ABSTRACT

This research is motivated by concerns about how climate change is affecting Indigenous communities across the globe. Many residents of the Navajo Nation on the southern Colorado Plateau are concerned that the future climate of the region will be warmer and drier than observed in the 20th Century. Droughts during the late 1980s through 2004 over this region have resulted in the decrease of many native plant species and an increase in sand dune mobility causing social harm, including damage to infrastructure and the loss of agricultural productivity. Effectively mitigating sand dune mobility requires understanding the annual and seasonal climate variability, which can affect sand dune development. A climatic sand dune mobility index using wind energy and effective precipitation was calculated to assess seasonal, annual, and decadal trends of potential sand dune mobility over the Moenkopi Plateau on the Navajo Nation from 1980 to 2004. The results demonstrated a large variation in seasonal and annual potential sand dune mobility. For the period from 1980 to 2004, an increasing trend in potential sand dune mobility was observed and appears correlated with a trend of decreasing effective precipitation. These results have provided a better understanding of the climatic conditions over the last 25 years over the Moenkopi Plateau, and show how these conditions relate to increased sand dune mobility. This work shows that the index can be used for other areas on the Navajo Nation, to identify locations at risk and help in planning efforts to mitigate effects from climate change.
1. Introduction

a.) Objective

The goal of this study was to identify the monthly, seasonal, and annual variability as well as, decadal trends of potential sand dune mobility on the Moenkopi Plateau area of the Navajo Nation. This project used climate data consisting of wind speed, precipitation, and potential evaporation to identify key periods of potential sand dune mobility from 1980 through 2004. By using the past 25 years of climate data, the magnitude of the effects of dry seasons and years of drought on the potential sand dune mobility over the Moenkopi Plateau was assessed. This project is part of an ongoing assessment of the impacts of climate change on the Colorado Plateau by the U.S. Geological Survey and the Navajo Nation.

b.) Background

The motivation for this research project stems from the concerns of the effects of climate change on the Navajo Nation. Across the globe climate change has severe implications for many Indigenous communities. Warmer annual temperatures have contributed to erosion and permafrost melting causing the destruction of home and building foundations in Native Alaskan villages. In the South Pacific sea-level rise with warmer global temperatures threatens to flood out many communities of Indigenous people of the Pacific Islands. In the U.S. Southwest Native American nations are concerned climate change could increased the duration and intensity of drought, which could threaten the livelihood of many communities.

A specific environmental concern for communities on the Navajo Nation of the U.S. Southwest is the activation and movement of sand dunes from wind transported sand
deposits. This concern is placed in the top priority due to the impacts on the Navajo Nation from the recent 7-year drought (1998 – 2004) over the U.S. Southwest. Extended periods of drought place a high stress on sand dune stabilizing vegetation. The result is often a shift from a grass-dominated landscape towards a shrub-dominated landscape with a lower percent of surface vegetation coverage and an increased potential for sand dune mobility (Lancaster, 1998). Sand dune mobility is a potential geologic hazard for communities on the Navajo Nation. Impacts from sand dune mobility include: the blockage of roadways, inundation of housing, hazardous driving conditions from reduced visibility during dust storms, loss of plants for ceremonial use, loss of land for livestock grazing, and a reduction in local air quality from wind-driven dust storms (Hiza-Redsteer, 2005).

The Navajo Nation covers an area of approximately 65,000 km² on the southern Colorado Plateau. This area covers most of northeastern Arizona, northwestern New Mexico, and parts of southeastern Utah. Most of the area is semi-arid and the environment is sensitive to both long-term and short-term climate variability. This area is known to experience extended periods (years or decades) of drought, which places a higher stress on the local ecosystem and human communities residing within it.

