/PLANT REDISTRIBUTION AND DESERTIFICATION DUE TO SUBSIDENCE
FISSURES IN THE WILLCOX AREA, ARIZONA/

by

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B. S., Northern Arizona University, 1982

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A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF ARTS

Department of Geography

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1984

Approved by:

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## INTRODUCTION

Since about 1910 groundwater in the Willcox area of South-eastern Arizona has been used for irrigation. At first only relatively small amounts of water were extracted from the alluvial aquifer of the area, and it wasn't until about the mid-1940's that significant amounts were withdrawn (Brown and Schumann 1969). As development progressed, however, larger and larger amounts of water were withdrawn until withdrawals have greatly surpassed the estimated recharge rate (Brown and Schumann 1969, Mann, White, and Wilson 1978). This large scale extraction of water has left its imprint on the aquifer and some interesting environmental changes have occurred.

### Background

The Willcox Basin is located in the northern part of Cochise County and the southern part of Graham County, Arizona (Figure 1). It is a moderately large closed basin on the eastern edge of the Basin and Range Province and extends about 48 miles at its widest point and about 65 miles long (Brown and Schumann 1969). Topographically, the Willcox area consists of three main features: mountains, alluvial slopes, and a playa flat.

The basin is bounded on the east by the Chiricahua and Dos Cabezos Mountains, on the north by the Pinaleno Mountains, on the northwest by the Galiuro and Winchester Mountains, and on the west
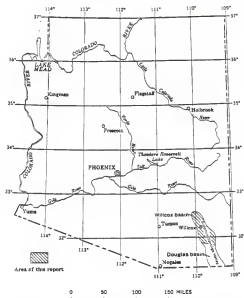
Figure 1. The Willcox Basin within Arizona
(Brown and Schumann 1969)

by the Dragoon and Little Dragoon Mountains (Figure 2).

The average annual precipitation is 12 to 14 inches and the
average annual temperature is 60° to 62° F (Soil Conservation Service
1976). The climate of the area is characterized by hot summers and
cool moderate winters. The summer moisture comes from convective
type thunderstorms and winter moisture comes from frontal-type storms.
July and August have the most precipitation and April and May the least.
The average pan evaporation at Willcox is 84.59 inches (Brown and
Schumann 1969). This figure is about seven times that of the average
precipitation so there is a definite water deficit in the area.

Figure 2



WILLCOX AREA, ARIZONA
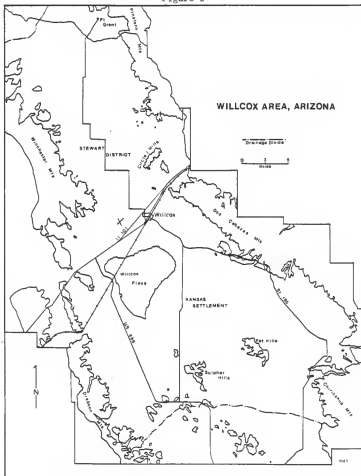
The vegetation of the basin varies from low salt resistant shrubs near the playa flat to dense forests of Douglas Fir, Pine, Aspen and Spruce on the higher peaks of the Pinaleno and Chiricahua ranges. Most of the basin however, is occupied by desert grassland and shrubs. The desert grassland covers extensive bajadas that enclose the playa and is intermixed with shrubs characteristic of the Chiricahua Desert. Mesquite (Prosopis juliflora) is the dominant shrub and has its best growth on fine soils underlain by a fairly high water table (Martin 1963).

## Groundwater Use and Development

The City of Willcox, which lies near the center of the basin, had its origins in 1877 as a railroad camp formed by men doing the grading for the incoming Southern Pacific Railroad. The town was able to remain intact after the completion of the railroad through the basin because it was one of the best grazing areas in Arizona and because it had a good source of water. The groundwater in the area was so near the surface that it could be easily reached with hand tools (Schultz 1964).

Up until the early 1900s livestock grazing was the main enterprise, although some mining was going on, and at its climax in 1891 it is estimated that 1.5 million cattle were in the valley. As many as nine trainloads of cattle were shipped from Willcox in a day, and several thousand head were held on the range awaiting trains (Soil Conservation Service 1976). One of the obvious needs of the cattle industry in the early days was a dependable year-round water supply. According to Schultz (1964), the Territorial Legislature

in 1875 offered a reward for the first artesian well to encourage water development. This was won by W. J. Sanderson of the Willcox area for his well which began producing on May 12, 1883. It was 6 inches in diameter and 38 feet deep. It had a flow of between 28 and 35 gallons per minute.

Schultz further stated the Chiricahua Cattle Company had a well driven by a steam engine which produced 250 gallons per minute as early as 1888 and had also installed windmills on other parts of its range. Other cattle outfits followed suit when they found that in most parts of the valley water was relatively close to the surface.

The unusually wet year of 1905 brought about some interest in dryland farming in the area. B. H. Tillotson of Olathe, Kansas persuaded his relatives and friends to take advantage of the fertile land available, and the Kansas Settlement, which begins about 5 miles southeast of Willcox, was settled. The rains continued and by 1906 a steady stream of farmers were arriving in the basin. The discovery of artesian water was another big incentive for farmers to come to the area. By 1908 farmers were starting to settle the area north of Willcox as well (Schultz 1964). The rains began to diminish by that year, however, and in the following years only those who were practicing efficient dryland methods or could obtain water by diverting floodwater or by pumping groundwater were able to continue farming (Soil Conservation Service 1976).

Windmills and pumps driven by small gasoline engines were gradually replaced by larger motor-driven pumps. This was made possible by the formation of the Sulpher Springs Valley Electric Cooperative which came into being in 1938 upon application to the

Rural Electrification Administration of the federal government. World War II brought about a rise in agricultural prices and an increase in demand for land. This, coupled with the available electric power, brought about a large increase in the amount of acreage brought under cultivation. After the war, this trend continued and by 1949 there were 25,297 acres being irrigated. In the following decades development of farmland increased even more rapidly. Between the years of 1947 and 1964 an additional 60,000 acres was brought under cultivation (Schultz 1964) By 1976 the figure of total acres under cultivation and ultimately irrigation, (since all crops must be irrigated) had risen to 150,000 acres (Soil Conservation Service 1976). By 1983 the total acreage under cultivation had declined substantially with only 33,000 acres being reported as being used for crops (Agriculture Stabilization and Conservation Service Records 1983). The decline in the amount of land used for agriculture has probably been affected by high natural gas prices and lowering water tables. These large acreages of irrigated land have brought about a large demand on the underlying aquifer, especially since many of the crops such as corn, lettuce and alfalfa have a high demand for water.

## Changes Caused by Groundwater Overdraft

As groundwater began to be used extensively for irrigation in the area profound changes began to take place. One of these changes was a drastic deformation of normal pressures and water levels within the aquifer itself. In 1910, prior to any extensive pumping, the aquifer was probably in equilibrium. The shape of the piezometric surface (level to which water under pressure caused

by confined conditions would rise in wells penetrating the confining layer) was in the form of an elongated depression, and it sloped toward the playa from all sides. Since then large scale pumping has greatly changed the piezometric surface. By 1963 the static water level had dropped drastically. Instead of the piezometric surface sloping toward the playa two large depression cones had formed. One cone encompassed Willcox and most of the Stewart area and another formed in the Kansas Settlement area extending northward to a point about 5 miles east of Willcox. This extensive pumping has brought about large scale alterations in the entire system changing the natural direction of flow and completely reversing it in some places (Brown and Schumann 1969). Between the years of 1954 and 1975 water levels declined more than 200 feet in 9 of 36 checked periodically (Mann, White and Wilson 1978). The average water decline from 1952 to 1964 was 29 feet in the Stewart area and 74 feet in the Kansas Settlement area (Brown and Schumann 1969).

Along with the large changes in the aquifer has come a decrease in the elevation of the land surface in some areas. This subsidence of the land surface occurs where there is a compaction of the sediment between the dewatered zone and the water table.

Along with land subsidence, earth cracks or fissuring has occurred. It is currently believed that these fissures are formed above buried hard rock areas that control the thickness of soft sediment, particularly along the margins of the basin. The hard rock areas continue to hold up soft sediment while the buoyant force holding up sediment in the heavily pumped area is reduced. This causes a stress on sediment adjacent to, and above the hard rock

area sufficient to cause it to pull apart and form a crack or fissure which extends to the water table (Arizona Water Resources Project Information 1980).

The location of fissuring is not static and the zone of activity may migrate. B. E. Lofgren found in an area 50 miles east of Picacho, Arizona that active new fissuring has moved progressively eastward toward the mountains as maximum pumping drawdowns have moved eastward. He believed that all fissures in the area were surface manifestations of deep horizontal and vertical ground movements, related to water level declines caused by pumping overdraft (Lofgren 1978).

