountains and Defiance Plateau) of stations collecting information on all parameters, and the paucity of precipitation and streamflow observations in the eastern part of Navajo Nation. Streamflow observations are sparse throughout western Navajo Nation, although the USGS and the Hopi Tribe operate some gages in the western area.

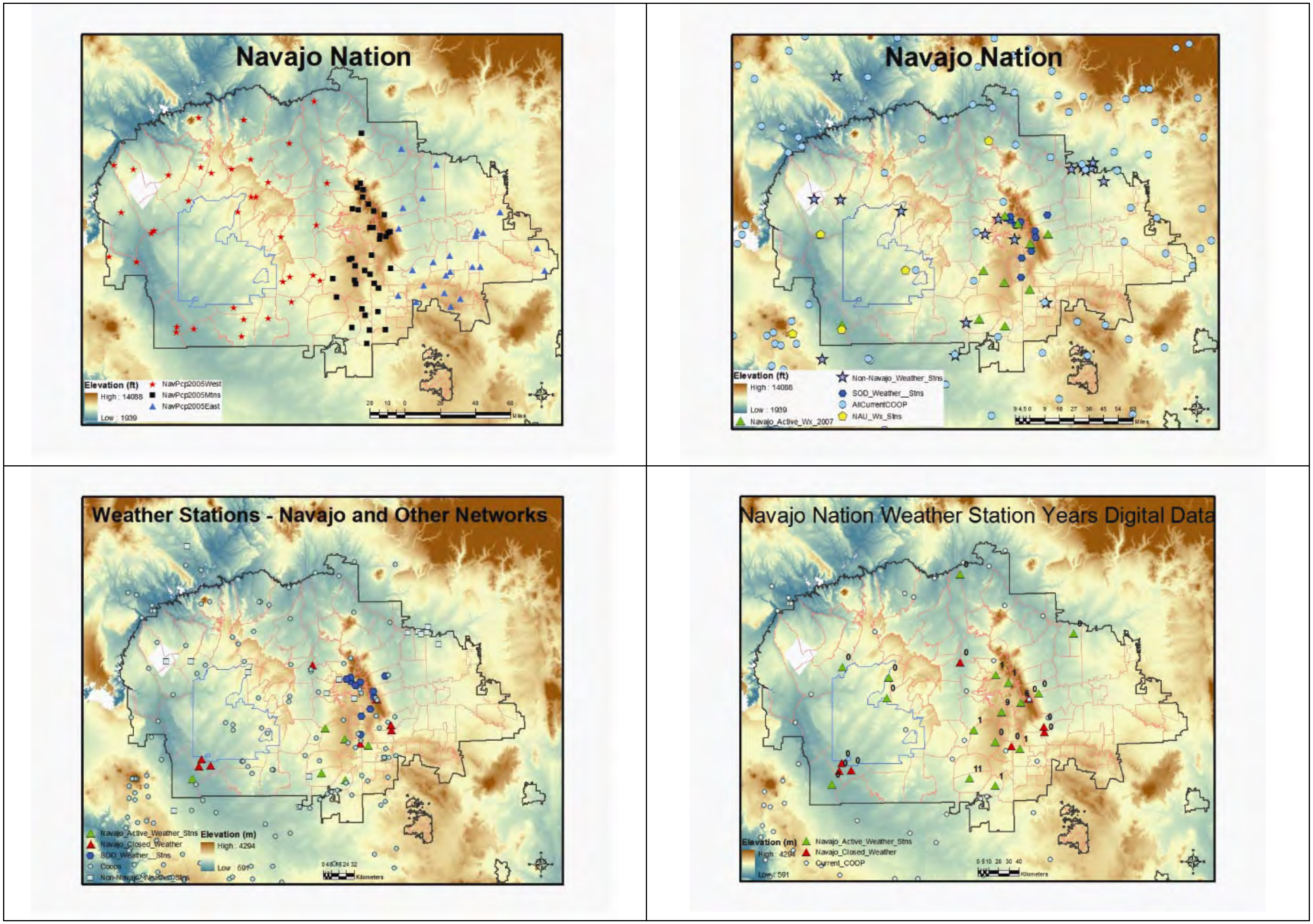
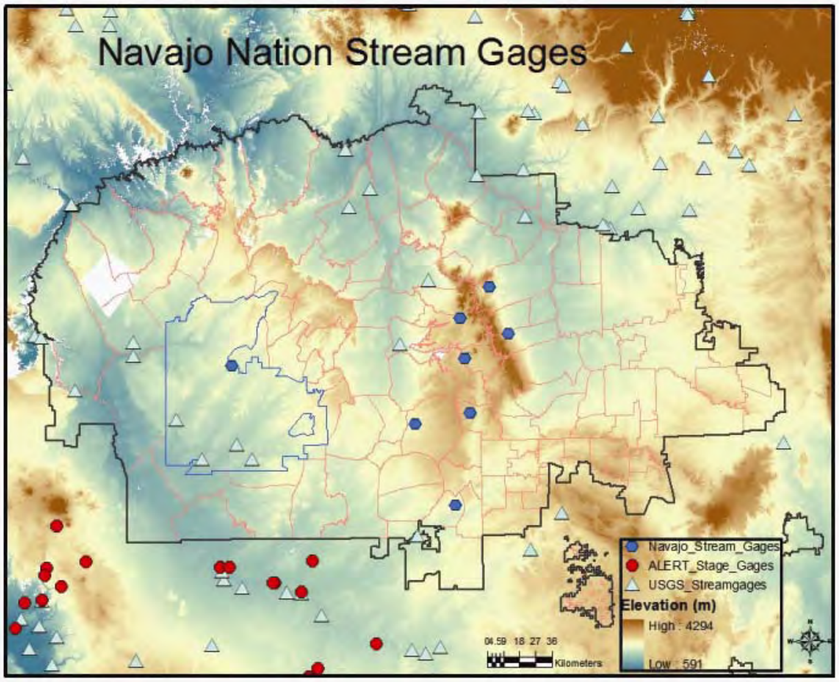


Figure 1.1. Navajo Nation precipitation gages ("rain cans") (upper left); non-Navajo precipitation gages (upper right); regional weather stations (lower left); Navajo Nation weather stations – total number of years with digitized records. Note that English measurements are used in the top figures, and metric measurements in the bottom figures.



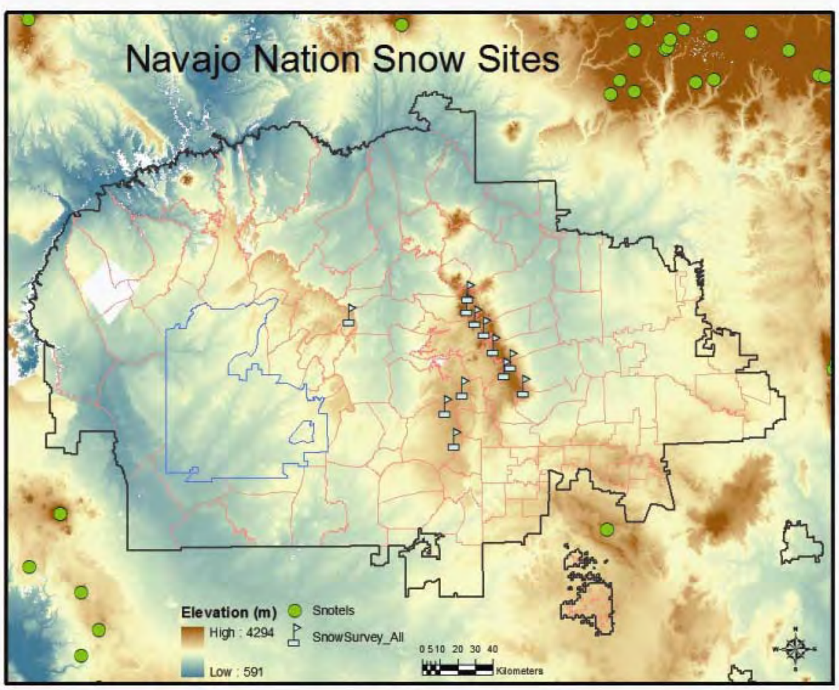


Figure 1.2. Navajo Nation streamflow gages (top); Navajo Nation snow courses (bottom).

Section 2. Navajo Nation Department of Water Resources Precipitation Gauge Analysis

Abstract. The Navajo Department of Water Resources (NNDWR) Water Management Branch has nearly 100 precipitation gauges for which data are collected each month, but on a variable schedule that is dictated by available manpower and weather conditions. The data collected prior to 2001 are generally of poor quality with significant percentages of missing data. The data collected since 2001 are useful only for seasonal or annual analyses of the spatial distribution of precipitation. To improve the utility of the data, and potentially reduce the manpower requirements for data collection, we recommend the following:

- Remove stations that are within 15 km (10 mi.) of other networks that collect precipitation – since the other networks report data either daily or hourly. There are 36 NNDWR gauges located within 15 km (10 mi.) of non-NNDWR monitoring sites. Discontinuing collection at these gauges will reduce manpower needs, while continuing to provide data.
- Find cooperators for as many stations as possible and integrate them into the National Weather Service (NWS) Cooperative Observer (COOP) network. Consider locating a rain can at each Chapter House, if the Chapter House conducts business 7 days a week, or if there is someone available to take observations on days when the Chapter House is not occupied. This will increase the reporting frequency to daily, make the data easier to integrate with data from other sources, and make the data more useful for water resource management. Daily data are also easier to collect than monthly data, as there is no need for the use of antifreeze or oil, which complicate the process. The NWS has automated reporting systems, either by telephone (a toll-free call) or Internet for daily reporting. Stations can be either precipitation only, or temperature and precipitation. This step will increase the number of stations, without increasing the WMB manpower requirements, as site visits will be limited to semi-annual maintenance visits. Moreover, all Chapter House gauges will be easily accessible. Also, manpower needs will be reduced, because the NWS will quality control the data. (Note: we recognize that many Chapter Houses will not meet the aforementioned requirements).
- In easily accessible locations upstream of stream gauges, replace manual precipitation gauges (read monthly) with recording gauges equipped with dataloggers (read hourly or more frequently), in order to provide daily and event data. In more remote areas, gauges that can be equipped with telemetry will reduce manpower needs. The event-based data that will be recorded are critical to establishing rainfall-runoff correlation. The shorter reporting interval will make the data more useful and easier to integrate with data from other sources.
- Systematically automate the precipitation gauges to ALERT standards, starting with gauges in flashy creeks and washes, and those upstream of population centers. This will provide real-time data, important for a range

of public safety applications, including flood forecasting by the NWS Colorado Basin River Forecast Center, floodplain management and planning, streamflow analyses, and precipitation and flood frequency analysis. If the data are ingested into the NWS Meteorological Assimilation Data Ingest System (MADIS), NWS will perform the analyses necessary to ensure adequate data quality.

- Automate the weather stations – including their precipitation gauges, to hourly reporting through a telecommunications system. This provides the most economical solution, since the dataloggers being used are already suitable for telecommunications; automated stations that communicate through telemetry can deliver many important environmental monitoring variables, in addition to precipitation.

2.1. Introduction

The Navajo Nation encompasses over 70,000 km^2 (27,000 mi^2) in northeastern Arizona, southeastern Utah, and northwestern New Mexico (Figure 2.1). The Hopi Reservation lies within the Navajo Nation boundaries in the western plateau. Although most of the land is contiguous, there are several smaller areas in northwestern New Mexico that are not physically connected. These smaller "islands" of reservation land lack rain, weather, snow, or stream gauges. The Navajo Nation is in a semiarid part of the Colorado Plateau that is sparsely populated, difficult to access, and subject to weather extremes. The Nation has a network of precipitation gauges that has numbered nearly 250 in the past, and presently has 98 units in operation with at least five years of data each. A number of other agencies also have precipitation gauges operating within the Navajo Nation reservation lands. Most of these gauges are part of a weather station or are located in tandem with a stream-gauge, and therefore they collect data at a sub-monthly time scale (generally daily or hourly). Currently the Navajo Nation Water Management Branch (WMB) has access to the data generated by some of these stations, generally through the Internet. Many of the associated networks have automated data collection, and data are communicated through telemetry (either radio, satellite, or modem), making them real-time or near real-time data. An opportunity to share data with these other network operators would increase the precipitation information available to the Navajo Nation, and to all the other network operators, and potentially eliminate redundancy of sensors.

Since the NNDWR precipitation data are only collected monthly, require considerable logistical and manpower support, and are constrained by limited available resources, the analyses of the precipitation network have two goals. The first goal is to determine the utility of the archived data and the second goal is to advise Navajo Nation on how the network should evolve to provide the highest quality information that describes the climatic and hydrologic conditions across Navajo Nation. The utility of the network must be balanced by the resources necessary to maintain the network, the database itself, and the translation of the data into useful information for the agricultural, water resources, climate, and public safety communities both within and surrounding the Navajo Nation. Information that can improve the timeliness and quality of flood warnings, drought planning and response, and agricultural and water resource decision making are among the highest potential uses of the data.

2.2. Research Methods

2.2.1. Data

The Navajo Nation Department of Water Resources has a network of 98 precipitation gauges (not including automated weather stations) that are currently in operation. There are additional operating gauges, but through September, 2006, only 98 had sufficiently low percentages of missing data (discussed below) to permit analysis. The instruments are a mixture of recording rain gauges and manual gauges. The first three gauges (Marsh Pass, Klagetoh 9NE, and Little White Cone) were installed between 1952 and 1962. In 1984, more gauges were added, at a rate of between three and six per year, until 1989 when the rate of installation jumped to 12 per year for two years. Weather stations and snow courses were also installed. In 1992, 14 gauges were installed, and 21 gauges were added to the network in 1993. Between 1995 and 2000, about 4 gauges were added per year. The gauges were distributed across the Nation near population centers or near higher elevation areas that tend to have greater precipitation. Although gauges are distributed across the entire Nation, they are not uniformly distributed. In parts of the Nation, gauges are clustered, while in other regions, such as the eastern and western plateau regions, there are large gaps between gauges. The precipitation data are collected monthly, between the 25th of the month and the 5th of the following month, depending on weather, road conditions and available personnel. Of the 98 gauges, 35 are located west of the Chuska Mountains, 21 are located east of the Chuska Mountains, and 42 are located in the vicinity of the Chuska Mountains and the Defiance Plateau (Figure 2.2).

A number of other agencies also have precipitation gauges operating within Navajo Nation lands, and many of these stations are shown in Figure 2.3. They include the Navajo Safety of Dams Branch (SOD); Navajo Indian Irrigation Project (NIIP); National Weather Service/Federal Aviation Administration (NWS/FAA; airport weather stations); the Colorado Basin River Forecast Center (CBRFC; part of NWS), the National Weather Service; the National Park Service (at various national monuments both within and outside the Navajo Nation boundaries); the National Weather Service Cooperative Observer program (COOP); Arizona Department of Transportation; the Peabody Western Coal Company; Pittsburgh and Midway Mining Company; USDA-Natural Resources Conservation Service (NRCS); the Bureau of Land Management (BLM); United States Geological Survey (USGS); Northern Arizona University (NAU); and Arizona Public Service (APS).

2.2.2. Analytical methods

We mapped all hydroclimatic monitoring sites in the region of Navajo Nation, to get a sense of the scale of the research area. Site visits to several precipitation gauges, weather stations, stream gauges, and snow courses were conducted to view the typical site conditions, as well as the surrounding topography. The technicians who collect the data and service the equipment were interviewed as they guided us from site to site, and they explained their methods and communicated some of the difficulties in accessing the sites and collecting the data. We also learned how they enter the data into the database. We received the digital databases for each type of environmental parameter, and conducted our own queries to extract the data we needed for analyses. This analysis is limited to the precipitation gauges, as the stream gauges and weather stations are addressed elsewhere in this report.

The approach to the precipitation data analyses was determined based on the aforementioned site visits and the characteristics of the available data. We first assessed the percent of data available at each gauge, and retained stations with 83% of data available. Since the data were monthly totals, each month of missing data represents just over 8% of the annual data. Most stations were missing a maximum of 2 months of data per year (16.33%). After determining the pool of stations that could be rigorously analyzed, we conducted statistical analyses to summarize the data. We conducted some one-to-one comparisons between NNDWR and NWS stations, where (a) the stations were in close proximity to each other, and (b) the NWS stations had daily data. We could not analyze every NNDWR station in this fashion, because NNDWR data collection varied from the NWS standard of reporting totals for each calendar month, i.e., NNDWR data exhibited heterogeneous time intervals for monthly data collection. We analyzed the entire NNDWR station network using seasonal data and spatial statistics methods, as a one-to-one comparison could not be made for every station.

2.2.3. Statistical methods

We used descriptive statistics to summarize key data attributes, such as mean, median, standard deviation, outliers, frequency distribution and normality. We assessed the relationships between NNDWR stations and neighboring stations from other networks, using linear regression. In order to determine station density, station proximity, and spatial autocorrelation, we calculated semi-variograms using Geographical Information System (GIS) software. Semi-variograms are statistical functions that calculate the degree of similarity between values at two points (precipitation, in this case), based on the distance between them. This information is used to krig (interpolate) between the data points. Spatial patterns were examined using kriging methods of interpolation after gridding the station data, based on the semi-variograms (Burrough and McDonnell 1998). The gridding used ordinary spherical kriging since no consistent directional trend was found for all the years. We did not incorporate finer scale methods of including digital elevation data into the regression (Daly, Neilson et al. 1994; Carbone and Bramante 1995; Comrie and Broyles 2002), as the purpose of our study is to assess the utility of the data for such research. We conducted subjective assessments to compare stations, when insufficient data were available for regression analyses; for these, we graphed the precipitation data and visually assessed spatial trends and data variability.

2.3. Research Context

The analyses of the precipitation data have a geographical context and an institutional context, but the recommendations are related to the context of NNDWR needs. The geographical and institutional contexts are related to the amount of missing data. Although the majority of stations have been in operation since approximately 1992, the amount of missing data is near 50% per year for many stations. This is probably due both to the difficult terrain and road conditions within the Navajo Nation, and to the availability of manpower and resources required to collect the data and to maintain a digital database. Beginning in 2001, the amount of missing data is almost negligible for most sites, averaging between 0% and 16.67%, where the latter number represents two months. Since the gauge accessibility has not changed radically (as far as we can tell), this is probably an institutional shift in realizing the importance of the network for the welfare of the Navajo Nation.

The intended use of hydroclimate data and information by Navajo Nation also influences the recommendations generated by this work. For example, recommendations for determining and monitoring long-term trends and mapping hydrologic floodplains would be very different than recommendations for data collection to ensure public safety through improved warnings of floods, severe storms, freeze conditions, and road hazards. At present, the intended use of the network going forward is not clear. Archived data from the network have few uses, as they correspond to non-standard monthly intervals (i.e., not calendar months), and the portion of the period of record where there is sufficient data is too short to analyze trends. Going forward, higher reporting frequency (at least daily) would be beneficial, but the change would add to the complexity of the database and to the equipment maintenance, due to the requirement of automated equipment. Therefore, the scope of recommendations will have to include the balance between data/information needs and available resources.

2.4. Results

2.4.1. Precipitation Summary and Station Density

2.4.1.1. Missing data. Using the entire period of record, we evaluated the percent of missing data for each gauge. The percent of missing data at each station ranged from 5.7% to 72.9% (Figure 2.4). The record length varied from 54 years to 6 years, with only three sites having records longer than 43 years. The high percentage of missing data is testament to the difficulty in accessing the sites in inclement weather and in maintaining sufficient staff and resources to manage the large network. Since 2001, the percentage of missing data has dropped dramatically to a range of 0.0-16.7% missing. Since large amounts of missing data skew the analyses, subsequent analyses were restricted to precipitation data collected between 2001 and 2005.

2.4.1.2. Precipitation variability. Table 2.1 shows mean and standard deviation for winter, and summer precipitation for all NNDWR data for 2001-2005. The mean rainfall was greater for summer than winter in every year except 2005, which had an exceptionally wet winter. For the two years with the driest winters, 2001 and 2002, the variance was greatest in summer, but for the three wet years of 2003-2005, the variance in precipitation was greater in winter than summer. This is a bit unusual, as summer precipitation (convective storms) is typically more variable than winter precipitation (frontal storms). This result is consistent with a study by Richard Hereford (2007) for Flagstaff precipitation. Hereford found that Flagstaff winter precipitation is more variable than summer precipitation; and summer precipitation tends to be greater than winter precipitation. Extreme variability is normal for arid climates, and northern Arizona is at the southern edge of the westerly frontal storm boundary. Since the summer convective activity provides more than half the annual precipitation in Navajo Nation, a more dense distribution of precipitation gauges is required than in locations where more spatially uniform frontal precipitation dominates.

The mean and standard deviation of precipitation for the three regions are presented in Table 2.1. As expected, the highest mean precipitation was in the mountains, and, with the exception of 2002 (the driest year), the greatest variability was also found in the mountains. The dry year of 2002 has the greatest variability in the east region. In 2001-2003, the west had greater mean precipitation than the east, and in 2004-2005, the east had greater precipitation than the west.

2.4.1.3. Station density and distribution. The overall density of NNDWR precipitation gauges is about 1 rain gauge per 727 km^2 (281 mi^2). The density of stations is very different in the three regions of the Navajo Nation. The western region has an approximate density of 1 rain gauge per 1231 km^2 (475 mi^2), the eastern region has 1 gauge per 684 km^2 (264 mi^2), and the Chuska Mountain – Defiance Plateau region has a density of about 1 gauge per 328 km^2 (127 mi^2). Figure 2.2 shows the eastern, mountain, and western precipitation gauges. There are large areas without rain gauges in the east and west regions. The spatial distribution is quite clustered, particularly around the Chuska Mountains and Defiance Plateau. The distribution is a result of installing stations for a number of research studies over a period of 15-20 years, including a study of weather modification on rainfall over the mountains. In the eastern area there is also a cluster of sites around Farmington, NM, where New Mexico State University operates an Agricultural Science Center.

Table 2.1. Descriptive statistics for winter and summer NNDWR precipitation. Mean (standard deviation) for annual, winter, and summer precipitation for the western, mountain, and eastern precipitation gauges, in inches. Full descriptive statistics are shown in Appendix A.

	Annual				
Year	West	Mtns	East	Winter	Summer
2001	8.77 (3.48)	15.05 (3.73)	9.29 (2.95)	4.66 (2.32)	6.22 (2.84)
2002	5.61 (1.85)	11.35 (2.69)	8.11 (2.71)	3.39 (1.76)	5.08 (1.96)
2003	7.63 (2.54)	14.25 (4.84)	7.68 (2.44)	5.03 (2.76)	5.13 (2.34)
2004	8.76 (3.00)	14.35 (4.50)	8.72 (1.94)	5.16 (2.49)	5.73 (2.33)
2005	9.71 (3.23)	16.40 (4.53)	9.28 (2.23)	6.25 (2.83)	5.88 (2.40)

2.4.2. Spatial variability

We computed semi-variograms for five years of annual precipitation for each of the three major regions of the Navajo Nation. The semi-variograms were also calculated for winter and summer precipitation for the entire NNDWR network. We anticipated that the similarity of terrain over much of the western and eastern regions would result in significant spatial autocorrelation between rain gauges, when aggregated over an entire year, or at least during the winter season, when precipitation should be relatively uniform over a wider area than in summer when precipitation tends to be more localized (Adams and Comrie 1997; Sheppard, Comrie et al. 2002). The western region had the least spatial autocorrelation for all years except 2005, which was a very wet year (Table 2.2). The greatest spatial autocorrelation distance was in the mountains for all five years. This makes sense considering that the density of gauges in the mountains is nearly twice that of any other region, and the mountains have the highest precipitation every year. The smallest distance for spatial autocorrelation was 16 km (10 mi) in the west, in 2002, which was a very dry year, especially in winter. This also makes sense as the summer precipitation was greater than the winter precipitation in that year, and the west as a region actually has more topographic variability than the mountains or the east.

Table 2.2. Distance in km (mi) of spatial autocorrelation of NNDWR precipitation gauges.

	Annual				
Year	West	Mtns	East	Winter	Summer
2001	86(53)	**130 (81)**	124(77)	89 (55)	**130 (81)**
2002	16(10)	**186(116)**	142(88)	**237(147)**	226(140)
2003	77(48)	**150 (93)**	98(61)	**83 (52)**	66 (41)
2004	80(50)	**186(116)**	142(88)	**104 (65)**	79 (49)
2005	91(56)	**186(116)**	43(27)	87 (54)	**97 (60)**

2.4.3. Station comparisons

The rainfall data from 2001 through 2005 were analyzed to evaluate data quality and to investigate how well the network captures localized events, typical of summer precipitation, which often lead to flash flooding. The NNDWR rain data were compared to the National Weather Service Cooperative Observer (COOP) data. The comparison by month was not possible for the entire network as the monthly COOP data are totaled for calendar months and NNDWR data are totaled for irregular time periods, that vary by station and by month. So, for example, in a particular month the Navajo stations could have 10 different starting and 10 different ending dates. Also, the Navajo data are missing some collection periods, and it is difficult to determine whether the next collection includes all the precipitation from the previous missed collection period, or whether the data are only representative of the most recent period.

Three station pairs were selected to test monthly data; the COOP stations were selected based on proximity to the Navajo NNDWR stations. Each pair is located within 5 km (3.1 mi) of each other, and all had more than 10 years of monthly data. The three pairs are mapped in Figure 2.5, where the red squares are the COOP sites and the yellow triangles are the NNDWR sites. The sites are Ganado (1989-2006), Teec Nos Pos (1990-2006), and Canyon de Chelly – Chinle (1987-2006). The Navajo collection dates were used to determine the start and end dates for summing the daily COOP data into an equivalent month. Since there was no way to determine if any precipitation was not recorded when a monthly Navajo collection period was missed, we marked missing collection periods and assumed that the next collection was for one month only. The total missing data for the period of record for Chinle was 22.9%. The data were evaluated for all months, as well as for the winter months (October-March) and summer months (April-September). We used linear regression, using Navajo station data to predict COOP station precipitation. The results of the analyses for the Chinle (Navajo) versus Canyon de Chelly (COOP) comparison were unexpectedly poor. (Table 2.3).

Table 2.3. Regression analyses for Chinle-Canyon de Chelly. Mean and standard deviation values are expressed in inches.

Time	Stations	Mean	Std Dev	r^2	p	Standard Error of Estimate
All Months	Chinle (NN)	0.631	**0.638**	0.043	0.005	0.707
	Canyon de Chelly (Coop)	0.718	**0.733**			
Winter (Oct-Mar)	Chinle (NN)	0.634	**0.648**	0.046	0.038	0.628
	Canyon de Chelly (Coop)	0.616	**0.641**			
Summer (Apr-Sep)	Chinle (NN)	0.628	**0.630**	0.044	0.049	0.774
	Canyon de Chelly (Coop)	0.818	0.803			

The Navajo precipitation explained less than 5% of the month-to-month variance in the COOP precipitation, even in winter. Winter precipitation tends to be more uniform, particularly across a distance as small as 5 km (3 mi), but here the difference between summer and winter explained variance is only 0.3%. The standard deviation was greater than the mean precipitation for all data subsets except Canyon de Chelly in the summertime. In a dry climate, this is not unusual. Assuming similar terrain, elevation, and site conditions, two sites within 5 km (3 mi) should be more highly correlated. However, Chinle and Canyon de Chelly do not have similar terrain and site conditions. Canyon de Chelly is in a steep-walled canyon, while Chinle is downstream of the canyon on a relatively flat plateau. Although we did not visit these two sites, the conditions at the sites themselves may also be very different. The two sites have an elevation difference of 38 meters (124 feet). Canyon de Chelly generally had greater precipitation than Chinle, so the Chinle site may be blocked by a nearby obstacle. Even when aggregated to annual values, there is little correlation between precipitation at these two stations (Figure 2.6). Means were 6.16 for Chinle (standard deviation = 1.81), and 8.12 for Canyon de Chelly (standard deviation = 3.38). Dry years (2002) seem to have better agreement than wet years (1993 or 1997). The lack of spatial similarity between these two sites indicates the importance of local site conditions in determining sufficient station density. Neither of these stations represents the precipitation conditions at the other station, so proximity cannot be used alone as the criterion for reducing the number of stations.

At Teec Nos Pos, Navajo and COOP stations are in the northeast part of the Navajo Nation, in a relatively flat area, north of the Chuska Mountains. They are about 2.1 km (1.3 mi) apart, and the Navajo site had 17 years of data from 1990 through 2006, with 25.98% missing data. Here, almost none of the variance in the COOP precipitation was captured by the Navajo precipitation gauge (Table 2.4), and none of the results are significant. Again the standard deviation is greater than the mean for all but the summer months. The same assumptions about the missing collections were made as before for the previous station pair. Aggregating to annual totals yielded a better result, where the two stations were within 1 inch of each other in 9 of the 17 years (Figure 2.7). The means and standard deviations for the annual totals were much closer than for Chinle-Canyon de Chelly. The Navajo site had a mean of 8.06, and a standard deviation of 3.72, while the COOP site had a mean of 7.60 and a standard deviation of 3.92. However, in four of the years the differences were greater than 2.3 inches. It's likely that specific site conditions may explain some of the difference, and the sporadic collection may also be a factor.

Table 2.4. Regression analyses for Teec Nos Pos Navajo and COOP sites. Mean and standard deviation values are expressed in inches.

Time	Stations	Mean	Std Dev	r^2	p	Standard Error of Estimate
All Months	Navajo	0.917	**1.110**	0.001	0.737	0.787
	Coop	0.662	**0.820**			
Winter (Oct-Mar)	Navajo	0.900	**1.172**	0.019	0.250	0.502
	Coop	0.514	**0.591**			
Summer (Apr-Sep)	Navajo	0.932	0.119	0.001	0.778	0.961
	Coop	0.806	0.097			

The third station pair, located only 1.5 km (0.9 mi) apart, had the best monthly results (Table 2.5). Ganado (NNDWR) precipitation explained about 42% of the monthly variance in the COOP precipitation data, and explained a higher percentage of variation for winter (57%) precipitation than for summer precipitation (34%). For the most part, the standard deviation was less than the mean. Ganado had 24.54% missing data for the period of record 1989-2006. Almost all of 1999 was missing. In the early part of the record, the Navajo site had greater precipitation while toward the end of the record the COOP site had greater precipitation. This may indicate a substantial change in site characteristics, particularly the location of blocking obstacles. The annual totals had much greater differences than the Teec Nos Pos stations, with seven years having a difference less than one inch, and eight years having a difference greater than two inches (Figure 2.8). The NNDWR mean was 9.08 (standard deviation = 3.92), while the COOP site mean was 9.60 (standard deviation = 3.59).

Table 2.5. Regression analyses for Ganado Navajo and COOP sites. Mean and standard deviation values are in inches.

Time	Stations	Mean	Std Dev	r^2	p	Standard Error of Estimate
All Months	Navajo	1.003	0.888	**0.422**	**0.000**	0.667
	Coop	0.877	**0.924**			
Winter (Oct-Mar)	Navajo	1.019	0.868	0.574	0.000	0.497
	Coop	0.831	0.781			
Summer (Apr-Sep)	Navajo	0.989	0.913	0.339	0.000	0.801
	Coop	0.923	**1.099**			

The results of the station pairs comparison does not instill high confidence in the use of NNDWR data for analysis at monthly time scales. Since these data are not collected strictly by calendar month, but have overlaps, and frequently have multiple collections within the same month, their usefulness is limited to larger scale water resource questions, such as seasonal or annual basin groundwater recharge or forage production, or long-term, slowly evolving phenomena, such as drought. These data cannot address issues related to short-term precipitation variations, such as flash floods. They are also not suitable for real-time weather forecasting or verification. However, when aggregated to annual time scales, they provide better spatial resolution than COOP network data for examining precipitation on the Navajo Nation.

2.4.4. Spatial Patterns of Precipitation

We interpolated precipitation data from the NNDWR and COOP networks, in order to see how well they captured the spatial distribution of precipitation across the Navajo Nation region, and to determine the value added by the NNDWR network. We interpolated each network's data separately (i.e., a COOP interpolation and an NNDWR interpolation) for the comparisons. Finally, we interpolated the combined NNDWR and COOP dataset, to determine the value added by each network. We performed the interpolation exercises for each year from 2001-2005, as well as for summer, winter and annual periods. The results show that the COOP data alone do not adequately capture the spatial variability of regional precipitation, particularly in the area of the Chuska Mountains and the foothills to the north.

Winter 2002, the driest year analyzed, is presented as an example of the contrast and complementary information given by these networks (Figures 2.9-2.11). First, the COOP network alone (Figure 2.9) fails to represent any of the precipitation around the Chuska Mountains; the pattern implies a very dry plain across the western portion of the Navajo Nation, extending all the way across to the east, with a slight increase in precipitation around the Defiance Plateau. The NNDWR data independent interpolation is inserted within the depiction of the COOP interpolation pattern, so the edge differences can also be seen (Figure 2.10). The NNDWR data show higher precipitation in both the Chuska

Mountains and the western mesas, but do not show the gradient in the west up toward the San Francisco Peaks. The NNDWR data also do not show the extent of the gradient toward the San Juan Mountains to the northeast. When the data are combined (Figure 2.11), gradients are smoothed by the additional data points, and show a dry area in the west where the Hopi Reservation lies. The dryness in this area may be exaggerated, due to the fact that we did not include Hopi Reservation data. However, research presented at the 9th Biennial Conference on Colorado Plateau Research (Margaret Hiza, USGS, personal communication) showed that this arid area contains sand dunes, some of which are still active. Also, a site visit showed that this area is extremely dry. The combination of the data sets provides a much different representation of winter precipitation during the dry 2002 winter than does either dataset alone.

We also analyzed precipitation for 2004, which exhibited more typical rainfall totals (Figures 2.12-2.14). Figure 2.12 (COOP data only) shows the greatest precipitation to be located in the highest mountains, and only a hint of precipitation in the higher elevation mesas in the northwest part of the Navajo Nation, as well as a small indication of precipitation in the higher elevation of the Defiance Plateau in the southeast. The NNDWR data alone (Figure 2.13) show more substantial precipitation in the Chuska Mountains, Defiance Plateau and the northwest mesas. They adequately represent the gradient of precipitation toward the San Juan Mountains, but they don't show the gradient toward the San Francisco Peaks. When both sets are combined (Figure 2.14), the strikingly steep gradient of precipitation in the Chuska Mountains, compared to the plateau around them is apparent. The elevational gradient of precipitation is clearly expressed; even the Defiance Plateau is relatively dry, compared to the Chuska Mountains. If the goals of data analysis are determination of trends, examination of year-to-year variability, and drought monitoring, then a fine-scale complex regression mapping technique (such as PRISM; Daly et al., 1994) can be used; PRISM estimated precipitation can be used to calculate SPI for drought monitoring, because SPI depends on current data in relation to historical data. However, if precise precipitation totals at mountain locations are needed (e.g., to make operational decisions about irrigation allocations, forest conditions, etc.) then PRISM would not provide sufficiently exact estimates; an example is that even though the Defiance Plateau and foothills south of the Chuskas have relatively steep topography, they remained much drier than their elevation, a key variable in generating PRISM estimates, might suggest. A mapping technique might erroneously depict these areas as wetter than they actually were if only the COOP data or only the NNDWR data were used as the basis for interpolation.

In general, the use of elevational mapping techniques can help fill in areas that have no data, but there are limits to how large the spaces between stations can be in order to provide a realistic representation of the precipitation patterns. In areas where there are no major topographic features or small scale climate forcing factors, such as rain shadows or cold air drainages, and gauge spacing is on the order of 100 km, interpolation may be able to adequately represent climate conditions between gauges (Daly 2006). If there is significant topography, but no small scale forcings, complex regression techniques with elevation may be suitable. But when there are both major topographic features and small scale forcings, such as on the Navajo Nation, the monitoring network must have closer spacing to be able to capture the smaller scale variability. For this reason, the NNDWR precipitation network should not be reduced unless there are other nearby stations that can continue to collect the precipitation data.

2.4.5. Summer vs. winter precipitation

It was suggested that the spatial patterns are related to summer vs. winter precipitation, in that the southern half of the Navajo Nation receives more precipitation in summer and the northern half receives more in winter. To investigate how evenly split the summer and winter precipitation were, the percentage of annual precipitation occurring in both summer and winter were calculated, for the combined NNDWR and COOP dataset for each of the five years, 2001 through 2005. The means were compared to see how the wet and dry years compared in distribution of rainfall between the two seasons, and the percentages were mapped to see if there were any spatial patterns. We tested the hypothesis that the southern half or third of the Nation has a greater percentage of annual precipitation occurring in summer, while the northern half or third has a greater percentage occurring in winter. The results were quite the contrary.

