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DUNES ON THE NAVAJO UPLANDS OF NORTHEASTERN ARIZONA: THEIR RELATIONSHIP TO SELECTED ENVIRONMENTAL VARIABLES

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DUNES ON THE NAVAJO UPLANDS OF NORTHEASTERN ARIZONA:

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Approved by:

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Investigation of the selected geomorphic, meteorologic, and lithologic variables and the occurrence of dunes on the Navajo Uplands of Northeastern Arizona yielded a number of interesting insights into the relationship between dunes and the environment responsible for their existence.

The study area is characterized by nearly horizontal, sedimentary, eolian, sandstone formations with scattered areas of shale. The climate is semi-arid to arid and landforms consist primarily of broad open valleys. A variety of dune types are present, however longitudinal dunes tend to be most common. The area is included almost entirely within the Navajo Reservation where overgrazing has contributed to the destruction of vegetation and the development of dunes.

Fifteen variables were selected as possible indicators of dune occurrence. Analysis of the variables by the

hypothesis testing portion of the discriminant analysis routine determined the relationship between means of the dune and non-dune group and the discriminating power of each of the variables. Those variables whose means were not significantly different were rejected from further consideration.

The 12 significant variables were subjected to factor analysis to determine the relationships between the variables and to produce the independent factor scores necessary for the model development. Four factors were discernable.

Factor scores from significant variables were used in the classification portion of the discriminant analysis routine and produced the model. The model was tested on 100 new sites to determine its classification ability. Factor scores from the 100 "new" sites were classified according to the model developed on the 100 "original" sites. Of the 18 sites classified as belonging to the group dune, 16 were actual dunes. Sixty-nine of the 82 member non-dune group were correctly classified.

As a result of the analysis, it was possible to predict dune prone areas within the study area based upon the physical environmental attributes of specific sites.

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TABLE OF CONTENTS

LIST OF MAPS

LIST OF FIGURES

LIST OF TABLES

LIST OF GRAPHS

LIST OF PLATES

DUNES ON THE NAVAJO UPLANDS OF NORTHEASTERN ARIZONA: THEIR RELATIONSHIP TO SELECTED ENVIRONMENTAL VARIABLES

CHAPTER I

INTRODUCTION

Purpose

Numerous authors have described the physical characteristics of eolian landforms. Some have explored specific physical features of the eolian processes. However, few have attempted to determine the relationship that exists between selected physical variables and the occurrence of dunes at specific sites. It is my intent, therefore, to research an area which has been only rarely scrutinized, namely, the dune processes on the Navajo Uplands of Northeastern Arizona.

This study attempts to develop a model which will determine the relationship that exists between selected, measurable geomorphic, meteorologic, and lithologic variables and the occurrence of dunes on the Navajo Uplands of Northeastern Arizona. The model developed on one set of study area quadrats will be applied to a different set to determine the model's ability to predict the occurrence of dunes based upon the environmental characteristics of the sites. This study attempts to answer the question: Can a model based on selected, measurable geomorphic, meteorologic, and lithologic variables be developed to predict dune occurrence on the Navajo Uplands of Northeastern Arizona?

Research Question

Pursuit of and an answer to the research question falls well within the framework of scientific inquiry as stated by Kuhn (1970), Nagel (1961), Harvey (1969), Lachman (1960), and Braithwaite (1955). Hemple (1968, 45) believed that the motivation for scientific research is man's "desire to improve his strategic position in the world by means of dependable methods for predicting and, whenever possible, controlling the events that occur within it."

Lachman (1960, 20) emphasized the need for understanding prior to prediction. He stated: "Often comprehension or understanding preceeds prediction, which in turn preceeds control" In the case of the research question, understanding the functions and contributions of the variables would be necessary prior to their use as predictors. In the case of environmental characteristics, it is not always possible to completely understand each one. Lachman (1960, 22) commented on that problem: "Frequently it is possible to predict or control natural phenomena, however, without really appreciating or understanding the phenomena, their relevant relationships, or many of the necessary antecedant conditions."

Lachman (1960, 24) also stated that science has two objectives:

1. To provide extensive and intensive descriptions of phenomena which occur within the universe.
2. To provide "explanations" for those phenomena by designating relationships which exist between them.

The field of eolian geomorphology has met the first objective; however, the second, which suggests that science provide an understanding of relationships that exist and an explanation regarding the occurrence of a phenomena, has been nearly ignored.

Kitts (1974, 3) has similar views of science. He believed that scientists seek to explain events and that: "There is a widely held view that the history of a science proceeds from description of phenomena, through a state of empirical generalizations, to a final state of theory formation."

Review of Related Literature

To comprehend the development and present level of research and knowledge in the field of eolian geomorphology, it is important to delve into a brief history of the study of wind as a geomorphic agent. It is apparent that geomorphologists have not focused as much attention upon wind as on other geomorphic agents (Peel, 1960).

Fluvial processes have dominated the literature of geomorphology in recent years. The popularity and interest in fluvial geomorphology has exceeded that of eolian processes for several reasons. First, fluvial processes alter a much larger portion of the earth's land surface. In addition, the fluvial areas tend to be more densely populated than areas where the effects of eolian forces are manifest; as a result, the number of people exposed to the erosional forces differ greatly (Bagnold, 1954, XX).

William Morris Davis (1905) did little to foster interest in eolian processes. His initial discussion of the Geographic Cycle referred to that occurring in humid areas as "The Ideal Geographic Cycle." Such a practice may have lead early geomorphologists to assume that any other geomorphic processes were other than "ideal." Interestingly, when dealing with arid lands, Davis' (1905) description concentrates upon the effects of water in areas of interior drainage. The role of wind as a geomorphic agent is largely ignored in the desert landscape he refers to as an "Inselberglandschaft."

It would be unfair to place the entire blame for the 50 years of limited interest that geomorphologists have taken in arid areas upon Davis' terminology. Peel (1960, 241) stated:

> ...although his choice of terms may have been unfortunate, to blame him for the comparative neglect of dry-land studies is surely unwarranted. His attitude has at least had no such effect on his other "abnormal,"

> the lands of ice and snow; indeed nothing so sharply underlines the neglect of the arid deserts as a comparison of the volume of study devoted to them with that devoted to the glacial regions. In the latter field we have by now almost a subject in itself, nourishing a vast literature of thousands of articles, several specialized journals, and shelves of weighty texts and major monographs.

Other geomorphologists of Davis' time claimed that eolian activity was significant in the development of arid area landscapes. Among the best known were Albert Penck (1905) and C. R. Keyes (1912). Keyes (1912, 541) indicated that "recent investigations in arid and semi-arid countries appear to demonstrate beyond all shadow of doubt that as a denuding, transportive and depositional power the wind is not only fully competent to perform such work, but that it is comparable in every way to water action in a moist climate." Keyes was attempting to describe a "geographic cycle" based on wind comparable to the cycle Davis believed resulted from fluvial processes.

Keyes' views as well as those of other "aeolianists" were not widely accepted because of limited data. It did, however, focus attention on the problem of determining the importance of wind as a geomorphic agent. That problem remained unresolved for decades to come (Cooke and Warren, 1973).

Following the works of Davis (1905) and Keyes (1912) a variety of works encompassing descriptive features of varying dune types ensued. Typical of those works was

Coffey's (1909) work on clay dunes, Bailey's (1917) work on the sand dunes of Indiana, Blackwelder's (1934) work on yardangs, and Hill's (1940) work on lunettes.

The emphasis was on unique individual landforms rather than entire landscapes. "Thus desert geomorphology has come to be characterized by concern for specific landform types (such as zeugen, yardangs, dreikanter, or barchan) which may be neither very common nor of great significance" (Cooke and Warren, 1973, 5). Bagnold (1954, 188) agreed: "The existing literature on windblown sand formations is large...much of it deals with small areas where special local conditions prevail."

A. K. Lobeck's (1939, 385) text on geomorphology discussed the location of dunes in general terms. He stated that: "Sand dunes occur in three kinds of localities: as (a) shore dunes, (b) river-bed dunes, and (c) inland or desert dunes." Specific sites where dunes are most likely to occur were not discussed. Lobeck does mention an additional possible dune location--those which occur on glacial outwash.

During the 1940's there was a continuation of previous activities in Bryan and McCann's work (1943) on sand dunes and alluvium in New Mexico. However, a new series of articles more encompassing of dune types and possible relation to some environmental features were produced by Melton (1940) and by

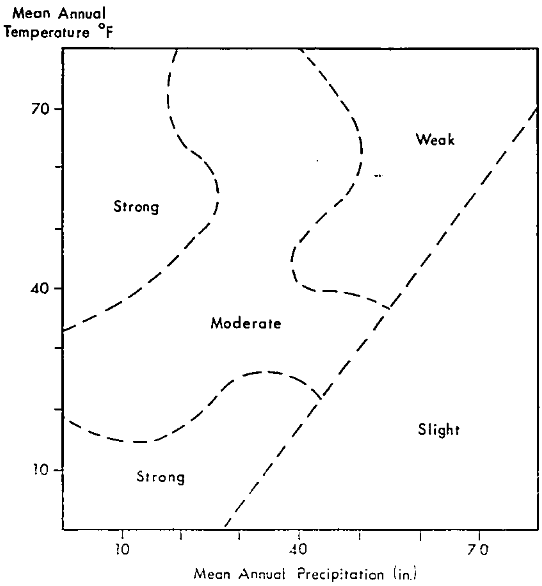
Hack (1941). By far the most significant eolian work of that period was Bagnold's (1941) monumental text, The Physics of Blown Sand and Desert Dunes. Its importance even today is probably best illustrated by the numerous citations it receives in current literature.

Bagnold's text concentrated on both the transportation of the sand grains as well as the various forms of accumulations. In the first portion (1954 reprint) Bagnold concentrated on the various aspects of eolian transportation, dealing with particle size, its behavior in air, and the relationship between wind and the action of the sand grains transported by it. The second portion described and analyzed the varying forms of sand accumulations. Bagnold discussed dune formation and its relationship to wind fluctuations and focused upon types of movement and accumulation, not the environmental conditions necessary for their formation. Bagnold (1954, 168) stated: "The most typical kind of country on which desert dunes are found is a flat erosion surface, so arid that the conplications introduced by rainfall and vegetation are negligible." He assumed the sand was free to move; therefore, the dunes were thought to be the result of wind velocity and directional characteristics.

After Bagnold's text, many researchers continued in the localized, descriptive trend of previous decades. Works such as Eyman's (1953) "A Study of Sand Dunes in the Colorado and Mohave Deserts," Cooper's (1958) study of "Coastal Sand Dunes of Oregon and Washington," Finkel's (1959) article "The Barchans of Southern Peru," Evans' (1962) "Falling and Climbing Sand Dunes in the Cronese ("Cat") Mountain area, San Bernardino County, California," Long and Sharp's (1964) "Barchan-Dune Movement in Imperial Valley, California," Dean's (1978) "Eolian Sand Dunes of the Great Salt Lake Basin," Smith's (1980) "Saskatchewan sand dunes: a touch of Araby," and Denny's (1970) "Sand Dunes on the Central Delmarva Peninsula, Maryland and Delaware" generally stressed unique features of the specific sites. They were more precise in their descriptions than earlier works; however, they too did little toward explaining the intricate relationships between dunes and the environmental characteristics that produced them.

Works from that period typically indicated that dunes were the result of the unmeasurable interaction of a limited number of physical variables. Probably the most widely accepted examples of that assumption were Peltier's (1950) diagram (Figure 1) indicating that wind as a geomorphic agent would be influenced by mean annual temperature and mean annual precipitation and Hack's (1941) model (Figure 2) explaining dune types by three "semi-quantified" variables of wind, sand supply, and vegetation cover. Unfortunately, Hack was not specific regarding the values of each variable,

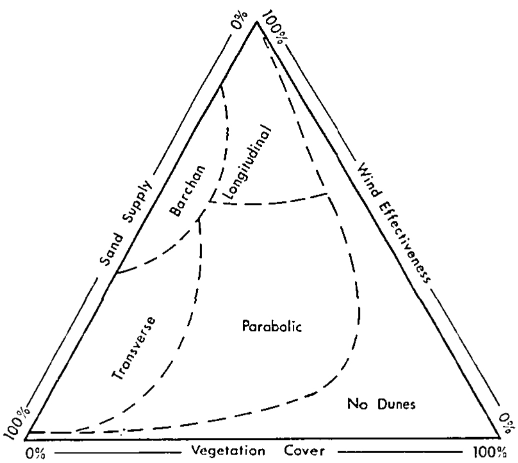
WIND AS A GEOMORPHIC FORCE



After Peltier

Fig. 1

DUNE FORMS



After Hack

Fig .2

nor was he able to ascertain their interrelationships.

In Thornbury's (1954, 292) text dunes were discussed under a variety of climatological conditions. In addition to arid locations, "The four nondesert environments in which sand deposits may be found are: (a) along shore lines, (b) along stream courses in semi-arid regions, (c) in areas where loosely cemented sandstones have disintegrated to supply sand, and (d) in areas of glacial outwash." His approach was typical in that it did not discuss specific sites, but, instead, discussed broad general environmental characteristics.

The limited comprehension of variable involvement in the production of natural features was not restricted only to eolian geomorphologists. For example, Chorley (1962, 10) analyzed the problem of that time by stating that:

> It is of interest to note that the physical, and resulting psychological, inability of geographers to handle successfully the simultaneous operation of a number of causes contributing to a given effect has been one of the greatest impediments to the advancement of their discipline. This inability has prompted, at worst, a unicausal determinism and, at best, an unrealistic concentration upon one or two contributing factors at the expense of others.

In addition to the limited understanding of the number of factors contributing to the occurrence of sand dunes, at that time the entire field of arid-area geomorphology was suffering from a lack of research and publication. Peel (1960, 241) summarized the problem by stating:

> The geomorphologist interested in deserts will find no single journal devoted exclusively to his interests, an article literature to be numbered only in hundreds, and no comprehensive textbook more recent than Johannes Walther's Das Gesetz der Wüstenbildung first published in 1900. And yet, as L. C. King and others have repeatedly stressed, by any definition the dry lands occupy a good third of the earth's surface, whereas glaciation, although expanded to cover about the same fraction during the Pleistocene maximum, today affects no more than about ten per cent.

Cooke and Warren (1973, 5) point out that research was not only limited in quantity, but also in depth. "Geomorphological descriptions of deserts have tended to be superficial" and there has been "an emphasis on description rather than on analysis of desert landforms."

Cooke and Warren's concern for the shallow nature of eolian research and Chorley's frustration with geographers' inability to handle a number of factors contributing to a given effect may be explained by the lack of tools necessary to handle and analyze the interactions of numerous variables. The advent of digital computers provided researchers with the equipment necessary to understand the simultaneous interaction of a number of contributing variables.

The arrival, acceptance, and use of digital computers coincided with a rapid growth of knowledge and voluminous publications of materials. As a result, researchers found it impossible to keep abreast of knowledge in a broader sense and were forced to specialize (Crossen, 1967). Ironically, when it finally became possible to understand a broad series of variables and their relationship to dunes, the focus of scientific inquiry became narrow.

The specialization of the 1960's continued through the 1970's. Articles such as Brown's (1974) study of eolian sediment transport potential, Svasek and Terwindt's (1974) article, "Measurement of Sand Transport on a Natural Beach," and Sakamoto-Arnold's (1981) "Eolian Features Produced by the December 1977 Windstorm, Southern San Joaquin Valley, California," rather than broad encompassing articles discussing the interaction of numerous variables have typified the literature.

Even though these areas of research became more specialized, interest in arid-area geomorphology increased. Cooke and Warren (1973, 4) state:

> Today there is a growing body of desert research workers who are motivated more by a desire for scientific enquiry and for knowledge about optimum human adjustment to aridity than by the simpler motives of exploration or exploitation. Many operate from permanent research organizations within desert areas--such as The University of Arizona, the Negev Institute for Arid Zone Research, L'Institut Fondemental de L'Afrique Noire, the Universidad del Norte (Antofagasta, Chile), the Turkmanistan Academy of Sciences, and the Academy of Sciences of the People's Republic of China (UNESCO, 1953). Publications in the field of desert research are widely disseminated through numerous systematic and regional journals, but in recent years the Arid Zone Research series of UNESCO has provided an important focus of desert publication, and bibliographic work at the University of Arizona (McGinnies et al., 1968) has helped to provide cohesion to the burgeoning literature.

Cooke and Warren go on to state that "today, studies of arid and semi-arid environments remain in the vanguard of geomorphological progress in the United States."

Cooke and Warren's (1973) beliefs on the widespread interest in eolian processes have not been shared by all geomorphologists. The geomorphology texts of today, such as Rice's (1977) Fundamentals of Geomorphology, completely ignore wind as a geomorphic agent in arid lands. Other general texts, including McCullogh (1978), Sparks (1975), Garner (1974), and Butzer (1976), do not provide the reader with material any more current than Bagnold (1941). The trend in current geomorphology texts is to adopt the material of the past rather than delve into the underlying causes for dune occurrence. The absence of new material in current texts may be a reflection of limited research resources available to authors. A noticeable void exists in journal articles relating to environmental variables and their effect on eolian processes. The following brief analysis of several current texts in geomorphology indicates the lack of recent research in eolian geomorphology.

Easterbrook's (1969) text maintains the general approach reitterating Bagnold's views on sand movement and accumulation as well as a general description of dune types. Specifics relating to the site of dunes are absent; instead, they are handled by phrases such as: "Where the wind direction is relative and uniform and vegetation is scarce, crescent shaped barchans are formed" (Easterbrook, 1969, 294); "In regions where the prevailing wind direction is variable, dunes may be strung out in long chains, often referred to as seif dunes" (Easterbrook, 1969, 295); "Longitudinal dunes, consisting of long sand ridges parallel to the direction of prevailing winds, may be formed where the wind funnels sand through a gap or notch in a rock ridge" (Easterbrook, 1969, 296); and "Transverse dunes formed at right angles to prevailing winds may develop under certain conditions...occasionally, because of vegetation or other contributing factors, transverse dunes up to several thousand feet in length may form at right angles to the wind" (Easterbrook, 1969, 298). The text would lead one to believe that dunes are the result of wind, vegetation, notches in rock, and "other contributing factors."

Bloom (1978, 338) dealt with the mechanics of wind and classification of dune types with frequent citations from Bagnold. His comments regarding dune formation tend to be general: "Transverse dunes are actually very common in areas of copious sand supply and weak winds...In semi-vegetated areas, blowouts are paired with downwind parabolic dunes." Bloom also used Hack's (1941) diagram (Figure 2) to determine dune types. He stated: "The basic dune forms can be classified by reference to three controlling variables: wind effectiveness, vegetative cover, and sand supply" (1978, 338). It is apparent that many of

Hack's ideas of 1941 have not been updated and are widely accepted by geomorphologists today.

Ritter (1978, 309) used a similar tactic of determining dune location by stating: "Regions having sparse vegetation and unconsolidated sediment not tightly bound by rooting systems are most susceptible to wind attack."

Mabbutt's (1977) text departs from the typical geomorphology text in that it is entirely devoted to desert landforms. However, his material on eolian processes is similar to other texts. He used Bagnold's material in describing the movement of the sand grains while descriptions of dune types are made according to a variety of previous works. Locations of dunes are assumed to result from a limited number of variables including the location of obstacles. Mabbutt also used Hack's (1941) diagram (Figure 2) as an explanation of dune types resulting from the three variables of sand supply, wind strength, and vegetative cover.

It is apparent that the understanding of the number of variables involved and their degree of responsibility in the location of dunes has not been an area of research for current geomorphologists. Instead, discussion of eolian activities characteristically refers to the ideas of Hack, Melton, and Bagnold, all significant authors of the 1940's.

Interestingly enough, attempts at describing the kinds of variables relating to wind erosion and deposition have been made by individuals outside the field of geomorphology. Chepil (1965, 130), through his attempts to understand factors that influence the erodibility of soil (1945, 1951, 1953a, 1953b, and 1955), arrived at a functional equation describing possible wind removal of surface soils:

$$E = f\,(I, C, K, L, V)$$

E - potential average annual soil loss is a function of:

- I - soil erodibility
- C - local wind erosion climate factor
- K - soil roughness
- L - the maximum unsheltered distance across the field along prevailing wind erosion direction
- V - equivalent quantity of vegetation cover

$$L = Df - Db$$

- Df - total downwind distance across the field
- Db - the distance fully protected from wind erosion by a windbreak or barrier

$$V = R\ S\ K_o$$

- R - weight of vegetation above ground
- S - a factor for kind of vegetation cover
- K_o - a factor for orientation of the cover (standing, flattened, or leaning)

Chepil's work followed the United States Department of Agriculture model referred to as "A Universal Equation for Measuring Wind Erosion" (Agricultural Research Service, 1961). The 1961 equation is $E = I\ R\ K\ F\ C\ W\ D\ B$ where:

I - soil cloddiness factor
R - surface cover factor
K - ridge roughness equivalent factor
F - soil abradability or stability factor
C - wind velocity-surface moisture factor
W - field width factor
D - wind direction factor
B - protection by shelterbelts or tall stubble-wind barrier factor

The first variable, I, is determined by clod diameter. Soil clod diameters in the range of .84 mm to 6.40 mm are considered ideal, for they are large enough to resist wind's erosive force as well as shielding smaller, erodible clods (Agricultural Research Service, 1961, 4). Hence this variable becomes a surrogate for soil erodibility.

Surface covers and crop residues (R) protect the soil from wind. The three factors of amount, kind, and orientation were considered; however, in the final consideration, only the weight of such material per acre was included (Agricultural Research Service, 1961, 5).