Like the fissures in the Picacho area, the location of fissuring in the Willcox basin is not static. However, fissuring seems to be migrating away from the mountains instead of toward the mountains like in the Picacho area, but like the Picacho area, migration is thought to be moving toward the area of greatest withdrawals and subsidence.

Along with the fissuring some vegetational changes seem to be taking place. The fissures are often perpendicular to the natural drainage pattern and capture runoff and channel it in a different direction. This increases the amount of soil moisutre available along the fissure and reduces it downslope. Therefore, a change in the plant community density and distribution would be possible, and there seems to be some evidence of it.

## Statement of Problem

Land subsidence has been associated with extensive groundwater withdrawals, and fissuring has been associated with land subsidence.

It is the hypothesis of the researcher that fissures developing in the Willcox area are successively moving toward the valley in the direction of the area of greatest water withdrawals and subsidence. Further, since these fissures are often perpendicular to natural drainage they are responsible for a redistribution of the natural vegetation with it becoming more dense around the fissures as a process of desertification takes place downslope.

## Justification

In the past the earth has been exploited by man with little regard to natural environment. There was a "taming the wilderness" attitude. In the last few decades, however, these views have been opposed and a growing concern about the environment has emerged (Spencer and Thomas 1978). With this growing concern an increasing amount of emphasis has been placed on studies that have centered on man's impact on the environment. These studies have been valuable in making policy decisions on resource use and conservation.

This particular study will be useful in assessing the environmental changes made by the withdrawal of water from an enclosed, confined aquifer. If subsidence fissures are indeed responsible for degradation of the grass and shrub land of the basin, and if they are indeed migrating, then over a period of time larger and larger areas will be degraded. This will be significantly important to those individuals using the area for grazing and also for those concerned with preserving the landscape and grasslands of Southeastern Arizona.

There seems to be a lack of detailed studies on the vegetational

impacts of subsidence fissures and this study attempts to fill a gap
in the body of research done on fissuring and desertification. It
is spatial in nature as it deals with the arrangement of fissures and
the arrangement of vegetation in relation to the fissures. It fits
well in geography as a man-land study which put its emphasis on the
relationship between man and his environment.

## Methodology

The problem of fissure-induced vegetation changes was
approached in three main steps. Each step was intended to build
upon the other until a conclusion was reached. Step one was a
review of pertinent literature to find what has been done in previous
studies related to fissuring and plant community changes and
desertification.

The next step was to assess the direction of successive
fissuring. This was done by building on current fissuring theories
and applying them to hydrological data in the area. The hydrological
data used in this study was taken from a report of the hydrology of
the Willcox area by Brown and Schumann (1969) and from a publication
of maps and well logs by Brown, Schumann, Kister, and Johnson (1963).
Through the use of well logs and topographic data obtained from maps,
aquifer cross-sections were constructed and information extracted
for the use of building a theoretical model of fissure progression.
Through the use of temporal aerial photographs the actual fissure
sequence was obtained and compared with the theoretical sequence.
A fissure area that is approximately six miles northwest of the city
of Willcox was used as a case study because: 1) the expense of obtain-

ing temporal photo coverage of all fissure areas, and, 2) this
particular fissure area is thought to be among the oldest and most
active.

Step three was an assessment of vegetation changes in relation
to the fissures. This was done by means of a series of nearest-
neighbor analyses taken in the fissure area and a carefully selected
control area (an area similar to the fissure area but devoid of
fissures) for the purpose of comparing changes in the spatial
distribution of mesquite in a fissure and non-fissure area. Mesquite
was chosen because of its great resistance to drought and the fact
that it would be the last plant affected by prolonged dry periods
within this particular biome. Eight sample areas of 2500 square feet
were randomly obtained within both the fissure and control areas for
analysis. The nearest-neighbor indices were obtained then tested
for significance using the method described by Clark and Evans (1954).
An analysis of variance between the indices was conducted for the
purpose of detecting differences between indices within the fissure
and non-fissure areas.

In addition to assessing distribution changes a small sample
t-test was done to compare differences in the densities of samples
in the fissure area as opposed to those in the non-fissure or control
area.

Finally, by the use of temporal aerial photography the
vegetational changes in the fissure and control areas were assessed
and conclusions made.

## Plan of Study

A review of literature related to land subsidence and fissuring, vegetation redistribution, and desertification is given in Chapter Two. Chapter Three deals with subsidence fissures and the fissuring sequence. Chapter Four deals with the redistribution of vegetation and desertification in relation to subsidence fissures. Finally, a conclusion and summary are included in Chapter Five.

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Chapter 2

# REVIEW OF PERTINENT LITERATURE

A review of literature pertinent to the study was necessary
for an understanding of what has been previously done and for back-
ground information. The review was divided into two main areas:
1) information dealing with groundwater withdrawals, subsidence,
and fissuring, and 2) information dealing with vegetation redistri-
bution and desertification. The division between subjects was made
because studies that span the two are practically non-existant.

## Subsidence and Fissuring Studies

Subsidence studies, including general subsidence information
as well as many case studies have become increasingly numerous. An
overview article by Poland and Davis (1969) noted that since 1940
land subsidence due to fluid withdrawals has become quite common.
Some major locations that are mentioned include areas in Japan,
Mexico City, Texas, California, Arizona, and Nevada. The article
includes a brief examination of the causes of subsidence and a
discussion on how subsidence can be stopped. The authors noted that
the greatest subsidence has taken place in California where the land
had fallen 27 feet.

Ben E. Lofgren (1968) in a Geological Survey Professional
Paper dealt with the stresses responsible for land subsidence. He
noted that in intensive groundwater withdrawal areas, land subsidence

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is caused by increased effective loading stresses, which are responsible for compaction of deposits. These effective stresses are changed in two ways: 1) a drop in the water table decreases the buoyant support of the sediment grains in the area of change and, 2) a change in the water table or the piezometric surface or both can cause vertical hydraulic gradients and seepage stress in the sediment. This stress is algebraically additive to gravitational stress and is transmitted downward to all underlying deposits. Lofgren concluded that in an unconfined aquifer with a deposit porosity of 40%, the effective stress would increase 0.6 feet for each foot of water table decline. In the situation where an unconfined aquifer overlies a confined aquifer with a porosity of 40% a water-table rise of one foot would cause a 0.4 foot increase in effective stress and a one foot decline in the piezometric surface would cause a one foot increase in the effective stress. The change in the effective stress differs with different porosities.

Some of the literature relates fissuring to subsidence. In a project bulletin of the Arizona Department of Water Resources (1980) an expose on subsidence and fissuring was made. The article stated that subsidence is lowering hundreds or maybe even thousands of square miles of Arizona's land surface and much of the subsidence has yet to be documented. Water-table decline data is somewhat more available however, and this data is essential for anticipating land subsidence since decline of the water-table is a major cause of it. The article also states that fissuring has also become a problem in Arizona. These fissures are thought to be formed above buried hard rock areas which control the compaction of soft sediment along basin margins.

Fissures occur in Cochise, Pinal and Maricopa counties where there are more than 100 individual fissures in the latter two counties alone. This article concludes that subsidence and fissuring are readjustments made by nature in response to mans' tampering with natural balances. In less than one generation a balance that has taken nature thousands of years to create has been disturbed and as long as large quantities of water are withdrawn from Arizona's aquifers, subsidence and fissuring will continue.

In an article by William Kam (1965) the effects of fissures that close natural drainages are discussed. Kam stated that when a subsidence crack transects a drainageway a lower local base level is produced and gullying is likely to occur in the upstream segment of that drainageway. Runoff entering a fissure does not normally run laterally along it but instead moves downward into unsaturated sediment or even all the way to the water-table. Water will run laterally however, when the amount of water entering a fissure is more than can be transmitted downward. This would allow gullying to take place along the fissure and result in a change in the surface flow pattern.

In a publication written by William E. Strange (1983) which outlines a subsidence monitoring plan for the state of Arizona information is given concerning the occurrence of subsidence which is affecting some 3,000 square miles of southeastern Arizona. This publication includes general information about subsidence and fissuring as well as specific local information which includes leveling data for many areas in southern Arizona including the Willcox area. Different methods of monitoring subsidence are discussed and an

outline of a statewide monitoring plan is given.

A different look at land subsidence was made by Charles McCauley and Russell Gum (1975) who tried to analyze the economic impact of subsidence and fissuring. The eastern half of Pinal County, Arizona was chosen as a study area. Cost of damages caused by subsidence were divided into two categories: damages to man-made structures, and damages to natural structures. The damage to man-made structures were categorized into: transportation facilities, domestic and urban structures, and agricultural structures. The damages to natural structures included general sinking of the land, cracking of the surface along basin margins, reduction in storage capacity of the aquifer, gully generation, and deterioration of the scenic value of the land. No mention of vegetational changes were made. They found that $187,250 worth of damages were made to agricultural structures, $19,800 worth of damages were made to the transportation structures and no damage done to domestic and urban structures. The natural damages were either not assessed or were not considered significant. A benefit-cost analysis revealed that the current management practices were adequate, given existing institutional and economic constraints and the authors felt that the importance of subsidence has been grossly overstated.