Table 2.6 shows the mean, median, standard deviation, and percentage of stations with more than 50% of the precipitation received in summer. Two of the five years had very dry winters and wet summers, with 71.6% of the annual precipitation falling in summer for 2001 and 88.8% for 2002. The next two years had a reasonably even split of summer and winter precipitation, with 56.9% and 54.8% of the precipitation falling in summer. The last year, 2005, had a very wet winter, and only 35.4% of the precipitation fell in summer. The average for all five years was 61.5% of the precipitation occurring in summer.

Table 2.6 - Statistics for summer as a percentage of annual precipitation.

Year	Mean	Median	Std. Deviation	Stns > 50%
2001	56.13	56.80	11.05	71.6%
2002	61.17	60.53	10.74	88.8%
2003	52.03	51.89	11.24	56.9%
2004	51.53	50.94	11.53	54.8%
2005	46.15	46.89	9.92	35.4%
All 5 Years	53.26	53.40	10.90	61.5%

None of the five years showed a north-south gradient in the percentage of annual precipitation occurring in summer. During 2004 there were many stations along the southern border near the Defiance Plateau that recorded less than 40% of their annual precipitation in summer, and many stations in the east and northeast region that received more than 70% of their annual precipitation in summer.

Around the Chuska Mountains, there were stations receiving the majority of their precipitation in winter that sit adjacent to stations receiving the majority of precipitation in summer.

Outside the Nation, the stations to the west seem to receive less of their precipitation in summer, while stations to the east receive more of their precipitation in summer. The cause of this pattern is not clear at this time, but may be related to the moisture source in the different seasons. In the summer, the moisture for the eastern region comes primarily from the Gulf of Mexico, through Texas and New Mexico. Summer thunderstorms tend to be of short duration, precluding widespread coverage, such that any thunderstorms that form over the mountains to the east may not reach the mountains in the west. Conversely, winter storms move from the northwest or west to the east, blanketing the western mountains, then moving across to the Chuska Mountains, with some rain shadowing on the eastern side of the Chuskas. There seems to be more of an east-west gradient than a north-south gradient.

2.4.6 Eliminating redundant stations

There are many non-NNDWR precipitation monitoring stations in the region. All of them gather data more frequently than on a monthly basis, with most taking observations daily or hourly. These networks include Navajo Nation agencies, such as the Safety of Dams and the Navajo Indian Irrigation Project, as well as federal or state government agencies and private companies. Figure 2.16 shows most of the other network gauges, along with the current NNDWR precipitation gauges (red stars). The GIS program was used to identify NNDWR precipitation gauges that have nearby gauges within 10 or 15 kilometers (6 or 9 miles). Only a few of the NNDWR gauges are within 10 km (6 mi) of other gauges, but 51 of the 98 current gauges are within 15 km (9 mi) of another precipitation gauge, called a neighboring gauge. These 51 stations will hereafter be referred to as NDWR15. If the data from the neighboring gauges are available to the NNDWR on at least a monthly basis, then the NNDWR network could be reduced by as many as 51 gauges, depending on the individual utility of the seemingly duplicate gauges. As noted with the station pairs, proximity alone cannot be used to determine whether neighboring gauges record similar daily or monthly precipitation.

Beyond eliminating gauges, in order to reduce data collection and maintenance burdens, shifting to gauges in other networks should provide more useful precipitation data, as other networks collect data more frequently. Data collected daily, as with the COOP network, will allow some hydrological monitoring, since most days only have a single precipitation event. Shifting to stations that collect data hourly or on an event-by-event basis, would allow for a wider variety of hydrologic and climatological uses, including flood and severe storm forecasting and forecast validation. While mechanical recording rain gauge measurements can help improve collection of rain event data, labor intensive data digitization, accessibility of sites, and needed timeliness of collection (every week) imply that replacing mechanical recording rain gauges with digital tipping bucket gauges (good), or altogether removing the mechanical-recording gauges (less good) is a preferred labor-saving option.

Long records are desirable to provide perspectives on historical climate, as well as for documenting drought and flood occurrences, and for trend analyses in flood or drought research focusing on climate change and variability. Unfortunately, few of the existing NNDWR rain gauges have long records without large amounts of missing data. So, removing NNDWR rain gauges (especially manual gauges) in favor of stations from other networks will not adversely impact the available period of record, since some of the other networks have longer periods of record and fewer missing data. Figure 2.17 shows the 47 NNDWR precipitation stations (red stars) that would remain, if the redundant stations were retired.

2.5. Implications

2.5.1. The current method of collecting precipitation data on a monthly basis across Navajo Nation is manpower intensive and weather dependent. The data cannot readily be compared to other sites on a monthly basis due to variability in the length and dates of the monthly interval. This limits the utility of the data to patterns of seasonal and annual spatial distribution. Prior to 2001, the amount of missing data is large enough at most stations that length of data record or data quality are not useful criteria for selecting stations to keep in the network. The exceptions to this are Forestry, which has an 18-year period of record with no more than two months of missing data in any year, and Klagetoh 9NE, which has 21-year period of record with no more than one month of missing data per year. To the extent that other observational networks within and surrounding Navajo Nation have precipitation gauges within 15 km (9 mi) of current NNDWR precipitation gauges, and are willing and able to share the data with the NNDWR, the NNDWR15 gauges could be removed and potentially re-located to areas lacking gauges. Table 2.7 lists the potential sites to be removed, along with their nearest neighboring site.

Of the 51 possible sites to remove from the precipitation can network:

- nine are co-located with NNDWR weather stations, meaning that they could be replaced by using the weather station data,
- five are at snow courses and could be replaced by snow course data collections in winter, but otherwise could not be removed,
- the Forestry site should remain due to its long record.
- If a neighboring site from another observational network has no precipitation gauge, one should be added, if possible.
- Ten sites are near Safety of Dam sites. All of the Navajo Nation Safety of Dams sites should have precipitation gauges, if they do not already, so the precipitation data are available in real-time to both the SOD and the NNDWR.

Table 2.7. NNDWR Precipitation Stations to consider for removal, with nearest neighbor station and network. Stations in italics may best be left in the network due to their record length. (R) indicates a recording gauge.

ID	Station_Na (NDWR15)	Neighbor	Neighbor Network
2	Arbab's_Forest_SC	Summit	WMB_Wx
10	Beaver_Springs_SC	TsaileCreek	NNDWR_SOD
17	Black_Hat_WX	BlackHat	WMB_Wx
18	Blue_Canyon_Dam (R)	Forestry/NN_SOD_Master	WMBRain/SOD
21	Bluff_WX	Bluff	COOP_NWS
27	Bowl_Canyon_SC	ToadacheenieLakeDam/Crystal	SOD/WMB_Wx
30	Buffalo_Pass	Lukachukai	COOP_NWS
32	Butler_Building	ToadacheenieLakeDam / SheepSprings	NNDWR_SOD/WMB_Wx
45	Chinle_O&M	CanyondeChelly/WashPass	COOP_NWS/RAWS
48	Coalmine_Road	BlakHat/NN_SOD_Master	WMB_Wx/SOD
55	Cross_Canyon	Woodsprings/Ganado	WMB_Wx/COOP_NWS
61	Crystal_Diversion	ToadacheenieLakeDam/Crystal	NNDWR_SOD/WMB_Wx
63	Crystal_WX	AsaayiDam/Crystal	NNDWR_SOD/WMB_Wx
71	Dine_Bi_Keyah	Lukachuki	COOP_NWS
81	Forest_Lake_WX	Hopi_AZ	RAWS
82	*Forestry*	NN_SOD_Master	NNDWR_SOD
86	Gallo	ChacoCanyonNM	COOP_NWS
87	Gamerco	GallupMuniAP/Gallup	COOP_NWS/FAA_AP
88	Ganado_6_NW	HubbellTP/Woodsprings	COOP_NWS/WMB_Wx
95	Hidden_Valley_SC	WheatfieldsCreek	NNDWR_SOD
98	Houck_WX	Houck	WMB_Wx
99	Hubble_Trading_Post	HubbellTP	COOP_NWS
109	Kerley_Valley	TubaCity/TubaCtyJHS	COOP_NWS/NAU_Wx
112	Leupp_O&M	NorthLeuppFarm/LeuppHS	WMB_Wx/NAU_Wx
114	Little_Whiskey	Toh-ni-TsaLookOouTower/ ToadacheenieLakeDam	NNDWR_SOD/SOD
115	Little_White_Cone	WheatfieldsDam/WindRockAP	NNDWR_SOD/NWS_FAA
124	Marsh_Pass	Betatakin	COOP_NWS
129	Missionary_Springs_SC	ToadacheenieLakeDam / SheepSprings	NNDWR_SOD/WMB_Wx
132	Nageezi	Lybrook/Otis	COOP_NWS/COOP_NWS
133	NAPI_WX	FarmingtonAgSci	COOP_NWS/NWS-FAA
140	Newcomb	CaptainTomDam	NNDWR_SOD
141	NFPI	NFPI	NNDWR_SOD
143	North_Leupp_Farm_WX	NorthLeuppFarm	WMB_Wx
147	Ojo-Encino	StarLake	COOP_NWS
158	Piney_Hill	Summit/NN_SOD_Master	WMB_Wx/NNDWR_SOD
162	Pueblo_Alto	ChacoCanyonNM	COOP_NWS
163	Pueblo_Bonito	ChacoCanyonNM	COOP_NWS
171	Resting_Cattle	Hopi_AZ	RAWS
186	SheepSprings_WX	SheepSprings	WMB_Wx
187	Shiprock_O&M	ShiprockNM	COOP_NWS
188	Shonto_School	Betatakin	COOP_NWS
196	South_Gap	ChacoCanyonNM	COOP_NWS
203	Summit_South	Summit	WMB_Wx

ID	Station_Na (NDWR15)	Neighbor	Neighbor Network
206	Teec_Nos_Pos_O&M	TeecNosPos	COOP_NWS
211	Toadlena_Fish_Hatchery (R)	Toh-ni-TsaLookOutTower	NNDWR_SOD
219	Torreon	Torreon_Navajo_Mission	COOP_NWS
221	Tsaile_#1_SC	Lukachukai/TsaileCreek	COOP_NWS/NNDWR_SOD
222	Tsaile_#3_SC	Lukachuki	COOP_NWS
224	Tsaile_DCC_WX (R)	TsaileDam/PineyHill	NNDWR_SOD/RAWS
225	Tsaile_SG	TsaileDam/WheatfieldsDam	NNDWR_SOD
227	Tuba_City_O&M	TubaCityJHS/TubaCity	NAU_Wx/COOP_NWS

Recording gauges (e.g., tipping bucket gauges) that can be automated with telemetry or datalogging (monthly collection) should be deployed upstream of stream gauges. After data collection, the recording gauge data should be downloaded and added to the database to resolve the precipitation data to the smallest time interval possible. This is critical because the data from recording gauges can be resolved to both storm event and daily values, so they can be used for rainfall-runoff correlation and comparison to other gauge data at daily and monthly timescales.

The NNDWR should consider converting sites that are in population centers into COOP sites to ensure that the data are collected on a daily basis. Cooperators can be citizens or employees of an institution that has a continuous operation. For example, Chapter Houses would be an ideal location and cooperator for daily observation. All the staff could be trained to take the observations, which are reported daily using either telephone or Internet automated reporting systems. Data quality control (QC) tests for the NWS COOP data are performed by the National Climatic Data Center – which would relieve NNDWR of the burden of this time consuming and technically arduous task. These suggestions are low cost options that should not require additional resources or manpower. (Note: recommendations for using Chapter Houses as COOP sites depend on the reliability of telcommunications at the Chapter House, as well as the reliability and willingness of observers at Chapter Houses to record these data free of charge).

2.5.2. The NNDWR cannot remove redundant precipitation stations if the other network operators are not both willing and able to share their data with the NNDWR. If other network operators are willing to integrate their data into a “Four Corners database,” they will benefit from the large network of precipitation gauges the NNDWR manages. For this integration to work, all parties would need to enter into a long-term agreement to share the data freely with each other for the benefit of all.

2.5.3. Another improvement to the NNDWR network would be automation of precipitation gauges, similar to the ALERT (Automated Local Evaluation in Real Time) networks. The ALERT gauges use telemetry (satellite, radio, Law Enforcement Telecommunication System [LETS], or cellular telephone) to report precipitation as it occurs, and the data are generally stored cumulatively through the water year. This provides the ability to improve flood warning, forecast floods and to verify the forecasts, to create stream hydrographs, and to improve flood planning. Also, if the data are transmitted in real-time or near real-time, they could be ingested into the NWS MADIS system where NWS would handle the QC of the data and maintain the database. This would reduce NNDWR data collection manpower and resource issues as well as data reduction issues; however, there would be a trade-off, as existing technicians might need additional training or technicians with sufficient skills would be needed to maintain (i.e., examine and calibrate) the automated equipment on an annual or semi-annual basis. In addition, technicians would need to be responsive to occasional equipment failure. The automation effort can be undertaken in stages, by first automating the gauges in the most critical areas, such as those upstream of flash flood prone creeks and washes, or upstream of population centers. Automating existing NNDWR weather stations would also include their precipitation gauges, and would be the logical place to start the effort as many of their dataloggers are already capable of transmitting hourly or daily data with the addition of a communications module and transmitter. Alternatively, as suggested by participants in the Navajo Nation Hydroclimatic Data Workshop, existing NNDWR automated weather stations could be moved to locations with easily accessible communications, such as some Chapter Houses.

2.5.4. Hydroclimatological data are most useful when they are available in regular intervals in real-time. This allows comparison to other data, prompt quality control, and instant feedback on equipment problems and emergency situations. Real-time data can be used for public safety through forecasting and warning of severe weather or flooding. Long, quality records are necessary for agriculture and water resource management and planning with a goal of mitigating the impacts of both flood and drought situations. The data are only useful if they can be converted to information through research or data analyses, so it is important that the NNDWR have a plan for the information and products that they want to produce from the data. The manager of the system can then determine what research or analysis is necessary to generate those products and what data are necessary to complete the analyses. For these purposes, it is not critical where the database is located, simply that all the data are accessible in real-time to forecasters, farmers, ranchers, managers, and researchers. The data also need to be quality controlled in near real-time to improve their usefulness. This can be done at the NNDWR with a highly skilled database manager or hydrologist, or it can be done by NWS in the MADIS or COOP systems. Near real-time data were identified as a high priority by participants in the Navajo Nation Hydroclimatic Data Workshop, because the data could serve a variety of purposes for NNDWR and many agencies within the region.

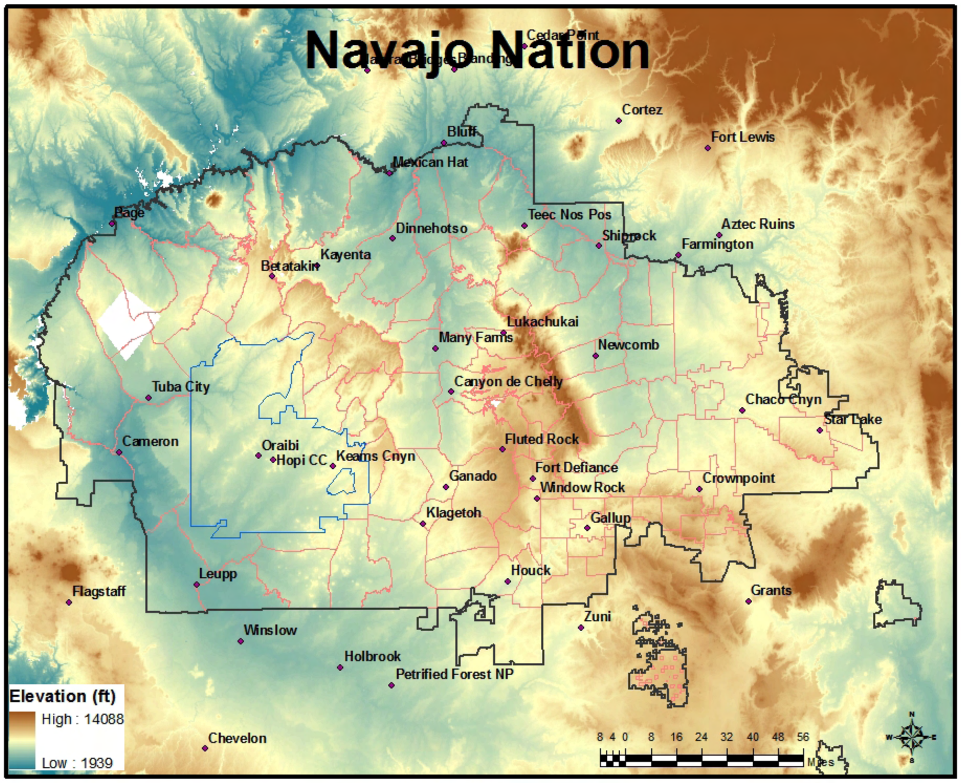


Figure 2.1. Map of the Navajo Nation with elevations and population centers. Pink boundaries are chapters, light blue boundary outlines Hopi Tribe lands, white patches are blanked out locations in the Digital Elevation Model (DEM) background.

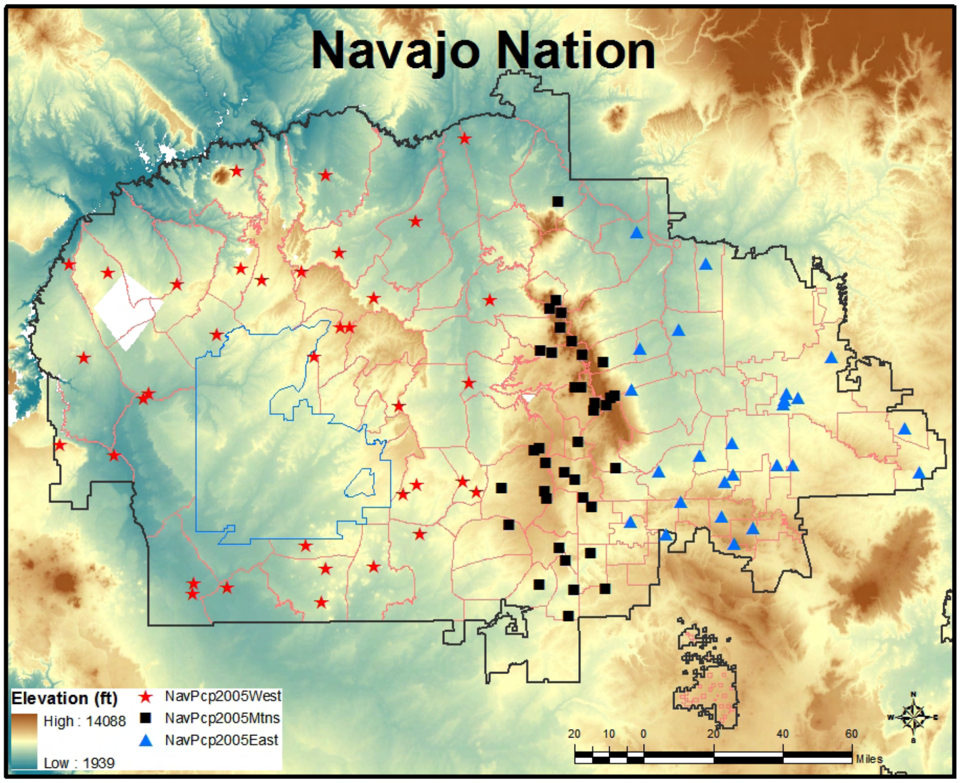


Figure 2.2. Navajo Nation and the current precipitation gauge ("rain can') network. Shading indicates elevation. Red stars are stations in the west region, black squares are stations in the mountain region, and blue triangles are stations in the east region.

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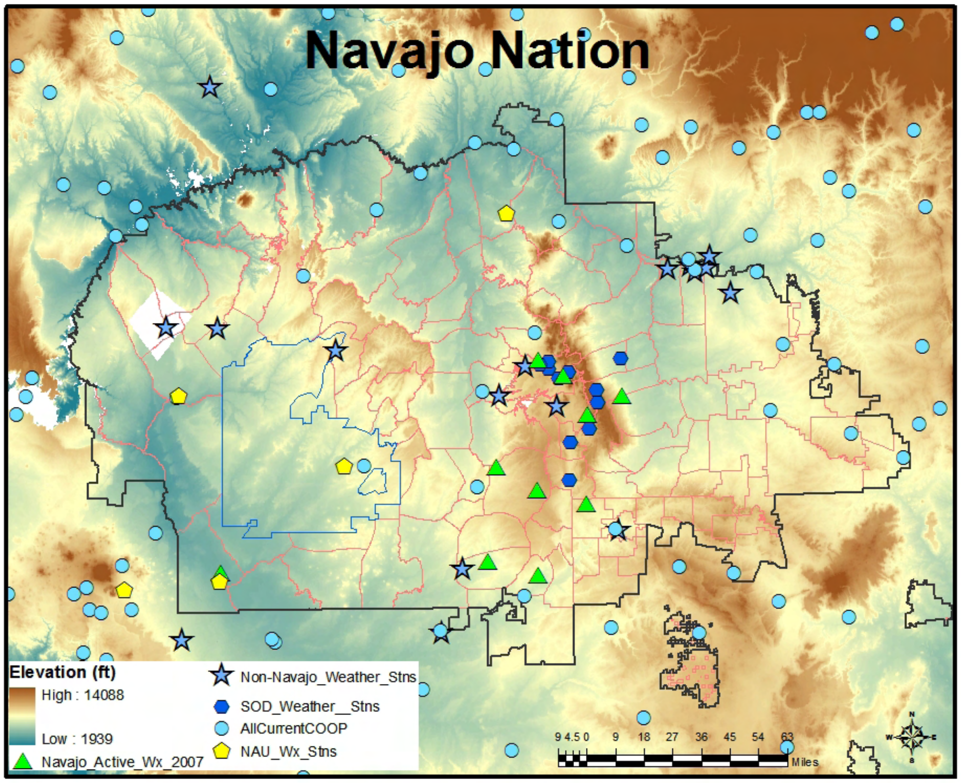

Figure 2.3. Precipitation gauges in networks other than Navajo Nation Department of Water Resources. Green triangles are NNDWR weather stations, yellow pentagons are NAU weather stations, dark blue circles are NNDWR SOD weather stations, light blue circles are COOP weather stations, and blue stars are other non-Navajo automated weather stations. Hopi Tribe, BLM RAWS, and some other networks are not represented.

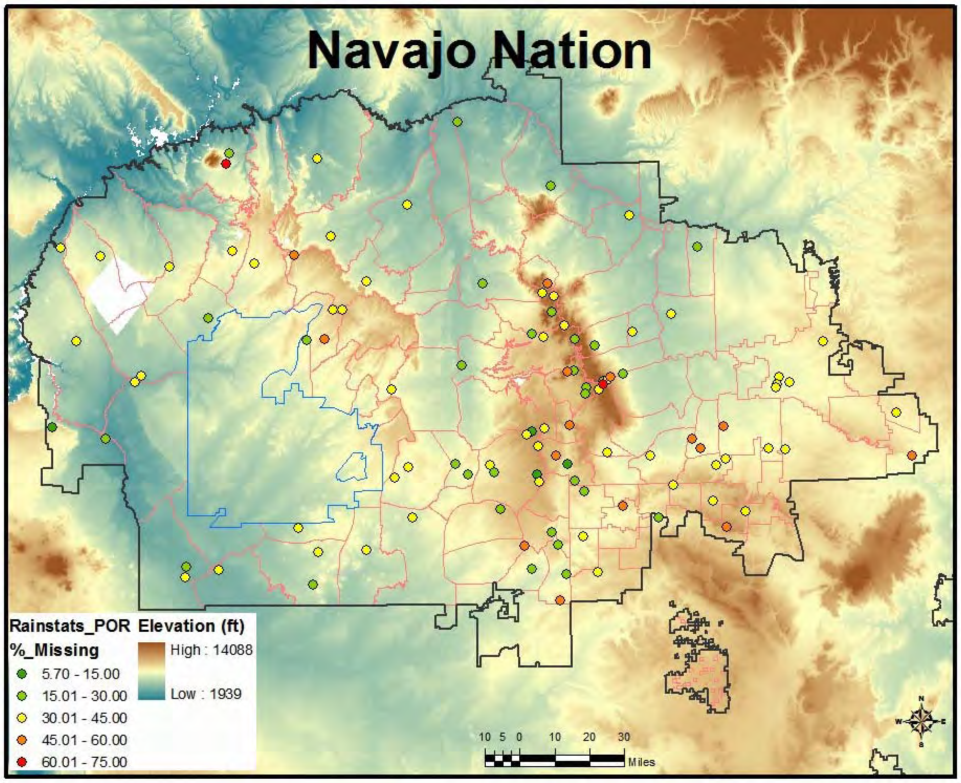

Figure 2.4. Percent of missing data for all NNDWR precipitation gauges for each station's full period of record. Stations depicted in red or orange are missing 50% or more of the data over their entire period of record.

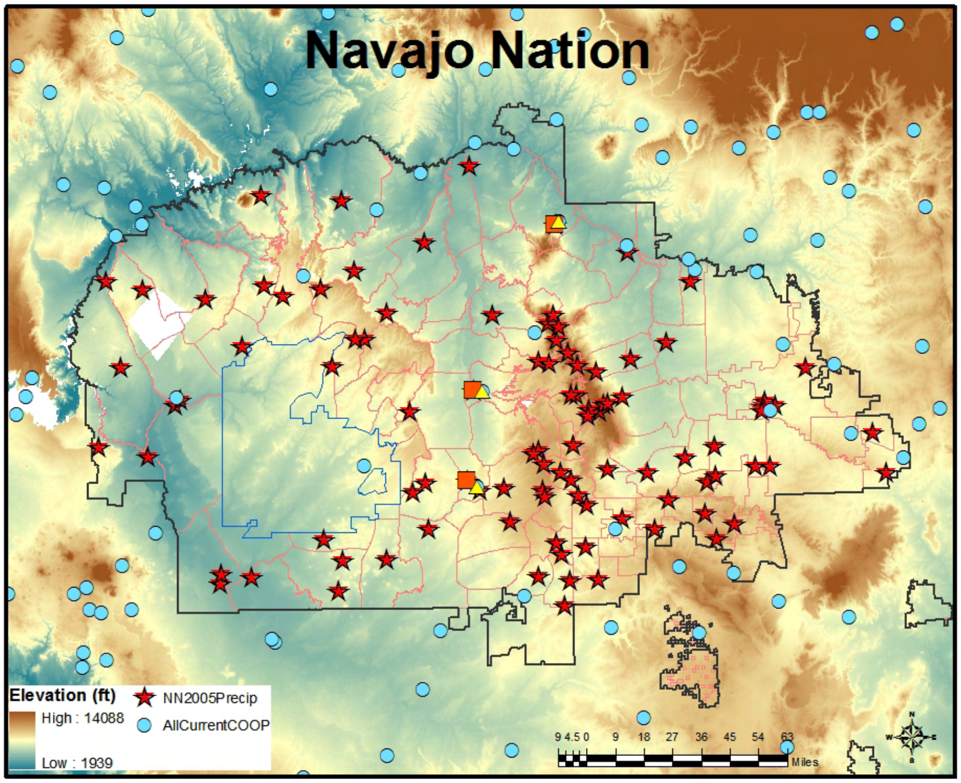

Figure 2.5. NNDWR (red stars) and NWS COOP (blue circles) precipitation gauge sites. Three sites for station-to-station comparisons between NNDWR (yellow triangle) and COOP (red squares) stations are also shown.

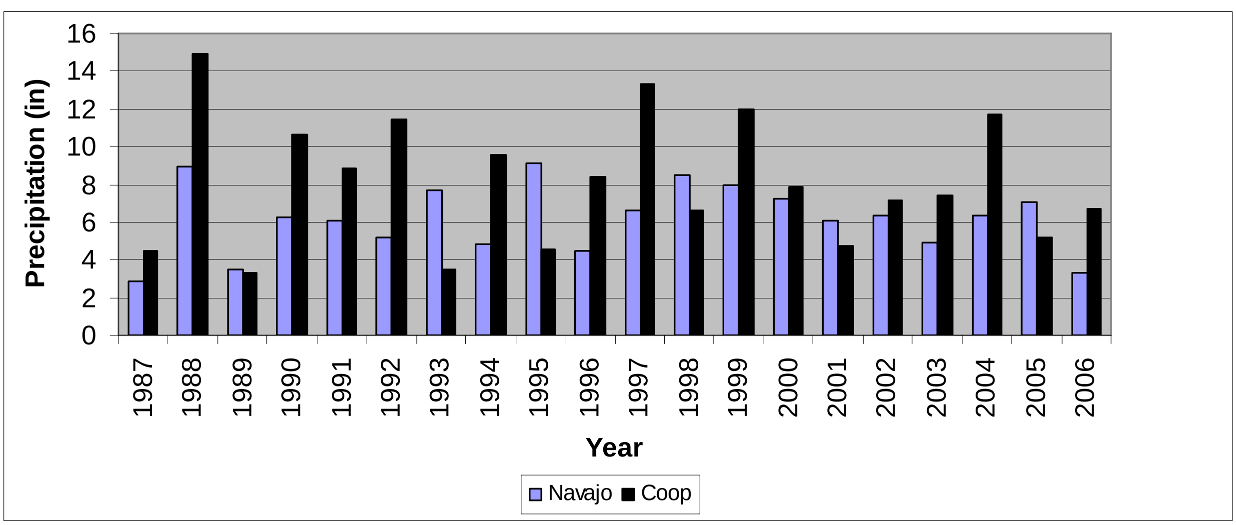

Figure 2.6. Annual precipitation for Chinle (Navajo-blue) and Canyon de Chelly (COOP-black), in inches.

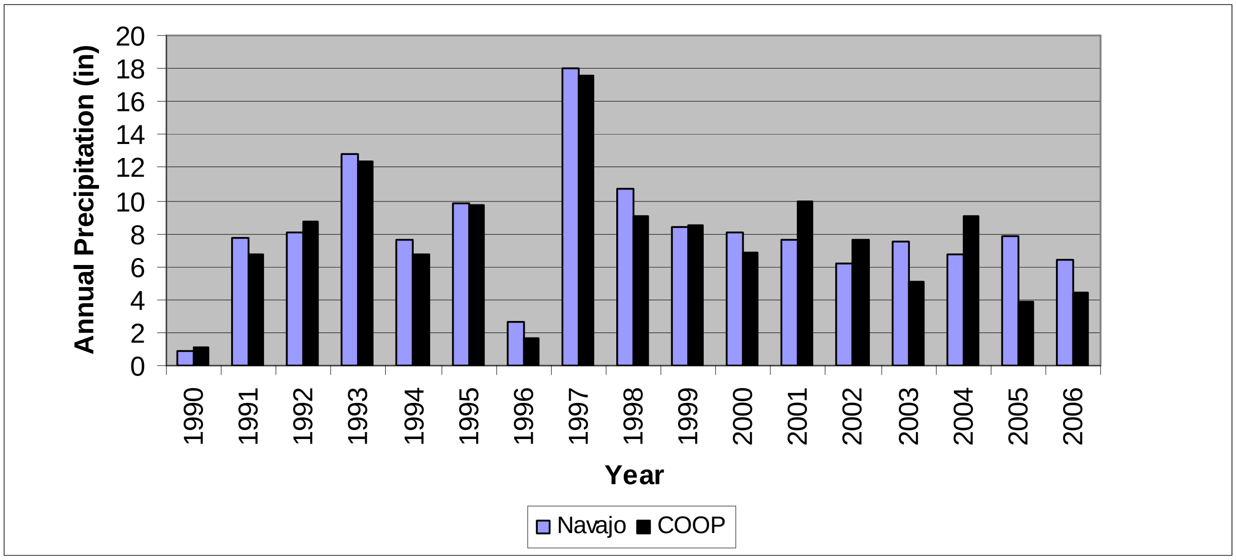

Figure 2.7. Annual precipitation for Teec Nos Pos Navajo (blue) and COOP (black) stations.

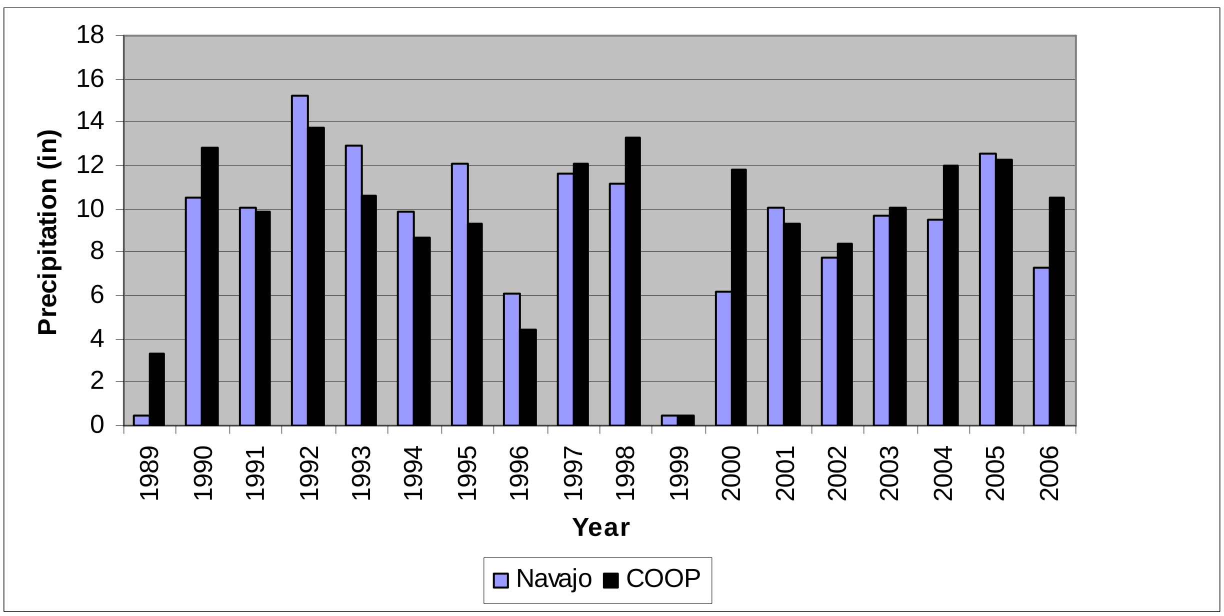

Figure 2.8. Annual precipitation for Ganado Navajo (blue) and COOP (black) stations.

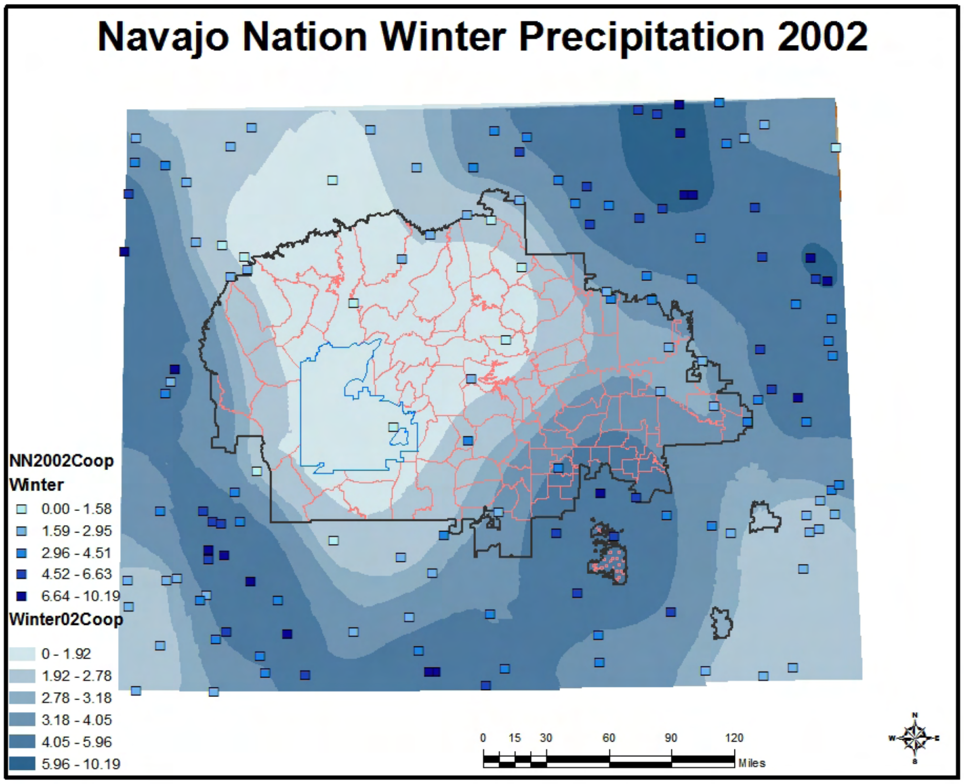

Figure 2.9. Interpolation of winter precipitation in 2002, using only the COOP data. The shading of the squares represents the measured values for comparison to the interpolated contours (Winter02Coop).

