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Disaster Risk Assessment Case Study: Recent drought on the Navajo Nation, southwestern United States

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ABSTRACT

The Navajo Nation is an ecologically sensitive semi-arid to arid section of the southern Colorado Plateau. In this remote part of the United States, located at the Four Corners (Arizona, New Mexico, Colorado, and Utah), traditional people live a subsistence lifestyle that is inextricably tied to, and dependent upon, landscape conditions and water supplies. Soft bedrock lithologies and sand dunes dominate the region, making it highly sensitive to fluctuations in precipitation intensity, percent vegetation cover, and local land use practices. However, this region has sparse and discontinuous meteorological monitoring records. As a complement to the scant long-term meteorological records and historical documentation, we conducted interviews with 50 Native American elders from the Navajo Nation and compiled their lifetime observations on the changes in water availability, weather, and sand or dust storms. We then used these observations to further refine our understanding of the historical trends and impacts of climate change and drought for the region. In addition to altered landscape conditions due to climatic change, drought, and varying land use practices over the last 130 years, the Navajo people have been affected by federal policies and harsh economic conditions which weaken their cultural fabric. We conclude that a long-term drying trend and decreasing snowpack, superimposed on regional drought cycles, will magnify drought impacts on the Navajo Nation and leave its people increasingly vulnerable.

Introduction

The Navajo Nation of northeastern Arizona, northwestern New Mexico, and southeastern Utah in the Four Corners region of the United States, is an ecologically sensitive semi-arid to arid area where rapid growth of the largest population of Native Americans is outstripping the capacity of the land to sustain them. Recent drought conditions, combined with increasing temperatures, are significantly altering the habitability of a region already characterized by harsh living conditions. Today, the Navajo land base is more than 65,700 km^2 (25,350 mi^2), slightly larger than the state of West Virginia (Figure 1). It is the largest reservation in the

United States, constituting 36% of all reservation lands. Navajo land completely encircles the lands of the Hopi and San Juan Paiute, and is adjacent to lands of the Jicarilla Apache, Ute Mountain and Zuni tribes. In this remote region, traditional people live a subsistence lifestyle that is inextricably tied to, and dependent upon, landscape conditions and water supplies. People presently living on these Native lands are unique in American society as their traditional lifestyle requires intimate knowledge of the ecosystem, knowledge that has been passed on for generations through oral traditions.

The Navajo Nation is home to a burgeoning population, with a median age of 18.8 years. In 1997 the per capita income was $5,599 (U.S. Dollars) with sixty percent of the population living in poverty. Variable employment figures indicate an overall unemployment rate of about 50% (Navajo Nation Economic Profile, Navajo Nation Council). Roughly 5% of the population has attended some classes at the university level. Elderly Navajo people are usually not fluent in English, and are likely to have never attended school, in part because schools across the reservation were closed during WWII (Bailey and Bailey, 1986). Many residents, especially the elderly, have relied on raising livestock as a significant part of their livelihood or as a supplement to food supplies (Iverson, 2002). Over half of the reservation population lives in housing without indoor plumbing or electricity (Choudary, 2003). Homes without plumbing are dependent on hauling water from nearby sources, and often use unregulated water supplies intended for livestock rather than domestic use (Redsteer, unpubl. data). Many of the water supplies on the Navajo Nation are derived from shallow alluvial aquifers that are sensitive to fluctuations in precipitation during drought, and prone to local system contamination (Breit and Redsteer, 2001). During the dry season the water is often salty. Livestock congregating at water points leave the large amounts of animal waste that flushes into shallow water sources during the rainy season, leading to nitrate contamination after the onset of the monsoon (Breit, Redsteer, and Pandamouz, unpubl. data).

Regional Characteristics

The Navajo Nation is divided by the Lukachukai Mountains on the New Mexico-Arizona border with two-thirds of the Nation located to the west, and one-third to the east. In the approximate center of the Navajo Nation, at 2,000-2,200 m elevation is the upland region of Black Mesa (Figure 1). The Lukachukai Mountains, 3,000 m high at the crest, receive the greatest proportion of the regions snowfall and rainfall, followed by Black Mesa. Annual precipitation totals in the more arid lowlands of the Navajo Nation average from 100 - 150 mm, in contrast to wetter upland regions of Black Mesa and the Lukachukai Mountains that average from 250-300 mm. Lowlands on the western half of the Navajo Nation at 1200-1500 m in elevation are the hottest and driest, the eastern Navajo Nation that lies below the Lukachukai Mountains in New Mexico is the second driest. There are also large seasonal and diurnal variations in temperature, with average annual temperatures from 11.0^{o} C in areas of higher altitude, to 14.5^{o} C in the valleys and lowlands.