Since land subsidence and fissuring are directly affected by aquifer conditions the following publications were of particular use to this study as they give details of the hydrological situation of the Willcox area.

A publication on the geohydrology and water utilization in the Willcox Basin by Brown and Schumann (1969) contains a considerable

amount of information about the aquifer in the Willcox Basin.
Information on recharge, well yields, nature of sediments and maps
on water-level changes are included.

A publication on basic groundwater data of the Willcox Basin
by Brown, Schumann, Kister and Johnson (1963) includes maps showing
location of selected wells, wells with drillers logs and groundwater
level changes. Data concerning groundwater quality are also given
in tabular form as are selected well logs.

A set of maps showing groundwater conditions in the Willcox
area by Mann, White and Wilson (1978) include data on groundwater
withdrawals, water level changes, distribution of dissolved solids
and flouride content in water, depth of water and the depth of the
well for selected wells.

## Vegetation Redistribution and Desertification Studies

David R. Harris (1966) studied the vegetational changes which
have come about in the last hundred years in the semi-arid Southwestern
United States. Harris claims in his study that based on historical
evidence and field observation there has been an invasion of woody
plants on native grasslands and stream courses. He attributes this
invasion to the occupation of the area by American settlers. It was
the introduction of new land use systems that brought about these
rapid ecological changes. Of the invaders mentioned by Harris
(mesquite, one-seed juniper, and salt cedar) the mesquite invasion
of the grasslands was of particular interest as it is pertinent to
this study. The spread of this woody plant is attributed to the
commerical development of livestock ranching which led to an increase

of the dispersal of seeds through droppings, overgrazing, and the reduction of grassland fires through suppression. This invasion is a good example of how man may unintentionally change the distribution of vegetation when he makes land use changes.

Another study of man-induced vegetational change by Vankat and Major (1978) was of interest; not particularly because of content but because of the methods used to arrive at their conclusions. Their study dealt with vegetation changes in Sequoia National Park. The authors showed the changes in vegetation correlated with past land use. To arrive at these conclusions research was done on past land use, using temporal photo coverage of the same area and field reconnaissance of the present vegetational conditions. They concluded that grazing practices and fire suppression were responsible for the changes.

Another vegetation change study by Bahre and Bradbury (1978) dealt with vegetation changes along the U. S. - Mexico Border between Arizona and Sonora. The authors of this article used similar methods as Vankat and Major to arrive at their conclusions. Using photos taken of border monuments for 1892, 1969, and 1976 they documented vegetation change in the area. To measure present day contrasts in vegetation they used a modified point-step sampling method in a series of five parallel transects of 20 points each 20 m on each side of the boundary fence. They also compiled a detailed land-use history. Using this information they concluded that there has been an increase in the amount of woody species in the area resulting in greater and taller grass cover on the U. S. side as compared to the Mexico side. The enhanced grass cover in the U. S. was a result of different land use

histories and grazing practices of the two countries.

The subject of desertification is broad and much has been written on the subject. The United Nations has had an interest in desertification and has been responsible for a large portion of the work that has been done. Numerous case studies have been conducted under the direction of the U. N.; many of which have been collected and put into volumes such as the book, Desertification, edited by Margaret R. Biswas and Asit K. Biswas (1980).

The World Watch Institute has published information on desertification as well. In his paper on the use of firewood as an energy source Erik Eckholm (1975) points out that the human need for fuel in many countries has been responsible for deforestation and the creation of desert-like conditions. A later paper by Eckholm and Brown (1977) published by the World Watch Institute deals exclusively with the world wide problem of desertification. The mismanagement of grazing animals, poor irrigation practices, putting crops on marginal lands, deforestation, and increased population pressures (all of which are enhanced by drought) are some causes behind the desertification problem.

Once the mechanism for desertification is started it seems to compound itself. For example, in an arid environment where vegetation begins to thin out, more of the land surface begins to be exposed, resulting in increased exposure and the possibility for gullying. This in turn may be a mechanism for a further decrease in the amount of vegetation. Also as more ground becomes bare there may be an increase in the albedo. In a study by Charney and others (1977) it was found that an increase in the albedo reduced the amount

of local rainfall, further enhancing the desertification process.

It is interesting to note that although desertification studies are numerous there are relatively few that attribute groundwater over-draft as a possible contributor to the problem. An article that does discuss groundwater overdraft as a contributor to desertification is one by Matlock (1976). Land subsidence and fissuring are not discussed in the article but the author points out that farmland has been left idle because of problems associated with the withdrawal of groundwater. The result is areas devoid of vegetation associated with deficit moisture levels.

A study by Alger (1982) does deal directly with fissures as a source of degradation to the environment. Alger studied a fissure area in the Phoenix, Arizona area and used remote sensing techniques to identify degradation. In addition ground surveys were carried out which involved taking transects across various fissures for the purpose of providing information on vegetational stress, thermal characteristics, erosional characteristics, and changes in the natural drainage. The results of his analysis were that the occurrence of true desertification did not exist but degra-dation certainly did. He felt that this degradation, particularly erosion, will increase and eventually lead to desertification.

## Conclusions

The problems of land subsidence, fissuring, vegetational changes, and desertification are certainly not new. A significant amount of literature has been written about each of these and there is little doubt of their reality.

There hasn't been any strong evidence presented of an inter-relationship between subsidence, fissuring, vegetational changes and desertification however, and it is the belief of the researcher that such an inter-relationship exists under certain conditions. These conditions are present in the Willcox area of Arizona and the following chapters are an analysis of these conditions and inter-relationships.

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Chapter 3

LAND SUBSIDENCE AND FISSURING

The withdrawal of water from an alluvial aquifer may have
a profound impact upon the arrangement of the sediment therein.
Increased stress between sediment grains may cause them to compact
and become more consolidated, and ultimately a decrease in the
elevation of the land surface may result. The process of land
subsidence is dependent upon several conditions including geology
of the aquifer, the nature of the sediments, and the amount and rate
of discharge as opposed to recharge. The conditions in the Willcox
area must be conducive to this process because subsidence has been
present for quite some time. In addition to the subsidence in the
area, fissuring has been present for a number of years as well and
activity within these fissure areas seems to still be present though
it is thought now to have slowed considerably. An analysis of the
conditions and processes associated with subsidence is important to
understanding the occurrence and distribution of related environmental
changes.

Geologic Background

The Willcox basin was formed, it is thought, in middle to
Late Tertiary time with large scale normal faulting accompanied by
the uplift of mountain ranges on a northwest-southeast direction.
The highest mountains are the Chiricahua and Pinaleno ranges both

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having peaks over 10,000 feet. These mountain ranges consist of
sedimentary igneous, and metamorphic rocks ranging from Precambrian
to Tertiary in age (Brown and Schumann 1969). After and during
the formation of the basin, large quantities of sediment were eroded
from the mountain ranges and deposited in the basin. It is thought
that the alluvium at the bottom of the valley is largely from volcanic
origin, but as erosion progressed the volcanics wore down and other
rock types began to surface, wear down, and be added to the alluvium.
One or more lakes occupied the basin with their shorelines fluctuating
from time to time due to climate variation. After the bulk of the
alluvium had been deposited, basaltic lavas were extruded near the
base of the mountains. These lavas became interbedded with the fill
or flowed upon its surface. Erosion then cut a pediment surface
on the basalt and valley fill. Pediment surfaces were also cut on
older rocks in the valley (Jones and Cushman 1947). Today erosion
is still taking place moving material from upslope down into the
valley to be deposited there.

## The Aquifer

The alluvium in the valley, which is the main source of water
in the basin, can be classified into one of three groups: moderately
consolidated, poorly consolidated and unconsolidated. The moderately
consolidated alluvium overlies the rocks of the mountain block in
an irregular fashion and is overlain in most places by the poorly
consolidated and unconsolidated alluvium. The water bearing capacity
of the moderately consolidated alluvium is not well known because
most wells penetrate both the moderately consolidated and the

unconsolidated alluvium and extract water from both. However, as
the water table has declined and more of the poorly consolidated and
the unconsolidated alluvium is dewatered the capacities of the wells
have diminished greatly, indicating that the consolidated material
is much less permeable. The poorly consolidated alluvium is much
like the moderately consolidated alluvium, so it is hard to distinguish
the two in well logs. The unconsolidated alluvium underlies most of
the valley floor and is made up of two facies - stream deposits and
clays. The stream deposits consist of lenses of gravel, sand and
silt and mixtures of these. The Stewart area gets most of its water
from these stream deposits of the unconsolidated fill while the wells
in the Kansas Settlement area get its water from the unconsolidated
alluvium and the poorly consolidated and moderately consolidated
alluvium beneath it. The clay deposits of the unconsolidated alluvium
are associated with the old lakes that once occupied the basin and
act as a confining layer which causes local artesian conditions near
the present day playa. The unconsolidated alluvium is the principal
aquifer of the Willcox area with the poorly and moderately consolidated
alluvium yielding smaller amounts of water (Brown and Schumann 1969).