The Navajo Nation is the fastest growing and the largest Native American reservation-based community in the United States (U.S. Census 2000). In 2000 the Navajo Nation listed 255,453 enrolled tribal members with a population of 180,000 people living on the reservation and an additional 80,000 people living on areas just outside the reservation boundaries (Navajo Nation Washington Office 2005). Much of income generated on the Navajo Nation comes from economic sectors of
tourism/recreation and agriculture/livestock, which are both highly sensitive drought impacts (Navajo Nation Department of Water Resources, 2002). To accommodate fast growing communities and mitigate impacts from natural hazards, such as drought, the Navajo Nation is working to develop land-use plans and efficient infrastructure. These plans require information on geologic hazards and climate variability (Hiza-Redsteer, 2005).

c.) The Moenkopi Dunes

This study focuses on Coalmine Mesa chapter area of the Navajo Nation located on the Moenkopi Plateau. This area is south of the community of Tuba City and east of the community of Cameron, Arizona. The climate on the Moenkopi Plateau is on the threshold between arid to semi-arid and annual precipitation is frequently less than 5 inches. The geology on the surface of the plateau consists of the Navajo Sandstone formation. The Navajo Sandstone is the source of wind blown sand, which has formed linear sand dunes over the plateau. This sand from the Navajo Sandstone is very fine sand with grain sizes less than 300 μm (Lancaster and Helm, 2000). At present (2005) most of the linear sand dunes are anchored by vegetation, but with some sand dunes showing bare spots with minimum vegetation on the crests (figure 1).

Figure 1. Linear sand dunes on the Moenkopi Plateau (Hiza-Redsteer USGS, 2004)
2. Methods

a. The Climatic Dune Mobility Index

The climatic dune mobility index (M) developed by N. Lancaster in 1988 uses two critical variables to determine dune mobility: effective precipitation (P/PE) and wind energy (W) (Lancaster 1988). Wind energy (W), also known as the “sand transport potential,” is essentially the wind velocity threshold exceeded to transport grains of sand (Lancaster & Helm 2000). The equation for the dune mobility index is as follows:

\[ M = \frac{W}{P/PE} \]  

(1)

The dune mobility index was tested and verified by Lancaster and Helm in 2000 for three locations in the U.S. Southwest, including Gold Spring, for the time period from 1986 through 1997. The values (M) of the dune mobility index were on a scale from 0 to over 200. Indices of less than 100 indicated dunes were stabilized by vegetation, indices between 100 and 200 indicated the sand dunes were active (immobile but bare in some areas with less vegetation exposing wind blown sand), and indices over 200 indicated the sand dunes had little or no vegetation and were mobile in accordance to the prevailing wind direction. The results from tests using annual wind energy (W) and effective precipitation (P/PE) values for Gold Spring produced a comprehensive mean index of 133 between 1986 and 1997, a minimum annual mean index of 46 in 1992, and the maximum annual mean index value of 454 in 1996 (Lancaster and Helm 2000). The dune mobility has also been used to understand and verify dune mobility for locations in the Sonora, Chihuahua, Kalahari, Namib deserts, and the U.S. Great Plains (Lancaster, 1988 & 1995; Lancaster & Helm, 2000; and Muhs & Maat, 1993).
b. Data

The wind data used was recorded at the Gold Spring geometer station, which is operated and maintained by the U.S. Geological Survey’s Flagstaff, Arizona office and local residents living near the site. The U.S. Geological Survey Desert Winds Project installed the Gold Spring geometer station on August 2, 1979. Gold Spring is located on the southwestern edge of the Moenkopi Plateau approximately 1.5 km from the cliffs, which mark the boundary of the plateau (figure 2). The elevation of Gold Spring is 1,667 meters above sea level and its coordinates are 35º N and 111º W.

The wind data used were the wind velocities recorded at 6.1 m above the surface. The 6.1 m height is a standard height to assess sand transport potential at geometer stations (Lancaster & Helm, 2000). Wind velocity data is an ongoing dataset, which has been recorded at Gold Spring every 30 minutes from October 1979 through April 1980, and every 6 minutes from April 1980 through 2004. The wind velocity data are collected by the USGS and are placed in an ASCII file format.

The data needed to calculate P/PE were also obtained from the USGS. The P/PE is calculated using temperature and precipitation data recorded at Gold Spring. The

Figure 2. Map of location of Gold Spring on the Moenkopi Plateau (Billingsley USGS, 1987b)
temperature and precipitation data has been recorded at Gold Spring every 12 minutes from January 1980 through 2004. Due to vandalism of the Gold Spring station in 2001, no data for wind, precipitation, or temperature was available for that year.

c. Methodology

1.) DATA QUALITY

The first procedure was the assessment of the wind data quality and amount of missing data. A plotted time series of wind data recorded at Gold Spring from October 1979 through December 1992 was assessed to identify extended periods of missing data (figure 3). For the time period of 1993 through 2004 recorded wind data from monthly ASCII files was assessed to account for missing data. There were a total of five extended periods of missing wind data from the entire dataset, October 1979 through December 2004. These significant areas of missing data include: (1.) July 15 through August 26, 1981; (2.) April 17 through June 6, 1984; (3.) August 14 through October 4, 1985; (4.) November 4 through November 19, 1985; (5) April 1 through July 31, 2000; and (6) October 1, 2000 through December 31, 2001.