The boundary of the modern Navajo reservation, set aside after the war between the United States and the Navajo ended, was established over time, beginning with the Navajo Treaty of 1868. The reservation established by the 1868 treaty occupies a relatively small area in the middle of the traditional Navajo homeland (Correll and Dehiya 1978). It includes some of the wettest parts of the present reservation (Lukachukai and Chuska Mountains) as well as some of the driest (southeast of Monument Valley). In the late 1800's, fierce competition among Anglo and Hispanic populations for the best rangelands beyond this early reservation boundary precluded the retention of the more verdant traditional lands for Navajo use (Bailey and Bailey, 1986). The federal government was most successful in expanding the reservation into the drier country west and southwest of the treaty reservation in Arizona, where non-Indian ranchers did not oppose the extensions as strenuously as they did in the wetter country to the east in New Mexico. The major extensions were in place by 1934, with one exception: land in Arizona along the boundary with New Mexico south of the 1934 reservation boundary. This land was added in 1980 (the so-called "New Lands") to accommodate Navajos displaced from lands to the northwest partitioned to the Hopi Tribe. The 1980 extension is wetter than most of the Navajo land farther west, and in the 1930s, ranchers successfully opposed extension of the Reservation to include this area, even forcing its Navajo occupants to relocate (Kelley and Francis, 2001b, c; White, 1983; Parman, 1976). As a result, the reservation consists of the driest one-third of the traditional homeland of the Navajo people, defined by the Four Sacred Mountains that encompass the perimeter of Navajo land. Overall, the average annual precipitation on the Navajo Nation is one-third that of the Sacred Mountain regions of the traditional Navajo homeland, and the average annual temperature is 7^{o} C warmer.

The boundary extensions between 1868 and 1934 were to accommodate the Navajo population already living in these areas, so that they could raise livestock to the fullest extent. The federal government before the 1920s encouraged both livestock raising and farming to maximize Navajo self-sufficiency, even to the extent of restricting general-merchandise traders from buying livestock (White 1983). Before 1868, Navajo families raised sheep, goats, and horses (as well as some cattle) mixed with farming, hunting, and gathering, mainly for the family's direct consumption rather than for trade. This subsistence mix had required families to range widely over the vast area amid the sacred mountains (Kelley and Francis 2004). After

1868, as non-Indian settlers cut them off from the wettest areas best for hunting, gathering, and summer grazing, Navajo families were forced to depend more heavily on farming and especially stock-raising in the drier center of their homeland, and to trade wool and other livestock products for mass-produced foods and other goods. By the early 20th century, government and other observers were warning about erosion and overgrazing on Navajo ranges (Kelley and Whiteley, 1989; White, 1983).

By 1930, federal government studies predicted that massive erosion from Navajo land and western mountain ranges would silt up Boulder (Hoover) Dam, then under construction to provide electric power for Los Angeles. Therefore, in the 1930s the government began to regulate grazing on lands within its jurisdiction, including the Navajo Reservation, where the goal was to reduce the number of livestock by half and get more Navajos into wage jobs and to build water, erosion-control, and irrigation facilities. The government required each Navajo family to have a permit to raise livestock, not to exceed a certain number, and to sell all their stock in excess of that number. Accordingly, the government also divided the reservation into about 20 land-management (grazing) districts, where the grazing permits required each family to stay all year within a particular district (Kelley and Whiteley, 1989; White, 1983; Young,1961). These grazing regulations remain in force to this day. Before these regulations, families in normal years had moved their livestock around core customary grazing areas shared by networks of interrelated extended families, while during droughts they used other kinship ties to gain access to more distant places where conditions were better. This land-use regime had helped families distribute their livestock over the range as conditions warranted (Kelley and Francis, 2004; Fanale, 1982). Encroachment by non-Indian ranchers into the best parts of the traditional Navajo homeland had increasingly constrained this traditional range-conservation pattern. The federal government's grazing permit system was even more restrictive, and especially hard on extended families that were split by district lines (Iverson, 2002; Kelley and Whiteley, 1989; White, 1983).