## Hydraulic Properties

In discussing the hydraulic properties of the aquifer it can
be most easily understood by comparing the wells in different areas.
The two main areas in which discussion will be centered are the Stewart
and Kansas Settlement areas. The specific capacity (a well's yield
in gallons per minute per foot of drawdown caused by pumping) of
the wells in these areas is related to the water-bearing properties

of the sediment in which they are located. It must be recognized
that the specific capacity is affected by the way a well is cased,
screened and developed and is only an approximation of the way water
is transmitted through the aquifer.

In an analysis of the specific capacities in the two areas
by Brown and Schumann (1969) it was found that in the Stewart area,
which receives its water from the unconsolidated alluvium, the median
capacity of the wells was 20 gpm (gallons per minute) per foot of
drawdown per 100 feet of saturated material penetrated. One-fourth
of the wells in the area had a specific capacity per 100 feet of
saturated material of greater than 48 gpm per foot and one-fourth
of the wells had a specific capacity per 100 feet of saturated
material less than 8.5 gpm per foot. The large difference between
the upper and lower 25% of the wells indicates a wide range in the
water-bearing properties of the materials composing the aquifer in
the area.

In the Kansas Settlement area, which obtains its water from
the poorly consolidated and moderately consolidated alluvium, the
wells had a median capacity of 7.4 gpm per foot of drawdown per
100 feet of saturated material penetrated. The specific capacity
per 100 feet of saturated material for one-fourth of the wells was
greater than 12 gpm per foot and less than 4.5 gpm per foot in
another fourth of the wells. The distance between the upper and
lower 25% of the wells indicates that the water bearing properties
of the materials which make up the aquifer in the Kansas Settlement
area are quite similar.

In comparing the two areas it was noted that the materials in the aquifer in the Kansas Settlement area are much less permeable than in the Stewart area and the water bearing characteristics of the former varies much less than the latter, indicating that the poorly consolidated and moderately consolidated alluvium are relatively homogeneous.

In addition to the analysis of specific capacities Brown and Schumann (1969) calculated a coefficient of transmissibility. They defined the coefficient of transmissibility as the rate of water flow at the prevailing temperature through a vertical strip of the aquifer one foot wide and extending the full length of the saturated material with a hydraulic gradient of 100% in gallons per day and is represented mathematically by the equation:

$$T = 1,750 \frac{Q}{Sw}, \text{ where}$$

Q = well discharge, in gallons per minute

Sw = drawdown, in feet below static water level

The coefficient of 1,750 was determined by comparing aquifer-test data and specific capacities of wells in other areas of similar lithology. It was found that the transmissibility in the Stewart area was 160,000 gallons per day per foot of drawdown (gpd per ft.). In the North Kansas Settlement area it was 140,000 gpd. per ft. and in the South Kansas Settlement area it was 93,000 gpd. per ft.

Estimated Natural Recharge

It is believed that the aquifer in the Willcox basin receives little or no recharge from direct precipitation on the valley floor, rather water is received from stream flow along the mountain fronts.

The amount of recharge was estimated by Brown and Schumann (1969)
using two separate methods. Using the assumption that in equilibrium
state natural discharge would equal natural recharge, historical data
was collected on evaporation of shallow groundwater from the playa
area, the transpiration rate of salt grass near the playa, and the
transpiration rate of mesquite within the area of a water table depth
of 25 feet or less. They concluded that in 1910 Mesquite transpired
22,000 acre-feet of water, salt grass transpired 20,000 acre-feet
and 33,000 acre-feet was evaporated from shallow groundwater. Therefore,
if discharge equals recharge the estimated rate was 75,000 acre-feet.

The second method they used estimated the quantity of water
flowing through the aquifer to the discharge area by the use of the
equation:

$$Q = T \cdot I \cdot L, \text{ where}$$

Q = underflow in gallons per day

T = coefficient of transmissibility

I = hydraulic gradient, in feet per foot

L = equals width, in feet of cross section through
which the flow takes place

In 1910 parameters it was estimated that there was 54,000 acre-feet
of underflow. They concluded therefore that the natural recharge
of the aquifer in 1910 was between 54 and 75 thousand acre-feet per
year and that it probably is the same today.

## Changes Within the Aquifer

In 1910, prior to any extensive pumping, the aquifer was
probably in equilibrium. Since then, however, changes have come
about through the artificial discharge of ever increasing amounts

of water. In the 25 year period between 1915 and 1940 it is estimated that only 29,000 acre-feet of water was withdrawn (Mann, White, and Wilson 1978). This sum is less than that of the estimated natural recharge for one year. In the following five years the rate of withdrawal increased to about five times that of the rate of the previous 25 years. It wasn't until 1953, however, that yearly withdrawals were greater than the natural recharge and water levels in the aquifer began to decline substantially (Table 1).

In the equilibrium state the piezometric surface was in the form of an elongated depression which sloped toward the playa in all directions. As withdrawals increased two large depression cones or groundwater sinks developed whose centers are the areas of greatest withdrawals. One of these cones encompassed Willcox and most of the Stewart district area and the other formed in the Kansas Settlement area. The formation of these cones has greatly altered the direction of natural flow; totally reversing it in some areas (Brown and Schumann 1969). These changes in water level and natural flow have been responsible for changes in the applied stress (the weight per unit area of sediments and moisture above the water table, plus the submerged weight per unit area of the saturated sediments overlying the aquifer boundary, plus or minus the net seepage stress or hydrodynamic drag generated by downward or upward components of flow within the specified saturated sediments).

When there is a change in the applied stress in an aquifer system an immediate equivalent change in the effective stress (pressure that is borne and transmitted through the grain to grain contacts of a deposit, thus affecting its porosity and other physical properties;

TABLE 1

ESTIMATED GROUNDWATER PUMPAGE IN
THE WILLCOX AREA

(Numbers rounded to nearest
thousand acre-feet)

| Year | Pumpage, in thousands of acre-feet | Year | Pumpage, in thousands of acre-feet |
|------|------|------|------|
| 1915 | 2 | 1947 | 20 |
| 1916 | 2 | 1948 | 23 |
| 1917 | 1 | 1949 | 28 |
| 1918 | * | 1950 | 35 |
| 1919 | * | 1951 | 38 |
| 1920 | * | 1952 | 39 |
| 1921 | * | 1953 | 94 |
| 1922 | * | 1954 | 105 |
| 1923 | * | 1955 | 110 |
| 1924 | * | 1956 | 120 |
| 1925 | * | 1957 | 135 |
| 1926 | 1 | 1958 | 155 |
| 1927 | 1 | 1959 | 183 |
| 1928 | 2 | 1960 | 195 |
| 1929 | 2 | 1961 | 184 |
| 1930 | 1 | 1962 | 180 |
| 1931 | 1 | 1963 | 180 |
| 1932 | 1 | 1964 | 220 |
| 1933 | 1 | 1965 | 250 |
| 1934 | 1 | 1966 | 240 |
| 1935 | 1 | 1967 | 300 |
| 1936 | 1 | 1968 | 290 |
| 1937 | 1 | 1969 | 291 |
| 1938 | 2 | 1970 | 289 |
| 1939 | 2 | 1971 | 309 |
| 1940 | 2 | 1972 | 292 |
| 1941 | 5 | 1973 | 305 |
| 1942 | 5 | 1974 | 339 |
| 1943 | 5 | 1975 | 293 |
| 1944 | 5 | . | . |
| 1945 | 9 | . | . |
| 1946 | 15 | 1983 | 110 |

* Pumpage was 500 acre-feet or less.

Source: (Mann, White, and Wilson 1978)
(Cochise County Extention Information 1983)

it is the algebraic sum of stress caused by the weight of overlying
deposits called gravitational stress and the stress caused by the
viscous drag of vertically moving interstitial water called seepage
stress) is made in the aquifers' coarse-grained beds. The change
in effective stress in fine-grained beds increases only as rapidly
as excess pore pressures can decrease (Poland, Lofgren, and Riley 1972).
These changes in the applied and effective stresses are responsible
for land subsidence.