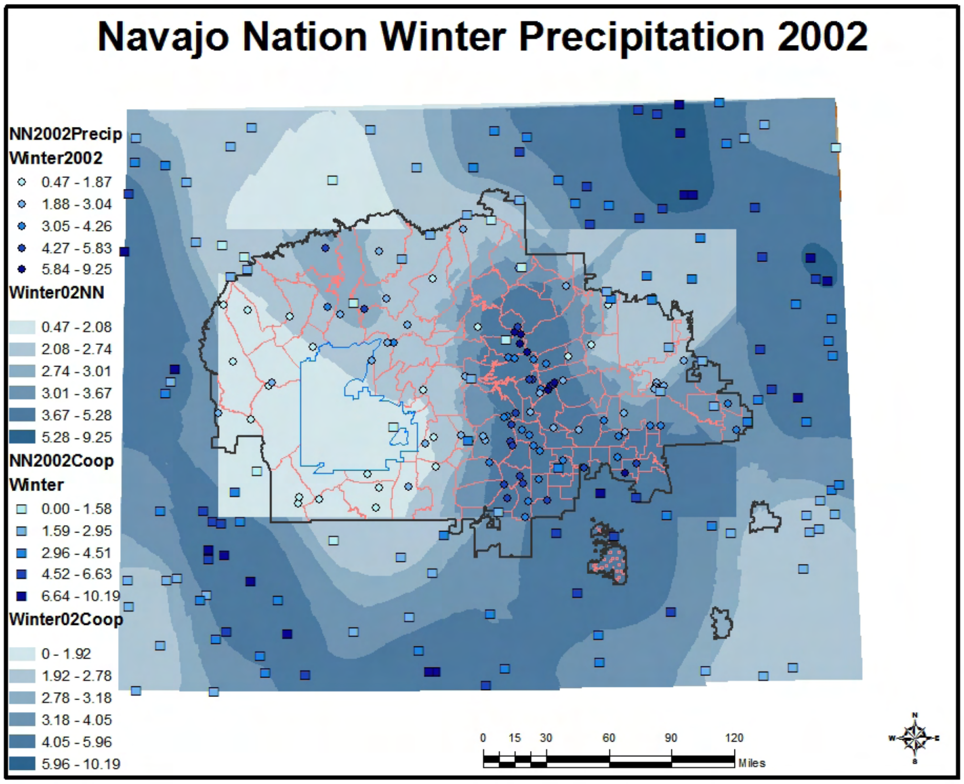

Figure 2.10. Larger frame is interpolation of 2002 winter precipitation, using only the COOP data. The shading of the small squares represents the measured values for comparison to the interpolated contours (Winter02Coop). Inset box is interpolation of 2002 winter precipitation, using only the NWRD gauge data. The shading of the small circles represents the measured values for comparison to the interpolated contours (Winter02NN).

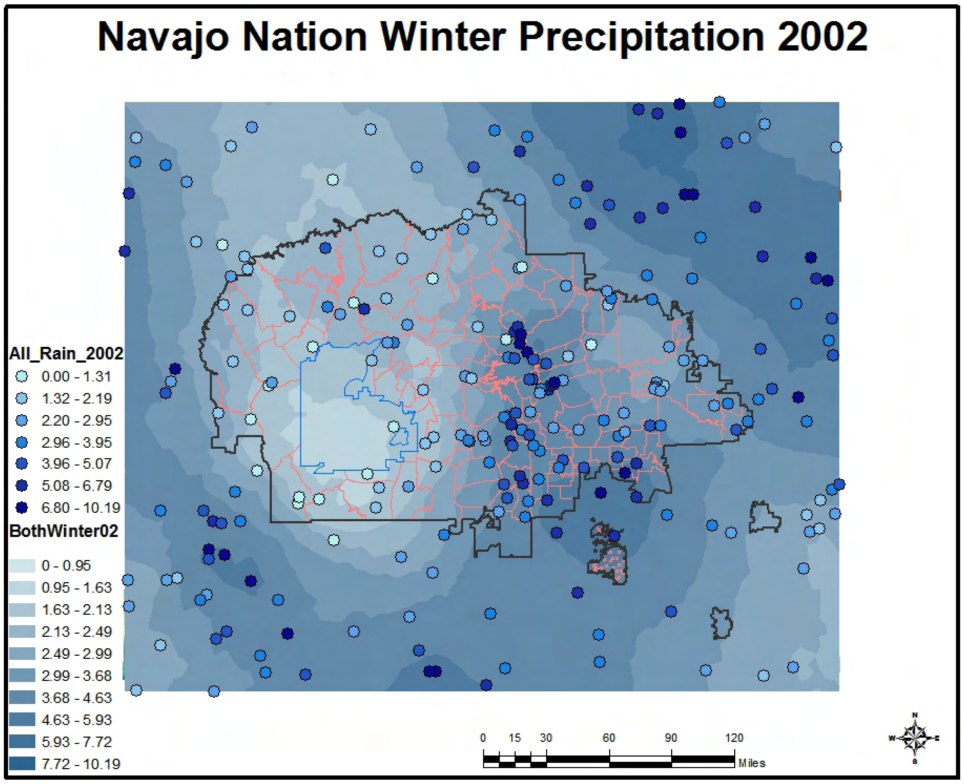

Figure 2.11. Interpolation of 2002 winter precipitation, using both the COOP and NNDWR data. The shading of the circles represents the measured values for comparison to the interpolated contours (BothWinter02).

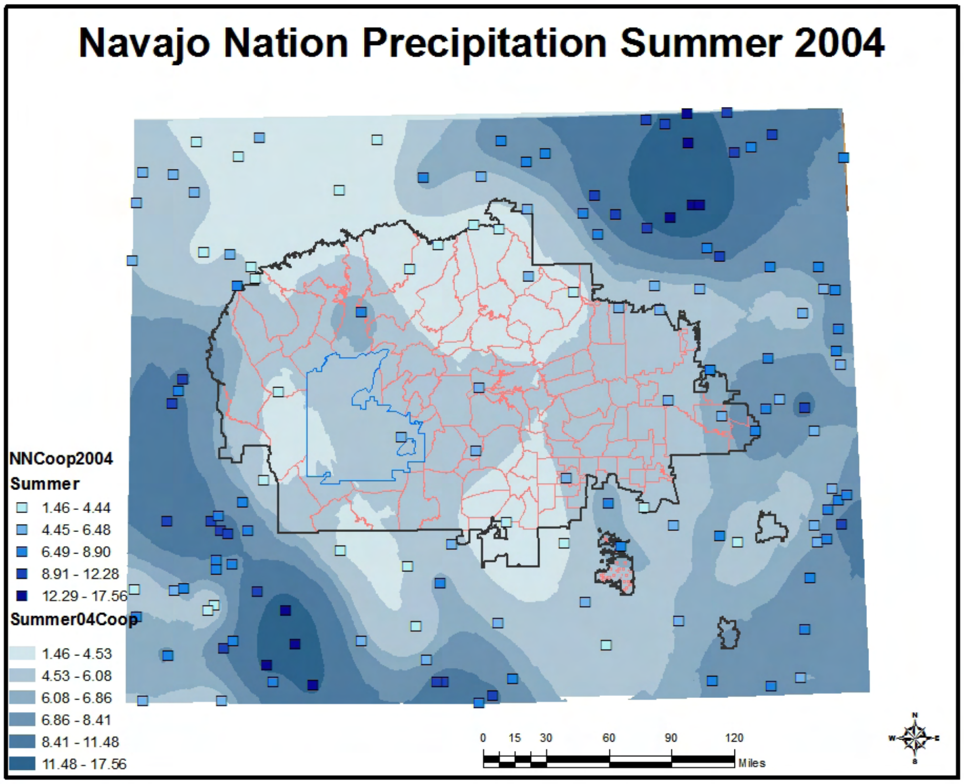

Figure 2.12. Interpolation of 2004 summer precipitation, using only the COOP data. The shading of the squares represents the measured values for comparison to the interpolated contours (Summer04Coop).

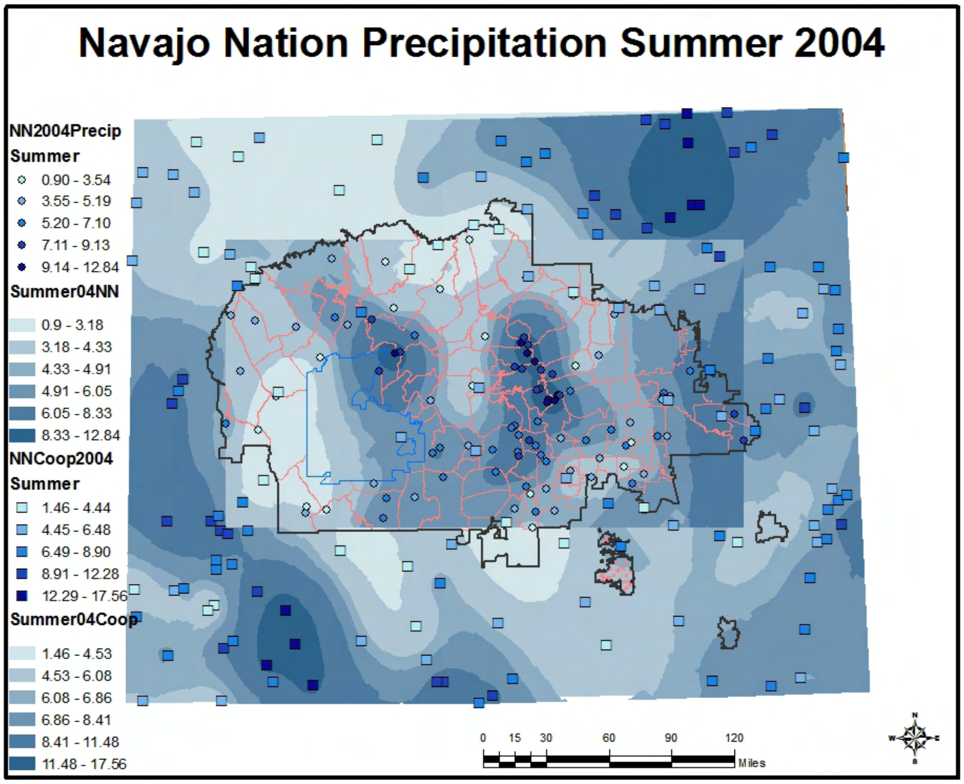

Figure 2.13. Interpolation of 2004 summer precipitation, using only the COOP data. The shading of the squares represents the measured values for comparison to the interpolated contours (Summer04Coop). Inset box is the interpolation of 2004 summer precipitation, using only the NNDWR gauge data. The shading of the small circles represents the measured values for comparison to the interpolated contours (Summer04NN).

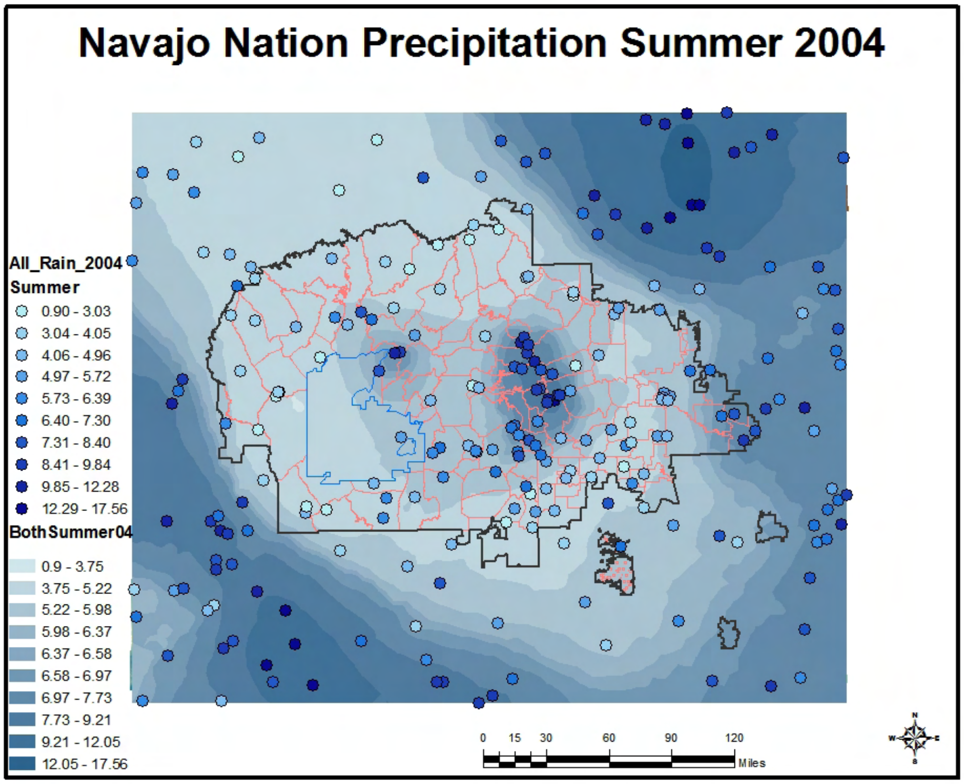

Figure 2.14. Interpolation of 2004 summer precipitation, using both the COOP and NNDWR data. The shading of the circles represents the measured values for comparison to the interpolated contours (BothSummer04).

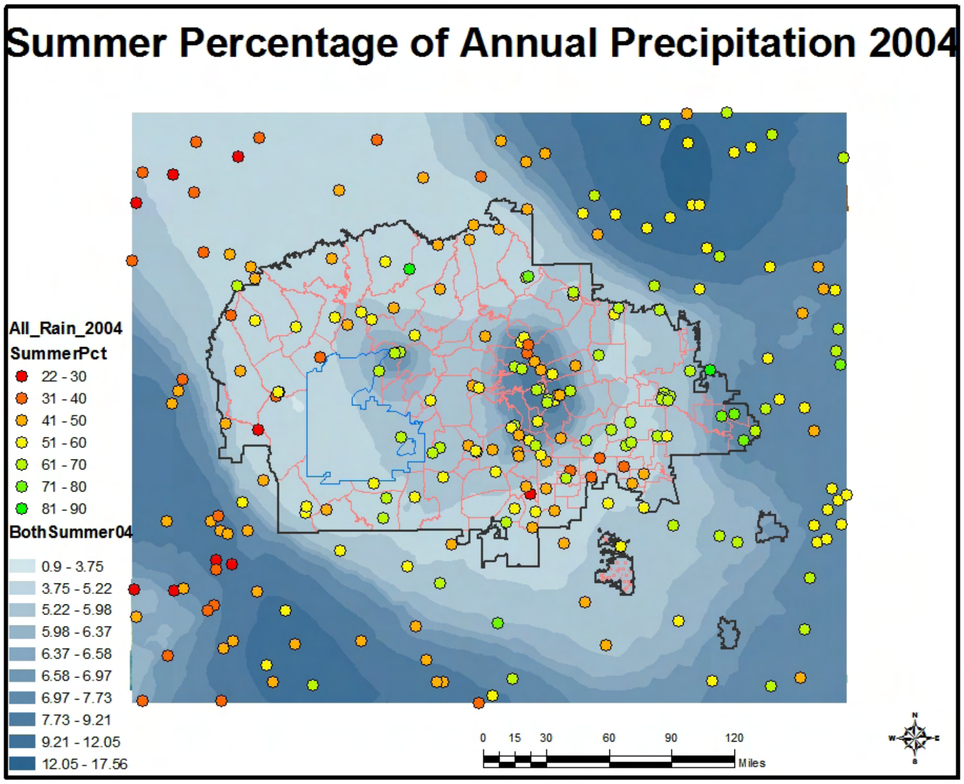

Figure 2.15. Blue Contours are 2004 summer precipitation, using both the COOP and NNDWR gauge data. Colored circles are summer precipitation as a percentage of annual precipitation for 2004 for the NNDWR and COOP precipitation gauges in the Navajo Nation region. Red circles mean 22 to 30% of annual precipitation falls in summer, and deep green circles mean 80 to 90% of annual precipitation falls in summer.

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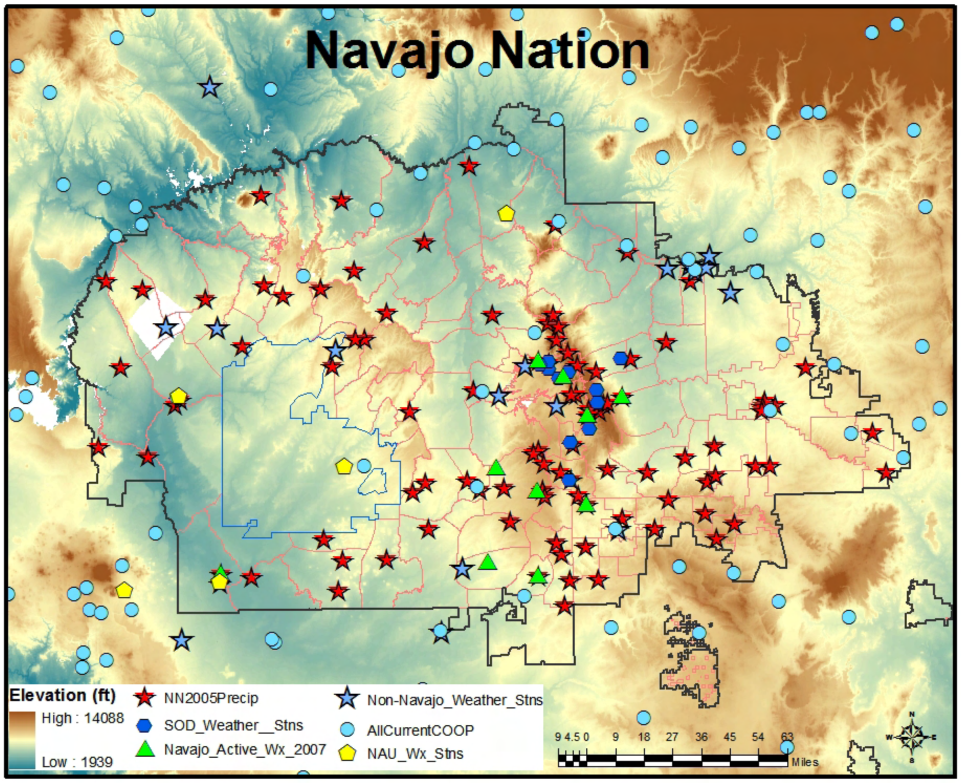

Figure 2.16. Precipitation gauges in the Navajo Nation region. NNDWR current rain gauge locations are denoted by red stars (n=98); NNDWR SOD automatic weather stations (n=11) are denoted by dark blue circles, WMB weather stations are denoted by green triangles (n=10), Northern Arizona Mesonet (NAU; n=5) stations are denoted by yellow pentagons, NWS COOP stations are denoted by light blue circles, and other non-Navajo weather stations are denoted by blue stars (n=17).

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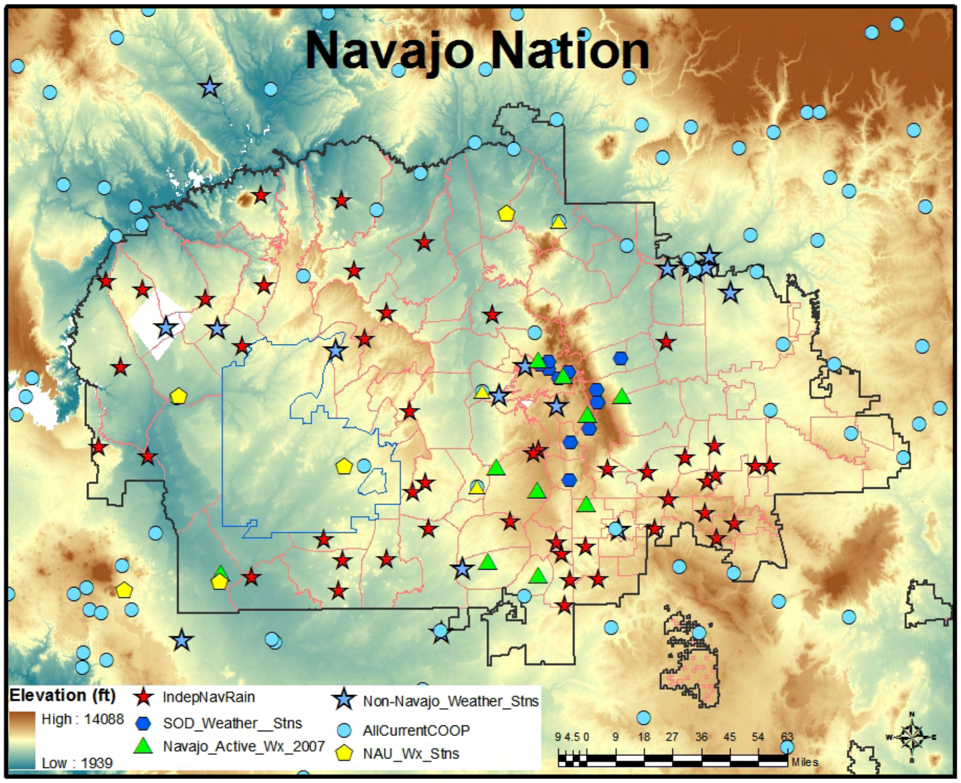

Figure 2.17. NNDWR precipitation gauges (red stars) that are not within 15 km of gauges in other networks (n=47) shown along with the other network precipitation gauges. These precipitation gauges would remain after other, redundant gauges are retired, and the data are collected through other networks.

Section 3. NNDWR Automated Weather Station Calibration Information

3.1. Introduction

3.1.1. Project Overview and goals

The main objective of this aspect of the project was to determine the recommended calibration schedule and cost for deployed NNDWR automated weather station instrumentation. The NNDWR maintains fifteen automated weather stations, thirteen that are currently operational, that use the Campbell Scientific CR10X model data logger (Table 3.1).

Table 3.1. NNDWR Automated Weather Stations (from N. Selover, 6/7/07)

Weather Stations	Easting	Northing	Elev (ft)	Operational
Houck	689995	3909020	6355	Yes
Tsaile	660320	4017460	7102	Yes
Wheatfields	762995	3909020	7350	Yes
Sheepsprings	699920	3998735	7010	Yes
Crystal	685000	3989600	7670	Yes
Blackhat	684278	3945256	7023	Yes
Summit	660500	3951200	7420	Yes
Woodsprings	640995	3965300	6897	Yes
WideRuins	634910	3916090	6072	Yes
NorthLeupp	500050	3908050	4680	Yes
Bluff (UT)	625414	4116165	5108	No
RedLake	510075	4025125	5590	Yes
NAPI	736930	4057985	5700	Yes
ForestLake	555647	4014877	6430	No
WhiteValley	553894	3994976	6030	No

3.2. Research Methods

3.2.1. Data

Information on station distribution, deployment history, integrated components, hardware type, and site suitability (short and long-term) were collected in verbal and written form from the NNDWR staff. Two field visits (January 4-5 and June 4-5, 2007), were made to view selected weather stations. Instrument vendors and model numbers of automated weather station instrumentation was acquired from NNDWR staff and summarized by N. Selover (Table 3.2). Information on recommended calibration schedule and procedures was acquired from the vendor websites and phone conversations with customer sales representatives and technical service personnel at MetOne, Vaisala, Li-Cor, Texas Electronics, Wescor, Delmhorst and Campbell Scientific.

Table 3.2. Vendors and Model Numbers of Sensors of NNDWR Automated Weather Stations (from N. Selover, 6/7/07). Ws: wind speed; Wd: wind direction; PG: wind gust; T: temperature; RH: relative humidity; Sol: solar radiation; Pcp: precipitation; SM: soil moisture; ST: soil temperature.

Variables	Vendor and Model	Sampling Increment and Unit
Ws, Wd	MetOne 034 Windset	Hourly average vector Wind Speed (mph) and Direction (degrees)
PG		Hourly Maximum wind speed 1 second sample
T, RH	Vaisala HMP35C Temperature and RH sensor	Hourly averages (F and %)
Sol	LiCor LI200X Pyranometer	Hourly sample (MJ)
Pcp	Texas Electronics TR-525I 6" Rain Gauge	Hourly Total (in.)
SM	Omnidata International Soil Moisture sensor	Hourly averages (kOhms, kPa)
ST	Omnidata International ES 060 Soil Temp	Hourly averages (F)

3.3. Results

The current wind sensor is a MetOne Wind Sensor 034. Calibration of the new model, the Wind Sensor 034B, is recommended by the vendor at once per year. Calibration may be done in the field with MetOne calibration equipment, or sent to MetOne for calibration (Table 3.3.) Field calibration requires the purchase of $930 – $1,560 MetOne equipment. Sending the sensor to MetOne for annual calibration would cost $100/year/unit plus shipping costs.

Table 3.3. Wind Sensor: Vendor, Model Number, Calibration Recommendations and Information Source

Vendor	Instrument	Calibration Recommendations	Notes/URL/Contact
MetOne	Wind Sensor 034B *original probe no longer available*	Calibration recommended annually Two calibration options 1) may be calibrated by NNDRW using a motor drive ($695 for single speed 300 rpm or 600 rpm, $1325 for variable speed), an adaptor ($85), and degree wheel for linearity ($150) 2) may be sent in for calibration for $100/unit, includes replacement of bearings	The MetOne 034B has replaced the 034A Replacement 034B Wind Sensors $495 *metone.com/meteorology.htm* *metone.com/documents/034b%20Wind%20DS.pdf* *metone.com/documents/053.PDF* *Contact: Troy at 541-471-7111*

The current temperature and relative humidity sensors are Vaisala model HMP35C. The website did not include information on the HMP35C; specifications listed in Table 3.4 were for the HMP45A. No specific recommendations beyond that available on the web were acquired for this report. Calibration services are provided by the vendor.

Table 3.4. Temperature and Relative Humidity: Vendor, Model Number, Calibration Recommendations and Information Source

Vendor	Instrument	Calibration Recommendations	Notes/URL/Contact
Vaisala	HMP45A *original probe, HMP35C, not found*	Calibration services are available at Vaisala for a fixed price. -Accredited calibrations (ISO17025) -Factory calibrations (ISO9001) Calibration price includes: -calibration and certificate before -adjustment to meet specifications -calibration and certificate after adjustment -replacement of wearing parts	Vaisala HMP35C not found on website, no return call from vendor *vaisala.com/weather/products/weatherinstruments/humiditytemperature/hmp45ad* *No contact, only web information*

The current solar radiation sensor is the LI200X pyranometer, made by LiCor and modified by Campbell Scientific. Calibration is recommended every 1 or 2 years. In addition, LiCor recommends a monthly leveling check, clearing of dust and debris on the sensor, and a check of obstructions in the drain hole. On-site field calibration may be achieved with an initial cost of $980 for a class 2 pyranometer. Annual calibration by LiCor or Campbell Scientific would cost $95 - $120/unit per year plus shipping costs (Table 3.5).

Table 3.5. Solar Radiation: Vendor, Model Number, Calibration Recommendations and Information Source

Vendor	Instrument	Calibration Recommendations	Notes/URL/Contact
Campbell Scientific	LI200X	Calibration recommended annually Two calibration options 1) Send unit to Campbell, cost of calibration is $120/unit at Campbell, they determine the a new calibration coefficient. 2) NNWRD may purchase a class 2 pyronometer ($980) and run side by side for 2 weeks to determine offset or multiplier differences.	Replacement LI200X $320 plus cable *campbellsci.com/li200x-l* *Contact: Mike Hansen at 1-435-753-2342*
LiCor	LI200 or LI200SA	Calibration recommended every 2 years Calibrated at LiCor against an Eppley Precision Spectral Pyranometer (PSP) under natural daylight conditions. Typical error under these conditions is ± 5%. Cost $95/unit, turnaround 3 weeks.	The LI200x is a modified version of the LI200 sold by LiCor. The modifications are done by Campbell Scientific in usually includes addition of a minivolt adaptor. Cost of LI200 is $195 with bare wire, the LI200SA is $205 with minivolt adaptor. *licor.com/env/Products/Sensors/rad.jsp* *Contact: Tan at 1-800-645-4267*

The precipitation gauge is a Texas Electronics TR-525I. According to Texas Electronics staff, calibration tests are recommended every six months. Options include use of a dynamic field calibration kit at $145, or dynamic lab calibration at $80/unit. Since the replacement cost is $85, it is more cost effective to simply replace the unit if recalibration is needed.

Table 3.6. Precipitation: Vendor, Model Number, Calibration Recommendations and Information Source

Vendor	Instrument	Calibration Recommendations	Notes/URL/Contact
Texas Electronics	TR-525I	Calibration test recommended every 6 mos. Calibration options 1) static calibration 2) dynamic field calibration using FC525 field calibration kit ($145) 3) dynamic lab recalibration at Texas Electronics ($80)	Replacement TR-525I $85 *texaselectronics.com/detail_tr525i.htm* *Contact: 800-424-5651*

The current soil temperature sensors are Omnidata International ES060 Soil Temperature Probes. Omnidata was acquired by Wescor in 2006 and has a similar unit available; the S060, with a replacement cost of $70. Statements by NNDWR staff on the 6/7/07 field visit suggested that the Omnidata International Soil Temperature Probes were not programmable with the existing data loggers. Therefore, a Campbell Scientific Soil Temperature sensor was identified as a possible replacement. The replacement cost is $31.81 per probe. Further study is recommended to evaluate options for potential soil temperature sensor replacements.

Table 3.7. Soil Temperature: Vendor, Model Number, Calibration Recommendations and Information Source

Vendor	Instrument	Calibration Recommendations	Notes/URL/Contact
WesCor	ES060 *original probe no longer available*	No recommended calibration schedule Calibration test: immerse in ice water to verify temperature	OminData International ES060 Soil Temperature Probe no longer available, replacement unit Wescor S060 ($70) *wescor.com/environmental/index.phtml* *Contact: Lyn at (435) 752-6011 ext. 1310*
Campbell Scientific	105T-L	No calibration recommended for probe Calibration every 2-3 years for data logger	Campbell sensor an option for replacement ($31.81/ft) *campbellsci.com/soil-temperature* *Contact: Matt at 1-435-753-2342*

The current soil moisture sensors are from Omnidata International and were probably gypsum blocks. Omnidata was acquired by Wescor in 2006 no longer carries that type of soil moisture sensor. Wescor staff recommended Delmhorst as carrying a similar sensor. The Delmhorst KS-D1 a gypsum block unit, with a replacement cost of $300 for the monitor plus cable gypsum blocks ranging from $7.50 - $15.00 each. The Campbell Scientific CS616 is another potential replacement, with a cost of $150 plus 0.74/ft of cable. No calibration recommended for either model. Further study is recommended to evaluate options for potential soil temperature sensor replacements.

Table 3.8. Soil Moisture: Vendor, Model Number, Calibration Recommendations and Information Source

Vendor	Instrument	Calibration Recommendations	Notes/URL/Contact
Delmhorst	KS-D1 *original probe no longer available*	No recommended calibration Monitor may be sent to Delmhorst for calibration for $65, with NIST letter, $80. Gypsum blocks usually last for one season in agricultural settings. Blocks don't work well in sandy soil.	OnmiData International Soil Moisture Probe no longer available. Wescor staff recommended trying Delmhorst for an equivalent sensor. Delmhorst KS-D1 monitor ($300) and gypsum blocks with cable; 6' pack of 10 fro $75, 25' @11.25 each, 50' @$15 each. *delmhorst.com/products_soil.html* *Contact: Vincent at (973) 334-2557*
Campbell Scientific	CS616	No calibration recommended Does not drift	Campbell sensor an option for replacement ($150 + $0.74/ft cable) *campbellsci.com/cs616-l* *Contact: Matt at 1-435-753-2342*

3.4. Implications

Calibration requirements for the various sensors vary from 6 months to every two years. Options include purchase of calibration equipment from the vendor; these may be employed by NNDWR staff. Sensors may also be sent to the vendors for calibration, this would required the purchase of additional sensors to switch out when units are undergoing calibration. If the soil moisture and soil temperature sensors are incompatible with the existing data loggers, new sensors need to be identified to meet NNDWR needs.

3.5. Conclusions

A calibration schedule should be developed for the NNDWR automated weather stations. Regular calibration would help prevent potential drift of the sensors and maintain data integrity. Scheduling calibration will depend on manufacturer recommendations for each individual instrument.

Section 4. Navajo Nation Automated Weather Station Density Analysis

Abstract. The major results of our study are as follows:

- Navajo Nation operated stations are concentrated in the center of the Reservation.
- If non-Navajo stations (COOP and Northern Arizona Mesonet) are included, spatial coverage is fairly good at a maximum distance between stations of 50 km.
- We identified five regions which have no stations within the 50 km maximum distance.
- These regions could be covered with the addition of six weather stations at reasonably easy to visit sites.
- We were able to determine the location and ownership of cell towers nearest each proposed station.
- We were not able to calculate a cost to visiting sites due to the unavailability of road data with usable impedance values.

4.1. Introduction
4.1.1. Project Overview and goals

The major goal of the automated station density analysis was to determine whether positioning of active weather stations on the Navajo Reservation is adequate and where additional stations might be sited if needed. Using a Geographic Information System we analyzed the current locations of automated weather stations (Table 4.1, Figure 4.1), the distribution of stations and looked for reasonable locations for additional stations which can be used to complete the spatial coverage of the network. A 50 km (31 mile) maximum distance between stations was chosen in order to minimize the cost of network additions while still providing a reasonably even distribution of stations. The Spatial Analyst tool was used to construct 10 km, 25,km and 50 km buffers around each active station. (The term *buffer* denotes the diameter of a circle, with the station at the center; thus a 50 km buffer describes a circle with a 25 km radius from the station, encompassing a 1963 sq. km area [~1750 sq. mi.] around the station). The radius of these buffers was chosen arbitrarily, although the 10km minimum buffer does make sense if we are primarily interested in meso-scale effects. “Empty regions” were identified by calculation the disjoint of all 50 km buffers around current stations. (The term *disjoint* refers to areas not covered by buffers, or in common terms, the places where buffers do not overlap). Additional sites were chosen using the following criteria: (1) the site should provide coverage of at least one blank area; (2) the site should be adjacent to a major road (at least USGS Class 4 – improved dirt), so that access is possible in all seasons; (3) the site should have moderate topography (not in a depression) to provide a possibility of radio reception; (4) the site should be topographically representative of the majority of the blank area it is intended to cover.

4.2. Research Methods

4.2.1. Data

Data were collected from the Navajo Nation Department of Water Resources (NNDWR) staff, the Arizona Geographic Information Council (AGIC 2007), the New Mexico Resource Geographic Information System (RGIS 2007) the United States Geologic Survey (USGS 2007), Merriam-Powell Center for Environmental Research (MPCER 2007), the Federal Communications Commission (FCC 2007) and the Navajo Nations "Chapter Images 2004" publication (LSR 2004). All spatial layers were reprojected to NAD27 UTM Zone 12 (ESRI 2007) North and clipped to cover the Navajo Nation, if necessary. New feature classes were created to represent the locations of the Northern Arizona Mesonet weather stations and Census 2000 data were added as a new field in a Navajo Chapters shape file provided by Navajo Nations Water Resources Department. We attempted to acquire a roads network with impedance data from several sources, but were unable to do so. Collection of raw data of this sort is outside of the scope of this project. (Impedance is a parameter used to express how quickly you can travel on a road. For example, a road with high impedance requires very slow travel speeds. A low impedance implies that you can travel quickly on that road. Impedance data allow for calculation of the fastest route from one point to another.)

4.2.2. Analytical methods or philosophy

The data were used to construct a geographic information system (GIS) using ArcGIS 9.2 SP3 (ESRI 2007). The following derived data layers were created.

1. Census 2000 population density by Chapter expressed as people per acre (LSR 2004, US Census 2007).
2. Change in population density from Census 1980 until Census 2000 expressed a people per acre (LSR 2004, US Census 2007).
3. A hillshade raster was generated from a USGS 30m digital elevation model (DEM; USGS 2007) using Spatial Analyst. This was blended with the 30m DEM to enable easier interpretation of regional topography.
4. 10 km, 25 km, 50 km, 75km and 100km buffers around each active weather station in the COOP, Northern Arizona Mesonet and NNDWR systems were constructed using ArcMap 9.2 Spatial Analyst (ESRI 2007). Only the 50 km buffers were used in further calculations.
5. Empty areas (defined as regions with no weather stations from any network within 50 km) were found by calculating the disjoint of all 50 km buffers using Spatial Analyst.
6. Using a major roads line feature, 30 meter digital elevation model (DEM), a 30m hillshade, and major landmarks feature layer we choose possible weather station locations using the criteria described in the Introduction.