The stock reduction program, in combination with subsequent federal programs, such as education and infrastructure development, as well as policies resulting from World War II restrictions, have resulted in the present Navajo family subsistence pattern, whereby wages and various forms of assistance (social security, etc.) provide most income (Choudhary, c2003). Stock-raising nevertheless remains important to family subsistence. Livestock, especially cattle, are a major form of savings for the many Navajo families whose money incomes are stretched to the limit. Livestock also is necessary, according to both custom and Navajo Nation law, to validate a family's use and occupancy rights on land that it has occupied for many generations. Finally, sheep, especially, are essential to traditional Navajo ceremonies. Though livestock numbers have stayed well below pre-stock-reduction levels, they have consistently exceeded carrying capacities that the government established in the 1930s for most grazing districts (Young, 1961). Recent loss of livestock from lack of water and forage, as well as feral horse round-ups and auctions since the beginning of drought in 1996 have also reduced current livestock numbers. Erosion continues to be a problem, though range managers now recognize that climate, landscape conditions and other hydrological processes cause regional soil erosion even without overgrazing (Redsteer et al, 2010; Redsteer and Block, 2004; White, 1983).

In interviews with elderly Navajos, anguish was often expressed over the cultural erosion resulting from the shift away from traditional stock-raising. The results include replacement of kin-based, reciprocal range-sharing by grazing disputes among individuals who claim that their permits grant exclusive use or property rights. Another result is the shift away from traditional Navajo cosmological knowledge and practices, since people who no longer depend on livestock are insensitive to the needs of the land and the deities to whom their elders and forebears have offered prayers for rain, vegetation, and other blessings (Kelley and Francis 2001a; Fanale, 1982).

Drought Characteristics

Navajo lands are characterized by a bimodal precipitation pattern. Winter precipitation typically occurs from December through March, and summer precipitation resulting from the North American monsoon, lasts from July through September. Approximately 45% of total annual precipitation occurs during the monsoon season (calculated from all available sources of precipitation records on and adjacent to the Navajo Nation). These two wet seasons are separated by a dry, windy season in the spring.

Documentation of drought within the region is difficult because it is topographically and climatically variable, and large portions of the region are poorly monitored. The density of operating National Weather Service (NWS) COOP monitoring stations on the Navajo Nation is roughly one station for every 6400 km^2. A majority of these stations only record precipitation. The US Geological Survey Navajo Land Use Planning Project has supplemented the meteorological monitoring network with four additional sites in the arid southwestern Navajo Nation, in order to examine the relations of drought to sand dune movement and rangeland health. However, because it affected the entire region, drought conditions during the past ten years were apparent even without a denser set of observations.

Currently, the Navajo Nation is hoping to recover from drought in the Four Corners Region that lasted officially from 1999-2009. (The year 2010 had higher snowfall and summer rains that have abated the drought at least temporarily.) Local residents would argue that the drought began at least three years earlier, in 1996. Sparse data from within the western Navajo lowlands, as well as data from a USGS weather station, recorded very dry conditions in 1996, suggesting that at least part of the Navajo Nation received only 35% of normal total precipitation that year. Additionally, in the two years preceding 1996, below normal rainfall was also recorded in the western Navajo Nation, suggesting that it took a few sequential dry years for the rangeland to show deterioration from drought. This data also suggests that the drought may have begun in the drier western lowland area of the Navajo Nation, and spread in subsequent years. If percent of normal precipitation is calculated for only the stations falling within and close to reservation boundaries, the drought conditions of the mid-1990's are at least as severe as the years of drought that are more widely recognized for the larger Four-Corners region. If the most recent drought can be considered as lasting from 1996 to 2009 (or since 1994, as we suggest), it is one of the longest droughts in recent history on the Navajo Nation, lasting longer than other major droughts of the 20th century (Figure 2). Although there was some variability in drought intensity from year to year, the Navajo Nation was drier than normal or just at normal conditions during this entire period. A brief recovery from drought did occur from 2004-2005, but it did not last long enough for a complete recuperation from drought conditions.