## Land Subsidence

In his paper on the analysis of stresses that are responsible
for land subsidence, Lofgren (1968) pointed out that wherever subsi-
dence was studied in the San Joaquin Valley of California a correlation
could be made between it and water-level declines. He further noted
that the magnitude of the subsidence was dependent upon the following:
1) the magnitude of the effective stress increase, 2) the amount of
time the increased stress is applied, 3) the compressibility of the
deposits, 4) the thickness of the compressible beds, and 5) whether
the increased stress has been applied for the first time or has been
attained or exceeded previously.

The magnitude of the effective stress increase is a function
of the magnitude of water-level decline. A small decline in the water
level will result in a small increase in the effective stress, whereas
a large decline would result in a large increase in the effective
stress. In a water-table situation (unconfined) the lowering of
the water table has the effect of increasing the gravitational stress
by reducing the buoyant support of individual grains in the zone of

change. This increased gravitational stress is transmitted to all underlying deposits. Therefore, the greater the water-level decline the greater the dewatered area and the resulting stress will be. In the artesian condition (confined) a change in the water table or piezometric surface or both may induce hydraulic gradients across the confining beds and by so doing induce a seepage stress. This seepage stress is additive to the gravitational stress and is transmitted to all underlying deposits. Lofgren also noted that if a pre-existing seepage stress is altered in direction or magnitude by a change in head, there will also be a change in the effective stress. Here again the greater change in the artesian pressure surface the greater the change in the effective stress.

The amount of time a deposit is subject to an increase in the effective stress also has an effect on the amount of subsidence. Todd (1980) noted that in coarse-grained sediment the adjustments made to the increased stress is instantaneous. In fine-grained sediment such as clay, however, the adjustments may take months or even years. Therefore, in fine-grained sediment the change in the effective stress must be for a period long enough for a reaction to take place.

Another factor influencing land subsidence is the compressibility of the affected beds. Obviously, the amount of previous consolidation would be a big factor. An unconsolidated facies would normally be much more compressible than a consolidated facies. Often clay materials are highly compressible (depending on the microstructure) and are probably the beds that undergo the most consolidation in the subsidence process, owing to the fact that sand and

gravel deposits are less compressible. Therefore the increased intergranular pressure has a negligible effect on coarse-grained materials (Todd 1980).

The thickness of the compressible beds will also have an effect on the magnitude of subsidence. If a compressible bed such as a clay layer is only a few inches thick, then the amount of subsidence caused by compaction of the bed will be minimal. On the other hand, if a compressible bed is several feet thick and an increased effective stress causes compaction within such a bed then the resulting subsidence may be substantial.

The sediments which comprises the aquifer in the Stewart area are mainly unconsolidated sands and gravels interbedded with layers of clay. Therefore, when effective stresses have been applied the sediment has responded by compaction and subsidence of the land surface. The greatest area of subsidence would be in an area that has a relatively thick compactable bed and this is subject to the greatest effective stress change for long enough periods to allow the compaction to take place. Such an area would likely be in the area of the greatest and most intense withdrawals. Though subsidence has not been actively monitored in the Willcox area, one study was conducted in 1980 by T. L. Holzer which compared leveling data from 1974 with leveling carried out between 1937 and 1945 in the Stewart area. He found that the greatest subsidence was at a point near the center of the cone of depression of the water table, which encompasses most of the Stewart area and the City of Willcox. Subsidence in this area was measured at 5.4 feet (Strange 1983).

No leveling has been analyzed in the Kansas Settlement area but it is thought that subsidence has been occurring there also. The amount of subsidence may be considerably less in this area, however, owing to the fact that this portion of the aquifer consists of more consolidated materials.

Subsidence occurs subtly, usually lowering large areas and would probably go unnoticed if it were not for some obvious side effects. One of these side effects is the protrusion of well casings above the ground. Since well casings often extend below the compacting beds they are held in place and when subsidence occurs the casings retain their original elevation and a contrast becomes apparent between the top of the casings and the new elevation of the land surface. This has been a problem to well-owners as well seals have been broken and discharge pipe and engines to pump drive lines have been misaligned. Figure 3 is example of a well that had to be trimmed back as subsidence of two feet or greater has occurred. Well collapse and misalignment has also been known to occur as a result of land subsidence. Correctional measures have to be made often to the great expense of the owners.

Subsidence also has the potential in damaging other man-made structures such as houses, sewer systems, power lines, and pipelines. Repairs to such damages could be costly and potentially hazardous as oil and gas lines could be broken or sewer system damage could cause pollution of water supplies.

## Subsidence Fissures

Another effect of land subsidence is the formation of earth cracks or fissures. Fissuring occurs where there are horizontal

Figure 3. Protruding well casing in the Stewart
area as a result of land subsidence

stresses caused by differential compaction of sediment beds. Diff-
erences in compaction could be caused by differences in the effective
stress applied in different locations. Differences in the thickness
of the compressible beds may be another cause of differential compaction.
The most effective cause of differential compaction, however, is the
presence of subterranean hard rock areas which locally control the
thickness of the overlying beds. When these horizontal stresses
become great enough a small crack will appear on the surface which
may extend downward to the water table. Erosion may quickly widen
these cracks to considerable widths (Strange 1983, and Arizona Water
Resources Project Information 1980). The fissures in the Willcox
area may range from less than an inch to over 12 feet wide. The
length may range from about 50 feet to over a mile. Figure 4 is a

Figure 4. Vertical view of a recently formed fissure near the Winchester range in the Stewart area

vertical view of a fissure that is about two feet wide, 100 feet long, and with an unknown depth.

Fissuring can cause a number of different problems including structural damage to irrigation systems, road, piplines, and other man-made features as well as environmental damages. Environmental damages include increased erosion and gullying by changing local base levels (Kam 1965), pollution of groundwater by allowing the direct injection of surface water into the water supply (Strange 1983), and desertification which is the focus of this study.

There are at least five locations in which fissuring is taking place in the Willcox area (Figure 5). Four of these areas are found around the edges of the mountain blocks and small volcanic hills. The fifth area was out in the valley several miles from any surface expression of a hard rock area. An examination of well logs was

Figure 5



LOCATION OF SITED FISSURES

- WILLCOX AREA, ARIZONA

done in wells near four of the fissure areas in order to get a feel for what may be the cause of the great horizontal stresses involved in the development of fissures.

A well log is a record that is kept on a well while it is being drilled. The driller records what type of sediment or rock is penetrated and some record where water is struck. Cross-sections of the aquifer were constructed by aligning wells with available logs and using elevation data from topographic maps. The water levels for 1910, 1963, and 1975 were then plotted in. Figure 6 shows the location of the selected cross-sections. Particular attention was given to solid rock formations as these would be the least compressible materials and their presence in one area of a formation and not another would be a source of horizontal stress caused by differential compaction. These hard rock areas were included in the cross-sections where penetrated by a well and approximated where they had a surface expression.

In cross-section A to A' hard rock was struck in the bottom of both well (D-13-24)1baa (see well numbering system and logs in Appendix A) and well (D-13-24)2baa. This basement rock is probably responsible for controlling the thickness of the overlying sediment in areas where it is close to the surface. The water table dropped much more in the aquifer boundary between 1963 and 1975 than it did between 1910 and 1963, therefore most of the fissuring in this area probably occurred between 1963 and 1975. The hard rock boundary has a slope that drops about 600 feet per mile (Figure 7a).

In cross-section B to B' blue shale was penetrated in the well furthest out in the valley (D-13-24)18aaa, but no hard rock

Figure 6



LOCATION OF SELECTED
CROSS-SECTIONS
· WILLCOX AREA, ARIZONA

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Figure 7
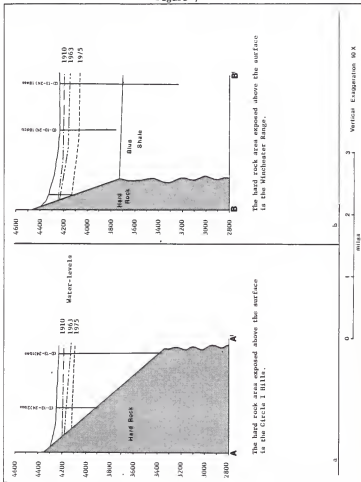
(Adapted from Brown and Schumann 1969)

was penetrated in the well nearest the exposed mountain block
(D-13-24)18dcb. Fissures in the area near the mountain block suggest
that like cross-section A to A', there is basement rock controlling
the thickness of overlying sediments. The steepness of the boundary
is not known and is probably over exaggerated in Figure 7b.

In cross-section C to C' neither of the wells (D-16-26)8cdd
and (D-16-25)25aaa penetrate a hard rock area even though one of the
wells is fairly close to an exposed hard rock surface. The water
table dropped drastically in both intervals 1910 and 1963 and 1963
to 1975. Again the steepness of the basement rock is unknown but
since one of the wells was fairly close to its surface expression
and did not penetrate it, the basement rock must be quite steep
(Figure 8a).