4.3. Results

In order to fill in empty regions in the current Navajo hydroclimate network, we used data on weather station density, weather station spatial coverage, road condition, topography, cell tower locations and population trends to find reasonable sites for new weather stations. First we constructed buffers (Figure 4.2) around each current station in the Navajo Water Resources, Northern Arizona Mesonet and COOP networks at scales of 10, 25 and 50km (6.2, 15.5 and 31 miles). By calculating the disjoint of these buffers we found the areas which are not covered by any stations at each buffer's scale (Figures 4.3-4.4). At this point we decided to use 50km as the maximum distance we would allow between stations. This value was chosen to give a reasonable number of proposed stations. We added information on road location and condition to find accessible sites (Figures 4.5-4.13). We decided to only include sites accessed by USGS Class 4 (improved dirt) and better roads. Class 5 includes 4x4 roads, which were deemed unsuitable for winter access. The location and ownership of cell towers was added to attempt to site stations so that they could be accessed using cellular modems. Along with topographic information, this gave us a reasonable idea of whether a site is likely to be accessible via cell communications. An on-the-ground site survey of each site will still be necessary to insure that a particular site is reachable by a specific network. Finally, we produced maps (Figures 4.13-4.15) showing population trends for each chapter house using the Chapter Images: 2004 (LSR 2004). This gave us an idea of which empty regions might be most important to cover in order to provide weather information to the most people. The census data used to calculate population density change is of unknown quality and may not accurately reflect real population trends. Population density trends (Figure 4.15) were calculated using chapter census data and may not be accurate at scales below that of whole chapters. The Crownpoint, Dilkon and Rock Point proposed stations lie in regions of population growth. The Hopi, Navajo Mountain and Pueblo Pintado proposed stations lie in regions undergoing population decrease. The Bodaway Gap site is neutral.

Table 4.1. Locations, road condition, distance to closest cell tower and network ownership for the seven proposed weather station sites. Note: Google Earth shows what appears to be high schools or community colleges near the Navajo Mountain, Crownpoint and Pueblo Pintado, it may be possible to locate stations near those schools for phone or internet access.

Site Name	**Lat, Lon, Elevation of recommended site**	**Recommended site (description) and Road condition**	**Justification and distance to closest cell tower**
Bodaway Gap	35 21 06.07N 110 19 27.08W 6059 Feet	Indian Service Route 6110, USGS Class 4 (dirt road)	24 miles to Verizon KNKN232:12, Alltel KNKQ397:32 , reasonable winter access
Crownpoint	35 41 46.50N 108 08 05.50W 6778 Feet	State Highway 57, USGS Class 2 (secondary highway)	1 mile from Alltel tower KNKN270:25, excellent winter access, option of using high school
Dilkon	35 21 06.78N 110 19 27.08W 6059 Feet	Indian Service Routes 60 and 15, USGS Class 4 (dirt road)	11 miles from Smith Bagley KNKN208:13&17 may be obstructed by terrain, reasonable winter access
Hopi	35 42 51.95N 110 53 14.05W 5534 Feet	Indian Service Route 58, USGS Class 4 (dirt road)	17 miles from Smith Bagley NKN208:134, reasonable winter access
Navajo Mountain	37 03 43.89N 110 45 56.33W 5652 Feet	Indian Service Route 6310, USGS Road Class 4 (dirt road)	6 miles from Alltel KNKQ379:21, Verizon KNKN293:3, reasonable winter access, option of using high school
Pueblo Pintado	35 57 54.08N 107 38 59.21W 6459 Feet	Indian Service Route 9,USGS Class 2 (secondary highway)	10.5 miles from Smith Bagley KNKR316:7&8 Excellent winter access
Rock Point	36 30 31.47N 109 53 46.49W 5646 Feet	Indian Service Routes 59 and 118, Class 3 (paved road)	11 miles from Smith Bagley KNKN208:11 USGS, Good winter access

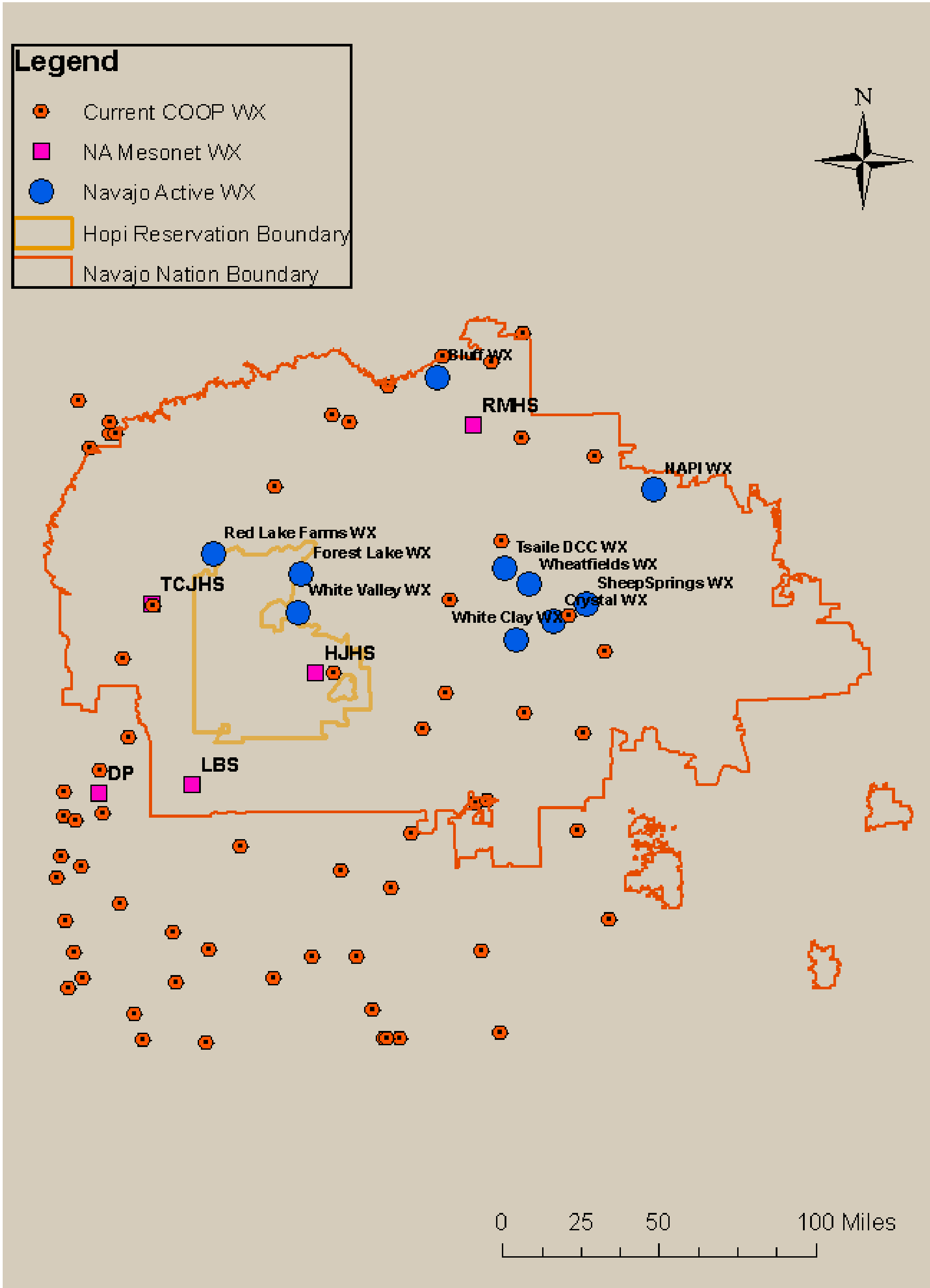

Figure 4.1. The locations of currently active weather stations in the COOP, Northern Arizona Mesonet and NNDWR networks. Notice that the Navajo Nation operated stations are concentrated around the center of the reservation. The COOP and Northern Arizona Mesonet stations complement the distribution of Navajo Nation stations.

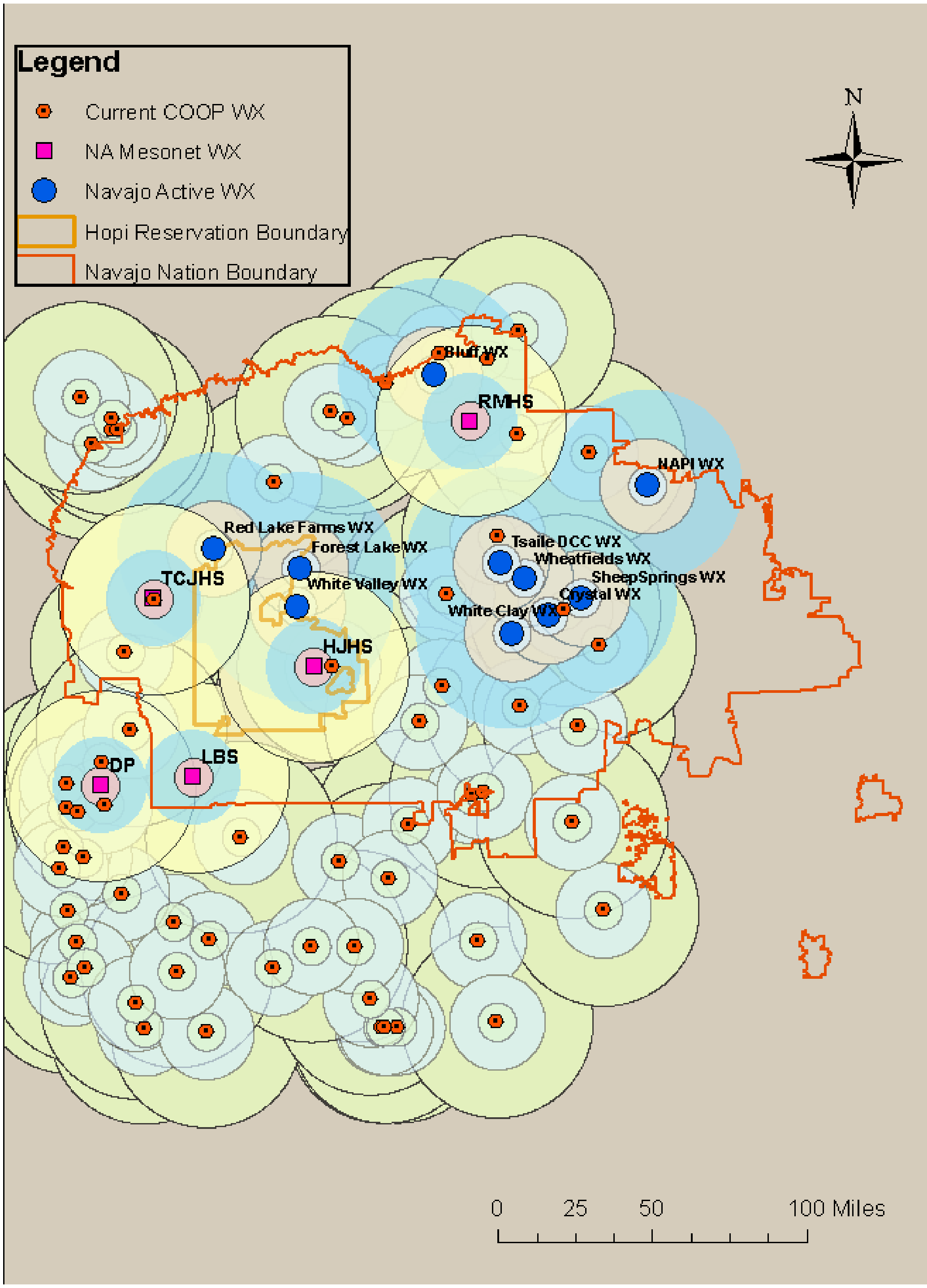

Figure 4.2. Buffers constructed around each active weather station in the three networks at 10 km, 25 km and 50 km intervals. The COOP and Northern Arizona Mesonet stations complement Navajo Nation operated stations.

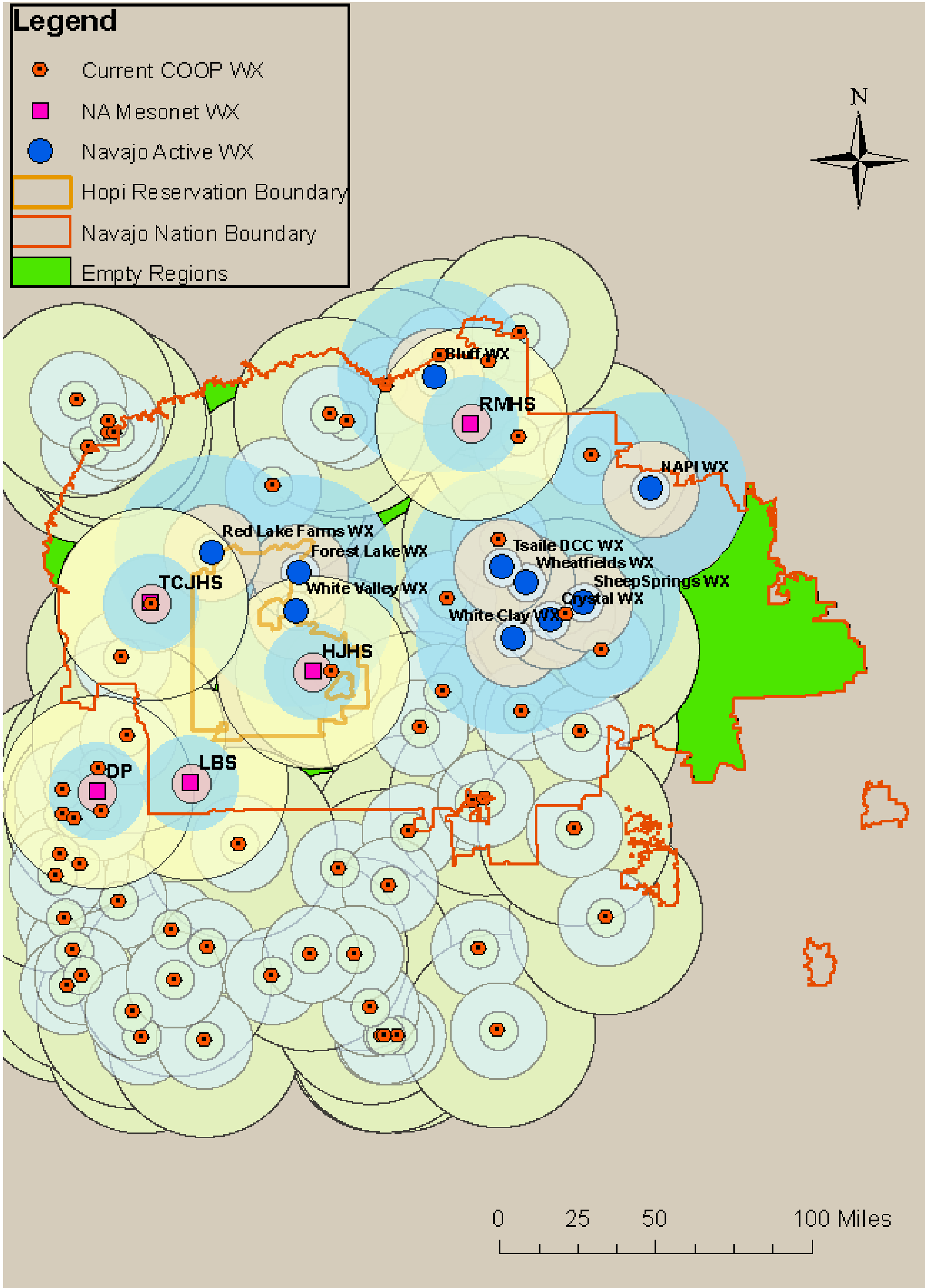

Figure 4.3. The *disjoint* of all of the 50 km constructed buffers as green polygons along with the 10, 25 and 50 km buffers. Seven empty regions, or lacking sufficient automated weather station coverage, were identified.

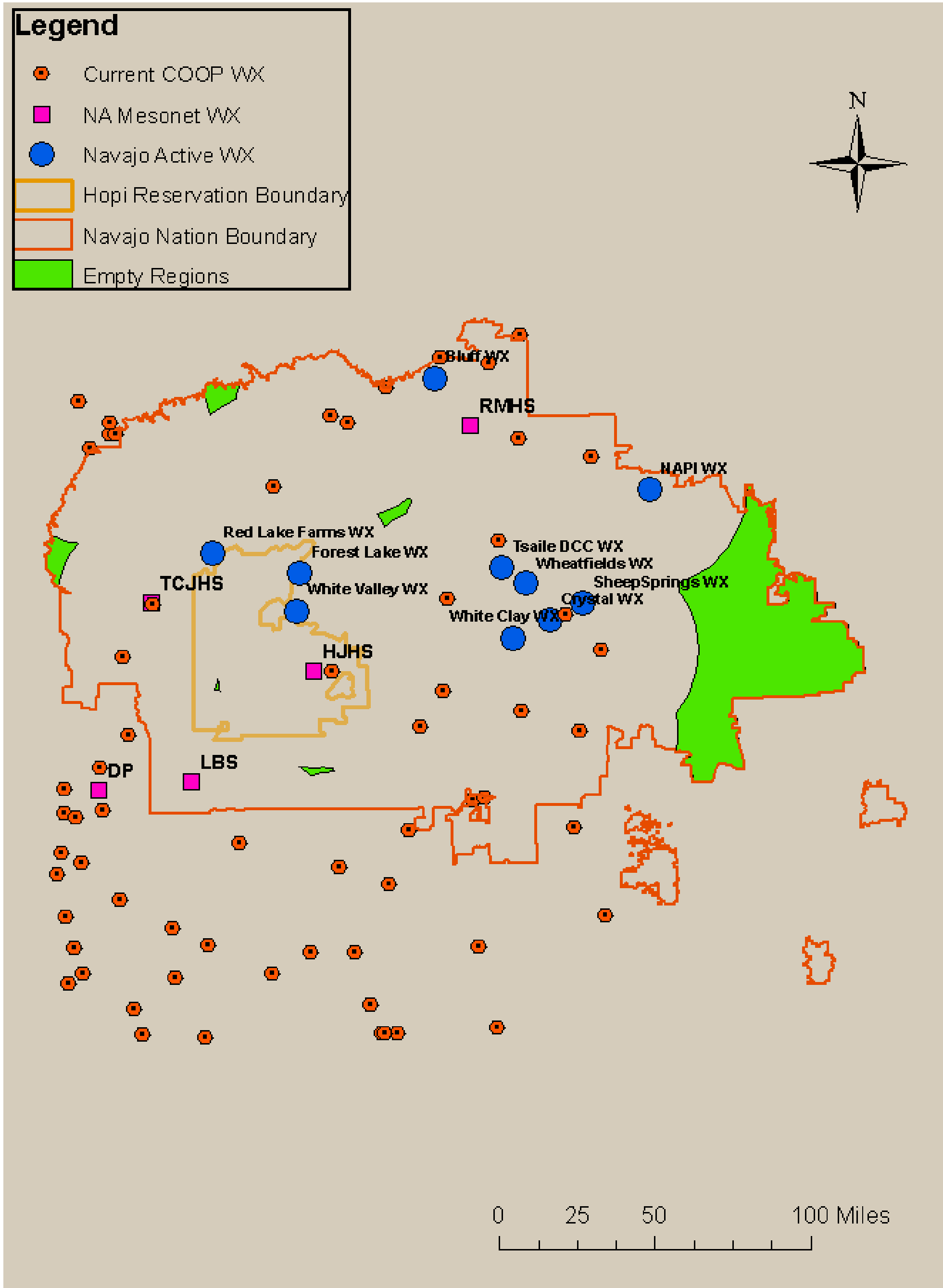

Figure 4.4. Empty regions and currently active weather stations. Six empty regions were identified and named according to the Chapter House in which the majority of the blank occurs. From the top center, moving counter clockwise, they are Navajo Mountain, Bodaway Gap, Hopi, Dilkon, Rocky Point and Eastern Navajo. Eastern Navajo is by far the largest blank spot and would require two additional stations to cover the majority of the empty region To cover it entirely, would require 3-4 additional stations. We recommend two additional stations for this region, which cover most population centers in the region.

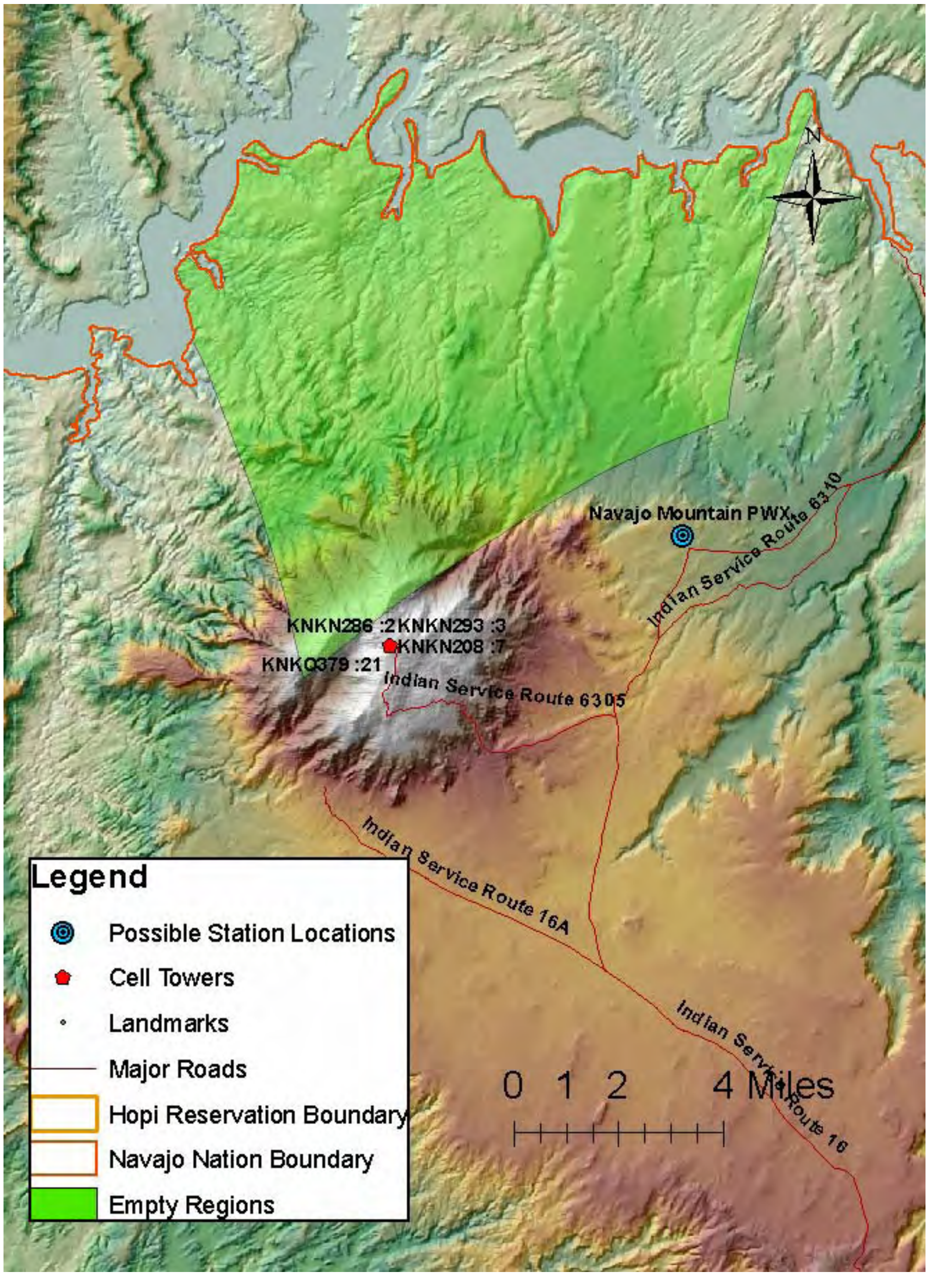

Figure 4.5. A close view of the Navajo Mountain empty region, including topography and major roads. Whenever possible, we tried to choose possible weather station sites near USGS Class 4 (good condition dirt roads) or better roads, on level sites likely to have good access and radio reception. Given the proximity of Navajo Mountain, it may make sense to locate the station at the summit (for radio reception in this remote location), but we recommend the site along Indian Service Route 6310 for winter access and to better represent the terrain in the empty region. This site should have a good line of site to the cell tower on Navajo Mountain.

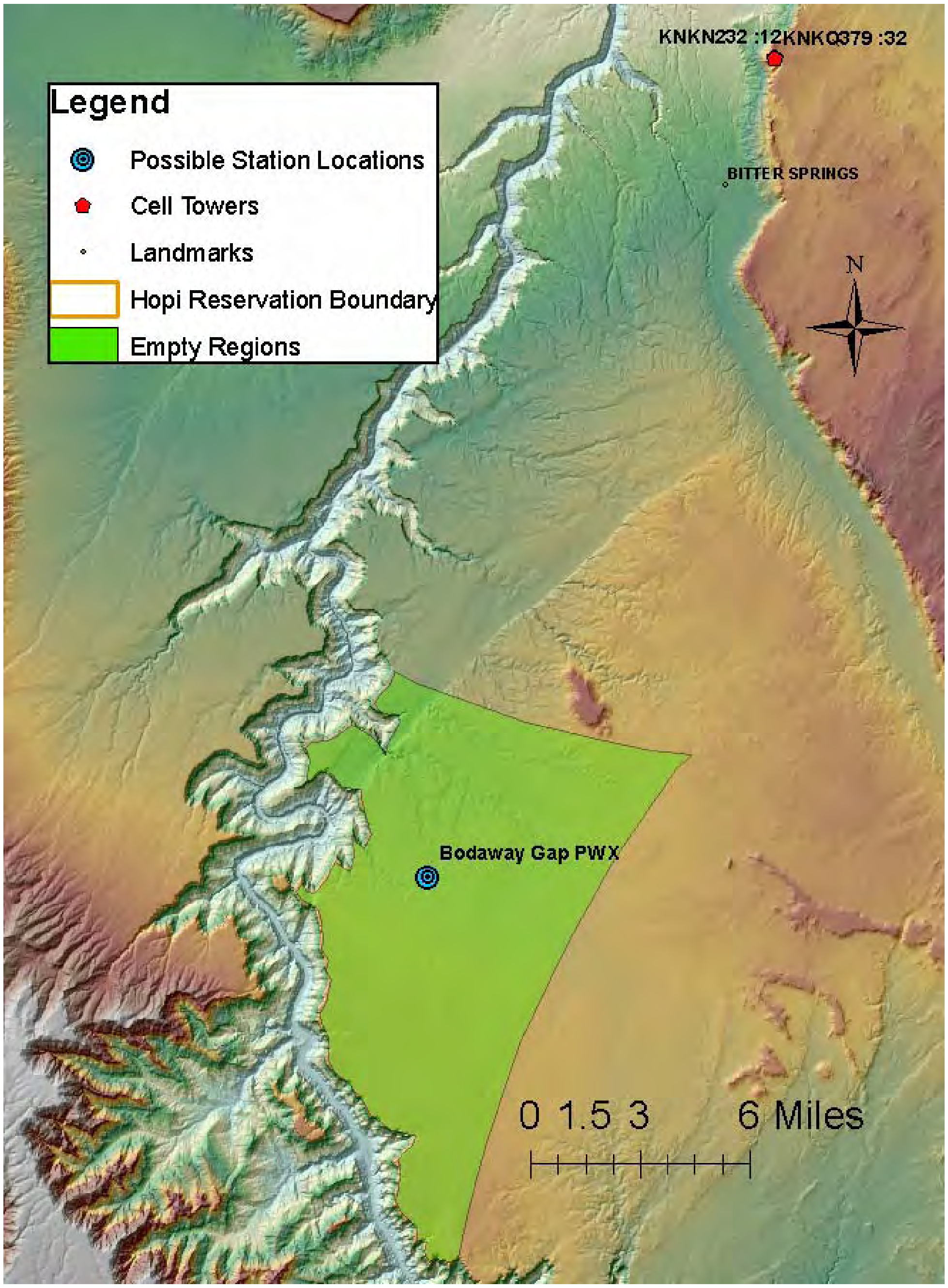

Figure 4.6. The Bodaway Gap site. We recommend locating a station near the center of the empty region, along a good quality road and in moderate terrain. Given the very flat terrain and uniform elevation it should give good representation of conditions associated with the the average elevation terrain. This site should have a good line-of-site to the closest cell tower, but may be beyond cellular range at 24 miles. A high-gain directional cell antenna may help.

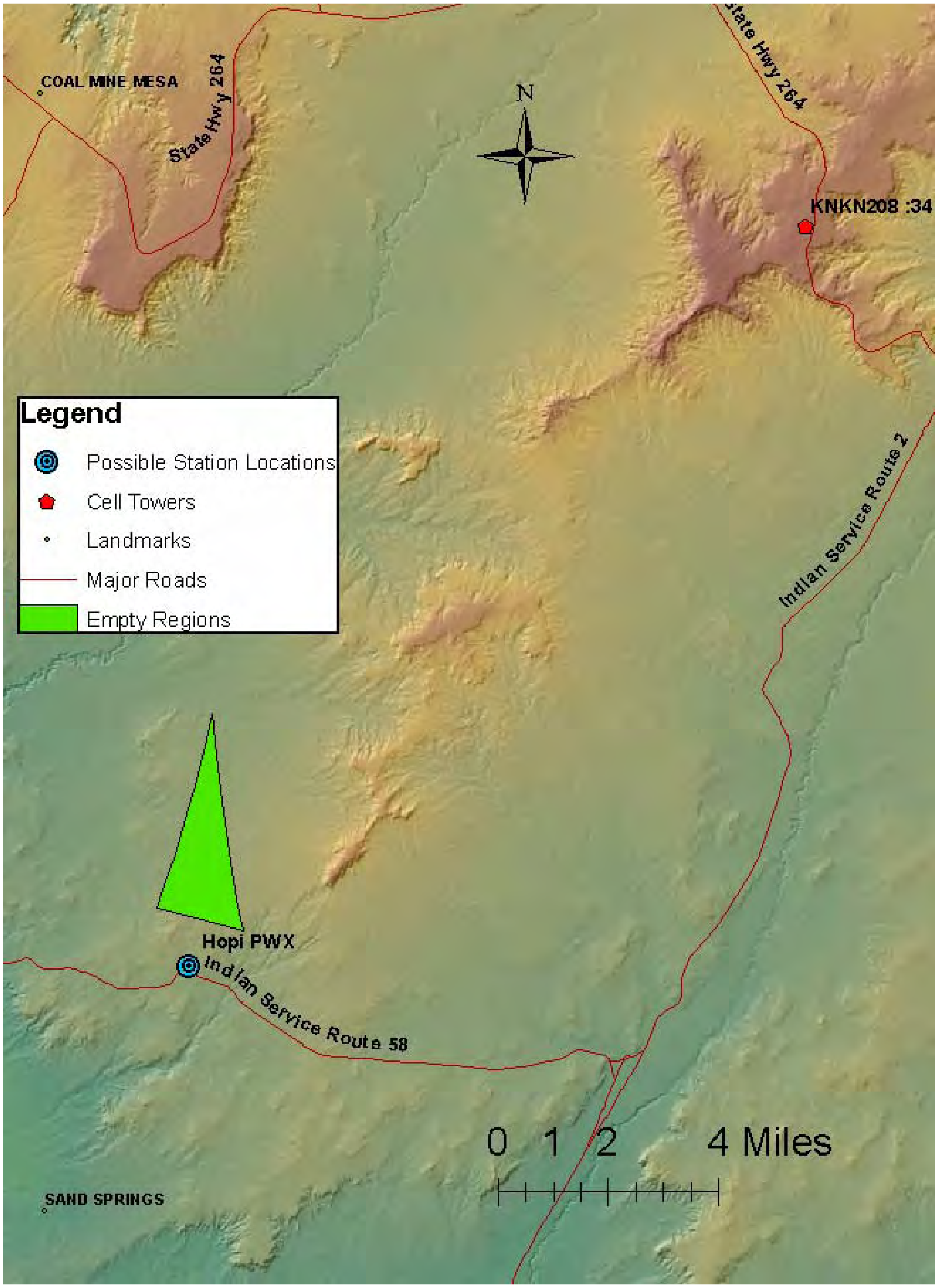

Figure 4.7. This small empty region on the Hopi Reservation can be covered by a site located along Indian Service Route 58. The proposed site is of similar elevation, aspect and terrain as the empty region. It is possible that the site is obstructed by terrain; a ground site survey should be done to determine the best location for reception.

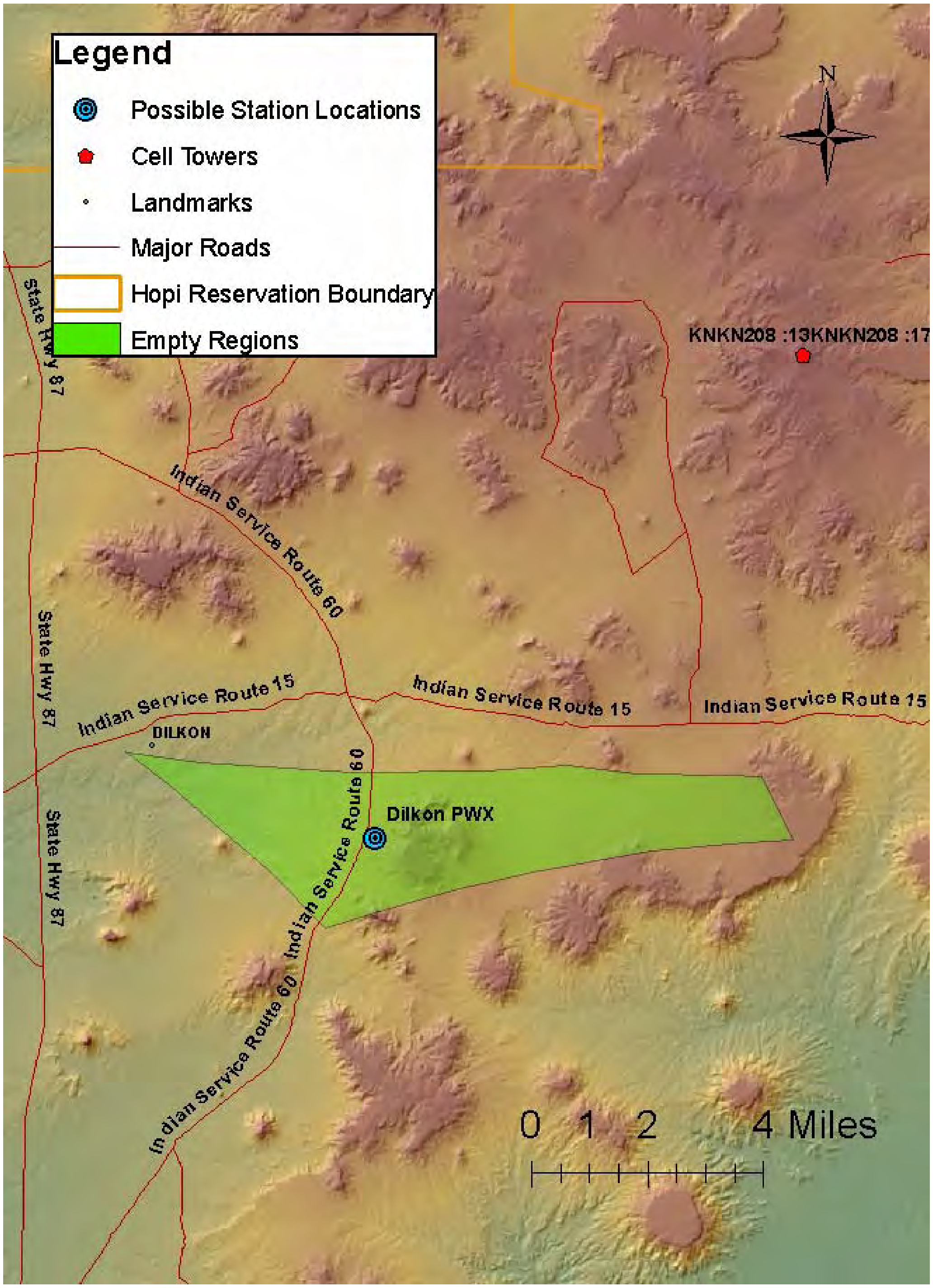

Figure 4.8. This empty region, near the town of Dilkon, can be covered by a weather station sited along Indian Service Route 60. The empty region is in the Hopi Buttes region. We recommend positioning the station so that it is representative of the typical terrain at the average elevation for the empty region. This site may be obstructed from the closest cell tower by terrain. It may be necessary to move the site north along ISR 60.