The surface roughness factor (K) is determined by vegetative height, length, density and orientation and "on size, shape, and lateral frequency of clods, ripples, and ridges" (Agricultural Research Service, 1961, 5). The relationship existing between roughness features and soil loss is due to friction resulting from an uneven surface. Rough surfaces trap moving particles as well as create friction which slows surface wind speed (Agricultural Research Service, 1961, 5).

Soil abradability (F) involves the abrasive cutting action of wind-transported materials upon the soil surface crust. The abrasive action of moving particles releases additional grains that in turn become abrasive. The abradability factor is determined by the soil texture (Agricultural Research Service, 1961, 5).

The wind velocity-surface soil moisture factor (C) is based upon soil loss at Garden City, Kansas. Using the climatic data for other locations, a map showing soil loss in Anglo America is used as an indicator. Five categories with losses from 0-10% to as high as 150% of the Garden City value were derived. The appropriate value for the formula was determined from the map (Agricultural Research Service, 1961, 5).

Field width (W) and associated soil loss values increase proportionately from 0 to a maximum rate depending upon the soil's erodibility and wind velocity (Agricultural Research Service, 1961, 6).

Wind direction (D) is an indicator of the relationship between wind direction and the long axis of the fields. Wind direction paralleling the long axis of the field results in increased W variable values (Agricultural Research Service, 1961, 7).

Wind barriers (B) indicate the downwind reduction in velocity due to the barrier. The protected zone fluctuates according to wind speed and barrier height. For a 40 mph wind on highly erodible soil it is approximately 10 times the barrier height (Agricultural Research Service, 1961, 7).

Chepil's formula as well as the United States Department of Agriculture's version is frought with problems. Chepil's attempt is functional and, as such, makes no attempt at determining values for each of the variables, the interrelationships that exist between them, nor the regional implications which interest geographers. The United States Department of Agriculture's version is more sophisticated in its attempts to obtain values for each of the variables, but by no means can it be substituted for the model to predict dune sites. Its inapplicability as a dune predictor lies primarily in the areas of:

1. It deals with removal of soil, not dunes or other depositional features.

2. Variables are measured in a vague, imprecise manner (especially C).

3. Measurement of some variables does not consider their dynamic nature (especially R, K, and C).

4. Some variables are not applicable to range land (especially W and D).

5. Most of the data is best suited for laboratory wind tunnel analysis as opposed to field conditions.

6. No consideration is given to the possible interrelationships between the variables.

Both formulas may provide material for consideration in determining dune sites, but neither can be considered a model for dune prediction.

An entirely different model, one designed to predict accumulations of wind-transported materials, was developed by Hutton (1947). His study of loess-derived soils in Southwestern Iowa lead him to the conclusion that accumulations could be described by the following formula:

$$Y = 1250.5 - 528.5 \log X$$

Y - thickness in inches

X - distance in miles from the Missouri River

Hutton's study differs from Chepil's and the United States Department of Agriculture's due to its prediction of depositional amounts. However, it is considerably less complex due to its assumption that loess thickness is the result of one variable.

While neither Hutton nor Chepil were geomorphologists, it is interesting to note the different positions they held in regard to predicting wind related phenomena. Chepil's realization of the number of variables involved in annual soil losses and Hutton's predictive model based on numerical data are both conclusions advanced beyond the level of many eolian geomorphologists of the time.

Conclusion

Numerous researchers have attempted to explain the physical characteristics of eolian accumulation and the nature of wind as a transporting agent. However, the study of eolian processes has not been continuous nor has it been complete (Peel, 1960).

Eolian geomorphology has been characterized by both specific and general works. One level of investigation relating to the specific movement of sand and soil particles was represented by Bagnold (1941) and Chepil (1945, 1951, 1953a, 1953b, and 1955). An additional level of research relating to general works on arid landforms and arid environments has been typified by the works of Davis (1905), Keyes (1912), and Cooke and Warren (1973).

Eolian geomorphology has, however, lacked a level of study focusing on environmental interrelationships and eolian features. Cooke and Warren (1973, 50) comment on the absence of a middle level hierarchial unit. "There is no meaningful unit at the regional scale in the eolian system that corresponds to the regional unit of the fluvial system." That absence may be part of the reason for the limited research accomplished at a "middle level" in eolian geomorphology.

Higgins (1975, 2) stated that: "...historically, geomorphologists have at one time or another attempted to answer three different sorts of questions about the Earth's landforms and landscapes:

1) How can these features best be described?
2) How have they formed and changed through time?
3) What processes are responsible for them and how do these processes work?"

The first question received a great deal of attention, particularly from Hack (1941), Melton (1940), Blackwelder (1934), and Thornbury (1954). The second question generated a limited response (Bagnold, 1941, and Mabbutt, 1977); however, dune formation was often considered to be unicausal and, at best, the response to a limited number of variables. The third question has been virtually ignored.

Cooke and Warren (1973, 38) believed: "There has always been a need in geomorphology for comprehensive explanatory models which satisfactorily explain the landscape of an area and the individual features within it." In meeting those goals other portions of geomorphology have progressed farther than the eolian processes. Ritter (1978, 309) believed "definite, quantitative data concerning eolian processes and features are woefully few." Richter (1981, 215) agreed and indicated that the explanation of the development of landforms "cannot succeed without quantitative research."

Man, as Hempel (1968, 54) indicated, is motivated by "his deep concern to know the world he lives in, and to explain, and thus understand, the unending flow of phenomena it presents to him." Yet, eolian geomorphologists have been reluctant to involve themselves with eolian activities to the extent of determining either the interrelationships or the role specific variables play in determining dune occurrence, nor have they developed a model to predict dune occurrence.

Eolian geomorphology has chosen to ignore the broader spatial aspect of explanation and instead focuses its discussions on the various modes of transporation of sand and descriptions of the physical characteristics of dunes. In discussing dune occurrence the approach has been to assume non-fixed sand is present and to then describe the types of dunes likely to occur based on wind characteristics. Factors relating to the effectiveness of the wind and those relating to the varying degrees of fixation of sand by vegetation are largely ignored.

Data on specific dune sites as well as the interrelationships of meteorologic, lithologic, and geomorphic variables responsible for their location are nearly absent. A number of factors point to the need to develop an understanding of those relationships in an academic manner. They are:

1. The comments of Kuhn (1970), Nagel (1961), Harvey (1969), Hemple (1968), Lachman (1960), Kitts (1974), and Braithwaite (1955) regarding scientific inquiry.

2. The comments of Chorley (1962), Peel (1960), Richter (1981), Cooke and Warren (1973), and Ritter (1978) on the need for quantitative data dealing with geomorphic processes.

3. The limited eolian material deployed in current geomorphology texts (Mabbutt, 1977; Rice, 1977; McCullogh,1978; and Garner, 1974).

It would appear that research attempting to answer the research question would be justified within the realm of eolian geomorphology. Many questions relating to arid climates and sand movement have been answered by geomorphologists. They have not been able, however, to identify the interrelationships between contributing variables necessary for dune formation. As a result, they have not been able to develop a model that can be used to predict dune location based on the physical environmental characterisitics of an area.

The proposed research will attempt to determine the contributions of each of the physical variables selected and their relationship to the occurrence of dunes. The contributions of each variable will then be used to develop a model capable of predicting dune locations.

CHAPTER II

THE RESEARCH AREA

The development and testing of a model using measurable geomorphic, meteorologic, and lithologic variables to predict dune occurrence required the selection of a suitable study area. Dunes, as indicated by Bagnold (1941), Melton (1940), Hack (1941), Thornbury (1954), and Cooke and Warren (1973), may occur under a variety of environmental conditions which include non-desert locations on or near the following conditions: shorelines, loosely consolidated sandstones, river channels, and glacial outwash (Thornbury, 1954). In the non-desert environments, the distribution of sand is often localized by the sorting action of water. As a result, the associated dunes may be confined to locations on or adjacent to the sand source (Thornbury, 1954). Such non-desert locations would not be suitable as a study area.

In desert environments dunes are often dispersed over sizeable areas. Hack (1941) indicated that dunes require a sand supply, wind to move the sand, and freedom of the sand to move. Therefore, semi-arid to arid areas, possessing the three requirements, would provide the best sites for developing and testing the model. It would provide an opportunity for the variables to fluctuate and interact independent of the limitations present in more humid environs.

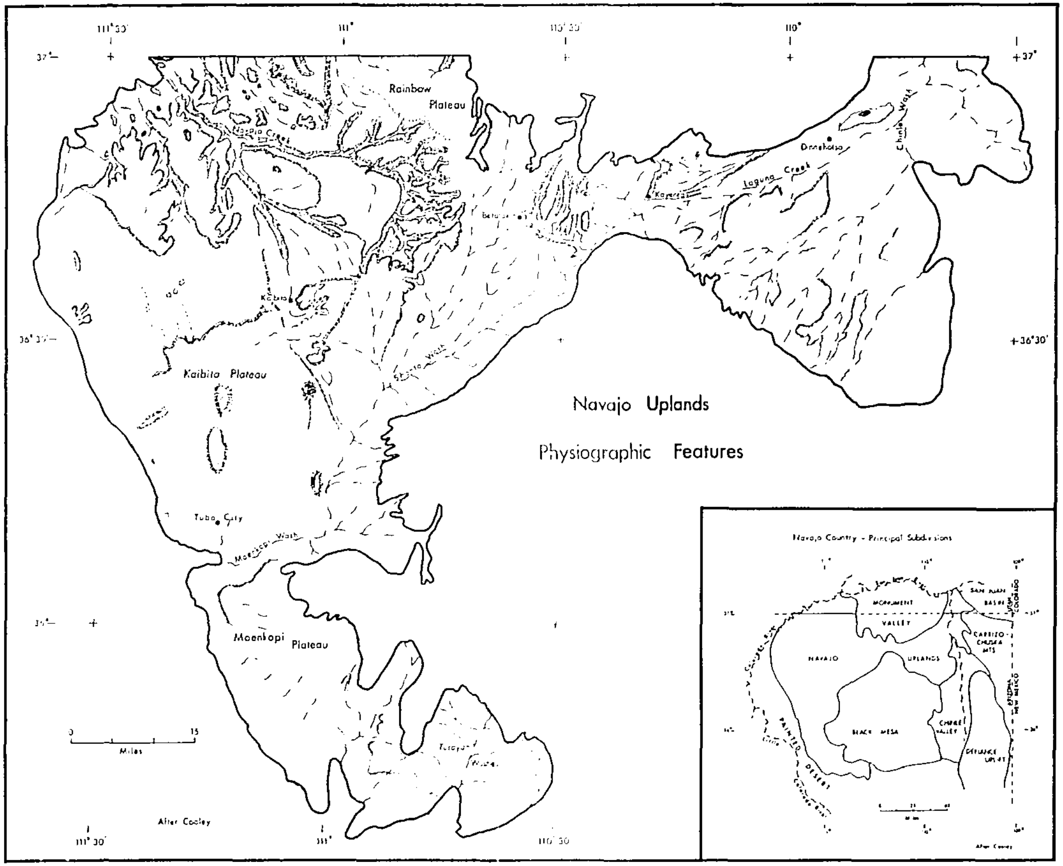
The model requires a research area where significant fluctuations take place within the selected variables, as well as a location where scattered dunes occur. Areas Hack (1941), Peltier (1950), and Bagnold (1941) considered most suitable for dune formation are semi-arid to arid locations. In Hack's article (1941), "Dunes of the Western Navajo Country," his ideas on dune characteristics were applied to a specific area where dunes were numerous and a variety of types were present. Hack (1941, 240) stated: "Their development depends on the ability of the vegetation cover to resist the movement of the sand." As a result of the comments on dunes by Bagnold (1941) as well as other eolian geomorphologists and the specific research conducted by Hack (1941), it appeared that a portion of the Navajo Country was well suited for the proposed model development and testing and was selected as the study area.

The area selected was a portion of the Navajo Uplands in Northeastern Arizona. Its geomorphic, meteorologic, and lithologic features vary to the extent that they provide a suitable basis for their investigation with regard to dune occurrence. The following brief discussion of selected characteristics should provide the reader with a general background of the study area.

The study area is included within the Colorado Plateau Physiographic Province, an area characterized by approximately horizontal rock formations, erosional as opposed to structural slopes, high elevations, steep canyons, arid climate, and sparse vegetation (Fenneman, 1931; Pirkle and Yoho, 1977; and Hunt, 1967). The physiographic province has been subdivided into sections, one of which is the Navajo Section.

The Navajo Section (Map 1) (Fenneman, 1931, and Hunt, 1967) or Navajo Country (Stokes, 1973) lies primarily in Northeastern Arizona and Northwestern New Mexico and includes a small area south of the San Juan River in Utah. It is characterized by nearly horizontal sandstone with scattered areas of shale (Navajo Sandstone and Carmel Formation), semi-arid to arid climate, elevations often between 5,000 and 7,000 feet, synclinal basins, cuestas, and dry washes (Pirkle and Yoho, 1977, and Fenneman, 1931). Durrenberger (1972, 214) described it as an area that "consists mainly of mesas separated by broad open valleys."

"The Navajo Section, a structural depression, is a young plateau with less relief than the Canyon Lands section to the north. It contains both anticlinal and 'laccolithic' uplifts and is characterized by mesas, buttes, escarpments, canyons, and dry washes" (Pirkle and Yoho, 1977, 260). Fenneman (1931, 312) described it as "mainly a country of sandstone with lesser amounts of shale. As the


Navajo Uplands
Physiographic Features
Rainbow Plateau
Kaibito Plateau
Moenkopi Plateau
Kaibito
Tuba City
Moenkopi Wash
Dennehotso
Laguna Creek
Chinle Wash
111°30'
111°
110°30'
110°
37°
36°30'
0
15
Miles
After Cooley
Navajo Country - Principal Subdivisions
MONUMENT
VALLEY
NAVAJO
UPLANDS
BLACK MESA
PAINTED DESERT

Map 1

beds are generally not quite horizontal and have been subject to great erosion in an arid climate, the mesa, cuesta, rock terrace, retreating escarpment, canyon and dry wash are the distinctive features of the landscape."

Stokes (1973, 61) described the Navajo Country as a "photogenic land" with "famous mesas, buttes, spires, canyons, dunes, and badlands." He believed that "the serious geomorphologist sees a landscape in transition from what has been to what will be," and that geomorphological work in the area has "laid a descriptive background that will be built upon with increasing perception by students armed with the tools of the quantitative geomorphologist."

The portion of the Navajo Country selected as a study area is the Navajo Uplands of Northeastern Arizona (Map 1). Stokes (1973, 62) described its physiography:

> The Navajo uplands occupies much of the northwestern corner of the region with a tapering wedge curving southward and southeastward almost to the Hopi Buttes. There is also an irregular arm to the north of the Black Mesa subdivision which takes in the valley of Laguna Creek and the lower reaches of Chinle Valley. As a practial matter the inner border of the cresent-shaped Navajo uplands is the base of the slope which leads up to Black Mesa.
>
> The bedrock of this tract is chiefly the Glen Canyon Group of which the Navajo Sandstone is the most widespread and conspicuous component. Much of the area is mantled by thin deposits of sand or sandy soil which is supplied in abundance by weathering of the bedrock.
>
> The elevation is generally between 4,000 and 6,500 feet. Navajo Mountain, reaching 10,388 feet, is the high point of the entire region. Except for Navajo Mountain the precipitation ranges between 6 and 14 inches. Reactions between the prevailingly sandy formations and the agents of weathering and erosion has produced a combination of barren "slickrock" surfaces

> laced with deep gorges eroded below the general level of the terraced surface. The famous ruins of Inscription House, Betatakin and Keet Seel are found in secluded canyons of the Navajo Sandstone. Drainage is chiefly northward into the Colorado River but large tracts are essentially undrained because the meager run-off is absorbed into the prevailing sandy regolith.

Cooley (1969, A24) described the Navajo Uplands as "...an area of dunes and stripped plains that forms an embossed surface on the Navajo Sandstone between the brinks of canyons at the bases of mesas." Fenneman (1931, 313) follows Gregory's (1916) divisions and has divided the Navajo Uplands into numerous subdivisions. They include all or a portion of: Northern Chinle Valley, Segi Mesas, Shonto Plateau, Kaibito Plateau, Moenkopi Plateau, and Tusayan Washes (Dinnebito, Oraibi, Polacca, and Jadito). Current published material tends to eliminate the subdivisions of the Navajo Uplands (Hunt, 1967, and Pirkle and Yoho, 1977) and instead refer to Fenneman (1931), Gregory (1916) or Atwood (1939) for references to specific portions of the province.

Navajo Sandstone (itself a wind blown deposit), the upper portion of the Glen Canyon Group, underlies much of the study area. It is an even-grained, wind-deposited sandstone displaying large-scale crossbeds. Isolated areas of the Carmel Formation, a red sandstone and siltstone, occur primarily in the northwestern portion of the study area (Cooley, 1969). Weathering of the bedrock has supplied the area with a thin covering of sand and sandy soil (Stokes, 1973). The weathered materials, originally eolian in nature, provide excellent material for new dunes.

Vegetation

The natural vegetation of the area includes a variety of plants, shrubs and trees. Their distribution is determined by temperatures and available water supplies, which in turn are affected by elevation, slope aspect, and the climatic characteristics of the area.

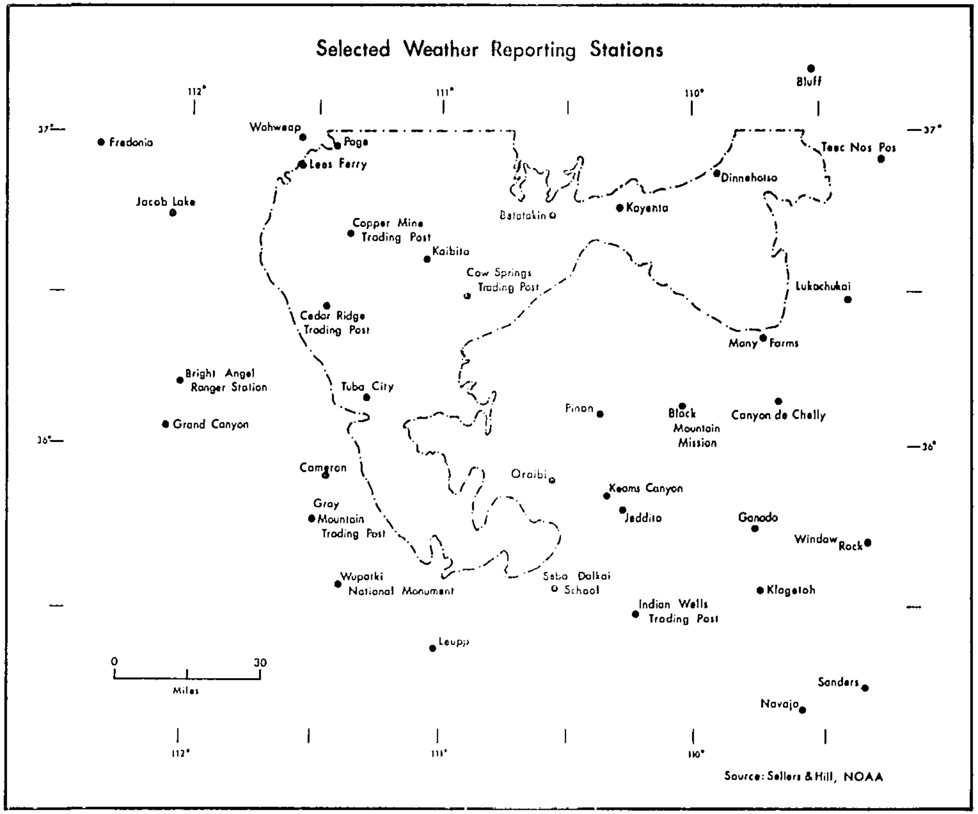
In the higher elevations, from approximately 5,000 to 7,000 feet, scattered Junipers (Juniperus utahensis) and Piñon pines (Pinus cimbroides) are found (Fenneman, 1931; Johnson, 1975; Hunt, 1967; and Sellers and Hill, 1974). Species found by Hack (1941, 251) as well as Boyce (1974, 253) are indicated in Appendix I.

Locations along stream courses characteristically are dominated by phreatophytes. Stands of cottonwood, sacaton grass, willow, rabbitbrush, and salt cedar are common (Johnson, 1975, and Hunt, 1967). Along dry channels, where runoff collects, Juniper and piñon pine extend into the sagebrush and grassland vegetation zones (Hunt, 1967).

Climatic Characteristics

Climatic characteristics of the Navajo Uplands vary according to latitude and elevation. The number of reporting stations in the Navajo Country limits the amount of data available. However, general characteristics are evident. Reporting stations in or near the study area are indicated on Map 2.

Map 2


Selected Weather Reporting Stations
112°
111°
110°
37°
36°
Bluff
Fredonia
Wahweap
Page
Lees Ferry
Teec Nos Pos
Dinnehotso
Jacob Lake
Betatakin
Kayenta
Copper Mine Trading Post
Kaibito
Cow Springs Trading Post
Lukachukai
Cedar Ridge Trading Post
Many Farms
Bright Angel Ranger Station
Tuba City
Pinon
Black Mountain Mission
Canyon de Chelly
Grand Canyon
Cameron
Oraibi
Keams Canyon
Gray Mountain Trading Post
Jeddito
Ganado
Window Rock
Wupatki National Monument
Saba Dalkai School
Klagetoh
Indian Wells Trading Post
Leupp
0
30
Miles
Sanders
Navajo
Source: Sellers & Hill, NOAA

Climatologically the research area straddles a Steppe-Desert border. Many of the lower elevations fall in the BW Koeppen classification (Tuba City, Wapatki, and Bluff), while the areas with slightly higher elevations benefit from orographic precipitation as well as lower temperatures and fall within the BS (Steppe) area (Betatakin, Kayenta, Kaibito, and Chinle (Map 2 and Appendix II).