The cross-section D to D' was different from the others as
it was some distance away from any surface expression of a hard
rock area. What was found, however, in well (D-16-26)6dda was 4
hard rock facies interbedded in the alluvium. These are probably
related to the lavas that were extruded and interbedded in the
early Quaternary. In well (D-16-25)ladd, which is just a little
over a mile away, these beds do not appear. Evidently these hard
rock beds are controlling the thickness of the sediment directly
above them but on their edges the sediment has been allowed to
compact to a greater degree causing a sufficient horizontal stress
to cause fissuring in the area. Fissures probably occurred between
1963 and 1975 since this is the interval that the water table dropped
below the first hard rock area (Figure 8b).

Figure 8

The hard rock area exposed above the surface in the Three Sisters Butte.

Mid-Valley - Kamano Settlement Area

Vertical Exaggeration 10 X
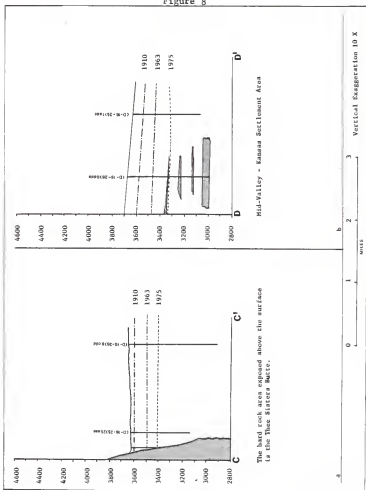
From the location of fissures and from the analysis of the aquifer cross-sections it can be concluded that fissuring in the Willcox area is associated with non-compressible subsurface facies in areas where land subsidence is present. These subterranean non-compressible facies are generally associated with the mountain blocks and volcanic hills which form the aquifer boundary at the margins of the basin. If the configuration of this boundary was known the configuration of new fissuring might be predicted given water withdrawal and compaction rates. In an ideal theoretical situation where a hard rock boundary has a uniform slope, fissuring may occur in a step-like configuration. As the water uniformly declines fissures would progress downslope toward the valley. The distance between the fissures would depend on the nature of the compacting beds, the rate of water withdrawal, and the slope of the boundary (Figure 9).

In the fissure area which is located near the southern end of the Winchester range and about 6 miles northwest of Willcox in Sec. 12 T.13 S.R.23.E., a step-like progression of fissuring seems to have occurred. An analysis using temporal aerial photography was done to trace the actual sequence of fissuring so that it could be compared to the theoretical sequence. Temporal air photo coverage was limited for this area, however, and only the years of 1935, 1953, 1976, and 1982 were obtained for analysis.

In 1935 there were no fissures in the analysis area. By 1953 not only was fissuring present but a sequence was already evident. The withdrawal of water did not begin to exceed the natural recharge rate until 1953 but a lot of development occurred near this boundary area which would have the effect of rapidly lowering the water level

Figure 9



THEORETICAL CROSS-SECTION SHOWING DECLINING WATER TABLE
AND FISSURING PROGRESSION
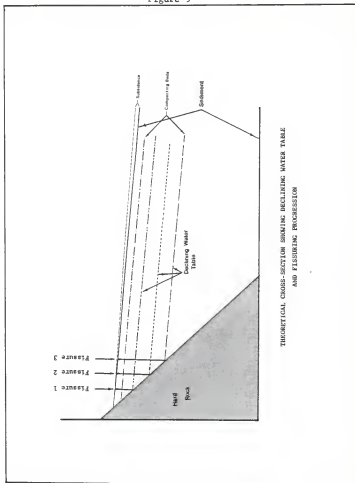
between the boundary and discharge area during pumping periods (Todd 1980).
Since the pumping period occurs during the dry season the natural recharge
is at a low which further enhances maximum drawdown. The pumping period
is about three months long which allows time for compaction of dewatered
beds and subsidence to take place and fissuring to begin to develop
along or near the groundwater boundary. Unfortunately photo coverage
dates did not allow following the sequence of the first fissures that
appeared in the area (Figure 10).

Between 1953 and 1976 groundwater withdrawal began to greatly
exceed the estimated recharge and water levels dropped substantially.
The length of the fissures in the coverage area increased substantially
and new fissuring appeared in the direction of the valley and area of
greatest water decline. Figure 11 shows the increase in fissuring
between 1953 and 1976. It should be noted that only the largest and
most recognizable fissures are represented in the configuration maps.
Since many fissures begin as very small cracks usually an inch or less
in width it was difficult to see them on aerial photographs. Also it
was difficult to distinguish fissures from natural gullying when they
paralleled natural drainage. Therefore maps show only the general
configuration.

Between 1976 and 1982 groundwater withdrawals decreased but
still exceeded the rate of natural recharge. No new fissuring could
be detected in the selected fissure area. Because the area toward
the valley has been converted to farmland any fissuring in this area
would be repaired by farmers. From field checks made in August of
1983 it was found that at least one fissure had cut through a farm
road, concrete ditch and into a field in the area downslope and toward

FIGURE   10



4285

Sec.12,T13 S.,R.23 E

4250

N

0      1000      2000
FEET

——— Fissures 1953

FISSURE CONFIGURATION  1953

FIGURE 11



4285

N

4250

Sec 12 T.13S. R.23E

0    1000    2000
    FEET

——— Fissures 1953

– – – Fissures 1976
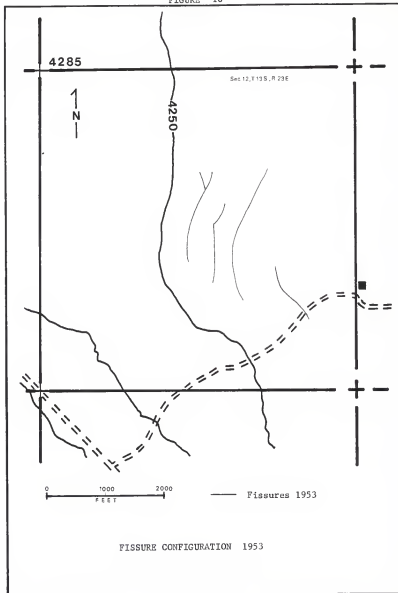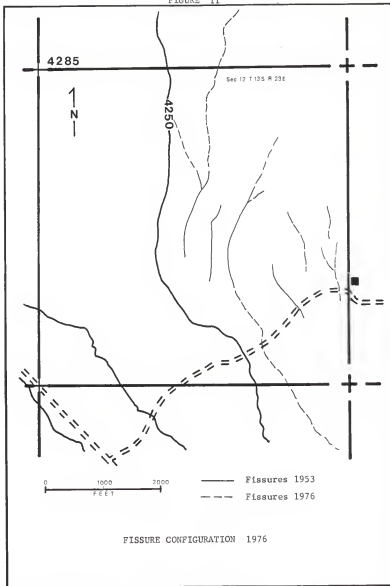
FISSURE CONFIGURATION 1976

mid-valley from the photo analyzed fissure area. This indicated that the newest fissuring is moving toward the valley.

The devised theoretical situation corresponds with the actual situation in that new fissures are occurring toward the valley. The driving mechanism is probably quite similar though the actual parameters are not known. From the two lines of inquiry, theoretical and actual observed, it can be stated that the fissuring sequence responds to the amount of subsidence caused by groundwater withdrawal and the presence and configuration of basement rocks which may control the thickness of the sediment particularly at the basin margins.

## Conclusion

The geological and hydrological properties of the aquifer in the Willcox area are conducive to land subsidence when large changes in the water level are made through the mining of groundwater. The land has decreased in elevation almost 5½ feet in the area of greatest water level decline. This decrease in elevation is not always uniform and horizontal stresses are exerted. Where these horizontal stresses are the greatest the land may pull apart and form an earth crack or fissure.

Through the analysis of aquifer cross-sections involving the use of well logs, a theoretical situation was devised to explain the occurrence and distribution of fissures. This analysis was compared to the actual occurrence and distribution of fissures taken from temporal and aerial photographs. It was found that the two sequences (theoretical and actual) were similar in that fissuring progresses towards the valley as the water level declines. This

would mean that if water levels continue to decline it would be expected that a larger and larger area of the basin may be subject to fissuring.

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Chapter 4

VEGETATION REDISTRIBUTION AND DESERTIFICATION

Fissuring has a definite effect on vegetation in the study
area. The nature of this effect was examined using statistical
methods and from measurements and observations taken from aerial
photographs. The statistical methods include a series of nearest-
neighbor analyses, a significance test for the nearest-neighbor
indices, an analysis of the variance between the indices, and a
small sample t-test for comparing the mesquite population densities
of the fissure area as opposed to an unaffected area. Aerial
photographs were used in the observation of vegetational changes
and to measure areas undergoing desertification.