![Figure 3. Time series of wind data recorded at 6.1 m from the Gold Spring geome site October 27, 1979 through December 10, 1992 (USGS, 2005).](image)
2.) WIND ENERGY

The next procedure was the calculation of the variable of wind energy (W) in order to apply the dune mobility index monthly, seasonally, and annually. To maintain consistency with past works using the dune mobility index model, wind data velocity data recorded in miles per hour (mph) was converted to meters per second (m/s) using the equation:

\[ y = \left(\frac{x}{3600}\right) \times 1600, \quad x = \text{wind velocity (mph)} \]  

The next calculation was the wind energy (W) for every available month from January 1980 through August 2004. Wind energy (W) was not calculated for months with more than 2-weeks of missing data. The 6-minute wind velocity data was used to calculate the W, essentially the percent of time the wind velocity was above the minimum sand transport threshold for Gold Spring. A minimum sand transport value of 4.25 m/s was used to calculate the monthly W for Gold Spring. This value is lower than the 5.85 m/s minimum sand transport threshold used by Lancaster and Helm 2000. The reasoning behind the use of a lower minimum sand transport threshold is the fact that the mean sand grain size on the Moenkopi Plateau is less than 300 \( \mu \text{m} \) and requires a lower wind velocity to be transported (Lancaster & Helm, 2000). Once monthly wind W values had been calculated, seasonal W was calculated each year for January through March (JFM), April through June (AMJ), July through September (JAS), and October through December (OND). Wind energy (W) was not calculated for seasons when more than one month of data was missing. Lastly, W was calculated annually from 1980 through 2004 with the exception of 2001.
3.) EFFECTIVE PRECIPITATION

Effective precipitation (P/PE) was calculated using mean total precipitation (P) and mean temperature data to calculate the potential evaporation (PE). The P/PE was calculated monthly, seasonally (JFM, AMJ, JAS, and OND), and annually from 1980 through 2004. For the months from 1980 through 2000 when precipitation and temperature data were missing from Gold Spring, precipitation and temperature data from Cameron, Arizona were used (Cameron and Tuba City show the closest relationship to Gold Spring in terms of precipitation and temperature). For the months after 2000 when precipitation and temperature data were missing, Tuba City precipitation and temperature data were used. These substitutions were done for 19 months or 6.6% of the months from 1980 through 2004 (excluding 2001).

4.) APPLYING THE SAND DUNE MOBILITY INDEX

The climatic sand dune mobility index was applied monthly, seasonally, and annually for Gold Spring from January 1980 through September 2004. Monthly sand dune mobility calculations used monthly W and P/PE. Seasonal and annual sand dune mobility calculations also used the corresponding W and P/PE values. A polynomial trend line was superimposed on the annual sand dune mobility indices to assess the decadal trends in potential sand dune mobility for the time period.
3. Results

a. Monthly sand dune mobility

The calculated monthly sand dune mobility indices yielded a wide range of values from month to month (figure 4). Among the months where the monthly sand dune mobility indices were calculated the values ranged from a minimum of 0.238 for December 1986 to a maximum of 23,998 for June of 1984. The extremely high sand dune mobility indices greater than 1,000 were the result of low P/PE values less than 0.03. This occurred for thirty-one months with all of them between April and September. Sand dune mobility indices over 20,000 occurred with P/PE values less than 0.003 for June of 1984, 1985, and 1996. The months of May (14%) and June (15%) demonstrated the highest frequency for having sand dune mobility indices over 200 (figure 5).