Total annual rainfall and average annual temperature are not the only factors affecting the degree of drought impacts to rangeland. In the period of 2001-2002 Navajo officials reported that 30,000 cattle perished. The sky turned red with blowing dust. During these same years the monsoon rains arrived late, occurring as large, high intensity storms that caused widespread flooding in the month of September. In 2009, the last of recent drought years, precipitation was 30-35% of normal, and arrived in the form of rain during the spring months that are usually the driest part of the year. Although drought is characterized by a general decrease in precipitation, seasonal variations and the timing of precipitation events are critical to assessing drought and rangeland impacts. If there is inadequate moisture from winter snowfall, it is difficult for vegetation to survive the long dry period in the spring, until the arrival of the monsoon. If the monsoon arrives late, the rangeland suffers because spring plant growth must survive a longer dry period. During 2006-2009 drought was also characterized by a less reliable monsoon, with a larger deficit in precipitation during the warm season (USGS and NWS data).

Long-term Trends

Significant changes in long-term average temperature and precipitation have produced concomitant changes in the physical and hydrologic environment, making the region more susceptible to drought impacts. Inadequate rainfall during recent years was coupled with average temperatures that were 2^{o} C warmer than previous droughts. By using the Thornthwaite calculation for evapotranspiration, it is estimated that an additional 50 mm of precipitation is lost to evapotranspiraton for every degree C of temperature increase. Weiss et al. (2009) compared southwest regional evapotranspiration rates between the 2000s drought and the 1950s drought, and found that a significant increase in evapotranspiration occurred during the warm seasons of the 2000s drought due to higher temperatures. Additional temperature effects are suggested by Thornbrugh et al (2006) in a comparison of NDVI on the western Navajo Nation to local meteorological records. This study found that abnormally high spring temperatures were linked to a decrease in the amount of greening vegetation during recent drought years (Figure 3). This work suggests that because warm spring temperatures lead to early germination of vegetation, plants that are no longer dormant begin utilizing available soil moisture more quickly, and must survive a longer dry period before the arrival of the monsoon.

In order to obtain a more complete history of the changes that have occurred on the Navajo Nation, more than fifty tribal elders were interviewed, providing information concerning the availability and quality of water, observed weather patterns, changes in farming and grazing practices, and the availability of local medicinal plants. Interviews were conducted with a Navajo translator, and taped in order to review and compile responses. A standard checklist of questions was used to document observed changes in weather, location of water sources, local land use, and other observed changes to the landscape.

Among the most cited changes were a long-term decrease in the amount of annual snowfall over the past century, (noted in 100% of the interviews), and a decline in surface water features and water availability (85% of the interviews). The lack of available water, in addition to changing socioeconomic conditions, was mentioned as a leading cause for the decline in the ability to grow corn and other crops (75% of the interviews). Other noted changes include the disappearance of springs, and of plant and animal populations (particularly medicinal plants, cottonwood, beavers, and eagles). Changes in the frequency of wind, sand and dust storms (more frequent in the 1950's and increasing in the 1990's) were also commonly observed.

Trends in records of total annual snowpack derived from 25 sites in the region corroborate the observed decrease in annual snowfall totals, and show that the trend began in the early 1900's

(Figure 4). Some meteorological monitoring sites were also historically the locations of annual snowfall measurement, yet today, snowfall is an unusual event at these sites. These locations, which are primarily in the western lowlands of the Navajo Nation, are not included in the graph of declining snowfall. Weather stations across the Navajo Nation also show a long-term decrease in regional precipitation, with the years of more than 50% above normal precipitation occurring before 1950 (Figure 2).

A compilation of historic observations of surface water features and streamflow show significant changes over the past century. More than 30 major surface water features on the reservation are now dry year-round or are ephemeral, and began to disappear in the 1920's. Moreover, significant changes in the number and length of stream reaches with perennial flow have occurred since 1915, and some of the ephemeral water features of the past no longer exist (Figure 1). Along with changes in stream discharge, large scale changes to the riparian vegetation began in the 1940's, to more drought and salt tolerant species. The Little Colorado River on the southern border of the Navajo Nation, a major tributary to the Colorado River, became ephemeral at Holbrook in 2007, after six concurrent years of sparse winter snowfall (Figure 4). Discharge from the Little Colorado River is characterized by rapidly declining stream flow during the dry spring season, with no stream discharge in the month prior to monsoon season rains. These conditions became characteristic of smaller streams within the Navajo Nation more quickly: Moenkopi Wash became entirely ephemeral after 1960, as did the lower reaches of Chinle Wash. The declining trend in snow pack, and earlier stream discharge of snowmelt in the spring from higher temperatures, are likely factors in the disappearance of perennial flow during the last century (Hidalgo et al, 2009; Stewart et al, 2005). Other attributable factors include the long-term decrease in precipitation and increasing aridity resulting from higher evapotranspiration rates resulting from increasing temperature.