Precipitation totals and distributions are indicated in Appendix II. Monthly precipitation characteristics indicate a bimodal distribution with summer maximum amounts occurring in July and August and winter maximums from December to March. The bimodal nature of the distribution may be due to the moisture source during each season.

Much of the moisture for the summer precipitation originates from the tropical maritime Gulf of Mexico air masses and is convectional in nature (Sellers and Hill, 1974; Jurwitz, 1953; Trewartha, 1961; and Johnson, 1975). The moisture comes "sweeping into Arizona from the southeast around a high pressure cell protruding into the central part of the United States from the Atlantic Ocean" (Sellers and Hill, 1974, 10). According to Sellers and Hill (1974), ideal conditions for such a moisture influx and associated afternoon thunderstorms would consist of a surface high pressure cell centered over the Tennessee-North Carolina border combined with a high at the 500 millibar pressure level centered over northern Texas or western Oklahoma. Sellers and Hill (1974) believed that in addition to the mean flow patterns the convective precipitation characteristics are substantiated by: (1) the greater totals in eastern Arizona closer to the moisture source, (2) the abrupt, intermittant nature of the precipitation, and (3) the late afternoon maximum-morning minimum occurrence of the precipitation. Johnson (1975, 33) believed that the summer thunderstorms of longest duration and, therefore, greatest accumulation are the result of "rare surges of moist, tropical air from the Gulf of California moving into the state from the southwest." Sellers and Hill (1974) believed such influxes produce record precipitation amounts and usually occur in August and September as an aftermath of tropical hurricanes originating off the west coast of Mexico. They also believe similar conditions may result from occasional tropical hurricanes moving west off the Gulf of Mexico.

Winter precipitation is primarily the result of cyclonic storms and moisture brought into the area from the Pacific Ocean (Sellers and Hill, 1974; Trewartha, 1961; Jurwitz, 1953; and Johnson, 1975). When the storm centers come ashore on a northerly track in Washington and Oregon, they produce little precipitation in the study area. However, if they pass south of San Francisco, amounts of rainfall are greater. Such storms usually produce light to moderate amounts of precipitation and may last up to two days in length (Sellers and Hill, 1974). Occasionally, winter storms may stagnate and intensify off the California coast. When they move onshore precipitation intensity may be comparable to that occurring during summer convectional storms (Sellers and Hill, 1974).

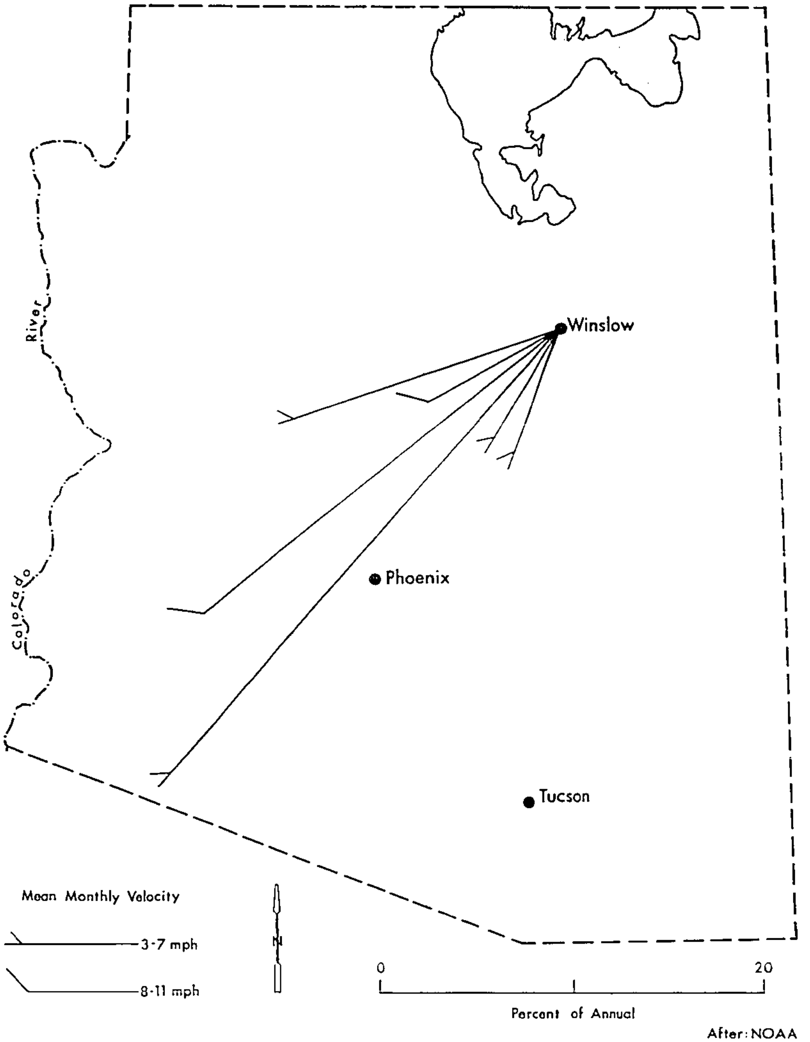
Mean monthly and annual temperature characteristics are indicated in Appendix II. Fahrenheit temperature averages for reporting stations in the study area are in the upper 20's to low 30's in January while July means vary from the low 70's to approximately 80°F. Mean annual temperatures are in the 50's.

The continental location is responsible for the annual range, while diurnal ranges of 30°F to 45°F throughout the year are due to high elevations, low water vapor content of the atmosphere, and large amounts of sunshine (Johnson, 1975, 25).

The effects of wind on the landscape are present in nearly all areas. Typical southwest-northeast patterns are widespread. Hack (1941, 240) commented on the force and consistency of the wind: "The strong winds blow almost constantly from one direction, the southwest." The accompanying wind rose constructed for the nearest station with wind data, Winslow, Arizona, indicates direction and velocity characteristics for 1973 (Map 3). Strongest winds occur in spring, the time of lowest precipitation amounts (Hack, 1941).

Winslow, Arizona 1973

Annual Wind Rose



Map 3

Dune Types

Wind blown sand accumulations take a variety of forms. The attempted classification of those forms into categories has occupied the time of numerous individuals. McKee (1979) believed that geomorphologists are faced with selecting either a local term, adapting one from another area, or selecting a new one to describe dunes of specific areas. He believed that the two principle attempts at classification were those of Melton (1940), "A Tentative Classification of Sand Dunes: Its Application to Dune History in the Southern High Plains," and Hack (1941), "Dunes of the Western Navajo Country." Since the purpose of this research is to determine dune site characteristics rather than dune type categorization, Hack's classification and terminology will be followed. The categories described by Hack (1941) tend to be repeated in numerous areas throughout the study area. Wilson (1972, 173) commented on the repetitious nature of dunes. "Surfaces of wind-laid deposits are almost invariably formed into a regularly repeated pattern of one size or another."

Dunes, as Bagnold (1954, 88) described them, "may be defined as a mound or hill of sand which rises to a single summit," and, according to Wilson (1972, 173), "form whenever a wind blowing over a sandy surface is strong enough to move sand." In the Navajo Country four dune shapes predominate: transverse, parabolic, barchan, and longitudinal (Figure 3). The four types (Hack [1941] believed there are

Study Area Dune Types

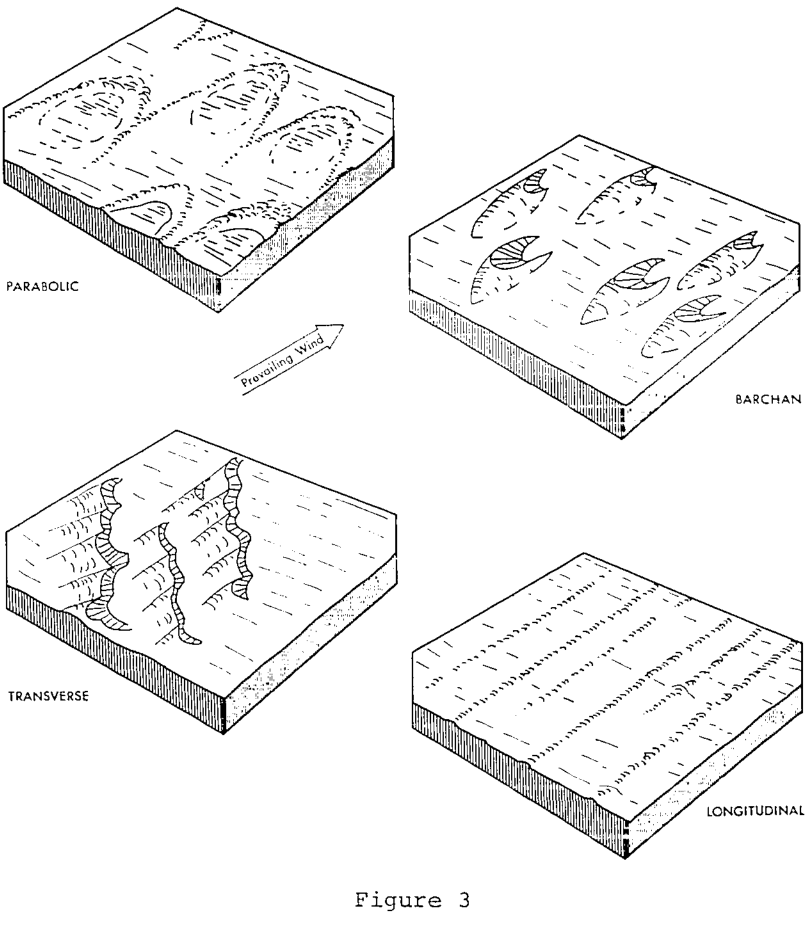


Figure 3

three with barchans being a type of transverse dune) "occur side by side, under the same conditions of wind and climate" (Hack, 1941, 240).

Parabolic dunes are the result of "the removal of sand from the windward hollows by the wind and the deposition of sand on the leeward slopes" (Hack, 1941, 242). The results are "long, scoop-shaped hollows or parabolas of sand with points tapering to windward" (Hack, 1941, 242). Hack also stated that, in addition to arid environments, such dunes may be found along coastal locations where they are often called "blowout" dunes. He goes on to say that in the Navajo Country such dunes may be the result of either deflation or accumulation.

Hack's (1941) description of parabolic dunes closely coincides with the description given by Butzer (1976, 387) when he described them as dunes "with a sand ridge located downwind of a deflation scar, the arms pointing upwind." Ruhe (1975, 155) described them as U-shaped and stated that: "The closed end points downwind." He further explained: "Deflation on the windward slope forms a blowout depression, and sand is transported across the crest and dumped down the slipface."

Hack (1941, 243) described the longitudinal dunes of the Navajo Country as "long, narrow ridges of sand which extend in a direction parallel to that of the prevailing wind. In the Navajo Country they are generally 6-30 feet high, from 200 feet to several miles long, and about 300 feet apart."

Hack's description corresponds to Ruhe's (1975, 155) belief that longitudinal dunes are "long, parallel ridges aligned with wind direction." Butzer (1976, 388) described them as "sinuous ridges running parallel with the effective wind direction."

Hack (1941, 241) described a barchan as a "crescent-shaped dune whose tail or tip points to leeward." He believed that large numbers of them may merge into "waves of sand," which resemble "gigantic ripple marks with steep leeward slopes and gentle windward slopes." Due to that relationship he considered barchans as a type of transverse dune. Wilson (1972, 181) agreed and indicated that barchans are "the normal development of any transverse sandy ridge isolated on a sand free basement." He believed they are quite common and "can be found in snow, gypsum or limestone sand as well as quartz sand."

Hack's description closely coincided with that of Ruhe (1975, 157). "The ground plan of barchan dunes is crescent-shaped with a convex trailing edge but with the crescent's horns pointing downwind." Butzer (1976, 388) considered them "crescent-shaped...with horns facing downwind."

The transverse dunes of the Navajo Country as described by Hack (1941) are comparable to "waves of sand." Ruhe

(1975, 154) considered transverse dunes to be "ridges of sand whose parallel crests are perpendicular to wind direction and whose profile has a gentle windward slope and a steeper leeward slipface. Parallel ridge crests are usually evenly spaced." Butzer (1976, 288) stated that transverse dunes are the result of merging barchans and are ridges "running perpendicular to the effective wind direction."

People on the Land

The study area is included almost entirely within the Navajo Indian Reservation. A small portion is contained within the Hopi Reservation. The intent of the research was to consider only physical variables in the construction of the model. That decision was made in part due to the uniform human pressures applied to the study area by the inhabitants of the area. However, a brief summary of their history and land use practices may facilitate a general understanding of their influence upon the land.

The Navajos were "late arrivals" in the Southwest. The land had already experienced "the Folsom, the Cochise, the Hohokam, the Salado, and others" (Terrell, 1970, 8) prior to their arrival. "...it was the Anasazi, or Basket Maker-Pueblo, civilization that more than any other influenced the lives of the Navajos and shaped their history" (Terrell, 1970, 8). Evidence of the Anasazi culture remains evident today in ruins located on the Reservation (Terrell, 1970).

From the Pueblo people the Navajo learned agricultural practices, weaving, and the use of tools. Those products which could not be produced were obtained by staging raids into surrounding areas or by trading. In 1583 Antonio de Espejo lead a group of Spanish into the Navajo lands. He stated that the Navajo "carry on trade with those of the settlements, taking to them salt, game, such as deer, rabbits, and hares, tanned deerskins, and other things, to trade for cotton, mantas, and other things" (Terrell, 1970, 22).

That initial Spanish contact exposed the Navajo to horses--the first exposure to domestic livestock. In addition to horses, the Spanish soon introduced other domestic livestock. "...the greatest revolution in Navaho economy was that consequent upon the introduction of domestic animals and the associated trait-complex of saddles, bridles, branding, shearing, and the like" (Kluckhohn and Leighton, 1962, 37).

While horses increased the Navajo mobility,

> Sheep and goats, which had been brought into the Southwest by the Spaniards, provided a larger and more dependable food supply, and this was a fundamental condition of Navaho population increase. Furthermore, livestock animals, wool and mohair, hides, and woolen textiles revolutionized Navaho economy in another way: they supplied a steady source of salable or exchangeable wealth, permitting the acquisition of metal tools and other manufactured articles. Surpluses were now more than occasional, and they ceased to be disposed of mainly by intra- and inter-tribal gift and exchange. As the bounds of trade were thus widened, a whole new series of demands for goods from the European world was gradually

created. Finally livestock formed the basis for a transition to a capitalistic economy, with new goals for individuals and for family groups, a new system of social stratification and prestige hierarchy, an altered set of values (Kluckhohn and Leighton, 1962, 39).

Rapid increases in livestock densities did not begin until a relatively stable period beginning in 1868, five years after Colonel Kit Carson's orders in June of 1863 to destroy all Navajo crops and livestock (Kluckhohn and Leighton, 1962, and Meinig, 1971). Government estimates indicate changes in population and livestock numbers (Terrell, 1970, 245):

Year	Population	Sheep	Cattle	Goats	Horses
1869	8,181*	30,000			
1872	9,114	130,000			10,000
1875	11,768	175,000	2,500	30,000	14,000
1879	14,000**	500,000	1,600	40,000	22,500
1880		700,000			40,000

*Later studies indicated it was at least 3,000 more.
**A few months later it was estimated at 16,000.

Terrell (1970, 245) believed those figures on livestock increases "tell an amazing story of a people's determination and courage that appalling adversities had failed to destroy." Downs (1972, 12) explained the relationship between increased herd size and labor demands. "Because herds of livestock can be increased without increasing the demands for labor, many Navajo began to hold very large herds of sheep, goats, and horses."

It was apparent that the Navajo had become pastoral people. By the 1890's it became evident that the heavy dependence upon grazing by the Navajo was causing soil erosion and a reduction in the range quality (Terrell, 1970, and Kelly, 1968). "The result was that poorer animals were being produced. Overgrazing was destroying ground cover" (Terrell, 1970, 287). Father Anselm Weber, a missionary at St. Michaels, Arizona, described the range conditions in 1912 (Terrell, 1970, 289):

> "The Navajo Reservation is stocked heavier and its range is more overgrazed and run down than the range in other parts of Arizona and New Mexico. The Navajos have 1,800,000 head of sheep and goats, and if other classes of livestock (horses, cattle, mules, and burros) were converted to sheep units there are 2,328,000.
>
> As a result, the soil is eroding badly in many places...Over considerable areas very little plant life is left, except sagebrush, scrub juniper and pinon. The former heavy stand of gramma grass over much of this region is nearly extinct."

The concentration of grazing livestock, and the resulting range deterioration, has resulted in several attempts at reducing their numbers. In November, 1928, the Assistant Indian Commissioner, A. B. Merritt, and District Superintendent, Chester E. Faris, tried to convince the Navajo Tribal Council to provide a more equitable distribution of the livestock among the tribal members as well as limited the number of livestock per individual. "Their plan was not only foolish...but totally impractical (Terrell, 1970, 296).

In 1930 William Zeh took "the first critical look at the depletion of the Navajo range resources" (Roessel, 1974, 219). His studies found that overgrazing was common (a situation brought to the attention of Congress by H. J. Hagerman), and recommended that corrective measures be taken. His recommendations were mild compared to those that followed. He "did not recommend reduction of sheep or horses--only culling of flocks and reduction of surplus goats" (Roessel, 1974, 219).

John Collier, Commissioner of Indian Affairs, was appointed by Franklin D. Roosevelt in 1933. Through his efforts an experiment station established at Mexican Springs found that the Navajo Reservation, through proper range management, could adequately support less than one-half the number of sheep found there at that time. The findings created a shock, for to the Navajo "large herds were not simply sources of meat, wool, and money, but status symbols, symbols of a life that was right and proper. Most important of all, animals, especially sheep and horses, were significantly symbolic in their culture and religious beliefs" (Terrell, 1970, 299). Similar statements were expressed by Kelly (1968) and Young (1961).

The Navajo belief was:

> ...that livestock was a gift from the Holy People. The Holy People watched with pleasure and bestowed their blessings--rain and vegetation--upon the increasing flocks of animals. They were glad to see the Navajos care for these gifts and to see the livestock multiply. Reduction in itself, and particularly when combined with the cruel and inhumane slaughter of these sacred gifts, repelled and shocked Navajos (Roessel, 1974, 224).

The Navajo had "deep-seated antagonism" toward

Collier, primarily as a result of the stock reduction program (Boyce, 1974, 54). One can appreciate the misgivings the Navajo had regarding Collier's contradictory attempts at stock control. In the spring of 1933 he had convinced Congress to appropriate $410,000 in relief appropriations to help cover damage and losses suffered during the previous harsh winter when 150,000 sheep had frozen to death. In the fall of that same year he proposed a program to reduce the number of livestock on the range land (Kelly, 1968).

The program was plagued by "prolonged wrangling," poor management, red tape, and conflicting regulations on the part of the government, and emotional outbursts, anger, fright, and suspicion on the part of the Navajo (Terrell, 1970, 299).

> Although the opposition of the Navajos to the stock-reduction, soil-conservation, and restricted-grazing programs would not subside with the passage of years--the controversy continues as these words are written--it is indisputable that many benefits have been derived from them. Large herds of useless horses no longer consume valuable forage. Through breeding experiments conducted at government stations a sheep has been developed that is vastly superior in every way to the animal grazed in the past. Wool production has been increased at least 40 percent. Lambs are heavier. Meat is high grade (Terrell, 1970, 303).

Aberle (1944) considered the livestock reduction to be the most devastating experience the Navajo had suffered since their imprisonment at Fort Sumner. He believed that, based on 1930 per capita holdings, the Navajo had lost 80% of their animal holdings by 1959. Roessel (1974) believed losses were nearer 65%. According to Young (1961, 167), total mature sheep units totaled 1,862,500 in 1928. That number declined to 433,983 in 1952.

In addition to grazing activities, other agricultural endeavors are limited in extent by the length of the growing season and available water supplies. As a result, non-pastoral agricultural areas are scattered and localized.

The problems of past agricultural practices are evident today. Those resulting from grazing pressures continue on both human populations (estimated to be over 160,000 [Bureau of Indian Affairs]) and their associated livestock numbers.

Conclusion

The diverse physical nature of the study area allows for a wide range of possible combinations of environmental characteristics. That environmental diversity, in combination with the scattered distribution of dunes, would appear to be an acceptable area to develop and test a model for dune location prediction based upon the selected environmental features.

Now that the research problem and the study area have been described, it is appropriate that we move to the identification of and rationale for the variables necessary for model development.

CHAPTER III

VARIABLE SELECTION AND JUSTIFICATION

The initial portion of this research paper dealt with the identification of the research problem, while the second chapter was concerned with the selection and description of the study area. Upon completion of those requirements the next logical consideration appears to be the selection and justification of the variables to be considered in developing the model.

The focus of this research is to ascertain the relationships that exist between selected, measurable geomorphic, meteorologic, and lithologic variables and dune occurrence on the Navajo Uplands of Northeastern Arizona and to use those relationships to develop a model capable of predicting dune occurrence based on the characteristics of specific sites.

One of the values of models, as Chorley and Haggett stated, is "that prediction can be made about the real world" (1967, 23) and that they can be used to "explain how a particular phenomena comes about" (1967, 24). They go on to state that normative models are concerned with "what might be expected to occur under certain stated conditions" (1967, 25).