![Gold Spring monthly sand dune mobility index 1980-2004](image)

*Figure 4.* Monthly sand dune mobility indices at Gold Spring 1980 through 2004.
The sand dune mobility index could not be calculated for eighty-nine months or 31% of all months from 1980 through 2004. There were three reasons why the monthly sand dune mobility index could not be calculated for these months. (1) The sand dune mobility index could not be calculated when the P/PE value was zero. The monthly P/PE values were zero for months when no measurable precipitation was recorded (P = 0). There were forty-nine months from 1980 through 2004 where no measurable precipitation was recorded at Gold Spring. (2) The sand dune mobility index also could not be calculated when the potential evaporation (PE) value was zero and P/PE was indefinable. This occurred for ten months, which were December or January and the mean monthly temperature was at or below the 32°F. The Thornthwaite method used to calculate P/PE assumes a PE value of zero when the temperature is at or below freezing (Thornthwaite, 1957). (3) Sand dune mobility indices could not be calculated for months
lacking the sufficient wind data (i.e. more than 2-weeks missing) to calculate the variable W. This was the case for thirty months including the entire year of 2001.

b. Seasonal sand dune mobility

The calculated seasonal sand dune mobility indices also demonstrated a wide range of values from season to season. The range of the seasonal sand dune mobility indices were from a minimum of 15.16 for the winter season (JFM) of 1980 to a maximum of 45,350.96 for the spring season (AMJ) of 1996. The spring 1996 demonstrated an incredibly high sand dune mobility index because for AMJ in 1996, W was 37.5% and the P/PE for 0.00087 inches (figure 6). For this entire three-month period the total precipitation (P) was 0.01 inches and was received in June. Of the thirty-five seasons between 1980 and 2004, which exceeded the sand dune mobility threshold of 200, twenty of these (57%) were the spring (AMJ) season (figure 7).

![Gold Spring seasonal sand dune mobility index (M) 1980-2004](image)

**Figure 6.** Seasonal sand dune mobility indices for Gold Spring 1980-2004
The sand dune mobility index could not be calculated for thirteen seasons or 13% of all the seasons in the time period from 1980 through 2004. Four of these seasons were from 2001 where there were no data for wind or precipitation. Seven of the seasons could not be calculated because there was insufficient wind data (i.e. more than one month a data were missing). There were two seasons, the winter (JFM) and the fall (OND) of 1999, where the sand dune mobility index could not be calculated because P/PE was zero. During both of these seasons there was no measurable precipitation for the entire three-month period.

c. Annual sand dune mobility

The calculated annual sand dune mobility ranged from a minimum of 76.63 in 2002 to a maximum of 782.39 in 1996. The year of 1996 was the peak year of the 1990s drought, which received the least amount of precipitation. At Gold Spring the annual total precipitation (P) was 1.08 inches and the annual total P/PE was 0.034 inches. The
1990s decade also exhibited the most number of years where the sand dune mobility index exceeded 200. Of the eight years that the sand dune mobility index exceeded 200, six of these years (75%) were of the 1990s decade (1991 & 1994-1998), one year was 1989, and one year was 2000. The decadal trend clearly showed higher sand dune mobility indices for the 1990s decade (figure 8).

Sufficient wind data were available to calculate W for all years in the study period with the exception of 2001. All years in the study period also received a measurable amount of precipitation enabling the annual P/PE to be calculated and used to calculate the annual sand dune mobility index. Since the year of 2001 is missing there is some uncertainty about the decadal trend of the sand dune mobility indices from the 1990s decade through 2004, however 2002 through 2004 show lower sand dune mobility indices than the years of the middle and late 1990s decade.
4. Discussion

The principal lesson learned from applying the climatic sand dune mobility index using the Gold Spring climate data is the challenge of applying the index for time scales on the order of months and seasons. To calculate the sand dune mobility index the data must consist of some measurable precipitation and mean temperatures above 32°F for the calculation of potential evaporation (PE). The Moenkopi Plateau is a region where the climate is on the threshold of arid to semi-arid and frequently months occur that have no measurable precipitation. The data for the 1990s also demonstrated that entire three-month periods could pass with no measurable precipitation. The Moenkopi Plateau’s temperate climate also has cold winters when some winter months may have a mean temperature at 32°F or colder. This prevents the assessment of potential sand dune mobility using the index during particularly cold winter months.