Many of the regional water supplies are from local alluvial aquifers that are compromised in both quality and quantity during drought conditions. For example, the regional water supplies in Greasewood Springs of the southwestern Navajo Nation have become increasingly saline resulting from lack of recharge and over-utilization (Pandamouz, unpubl. thesis). Some of the wells in this region have been capped in recent years, because they are too saline to be acceptable for livestock, and have continually corroded the pipes and equipment used to bring the water to the surface (Redsteer, upubl. data). Several area springs that were sampled for a water quality study in 1999 were dry in 2002, and have remained dry since. During exceptionally dry years, more than half of the water system supply area that relies on Greasewood Springs is cut off from the water supply, and communities that normally have running water must find alternate sources of domestic water supplies. Water conservation programs to mitigate drought impacts have had a minimal effect because the per capita water use of 20 gallons/day is already well below the amount of water used in modern households off the reservation (Navajo Nation Water Management Report, 2000). In the most remote areas of the Navajo and Hopi lands, water disputes have become commonplace, as shallow wells go dry and people in need of water cross political boundaries in search of new water sources. In other areas, people who routinely haul water, compete for depleted resources from local springs, often visiting these springs in the middle of the night, in order to obtain water that has begun to recharge the spring after the end of the day (Redsteer, unpubl. data).

During drought years the Navajo Nation has augmented the dwindling supplies of water and forage by trucking in water to most affected areas, and providing hay for livestock at a reduced cost (Navajo Nation Water Management Report, 2002). These measures have worked well for the short dry spells of the past 30 years, but are not effective during longer droughts. However, one of the unexpected consequences of this mitigation strategy is that importing inexpensive hay has contributed to the spread of invasive species, resulting in extensive, long-term damage to the rangeland (Draut and Redsteer, in prep).

Sand and Dust Storms

The landscape of the Four Corners region, and particularly the Navajo and Hopi lands within it, is acutely susceptible to rangeland impacts from drought because the landscape is blanketed with easily erodible surface sediments and ubiquitous sand dune deposits. Dune deposits cover over one-third of Navajo lands, but drought conditions on the Navajo Nation are producing significant changes in dune mobility (Redsteer, 2002). Sand and dust movement in the region is closely linked to regional aridity, ephemeral flood events in riparian corridors, and regional wind circulation patterns. Climatic factors controlling dune mobility include the ratio of precipitation to potential evapotranspiration (P/PE), because of its direct link to the amount of stabilizing vegetation (Lancaster, 1988). Thresholds in P/PE are based on observations by Muhs and Holiday (1995): where P/PE is < 1.0 there is an overall moisture deficit, transitions from mostly stable to mostly active sand occur at P/PE = 0.315, and transitions from mostly active to fully active sand takes place at P/PE = 0.125. Historical meteorological data indicates that P/PE on the Navajo Nation has consistently fallen below 1.0 (Figure 5a). During drought conditions, however, all of the dune fields within the Navajo Nation fall below the threshold of partly active (0.315) (Figure 5b). With increasingly arid conditions, more dune fields fall below the threshold of P/PE for mostly active (0.125) indicating that not enough moisture is available for any dune stabilizing vegetation to grow (Redsteer and Block, 2004). The continuation of drought, projected in climate change models by Seagar et al (2007) is a major concern, because a prolonged drought would alter regional dune fields to a perpetually mobile state (e.g. Yizhaq et al, 2009), and alter the local ecosystems upon which people depend for their livelihood.

Active sand dunes began to occur downwind of dry rivers and washes during the drought of the 1950's, because the dry stream beds provided an abundant source of fine-grained material. These dune fields have been moving downwind at the rate of 35m/yr and are growing in size (Redsteer et al, 2010). During the latest drought, from 1996 to 2009, these dune fields grew about 70% in extent. The reactivation of stabilized sand is contributing to myriad problems for the Navajo people, including housing inundated by sand, a loss of rare and endangered native plants, degradation of farming and grazing land, and lower air quality from periodic dust storms. Some communities in the southern and western areas of the Navajo Nation may be forced to relocate because the recent appearance of moving dunes are encroaching on their homes and blocking roadways.