In order to accurately fulfill the predictive powers of models as indicated by Chorley and Haggett (1967) it is essential that variables be selected that may contribute to the occurrence of dunes. Hack (1941) and Bloom (1978) stated that dune formation requires: (a) a sand supply, (b) an effective transporting agent, and (c) the freedom of that sand to move.

Within the study area the first requirement has been satisfied by the residual soils formed upon the sandstone bedrock (Cooley, 1969, and Hack, 1941), while the transporting agent or wind is also present (National Oceanic and Atmospheric Administration, 1973, and Sellers and Hill, 1974). The primary concern involves the third variable--the freedom of the sand grains to move.

Free movement of sand grains may be the result of several major groups of measurable variables. The groups used in the study--geomorphic, meteorologic, and lithologic--may be subdivided to facilitate their understanding and for model development.

An important variable, in many cases a surrogate, for dune occurrence in an area with available sand supplies and a transporting agent is the presence or absence of vegetative cover. Vegetation, as Hack (1941) described it, is responsible for holding soil in place. The relationships between dune occurrence and characteristics of the vegetative cover have been indicated by biologists and geomorphologists. Bagnold (1954, 168) stated: "The most typical kind of country on which desert dunes are found is a flat erosional surface, so arid that the complications introduced by rainfall and vegetation are negligible." Smith (1971, 109) claimed that: "A single clump of bunchgrass (Agropyron spicatum) may have two miles of fine roots within the four cubic feet of soil where it grows." Thus in order to better understand dune occurrence it is essential to consider some of the variables that affect the vegetative cover. If vegetation were the dependent variable, the independent variables should probably include climatologic, lithologic, and geomorphic features which have an effect upon plants and associated soil stability.

All the listed variables may affect vegetation characteristics. If, however, a single variable from the group was extended beyond the range of tolerance for the vegetative cover, that variable would then be responsible for ground cover destruction and possible dune occurrence. Even though all other variables were well within the limits of tolerance of the specific vegetation association, the one that was not becomes the most important (Shelford's Law) (Odum, 1971). Ground cover characteristics result from the interactions of several variables; for as one variable approaches the critical value of excess or deficiency, the plant becomes less tolerant of departures from the optimum in others (Watts, 1971, and Odum, 1971). Dunes, then, are obviously an expression of a series of variables and their interactions rather than just one.

Groups of variables were selected with a concern for Bloom (1978) and Hack's (1941) beliefs relating to requirements for dune formation and Bagnold's (1941) beliefs on factors affecting wind as a transporting and depositional geomorphic agent. An organized systematic process was used in selecting the variables used to determine the relationship between dune occurrence and the environment. The conclusions reached, after investigating a number of selected supportive hypotheses, were used to analyze the research hypothesis. The supportive hypotheses, their reasons for selection, and their relationship to the study area are discussed in the following material.

Research Hypothesis

Research Hypothesis: There is a significant relationship between selected, measurable geomorphic, meteorologic, and lithologic phenomena on the Navajo Uplands of Northeastern Arizona and the occurrence of dunes and that relationship can be utilized to develop a model to predict dune occurrence at selected locations throughout the study area.

Null and Supportive Hypotheses

Precipitation-Dune Relationships

H_0 1 Dune occurrence on the Navajo Uplands of Northeastern Arizona is not related to mean annual precipitation amounts.

H_1 1 There is a positive relationship between mean annual precipitation amounts and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_2 1 There is an inverse relationship between mean annual precipitation amounts and dune occurrence on the Navajo Uplands of Northeastern Arizona.

One of the most important, if not the most important, control over vegetation is water. Nearly every plant process is affected in one way or another by the available water supply. Respiration, cell growth, cell turgidity, photosynthesis, food transportation, and gas exchange are all related directly to moisture availability (Tivy, 1971; Slatyer, 1967; and Rosenberg, 1974). Where moisture amounts are less than that required for optimum plant growth, the quality and/or quantity is diminished.

The relationship between precipitation totals and the occurrence of dunes has been stated by Hack (1941), Mabbutt (1977), Bagnold (1954), and Cooke and Warren (1973). Peel (1960, 261), when discussing arid area geomorphology, stated: "Much information points to the conclusion that the greater the aridity, the less actually happens apart from the action of wind..."

Most plant functions are related to the availability of water as stated by Tivy (1961), Slatyer (1967), and Rosenberg (1974), and their roots are responsible for holding soil in place, as stated by Smith (1971) and Laetsch (1979). One can readily agree with Bagnold's (1954, 168) conclusion that dunes are most likely where conditions are "...so arid that the complications introduced by rainfall and vegetation are negligible." Rosenberg (1974, 159) agreed, stating: "Water availability is probably the factor most critical in determining plant survival, development, and ultimate productivity."

Several attempts were made to ascertain the relationship between water availability and dunes. The first was to consider mean annual precipitation totals as a possible variable. A portion of those totals accumulate outside the growing season and may not contribute immediately to vegetative growth. However, part of that moisture may be stored in the soil for possible later use by plants (Gray, 1973).

Mean annual precipitation totals for specific sites are somewhat difficult to determine. Cooley (1969), in his study of the regional hydrology of the Navajo and Hopi Reservations, believed that annual totals are "related to altitude and orographic effects." He did not indicate exactly what those relationships might be, however. Johnson (1975), in his study of the Little Colorado River Basin, attempted to determine winter precipitation totals based upon elevation. His relationship was determined to be:

$$Y = -10.45 + .0028X$$

Y - annual precipitation in inches
X - elevation in feet

Johnson's coefficient of determination (R^2) was computed to be .66 which led him to believe "obviously, other factors... are significant" (1975, 38).

Goodman, however, was more successful in the use of elevation and wind/slope relationships as predictors of mean annual precipitation totals in his analysis of vegetation on the Navajo Reservation. His findings indicated that on windward slopes and on leeward slopes simple regression could be used to predict mean annual precipitation and associated vegetative patterns.

The values used in the study were interpolated from Figure 4, an isohyetal map prepared by Hiatt (1953) (and used by Cooley) who utilized a series of relationships between precipitation and the effects of elevation and topography upon seasonal and annual precipitation to determine the locations of the isohyets. He believed a stronger relationship between elevation and precipitation occurred during summer than during winter (1953, 197).

In addition to the mean annual totals, additional variables expressing precipitation characteristics may be important. For that reason, the second variable, relating to the distribution during the growing season, was chosen.

Precipitation distribution during the growing season was determined from National Oceanic and Atmospheric Administration (1973) data relating to the mean number of days per month with precipitation totals equal to or greater than

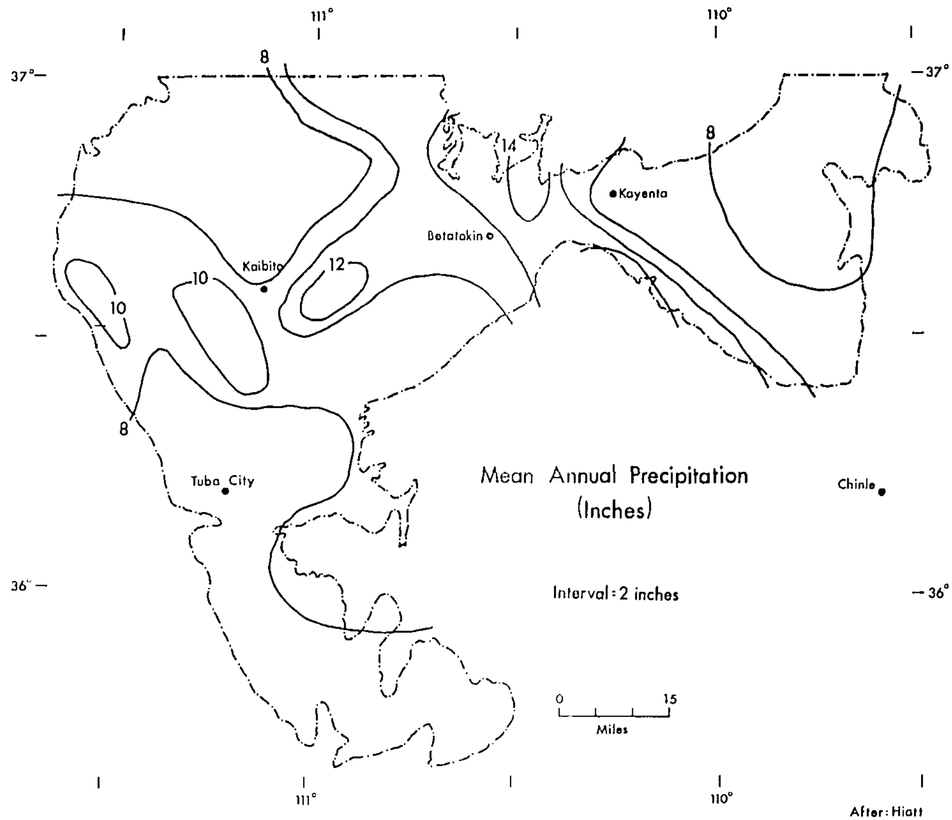

111°
110°
37°
36°
8
10
12
14
Kaibito
Betatakin
Kayenta
Tuba City
Chinle
Mean Annual Precipitation
(Inches)
Interval: 2 inches
0
15
Miles
After: Hiatt

Figure 4

0.01, 0.10, and 0.50 inches. The value of 0.10 inches was chosen for consideration in the model development. The choice was based upon the conditions that the number of days receiving 0.50 inches was so limited that little value could be gained by its use, while a value of 0.01 inches was an amount too insignificant to benefit the vegetative cover. (Thornthwaite [1948] stated that moisture must penetrate to the root level to affect plant growth.) The number of days with 0.10 inches or more was most indicative of the distribution of precipitation during the growing season.

H_0 2 Dune occurrence on the Navajo Uplands of Northeastern Arizona is not related to the number of growing season days with greater than 0.10 inches of precipitation.

H_1 2 There is a positive relationship between the number of growing season days with greater than 0.10 inches of precipitation and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_2 2 There is an inverse relationship between the number of growing season days with greater than 0.10 inches of precipitation and dune occurrence on the Navajo Uplands of Northeastern Arizona.

Precipitation values for selected sites were obtained from interpolation of isohyets plotted by the SYMAP computer mapping program. Vertices for 10 sites within the study area as well as 24 sites outside its boundaries were used as B-data points in the mapping routine.

H_0 3 Dune occurrence on the Navajo Uplands of Northeastern Arizona is not related to mean growing season precipitation.

H_1 3 There is a positive relationship between mean growing season precipitation and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_2 3 There is an inverse relationship between mean growing season precipitation and dune occurrence on the Navajo Uplands of Northeastern Arizona.

A third precipitation variable selected for possible inclusion in model development was mean growing season precipitation. Growing season was defined as the mean length of time from the last 32°F temperature of spring until the first 32°F temperature of fall. While all plant species of the study area may not be limited by those temperatures, the values obtained for specific sites may be useful for comparative purposes.

A portion of the precipitation occurring during the growing season contributes to the plants' growth and general health (Tivy, 1971; Slatyer, 1967; Rosenberg, 1974; and Laetsch, 1979). Therefore, precipitation totals during the growing season affect the ability of plants and plant roots to prevent soil erosion.

The author is well aware of the limitations in attempting to deal with growing season precipitation distribution and its availability to plants. Some of the problems are described by Tivy (1971, 55):

> The problems of defining the growing season in terms of the moisture available for plant growth are exceedingly difficult and have not been, as yet, satisfactorily solved. Plants vary in their minimum water requirements and also in their ability to tap soil- and ground-water supplies. Moisture becomes critical for growth when the amount available in the soil drops below

that necessary to make good the loss by transpiration. This value is dependent not just on the amount but on the effectiveness of the precipitation a place receives, and the latter, as we have already noted, is a function of a variety of interrelated factors among the most important of which are those which influence evaporation and transpiration.

Growing season precipitation values were determined for the same 34 sites indicated in Supportive Hypotheses 3. Those values were then used in the isohyetal mapping routine previously described. The values for selected sites were obtained from the SYMAP generated map.

Temperature-Dune Relationships

H_0 4 Dune occurrence on the Navajo Uplands of Northeastern Arizona is not related to mean annual temperature.

H_1 4 There is a positive relationship between mean annual temperature and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_2 4 There is an inverse relationship between mean annual temperature and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_0 5 Dune occurrence on the Navajo Uplands of Northeastern Arizona is not related to mean growing season temperature.

H_1 5 There is a positive relationship between mean growing season temperature and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_2 5 There is an inverse relationship between mean growing season temperature and dune occurrence on the Navajo Uplands of Northeastern Arizona.

A variable often considered inseparable from precipitation when discussing vegetation is temperature. It is difficult to consider its effects upon vegetation separately, for each is related to fluctuations in the other. The strong interwoven relationship that exists between temperature and vegetation was discussed by Thornthwaite (1948) and in more sophisticated recent studies by Daubenmire (1959), Gates (1968), Odum (1971), and Bidwell (1979). (Potential evapo-transpiration amounts vary across the study area as temperatures change; however, in warmer areas, amounts, according to Thornthwaite (1948), may be well into the mid 30 inch range.

In an attempt to ascertain the specific relationship between temperature features and the occurrence of dunes, two temperature variables were entered into the developmental phase of the model. An extensive variable indicating mean annual temperature and a more specific variable, mean growing season temperature, were considered.

The role of temperatures in, and its effects upon, vegetative cover and associated soil response to eolian processes in the study area is significant for as temperatures increase, the rate of water loss from the surface by evaporation increases. Gray (1970) discussed Penman's aerodynamic equation regarding evaporation and stated that air temperature is a prime factor in determining water loss in the evapo-transpiration process. Thornthwaite's (1948) model, as well as the Blaney-Criddle method (Gray, 1970) for estimating evapo-transpiration, considered temperature a critical variable.

Higher temperatures and the corresponding increase in water losses in the study area reduce the amount of vegetative growth. The implications of reduced vegetative growth are: (a) fewer roots to hold soils in place, and (b) less organic matter in the soil (Tivy, 1971). The reduction in plant root growth reduces the ability of the plants to hold soils in place. The reduction in organic material reduces the soil's water-holding capabilities, binding action, and ped formation, which results in a less desirable medium for plant growth (Tivy, 1971, and Cruickshank, 1972).

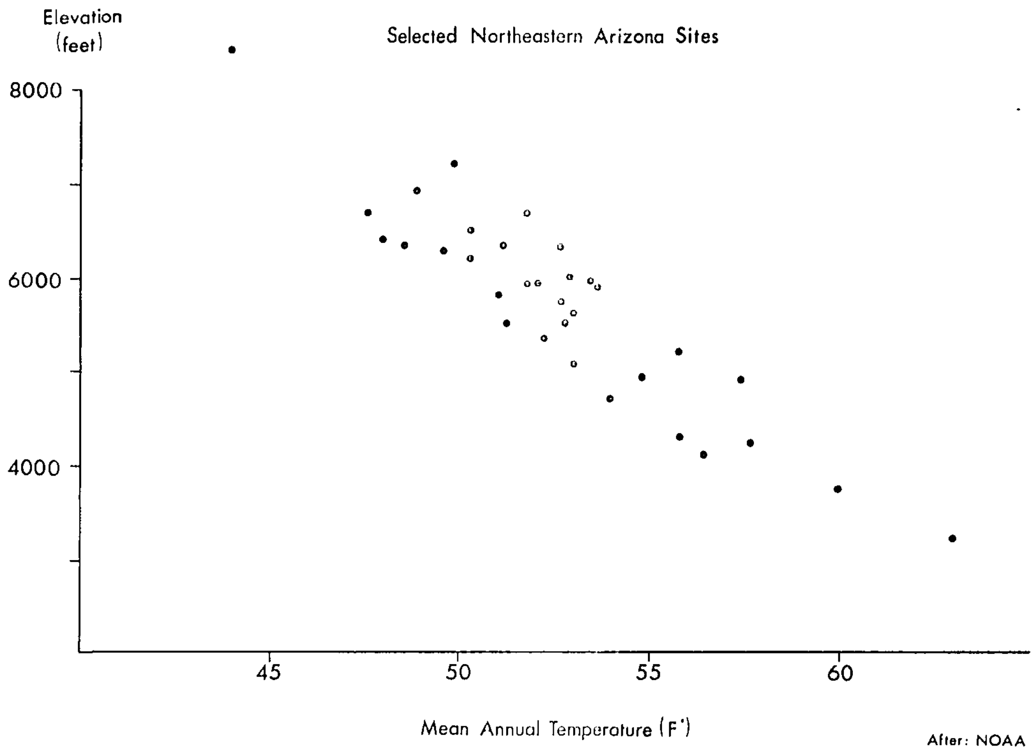
The size of the study area precludes large temperature ranges due to latitudinal differences. Instead, primary differences result from elevation variations.

Temperature values for specific sites were calculated from the data indicated in Graph 1. The process of computing mean annual temperatures from elevation values in the research area was used by both Cooley (1969) and Johnson (1975). Mean annual temperature values for reporting stations were obtained from both Sellers and Hill (1974) and National Oceanic and Atmospheric Administration (1973) data.

As the scatter diagram indicates, some values were over-estimated, while others were under-estimated. Johnson (1975) believed those anomalies are the result of air drainage due to topographic variances. Reporting stations with higher than expected temperatures, presumably, were the result of cold air draining downslope away from those sites.

Graph 1

ELEVATION – MEAN ANNUAL TEMPERATURE RELATIONSHIPS



Other stations which are the recipients of cold air drainage have lower than expected mean annual temperatures.

Slope-Wind-Dune Relationships

H_0 6 Dune occurrence on the Navajo Uplands of Northeastern Arizona is not related to the angle formed by the intersection of a vector indicating slope direction and a vector indicating mean annual wind direction, measured on a 0^o-360^o azimuthal basis.

H_1 6 There is a positive relationship between the angle formed by the intersection of a vector indicating slope direction and a vector indicating mean annual wind direction, measured on a 0^o-360^o azimuthal basis, and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_2 6 There is an inverse relationship between the angle formed by the intersection of a vector indicating slope direction and a vector indicating mean annual wind direction, measured on a 0^o-360^o azimuthal basis, and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_0 7 Dune occurrence on the Navajo Uplands of Northeastern Arizona is not related to the angle formed by the intersection of a vector indicating slope direction and a vector indicating the direction of the mean annual wind, measured on a 0^o-180^o basis.

H_1 7 There is a positive relationship between the angle formed by the intersection of a vector indicating slope direction and a vector indicating the direction of the mean annual wind, measured on a 0^o-180^o basis, and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_2 7 There is an inverse relationship between the angle formed by the intersection of a vector indicating slope direction and a vector indicating the direction of the mean annual wind, measured on a 0^o-180^o basis, and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_0 8 Dune occurrence on the Navajo Uplands of Northeastern Arizona is not related to the angle formed by the intersection of a vector indicating slope direction and a vector parallel to the direction of the mean annual wind, measured on a 0^{o}-90^{o} basis.

H_1 8 There is a positive relationship between the angle formed by the intersection of a vector indicating slope direction and a vector parallel to the direction of the mean annual wind, measured on a 0^{o}-90^{o} basis, and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_2 8 There is an inverse relationship between the angle formed by the intersection of a vector indicating slope direction and a vector parallel to the direction of the mean annual wind, measured on a 0^{o}-90^{o} basis, and dune occurrence on the Navajo Uplands of Northeastern Arizona.

In the study area, with its annual wind flow pattern (Map 3), the relationships that exist between that prevailing wind and lithologic and geomorphic features may be represented in specific dune locational patterns. The prevailing wind flow feature, for the purpose of this study, will be considered the "mean annual wind". The mean annual wind, an azimuthal value, was computed from data gathered at Winslow, Arizona, a nearby weather station collecting both directional and consistancy data on a monthly basis (Map 3). It was calculated by determining the mean of summed monthly azimuthal values weighted according to the frequency of occurrence.

Bagnold (1954) discussed the characteristics of wind movement over uneven surfaces and found surface velocities in the boundary layer to be affected by the drag resulting from uneven characteristics of the surface. Similar conditions of slopes and wind are discussed by Carson (1971) and by Rosenberg (1974). In an attempt to obtain an insight into the specific involvement between the slope direction-mean annual wind direction variable and the occurrence of dunes, three different methods of measurement were used (Figure 5).

The first technique (Figure 5A) measured the angle formed by the intersection of the slope and the mean annual wind direction as an azimuthal angle capable of ranging from 0^o to 360^o. That technique assumed that each angle was a unique value. As an example, a slope directly facing the mean annual wind direction would have an angle of 0^o while one sloping directly away would have a value of 180^o. An orthogonal slope to the left of the mean annual wind direction would have a value of 90^o while one to the right would have a value of 270^o.

The second technique (Figure 5B) considered the angle formed by the intersection of a line parallel to the slope and one parallel to the mean annual wind direction to be hemispheric and capable of ranging from 0^o to 180^o. That technique considered slopes with equal angular values to the right and those to the left of the mean annual wind direction to be equal in their relationship to dune occurrence.