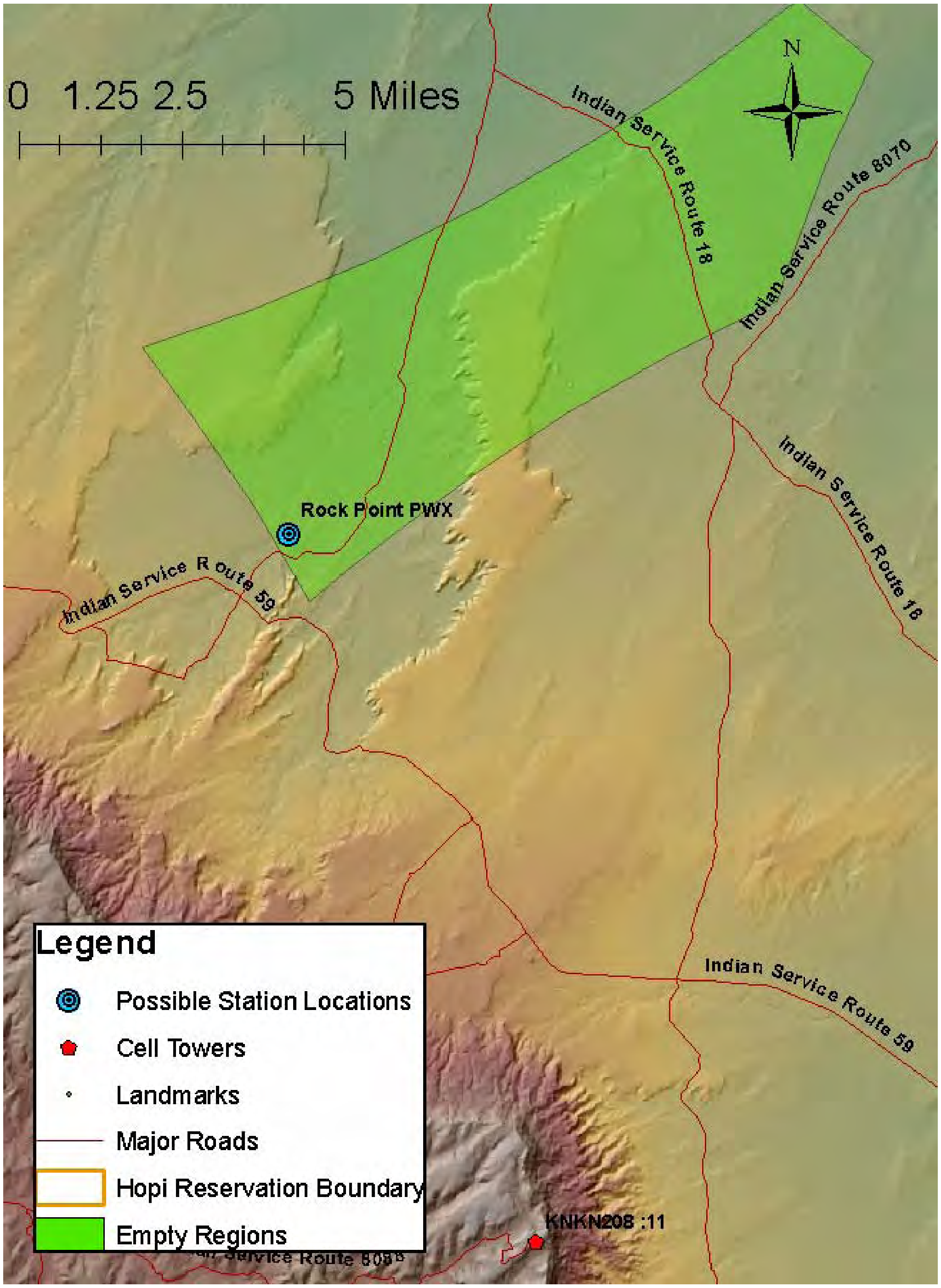

Figure 4.9. The empty region near Rock Point. We recommend a weather station site near the confluence of several roads, including Indian Service Routes 118 and 58, in order to ensure access. Since this site is in a slight depression, an alternative site near the intersection of Indian Service Route 18 and 8070 may have better cellular reception.

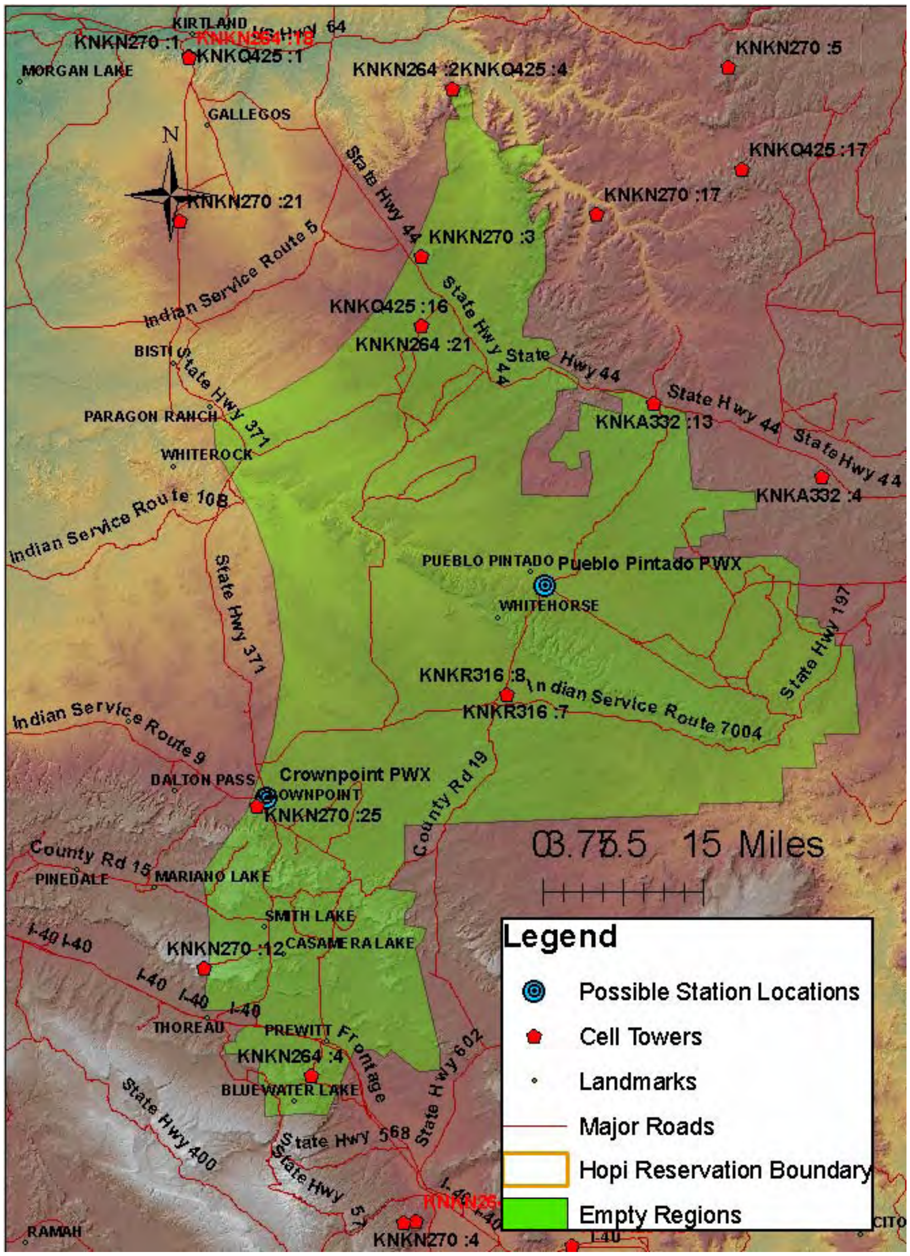

Figure 4.10. The eastern Navajo Nation in New Mexico comprises a large empty region. It will be useful to try to identify likely partner station networks in order to provide data coverage for this region. In order to cover the climatic characteristics of most of the region and cover the areas of greatest population density, we recommend two possible sites. The first site is in Crownpoint, where the High School would make a good addition to the Northern Arizona Mesonet. However, funds are not available for sites outside of Arizona under that project. The second site would be near Pueblo Pintado and Whitehorse. Both the Crownpoint and Pueblo Pintado sites have good line-of-site to their respective cell towers.

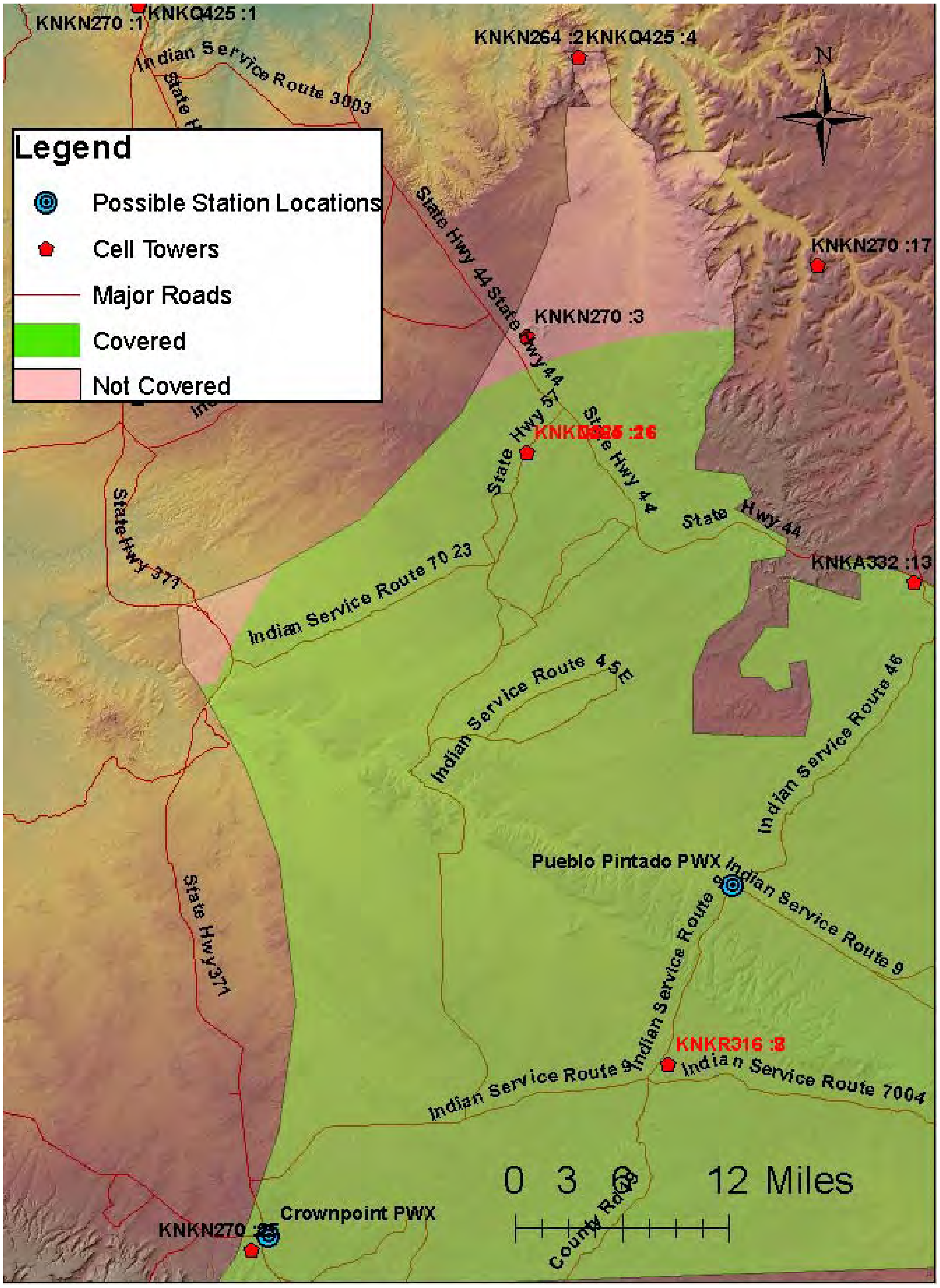

Figure 4.11. Proposed sites near Pueblo Pintado and Crownpoint. Note the two pink regions in the upper left. These are the only remaining empty regions at 50 km maximum distance. A third station northeast of Paragon Ranch would cover both sites, but there is no major road access to locations which cover both sites. We recommend a site visit to determine whether sufficient access exists.

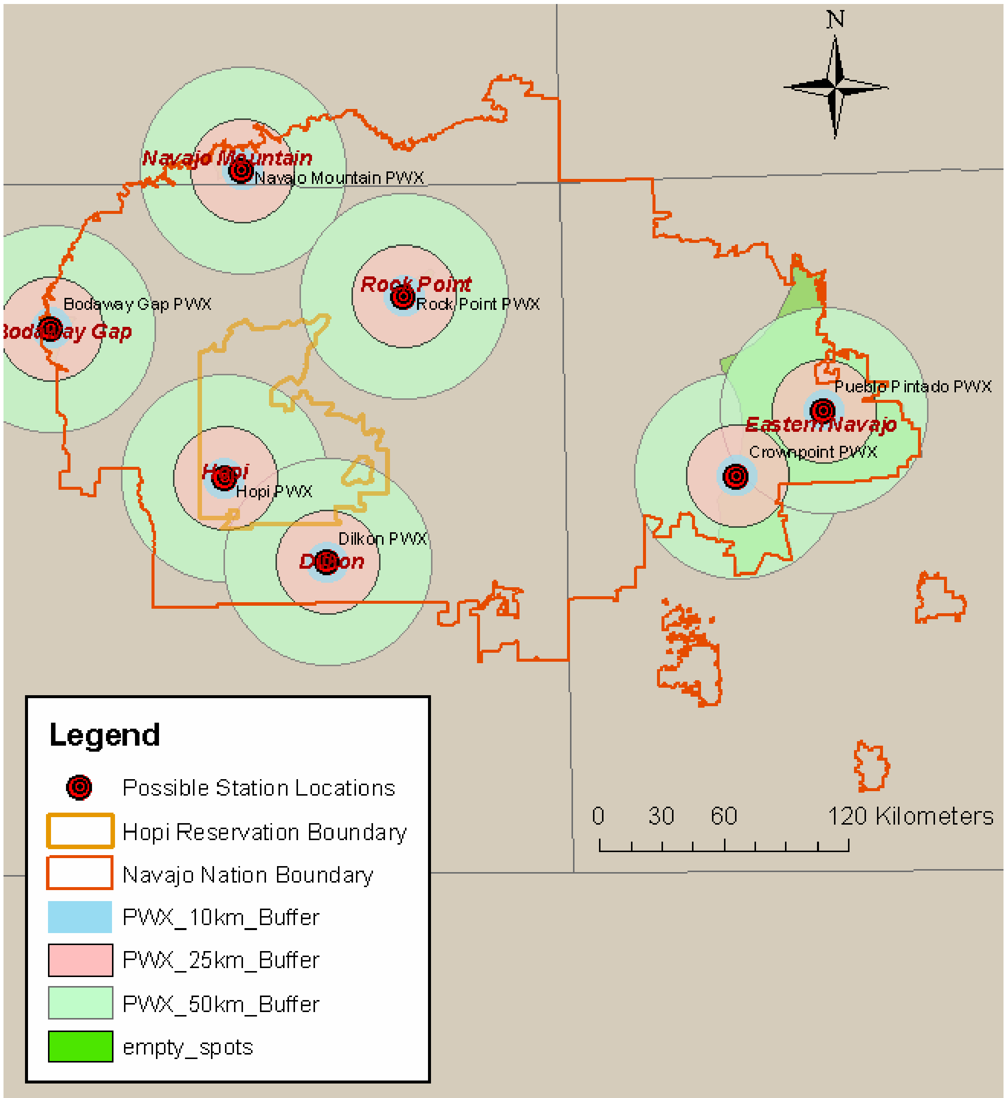

Figure 4.12a. Buffers of 10 km, 25 km and 50 km, constructed for the proposed weather station sites. These seven additional sites, with likely access, will cover in excess of 90% of the empty regions in the network. An additional station (eight total) will provide complete coverage at the 50 km maximum distance; however, accessibility to the eighth site is unknown.

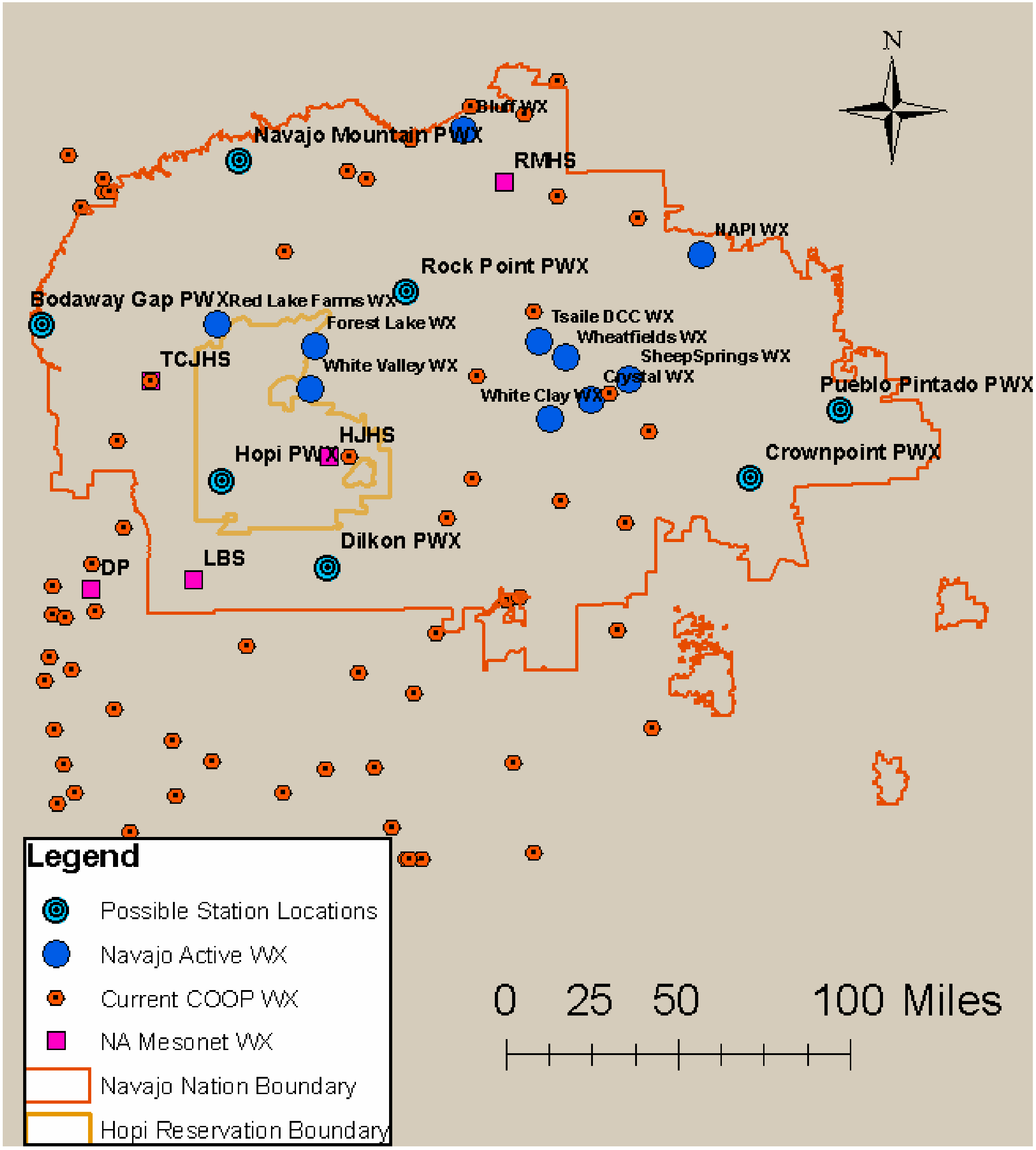

Figure 4.12b. This figure shows the whole proposed network including currently active Navajo Nation weather stations, Northern Arizona Mesonet weather stations, current COOP weather stations and the proposed new Navajo Nation weather stations.

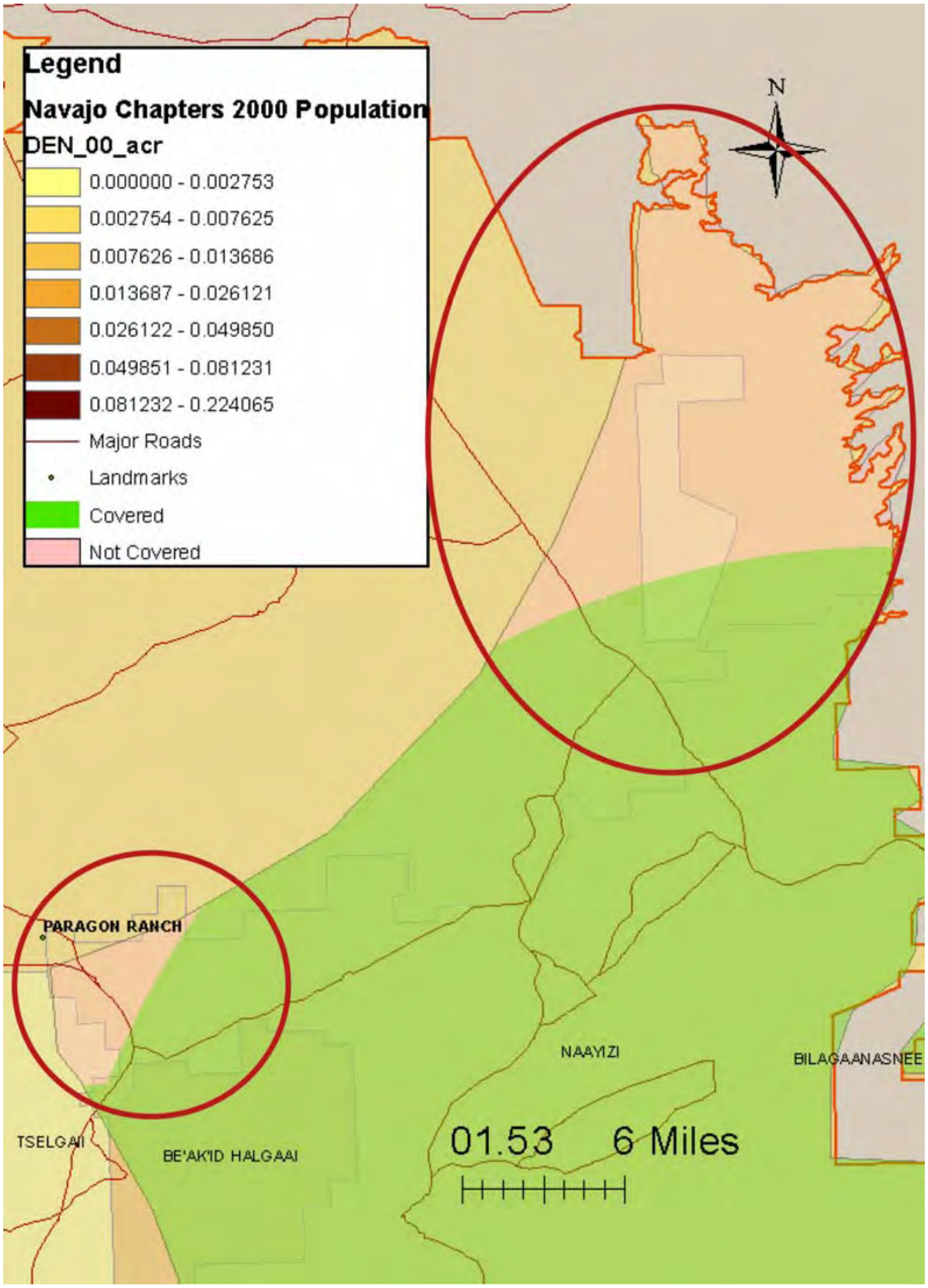

Figure 4.13. Population density by Chapter, according Census 2000 counts. The data are expressed as people per acre for the region surrounding the two remaining empty regions in eastern Navajo Nation. Notice that both sites are in areas of relative high population density for rural areas of the reservation, but low density compared to urbanized regions of the reservation. Some examples of high density areas are Tuba City with .037 people per acre, Shiprock with .075, Crownpoint with .042 and Window Rock with .081.

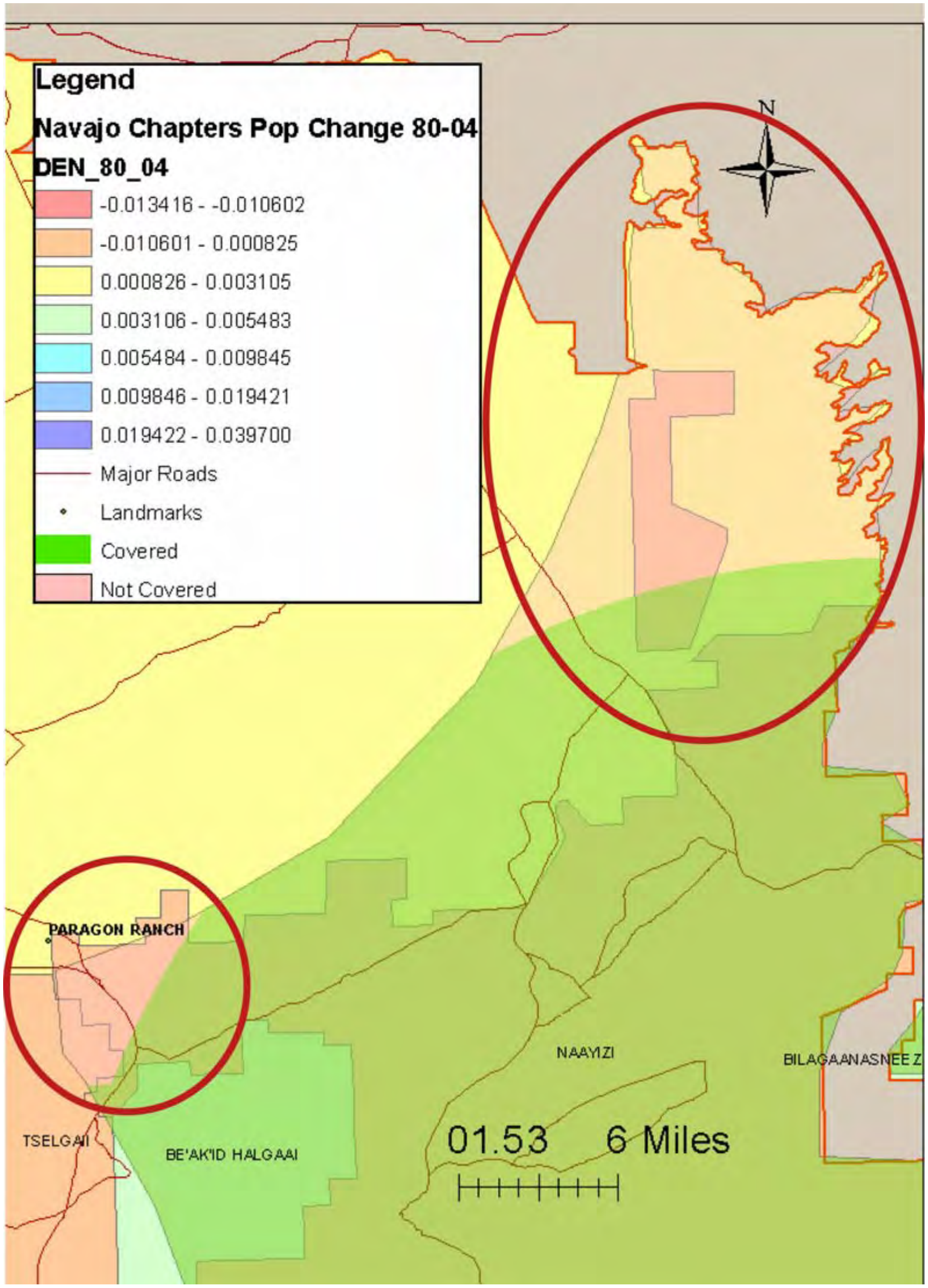

Figure 4.14. Change in population density between the 1980 and 2000 federal censuses, expressed as people per acre. Both remaining empty regions lie in regions with neutral or negative population growth. This suggests that neither of these sites are undergoing population increase and are unlikely to do so in the near future.

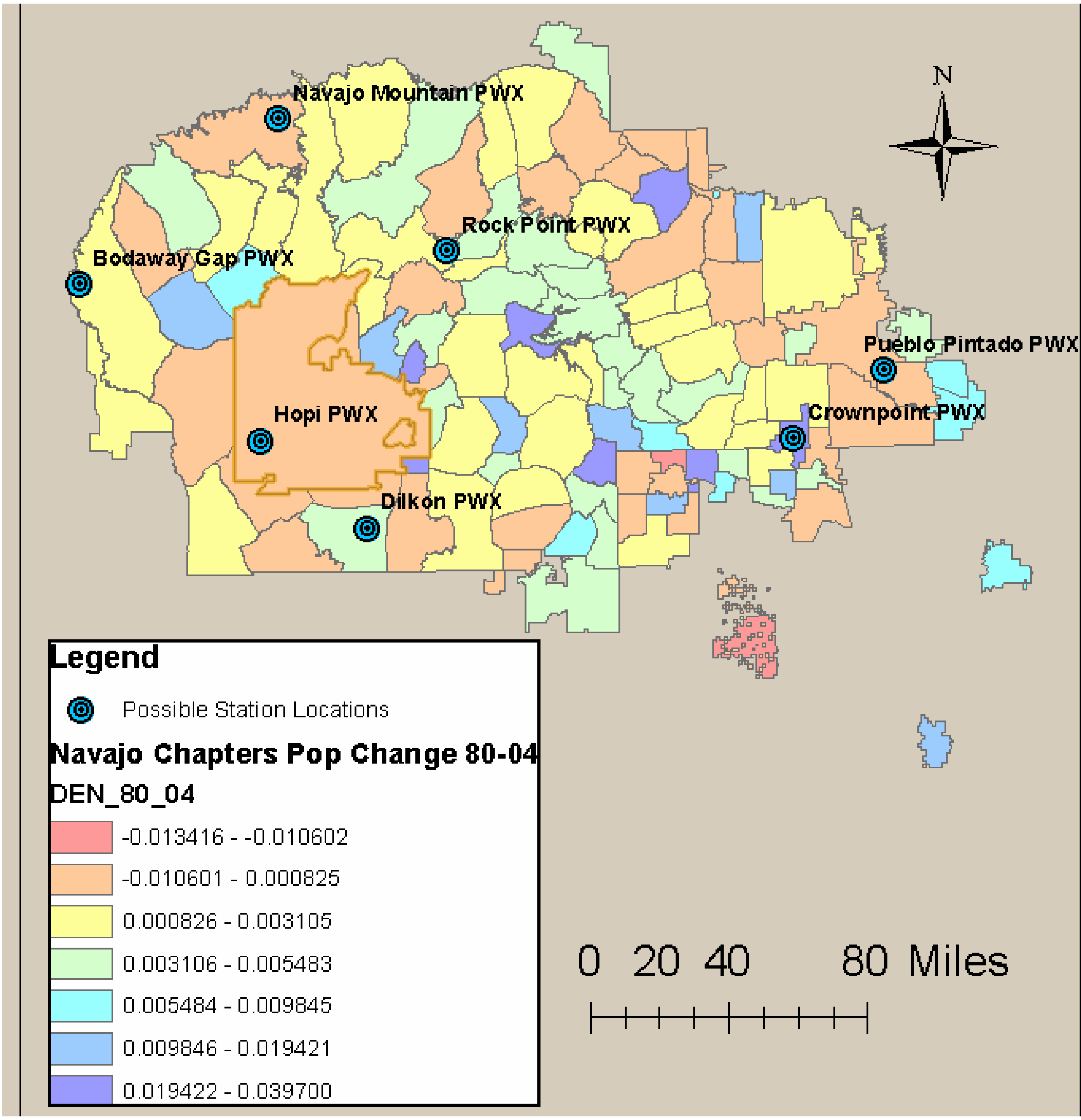

Figure 4.15. Population Density Trends for all Chapters. Colors toward the blue end of the spectrum indicate population growth, colors towards the red indicate population decrease. The Crownpoint, Dilkon and Rock Point proposed stations lie in regions of population growth. The Hopi, Navajo Mountain and Pueblo Pintado proposed stations lie in regions undergoing population decrease. The Bodaway Gap site is neutral. These indices of population density are calculated from chapter census figures and may not be accurate at scales below that of whole chapters.

4.4. Implications

4.4.1. Regarding Navajo Nation Department of Water Resources

By improving the uniformity of the spatial distribution of weather stations on the reservation, Navajo Nation Department of Water Resources will be better able to track and perhaps predict drought, climate change and water resources parameters on the reservation. This is especially important in areas of low rainfall, as such areas are most likely to show climate impacts first and most severely (Field *et al*. 2007). The seven proposed additional weather stations are the minimum number needed to give a maximum distance between stations of 50 km. (Note [December 28, 2007]: adding the NWS COOP stations in northwestern New Mexico would not alter the results of the spatial analysis, as the NWS stations are located at distances greater than 50 km from the proposed weather station sites.)

4.4.2. Regarding interactions with other data providers or information conveyance (e.g. Arizona Hydrologic Information system)

Cooperation with other data providers, such as the Northern Arizona Mesonet, is the most cost effective method of increasing station density and complete spatial coverage. The downside of cooperation is primarily in two areas. First, data sharing may be difficult due to differences in data collection systems or the interests of the cooperating parties. The cooperating parties may have different interests which lead them to collect data in different forms or even to collect entirely different parameters. Careful coordination will be required in order to maximize the usefulness of data sharing for both parties. The second downside is the possible difference in reliability of data collection between systems. Not all networks may have the required funding for long-term station operation. They may also lack fund required to maintain their stations in good working order.

4.4.3. Regarding strategies for making hydroclimate information more useful or available

The single greatest contribution to making hydroclimate data more useful would be to add telemetry to stations in order to allow near-real time collection of data. The problems inherent in doing this are mainly cost and availability of telemetry at each site. Cost can be broken down into the initial cost of installing telemetry hardware and the cost of bandwidth. The cost of initial installation of hardware can range from a few hundred to several thousand dollars per station, depending on the technology used. Bandwidth can range from no cost to tens of dollars per month per station depending on technology. Site assessments at each station will be required to determine what technology will best fit that location. All Northern Arizona Mesonet sites are located at High Schools which either provide telephone or internet connections, greatly simplifying telemetry connection.

Section 5. Northern Arizona Mesonet

Abstract. The Northern Arizona Mesonet (NAM) collects real-time weather data at various educational facilities across Navajo Nation. Data may provide a valuable supplement to Navajo Nation Department of Water Resources weather stations and precipitation gauges. Cooperative efforts such as the NAM may allow NNDWR to expand its existing network with very little increase in manpower requirements. Key points regarding NAM include:

- The NAM data are made available online through the website – http://www.cens.nau.edu/~nauws/nam.html.
- The National Weather Service (NWS) Flagstaff Forecast Office uses these data to supplement official data from NOAA Cooperative Observer (COOP) and Automated Surface Observing System (ASOS) networks, In order to improve weather hazard advisories to the Navajo Nation.
- For the Tsaile weather station site, instructional staff from Dine College are very interested in providing real-time weather data to students, and the NWS is very interested in the site due to the lack of real-time data in the region.
- Real-time data delivery and capture reduces station field visits to only those necessary for instrument maintenance and calibration.
- Potential problems with internet data delivery include stable power and internet access to the computer interface.

5.1. Introduction

5.1.1. Project Overview and goals

The main objective of this component was to facilitate the maintenance and deployment of additional MesoNet (NAM) stations on the Navajo Nation, to supplement existing data collection endeavors. The NAM provides additional data collection points and provides an opportunity for real-time data dissemination.