Increased aridity in combination with high regional winds contribute to dust transport from local silt-laden dry lake beds and the flood deposits from dry rivers in the southwestern Navajo Nation. These deposits are likely sources for well documented "dust on snow" events (Painter et al, 2010). Because dust on snow lowers the albedo, it shortens the duration of snowpack; the discharge of streams from affected watersheds is shortened as a result, creating downwind repercussions from drought in the Four Corners region.

Conclusions

Impacts from the recent drought on the Navajo Nation were especially severe for several reasons:

1) The drought was protracted, starting earlier on the Navajo Nation than in other parts of the Four Corners Region, beginning in the western arid lowlands in 1994.

2) Long-term trends of increasing temperature and lower amounts of snowfall (and precipitation) have led to increasingly arid conditions, superimposed on drought.

3) Reservation lands consist of easily erodible deposits of thick surficial sediment and soft erodible bedrock lithologies that provide large amounts of sediment that is available for transport by wind, in the form of sand dunes and far-traveled dust.

4) Historic U.S. Federal policies resulted in the establishment of Navajo reservation lands in a region characterized by harsh, dry conditions and sparse water supplies, even during normal conditions.

5) Dire economic conditions and cultural ties to livestock add land use stresses that create greater risk and vulnerability from drought impacts.

Increasing aridity combined with drought threaten the very existence of Navajo culture and the survival of traditional Navajo communities. Stock-raising by large numbers of Navajo families is important to preserve aspects of traditional culture that Navajo people value: kinship cooperation and cosmography-ceremonialism. Livestock, especially cattle, are also a significant source of economic and food security for large numbers of families. However, the current grazing permit system tends to undermine kinship cooperation by encouraging individuals to assert property rights against neighboring relatives, leading to disputes. Drought puts even more pressure on individual grazing permit holders to protect their livestock by trying to monopolize land and water sources. These disputes also exacerbate the permit system's restrictions on moving livestock in response to changing local range conditions, a necessary response to drought. The result is a threat to the well-being of the livestock that are the savings of families, as well as further threatening kinship cooperation and traditional ceremonial beliefs and practices.

Navajo Nation government grazing officials can and do mediate disputes, but apparently most disputes are not mediated and the process is reportedly cumbersome. As long as such disputes remain widespread, livestock numbers and their distribution on the land cannot be regulated effectively in response to drought. Even with better dispute resolution, the permit system itself hinders flexible livestock distribution on the land. Alternatives to the current permit system and dispute resolution processes seem desirable, but most stock-raisers seem likely to oppose changes that they perceive threaten the land-use rights that their permits validate. To be effective, changes must be developed by range-management officials working cooperatively with Navajo communities, a process likely to be too slow to cope with current rates of deterioration of Navajo range conditions.

Increasing aridity, and ecosystem stresses from increasing temperatures and decreasing snowfall, are trends we can expect to continue with climate change. A continuation of these trends, without addressing the economic and cultural needs of Navajo communities, is likely to result in further deterioration of rangeland conditions in the Four Corners Region. Because of the limitations in water resources, increasing disputes over water supplies appear eminent. In areas where sand dunes are numerous, and/or water supplies limited, entire communities may be forced to relocate. It is likely that younger generations of Navajo people will emigrate from the reservation lands in response to these conditions. This alternative is difficult, if not impossible, for the more traditional elderly who tend to be the poorest of the Navajo people.