The third technique (Figure 5C) considered the angle formed by the intersection of a line parallel to the slope and one parallel to the mean annual wind direction to be an acute angle in a quadrant. That technique considered slopes

Mean Annual Wind - Slope Measurement

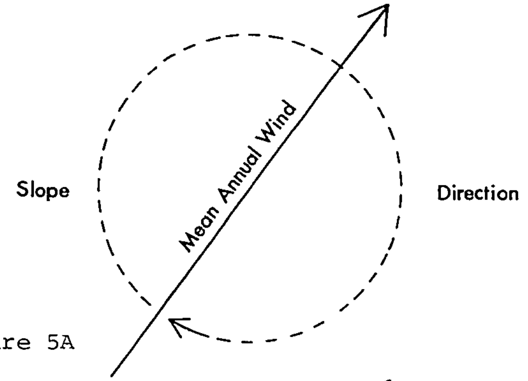


Figure 5A

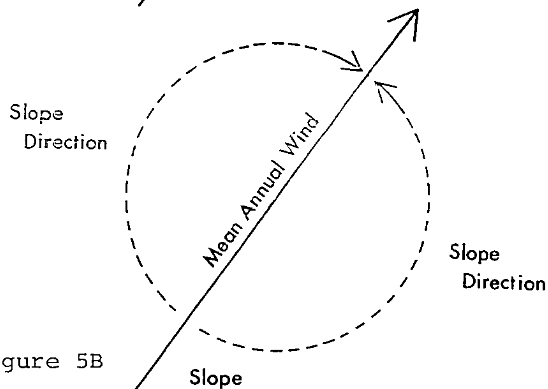


Figure 5B

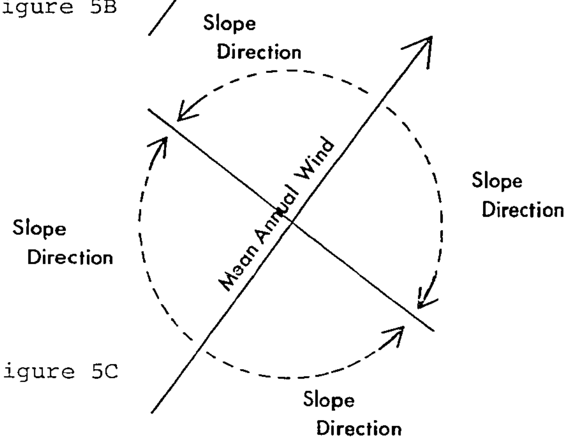


Figure 5C

of equal angular values to the right and to the left of the mean annual wind direction to be equal, as well as considered windward and leeward slopes with equal angular values to the mean annual wind direction to be equal.

Slope Aspect-Dune Relationships

H_0 9 Dune occurrence on the Navajo Uplands of Northeastern Arizona is not related to the angle formed by the intersection of a vector indicating south and a vector indicating slope direction, measured on a 0^o-180^o basis.

H_1 9 There is a positive relationship between the angle formed by the intersection of a vector indicating south and a vector indicating slope direction, measured on a 0^o-180^o basis, and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_2 9 There is an inverse relationship between the angle formed by the intersection of a vector indicating south and a vector indicating slope direction, measured on a 0^o-180^o basis, and dune occurrence on the Navajo Uplands of Northeastern Arizona.

Soil temperatures and the associated relationships with water and plant characteristics are affected by slope features. Within the latitudinal limits of the study area, slope and aspect are important especially during the growing season (Rosenberg, 1974). Rosenberg (1974, 145) analyzed the situation and believed that aspect and slope affect soil temperature and heat flux due to varying amounts of radiation absorption resulting from the "cosine effect". Lambert's cosine law states (Rosenberg, 1974, 11): "The radiant intensity (flux per unit solid angle) emitted in any direction from a unit radiating surface varies as the cosine of the angle between the normal to the surface and the direction of radiation." The more normal the sun's rays are to the surface, the more intense the radiation impinging on the surface. Aspect affects the heat flux in an obvious way. Those slopes that face the sun receive more energy per unit of surface area than those that face away from it.

Rosenberg (1974) described a number of factors resulting from changes in the angle of incidence of solar radiation that could affect vegetation and possible dune occurrence. They included:

1. changes in specular reflection
2. changes in evaporation rates
3. changes in soil temperature
4. alter the vegetation cover as a result of changes in evaporation and soil temperature characteristics
5. affect the rate of decomposition of organic matter in soil--which would change the vegetation cover.

Slope direction was obtained from the United States Geological Survey Topographic maps of the area and verified on the air photographs of the study area.

Bedrock-Dune Relationships

H_0 10 Dune occurrence on the Navajo Uplands of Northeastern Arizona is not related to the distance downwind from exposed bedrock.

H_1 10 There is a positive relationship between the distance downwind from exposed bedrock and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_2 10 There is an inverse relationship between the distance downwind from exposed bedrock and dune occurrence on the Navajo Uplands of Northeastern Arizona.

Distance to exposure of bedrock may serve two roles in the determination of dune locations. The first consideration was a source of sand for dune construction. Cooke and Warren (1973), Thornbury (1969), and Mabbutt (1977) have all discussed the location of sand dunes resulting from weathering of nearby sandstone bedrock. Their findings generally indicated that weathering of sandstone often provides a source for dunes. Cooke and Warren (1973, 256) stated that:

> Quartzose sand is abundant in deserts partly because many sedimentary rocks in deserts are sandstones (e. g. Brown, 1960; McKee, 1962; Monod and Cailleaux, 1945; Sandford, 1937). This in turn can be partly attributed to the continuing continental character of desert areas for long geological periods and the continuous loss of fine soluable material during that time.

The present dunes of the study area are probably recycled remnants of former dunes produced by breakdown of Navajo Sandstone. Locations close to the exposed sandstone bedrock may be more likely to be dune prone.

An additional relationship between exposed bedrock and dune occurrence may be a result of the effects of exposed bedrock upon wind flow patterns. Bedrock slightly elevated above the surface results in reduction in wind velocity as the air passes over the rock. As a result, accumulations of wind-transported material occur (Bagnold, 1954; Carson, 1971; and Mabbutt, 1977).

Slope Length-Dune Relationships

H_0 11 Dune occurrence on the Navajo Uplands of Northeastern Arizona is not related to slope length.

H_1 11 There is a positive relationship between slope length and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_2 11 There is an inverse relationship between slope length and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_0 12 Dune occurrence on the Navajo Uplands of Northeastern Arizona is not related to the distance upwind to the nearest drainage divide.

H_1 12 There is a positive relationship between the distance upwind to the nearest drainage divide and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_2 12 There is an inverse relationship between the distance upwind to the nearest drainage divide and dune occurrence on the Navajo Uplands of Northeastern Arizona.

The total length of the slope as well as the location of a site on the slope may be an important factor in determining dune probabilities. Chepil's (1965) functional equation considers "the maximum unsheltered distance across a field parallel to the prevailing wind erosional direction" to be an important variable in determining potential soil loss by wind. Chepil further believed that long, relatively smooth surfaces would result in less turbulence. The resulting laminar air flowage would increase friction at the surface and be more likely to result in the formation of dunes (Carson, 1971, and Bagnold, 1954). The resulting increase in horizontal wind velocity near the surface may also serve as a more effective erosional agent (Gray, 1973) and could result in a greater concentration of dunes.

In addition to total slope length, the location on the slope may be important. The distance measured parallel to the mean annual wind direction between a point and the nearest upwind drainage divide may provide the "unsheltered distance" considered by Chepil (1965) as important in determining potential for wind erosion (United States Department of Agriculture, 1961). In addition, the drainage divides could affect the turbulence factors described by Bagnold (1954), Carson (1971), and Mabbutt (1977). The nearer the drainage divides, the more likely turbulent rather than laminar air flowage patterns would occur.

Distance values for both variables were obtained from air photographs of the study area. Air photograph characteristics as well as the field checking techniques used to verify the data will be discussed in greater detail in the following chapter.

Escarpment-Wind Flow-Relationships to Dunes

H_0 13 Dune occurrence on the Navajo Uplands of Northeastern Arizona is not related to the angle formed by the intersection of a vector parallel to the face of the nearest upwind escarpment and a vector indicating the mean annual wind direction, measured on a 0°-360° azimuthal basis.

H_1 13 There is a positive relationship between the angle formed by the intersection of a vector parallel to the face of the nearest upwind escarpment and a vector indicating the mean annual wind direction, measured on a 0°-360° azimuthal basis, and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_2 13 There is an inverse relationship between the angle formed by the intersection of a vector parallel to the face of the nearest upwind escarpment and a vector indicating the mean annual wind direction, measured on a 0°-360° azimuthal basis, and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_0 14 Dune occurrence on the Navajo Uplands of Northeastern Arizona is not related to the angle formed by the intersection of a vector parallel to the face of the nearest upwind escarpment and a vector indicating the direction of the mean annual wind, measured on a 0°-180° basis.

H_1 14 There is a positive relationship between the angle formed by the intersection of a vector parallel to the face of the nearest upwind escarpment and a vector indicating the direction of the mean annual wind, measured on a 0°-180° basis, and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_2 14 There is an inverse relationship between the angle formed by the intersection of a vector parallel to the face of the nearest upwind escarpment and a vector indicating the direction of the mean annual wind, measured on a 0°-180° basis, and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_0 15 Dune occurrence on the Navajo Uplands of Northeastern Arizona is not related to the angle formed by the intersection of a vector parallel to the face of the nearest upwind escarpment and a vector indicating the direction of the mean annual wind, measured on a 0°-90° basis.

H_1 15 There is a positive relationship between the angle formed by the intersection of a vector parallel to the face of the nearest upwind escarpment and a vector indicating the direction of the mean annual wind, measured on a 0°-90° basis, and dune occurrence on the Navajo Uplands of Northeastern Arizona.

H_2 15 There is an inverse relationship between the angle formed by the intersection of a vector parallel to the face of the nearest upwind escarpment and a vector indicating the direction of the mean annual wind, measured on a 0^{o}-90^{o} basis, and dune occurrence on the Navajo Uplands of Northeastern Arizona.

Bagnold (1954) considered obstructions in the path of wind to be a major factor in determining the location of dunes. He stated (1954, 188):

> ...Deposits caused directly by fixed obstructions in the path of sand driving wind: for example by bushes, rocks, or cliffs. These sand shadows and sand drifts are dependent for their continued existence on the presence of the obstacle, and cannot move away from it.

Bagnold (1954, 189-190) went on to describe such obstacles and their effect on air and sand by stating:

> The air both in front and behind the obstacle is divided into two parts by a somewhat ill-defined surface of discontinuity...Outside this surface the air stream flows smoothly by; but the volume within the wind shadow of the obstacle is filled with swirls and vortices of air whose average forward velocity is less than that of the air stream outside. As we go down-wind from the obstacle the forward velocity of the air inside the shadow gradually increases and the shadow fades away to merge eventually with the general flow of the wind.

He believed that sand grains moving by saltation accumulate in the relatively stagnant air in front of and beyond the obstacle. Bagnold's observations were also confirmed by Dunbar and Rodgers (1957).

The relationship between escarpments and the mean annual wind direction is affected by the angle of incidence. As the angle approaches 90^{o} the effects of the escarpment are spread over a larger area. However, as the mean annual wind direction approaches a pattern parallel to the face of the escarpment, the resulting influence on wind flow decreases (Mabbutt, 1977, and Bagnold, 1954).

Angular values for the variable were measured from air photographs of the study area.

Dependent Variable

The fifteen independent variables previously discussed include all of those to be considered for model development. Their selection was based upon the rationale accompanying each set of supportive hypotheses and the source of the data values was described. Those variables will be used in an attempt to predict the dependent variable--the presence or absence of dunes--in selected study area quadrats.

The dependent variable and its assumed relationship to the independent variables was discussed in the previous hypothesis analysis. The determination of the dependent variable was made for each selected quadrat after field checking confirmed the interpretive process using air photographs.

Representation of the dependent variable was in a binary manner (compatible with the requirements of the discriminant analysis routine)--either dunes were present or absent in a particular quadrat. During the analysis of the air photographs the discovery of any dune type in the quadrat qualified it for a "dune present" classification. If no dunes were discernable, the quadrat received a "dune absent" classification. Those classification designations were used in the developmental phase of the model to derive the linear discriminant function and in the model testing portion to determine the accuracy of the model.

Summary

Variables selected for this study differ somewhat from those considered by others. Their number is far greater (possessing the potential to determine process rather than spatial correlations) than that considered necessary by either Peltier (1950), Hack (1941), or Bloom (1978), none of whom were attempting to consider the significance of each variable nor the interrelationships between them. They differ from those considered by either the United States Department of Agriculture (1961) or Chepil (1965) by being more extensive, yet more manageable and more specific.

CHAPTER IV

MODEL DEVELOPMENT, MODEL TESTING, AND VARIABLE ANALYSIS

The first three chapters of this research paper have dealt with (1) a description of the problem, (2) an analysis of the study area, and (3) the hypothesis-variable identification and justification. This chapter will focus upon the procedure used to analyze the variables, with the purpose of determining their role in dune formation, and selecting those worthy of consideration in model development. It will also describe the process of developing the model, testing the model, and the process of analyzing the variables considered.

A critical factor in developing and testing the model was the ability to gather data from air photographs of the study area. Information determined from that source included: the dependent variable (which will be represented in a binary manner as either dunes present or dunes absent), slope characteristics, escarpment characteristics, and the distance to exposed bedrock (to be represented in a manner indicated in the previous chapter).

Prior to the construction and verification of the model's predictive capabilities, the validity of information gathered from the photographs was ascertained. Verification of such information is essential, for errors in interpretation could have significant effects upon the quality and accuracy of the model. Fortunately, excellent air photos of the area at a scale of approximately 1:62,500 were available.

The photographs of the area were taken from U2 aircraft at an elevation of approximately 63,000 feet. Photo quality was outstanding and resolution was excellent. Individual juniper and pine trees were readily identifiable on the photographs. Interpretation was accomplished through the use of a mirrored stereoscope on the overlapping photos.

Verification of the air photo interpretation data was accomplished by selecting quadrats identical in size to those used in model development and testing. Test quadrat selection was made from the subset of the population adjacent to the road network of the research area. The process used was one similar to that described by Cole and King (1970).

From the population subset, 40 quadrats, 440 yards square, were chosen for test purposes. Those quadrats were classified according to the apparent presence or absence of dunes, and interpreted for slope, escarpment, and exposed bedrock features based on their characteristics visible on the photographs. Twenty-eight were classified as non-dune and 12 were classified dune. Each of those selected sites was then field checked to determine their actual characteristics. Field checking indicated the dune/non-dune classification technique as well as the additional data gathered from the photographs to be completely correct on the 40 quadrats. Each quadrat had been accurately classified based upon the characteristics evident on the photographs.

It was determined from field work that the use of stereo pairs of air photographs offers advantages over ground level observations. The perspective visible on the air photographs was superior to ground level viewing. Characteristic dune shapes and patterns were more evident on the air photographs than with on-site surface viewing (Plate B and C). The quality of the photograph in Plate A is inferior to those used for interpretive purposes due to the loss in resolution associated with the photographic reproductive process. However, it indicates the general characteristics of dune occurrence. Numerous longitudinal dunes are present in the lower left portion of the photograph (an area north of Tuba City). Plate B and Plate C are ground level photographs of the same dunes.

Model Development

The proven success of the interpretation technique was followed by the first stages in model development--the selection of sites and the gathering of the variable data for each.

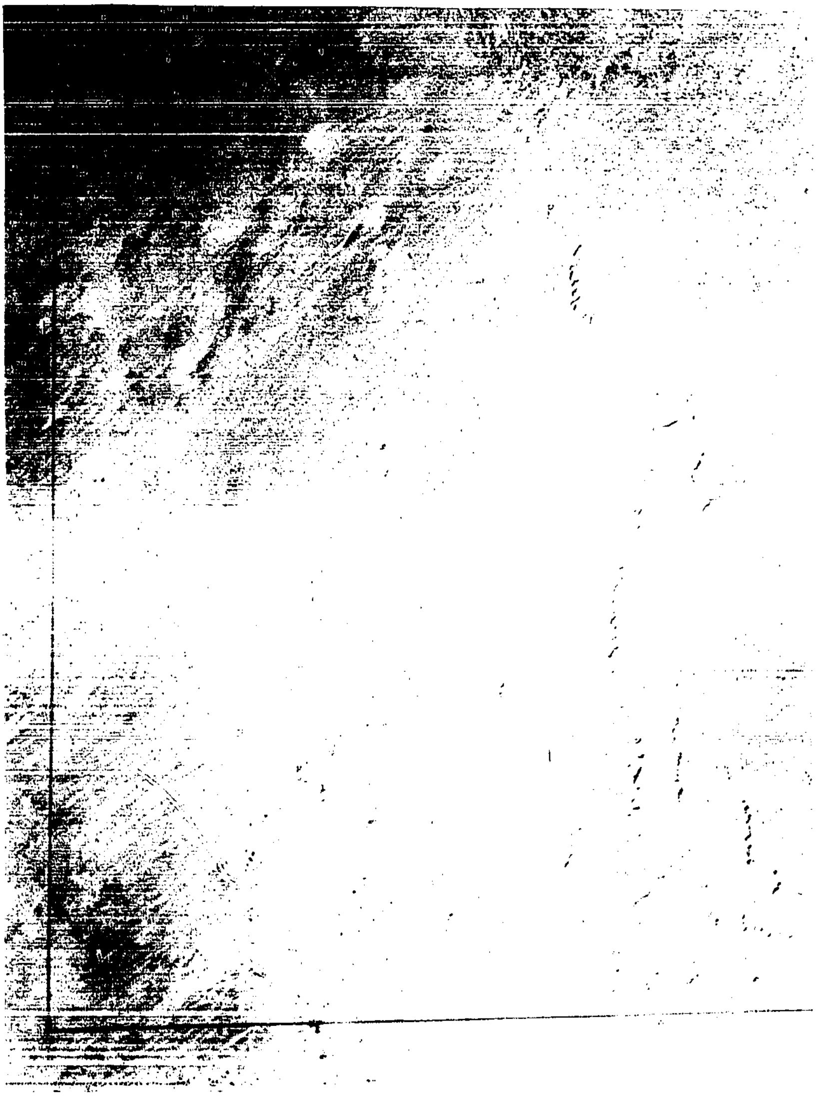


Plate A

An area of numerous longitudinal dunes north of Tuba City

Plate B

Surface view of the same area as Plate A

Plate C

Surface view of the same area as Plate A

Site selection for model development and for model testing was completed in the same manner. The process was accomplished by placing a grid over a map (scale of 1:316,800) of the study area. Abscissa and ordinate values for each quadrat were obtained from a random number table.

Quadrats 440 yards square (rather than points) were chosen so as to include dunes within close range of the study point (the center of the quadrat). Dunes (especially longitudinal dunes) throughout the study area are not contiguous. As a result, areas (for the dependent variable), rather than points, must be selected to insure proper classification procedures. Independent variable data were gathered for the central point of the areas.

Two groups of 100 quadrats were selected. One group was used to develop the model, the remaining for testing it. Variable values for all of the quadrats were obtained in the manner described with their rationale in Chapter III.

Upon completion of data gathering, consisting of 15 independent variables and one dependent variable, the initial step in model development was undertaken. It was necessary to determine those variables from the entire group that were suitable for model development and to determine the relative importance and interrelationships of each. Two multivariate statistical techniques were best suited to meet those needs--discriminant analysis and factor analysis. Both programs were run on an IBM model 158J computer at The University of Oklahoma.

Discriminant Analysis

The first step in model development involved the use of the multivariate analysis technique of discriminant analysis. The procedure was developed by statisticians working with anthropological and biological data. Fisher was the first to use the technique in 1936 to distinguish taxonomic characteristics of two plant species. Jolicoeur used the technique to study geographic variations in wolves, while Baker used it to determine chromosomal characteristics in bats (Bryant and Atchley, 1975).

The technique was developed to classify individual phenomenon into pre-existing categories (with the least possible chance of error) based upon the characteristics of the "new" individual and the characteristics of the existing classes (King, 1969, and Bryant and Atchley, 1975). "New" finds would often possess characteristics of several established classes, and researchers had difficulty in placing them in the correct group. Since its development, it has been used in research in a variety of disciplines. It has applications in economics, medicine, anthropology, biology, education, and geology (Aaker, 1971; Krumbein and Graybill, 1965; Eisenbeis and Avery, 1972; and Bryant and Atchley, 1975). Disciminant analysis has been used in discussions of grain size by Ather and Wyeth (1981) and by Tillman (1971). Its use in differentiating eolian deposits was demonstrated by Moiola and Spencer (1979).

There are several limitations in the use of discriminant analysis. It does not group heterogeneous data into new classifications. Instead, it assumes pre-existing categories are present (Kendall, 1957). It also assumes that each and every individual under consideration belongs to one group and one group only (King, 1969). Groups that are not mutually exclusive are not suitable for discriminant analysis.

The multiple discriminant analysis program used, MULDIS, was developed at the University of Wisconsin by Robert A. Eisenbeis and Robert B. Avery. They stated (1972, 1):

> The purposes of discriminant analysis are (1) to test for mean group differences and to describe the overlaps among groups and (2) to construct classification schemes based upon the set of m variables in order to assign previously unclassified observations to appropriate groups.

The first portion of the discriminant analysis program employed was the hypothesis testing section. That portion of the routine dealt with equality of mean vectors, equality of group variance structures, computation of discriminant functions, and stepwise discriminant analysis (Eisenbeis and Avery, 1972, 8).

Output from the hypothesis testing included variable measures such as mean, maximum values, minimum values, standard error of the means, standard deviations, pooled within-group dispersions, as well as numerical values relating to tests on equality of group dispersions and equality of group means.

Equality of group dispersion test output is given as an F statistic. In addition, the MULDIS program provides the level at which the F statistic is significant (rejecting the correct null hypothesis). Equality of group dispersions may not be an important as was once assumed. Eisenbeis and Avery (1972, 37) claim that there is some evidence that indicates non-multivariate normal data may be used without introducing significant bias into the results. Figure 6 indicates that normal dispersions would be beneficial in the classification process. If either dispersion differed in its distribution significantly from the other, the critical value developed as a mean of the dispersion means would not produce erroneous classifications on an equal basis. Distributions skewed away from the critical value would have a different possibility of misclassification than would those skewed toward the critical value.