Vegetation Redistribution Analysis

The redistribution of vegetation is a response to surface
morphology changes induced by the extensive withdrawal of groundwater
and the resulting subsidence and fissuring which occurs in certain
parts of the basin. A distance to nearest-neighbor analysis was
done to gain some understanding of vegetation changes. The distance
to nearest-neighbor analysis was used in this report because of its
simplicity. It is quite easy to obtain samples from a plant population
using this method of expressing spatial relationships and it is simple
to calculate. The resulting coefficient is easy to interpret as
well and is quite useful as an indicator of a population's grouping

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characteristics. Geographers have even used this analysis in other than vegetational problems because of its ability to objectively discern an objects clustering or dispersion pattern (Yeates 1974).

The nearest-neighbor analysis was derived by Clark and Evans (1954) as the result of a need for a statistical procedure to describe plant population dispersion patterns. It had been a previous assumption that individuals of plant populations were distributed at random. As this assumption began to prove erroneous the need for a method of indicating the amount of departure from random became apparent. Clark, using Poisson's exponential function, derived the mean distance between points of a random distribution with a given density. It was found that the mean distance between individuals in an infinitely large random distribution with a given density can be obtained by the formula:

$$r_e = \frac{1}{2\sqrt{p}} \text{ , where}$$

$\bar{r}_e$ = the expected mean distance between individuals.

$p$ = the population density.

An actual mean distance may be measured in a population by the selection of an area within the population in question and measuring the distances between the individuals in the area and their nearest-neighbor. These distances are then summed and divided by the number of observed distances (which should equal the number of individuals within the chosen area) producing a mean distance to nearest-neighbor from a sample of the actual population. The formula for obtaining the actual mean distance is:

$$\bar{r}_a = \frac{\Sigma r}{N}, \text{ where}$$

$\bar{r}_a$ = mean distance to nearest-neighbor of the actual population.

N = number of measurements.

The nearest-neighbor indice is then obtained by dividing the actual distance between individuals of a population taken from field observations by the expected mean distance between individuals having the same density as the area in which the actual distances were obtained. The formula is:

$$R = \frac{\bar{r}_a}{\bar{r}_e}, \text{ where}$$

R = nearest-neighbor coefficient.

$\bar{r}_a$ = actual mean distance to nearest-neighbor.

$\bar{r}_e$ = expected mean distance to nearest-neighbor.

In a random distribution (R = 1) when the actual mean distance is equal to the expected mean distance in the theoretical random distribution with the same density. In a condition of total clustering (R = 0) all individuals in the area occupy the same location. In the case of total dispersion (R = 2.1491) the individuals will be distributed in an even hexagonal pattern, and each individual will be equidistant from six other individuals. Therefore R may be looked at as a scale from 0 to 2.1491 whose end points represent total clustering and total dispersion.

Clark and Evans noted that the usefulness of the measure would be increased if its reliability can be ascertained. If an R value indicates a departure from random (any value other than 1) the significance of the difference between $\bar{r}_a$ and $\bar{r}_e$ can be tested by the normal curve. The procedure involves the calculation of the standard error of the mean distance to nearest-neighbor in a

population which is randomly distributed with the same density as the observed distribution. The formula of the standard error is:

$$\sigma \bar{r}_e = \frac{0.26136}{\sqrt{Np}}, \text{ where}$$

$N$ = the number of distances measured.

$p$ = the population density.

Once the standard error is obtained the significance of the observed distributions' departure from random may be obtained by the formula:

$$C = \frac{\bar{r}_a - \bar{r}_e}{\sigma \bar{r}_e}, \text{ where}$$

$C$ = the standard variate of the normal curve. $C$ values of 1.645, 1.96, and 2.58 represent the 10 percent, 5 per cent, and 1 per cent levels of significance, respectively, for a two tailed test.

In this study a nearest-neighbor analysis was applied for the purpose of analyzing differences in plant populations between areas that are affected by fissuring and those that are not. The procedure involved first choosing plant species that would be tested. Initially the analysis was going to be run on a number of major plant types that make up the plant community of the fissure area. However, based upon field observation and other information it was decided that only one plant species would be necessary in the report. Mesquite (Prosopis juliflora) is quite abundant in the fissure area. It is a hearty plant of shrub to tree size which has an elaborate root system for its size with a horizontal reach of about 50 feet and vertical reach of 25 feet or greater (Harris 1966). It is among the most drought resistant of the community in which it exists

in this study. This became apparent through observations in the
fissure area where it was the only plant surviving in places where
the surface drainage was restricted. Therefore, an analysis of
other plant species would be almost impossible. As it turned out it
was a problem even with mesquite.

After the selection of the plant species to be analyzed a
control area was selected. This selection was based on: 1) absence
of fissuring, 2) plant community, 3) soil type, 4) gradient, 5) eleva-
tion, 6) land use, 7) proximity to fissure area. The control area was
to be as close as could be in similarity with the fissure area and
still be absent of fissures. A soil survey made by the Soil Conservation
Service (1976) was very useful in the selection of the control area
as their soil classifications were based on soil type, gradient,
and the plant community. The Soil Conservation Service went to
considerable pains in classifying soils. This included taking soil
profiles and making laboratory measurements and assembling this
information for soils of the same type. The soil survey classified
the soil in the fissure area as Pima loam. This soil occurs where
slopes are dominantly 0.1 to 0.5 percent, runoff is slow and the
hazard of erosion is only slight. The plant community includes
vine mesquite, tobosa, cane beardgrass, black gramma, curly mesquite,
catclaw and mesquite. Pima loam is among the best soils for growing
crops in the area. Because of the soil survey the selection of the
area was simplified to finding an area classified as having Pima
loam as a soil type, being devoid of fissures, having about the
same elevation, and being within close proximity of the fissure area
so that different precipitation patterns are minimized. The control

area selected is located about 2½ miles north of the fissure area in Sec. 25, T.12 S., R. 23 E. The control area meets all the specifications mentioned above with only one note; from observations of early aerial photos it appears that the mesquite density in the control area initially may have been slightly less than that of the fissure area. This is not necessarily a big problem however, because the density of the fissure area has been getting smaller and comparing its density with an area that had a slightly smaller initial density would have the effect of reducing the significance of the results. Therefore, judgements based on the results would be conservative.

Once the control area was selected a sampling scheme was devised that would minimize biased sampling and still be controllable enough to keep sampling within the limits of area boundaries. The scheme required the selection of two random numbers for every area selected. One random number would indicate the direction and the second random number would indicate distance. The number indicating direction was an integer randomly selected between 1 and 8, having been assigned a direction. The second number was an integer randomly selected between 1 and 500. This would be the distance in feet from an initial point or subsequent reference points in which the sample would be taken. The 500 foot maximum was used to insure that sampling remained within the designated control or fissure area. Two sets of four paired random numbers intended to produce eight sample areas within both the control and fissure areas were generated by computer. Each set was started at a different initial point to insure better sampling coverage. The initial points were selected within the area at locations that could be identified on existing

maps or aerial photos. The first direction number was used as a reference direction to the remaining three randomly selected direction numbers. From the initial point the first direction number is oriented as closely as possible to the center of the area in a North, South, East, or West direction whichever may apply. In this manner the direction of the first coordinate was set by the researcher and the following directions would be random with respect to the first direction number. This again was done to insure that the sample would be taken within the designated areas. A sample area of 2500 square feet was used and oriented in a north, south, east, west direction with the reference point being the southeast corner. As a hypothetical example of the sample area selection procedure suppose we generated two random number pairs 3;265 and 6;450. Now suppose from an initial point selected by the researcher the center of the area is in a general northward direction. In this case the number 3 would be assigned the direction, north. The researcher would then move 265 feet from the initial point in the northward direction and drive a stake. This would be the reference point for the first sample area which would be arranged in a north, south, east, west direction with the reference point being the southeast corner. The sample would then be taken. After sampling the first area the researcher then moves back to the reference point of the sample and would move 450 feet in a southeast direction as indicated by the number 6 and drive a stake which becomes the reference point for the next sample (Figure 12). The location of the selected areas in the control and fissure areas are given in Figures 13a and 13b.

Location of sample areas given the random number pairs of 3 ; 256 and 6 ; 450

Direction assignment if the number three is given the direction of north.
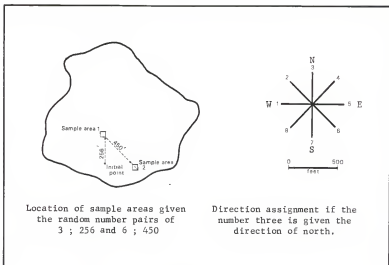
Figure 12

Hypothetical example of sample area selection

The actual sampling procedure was quite simple. Measurements were taken from each mesquite plant within the 2500 square foot sample area to its nearest neighbor. The number of measurements equaled the number of individuals in the area and this figure was used to calculate the population density. The formula used to calculate the density was:

$$p = \frac{n - 1}{2500}, \text{ where}$$

p = population density

n = number of individuals in the sample area

The samples collected had small values of n so to achieve a little more accuracy n-1 is used (Clark and Evans 1954). The distances were summed for each area and using the corresponding densities nearest-neighbor indices were calculated for each sample area within

Figure 13a

4262

N

4250

4250

3 2
1
4

8

7 6

5

0    1000    2000
Feet

Sec.12, T.13 S., R.23 E.