5.1.2. Background and context

The Northern Arizona Mesonet (NAM) is a network of wireless, solar-powered weather stations located throughout northeastern Arizona (Figure 1) that upload thirteen measured and calculated parameters automatically to a web server every 2 minutes. The network was initiated in 2003 through a partnership between NAU and the National Weather Service, and most of the stations were established as part of ABOR-sponsored teacher professional development opportunities to enhance technology-based physical science education. The stations are in the Flagstaff area, in rural, and in tribal communities, Table 5.1 shows the status of the sixteen stations as of October 2007. NAM data is utilized by the National Weather Service, secondary school teachers, and the general public. Aspects of the NAM project undertaken as part of this project include expansion of the network on the Navajo Nation, development of a searchable archive, and exploration of potential real-time access to the NNDWR Tsaile Weather Station.

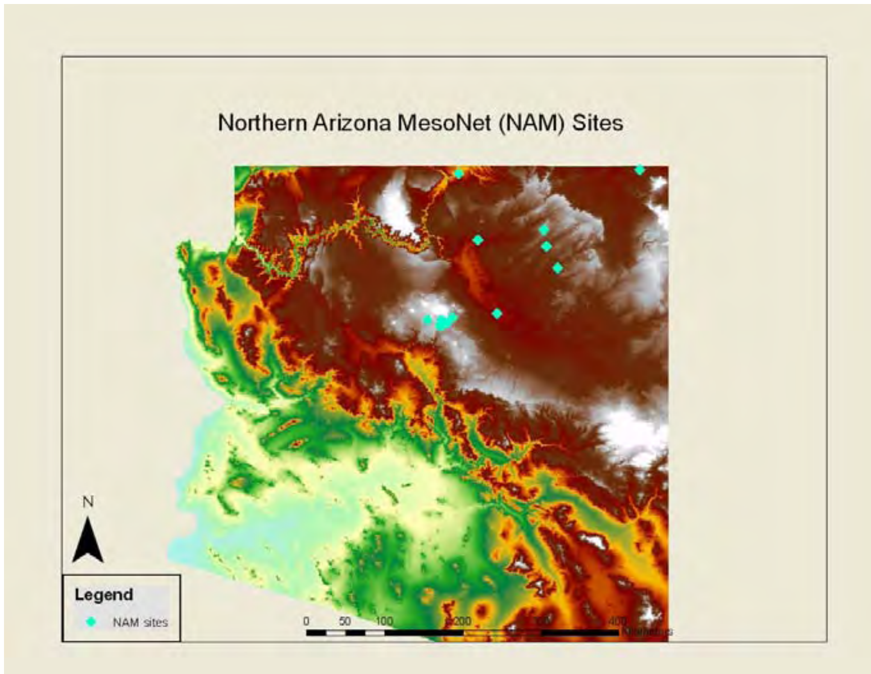

Figure 5.1. Location of Northern Arizona Mesonet (NAM) stations, shown in NE Arizona by cyan diamonds.

Table 5.1. Northern Arizona Mesonet (NAM) sites as of October 2007. A "–" denotes stations that are not yet deployed, a "+" denotes stations that are operating but are not available on the web, strikethrough indicates sites that are no longer in operation. Sites with an asterisk have been integrated into the MesoWest network; http://www.met.utah.edu/mesowest/.

Aspen Glen, Doney Park	*Leupp Schools Inc., Leupp
Aspen Trails Subdivision, Flagstaff	*Northern Arizona University, Flagstaff
Bellemont NWS Office, Bellemont	-Page Middle School, Page
*Coconino High School, Flagstaff	*Red Mesa High School, Teec Nos Pos
DeMiguel Elementary School, Flagstaff	-Rocky Ridge Boarding School
*Flagstaff Arts and Leadership Academy	-Shonto Boarding School
+Flagstaff High School, Flagstaff	*Sinagua High School, Flagstaff
Flagstaff Middle School, Flagstaff	~~Tuba City High School, Tuba City~~
+Hopi Jr / Sr High School, Keams Can.	*Tuba City Jr. High School, Tuba City
~~Kayenta Middle School, Kayenta~~	

NAM weather stations (except Bellemont), use Davis Weather Monitor II wireless, solar-powered weather stations equipped with sensors for air temperature, humidity, barometric pressure, wind speed, wind direction, and liquid precipitation (Figure 5.2). The weather station samples the atmosphere every few seconds[1], and sends the data via wireless radio to a receiver (Figure 5.3). The receiver is hardwired to a computer, which hosts software that processes the incoming data, prepares 30 hour trend graphs and instantaneous data tables, archives the data at two minute intervals, and updates to a web page every two minutes.

Figure 5.2. Davis solar-powered, wireless, Weather Monitor II Weather Station

[1] For a list of accuracy, resolution, range, and update schedule see the Davis Instrument Weather Monitor II product chart at http://www.davisnet.com/news/d_vs_c.asp.

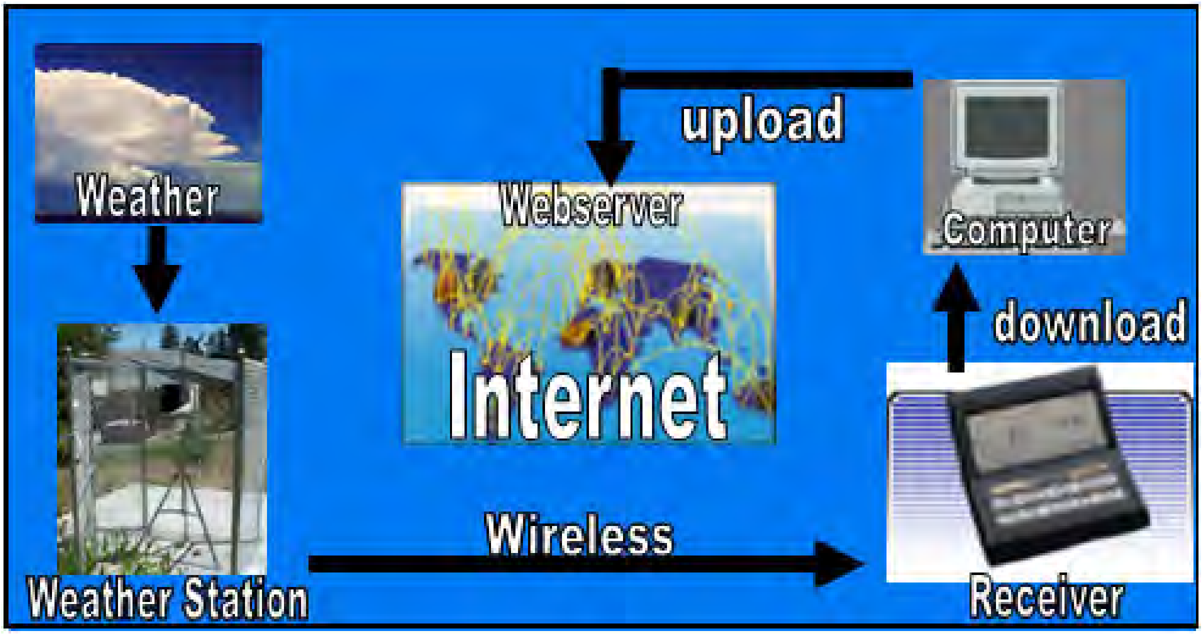

Figure 5.3. Northern Arizona Mesonet (NAM) data stream.

5.2. Research Methods

5.2.1. Data

Contacts were made with new schools (Beth McCauley at Rocky Ridge Boarding School and Leola Secody at Shonto Boarding School) and with new personnel at existing NAM schools (Jim Crittenden at Kayenta Middle School, and Marcella Katoney at Leupp Boarding School) to deploy or upgrade NAM weather stations on the Navajo Nation. National Weather Service meteorologists were contacted to assess their interest in developing the Tsaile Weather Station for real-time data delivery via the NAU NAM network.

5.3. Results

Stations have been purchased for Shonto Boarding School and Rocky Ridge Boarding School. Kayenta Middle School has opted out of the program, Tuba City Junior High School and Leupp Boarding School have been upgraded. NAU CEN ITS has developed an on-line archive for the NAM .txt files, accessible at http://www.cens.nau.edu/~nauws/archive; other NAM station data are accessible using the "/archive" path following the station url. Discussions are ongoing as to whether the Campbell Scientific data logger can be converted to deliver data to the Virtual Weather Station program for real-time display and archival on the internet. The NWS NAM site at Bellemont (http://www.wrh.noaa.gov/fgz/vws/wxo.php?wfo=fgz) operates in this manner (conversion from a Campbell station) and if real-time delivery of the NNDWR Tsaile Weather Station data occurs, it will follow a similar data flow.

5.4. Implications

It may be possible to provide real-time data access to the NNDWR for the Tsaile weather station. Instructional staff from Dine College-Tsaile are very interested in providing real-time weather data to students, and the NWS is very interested in the site due to the lack of real-time data in the region. A potential strategy is to continue the current mode of data collection but to also hardwire route the data stream to a receiver in a classroom at the college, to convert the data to Virtual Weather Station format, and to upload it to the NAU server. It is not clear at this time what role the NWS may take in assisting with sensor calibration. NAU is willing to host the data in the same manner as other NAM stations.

5.5. Conclusions

The NAM provides a supplemental source of data for the NNDWR and other users. The real-time data delivery provides information that may be used by the NWS to improve weather hazard advisories to the Navajo Nation. Real-time data delivery and capture also reduces station field visits to only those necessary for instrument maintenance and calibration. Potential problems with internet data delivery include stable power and internet access to the computer interface. A backup data storage system is recommended.

Section 6. Stream Flow Gaging Stations in the Navajo Nation: Their Present Conditions and Some Recommendations for the Future

Abstract. Investigation of Navajo Nation stream flow gages confirms a number of important points made in the Technical Memorandum (WMI-Memo, 2003), with regard to manpower needs for adequate stream gage maintenance. In addition, this report comments on data quality, adequacy, reliability and accessibility. Our key findings include:

- In the vicinity of the majority of gages, the stream channels are characterized by three factors that influence data gathering and produce false readings: channel aggradation, in-channel vegetation growth and sediment accumulation in the stilling wells.
- Data analysis indicates that stage-discharge relationships are reasonable for the following gages: Kinlichee Creek and Tsaile Creek.
- Stage-discharge relationships are probably influenced by in-channel vegetation growth and inadequate stream gage maintenance at Black Creek, Asaayi Creek, Chinle Creek, Wheatfields Creek, Whiskey Creek, and Captain Tom Creek; data for these gages do not meet USGS standards, and are probably not usable for many purposes, such as estimating water supply, determining the frequency and severity of extreme hydrologic conditions, setting minimum flow requirements to meet aquatic life needs, forecasting floods, and undertaking scientific studies of long-term changes in the hydrologic cycle.
- More efficient, reliable and adequate data collection, processing, archiving, and dissemination may be accomplished through ongoing and improved training of Navajo Nation Department of Water Resources technicians, and further investment in human resources when possible; Based on our assessment, key training needs include stream gage maintenance and data processing. Improved data collection and timely data processing may require investment in personnel and equipment; in particular, remotely operable digital data collection and communications increases the likelihood of producing more reliable data, while requiring fewer human resources. Shifting resources to gage maintenance, in combination with digital data recording and telecommunications (as opposed to chart recording sheets), will improve data quality and timely data communication.
- Improved multi-agency collaboration may provide opportunities for Navajo Nation to improve database organization and coordination with GIS mapping and data inventory.

6.1. Introduction

Adequate and reliable streamflow data are required for Navajo Nation Department of Water Resources to monitor and manage its scarce water resources, to protect lives and property from extreme hydrologic conditions such as drought and flooding, and to plan for future needs. As mentioned in the technical memorandum on Navajo Nation Water Management Branch monitoring programs (WMI-Memo, 2003), these requirements exceed Navajo Nation's current manpower capacity, expertise, and fiscal resources. Navajo Nation has 11 functioning stream gages, two of which are operated by the U.S. Geological Survey. The nine gages operated by the Navajo Department of Water Resources (NDWR) are mostly concentrated on and near the Chuska Mountains. Even though this area produces about two-third of the surface water in the Navajo Nation, hydrologic monitoring in this area does not represent conditions through out the majority of Navajo Nation lands.

6.1.1. Project Overview and goals

The major objectives of the stream gage analysis are (a) to perform a thorough and systematic analysis of conditions of the existing stream gaging network, and (b) to determine the state of data collection, distribution, processing and reduction procedures followed by analysis of data quality and reliability under the existing conditions.

6.1.2. Background and context

Precise measurement of stream discharge rate is needed to accurately estimate the total amount of water coming from surface and subsurface sources, as well as those leaving a watershed and becoming available for on-site and downstream users. The two most fundamental items of hydrologic information on a stream are stage, which is water depth above some arbitrary datum, commonly measured in feet or meters, and flow or discharge, which is the total volume of water that flows past a point on the stream for some period of time, usually measured in cubic feet per second, gallons per minute, or in cubic meter per second. Additional information on streamflow measurement and needs for streamflow data can be found in Appendix B.

6.2. Research Methods

The project team examined each NNDWR stream flow gaging site, during visits in January, June and July, 2007. The team evaluated gage types and instrumentations, gage location stream channel cross-sections, above and below gage location stream reaches, data collection methods, quality control and communication. They also interviewed NNDWR and USGS personnel to ascertain information about gage maintenance, data collection and archival procedures, and other pertinent information. The team augmented the aforementioned information with relevant literature (Van der Leeden, 1990; Bos et al., 1991; Cleaves and Doheny, 2000).

6.2.1. Data

The team obtained discharge rate and stage height data from the Navajo Nation Water Management Branch (WMB), and from the USGS (see Table 6.1). (Note: gages no longer in orperation and gages operated by other agencies are listed in the 2003 Technical Memorandum [WMI-Memo, 2003] in Tables 2.1, 2.3 and 2.4).

The team determined overall data quality by examining archived data adequacy, continuity, stage height-discharge rate relationships and, in some cases, evaluating time series trends. There are nine active WMB managed stream flow gaging stations in the Navajo Nation (Table 6.1). Three of the stations, Asaayi, Tsaile and Wheatfield Creeks, are operated cooperatively by the WMB and the SOD branches of the NNDWR. The other six, located in Captain Tom Wash, Lukachukai Creek, Black Creek, Kinlichee Creek, Whiskey Creek and Chinle Creek near Mexican Hat are solely operated by WMB. Table 6.1 also lists the period of record and type of equipment at the WMB-operated stream gages. Poor data quality and data discontinuities in the WMB data prohibited statistical analysis. However, we examined correlations between stage height and discharge through graphical comparisons. A brief description of non-Navajo streamflow data collection is provided in Appendix C. The Technical Memorandum (WMI-Memo, 2003) provides a thorough discussion of non-Navajo streamflow data collection.

Table 6.1. . NNDWR operated stream gage locations and other identifiers (Navajo Nation Department of Water Resources, Water Management Branch. 2003).

Navajo Nation managed Stream Gages				
Station Name and location	**Station Number**	**Type of gage & recorder**	**Operator**	**Period of Record**
Captain Tom Wash near Two Grey Hills	Navajo Nation 01	Stilling well Stevens FF data logger & Stevens A-71 recorder	WMB	Dec. 1993 - present
Lukachukai Creek near Lukachukai	09379050 NN 02	Stilling well Stevens A-71 & Sutron Recorders , GOES	WMB	Oct. 1993 - present
Black Creek near Houck	09395990 NN 03	Stilling well Stevens A-71 Recorders & A/F data logger	WMB	Aug. 1986 - present
Kinlichee Creek at Kinlichee	09400040 NN 04	Stilling well Stevens FF data logger & Stevens A-71 recorder	WMB	Aug. 1986 - present
Tsaile Creek near Tsaile	Navajo Nation 05	Transducer Rugid9 Recorder	WMB/SOD	May 1997 - present
Asaayi Creek above Asaayi Lake, NM	Navajo Nation 06	Transducer Rugid9 Recorder	WMB/SOD	July 1993 - present
Chinle Wash at Chinle	09379025 NN 07	Stilling well Stevens A-71 & Sutron Recorders , GOES	WMB	Dec. 1994 - present
Wheatfields Creek near Wheatfields	Navajo Nation 08	Stilling well, Rugid9, Stevens A-71	WMB/SOD	Dec. 1992 - present
Whiskey Creek near Little White Cone	Navajo Nation 09	Stilling well, 48" flume, Stevens A-71 Recorder & A/F data logger	WMB	1990 -present

6.3. The Research Context

The majority of gages examined are within the geographic province of central Navajo Nation, on and in close proximity to the Chuska Mountains and the Defiance Plateau (WMI-Memo, 2003) (Figure 6.1). The only exceptions are Captain Tom Wash, which is located on the eastern flank of the mountains and Black Creek located to the southwest of the mountains in the south central part of the Navajo Nation. The present locations of the stream gaging stations are concentrated around an area that produces about two-third of the surface water in the Navajo Nation. They are easily accessible by dry weather roads. Both their close proximity and accessibility enable visits by water resources technicians for equipment maintenance, data downloading and site observation. However, the spatial distribution of the gages does not represent the large area of the Navajo Nation. Many parts of the Navajo Nation remain ungaged with little or no surface flow monitoring and hydrological data availability. Thus, the gaging network does not represent the hydrologic conditions in the western and eastern portions of Navajo Nation. However, the gages monitor and the wettest area in the Navajo Nation, and the area draining into the most populated and economically most significant part of the Nation.

The WMB-managed stream gaging stations are of two types: (1) Stilling well Stevens A-71 & Sutron recorders and (2) Transducer Rugid9 Recorder (Table 6.1). The gages at Black Creek, Chinle, Kinlichee, Lukachukai, Captain Tom, Wheatfield and Whiskey creeks are of the first type while those in Asaayi and Tsaile creeks are of the second type. All the gages, except the Whiskey Creek gage, are constructed to measure stream stage and discharge across a regular stream cross-section; Whiskey Creek uses a 48-inch Parshall Flume.

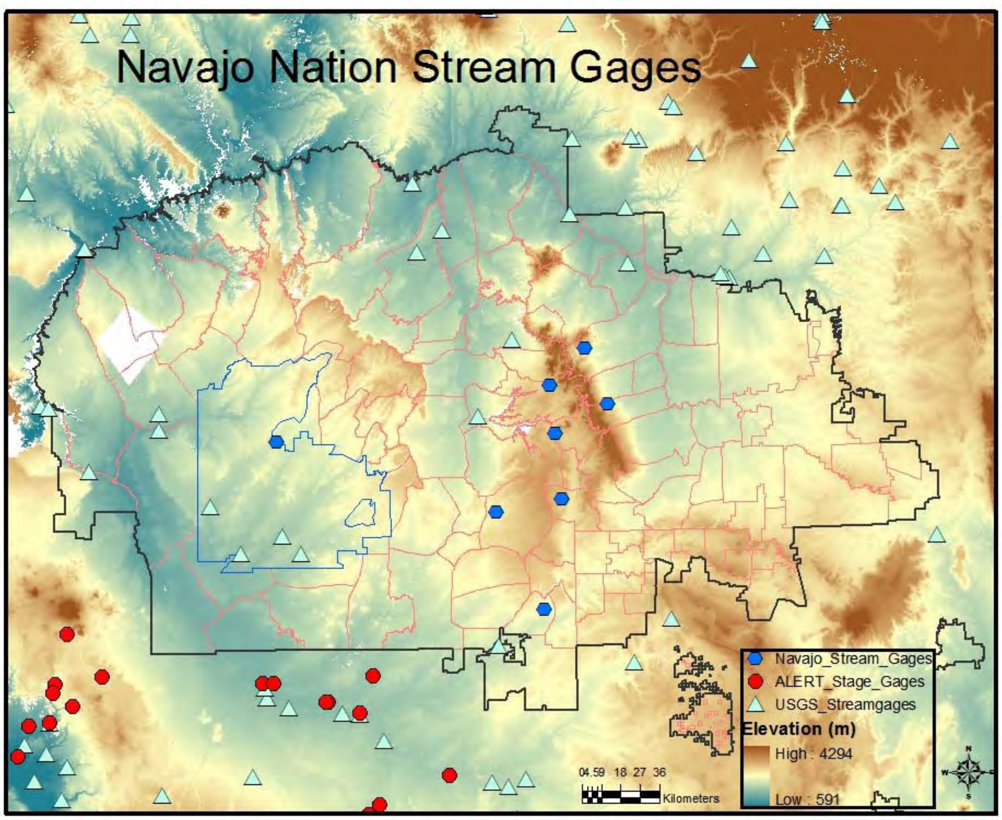

Figure 6.1. Streamflow gages managed by the Navajo Nation Water Management Branch and the USGS. Note that the two gages in the western side of the Chuska Mountains denoted by triangles are now operated by the NNDWR.

6.4. Results

Table 6.1 provides the specific stream locations of the NNDWR operated gaging stations, their identification number, types of equipment they use, period of operation and operating Navajo Nation unit(s) in charge of operating the gages. The present gages require substantial labor, including site visitations for instrument maintenance, downloading data and manual processing of the collected data. In the face of budgetary and skilled manpower constraints, such an arrangement comes with various challenges that are the causes for the problems we found with the gaging stations (Table 6.2).

Table 6.2 gives an overview of stream gaging site characteristics and data quality. In general, the data collected from NNDWR-operated gages lack the quality, adequacy, and reliability for use in most standard applications. The factors that affect data quality and reliability include:

- In the vicinity of the majority of gages, the stream channels are characterized by two factors that influence the accuracy of data measurement and thus lead to inaccurate readings. The factors are (1) in-channel vegetation growth and (2) sediment accumulation in the stilling wells and adjacent stream channel bed. Figures 6.2-6.4 illustrate typical problems. In particular, the most serious problems affecting stream flow measurements in the Navajo Nation are excessive sediment accumulation and rapid stream channel invasion by exotic plants such as Russian Olive and salt cedar;
- At most sites, data are not gathered following USGS protocols (Wahl et al., 1995); when USGS protocols are followed, it appears that data are not properly processed;
- Stage height-discharge relationships are reasonable for Kinlichee Creek and Tsaile Creek (see Figures 6.5–6.7);
- Stage-discharge relationships do not show good correlation in the gaging stations in Whiskey Creek, Black Creek, Asaayi Creek, Chinle Wash, Wheatfields Creek and Captain Tom Wash (see Figures 6.8–6.11);
- The gaging facilities in the Navajo Nation are too small in number and too localized to represent the climatic and topographic variations within Navajo Nation. The WMB-managed gaging stations are restricted to the central part of the Nation (WMI-Memo, 2003). The main reasons for this problem are budgetary and manpower constraints as well as inaccessibility and remoteness of many streams.

Table 6.2. Stream Gage Assessment Summary.

Gage	**Period of Record**	**Data Format**	**Site Characteristics**	**Flow-Discharge data quality**	**Notes** (many stage records lack corresponding flow rates)	**Recommendations**
Asaayi Creek	July 1991-present	Non-standard data record and format	Channel invasion by vegetation; large amount of channel bed sediment accumulation on observed date	Few high stage flows recorded; Possibly due to errors in data recording or instrument reading	Data have not been regularly recorded and processed. From 1991-2006, only 226 record times, many of them without stream flow data.	Clean cross-section of accumulated sediment; remove vegetation; maintain clean channel. Develop a new stage-discharge rate rating curve.
Black Creek	Aug. 1986-present	USGS-style; frequent interruptions	Channel invasion by vegetation; channel bed sediment accumulation; evidence of channel aggradation and degradation	Discontinuous data record; data recorded for alternating years; data quality is suspect	Continuous instrument operation, but data recording interruptions	Dredge accumulated sediment; remove vegetation; maintain clean channel. Develop a new stage-discharge rate rating curve.
Captain Tom Wash	Dec. 1989-present	Non-standard data record and format	Sediment accumulation inside stilling well; boulders in stream cross-section near stilling well; vegetation in stream channel	Data reliability in question due to gauge condition (many record periods do not contain flow data)	From 1989 to 2006, only 207 sporadic record times, many without stream flow data.	Remove accumulated sediment and from inside stilling well; outside stilling well, remove rock debris and vegetation growth; Maintain clean channel.
Chinle Wash	Dec. 1994-present	Non-standard data record and format	Flow taking place away from the gauge, due to stream braiding; abundant sediment accumulation; stream bottom vegetation growth.	Low correlation between stage-discharge; data may not be reliable for use (many record periods do not contain flow data)	Sporadic data collection; From 1994-2006, only 71 record period times; some periods completely lack data	Move stilling well to nearby bridge to avoid channel aggradation, in-channel vegetation growth, and to simplify cross-section maintenance. Develop a new stage-discharge rate rating curve.
Kinlichee Wash	1986-present	Non-standard data record and format	Stable location; no vegetation growth; little sediment accumulation	Near-perfect stage-discharge relationship. However, many record periods lack flow data	From 1988 to 2006, only 236 stream flow record periods; some lack stream flow data	The gage is located in a stable cross-section by a bridge and it needs no fixing.
Lukachukai Wash	Oct. 1987-present	Non-standard data record and format	High sediment accumulation along stream bed; vegetation growth along channel. Data unreliable	Poor relationship between stage and discharge; sediment accumulation and vegetation growth influence high stage measurements	From 1987 to 2003, only 115 record times; many periods lack data; Apparently, no data after 2003	Clean cross-section of accumulated sediment; remove vegetation; maintain clean channel. Develop a new stage-discharge rate rating curve.

Table 6.2. Stream Gage Assessment Summary (Continued)

Gage	**Period of Record**	**Data Format**	**Site Characteristics**	**Flow-Discharge data quality**	**Notes** (many stage records lack corresponding flow rates)	**Recommendations**
Tsaile Creek	May 1996-present	Non-standard data record and format	Gauge located in stable and clean reach; no problems with channel aggradation or degradation; no sediment accumulation	Stage-discharge relationship is good. Instrument not calibrated for flows that rise above bankful stage	Sporadic data collection; From 1996-2006, only 193 record times; many periods lack stream flow data	The gage is located in clear and stable channel. Occasional removal of debris from the cross-section where gage is located.
Wheatfields Creek	1989-present	Non-standard data record and format	Gauge located in stable reach; vegetation invasion above bankful stage (may affect accuracy of measurements)	Higher correlation at low flows than high flows, due to stream cross-section, which is stable near stilling well bottom, but affected by vegetation at higher levels	From 1999 to 2006, sporadic data collection with only 197 record times; many periods lack stream flow data	The gauge is in a stable cross-section. Interference from the stilling well itself, with a rise in the stream flow height, needs correction. Remove interference from vegetation. Gage needs recalibration.
Whiskey Creek	1990-present	Non-standard data record and format	Though the regions near the flume have some vegetation growth, site is in relatively good condition	The impact of the vegetation is evident from the lack of correlation in the stage-discharge relationship.	From 1990 through 2006, sporadic collection; only 241 record times, 46 lack flow data	The gage here is a Parshall flume which should be stable. However, the vegetation from the approach and forward channel should be removed and the flume kept clean.

Figure 6.2. Two photographs showing opposite sides of Chinle Creek at Chinle stream gaging station. The stilling well is on the left while most of the flow occurs on the right side opposite the stilling well. The large amount of accumulated sediment is responsible for the situation.

The location of gages on unstable stream cross-sections creates some problems. This is especially so in those gaging stations located in lower elevation and semi-desert areas, where there is a lot of sediment movement and deposition. Where streams have wide meandering floodplains, they tend to change their flow patterns and this usually affects the accuracy of measurements. This is the case in Chinle Creek (Figure 6.2) where large amount of sedimentation causes braiding in the flow pattern leading most of the base flow to run along the side opposite the location of the stilling well. There are also large amounts of sediment accumulation and vegetation growth in the bottom of the stream cross-section near the Chinle Creek gage. This may lead to both underestimation of stage height and discharge rate, as most of the flow occurs away from the gage, and overestimation, since the sediment accumulation tends to raise the level of flow in the stream. The impact of this situation on stream gaging function is evident in the scattergram of stage-discharge relationship data obtained from Chinle Creek shown in Figure 6.9. Relocating the gaging station about 100 ft upstream by the bridge (shown on the upper right-hand part of the Figure 6.2) would reduce problems.

Figure 6.3. Deep sediment accumulation and vegetation growth in the gaging station at Black Creek .Note the depth of the accumulated sediment on the right hand side photograph.

The impact of high sediment accumulation on stage height-discharge relationships should also be the same in Black Creek, where sediment accumulation is close to 2 feet deep (Figure 6.3). Black Creek also experiences heavy channel bottom vegetation invasion as well as channel aggradation and degradation problems. Sedimentation problems in Black Creek require continuous maintenance of the channel cross-section.

Figure 6.4. Accumulation of rock debris (outside) and sediment (inside) the stilling well in Captain Tom Wash. Both conditions would increase the stage height measured in this station.

Similar problems exist with the stream gaging stations in Captain Tom Wash, Lukachukai Creek, Wheatfield Creek and Asaayi Creek. The stream cross-sections near the gages in these streams are (1) heavily invaded by vegetation (Wheatfield and Whiskey Creeks), or (2) have heavy deposits of sediment or gravel and boulders (Figure 6.4), or (3) have both heavy sediment accumulation and vegetation growth (as in Lukachukai Creek and Asaayi Creek). The stage-discharge relationships for these gages are erratic (see Figure 6.8-6.11).

Only two stream gaging stations of the nine WMB managed stations have very stable cross-sections, with little or no interference from vegetation growth, sediment accumulation or stream bank or bottom instability. These gaging stations are located in Kinlichee and Tsaile Creeks. The Kinlichee Creek gaging station owes its stability and reliability to its location by a bridge overlying a well anchored rocky streambed (Figures 6.5-6.6). The stable stream gaging site in Tsaile Creek is located in a stream channel surrounded by a meadow clear of riparian vegetation and free from any kind of channel erosion or any other stream degrading conditions (Figures 6.5, 6.7). The only problem is that the instrument is not calibrated for flows that rise well above bankful stage. In contrast with the irregular stage-discharge relationships observed in many of the gaging sites described above, the stage-discharge data from the gaging sites in Kinlichee Creek and Tsaile Creek show good relationships (Figures 6.6, 6.7, respectively).

Figure 6.5. Stream flow gaging station locations for Kinlichee Creek (left) and Tsaile Creek (right). Note that these two streams have different gage types: a stilling well in Kinlichee Creek and a pressure transducer in Tsaile Creek.

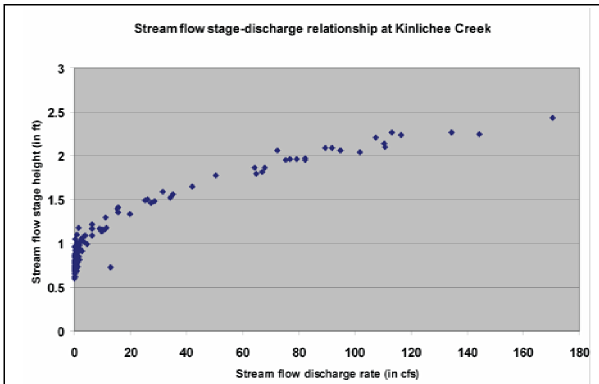

Figure 6.6. Stage height versus discharge rate for the gaging station at Kinlichee Creek. (Data: NNDWR)

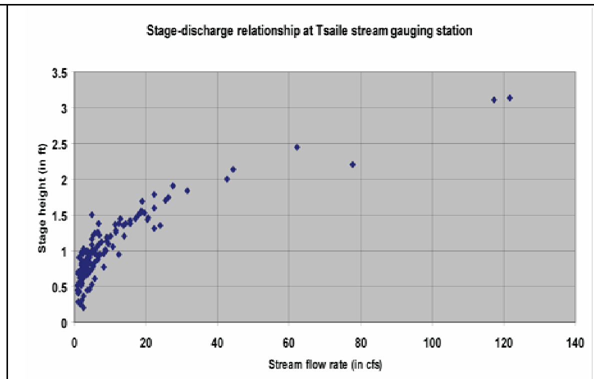

Figure 6.7. Stage height versus discharge rate for the gaging station at Tsaile Creek (Data: NNDWR)

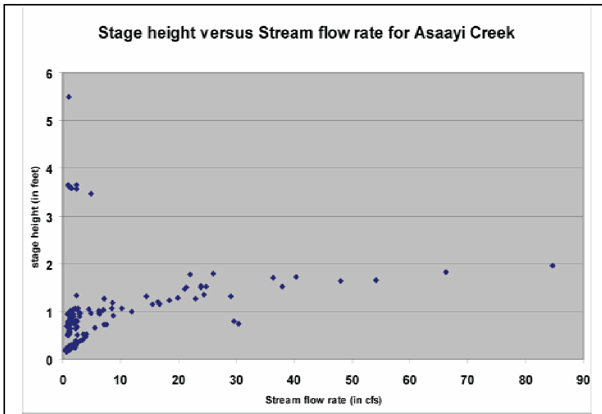

Figure 6.8. Stage height versus discharge rate for the gaging station at Asaayi Creek

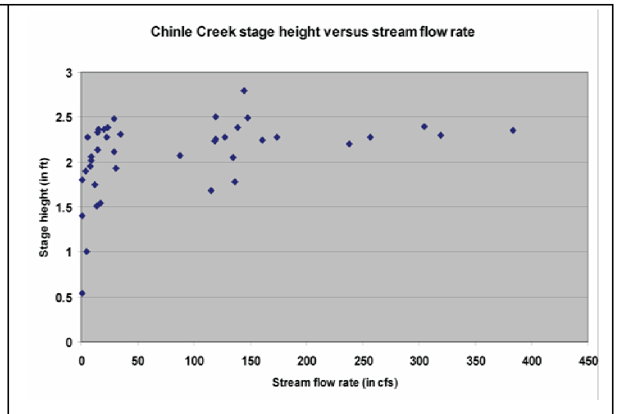

Figure 6.9. Stage height versus discharge rate for the gaging station at Chinle Wash

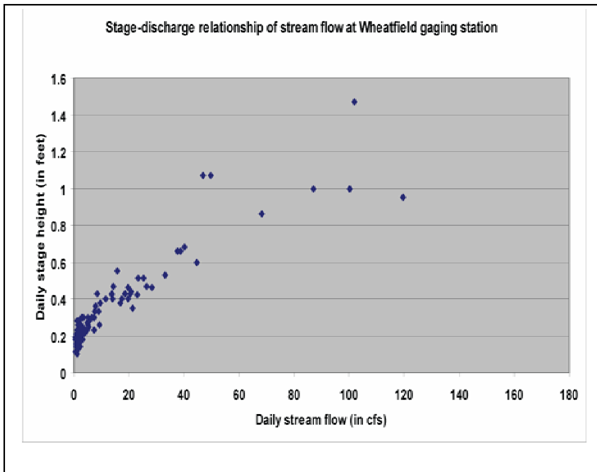

Figure 6.10. Stage height versus discharge rate for the gaging station at Wheatfields Creek

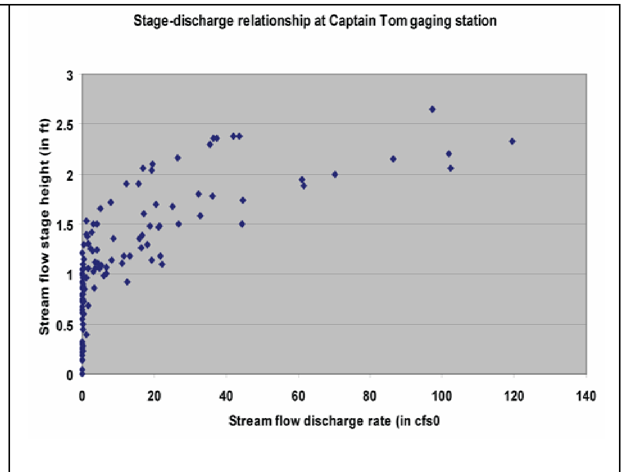

Figure 6.11. Stage height versus discharge rate for the gaging station at Captain Tom Wash

6.5. Implications

There are various implications of not having reliable hydrological data in the Navajo Nation.

6.5.1. Regarding Navajo Nation Department of Water Resources

The NNDWR is charged to manage the Nation's water resources, including having a very good knowledge of the sources conditions, their availability, proper use, conservation and adjudication (WMI-Memo, 2003). To do all these successfully requires having good measurement and reliable data. Without the latter, it will be difficult for the NNDWR to discharge its duties in the most efficient, equitable and sustainable manner.

6.5.2. Regarding interactions with other data providers or information and conveyance

The main reasons for having problems with quality and adequate data are related to lack of adequate financial resources and sufficient skilled manpower; thus, collaboration and interaction with other local and regional data providers would help significantly, as follows:

- It would lead to sharing existing available data and technology (Mason, 1995; USGS, 1995);
- It would make available necessary resources, such as spare parts or entire equipment, for maintaining existing gages or for gage installation in economically and hydrologically important streams;
- Experts from the collaborating organizations can train personnel and provide needed expertise in hydrology and water resources measurements; and
- It would facilitate development of joint projects that would be more efficient, cost effective and easier to manage.