Tests for equality of group means is represented as a Mahalanobis D^2 statistic. (The D^2 was developed by P. C. Mahalanobis to indicate the distance between the center points of clusters of data [Bryant and Atchley, 1975]). Through a transformation process the D^2 can be changed to an F statistic which is then used to indicate if there is a statistical difference between the two means. Significance levels are calculated for the F statistic. Morrison (1971, 130) has little faith in D^2 or any of its transformed statistics and states that: "The statistical significance of the D^2 statistic is a very poor indicator of the efficacy with which the independent variables can discriminate between Group 1 individuals and those in Group 2." Nevertheless, Figure 7 with a two group, one variable data display indicates that dispersions with means nearly equal would be poor discriminators. Figure 6 would be a better discriminator.

A major concern related to the variables used in discriminant analysis is the relative importance of each. The MULDIS program produces a table indicating the percentage of the total discriminating power accounted for by each variable in the original group. The values are obtained by summing and weighting the scaled functions.

Hypothesis Testing--Discriminant Analysis

The hypothesis testing portion of the discriminant analysis routine was used to explore the relative importance of each of the variables in discriminating between the dune and the non-dune locations.

The 15 raw variables used as input data for the program are shown in Table 1 and the results of the hypothesis testing portion of the discriminant analysis routine are indicated in Table 2.

The MULDIS program provides an F statistic indicating the significance of the difference between the means of the

Overlap Characteristics

Distribution with Small Group Overlap

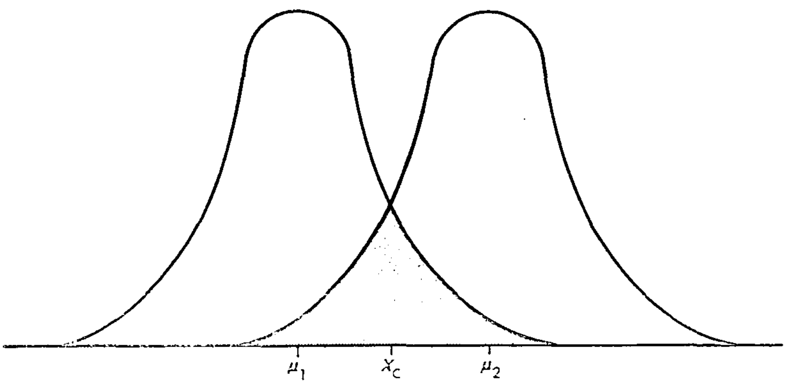


Figure 6

Distribution with Large Group Overlap

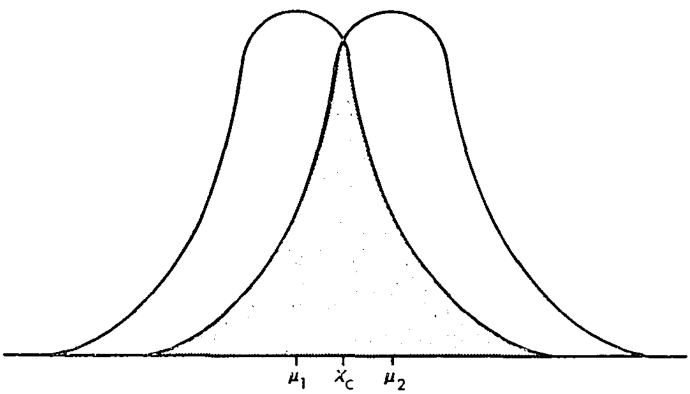


Figure 7

☐ Chance for Misclassification

After: Eisenbeis & Avery

TABLE 1

ORIGINAL VARIABLES

Variable	Description
1	Mean annual temperature.
2	Mean annual precipitation.
3	The angle formed by the intersection of a vector indicating slope direction and a vector indicating mean annual wind direction, measured on a 0°-360° azimuthal basis.
4	The angle formed by the intersection of a vector parallel to the face of the nearest upwind escarpment and a vector indicating mean annual wind direction, measured on a 0°-360° basis.
5	The angle formed by the intersection of a vector indicating down slope direction and a vector parallel to the mean annual wind direction, measured on a 0°-90° basis.
6	The angle formed by the intersection of a vector indicating south and a vector indicating down slope direction, measured on a 0°-180° basis.
7	Slope length.
8	Distance downwind from exposed bedrock.
9	Distance upwind to the nearest drainage divide.
10	The angle formed by the intersection of a vector parallel to the nearest upwind escarpment and a vector indicating the direction of the mean annual wind, measured on a 0°-90° basis.

11	The angle formed by the intersection of a vector indicating slope direction and a vector indicating the direction of the mean annual wind, measured on a 0^{o}-180^{o} basis.
12	The angle formed by the intersection of a vector parallel to the face of the nearest upwind escarpment and a vector indicating the direction of the mean annual wind, measured on a 0^{o}-180^{o} basis.
13	Mean growing season temperature.
14	Mean growing season precipitation.
15	The number of growing season days with greater than 0.10 inches of precipitation.

TABLE 2

ORIGINAL VARIABLE CHARACTERISTICS

Variable	F Statistic	Percentage of total Discriminating Power	Relative Importance Compared to Most Important
1	7.014	6.95	.403
2	5.20[illegible]	[illegible]	.565
3	[illegible]	[illegible]	[illegible]
4	[illegible]	[illegible]	[illegible]
5	[illegible]	[illegible]	[illegible]
6	[illegible]	[illegible]	[illegible]
7	[illegible]	[illegible]	[illegible]
8	[illegible]	[illegible]	[illegible]
9	[illegible]	[illegible]	[illegible]
10	[illegible]	[illegible]	[illegible]
11	[illegible]	[illegible]	[illegible]
12	[illegible]	[illegible]	[illegible]
13	[illegible]	[illegible]	[illegible]
14	[illegible]	[illegible]	[illegible]
15	14.1[illegible]	[illegible]	.102

TABLE 2

ORIGINAL VARIABLE CHARACTERISTICS

Variable	F Statistic	Percentage of total Discriminating Power	Relative Importance Compared to Most Important
1	7.014	6.95	.403
2	5.201	9.75	.565
3	.053	3.10	.180
4	.155	2.14	.124
5	10.220	5.93	.344
6	1.026	1.39	.080
7	31.657	17.23	1.000
8	15.872	5.07	.294
9	4.084	4.46	.258
10	11.538	9.38	.544
11	2.837	4.83	.280
12	2.846	7.08	.411
13	3.185	7.24	.420
14	23.774	13.62	.790
15	14.136	1.77	.102

two groups, the actual discriminating power of each variable, and a scaled value indicating the relative importance of each variable compared to the most important. As an example, Variable 1, mean annual temperature, has an F statistic of 7.014, indicating the difference between mean annual temperature means in dune areas is quite different from that on non-dune sites. Table 2 also indicates that Variable 1 accounts for 6.95% of the total discriminating power of the variables and is 403/1000 as important as the most important variable.

The third column in Table 2--percentage of total discriminating power--presents interesting data relating to the relative importance of each of the variables. Slope length (Variable 7) has a value of 17.23, the highest of the group. The importance of long slopes, as was indicated by Chepil (1945) in his description of "unsheltered distance," appears to be especially important on the Navajo Uplands. The next two most important variables, Variable 14 (Mean growing season precipitation) and Variable 2 (Mean annual precipitation), both dealt with precipitation characteristics and may reflect the interrelationships that exist between precipitation and plant vigor as indicated by Rosenberg (1974) and by Laetsch (1979).

Those variables whose F statistics fell below the critical value were removed from the remaining portion of the analysis. The critical value of the F statistic with

99 degrees of freedom and 99% confidence levels was 1.59. Since the F value in this case is an indication of the separation of the means of the two groups, those variables whose means are not significantly different (at 99% confidence level) will not be used in the classification portion of the model. As a result, Variables 3, 4, and 6 were removed from further consideration.*

As a result of the initial step in the data analysis, the null hypothesis indicating that there was no statistical difference between the means of the dune and non-dune group for each variable was rejected for 12 of the 15 variables used. The 12 variables, those whose F statistic indicated that the means of the dune group and the non-dune group were different, were used in the next portion of the analysis (Table 3).

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*Variable 3--The angle formed by the intersection of a vector indicating slope direction and vector indicating mean annual wind direction, measured on a 0°-360° azimuthal basis.

Variable 4--The angle formed by the intersection of a vector parallel to the face of the nearest upwind escarpment and a vector indicating mean annual wind direction, measured on a 0°-360° basis.

Variable 6--The angle formed by the intersection of a vector indicating south and a vector indicating slope direction, measured on a 0°-180° basis.

TABLE 3

SIGNIFICANT VARIABLES

Variable	Description
1	Mean annual temperature.
2	Mean annual precipitation.
3	The angle formed by the intersection of a vector indicating slope direction and a vector parallel to the mean annual wind direction, measured on a 0^{o}-90^{o} basis.
4	Slope length.
5	Distance downwind from exposed bedrock.
6	Distance upwind to the nearest drainage divide.
7	The angle formed by the intersection of a vector parallel to the nearest upwind escarpment and a vector indicating the direction of the mean annual wind, measured on a 0^{o}-90^{o} basis.
8	The angle formed by the intersection of a vector indicating slope direction and a vector indicating the direction of the mean annual wind, measured on a 0^{o}-180^{o} basis.
9	The angle formed by the intersection of a vector parallel to the face of the nearest upwind escarpment and a vector indicating the direction of the mean annual wind, measured on a 0^{o}-180^{o} basis.
10	Mean growing season temperature.
11	Mean growing season precipitation.
12	The number of growing season days with greater than 0.10 inches of precipitation.

Factor Analysis

The second step in the model development employed factor analysis.** Its primary purpose was to provide an insight into the relationships between the variables and to derive independent data (factor scores) for use in the third stage of model development. The factor scores not only represent a sizeable reduction in data but also eliminate a bias problem associated with the input of raw data. (Discriminant analysis routines assume that input variables are independent.) Factor scores derived from orthogonal rotation provide that independent characteristic. The data reduction accomplished by grouping related variables together provides a "framework" that facilitates a better understanding of the data. R-mode factor analysis was used to delineate the pattern of variation in the characteristics and to produce the data array.

Factor analysis yielded a number of interesting facets relating to the data involved in the study. The correlation coefficient matrix (or the cosine of the angle between the variable vectors when plotted on the cases), Table 4, indicates the degree of linear relationship that exists between the remaining 12 variables. The closer

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**The factor analysis program used was BMDX72 developed at the Health Sciences Computing Facility at the University of California--Los Angeles, revised April 5, 1972.

TABLE 4

CORRELATION MATRIX

	1	2	3	4	5	6
1	1.000					
2	-0.719	1.000				
3	-0.052	0.074	1.000			
4	0.082	-0.157	-0.220	1.000		
5	0.091	-0.161	-0.118	0.570	1.000	
6	0.075	-0.131	-0.150	0.700	0.553	1.000
7	-0.206	0.224	0.382	-0.215	-0.152	-0.105
8	0.167	-0.113	-0.249	0.084	0.006	-0.049
9	-0.003	0.034	-0.027	0.091	-0.055	0.149
10	0.503	-0.536	0.025	0.069	0.088	0.063
11	-0.378	0.367	0.063	-0.196	-0.325	-0.114
12	-0.525	0.587	0.078	-0.228	-0.266	-0.120

	7	8	9	10	11	12
7	1.000					
8	-0.170	1.000				
9	-0.079	0.188	1.000			
10	-0.152	-0.007	0.032	1.000		
11	0.043	-0.070	0.216	-0.261	1.000	
12	0.120	-0.109	0.166	-0.345	0.478	1.000

the values approach 1, the greater the relationship. Coefficients near 0 indicate little relationship. Negative values represent inverse relationships. The correlation coefficient when squared and multipled by 100 gives the percent variation in common between the two variables.

Noticeable relationships exist between a number of variables. A strong inverse relationship exists between mean annual temperature (Variable 1) and mean annual precipitation totals (Variable 2), indicating that warmer portions of the study area tend to be areas with the least precipitation. Slope length (Variable 4) is positively related to the distance upwind to a drainage divide (Variable 6). Such a relationship would be expected since on longer slopes one would expect to travel greater distances to the nearest upwind divide.

Other strong relationships between variables exist. However, they do not appear significant in Table 4 because the relationship is not linear in nature. An example of such relationships is that which exists between the angular values formed by the intersection of a vector indicating slope direction and one indicating mean annual wind direction. When such values are compared on an azimuthal basis it appears to be unrelated to a quadrant comparison of the same values. In reality one can be computed directly from the other.

The next significant portion of the analysis consists of the rotated factor matrix. An orthogonal rotation was used to best align the axes with the clusters of variables. Minimum eigenvalues of 1.0 were set for each factor.

The results of the rotated factor matrix are represented in Table 5. The columns represent the factors, while the rows represent the variables. The intersection of each column and row represents the loading for each variable on each column.

The rotated factor matrix (Table 5) is a useful tool in interpreting the data. The number of factors produced was four. Rummel (1967, 463) stated that the number of factors "is the number of substantively meaningful independent (uncorrelated) patterns of relationships among the variables." Those four factors can be interpreted as meaning that there are four different categories of data that are capable of describing the variables measured within the study area.

The loadings can be interpreted the same as the correlation coefficients. The value squared and multiplied by 100 equals the percent variation that a variable has in common with the rotated pattern (Rummel, 1967, 463).

A value of 0.7 (49% variation involved in the pattern) was arbitrarily chosen as the lowest limit of loadings to be included within a particular pattern.

TABLE 5

ROTATED FACTOR MATRIX

Variable	Factor			
	1	2	3	
1	-0.854	-0.005	0.147	-0.027
2	0.861	-0.085	-0.127	0.063
3	-0.089	-0.156	-0.792	0.129
4	-0.072	0.865	0.172	0.027
5	-0.100	0.797	0.039	-0.223
6	-0.050	0.883	-0.005	0.150
7	0.162	-0.132	-0.677	-0.059
8	-0.113	-0.091	0.643	0.139
9	-0.047	0.107	0.124	0.865
10	-0.760	0.023	-0.066	0.127
11	0.470	-0.229	-0.041	0.549
12	0.674	-0.183	-0.105	0.379

The first factor had loadings of greater than ± 0.7 from Variables 1 (mean annual temperature, -0.85), 2 (mean annual precipitation, +0.86), and 10 (mean growing season temperature, -0.76). Since the factor is composed entirely of meteorological variables (high negative temperature variables and high positive precipitation variables), it will be a considered a meteorological variable.

The second factor had high positive loadings from Variables 4 (slope length, +0.86), 5 (distance downwind from exposed bedrock, +0.79), and 6 (distance upwind to the nearest drainage divide, +0.88). Due to its pattern of variables, it will be considered a slope length variable.

The third factor had a high loading from Variable 3 (the angle formed by the intersection of a vector indicating slope direction and a vector parallel to the mean annual wind direction, measured on a 0°-90° basis, -0.79). That factor will be considered a wind-slope variable.

The fourth factor had one high positive loading, Variable 9 (the angle formed by the intersection of a vector parallel to the face of the nearest upwind escarpment and a vector indicating the direction of the mean annual wind, measured on a 0°-180° basis, +0.86). It will be considered the wind-escarpment variable.

The third significant portion of the factor analysis routine was the factor scores for each case. They represent the involvement of each variable in a particular pattern. The value of the score represents the degree of involvement. More involved variables have higher weights.

> To determine the score for a case on a pattern, then, the case's data on each variable is multiplied by the pattern weights for that variable. The sum of these weight-times-data products for all the variables yields the factor score. Cases will have high or low factor scores as their values are high or low on the variable entering a pattern (Rummel, 1967, 469).

The determination of factor scores concluded the second step in developing the model and provided the data necessary for the classification portion of the discriminant analysis routine.

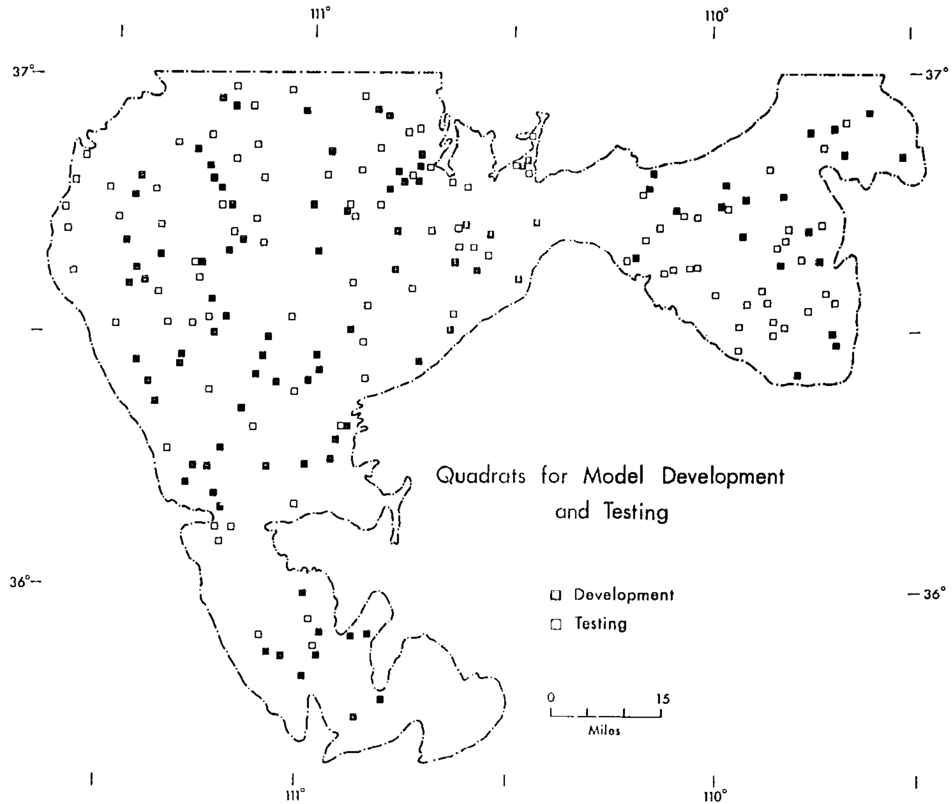
Model Testing

The third step in model development consisted of classification of the 100 "new" sites based upon the physical environmental characteristics of the 100 "original" sites.

The factor scores for the initial 100 sites (Map 4) produced in the second stage of model development were input into the discriminant analysis program for classification purposes. Those scores were used to obtain a discriminant function. In addition, the discriminating power of each factor was determined (Table 6). It is apparent that each variable is nearly equal in percentage of total variance. Values ranged from 23.23 to 26.94.

The discriminant function produced was used to classify the factor score data for the remaining 100 sites

Map 4



Quadrats for Model Development and Testing

(Map 4). The results of the classification scheme are indicated in Appendix III where probability for membership in group dune or in group non-dune are indicated. The designated membership based upon the classification portion of the discriminant analysis routine as well as the actual membership of each quadrat is indicated.

A major concern of the classification procedure is to determine the effectiveness of the scheme. A two by two confusion matrix was printed listing actual membership on one axis and predicted membership on the other. The closer the values off the diagonal approach zero, the better the classification scheme (Table 7). Of the 18 sites classified as dunes, 16 were actual dunes. Sixty-nine of those classified as non-dune were actually members of the 82-member non-dune group.

Variable Analysis

One purpose of the research was the development and testing of a model to predict dune occurrence. With the completion of that goal, the analysis of the contributing variables (a second purpose) would appear to be in order.

Analysis of the data has provided a basis for understanding as well as ascertaining those relationships and has yielded a number of insights into the nature of environmental variables and the occurrence of dunes in the study area.

TABLE 6

FACTOR VARIABLE DISCRIMINATING POWER

Variable	Percentage of Total Variance
Variable 1 (Meteorologic)	23.23
Variable 2 (Slope length)	26.44
Variable 3 (Wind-slope)	26.94
Variable 4 (Wind-escarpment)	23.37

TABLE 7

MODEL TESTING RESULTS

Actual Membership	Classified Membership	
	Group Dune	Group Non-Dune
Group Dune	16	13
Group Non-Dune	2	69

The initial analytical procedure involved the hypothesis testing portion of the discriminant analysis program. From that analysis of the equality of mean vectors it was possible to eliminate those variables that were not significantly different statistically. As a result of that test, three variables were identified that were not suitable for use in construction of the model. The null hypothesis could not be rejected for Variables 3, 4, and 6.

The first of those eliminated was Variable 3, the relationship between slope and mean annual wind direction measured on a 0^{o}-360^{o} basis. Since Variables 3, 5, and 11 measured the same phenomena, only in a different manner (0^{o}-90^{o} for Variable 5 and 0^{o}-180^{o} for Variable 11), the rejection of the 0^{o}-360^{o} measuring scheme may indicate that dune occurrence in the study area is related to more refined measurements of the relationship between slope and mean annual wind direction than those represented by an azimuthal measurement.

The second variable rejected as an azimuthal measurement relating mean annual wind direction to the nearest upwind escarpment (Variable 4). That variable was, no doubt, rejected for the same reason as Variable 3. Two additional variables, 10 and 12, both dealing with mean annual wind direction and nearest upwind escarpments, had significantly different means and were used in the construction of the model. A situation similar to that in Variable 3 may exist in that azimuthal measurements are not satisfactory means of measuring wind-escarpment or wind-slope characteristics. However, both characteristics when measured on a 0^{o}-90^{o} or 0^{o}-180^{o} basis are meaningful.