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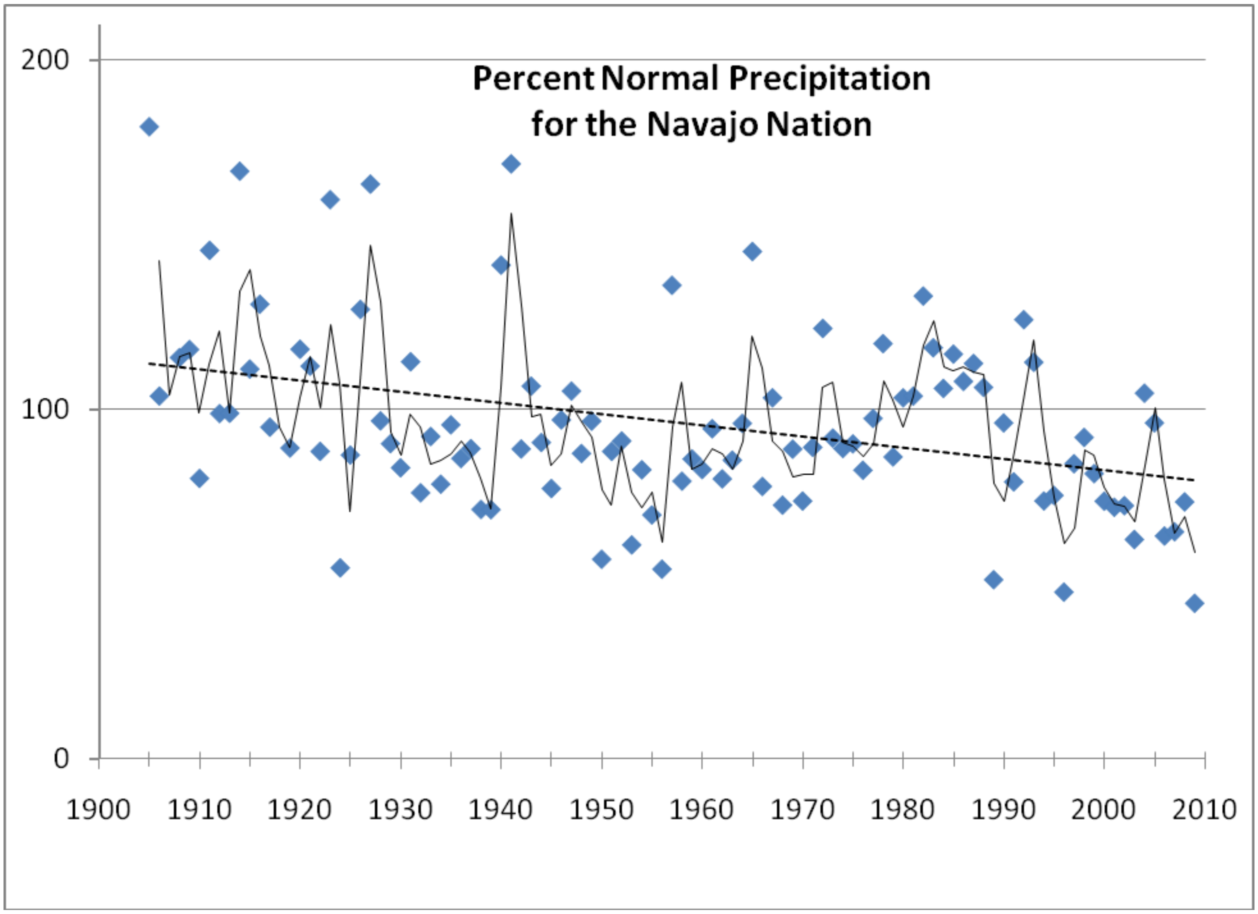
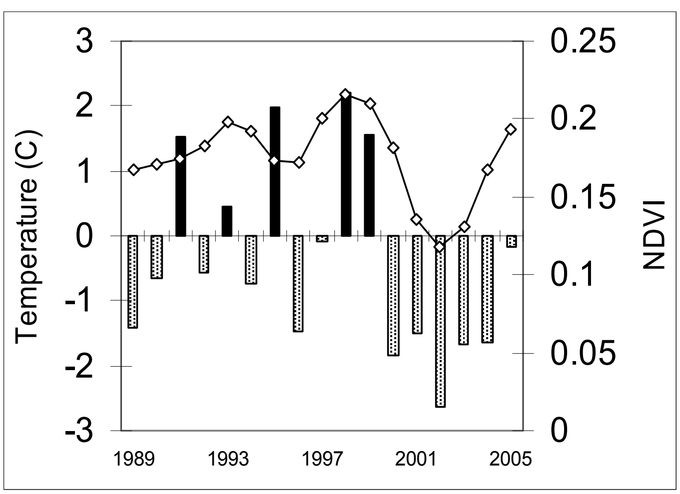


Figure 2.