However, efforts should be made to avoid any negative effects among collaborators that may arise from shortage in personnel, funding or parts.

6.5.3. Regarding technical or technological requirements

The problem with operating labor-intensive stream gaging stations may be resolved by introducing new remotely controlled and easy-to-use technologies and intelligent data processing systems. Such technologies may reduce manpower requirements for downloading data in the field, and processing them in the office.

6.5.4. Regarding gaging site and condition characteristics

Stream gaging operators and data users must ascertain certain key issues to make the data obtained more useful:

- To use the data measured for watershed modeling and estimating water yields, the gaging site must be located at the watershed outlet, if possible;

- The gages, in general, should be clean and well maintained to avoid any interference from channel aggrading or degrading conditions; and
- Data must be regularly downloaded following a standard protocol to avoid any information loss.

6.5.5. Regarding strategies for making hydroclimate information more useful or readily available to users.

A number of strategies may be developed to make hydroclimate data more available to Navajo Nation and other users, in order to achieve the streamflow monitoring and data-use goals listed in Appendix B (Cleaves and Doheny, 2000). The main strategies may include:

- Improved data processing training for new and existing personnel;
- Acquisition of new and better data acquisition and processing technologies that can simplify data collection and decrease manpower requirements;
- Collaboration with other data sources, managers and providers to make data availability easier and more cost-effective, and
- Training the public so they become good information consumers.

6.6 Conclusions

Successful water resources management requires knowledge of water quantity, quality, and streamflow timing. This is especially true in semiarid regions like the Navajo Nation, that are prone to water scarcity and flooding – with major consequences to the economy, and social and cultural conditions of the people. Given this context, we recommend that the Navajo Nation develop long term and short term hydrologic monitoring and management strategies and tactics, including:

- Obtain or allocate funds to hire and train at least two Navajo Nation technical staff; one to help in gaging station operation and the data collection process, and the other dedicated to work on data reduction and preparation for distribution to users;
- Improve stream gage, equipment, and site maintenance;
- Regularly download data and process them following a nationally accepted standard;
- Consider acquiring new technologies capable of remotely downloading data at prescribed intervals and processing them for distribution. Such techniques are currently available in the market (Hirsch and Costa, 2004);
- Develop a collaborative working relationship with local (Navajo), state and federal agencies to facilitate data exchange and ensure availability of needed hydrological information for various uses. This includes requesting federal agencies, especially the USGS, to support the

Navajo Nation to have proper hydrological data collection, maintenance and processing capabilities to meet its needs;

- Organize geologic and hydrologic data into a GIS database to provide better access for analysis and management of the Nation's water resources. The GIS will provide computerized mapping, database support, data reduction and analyses for monitoring and inventory of water resources; and
- In the long term, we suggest that the Navajo Nation makes funds available to expand the network of stream gages incrementally, by installing new gages in ungaged and inaccessible parts of streams that are hydrologically, economically and environmentally important to the Navajo Nation.

Section 7. Navajo Nation Hydroclimate Data Workshop

Abstract. On October 9, 2007, the project team convened a workshop for regional hydroclimatic data collection organizations to discuss data collection efforts, opportunities for partnership, data needs, and other concerns. Over 30 participants representing 13 organizations attended the workshop. The workshop facilitated important information exchange and opportunities for representatives of the organizations to meet each other, establish relationships, and develop the foundation for future collaborative efforts. Workshop participants expressed enthusiasm for collaborating with Navajo Nation on regional data and information exchange. In a lively workshop-closing discussion, participants developed recommendations for enhancements to regional data collection efforts, as well as suggestions for directions in which Navajo Nation can organize its efforts to make data more valuable to NNDWR and potential data partners. The most important recommendations from the workshop include the following:

- In order to make the best use of existing data and to best leverage resources for enhancing regional data collection, both Navajo Nation and its regional data partners need to formulate master plans that clearly articulate their collective regional data needs and uses. Participants recommended that the master plans be revised often and that they reflect both short-and long-term goals and needs, based on current and anticipated technologies. The project team strongly endorses this recommendation.
- Lack of automated data collection and electronic data communication are the key barriers to Navajo Nation hydroclimatic data network enhancement and data exchange. Workshop participants recommended that Navajo Nation select a few existing sites for automation, making use of Internet connectivity to facilitate data communication. The aforementioned may require moving existing automated stations to locations with nearby Internet connectivity.
- Workshop participants recommended leveraging resources, such as innovative pilot projects (e.g., Northern Arizona Mesonet), to expand or enhance parts of the regional hydroclimatic observation network.
- Other regional data collection organizations suggested that real-time data are the number one priority for most hydroclimatic data applications, such as for weather forecasting and flood warning. Workshop participants from neighboring Tribes suggested that drought monitoring is an equally high priority.
- Participants suggested that some Navajo Nation sites can be incorporated into the National Weather Service Cooperative Observer Network (NWS COOP). Sites will need to be selected carefully. Navajo Nation will need to invest manpower in order to participate in the NWS COOP data collection efforts. For individual observers to join NWS COOP requires little or no cost; however, adding automated stations to NWS COOP may require upgraded equipment. Data collected by NWS COOP observers

are given the highest degree of data reduction, quality control and assurance, through the National Climatic Data Center.

7.1. Introduction

7.1.1. Project overview and goals.

At the request of the Navajo Nation Department of Water Resources, the project team convened a workshop to assess the feasibility of establishing a collaborative data network, integrating NNDWR and other regional network data. The goals of the workshop were as follows:

- share information about the objectives of the various hydroclimatic data collection networks in the area
- discuss the benefits of an integrated regional network to NNDWR and its potential partners
- assess requirements and needs for integrating data
- develop recommendations for database hardware and software, quality control procedures, and data sharing protocols.

7.1.2. Background and context.

Given the vast size of Navajo Nation, the complex terrain, and the substantial human resources necessary to collect hydroclimatic data, maintain weather and stream gage stations, and perform adequate data quality control, it is essential for Navajo Nation to make the most of its human resources, by partnering with other regional data collection efforts. The first steps in establishing partnerships are identifying other regional data collection efforts, gaining knowledge of the parameters collected and the time periods for which ancillary data are available, and identifying data collection overlaps of mutual benefit to Navajo Nation. Hydroclimatic data, from any source, are essential to Navajo Nation, in order to improve drought and flood monitoring and planning, and agricultural and livestock management.

7.2. Research Methods

The project team cataloged regional data collection efforts. The team invited all potential agencies and organizations to the workshop. A list of workshop attendees can be found in Appendix D; fourteen agencies, including NNDWR, were represented at the workshop. In addition, the project team invited a representative of the Arizona Hydrologic Information System (AHIS) initiative to attend the workshop. AHIS is a collaborative effort between the Arizona Water Institute and Arizona's three state universities to develop comprehensive online access to hydrologic data. The project team also spoke with representatives of the Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI), an organization representing more than a hundred US universities. CUAHSI is in the process of finalizing a hydrologic information system for the nation; they have identified Navajo nation as a potential test site for their system. Although no representatives of CUAHSI attended the workshop, we have included information about the CUAHSI hydrologic information system in this section.

Each organization participating in the workshop gave a brief presentation outlining their data collection efforts, goals and objectives, equipment used, and other pertinent information. Presentations by workshop attendees can be found at the following web site: http://www.u.arizona.edu/~gmgarfin/nnawi.html. A brief summary of workshop presentations, as well as an agenda can be found in Appendix D. The project team concluded the workshop with a discussion to elicit suggestions on key mutual data needs, opportunities for collaboration, and proposals for next steps.

7.3. Results

The most important outcomes of the workshop were: (a) lively discussion of data uses, needs, and partnership opportunities, (b) information exchange, and (c) development of a means to facilitate communication between regional data collection organizations. The key recommendations are included in the table below; they are categorized by the following topics: vision, opportunities, barriers, technical needs.

Table 7.1. Key recommendations from workshop participants.

Vision
Master plan. Participants agreed that a solid master plan will help Navajo Nation and its regional data partners make the best use of existing data to meet organization-specific and common needs. Participants recommended formulating both short-and long-term plans, based on current and anticipated technologies. Participants recommended that the master plan be revised often, to reflect changing needs and technologies. Finally clearly articulating regional needs was cited as the most important aspect in formulating the plan.
Opportunities
Leveraging resources. Participants recommended leveraging resources through multiagency partnerships in order to bring new stations and equipment to the region. Two examples of leveraging that would benefit both Navajo Nation and its potential partners are (a) Utah Department of Transportation can use surface data from an Arizona for transportation safety forecasting -- UDOT would benefit from data sharing and Navajo Nation would benefit from improved forecasts on its Utah lands; (b) Hopi Tribe would benefit from more data for evaluating dryland agriculture and ranching conditions -- Navajo Nation would benefit from data exchange with Hopi Tribe.
Pilot projects. Some participants recommended an opportunistic strategy of using pilot research programs to build or enhance parts of the network. The Northern Arizona Mesonet (NAM) was suggested as an example of such a program. The NAM leverages funding from an education-based grant to provide real-time data used by educators, scientists, and the National Weather Service; these data could be a useful supplement to the existing Navajo Nation network.
Volunteers. Participants recommended augmenting the existing network through volunteer sites ("weather spotters"). They mentioned that user interest in maintaining stations is a key element to success, and that a sense of user ownership is a strong motivator for collecting good data.
National Weather Service Cooperative Observer Network (NWS COOP). Workshop participants suggested that some Navajo Nation sites can be incorporated into the NWS COOP network. Sites will need to be carefully selected. This will require an investment of manpower. Data can be called in to the NWS Flagstaff Weather Forecast Office from manned sites.
Research, Modeling, Monitoring. Some workshop participants recommended developing a heavily-instrumented reference watershed for the Colorado Plateau, sited in Navajo Nation, if desired. Such an effort would be good for research and for developing streamflow, drought, and other environmental predictions. Moreover this kind of effort could help fill in gaps in Navajo Nation monitoring, as well as provided resources for enhancing station automation.
Data access and facilitation. Workshop participants recommended data exchanged through existing efforts, such as MesoWest, AHIS, or CUAHSI.
Barriers
Automation and electronic communication. Participants suggested that network enhancement and data exchange would be hampered by a lack of automated data collection and electronic communication of data. They recommended overcoming this barrier by (a) selecting a few existing sites for automation, and expanding automation efforts incrementally; (b) making use of Internet connectivity to facilitate communications by relocating existing stations or siting new stations near Navajo Nation chapter houses where adequate Internet communications are available. Participants suggested that phone systems in western New Mexico are better than those in Arizona, thus providing an opportunity to improve communication of data on the New Mexico side of Navajo Nation. The Law Enforcement Telecommunications System (LETS) is used by the Oklahoma Mesonet to communicate automated weather station data, free of charge.
Funding. Participants were unable to identify secure funding options. They suggested working to stimulate state legislative action and working with county supervisors to help raise funding for data needed to improve public safety.

Technical Needs
Real-time data. Workshop participants identified real-time data as the number one priority for most hydroclimatic data applications. Data collection at intervals from five-minutes up to one-hour were recommended as most useful for operations. Workshop participants agreed that one-hour data reporting and distribution was the minimum time resolution for real-time data reporting. They noted that flash flood warning requires real-time data. They also noted that real-time data can be aggregated up to daily, weekly, monthly and other values useful for drought monitoring and other applications.
Drought. Some participants, notably those from Hopi Tribe and Zuni Tribe, mentioned drought as a high priority. They mentioned needs for seasonal drought forecasting (for livestock management), as well as calculations of potential evapotranspiration, and groundwater recharge.
Data accuracy. Workshop participants noted several data accuracy issues that can serve as barriers to successful data applications. In particular, they noted that *heated* tipping bucket precipitation gauges are required to get accurate winter precipitation estimates. They noted that real-time data collection often sacrifices accuracy, and that long-term data (such as those required for drought and climate change monitoring) require greater quality control and quality assurance.

7.4.2. Follow-up.

7.4.2.1. Workshop participants requested a list of data collection efforts in the region, including information about the temporal resolution of data collected, and whether the data are freely available on the Internet (see Appendix D). This information updates and complements information included in the Analysis of the Navajo Nation Water Management Branch Suface, Climate, and Ground Water Monitoring Programs (WMI-Memo, 2003). This table is also available from the project website.

7.4.2.2. Workshop participants mentioned that the Salt River Project is another important data contributor in the region. The project team will identify Salt River Project data collection efforts in the region.

7.4.2.3. The Law Enforcement Telecommunications System (LETS) mentioned by workshop participants as a potential avenue for free electronic data communication. Project team members will work with the Arizona Governors' Drought Task Force to investigate the possibility of Navajo nation and its partners using LETS bandwidth to communicate hydroclimate data.

7.4.2.4. Workshop participants recommended initiating an invitation-only email forum to share ideas. In order to facilitate communication between participants, the project team established the Discussion of Hydroclimate Data Projects in the Four Corners listserv (4CWXD-L@LISTS.NAU.EDU).

7.4.2.5. Workshop participants recommended developing a working group, in order to maintain momentum on regional data exchange and enhancement of regional observation networks. Lead investigator Garfin will take on this responsibility; this effort can be incorporated into a new Arizona Water Institute-funded project for Navajo Nation hydroclimate training and streamflow forecast development (Aregai Tecle, Lead investigator).

7.5. Implications and Conclusions

Based on the responses of workshop participants, and comments from invited participants who were unable to attend, there is great enthusiasm for working with Navajo Nation to improve regional hydroclimatic monitoring. The workshop provided an opportunity to jumpstart an effort to improve regional data exchange. The project team recommends that Navajo Nation remained engaged with other regional data collection organizations, including developing formal partnerships. To provide usable data to these entities, Navajo Nation will need to invest in upgrading existing automated data collection sites, replacing rain can sites with automated data collection equipment, and improving data telecommunication. Fortunately, regional data exchange can be facilitated through a number of data exchange portal efforts. The project team strongly recommends that Navajo Nation develop a master plan to articulate its data needs and data uses; as mentioned by workshop participants, both short-and long-term plans are necessary. Through ongoing communication with regional data collection organizations a regional master plan that includes mutually beneficial needs and specific resource leveraging opportunities can be developed.

Section 8. Synthesis, Conclusions, and Recommendations

Synthesis and Conclusions

The recommendations of this report are predicated on the following conclusions, assumptions, and overall philosophy, some of which build on the findings of the Technical Memorandum (WMI-Memo, 2003):

1. Conclusion. Hydroclimate data prior to 2001 are hampered by several factors, including: irregular data collection; many missing streamflow and manual precipitation gauge data; over-written automated weather station data, due to lack of timely data collection; a substantial backlog of data (quality unknown) that have not been digitized. Thus, for practical purposes, these data cannot be used.
2. Conclusion. Data collected subsequent to 2001 have a lower incidence of missing data, but they are still hampered by: missing streamflow and manual precipitation gauge data; the influence of in-channel vegetation and sedimentation on streamflow data; over-written automated weather station data, due to lack of timely data collection; manual precipitation gauge data collection that does not correspond with calendar months. These data can provide some baseline information that augments data collection from other agencies, if aggregated to coarse time scales (seasonal, annual), but records are not of sufficient length for determining average values (“climatology”), trends, or abrupt changes. As far as we know, these data are not used for operations.
3. Conclusion. Due to incompatibility in monthly data collection timing for manual precipitation gauge (“rain can”) data, these data are only usable when aggregated to seasonal or annual time scales. The manual precipitation gauge (rain can) data may be valuable for drought assessment, because (a) drought develops over long (seasonal, annual) time scales, and (b) our analyses demonstrate that these data can add to the spatial robustness of seasonal and annual precipitation estimates. As mentioned earlier, the reliable data record is exceedingly short (less than 10 years). Use of these data requires considerable effort to reconcile time frames, account for missing data, and aggregate spatial data. Thus, the rain can data collection effort provides a low return on investment of time and human resources.
4. Conclusion. The quality of streamflow data is compromised by site factors, such as vegetation encroachment in stream channels, sedimentation in stilling wells, and sediment aggradation in stream channels. Sporadic data collection also compromises the usefulness of the data.
5. Assumption. Navajo Nation Department of Water Resources will not receive budget increases of the magnitude that would allow for large-scale improvements in equipment, or substantial expansion of human resources.

6. Assumption. With rare exceptions, in the rest of the United States, as well as in Navajo Nation, hydroclimate data networks have been established piecemeal. Networks have been developed through the addition of stations and gages from projects and operations with varied goals (e.g., aviation safety, agricultural weather monitoring, flood warning, education, and others), using a variety of instruments, and observation platforms ranging from human cooperative observers to automated instruments to remote sensing instruments. Opportunities to create “ideal” data collection networks that represent some objective reality are rare, and it may be impossible to create such networks in cases where highly varied topography is present. Though trained climate and hydrology specialists can suggest "ideal locations" for data collection, and these locations will have common characteristics – such as open sites that are unimpeded by buildings and man-made surfaces, where there is low potential for vegetation to grow nearby the sensors, and that are located upstream of streamflow diversions – such station locations are likely to require high investment in equipment, maintenance, and manpower, due to the fact that they often require remote and relatively inaccessible sites.
7. Conclusion. Well articulated data uses, through master planning, will best guide station location decisions.
8. Philosophy. In the absence of a master plan, a general strategy for collecting climate and weather data consists of (a) maximizing the spatial extent and uniformity of distribution of data collection sites (within budgetary constraints), and (b) maximizing the potential uses of data at each location. Maximizing the potential data uses can be accomplished by collecting data at the smallest feasible time step, and by communicating data in as close to near-real time as possible. Moreover, in line with the goals of this project, and the recommendations of the Technical Memorandum, we believe that it is better to have fewer, but more reliable and usable data, than to invest resources in collection of data with low utility and low use. We follow this overall philosophy in our recommendations.

Recommendations

1. Develop a master plan for NNDWR data use. Articulate needs for hydrologic, climate, and weather data. Articulate ability (or desired ability) to follow through on implementing data uses. We recommend short- and long-term plans, and revising these plans annually or every two years. Based on comments from the Navajo Nation Hydroclimate Data Workshop, comparing these plans with those of other regional data collectors will help to create a common basis for leveraging data and hydroclimate monitoring to mutual advantage. Master planning is especially important, because *in most cases data continuity and data quality cannot be used to guide selection of existing gages* for future use; thus, needs will drive key selection criteria.

2. Enhancing data communication is probably the most important and substantial improvement that NNDWR can make to its hydroclimate data network. Enhancing communication through automating data collection and adding telecommunications will facilitate several benefits:
    a. Reduced visits to stations. Communicating data in near-real time will mean that the only reasons to visit stations will be maintenance and repair, rather than data collection or manual data download.
    b. Equipment malfunction alert. If data are communicated through electronic media and visualized through graphs, then it will be easy to identify instrument malfunction and data drift (requiring instrument calibration).
    c. Reduced burden of data reduction and quality control tasks. Digital data (not manually digitized data) can be easily communicated to collaborating agencies, such as the National Weather Service. In the Navajo Nation Hydroclimate Data Workshop potential collaborators offered data reduction and (at least) rudimentary quality control, in exchange for data that are communicated to them in a timely fashion.
3. One strategy for determining which stations to automate, is to systematically automate precipitation gauges to ALERT standards, starting with gauges in flashy creeks and washes, and those upstream of population centers. This will provide real-time data, important for a range of public safety applications, including flood forecasting by the NWS Colorado Basin River Forecast Center, floodplain management and planning, streamflow analyses, and precipitation and flood frequency analysis (the latter of which can be done in conjunction with investigators at Arizona's three state universities).
4. Leverage existing data collection networks, in order to reduce resources devoted to manual data collection. The precipitation gauge analysis (Section 2) demonstrated that at least half of the current rain can network can be eliminated, if NNDWR makes use of data from other networks. Many of these overlapping or adjacent networks communicate data in near-real time, or on an hourly-to-daily basis (see Table B.4). The Northern Arizona Mesonet (Section 5) is one effort that can help fill in gaps in NNDWR data collection, as well as reducing the need to collect data at human resource intensive rain can (and mechanical rain can) sites. The Arizona State Climatologist, a member of this research team, has offered to work with NNDWR to examine stations on a case-by-case basis, in order to ensure that the networks can make data easily accessible and to implement methods for aquiring data from existing networks.
    a. Note: Depending on computer skills available through NNDWR staff, this may require investment in human resources.
    b. Remember: there is little risk in abandoning NNDWR rain can and automated weather station data collection efforts, because (a) data

length is short, (b) many data are missing or over-written, (c) in many cases, data quality is relatively poor, (d) the data are not currently used for operations or research. Moreover, currently, several "blended data products" are available to provide near real-time, daily, and long-term archived hydroclimate data. Examples of these include the NOAA National Operational Hydrologic Remote Sensing Center (NOHRSC; http://www.nohrsc.nws.gov/) snow data, and the NOAA Advanced Hydrologic Prediction Service (AHPS; http://water.weather.gov). In the future, more of these blended products will be available, and more of them will be used for operations, planning, and data analysis. We suspect that this will be true for NNDWR as well as for non-Navajo Nation operations. Thus, while it is important for NNDWR to have an improved and manageable network of on the ground observations, we suspect that many NNDWR data needs can be met by using a relatively limited network of on the ground observations ("ground truth") in conjunction with data from adjacent and overlapping on the ground networks, and blended hydroclimate data products.

5. Fill-in gaps in the NNDWR automated weather station network, based on suggestions from the station density analysis (Section 4). The recommended sites take into account station and telecommuncation accessibility, in addition to distance between sites. Decommissioned automated weather stations, or stations that have not yet been deployed, can be used. The dataloggers currently being used by NNDWR are suitable for telecommunications. Alternatively, NNDWR might examine the possibility of deploying inexpensive automatic recording tipping bucket gauges, in cases where precipitation collection trumps the need for more spatially homogeneous (continuous) variables, such as temperature and humidity. For example, the SAHRA project at the University of Arizona has developed inexpensive tipping bucket gages that will store digital data. These are a great improvement over the rain cans, because they require fewer visits; they are also an improvement over the existing recording rain cans, because they do not require manually digitizing charts. The Arizona State Climatologist has identified a number of other relatively inexpensive options.
6. Augment rain can observations by enlisting cooperative observers. Although the Technical Memorandum (WMI-Memo, 2003) notes several problems related to cooperators, we suggest some innovations that may sidestep some of these issues.
    a. Have the cooperators collect data daily. This eliminates the need for antifreeze and oil, and will reduce the confusion associated with making monthly rain can calculations. The observers simply need to measure the amount of precipitation in the collection tube, report the values via phone or Internet to the National Weather Service (toll free), empty the tube and replace it in the rain can. The NWS

phone and Internet data ingestion programs check for obvious quality errors, such as negative precipitation totals.

   b. Make sure that the cooperators' rain cans or weather stations are located near telecommunications. Cooperators at (some) Chapter Houses, schools, and Dine College appear to be ideal candidates.
   c. The burden of data reduction and quality control is shifted to the NWS or other cooperating agency. This avoids the "data double dipping" mentioned in the Technical Memorandum, as well as significant manpower requirements associated with monthly site visits and data reduction.

7. We also expect that local cooperators will experience a sense of interest and ownership in data collection, because the data can be applied directly to impacts experienced by the Navajo Nation chapters, for example, or in science projects at schools.
8. Use freely available online interpolated data products for baseline climatology, drought monitoring, and climate trend analyses. Phenomena such as drought are spatially extensive, and are usually measured by Navajo Nation and others in terms of current data relative to some long-term standard. For example, the Standardized Precipitation Index (SPI), used for Navajo Nation drought monitoring (NNDWR, 2002), requires a long data time series and is calculated in terms of standardized departures from the long-term data distribution. Interpolated data products, such as PRISM (see Section 2) can be used to calculate SPI at high spatial resolution (minumum 4 km [2.5 mi.]), and the data will be valuable for monitoring, because they are expressed *relative* to the long sequence of data – thus, exact values are less important, unless they are specified for determining water allocations and other operational needs.
   a. Remember: NNDWR data series are not sufficiently long or of sufficient quality for use in SPI calculation or many other climate-related uses.
   b. Caveat: In some cases, it may be prudent to use NNDWR data as "ground truth," in order to adjust for biases in interpolated data products (see Section 2, with regard to Chuska Mountain precipitation).
9. For streamflow data collection, shift emphasis from time consuming sheet-recorded chart digitizing to efforts that improve data quality and usability, such as, gage maintenance, regular calibration, and timely and consistent data collection and communication. Our analysis does not recommend removal of any stream gages; however, we identified factors that significantly compromise data integrity and usability. If human resources can be shifted away from time consuming rain can data collection and mechanical rain can chart digitization, then it may be possible to redirect efforts to stream gage maintenance. As with the weather and climate data, usability can be enhanced through digital data that can be communicated in near-real time or daily time steps.

    a. Caveat: This may require investment in equipment or human resources. Table 6.2 shows gages that require enhanced maintenance. Guidance for prioritizing these efforts can be based on gage location, e.g., upstream of population centers or other fragile resources or infrastructure.

10. Communicate data through existing data-sharing networks, such MesoWest (http://www.met.utah.edu/mesowest/), or through networks in the process of being developed, such as AHIS and CUAHSI HIS. By deploying data through common-use networks, NNDWR can gain the benefit of online visualization, which may help to identify instrument malfunction or quality control needs. Moreover, these data sharing sites may provide other benefits to NNDWR, such as metadata management and access to data from regional data collectors.
    a. Note: Northern Arizona Mesonet personnel from Northern Arizona University may be able to provide assistance in setting up data communication with MesoWest and AHIS.
11. More efficient, reliable and adequate data collection, processing, archiving, and dissemination may be accomplished through ongoing and improved training of Navajo Nation Department of Water Resources technicians, and further investment in human resources when possible. Based on our assessment, key training needs include stream gage maintenance and data processing.

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Appendix A.

Navajo Nation Precipitation Gauge Data: Descriptive Statistics

Table A.1. Descriptive statistics for winter and summer NNDWR precipitation. Data are expressed in inches.

Dataset	Season	Count	Min	Max	Mean	StdDev	Median	Skew	Kurt
2001	Winter	88	1.70	15.32	4.66	2.32	4.09	1.84	7.96
2002	Winter	101	0.47	9.25	3.39	1.76	3.04	0.85	3.56
2003	Winter	99	1.75	15.75	5.03	**2.76**	4.55	1.55	5.63
2004	Winter	98	2.10	14.88	5.16	**2.49**	4.80	1.92	7.76
2005	Winter	98	2.18	15.35	**6.25**	**2.83**	5.70	1.10	3.89
2001	Summer	88	1.60	20.43	**6.22**	**2.84**	5.90	1.56	8.52
2002	Summer	101	1.27	9.60	**5.08**	**1.96**	4.97	0.27	2.46
2003	Summer	99	1.24	11.93	**5.13**	2.34	4.90	0.66	3.02
2004	Summer	98	0.90	12.84	**5.73**	2.33	5.51	0.58	2.98
2005	Summer	98	1.97	13.47	5.88	2.40	5.55	0.80	3.14

Table A.2. Descriptive statistics for annual NNDWR precipitation in the eastern, mountain, and western regions of the Navajo Nation, in inches.

Dataset	Area	Count	Min	Max	Mean	StdDev	Median	Skew	Kurt
2001	West	40	4.13	22.32	8.77	3.48	8.02	1.52	6.82
2002	West	35	1.82	10.85	5.61	1.85	5.08	0.63	3.49
2003	West	36	4.29	13.00	7.63	2.54	7.25	0.39	1.93
2004	West	37	1.90	17.23	8.76	3.00	8.45	0.40	3.64
2005	West	36	4.84	17.47	9.71	3.23	8.91	0.59	2.38
2001	Mtn	28	9.50	23.57	**15.05**	**3.73**	14.40	0.70	2.85
2002	Mtn	38	6.23	18.16	**11.35**	2.69	10.97	0.35	2.86
2003	Mtn	35	1.92	26.16	**14.25**	**4.84**	13.60	0.23	3.53
2004	Mtn	35	6.75	24.88	**14.35**	**4.50**	13.97	0.82	3.18
2005	Mtn	37	7.83	26.86	**16.40**	**4.53**	15.70	0.34	2.34
2001	East	25	5.11	15.77	9.29	2.95	8.55	0.53	2.47
2002	East	25	3.79	16.57	8.11	**2.71**	7.95	1.16	5.12
2003	East	25	3.53	12.45	7.68	2.44	7.65	-0.003	2.19
2004	East	25	5.64	13.70	8.72	1.94	8.65	0.46	3.06
2005	East	25	6.07	15.20	9.28	2.23	8.90	0.85	3.41

Appendix B.

B.1 Streamflow Measurement

B.1.1. Methods of Stream Flow Measurement

There are many different ways of estimating the amount and rate of a stream flow. The most common ones involve determining the discharge rate of a stream as a function of depth. In this case, it is necessary to construct a stage-discharge rating curve at a particular cross-section of the stream. The determination of discharge rate at the specific stage in the stream requires dividing the cross-section of the stream into subsections. To ensure a balanced average of flow velocity along the stream cross-section, no sub-section should account for more than ten percent of the total stream flow (Wahl et al., 1995). To measure the velocity of the moving water in each subsection, a current meter is lowered at various depths in the center of the subsection. Two types of commonly used current meters are a propeller meter and an electromagnetic meter. A propeller meter measures the rate of flow by relating it to the rotation of its propeller; an electromagnetic meter measures the voltage produced when water passes through a magnetic field produced by the meter.

The total discharge at a stream cross-section is determined by multiplying the velocity by the stream cross-sectional area. Then the level of the stream at that time can be used to compare the rate of flow at that time with other times. To construct the stage-discharge relationship, the rate of discharge in the stream must be determined at several different stream levels. Such a graphical stage versus discharge relationship is known as a rating curve.

Perhaps the most common method of measuring the stage of a river is through the use of a stilling well. Stilling wells are located on the bank of a stream or on a bridge pier and are topped by a shelter that holds recorders and other instruments associated with the station. The well is connected to the stream by several intake tubes, such that when the water level (stage) changes in the stream, the level simultaneously changes in the well (Figure B.1). The well damps out the momentary fluctuations in the water surface in the stream that are caused by waves and surging action in the river. An outside reference gage, typically a graduated staff, is read periodically to verify that the water level in the well is indeed the same as the water level in the stream and that the intakes are not plugged. As the water level in the well rises or falls, a float in the well also rises or falls. A graduated tape or beaded cable attached to the float and with a counterweight on the other end is hung over a pulley, which drives a recording device. Historically, recording devices have used a pen that records a graph of changes in the river stage; although graphic recorders are still in use, the stage is more commonly recorded in a digital medium or is transmitted by means of satellite telemetry.

Another commonly used method is pressure transducer, which is installed submerged in the flow channel and is usually used for long-term measurement and operation purposes. The instrument is usually connected to a data recorder by a sensor cable, but it may also be battery-operated, without using a cable. The transducer measures hydrostatic pressure (a linear function of depth) at user defined intervals.

Once a rating curve is established, the rate of discharge can be found if the height of the stream is known. To continuously monitor the stream height a float tube and a data logger, or a pressure transducer are usually used. To ensure a functional relationship, the stream height is manually checked periodically using a staff gage. In this way, a detailed description of a stream's water level over several months can be produced.

B.1.2. Purposes of stream measurement

Streamflow measurement provides the hydrologic information needed to characterize stream flow behavior, and to develop appropriate stream management and use prescriptions. In the United States, the federal agency charged with measuring streamflow and collecting other water resources data is the United States Geological Survey (USGS). In addition, there are state, tribal, local and private entities that measure and collect water resources data to meet their specific needs. The USGS is considered to be the standard setter and most important water resources data source. USGS stream flow measurement protocols produce continuous, well-documented, well-archived, unbiased, and broad-based water data and make it available to the public and other users in a reliable and consistent manner.

Adequate and reliable stream flow data are needed to serve the following functions:

- Enhancing public safety by providing data for forecasting and managing floods
- Delineating and managing flood plains
- Operating and designing multipurpose reservoirs
- Designing highway bridges and culverts
- Setting minimum flow requirements to meet aquatic life needs
- Monitoring compliance with minimum flow requirements
- Developing or operating recreation facilities
- Developing water-based power production
- Ensuring adequate water supply for wildlife and livestock needs
- Allocating water for municipal, industrial, and irrigation uses
- Administering inter-tribal or inter-governmental agreements or resolving any water-related conflicts
- Evaluating surface- and ground-water interaction
- Characterizing current water-quality conditions

- Determining input rates of various pollutants into streams and reservoirs
- Computing the loads of sediment and chemical constituents
- Understanding the biological effects of contamination
- Setting permit requirements for discharge of treated wastewater
- Undertaking scientific studies of long-term changes in the hydrologic cycle and water quality standards

Streamflow data are needed for immediate decision making and future planning and project design. Data, such as that needed to issue and update flood forecasts, are referred to as "data for current needs." Other data, such as that needed for the design of a future, but currently unplanned, bridge or reservoir or development of basin-wide pollution control plans, are referred to as "data for future or long-term needs." Some data, of course, fit into both classifications; for example, a station that supplies data for flood forecasting can also be used to define long-term hydrologic trends.

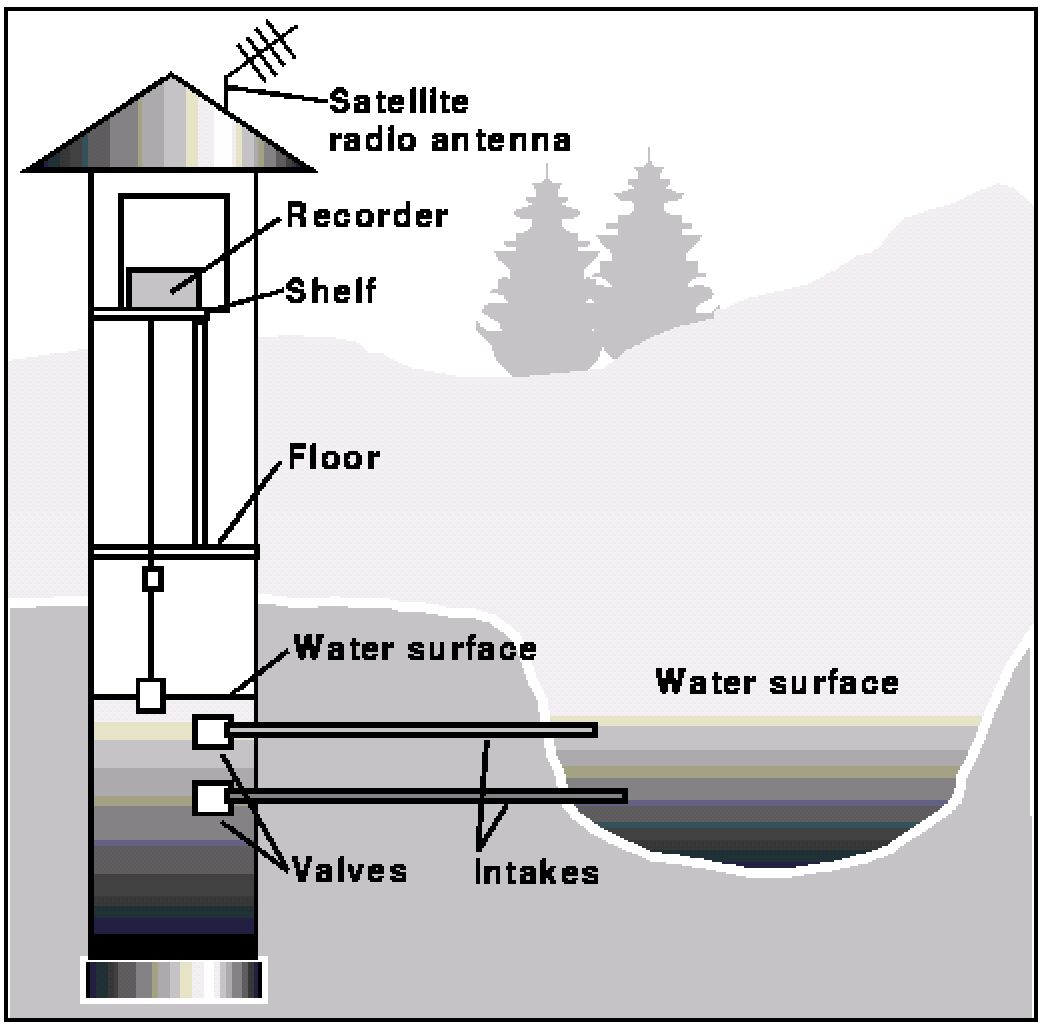

Figure B.1. A schematic representation of a stilling well and shelter at a stream-gaging station (Mason 1995).