Variable 6, the angle formed between a vector indicating down slope direction and one indicating south measured on a 0^{o}-180^{o} value range, was also rejected. It was initially assumed that the direction of slope and its resultant angle of interception of solar radiation would influence temperature and actual evapotranspiration rates. As a result, vegetation cover would be affected and the likelihood of dune occurrence would be influenced. Such a relationship apparently does not exist within the study area. The southerly slopes apparently are not steep enough to produce a significant change in surface conditions which affect vegetative characteristics.

The rejection of the three variables followed the pre-established criteria indicated in the methodological portion of the study. Their F scores indicated that their means were not significantly different for the dune and non-dune group.

Additional information produced during the hypothesis testing portion of the discriminant analysis routine was the discriminating power of each of the variables (Table 2).

The percentage of total discriminating power as well as the relative importance of the initial 15 variables compared to the most important variable was shown. Variable 7 (slope length--17.23%) and Variable 14 (mean growing season precipitation--13.62%) together, account for nearly one-third of the total discriminating power of 15 variables. If one were to include the next two most important variables for discriminating power (Variable 2--mean annual precipitation--9.75% and Variable 10--angle of the nearest upwind escarpment compared to the mean annual wind direction measured on a 0^{o}-90^{o} basis--9.38%), one would have accounted for approximately one-half of the total discriminating power by using just four variables.

Such an analysis of the discriminating power of each variable is beneficial in eliminating those that contribute little to the accuracy of the model. As an economic measure, an individual may wish to eliminate variables with low discriminating powers from the initial data acquisition processes. Such a step may be beneficial in terms of savings in cost and time. Variables 3, 4, 6, and 15 (Table 2) have low values for discrimination and probably should be eliminated in repeated studies in the research area.

The discriminating power does not directly correspond to the F statistics for each variable. Morrison (1971, 130) indicated that such a condition may arise. It is interesting to note that some variables, such as Variable 5 (number of growing season days with greater than 0.10 inches of precipitation), have a high F statistic (14.1) indicating that the means for the two groups are widely separated, while its discriminating power is only 1.77% (the second lowest of the group). Other comparisons among the variables indicate similar circumstances.

Supportive Hypotheses Evaluation

Analysis of the 15 variables during the hypothesis testing portion of the discriminant analysis routine provided the information necessary to evaluate the supportive hypotheses. Based upon the F statistics indicating mean separation of the dune and non-dune group, as well as the mean values of each of the groups, it is possible to make the following judgments on each of the Supportive Hypotheses.

Supportive Hypothesis $H_2 1$--There is an inverse relationship between mean annual precipitation amounts and dune occurrence on the Navajo Uplands of Northeastern Arizona--can be accepted. Results of calculations of mean values and the separation of means indicated it is possible to state that within the study area dunes are most apt to be found in locations possessing meager mean annual precipitation totals. The percentage of total discriminating power associated with mean annual precipitation amounts was 9.75, as compared to 17.23 for the most important variable, slope length. Mean annual precipitation may be expressed in vegetation density, associated ground cover, and soil stability.

The distribution of the precipitation throughout the growing season is important in maintaining soil stability. Supportive Hypotheses 2 investigated the relationship between the number of growing season days with greater than 0.10 inches of precipitation and the occurrence of dunes. As a result of the analysis, Supportive Hypothesis H_2 2 was accepted. It stated: There is an inverse relationship between the number of growing season days with greater than 0.10 inches of precipitation and dune occurrence on the Navajo Uplands of Northeastern Arizona. As the number of days with less than 0.10 inches of precipitation decreased, the likelihood of dune occurrence increased.

The relationship between mean growing season precipitation and the occurrence of dunes was considered in the analysis of Supportive Hypotheses 3. As a result, the two appear to be inversely related. Supportive Hypothesis H_2 3--There is an inverse relationship between mean growing season precipitation and dune occurrence on the Navajo Uplands of Northeastern Arizona--was accepted.

It is apparent from the analysis of Supportive Hypotheses 3, just as it was from Supportive Hypotheses 1, that as precipitation amounts decrease on a yearly or on a growing season basis, dunes are more likely to be present. The decrease in moisture amounts is no doubt reflected in the vegetation, associated ground cover, and soil erodibility.

The results of the data analysis indicated that it is feasable to accept Supportive Hypothesis H_1 4--There is a positive relationship between mean annual temperature and dune occurrence on the Navajo Uplands of Northeastern Arizona. The hypothesis testing portion of the discriminant analysis program indicated the means for the dune and non-dune group were significantly different statistically. The structure of the data for that variable related the highest mean value with the dune group. Within the study area, dunes tend to be associated with locations where higher temperatures are most common. Areas with lower mean annual temperatures are less likely to be associated with dunes. Mean annual temperature and its effect on moisture may be expressed in the vegetation cover, which in turn affects soil stability.

An additional factor to consider in association with mean annual temperature is elevation. While elevation and mean annual temperature are closely correlated (Johnson, 1975, and Cooley, 1969), conceptually they may represent two entirely different conditions affecting dune occurrence. Higher elevations may, due to erosional patterns, be more closely associated with exposed bedrock and the characteristic relationship between dunes and bedrock as described in the rationale for Variable 10. While elevational changes in the study area are less than many other areas on the Navajo Reservation, higher elevations, especially in the northwestern portion of the study area, do tend to be associated with areas of exposed bedrock.

Supportive Hypotheses 5 dealt with relationships that exist between dune occurrence and mean growing season temperatures. As a result of the analysis, Supportive Hypothesis H_1 5--There is a positive relationship between mean growing season temperature and dune occurrence on the Navajo Uplands of Northeastern Arizona--was accepted. It substantiated the conclusion reached in the analysis of Supportive Hypotheses 2. Throughout the study area, as mean annual temperatures and mean growing season temperatures increased, the frequency of dune occurrence also increased. The apparent influence of higher temperatures on actual evapotranspiration caused a reduction in ground cover. The sparse vegetation was not able to hold soil in place as readily and, as a result, dunes developed.

Within the sixth set of supportive hypotheses, data analysis indicated that the Null Hypothesis H_0 6 cannot be rejected. The test on mean separation for each of the two groups indicated that they are not significantly different statistically. Dune occurrence on the Navajo Uplands of Northeastern Arizona is not related to the angle formed by the intersection of a vector indicating slope direction and a vector indicating mean annual wind direction, measured on a 0°-360° azimuthal basis.

Through the analysis of Supportive Hypotheses 7 it was possible to accept Hypothesis H_1 7. It stated: There is a positive relationship between the angle formed by the intersection of a vector indicating down slope direction and a vector indicating the direction of the mean annual wind, measured on a 0°-180° basis, and dune occurrence on the Navajo Uplands of Northeastern Arizona. It indicated that dunes are more likely to occur on slopes facing away from the direction of the mean annual wind than those sloping toward it. It substantiated and clarified the conclusions reached through analysis of Supportive Hypotheses 8.

Supportive Hypotheses 8 indicated that dunes are more likely to occur on slopes parallel to the mean annual wind direction. However, due to the nature of the measurements (in Variable 8), slopes sloping toward and away from the direction of the mean annual wind were considered equal. Supportive Hypotheses 7 further clarified the matter and inferred that those slopes sloping away from the direction of the mean annual wind are more likely to possess dunes.

Analysis of mean values and their separation on Supportive Hypotheses 8 data indicated that they are significantly different statistically and that it is possible to accept the Supportive Hypothesis H_2 8. That supportive hypothesis stated: There is an inverse relationship between the angle formed by the intersection of a vector indicating down slope direction and a vector parallel to the direction of the mean annual wind, measured on a 0^{o}-90^{o} basis, and dune occurrence on the Navajo Uplands of Northeastern Arizona. Slopes that approach a parallel nature to the mean annual wind direction are more likely to be occupied by dunes. Those that approach an orthogonal relationship to mean annual wind direction are least likely to be associated with dunes.

In the final analysis of Supportive Hypotheses 9 data it was not possible to reject the null hypothesis. The H_0 9 Supportive Hypothesis stated: Dune occurrence on the Navajo Uplands of Northeastern Arizona is not related to the angle formed by the intersection of a vector indicating south and a vector indicating down slope direction, measured on a 0^{o}-180^{o} basis. Apparently, within the study area, the effects of concentration of solar radiation and increased evapotranspiration on south facing slopes as described by Daubenmire (1947) and Rosenberg (1974) was not significant enough to result in increased dune concentrations in those locations.

Analysis of the relationship between rock outcroppings and the occurrence of dunes led to the acceptance of the Supportive Hypothesis H_1 10--There is a positive relationship between the distance downwind from exposed bedrock and dune occurrence on the Navajo Uplands of Northeastern Arizona. The acceptance of that hypothesis is contrary to the original expectations. It was initially assumed that outcroppings of bedrock would serve as sources of sand. In addition, the effect of the outcrop was presumed to influence the flow of wind over the surface. As a result of those assumptions, dunes would be expected to be inversely associated with distance downwind from exposed bedrock.

One reason for the acceptance of the hypothesis relating dune occurrence to longer distances from exposed bedrock may be related to Supportive Hypotheses 11. It dealt with the relationship between dunes and slope length. In the analysis it was determined that dunes were most common on longer slopes. The affinity of dunes to greater distances from exposed bedrock may be another expression of the relationship between dunes and long slopes. One would assume that positions on long slopes would be further from exposed rock outcroppings than comparable positions on shorter slopes.

The analysis of Supportive Hypotheses 11 data resulted in the acceptance of the H_1 11 hypothesis. It stated: There is a positive relationship between slope length and dune occurrence on the Navajo Uplands of Northeastern Arizona. Apparently long slopes are more apt to have dunes located upon them than are short slopes. Those results support

Chepil's (1965) functional equation, as well as Bagnold's (1954) statements on dune occurrence and wind speeds.

Supportive Hypotheses 12 data reinforced the results obtained from the analysis of Supportive Hypotheses 10 and 11. The Supportive Hypothesis H_1 12 stated: There is a positive relationship between the distance upwind to the nearest drainage divide and dune occurrence on the Navajo Uplands of Northeastern Arizona. Once again, long distances from drainage divides were associated with dunes.

Similarities in the nature of the accepted hypotheses for Supportive Hypotheses 10, 11, and 12 all point to the fact that long slopes and locations far from divides and outcroppings tend to be most conducive to the formation of dunes. The pattern of movement and/or the concentration of dune materials seem to approach near optimum conditions necessary for the formation of dunes on long, gentle slopes.

Analysis of data for Supportive Hypotheses 13 indicated that the means of the dune and non-dune group are not signifcantly different statistically. Therefore, the H_0 13 Null Hypothesis--Dune occurrence on the Navajo Uplands of Northeastern Arizona is not related to the angle formed by the intersection of a vector parallel to the face of the nearest upwind escarpment and a vector indicating the mean annual wind direction, measured on a 0^o-360^o azimuthal basis--cannot be rejected.

In the analysis of Supportive Hypotheses 14 it was determined that Hypothesis H_2 14 was acceptable. The mean value for group dune was 89.48 while that for group non-dune was 109.01. Supportive Hypothesis H_2 14 stated: There is an inverse relationship between the angle formed by the intersection of a vector parallel to the face of the nearest upwind escarpment and a vector indicating the direction of the mean annual wind, measured on a 0^{o}-180^{o} basis, and dune occurrence on the Navajo Uplands of Northeastern Arizona.

Dunes appear to be most likely where escarpments are at right angles to the path of the mean annual wind. Such occurrences would substantiate the rationale that stated that escarpments at right angles to winds would alter wind flow patterns to the extent of producing areas of accumulations of wind transported material. However, the analysis of Supportive Hypotheses 10 indicated that dunes were more likely to form as distances downwind from rock outcroppings increased. The escarpments used for calculations for Supportive Hypotheses 14 were often the same locations considered as rock outcroppings in Supportive Hypotheses 10. Using that criteria, the acceptance of the two supportive hypotheses appears to be contradictory.

A second explanation may be in the analysis of the mean values. The values of the angle were measured on a 0^{o}-180^{o} basis with an expected mean of 90^{o}. The calculated mean for group dune (89.48) was near the expected mean based on a random distribution of occurrences. Since the two are nearly identical, dune occurrence may not be related to the angle the mean annual wind forms with the nearest upwind escarpment. Instead, their occurrence may be random with regard to the wind angle-escarpment angle variable.

In the analysis of the data for Supportive Hypotheses 15 it was apparent that Hypothesis H_2 15 was acceptable. It stated: There is an inverse relationship between the angle formed by the intersection of a vector parallel to the face of the nearest upwind escarpment and a vector indicating the direction of the mean annual wind, measured on a 0^{o}-90^{o} basis, and dune occurrence on the Navajo Uplands of Northeastern Arizona. The more closely the direction of escarpment parallels the mean annual wind direction the greater the probability dunes will occupy a portion of the surface. Once again, it would appear that "uninterrupted" winds are most likely to be associated with dune formation.

Factor Scores and Model Analysis

The second portion of the data analysis used the 12 variables whose F statistic was significantly different (between the dune and the non-dune category) to develop the model. It involved subjecting those 12 raw variable values to factor analysis. The results provided a number of interesting facts regarding the relationship of the variables as well as the necessary independent data (factor scores) necessary for the continuation of the analysis.

In addition to the correlation matrix (Table 4) independent patterns were discerned through orthogonal rotation of the axis. The factor loadings (Table 5) indicated the relationships that exist between the variables included within each pattern.

It is significant to note that four distinct independent factors were discerned. The four, meteorological, slope length, wind-slope, and wind-escarpment, indicated that four independent unique characteristics were responsible for describing the environmental characteristics of the study area. Each of the four was nearly equal in discriminating power (Table 6).

Factor scores produced in the factor analysis of the original 100 model development cases were used as input into the discriminant analysis program. The linear discriminant function derived from the 100 cases for model development (Map 4) was used to classify the 100 new cases for model testing (Map 4). The results of the classification portion of the program is indicated in Appendix III.

The most important aspect of testing the model was the determination of its ability to accurately classify the "unknowns" into the correct category. The results are indicated in Table 7. Of the 18 quadrats classified as members of group dune, 16 were actual members--a success rate of 88.9%. When compared to a random classification where success rate in dune classification would be 29%, the results are promising. Of the 71 quadrats whose membership was in non-dune group, 69 were predicted by the model to be members of that group. The primary area of misclassification was in grouping 13 actual dune quadrats into the non-dune group.

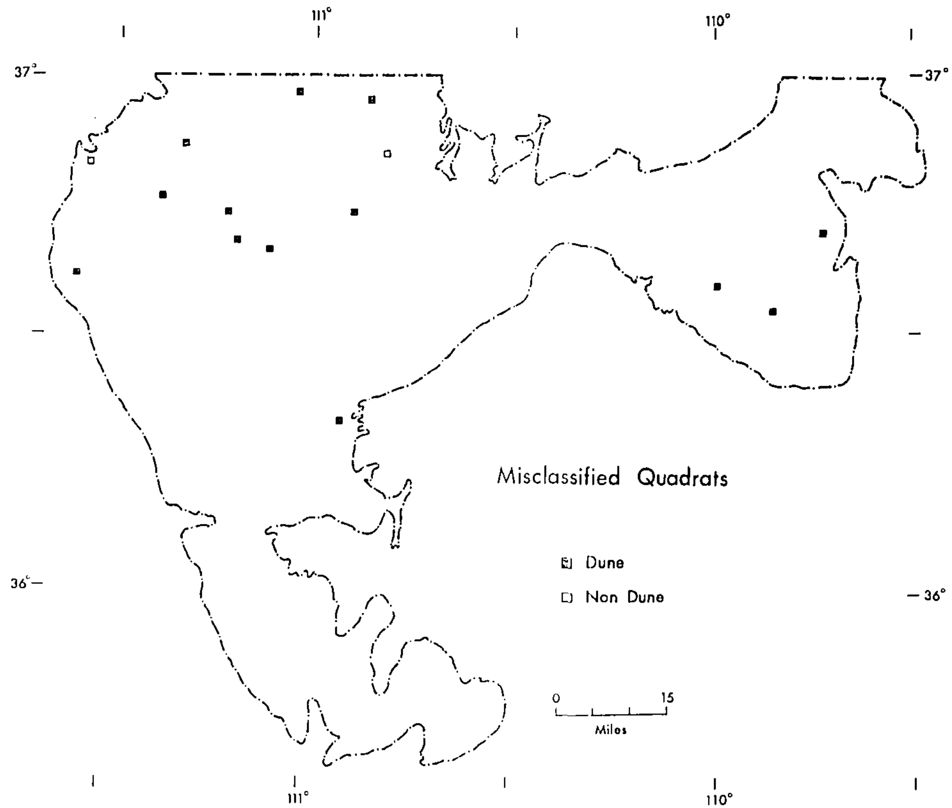
Those quadrats incorrectly classified are indicated on Map 5. The limited number and distribution make it impossible to discern a definate pattern.

The misclassified quadrats may be indicators of conditions worthy of additional considerations. As an example, locations possessing dunes that were classified as non-dunes may indicate some unmeasured characteristics were responsible for the destruction of the vegetation coverage and allowed dunes to develop. Conversely, non-dune locations classified as dunes may indicate fragile areas that are near the "breaking point." Such locations possess the environmental attributes of dune locations but, for some unknown reason, dunes have failed to develop. Those locations may need future monitoring to prohibit land abuse and possible dune development.

Misclassification Characteristics

Viewed in the context of the proposed research, the model is an unqualified success. The research was to determine the relationships that existed between dune occurrence on the Navajo Uplands of Northeastern Arizona and the

Map 5


111°
110°
37°
37°
36°
36°
111°
110°
Misclassified Quadrats
Dune
Non Dune
0
15
Miles

meteorologic, lithologic, and geomorphic features of the area. The relationships were successfully ascertained, and the model developed functioned satisfactorily. It was never assumed that the model would classify 100% of the sites correctly. The misclassified quadrats are a concern, even though their number is small.

One aspect of misclassification was the grouping of 2 of the 71 members of the non-dune quadrats into the dune group--an error of approximately 2.8%. Both quadrats had the environmental attributes of dune sites, but dunes failed to develop.

The second type of misclassification, and by far the more common of the two, was the classification of dune-bearing quadrats within the non-dune category. Sites that did not possess the physical environmental attributes of dunes nevertheless had dunes within their boundaries.

One might assume that both groups of quadrats were misclassified for one of two reasons: (1) the variable values considered did not accurately reflect the specific environmental attributes of the site, or (2) the list of variables considered was not exhaustive. The author is aware of both possible problems. In the first instance, numerous possibilities exist for limitations in variable values. As for the second, it was never intended to indicate that <u>all</u> dunes were <u>entirely</u> the result of the 15 variables considered in the previous chapters. Additional data, often nearly impossible to measure or determine, no doubt contributed to dune distribution in the study area. A brief analysis of that additional material is included in the following paragraphs.

Under the first assumption for possible misclassification, a careful scrutinization of the variables used for model development may indicate a source of shortcomings in the data used. Within one group of variables considered, the meteorological group, various aspects of temperature characteristics for specific sites were considered. Official temperature data disseminated by the National Oceanic and Atmospheric Administration (NOAA) are gathered by instruments placed above the surface. While those temperature readings may have been correct at the appropriate height, it may not be indicative of temperatures at or near the surface where most plants grow (Durrenberger, 1972, and Geiger, 1961). The degree and aspect of slope, as well as the soil surface color, would have a significant influence on absorption of solar radiation, associated soil temperatures, the water balance, and the vegetation and its ability to stabilize soils.

A second group of meteorological variables, precipitation characteristics, was also obtained from the best source available, NOAA. One can determine numerous limitations on such data. Mean precipitation totals were used as a basis in developing the model. Unfortunately, in areas of fluctuating totals, mean values do not indicate the departures from the mean. As an example, for the weather reporting station at Kayenta, the mean annual precipitation for the period of 1941-1961 was 7.83 inches. Yet an annual amount as low as 4.74 inches occurred during 1955 (Sellers and Hill, 1974).

Such fluctuations in precipitation totals may warrant consideration of precipitation totals during "abnormal" years, for one might assume that dunes would be more likely to be initiated during such unusually dry periods. Throughout the study area, abnormally dry years, or dry seasons, may be more important in initiating dunes than would mean annual precipitation totals.

An additional problem with the climatic data is the time frame in which the data was gathered compared to the time that dune formation was initiated. Both Cooley (1969) and Durrenberger (1972) indicated climates fluctuated during the past. As a result, using relatively current mean temperature and precipitation data as indicators of climatic conditions at the time of dune formation may be responsible for some misclassification problems.

An additional group of variables dealt with wind flow patterns and the relationships between surface obstacles and the ability of the wind to transport and deposit materials. Once again, conditions at the time of dune formation may have been different than today. It is quite possible that a living or dead plant or animal may have altered wind flow patterns enough to allow for the accumulation of a longitudinal dune on the leeward side as indicated by Hack (1941) and Wilson (1972), yet the obstacle may no longer be present today.

An additional factor of concern is the apparently short time necessary to initiate dune formation. Hilst and Nickola (1959), as well as Chepil (1965) and the United States Department of Agriculture (1961), indicated that as wind action begins to sort soil materials, the finer, more productive materials are the first to be lost. With their removal, the soil becomes less productive, and the eolian process becomes a continuing problem. Therefore, as the result of a relatively short term situation, which may not be indicated by using long term variable values, dunes could develop and flourish even though the stimulus which caused their initial formation may no longer exist. Similar time problems may exist with additional variables.

An entirely different set of circumstances may have lead to a portion of the misclassification problem--the absence of specific variables that could have contributed to the model.