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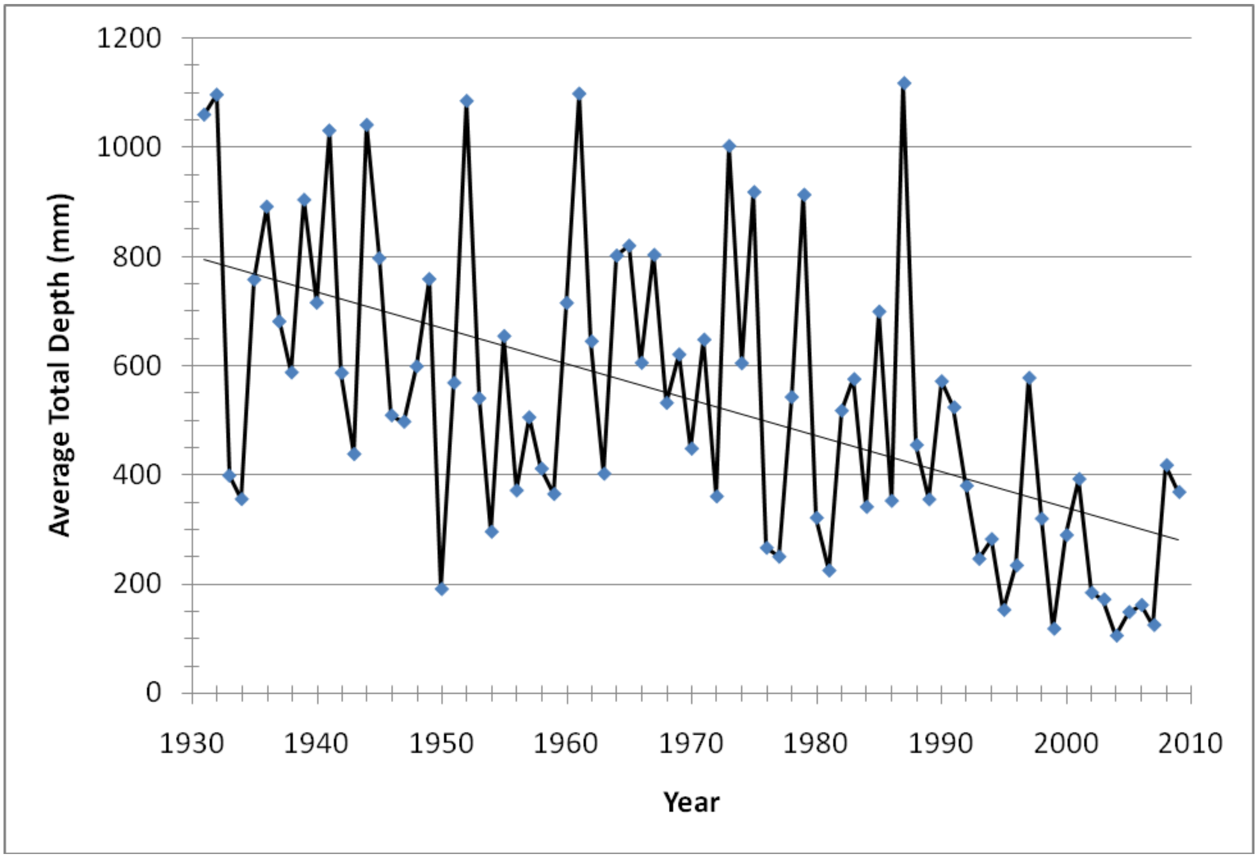

Figure 4. The average of total annual snowfall (in millimeters) from measurements at 25 sites on and near the Navajo Nation.

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Figure 2. Percent normal precipitation averaged from seven meteorological monitoring stations on and near the Navajo Nation: Betatakin, Canyon de Chelly, Ganado, Leupp and Moenkopi Plateau, Shiprock, Tuba City, and Winslow.

Figure 3. Graph showing inverse relationship of NDVI (Normalized Difference vegetation Index) to above normal spring temperature (for the months of April, May and June). Data from the Coalmine Mesa area of the Navajo Nation, (after Thornbrugh and Redsteer, 2006).

Figure 4. Graph showing the total annual snowfall for measurements from 1930-2009, averaged from 25 sites on and near the Navajo Nation.

Figure 5. The degree of dune mobility can be expressed as a function of climate variables, which includes the balance between precipitation (P) and potential evapotranspiration (PE), because of its link to dune stabilizing vegetation.

a) Map showing the distribution of normal average ranges of P/PE, calculated from all the years of record for each station (locations indicated on map). White areas are the mapped distribution of eolian deposits. Where white areas overlap with red regions of low P/PE, sand dune movement is likely to occur.

b) The second map shows P/PE for the drought years 2000-2002. Some of the meteorological stations compiled on map are no longer operating. For these areas, estimates for the changes in temperature and rainfall are based on linear correlations of the relative changes recorded by nearby monitoring sites for the period of operation.