Appendix C

Streamflow Measurement on Navajo Nation Lands by Other Agencies

C.1. Non-WMB Stream Gages

The non-WMB gages are those operated by:

- the USGS and Arizona Department of Water Resources (ADWR);
- the USGS and the U.S. Bureau of Reclamation;
- the USGS and the Bureau of Indian Affairs (BIA);
- Peabody Coal,
- Arizona Public Service (APS).

These gages are constructed and operated to serve the needs of the various groups. These non-WMB gages are described in some detail in the following sections.

C.1.1. USGS Surface Water Gaging Stations

The USGS is charged with gaging United States streams and collecting data to serve the various water resources-related needs and problems describe in Section 6. In the Navajo Nation, the USGS partly or wholly operates and maintains 7 of the 13 non-WMB gages in the Nation. The five USGS operated gages in the Navajo Nation consist of a station in the Little Colorado River, another one in the Puerco River and three in the San Juan River (see Figure C.1 [a repeat of Figure 6.1]). The other USGS-operated gages are located outside the Navajo Nation boundary, or in the Hopi Reservation. The data from such gages are transmitted via Geostationary Operational Environmental Satellite (GOES) to a data center where they are processed following standard USGS protocol and then electronically published to make the information available in real time to the user (http//:water.usgs.gov/realtime.html).

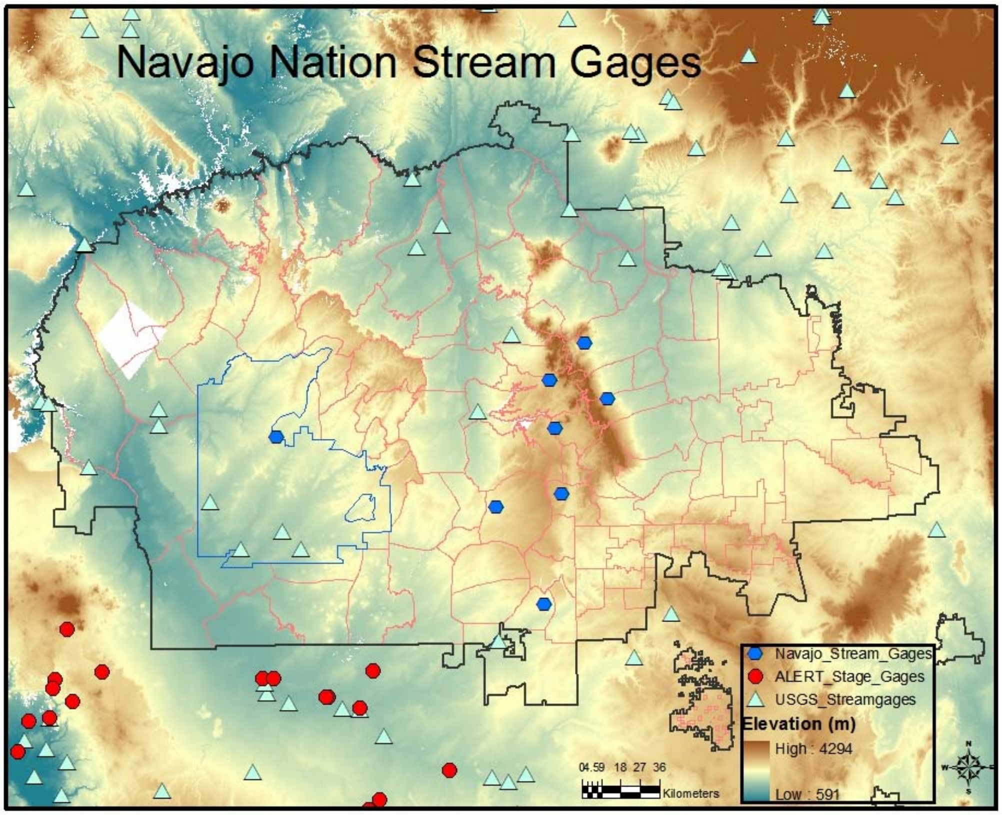

Figure C.1. Streamflow gages managed by the Navajo Nation Water Management Branch and the USGS. Note that the two gages in the western side of the Chuska Mountains denoted by triangles are now operated by the NNDWR.

Once the data are collected following appropriate USGS protocols, processed and formatted, they can be analyzed to show various hydrologic conditions as demonstrated using the data from the Little Colorado River (LCR) near Cameron and the San Juan River (SJR) at Four Corners. In Figures C.2 and C.3, we use the five year running average of data from both the LCR and the SJR, respectively, to show the stream flow trends with years. The LCR shows relatively low flows in the early and late parts of the record, with some wet periods in between, while the SJR exhibits decreasing flows with time Figures C.4 and C.5 show monthly average flow characteristics in the LCR and the SJR, respectively. The hydrograph for the LCR is bimodal, showing two wet (high flow) seasons separated by two lower flow periods, whereas the SJR hydrograph is unimodal, with a clear wet (high flow) season during late spring and summer; the SJR also has much higher flow values.

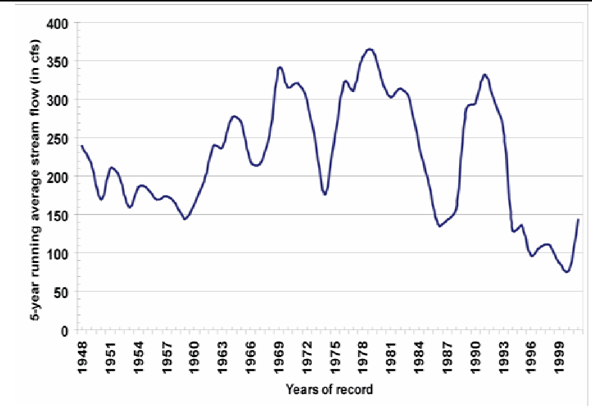

Figure C.2. Five-year running average of Little Colorado River discharge (cfs) near Cameroon, Arizona, 1947-2005. (Data: USGS)

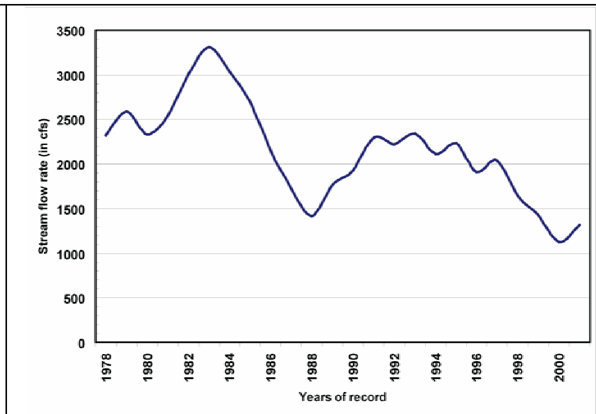

Figure C.3. A five year running average of, streamflow rate (cfs) for the San Juan River at Four Corners. (Data: USGS)

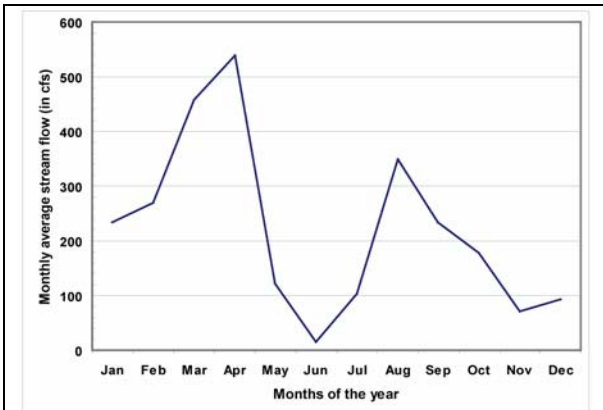

Figure C.4. Monthly average streamflow (cfs) of Little Colorado River near Camero Arizona.

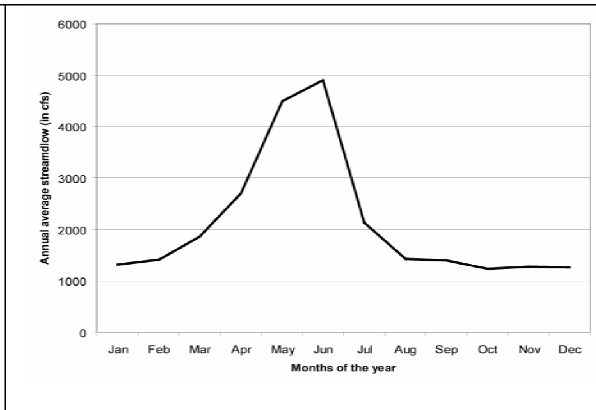

Figure C.5. 1978-2005 monthly average flow rate (cfs) in San Juan River at Four Corners, Arizona.

C.1.2. Navajo Nation Safety of Dams Branch Stream Gages

The NNDWR Safety of Dams (SOD) branch is responsible for evaluating the likelihood of failure of high hazard dams, for providing early warning for floods, and for preventing dam failures. As a result some of the streams in the Navajo Nation are installed, operated and maintained for the dual purpose of general purpose streamflow measurement, and to monitor safety of dams. Examples of such gages are those at Asaayi Creek, Tsaile Creek and Wheatfield Creek. Data from theses gages are transmitted in real time to the SOD office.

C.1.3 Other non-WMB stream gages

As noted in the Technical Memorandum (WMI-Memo, 2003), there are two gages operated by the BIA (Laguna Creek and Ojo Amarillo Stream), four operated by Peabody Coal, one operated by Pittsburg Midway Coal Company (PMCC), and one operated by APS. The Peabody Coal, PMCC and APS gages are operated to monitor changes in water quality and flow patterns related to company activities. Since there are no USGS or WMB gages in those areas, data from those gages can be useful to provide streamflow monitoring data for use by the Navajo Nation. The data from these gages are available in the WMB library.

Appendix D.

Navajo Nation Hydroclimate Data Workshop Documents

Table D.1. Workshop Participants
Table D.2. Agenda
Table D.3. Workshop Presentation Summaries
Table D.4. Regional Hydroclimate Data

Table D.1. Worskshop Participants.

Last Name	First Name	Agency	City, State	Email
Anderson	Diana	Northern Arizona University	Flagstaff, AZ	Diana.Anderson@nau.edu
Bathke	Deborah	NMSU State Climate Center	Las Cruces, NM	djbathke@nmsu.edu
Bekis	Jerome	Navajo Nation DWR	Fort Defiance, AZ	*NO EMAIL ADDRESS AVAILABLE*
Bemis	Kirk	Zuni Tribe	Zuni, NM	kbemis@ashiwi.org
Brady	Irving	Navajo Nation DWR	Fort Defiance, AZ	*NO EMAIL ADDRESS AVAILABLE*
Cochran	John	Peabody Energy	Kayenta, AZ	JCochran@PeabodyEnergy.com
DeSimone	Dino	USDA-NRCS	Phoenix, AZ	Dino.DeSimone@az.usda.gov
Ellis	Andrew	Arizona State University	Tempe, AZ	dellis@asu.edu
Garfin	Gregg	University of Arizona	Tucson, AZ	gmgarfin@email.arizona.edu
Haro	Jesus	National Weather Service	Albuquerque, NM	Jesus.Haro@noaa.gov:
Hart	Robert	USGS	Flagstaff, AZ	bhart@usgs.gov
Harvey	Caroline	Navajo Nation DWR	Fort Defiance, AZ	*NO EMAIL ADDRESS AVAILABLE*
Heinrich	Paul	Northern Arizona University	Flagstaff, AZ	paul.heinrich@nau.edu
Leeper	John	Navajo Nation DWR	Fort Defiance, AZ	johnleeper@navajo.org
Masek-Lopez	Sharon	Hopi Tribe	Flagstaff, AZ	aanu129@yahoo.com
Mason	Jon	Hopi Tribe	Kykotsmovi, AZ	jpmason60@gmail.com
Nutongla	Nat	Hopi Tribe	Kykotsmovi, AZ	nnutongla@hopi.nsn.us
Otte	Dieter	AZ Hydrologic Info System, NAU	Flagstaff, AZ	dieter.otte@nau.edu
Pagano	Tom	USDA-NRCS	Portland, OR	tom.pagano@por.usda.gov
Palucki	Jennifer	National Weather Service	Albuquerque, NM	jennifer.palucki@noaa.gov
Patterson	Ralph	Utah Dept. of Transportation	Salt Lake City, UT	ralphpatterson@utah.gov
Pavinyama	Avery	Hopi Tribe	Kykotsmovi, AZ	APavi@hopi.nsn.us
Peterson	Byron	National Weather Service	Bellemont, AZ	Byron.Peterson@noaa.gov
Spare	Dan	Navajo Agricultural Products Industry	Farmington, NM	dspare@navajopride.com
Staudenmaier	Mike	National Weather Service	Bellemont, AZ	Michael.Staudenmaier@noaa.gov
Suk	Jonathan	National Weather Service	Albuquerque, NM	jonathan.suk@noaa.gov
Taho-Nasafotie	Yolanda	Hopi Tribe	Kykotsmovi, AZ	ytnasafotie@hopi.nsn.us
Tallsalt Robertson	Jolene	Navajo Nation DWR	Fort Defiance, AZ	jolenetrobertson@navajo.org
Taylor, Sr.	Arnold	Hopi Tribe	Kykotsmovi, AZ	ATaylor@hopi.nsn.us
Tecle	Aregai	Northern Arizona University	Flagstaff, AZ	aregai.Tecle@nau.edu
Williams	Jeff	NorthWest Weathernet, Inc.	Salt Lake City, UT	jeff@nw-weathernet.com
Wendt	Gary	Peabody Energy	Kayenta, AZ	Gwendt@peabodyEnergy.com

Table D.2. Navajo Nation Hydroclimatic Data Workshop Agenda
Date: October 9, 2007, 9:30 AM-4:00 PM
Location: Northern Arizona University, ARD Building, Flagstaff, Arizona

Time	**Topic**	**Facilitators/Presenters**
9:30-10:00 AM	***Overview of Workshop***	Gregg Garfin (UA) and Andrew Ellis (ASU)
	Welcome	John Leeper (NNDWR)
	Participant Introductions	Gregg Garfin (UA)
10:00-11:00 AM	***Navajo Nation data collection: findings of the Arizona Water Institute project team***	Gregg Garfin (UA)
	NN Climate Weather Monitoring Overview	Jolene Tallsalt Robertson (NNDWR)
	NN Precipitation Network	Nancy Selover (ASU), Gregg Garfin (UA)
	NN Hydroclimate Network Density	Paul Heinrich (NAU)
	NN Streamflow Gages	Aregai Tecle (NAU)
11:00-11:15 AM	***Break***	
11:15 AM-12:00 PM	***Data collection and infrastructure presentations by participants (brief overviews of data collection efforts in the region)***	Andrew Ellis (ASU)
	Northern Arizona University	Diana Anderson (NAU)
	Hopi Tribe (presentation unavailable online; for more information – http://www.hopitribe.org/data.htm)	Nat Nutongla and Jon Mason (Hopi Department of Water Resources)
	Zuni Tribe	Kirk Bemis (Zuni Water Resources)
	National Weather Service	Byron Peterson and Mike Staudenmaier (NWS Flagstaff)
	USGS	Bob Hart (USGS Flagstaff)
12:00-12:45 PM	***Lunch (provided)***	
12:45-2:00 PM	***Data collection and infrastructure presentations by participants (brief overviews of data collection efforts in the region) -- continued***	Andrew Ellis (ASU)
	USDA-NRCS Snow Courses and SNOTEL	Tom Pagano (USDA-NRCS – Portland, OR)
	New Mexico State University (Farmington Agricultural Station) and Navajo Agricultural Products Industry	Deborah Bathke (NMSU); Dan Spare (NAPI)
	Peabody Energy Company	John Cochran (Peabody Energy)
	Utah Department of Transportation	Ralph Patterson (UDOT)
	Arizona Hydrologic Information System	Dieter Otte (NAU)

Time	Topic	Facilitator
2:00-2:10 PM	***Break***	
2:10-3:45 PM	***Barriers and Opportunities for developing a regional data network, protocols, infrastructure, interagency agreements***	Gregg Garfin (UA) and Andrew Ellis (ASU)
	***Vision**:* • **Benefits.** What kind of data exchanges would be most beneficial to Navajo Nation? To other agencies? • **Needs.** How would these data be used? Which is more important – real time or archived data? Are certain times of year more important than others? What additional stations, instruments, measurements are needed? • **Facilitation.** Which is most desirable – third party data handling (e.g., MesoWest, AHIS, CUAHSI) or direct agency-to-agency exchanges?	
	Opportunities: • What data archives/exchanges already exist? • What data archives/exchanges are in development? • Can your current data be adapted to existing or developing networks? • What funding opportunities exist?	
	Barriers: • Does your agency restrict data sharing? • Does your agency have a policy against making data available to the public? • Does data exchange require formal agreements? • What happens if one party fails to meet expectations?	
	Technical Needs: • Communication (stations to agencies) • Communication (agencies to partners or network) • Data format • Data quality control • Station and instrument maintenance	
3:45-4:00 PM	Wrap-up and action item discussion	Gregg Garfin (UA) and Andrew Ellis (ASU)

Acronyms:

AHIS – Arizona Hydrologic Information System, ASU – Arizona State University, CUAHSI – Consortium of Universities for the Advancement of Hydrological Science, MesoWest – University of Utah Weather Data and Information, NAPI – Navajo Agricultural Products Industry, NAU – Northern Arizona University, NMSU – New Mexico State University, NNDWR – Navajo Nation Department of Water Resources, NWS – National Weather Service, SNOTEL – Snowpack Telemetry, UA – University of Arizona, UDOT – Utah Department of Transportation, USDA-NRCS – United States Department of Agriculture-Natural Resources Conservation Service, USGS – United States Geological Survey

Table D.3. Agency Presentation Summary

This section contains brief summaries of the presentations given at the October 9, 2007 Navajo Nation Hydroclimate Data Workshop. For details on equipment, station distribution, and graphics, the presentations can be accessed from http://www.u.arizona.edu/~gmgarfin/nnawi.html.

Northern Arizona Mesonet
Presenters: Diana Anderson (Northern Arizona University, Center for Environmental Sciences and Education) and Mike Staudenmaier (National Weather Service, Flagstaff) (See Section 5 for details on the Northern Arizona Mesonet.)

Stations and data
1. Weather stations: 8 sites within Navajo Nation and Hopi Tribe lands
- Real-time weather data collection
- Wireless data transmission
- Data collected at schools
- Integrated into the MesoWest website (http://www.met.utah.edu/mesowest/)
    - o “If you can get the data to us, we can get it to the world.” Mike Staudenmaier

Uses
- Education
- National Weather Service monitoring, forecast verification, public safety

Website – http://www.cens.nau.edu/~nauws/nam.html

Hopi Tribe
Presenters: Nat Nutongla & Jon Mason (Hopi Department of Natural Resources – Water Resources Program)

Stations and data
1. Weather stations: 11 sites
- Data collected: soil temperature, soil moisture, solar radiation, wind speed/gust/direction, temperature, precipitation, humidity, leaf wetness

2. USGS collaboratively maintained stream gages: 4 sites
- Baseflow discharge
- Linked to USGS NWIS website: http://waterdata.usgs.gov/nwis
- Telemetered

1 manual streamgage

Uses
- Environmental monitoring
- Public safety
    - o Flood and drought monitoring
- Dryland agriculture and ranching

Website – www.hopitribe.org/data.htm

USDA-Natural Resources Conservation Service (NRCS)
Presenter: Tom Pagano (National Water and Climate Center, Portland, OR)

Data and Stations
1. Manual snow surveys

- Collection: large tube into snow pack, measure weight of tube when you pull it out; Primary method from 1910-1985
- Typical collection resolution: 2 times per month (1st and 15th), January to April, 1986-present

2. Automated SNOTEL

- Telemetered
- Snow water equivalent; snow depth; temperature; soil temperature; precipitation; solar radiation

Uses
- Water supply forecasting

Website – http://www.wcc.nrcs.usda.gov/snow/

New Mexico State University (NMSU)
Presenter: Deborah Bathke (New Mexico Climate Center, Las Cruces, New Mexico).
Comments: Dan Spare (Navajo Agricultural Products Industry).

Stations and data
1. Automated weather station data

  - Farmington Agricultural Science Center and Navajo Agricultural Products Industry stations
  - Hourly and daily time resolution
  - downloaded once per day
    - Wind Speed & Direction
    - Solar Radiation
    - Temperature
    - Relative Humidity
    - Soil Temperature
  - data quality described as questionable
  - currently lacking metadata regarding non-climatic influences on stations
  - Output format
      - maximum, minimum, and mean values for each day for all variables collected
      - interpolated values are used as the default for all missing variables
  - Changes to data management, processing, and data access are planned

Website – http://weather.nmsu.edu/

Zuni Tribe
Presenter: Kirk Bemis (Zuni Water Resources)

Stations and data
1. Hydroclimatic Monitoring
   - NWS Cooperative Climate Network
     - Zuni station cooperator is Zuni Tribal member
   - USGS Cooperative Streamflow Program
     - 2 New Mexico gages cost-shared by Zuni Tribe
     - 3 Arizona gages cost-shared by Zuni Tribe
   - NRCS Snow Survey Program
     - 3 courses surveyed by BIA Zuni Agency with assistance from Zuni Tribe
2. Safety of Dams Early Warning System
   - Tribal management for BIA via 93-638 contract since 1997
   - 1 system for Black Rock, Trapped Rock, and Pescado Dams
   - 16 remote stations linked by 2-way radio to 3 base stations
   - 10 rain tipping buckets sites, 4 reservoir level sites, 7 stream level sites, 1 weather station (rain, air temperature & relative humidity, wind speed & direction, and barometric pressure)
   - Data are shared with National Weather Service
3. Air Quality Monitoring
   - Managed by Zuni Environmental Protection Program
   - Located in Zuni village at Natural Resources offices
   - Established in November 2006 in collaboration with New Mexico Environment Department (NMED)
   - Pollutant monitoring
     - o SO2, CO, NOx, NO2, Ozone, PM2.5, PM10 and mercury
   - Meteorological monitoring
     - o Air temperature and relative humidity, wind speed and direction, solar radiation, and nephelometer
   - Data shared with NMED via remote internet access

Uses
- Drought monitoring, public safety (flood), air quality

Website – http://www.ashiwi.org

National Weather Service
Presenters: Byron Peterson and Mike Staudenmaier (Flagstaff Weather Forecast Office). *Comments:* Jesus Haro, Jennifer Palucki, Jonathan Suk (Albuquerque Weather Forecast Office)

Stations and data
Overview: Climatological, Hydrological and Real Time Observations
- Temperature, precipitation, wind speed and direction

1. Cooperative Observation Network (COOP)
    - Comprised of unpaid volunteers
    - 7 on Navajo Lands
    - 11 in close proximity to Navajo Lands
2. ASOS – Automated Surface Observing System
    - Primarily for real time aviation observations
    - Window Rock
    - Near Navajo Lands
        - Page
        - Flagstaff
        - Winslow
        - St. Johns
3. COOP/ASOS/Meso Network
    - This network incorporates local mesonet sites (home based weather stations)
    - These data are very valuable to 'fill in gaps'.
    - Data is usually not as reliable nor calibrated as past observations listed.
    - Additional daily data is received routinely once/twice a day through the COOP network:
        - Navajo N.M.
        - Tuba City
        - Canyon de Chelly
        - Petrified Forest
        - Wupatki N.M.
        - Sunset Crater

Uses
- Weather forecasting
- Public safety: flood warning, severe storm warning
- Aviation safety
- Drought monitoring

Websites –
Flagstaff – http://www.wrh.noaa.gov/fgz/
Albuquerque – http://www.wrh.noaa.gov/abq/

U.S. Geological Survey
Presenter: Bob Hart (Arizona Water Science Center, Flagstaff, Arizona)
Stations and data
1. Streamflow, climate data, groundwater
    - 180 telemetered stations in Arizona
    - Data recorded in 15 minute intervals
    - Transmitted every 4 hours
    - ALERT data can be sent in real time
    - Accessible through NWIS – National Water Information System
        - o Website – http://waterdata.usgs.gov/nwis
    - Partners with AZ Drought Monitoring Technical Committee (Chris Smith)

Uses

- Public safety: flood warning, water quality
- Drought monitoring
- Water use assessment

Website – http://waterdata.usgs.gov/nwis

Arizona Hydrologic Information System (AHIS)
Presenters: Dieter Otte (Northern Arizona University, Computer Science Department; Corinna Gries, Arizona State University)

Stations and data

1. Portal for making hydroclimatic data available
    - Agencies can input metadata, including images
    - Search interface allows user to find and display data
        - e.g., by hydrologic basin, political jurisdiction, etc.
        - geographic and key word searches
    - Web portal proposed for 2007-08 AWI proposed funding

Uses

- Potential outlet for data from workshop participating agencies, including NNDWR

Website – http://www.azwaterinstitute.org/ahis/

Peabody Energy - Mining
Presenters: John Cochran, Gary Wendt

Overview

- Peabody Western Coal Company (PWCC) Black Mesa Complex – operated since early 1970s
- Located in Northeastern Arizona on both the Navajo Nation and Hopi Tribal lands
- PWCC's Meteorological Program began in the Spring of 1980

Uses

- Primarily in support of a comprehensive Air Quality Monitoring Program
- Rainfall data required under PWCC's National Pollutant Discharge Elimination System (NPDES) permit, and under the Surface Mining Control and Reclamation Act of 1977 (SMCRA) mining permit for the Kayenta Mine

Stations and data

1. Meteorological data is collected at 9 locations:
    - one 40 m tower
    - three 10 m towers
    - eight tipping bucket gauges
    - Data attributes
        - Digital data is stored as 1-hr and 24-hr averages in each CSI data logger

        - Data is downloaded from the data loggers to CSI data storage modules, then transferred to PWCC personal computers and into relational databases
        - Wind Speed – 1-hr scalar mean values averaged from a continuously sampled signal, mph converted to knots
        - Wind Direction – Unit vector processing used to compile hourly averages
        - Sigma Theta – 1-hr values are calculated using four 15-minute values
            - Based on EPA's February 2000 "Meteorological Monitoring Guidance for Regulatory Modeling Applications"
        - Temperature, Barometric Pressure, and Solar Radiation – 1-hr values are compiled using the continuously sampled signals from each sensor
        - Precipitation – Hourly totals are calculated using the raw data set collected
    - Quality Control
        - Quality Assurance audits of meteorological sensors are performed semi-annually by an independent contractor to assess accuracy of the measurements
        - Complete system checks are performed for each monitored parameter including sensors and associated outputs

Website – http://www.peabodyenergy.com/Operations/CoalOperations-Southwest.asp

Utah Department of Transportation
Presenter: Ralph Patterson (Salt Lake City, Utah)

Stations and data
1. Road Weather Information Systems (RWIS) – 55 stations statewide
    - Atmospheric sensors
        - Anemometer
        - Precipitation Gauge
        - Relative Humidity
        - Temperature
        - Visibility
    - Surface sensors
        - Road status (wet or dry)
        - Road temperature
        - Eutectic point
    - Non invasive sensors
        - Cameras
    - Surface Pucks
        - Road Temp
        - Subsurface Temp
        - Wet vs. Dry
        - Eutectic Point (freeze point depression)
    - Non invasive sensors
        - Coefficient of friction

- Maintenance is a substantial expense

Uses

- Reduced material/chemical usage
- Near-real time condition reporting for operations and traveler information
- Activation of other expert systems
  - Bridge spray systems
  - High wind warning systems
- Support Traffic Onsite Consulting Meteorologists forecasting efforts

Partnerships

- NorthWest Weathernet
- National Weather Service
- USDA Avalanche Forecast Center
- River Forecast Center
- Dept of Energy
- Tooele County EOC
- Aurora Group
- University of Utah
- Utah State University
- Montana State University
- SLC International Airport
- FHWA
- ITS/AMS
- Private Sector Companies

Website – http://www.udot.utah.gov/

Table D.4. Regional Hydroclimate Data Synopsis

Data Provider	Data Type	URL (grey if no Internet access to data)	Notes
Arizona Dept. of Transportation (Rural Weather Information System)	Real-time weather and roadway conditions	http://www.az511.com/hcrsweb/hcrsweb.jsp	Variables: temperature, precipitation, rainfall rate, wind speed and direction, wind gust, barometric pressure, RH, dewpoint, roadway camera shots
Arizona Flood Warning and Drought Monitoring Webpage	Real-time weather and streamflow observations	http://data.afws.org/sui/frontPage.aspx AND data.afws.org/sui/Map.aspx	USGS, ALERT, NWS; Variables: precipitation, streamflow, stage; Time scales: real-time to daily
Arizona Hydrologic Information System (AHIS)	Hydrologic and drought data (expected)	http://www.azwaterinstitute.org/ahis/	In progress; Expected completion: Fall 2008. Should include integration with Arizona Flood Warning and Drought Monitoring, CUAHSI, and SAHRA's Arizona Wells data.
Arizona Office of the State Climatologist	Weather real-time	http://www.public.asu.edu/~aunjs/index.html	Links to MesoWest, NWS, Western Regional Climate Center -- weather and climate data; other useful information
BHP Billiton		http://www.bhpbilliton.com/bb/sustainableDevelopment/environmentalCommitment/climateChange.jsp	No data online
Bureau of Land Management (MesoWest ROMAN)	Real-time weather data from Remote Automated Weather Stations (RAWS)	http://raws.wrh.noaa.gov/roman/ AND http://www.met.utah.edu/mesowest/	Variables: temperature, precipitation, rainfall rate, wind speed and direction, wind gust, solar radiation, RH, dewpoint;Time scales: hourly; Graphs: hourly to monthly; can download spreadsheet data
Bureau of Land Management (Western Regional Climate Center)	Archived weather data from Remote Automated Weather Stations (RAWS)	http://www.raws.dri.edu/index.html	Variables: temperature, precipitation, rainfall rate, wind speed and direction, wind gust, solar radiation, RH, dewpoint;Time scales: hourly; Graphs: hourly, daily, monthly;

Data Provider	Data Type	URL (grey if no Internet access to data)	Notes
Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI)	Hydrologic Information System (functional, but under development)	http://www.cuahsi.org/index.html	EPA, NWIS, SNOTEL data; Variables include stream discharge, water quality, snow, others
Hopi Tribe	Archived weather observations	http://www.hopitribe.org/data.htm	Variables: soil temp. air temp., leaf wetness, % humidity, rainfall, soil moisture, solar radiation, wind gust, wind speed, wind direction; Time scales: hourly, daily; Spreadsheet download available
MesoWest	Real-time weather data; click on state; download up to 30 days of data from any station with account (downloading 24 hours of data remains available without an account)	http://www.met.utah.edu/mesowest/	Data from various networks: BLM, NWS, USDA-NRCS, UDOT, USGS, others. Variables: temperature, precipitation, rainfall rate, wind speed and direction, wind gust, solar radiation, RH, dewpoint;Time scales: hourly; Graphs and map display: hourly to monthly; can download spreadsheet data
NAPI - Navajo Pride	Weather real-time	http://www.navajopride.com/index.php -- Some data served through the New Mexico Climate Center	No data online
National Park Service (Western Regional Climate Center -- Climate Inventory Project)	Archived climate data by state; links to various sources	http://www.wrcc.dri.edu/nps/	Variables: temperature, precipitation, snow, derived variables (heating/cooling degrees, others)
National Weather Service	NOWData	http://www.weather.gov/climate/xmacis.php?wfo=fgz	Various daily and monthly summaries for all NWS stations, including records and extremes for current and previous month

Data Provider	Data Type	URL (grey if no Internet access to data)	Notes
National Weather Service, Albuquerque	Weather real-time	http://www.weather.gov/climate/index.php?wfo=abq	Variables: temperature, precipitation, wind speed and direction, wind gust, SLP, RH, cloudiness, snow;Time scales: daily, monthly; Various data displays
National Weather Service, Flagstaff	Weather real-time	http://www.weather.gov/climate/index.php?wfo=fgz	Variables: temperature, precipitation, wind speed and direction, wind gust, SLP, RH, cloudiness, snow;Time scales: daily, monthly; Various data displays
Navajo Nation Safety of Dams	Weather and streamflow real-time	Limited information served through Navajo Nation Water Management Branch web site	No website
Navajo Nation Water Management Branch	Maps with precipitation reports	http://www.frontiernet.net/~nndwr_wmb/water_monitoring__inventory.htm	precipitation rain cans only
New Mexico Climate Center	Weather real-time	http://weather.nmsu.edu/data/data.htm	Variables: precipitation, temperature, soil temperature, solar radiaton, humidity, wind; Time scales: hourly to daily
New Mexico Department of Transportation	Weather real-time	http://flex.nmroads.com/	Maps with weather summaries and road conditions
Northern Arizona MesoNet	Weather real-time	http://www.cens.nau.edu/~nauws/nam.html	Variables: temperature, precipitation, rainfall rate, wind speed and direction, wind gust, wind chill, heat index, SLP, RH; Weather data display; access to monthly, and 2-minute data (current and previous day)

Data Provider	Data Type	URL (grey if no Internet access to data)	Notes
NorthWest Weathernet, Inc.	Radar-generated weather maps	http://www.nw-weathernet.com/links.html	Locations include: NM -- Farmington; AZ -- Flagstaff, St. Johns, Page; UT -- Logan, Dugway, Milford, Price
Office of Surface Mining R & E		http://www.osmre.gov/	Mostly reports and information
Peabody Energy			Data kept on-site, no web access
SAHRA -- Arizona Wells (groundwater database)	Groundwater well database; Arizona Department of Water Resources data	http://www.sahra.arizona.edu/wells/	Variables: depth to groundwater; Time scales: monthly to annual; Extensive metadata
Salt River Project	Reservoir levels for Salt and Verde River watersheds	http://www.srpnet.com/water/dams/default.aspx AND http://www.usbr.gov/dataweb/html/saltriver.html	SRP and US Bureau of Reclamation Data and metadata
USDA-NRCS	reservoir levels, snow, water supply forecasts, streamflow forecasts	http://www.wcc.nrcs.usda.gov/	Daily, Monthly (some hourly)
USDA-NRCS	daily streamflow forecasts	http://www.wcc.nrcs.usda.gov/wsf/daily_forecasts.html	Streamflow discharge forecasts, skill assessment; Spreadsheet download available

Data Provider	**Data Type**	**URL (grey if no Internet access to data)**	**Notes**
USDA-NRCS SNOTEL	Daily snow, temperature, precipitation reports (some hourly data available); Extensive data archive	http://www.wcc.nrcs.usda.gov/snow/	Variables: snow water equivalent, temperature, precipitation; Time scales: hourly to daily
USDA-NRCS Soil Climate Analysis Network (SCAN)	daily soil moisture; others	http://www.wcc.nrcs.usda.gov/scan/Utah/utah.html	Hourly and daily data for current and previous month
USGS	Drought information	http://az.water.usgs.gov/droughtmaps/droughtmaps.htm	Maps for Arizona only
USGS	Real-time water data	http://waterdata.usgs.gov/nwis	Variables: precipitation, streamflow discharge, gage height; Time scales: hourly to annual; Spreadsheet download available
USGS - Arizona	Real-time Data for Arizona Streamflow	http://waterdata.usgs.gov/az/nwis/current/?type=flow	Variables: precipitation, gage height, discharge; time scales: daily, monthly, annual statistics; metadata on field measurements and sampling
USGS - New Mexico	Real-time Data for New Mexico Streamflow	http://waterdata.usgs.gov/nm/nwis/current/?type=flow	Variables: precipitation, gage height, discharge; time scales: daily, monthly, annual statistics; metadata on field measurements and sampling
USGS - Utah	Real-time Data for Utah Streamflow	http://waterdata.usgs.gov/ut/nwis/current/?type=flow	Variables: precipitation, gage height, discharge; time scales: daily, monthly, annual statistics; metadata on field measurements and sampling
Utah Department of Transportation	Real-time weather data and road condition monitoring	http://commuterlink.utah.gov/ie.htm	Text summaries of weather conditions. Some data served through MesoWest.

Data Provider	Data Type	URL (grey if no Internet access to data)	Notes
Western Regional Climate Center	Climate data archive	http://www.wrcc.dri.edu/ AND http://www.wrcc.dri.edu/Climsum.html (station data) AND http://www.cefa.dri.edu/Westmap/ (WESTMAP monthly to annual data back to 1895, by state, climate division, county)	NWS, RAWS, SNOTEL; Variables: precipitation, snow, temperature, wind; Time scales: hourly to annual; Station metadata; Various products: WESTMAP climate data; ACIS weather and climate maps
Zuni Tribe		http://www.ashiwi.org/	Homepage for the Zuni Tribe