A group of physical variables similar to those considered by Chepil (1965) and the United States Department of Agriculture (1961), may have been able to contribute to the model's predictive power. Variables relating to soil erodibility based upon roughness, cloddiness, and abradability and wind-moisture-vegetation relationships were found useful by Chepil in laboratory experiments. Those variables were not included in the study due to the problem of determining their values prior to dune formation as well as for reasons previously covered in Chapter I.

A second group, cultural variables, may have had an effect upon dune occurrence. The activities of man and his livestock probably contributed to formation of a portion of the dunes. A variety of human activities, such as gathering of wood for fuel, affects the vegetative cover, and ultimately soil stability (Kluckhohn and Leighton, 1962, and Terrell, 1970). The interaction between the people and livestock and grazing practices has led to destruction of vegetation near both hogans and available surface water supplies (Durrenberger, 1972). The opportunities people in the study area would have to alter the vegetation and the soil's stability would appear to be numerous as well as unique to the individual and his life style. Due to the difficulty in applying an erosive value to such unique features at the present time, much less in the past when dunes were initiated, was a contributing factor in the exclusion of cultural variables from the study.

The list of possible causes for the initiation of dune formation may be endless. Any activity, natural or man-made, recent or historic, that in any manner altered the vegetation of a location may be responsible for the formation of a dune. Although the previously discussed additions to the variables used in developing the model might be beneficial in model development, unfortunately, they are for the most part impossible or impractical to obtain and were not used in the study.

CHAPTER V

CONCLUSION

The initial purpose of this research was to attempt to determine the relationship between selected physical environmental variables and dune occurrence on the Navajo Uplands of Northeastern Arizona. A second portion of the study involved developing a model that would predict the presence or absence of dunes based upon the physical environmental characteristics of an area.

As a result of analyzing the data, evaluating the Supportive Hypotheses, and developing and testing the model, it was found that 85% of the quadrats could be correctly classified. It is possible without a doubt to accept the Research Hypothesis: There is a significant relationship between selected measurable geomorphic, meteorologic, and lithologic phenomena on the Navajo Uplands of Northeastern Arizona and the occurrence of dunes; and that relationship can be used to develop a model to predict dune occurrence at selected locations throughout the study area.

The procedure that lead to the acceptance of the initial portion of the research hypothesis is described in

Figure 8--Procedure for Analysis. The following brief description of that process may be beneficial in assisting the reader. After the research problem had been identified, the study area selected (as described in Chapter I and II), and the interpreted data from the air photographs verified, two groups of one hundred quadrats each were randomly chosen. The values for each variable selected (Chapter III) were obtained from the data sources indicated.

Data for the two groups of variables were used for developing the model and for testing it. The first step in data analysis involved identifying those variables whose means in the dune group were significantly different from those in the non-dune group.

The original variables, the F statistics indicating the difference in group means, as well as the discriminating power of each variable were determined by the discriminant portion of the discriminant analysis routine. As a result of that analysis three variables were removed from further consideration (Variables 3, 4, and 6 as listed in Table 1) due to the fact that their means in group dune and in group non-dune did not differ significantly.

The remaining 12 variables and their relationship to dune occurrence is indicated in Figure 9 in a graphic manner. On the left side of the diagram is a list of variables--from mean growing season precipitation through slope-mean annual wind direction relationships measured on a 0°-90°

PROCEDURE FOR ANALYSIS

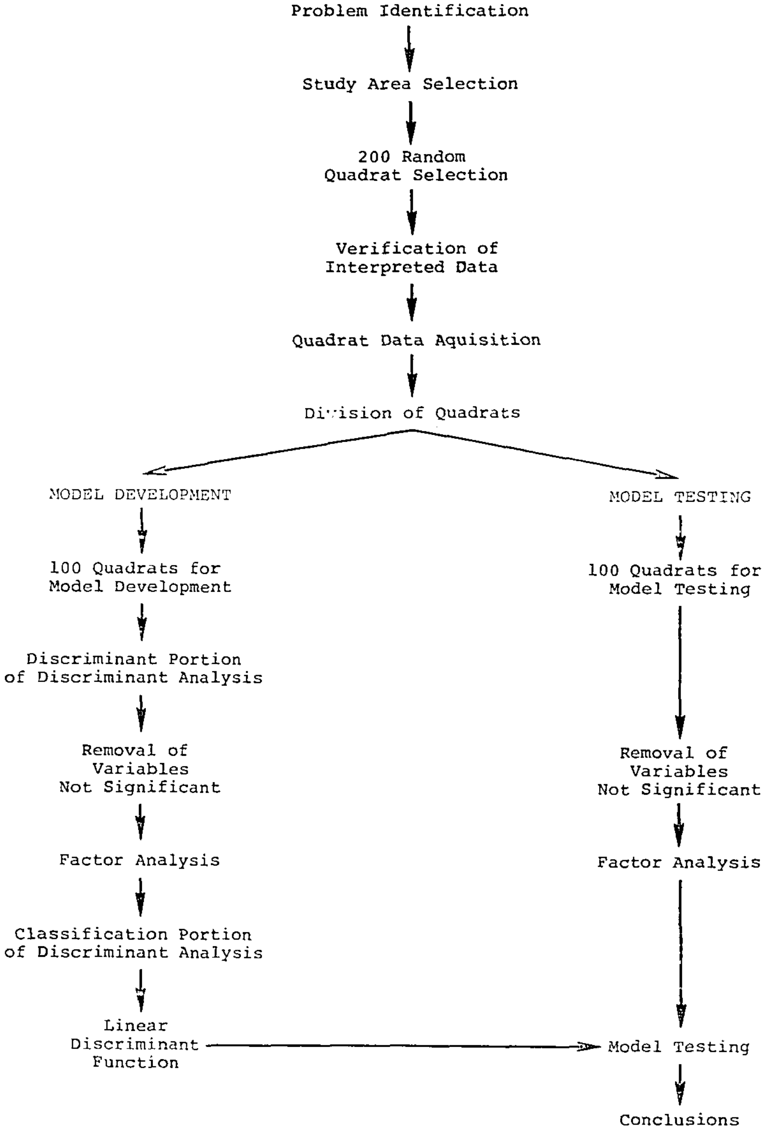


Figure 8

VARIABLE FLUCTUATIONS AND DUNE OCCURRENCE

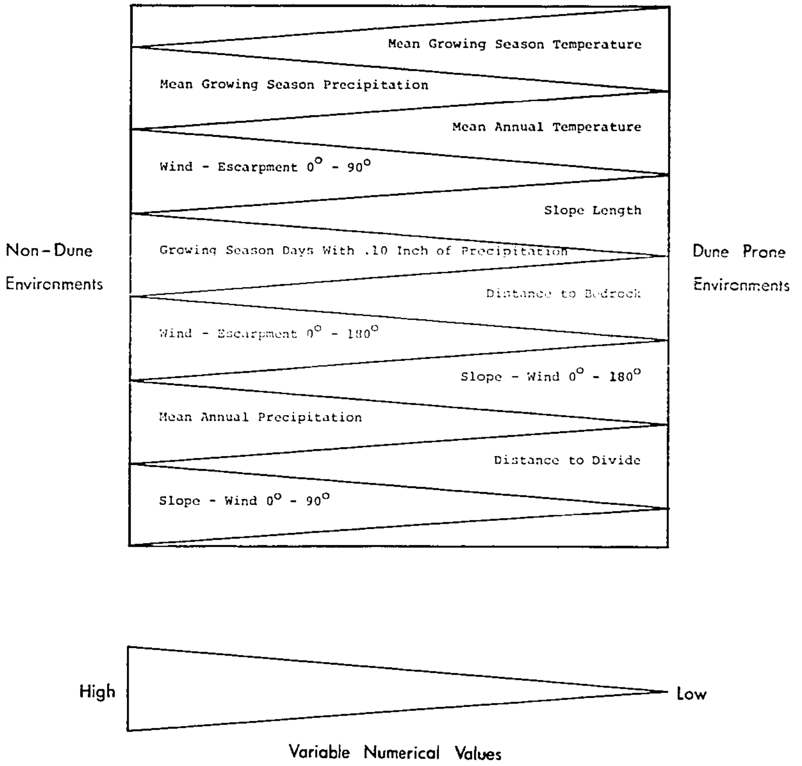


Figure 9

basis. The variables listed on the right side include mean growing season temperature through distance to the nearest upwind drainage divide. Variation in the vertical dimension of each variable segment of the diagram indicates a change in numerical value for that variable. Therefore, a decrease in numerical values for the variables on the left, or an increase in numerical values for those on the right, is associated with greater dune probability. Conversely, increased numerical values for those on the left and decreases for those on the right are associated with dune free areas. The ultimate dune prone area would have high values for mean growing season temperature, mean annual temperature, long slope length, long distance to bedrock, slopes facing away from the mean annual wind direction, long distance to the nearest upwind drainage divide, low mean growing season precipitation totals, escarpments nearly perpendicular to the mean annual wind direction, fewer growing season days with precipitation totals of 0.10 inches or more, escarpments facing more southwesterly than northeasterly, low mean annual precipitation totals, and slopes facing southwest or northeast rather than southeast or northwest. (It is purely coincidental that each group is composed of six members.)

As the model developed, it was possible to determine the contribution of each raw variable to the model. The discriminating power of each of the raw variables is indicated in Table 2. Variables such as slope length, mean annual precipitation, mean growing season precipitation, and angle of the nearest upwind escarpment compared to the mean annual wind direction measured on a 0^{o}-90^{o} basis contributed approximately 50% of the discriminating power. They might be considered the "core" variables for the research area.

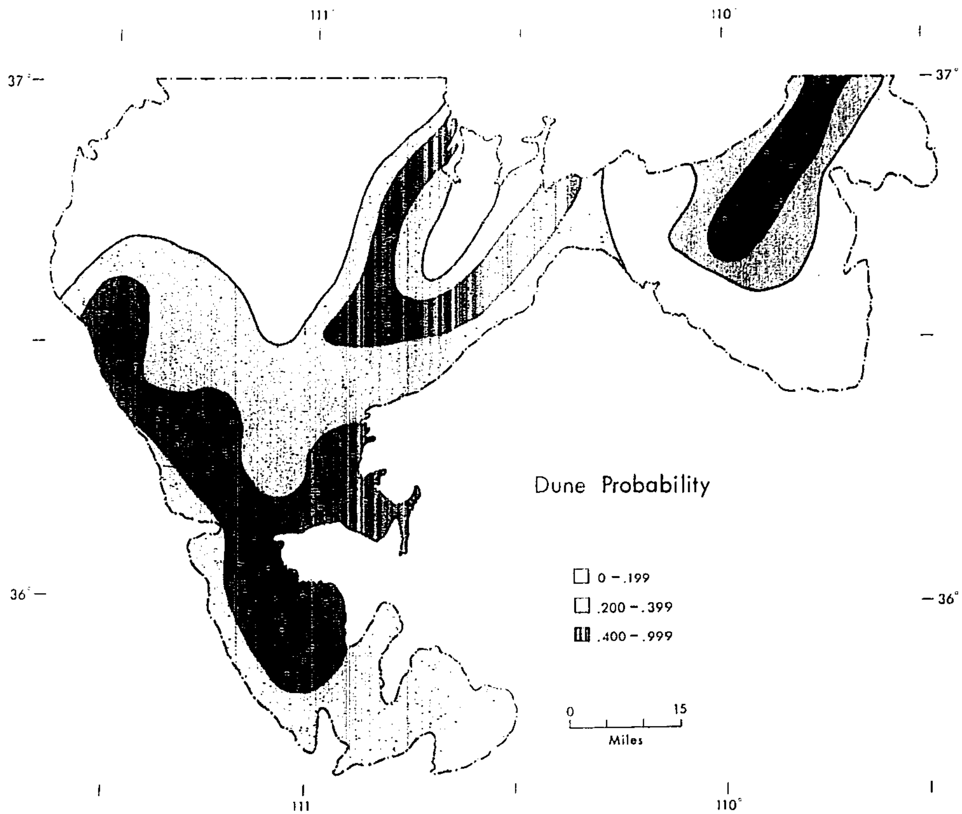
As the research proceeded the variables lost their individual identity and were regrouped and represented as factor scores. The results of factor analysis indicated that four distinct independent factors were involved in the environmental characteristics of the study area. The four, meteorological, slope length, wind-slope, and wind-escarpment, were nearly equal in discriminating power (Table 6).

The factor scores were used as input into the classification portion of the discriminant analysis routine. The linear discriminant function obtained from them was used to classify the factor scores from the 100 quadrats initially reserved for model testing. The results of that classification provided the basis for testing the model's predictive ability. The results of the testing are indicated in Table 7. Values falling on a diagonal from upper left to lower right are correctly classified. Those remaining sites were incorrectly classified. Based upon the 85% correct classification rate, the model could be classified as a success and the research hypothesis accepted.

The probability of membership in group dune and group non-dune for each of the quadrats is indicated in Appendix III. Map 6 displays the distribution of probability characteristics for group dune within the study area. The map is a generalization; as a result, within each zone, sites may occur that have probabilities considerably different than the majority of the members of that zone.

In addition to accomplishing the objectives of the research problem, it was also possible to apply the ideas of other researchers during the testing of the supportive hypotheses. Ideas that had often been field tested on a limited scale, or in other cases had never been applied outside of the laboratory, were applied to the Navajo Uplands of Northeastern Arizona.

Ideas relating to the influence of meteorological variables upon dunes as described (in Chapter III) by Rosenberg (1974), Tivy (1971), Slatyer (1967), Mabbutt (1977), Bagnold (1954), Cooke and Warren (1973), Peel (1960), Laetsch (1979), and Johnson (1975); of lithologic variables as described by Bagnold (1954), Carson (1971), Cooley (1969), Cooke and Warren (1973), Thornbury (1969), Mabbutt (1977), and Chepil (1965); and of geomorphic variables as described by Bagnold (1954), Carson (1971), Rosenberg (1974), and Chepil (1965) were tested in the study area. The results were indicated in the variable analysis portion of Chapter IV.


111°
110°
37°
36°
Dune Probability
0 – .199
.200 – .399
.400 – .999
0
15
Miles
111
110°

Map 6

Completion of this research project is also a step toward providing the information necessary to fill the void in eolian geomorphology described by Cooke and Warren (1973). They felt that a noticeable void existed in the "middle" level of eolian geomorphology. The study also applied research in the form of quantitative tools, a need expressed specifically by Stokes (1973) in his discussion of the study area and surrounding environment.

As a result of this research project, it is now possible for the first time to predict, with an acceptable degree of accuracy, sites within the study area that are likely to possess dunes based upon physical environmental attributes of that site. Areas suitable for dune formation were readily identified in the model testing portion of Chapter IV. The use of the predictive model and the implications of the physical environment upon vegetation's ability to stabilize soils has a number of applications within the research area, as well as other dune-prone locations (with modifications to include local environmental characteristics). Through the identification of dune-prone areas, any of a number of restrictive land use practices could be used to prevent the destruction of the soil's productive capabilities and the formation of dunes.

APPENDIX I

STUDY AREA VEGETATION

Croton weed	Croton texensis
Alkali sacaton	Sporobolous airoides
Bushmint	Poliomintha incana
Rabbit bush	Chrysothamnus biglovii
Dropseed grass	Sporobolus cryptandrus
Sand sage	Artemisia filifolia
False buffalo grass	Munroa squarrosa
Snakeweed	Gutierrezia spp.
Grama grass	Bouteloua gracilis
Sagebrush	Artemisia tridentata
Galleta grass	Hilaria jamesii
Spiny Muhley	Muhlenbergia pungens
Three-awn	Aristida spp.
Indian rice	Cryzopsis spp.
Black grama	Bouteloua eriopoda
Russian thistle	Salsola pestifer
Indian wheat	Plantago spp.
Heath aster	Aster leuceline
Sunflower	Helianthus spp.
Lupine	Lupinus spp.
Black brush	Coleogyne ramosissima
Chamise	Atriplex canescens
Mormon tea	Ephedra spp.
Yellowbush	Chrysothamnus greenii
Winter fat	Eurotia lanata
Cliffrose	Cowenia stansburiana
Piñon	Pinus edulus
Juniper	Juniperus monusperma Juniperus utahensis

Sources: Hack (1941, 251)
Boyce (1974, 253)

APPENDIX II

STATION	KOEPPEN SYMBOL	ELEVATION
Betatakin	BS	7,200
Cedar Ridge Trading Post	BW	5,920
Copper Mine Trading Post	BS	6,380
Cow Springs Trading Post	BS	5,700
Dinnehotso	BW	5,020
Kayenta	BS	5,675
Kaibito	BS	6,000
Tuba City	BW	4,936

Source: NOAA

APPENDIX III

Observation	Membership Probability Group Dune	Membership Probability Group Non-Dune	Designated Membership	Actual Membership
1	.109	.890	Non-Dune	Non-Dune
2	.728	.271	Dune	Non-Dune
3	.114	.885	Non-Dune	Non-Dune
4	.504	.495	Dune	Dune
5	.621	.378	Dune	Dune
6	.051	.948	Non-Dune	Non-Dune
7	.895	.104	Dune	Dune
8	.280	.719	Non-Dune	Non-Dune
9	.085	.914	Non-Dune	Non-Dune
10	.444	.555	Non-Dune	Non-Dune
11	.026	.973	Non-Dune	Non-Dune
12	.056	.943	Non-Dune	Non-Dune
13	.734	.265	Dune	Dune
14	.020	.979	Non-Dune	Non-Dune
15	.212	.787	Non-Dune	Non-Dune
16	.054	.945	Non-Dune	Non-Dune
17	.239	.760	Non-Dune	Non-Dune

18	.887	.112	Dune	Dune
19	.093	.906	Non-Dune	Dune
20	.043	.956	Non-Dune	Non-Dune
21	.160	.839	Non-Dune	Non-Dune
22	.007	.992	Non-Dune	Non-Dune
23	.384	.615	Non-Dune	Non-Dune
24	.235	.764	Non-Dune	Dune
25	.183	.816	Non-Dune	Non-Dune
26	.099	.900	Non-Dune	Non-Dune
27	.081	.918	Non-Dune	Non-Dune
28	.036	.963	Non-Dune	Non-Dune
29	.065	.934	Non-Dune	Non-Dune
30	.621	.378	Dune	Dune
31	.142	.857	Non-Dune	Non-Dune
32	.036	.963	Non-Dune	Non-Dune
33	.344	.655	Non-Dune	Non-Dune
34	.026	.973	Non-Dune	Non-Dune
35	.456	.543	Non-Dune	Non-Dune
36	.012	.987	Non-Dune	Non-Dune
37	.954	.045	Dune	Dune
38	.458	.541	Non-Dune	Non-Dune
39	.282	.717	Non-Dune	Non-Dune
40	.051	.948	Non-Dune	Non-Dune
41	.036	.963	Non-Dune	Non-Dune
42	.938	.061	Dune	Dune
43	.079	.920	Non-Dune	Non-Dune

44	.069	.930	Non-Dune	Non-Dune
45	.074	.925	Non-Dune	Non-Dune
46	.493	.506	Non-Dune	Non-Dune
47	.059	.940	Non-Dune	Non-Dune
48	.049	.950	Non-Dune	Non-Dune
49	.161	.838	Non-Dune	Non-Dune
50	.205	.794	Non-Dune	Dune
51	.176	.823	Non-Dune	Dune
52	.024	.975	Non-Dune	Non-Dune
53	.104	.895	Non-Dune	Non-Dune
54	.147	.852	Non-Dune	Non-Dune
55	.111	.888	Non-Dune	Non-Dune
56	.433	.566	Non-Dune	Dune
57	.208	.791	Non-Dune	Non-Dune
58	.237	.762	Non-Dune	Non-Dune
59	.219	.780	Non-Dune	Dune
60	.164	.835	Non-Dune	Non-Dune
61	.220	.779	Non-Dune	Non-Dune
62	.044	.955	Non-Dune	Non-Dune
63	.464	.535	Non-Dune	Non-Dune
64	.038	.961	Non-Dune	Non-Dune
65	.069	.930	Non-Dune	Non-Dune
66	.384	.615	Non-Dune	Non-Dune
67	.533	.466	Dune	Dune
68	.705	.294	Dune	Dune
69	.019	.980	Non-Dune	Non-Dune

70	.587	.412	Dune	Dune
71	.215	.784	Non-Dune	Non-Dune
72	.153	.846	Non-Dune	Dune
73	.537	.462	Dune	Dune
74	.999	.0006	Dune	Dune
75	.307	.692	Non-Dune	Dune
76	.170	.829	Non-Dune	Non-Dune
77	.560	.439	Dune	Dune
78	.018	.981	Non-Dune	Non-Dune
79	.041	.958	Non-Dune	Non-Dune
80	.525	.474	Dune	Dune
81	.060	.939	Non-Dune	Non-Dune
82	.122	.877	Non-Dune	Non-Dune
83	.118	.881	Non-Dune	Non-Dune
84	.390	.609	Non-Dune	Dune
85	.154	.845	Non-Dune	Non-Dune
86	.837	.162	Dune	Non-Dune
87	.192	.807	Non-Dune	Non-Dune
88	.169	.830	Non-Dune	Dune
89	.039	.960	Non-Dune	Non-Dune
90	.130	.869	Non-Dune	Non-Dune
91	.115	.884	Non-Dune	Non-Dune
92	.492	.507	Non-Dune	Dune
93	.246	.753	Non-Dune	Non-Dune
94	.810	.189	Dune	Dune
95	.279	.720	Non-Dune	Dune

96	.046	.953	Non-Dune	Non-Dune
97	.051	.948	Non-Dune	Non-Dune
98	.309	.690	Non-Dune	Non-Dune
99	.090	.909	Non-Dune	Non-Dune
100	.178	.821	Non-Dune	Dune

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