The climatic sand dune mobility index did provide information on the short-term time scale as to which months and seasons where likely to have conditions conducive to sand dune mobility. The Moenkopi Plateau is typically dry and windy during the spring season. The sand dune mobility monthly and seasonal indices demonstrate that the months of the spring season often have extremely dry conditions coupled with sufficient wind energy to mobilize sand dunes.

The climate sand dune mobility index could be used to assess annual potential sand dune mobility, as well as decadal trends potential sand dune mobility. The index demonstrated the magnitude of the effect that years of drought in the 1990s had on potential sand dune mobility. These years of drought and high sand dune mobility
indices were grouped together as a single event lasting from 1994 through 2000. It is interesting to note that although the sand dune mobility indices fell below the mobile threshold for the years of 2002 through 2004, the state of Arizona remained in a drought from 1998 through the fall of 2004 (McPhee, Comrie, and Garfin, 2004). One possibility is that short-term isolated precipitation events are the result of higher P/PE values, hence decreasing the annual sand dune mobility indices. For example in September 2002 two storms over northern Arizona (September 6th and 8th) amounted to the monthly total precipitation of 4.61 inches and a P/PE of 1.34 inches. The total precipitation in the following nine months amounted to 1.03 inches with a P/PE of 0.096 inches.

The trends in the mean temperature at Gold Spring from 1980 through 2004 are the main cause for concern for future potential sand dune mobility. The annual mean temperature at Gold Spring has been increasing since 1980 (figure 9). This is a concern because an increase in temperature will increase potential evaporation (PE) and decrease P/PE. Warmer temperatures with no change in precipitation or even an increase in precipitation could potentially increase sand dune mobility over the Moenkopi Plateau. Whether this will occur in the future may depend more so on changes of the timing of precipitation rather than changes in the amount of precipitation. When considering P/PE, the values are highest when significant precipitation is received during the cooler months of the year due to less evaporation. The P/PE can be very low even if much summer precipitation is received due to warmer temperatures and high evaporation rates. Warmer winters would decrease P/PE and extend the time period where sand dunes can mobilize. The past 25 years at Gold Spring have shown less occurrences of winter (JFM) P/PE exceeding one inch (figure 10).
Figure 9. Annual mean temperature trend at Gold Spring 1980 through 2004

Figure 10. Seasonal total effective precipitation (P/PE) at Gold Spring 1980 through 2004
5. Conclusions and Future Work

The climatic sand dune mobility index can be useful to assess how vulnerable a location may be to sand dune activation and mobility. This is extremely useful information to many residents on the Navajo Nation who are concerned about active sand dunes potentially mobilizing near their communities. The sand dune mobility index however is only one tool, which can be used in an assessment of sand dune conditions. Further studies are needed to gain information about real-world response times of sand dunes to changes in wind energy (W) and effective precipitation (P/PE). How long certain conditions of W and P/PE must persist in order to mobilize sand dunes also needs to be understood.

There are three immediate plans for research to gain a better understanding of how sand dunes respond to precipitation variability over the Moenkopi Plateau. (1) Past photos taken over the Moenkopi Plateau need to be collected where available and examined to see the conditions of vegetation and sand dunes. This is important to assess the conditions of vegetation and sand dunes during the 1990s drought, especially in 1996 when the sand dune mobility index exceeded 700. (2) Measurements of ground moisture are needed to compare with the calculated P/PE based on precipitation and temperature. This is important to gain information on true ground moisture amounts between wide temporally spaced precipitation events. (3) The climatic sand dune mobility index needs to be modified to account for a lag P/PE residence time from events and seasons where much total precipitation has occurred. The sand dune mobility index has been modified in recent research to calculate sand dune mobility indices after high precipitation events and months for the Kalahari dune fields in southern Africa (Thomas et al. 2005)
In addition to assessments of areas vulnerable to potential sand dune mobility, many residents and decision makers on the Navajo Nation also need information on how to respond to sand dunes, which are mobile and impacting communities. Current research relating to this project will be searching for ways in which mobile sand dunes can be stabilized by vegetation. This is a challenging endeavor and it will be necessarily to gain a better understanding of the relationship between sand dunes and vegetation over the Moenkopi Plateau. Future studies can also provide assessments of potential sand dune mobility and provide information identifying options for mitigation and response to active and mobile sand dunes impacting communities over other areas of the Navajo Nation.

6. References

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