LOCATION OF SAMPLE AREAS
WITHIN THE CONTROL AREA

Figure 13b

LOCATION OF SAMPLE AREAS
WITHIN THE FISSURE AREA
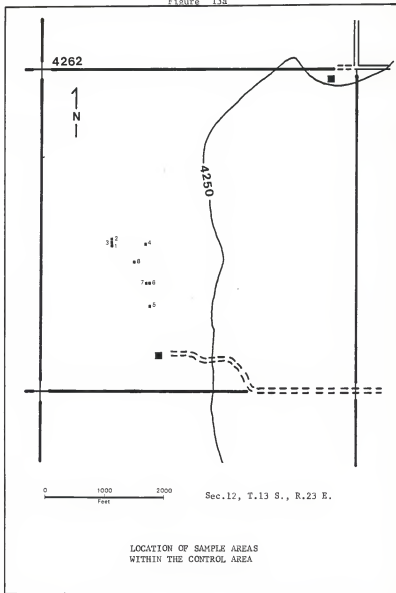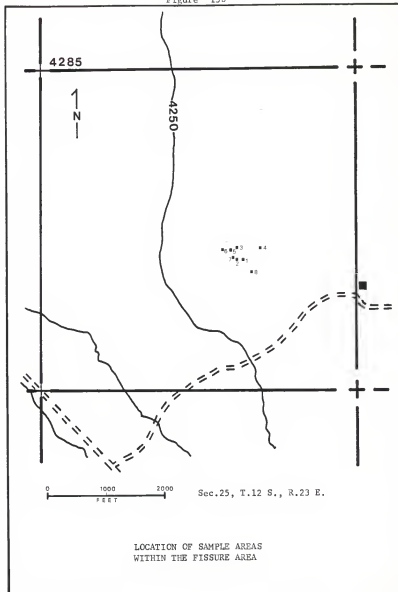
the fissure and control areas. (Distance between individuals in each sample are given in Appendix B). In addition a significance test was run for each indice and the C value was obtained. A summary of the calculations is found in Table 2. The nearest-neighbor coefficients in the control area indicate that all of the sample areas have a mesquite distribution that are near random but lean in the direction of dispersion. The minimum indice value was 1.1376 and the maximum value was 1.464, all of which lie between random and the midpoint between random and total dispersion. Of the eight samples in the control area five have a C value that is significant at the 0.10 level indicating that these five have a distribution that is significantly different from random. The remaining three are assumed to be random or nearly so.

In the fissure area there is a much greater diversity. Nearest-neighbor values range from 0.0 to 1.47, indicating a wide diversity in the population distribution from site to site. It must be noted that two of the selected sample areas were completely without mesquite population and therefore no nearest-neighbor or standard variates could be calculated. A third area had only one individual in it. Therefore, by necessity the calculations made for this area are based on a density calculated using n observation instead of the preferred n-1 observations. Of the six areas in which calculations could be made, half have values of C that were significant at the .10 level. Unlike the control area, two of the values were in the negative direction showing a tendency toward clustering. The other significant value was in the opposite direction where the distribution was tending toward dispersion.

TABLE 2

Summary of Calculations for Nearest-neighbor and
Standard variate of Control and Fissure areas

| Area | Size of area ft.² | No. of obser. n | Pop. density p | Square rt. of p √p | Summatn. of r Σr | Actual mean r̄ₐ | Expected mean r̄_e | Nearest neighbor R | Standard dev. r̄_e σ_r̄_e | Standard variate C |
|------|------|------|------|------|------|------|------|------|------|------|
| Control 1 | 2500 | 16 | .006 | .0774 | 120 | 7.5 | 6.4549 | 1.1619 | .8435 | 1.238 |
| Control 2 | 2500 | 6 | .002 | .0447 | 89.5 | 14.9166 | 11.1803 | 1.3360 | 2.3858 | 1.566 |
| Control 3 | 2500 | 8 | .0028 | .0529 | 101 | 12.625 | 9.4491 | 1.3360 | 1.7662 | 1.8186 |
| Control 4 | 2500 | 10 | .0036 | .06 | 122 | 12.2 | 8.3333 | 1.4640 | 1.3774 | 2.807 |
| Control 5 | 2500 | 8 | .0028 | .0529 | 107 | 13.375 | 9.4491 | 1.6154 | 1.7662 | 2.268 |
| Control 6 | 2500 | 12 | .0044 | .0663 | 130 | 10.833 | 7.5377 | 1.4372 | 1.1374 | 2.8974 |
| Control 7 | 2500 | 8 | .0028 | .0529 | 86 | 10.75 | 9.4491 | 1.1376 | 1.7662 | 0.7449 |
| Control 8 | 2500 | 14 | .0052 | .0721 | 133 | 9.5 | 6.9337 | 1.3701 | 0.9686 | 2.6693 |
| Fissure 1* | 2500 | 1 | .0004 | .02 | 0 | 0 | 25 | 0.0 | 13.0680 | -1.913 |
| Fissure 2 | 2500 | 2 | .0004 | .02 | 67 | 33.5 | 25 | 1.34 | 9.2404 | 0.9198 |
| Fissure 3 | 2500 | 6 | .002 | .0447 | 99 | 16.5 | 11.1803 | 1.475 | 2.3858 | 2.229 |
| Fissure 4 | 2500 | 0 | 0.0 | 0.0 | 0 | 0.0 | - | - | - | - |
| Fissure 5 | 2500 | 4 | .0012 | .0346 | 42 | 10.5 | 14.4337 | 0.7274 | 3.7724 | -1.0427 |
| Fissure 6 | 2500 | 13 | .0048 | .0692 | 107 | 8.2307 | 7.210 | 1.1404 | 1.0662 | 0.9756 |
| Fissure 7 | 2500 | 2 | .0004 | .02 | 19 | 9.5 | 25 | 0.38 | 9.2404 | -1.6774 |
| Fissure 8 | 2500 | 0 | 0.0 | 0.0 | 0 | 0.0 | - | - | - | - |

* The density was calculated on n observations.

The nearest-neighbor indices indicate that the samples in the control area are quite similar and those in the fissure area are somewhat different. A test that is useful in determining if there are significant differences between samples is an analysis of the variance or F-test. This test uses the ratio of the variance between the groups to the variance of within the groups. If there is a significant difference between the variances then it can be assumed that all samples are not alike in their degree of clumping. The formula used for computing the analysis of variance is as follows:

$$F = \frac{(c-b) \ (N_1 + N_2 + \ . \ . \ . \ N_k - P)}{(a-c) \ (P-1)}, \text{ where}$$

P = number of sample areas.

N = number of individuals in the sample.

$$a = p_1 \ \Sigma r_1{}^2 + p_2 \ \Sigma r_2{}^2 + \ . \ . \ . \ p_k \ \Sigma r_k{}^2$$

$$b = \frac{(\sqrt{p_1} \ \Sigma r_1 + \sqrt{p_2} \ \Sigma r_2 + \ . \ . \ . \ \sqrt{p_k} \ \Sigma r_k)^2}{N_1 + N_2 + \ . \ . \ . \ N_k}$$

$$c = \frac{p_1 \ (\Sigma r_1)^2}{N_1} + \frac{p_2 \ (\Sigma r_2)^2}{N_2} + \ . \ . \ . \ \frac{p_k \ (\Sigma r_k)^2}{N_k}$$

Again the calculations were based on population density (p) computed on n-1 observations. The critical values are taken from the F distribution based on P-1 degrees of freedom for the between group variance and $N_1 + N_2 + \ . \ . \ . \ N_k - P$ degrees of freedom for the within group variance (Clark and Evans 1954). A summary of the calculations are found in Table 3.

Calculations were made on both the control and fissure areas to detect differences within each. It was found that at the .10

TABLE 3

Summary of Calculations in Obtaining F

| Area | Values of a | Values of b | Values of c | Values of F | Degrees of freedom | Critical value .01 |
|------|-------------|-------------|-------------|-------------|--------------------|--------------------|
| Control | 46.9269 | 36.0743 | 36.3612 | 0.2870 | 7;74 | 1.78 |
| Fissure | 10.0688 | 8.0523 | 8.9935 | 2.5008 | 7;20 | 2.04 |

level there are no significant differences between the nearest-neighbor indices in the control area. In fact the calculated F value is far below the critical value indicating that the sample areas have distributions that are very much alike. In the fissure area however, there is a difference at the .10 significance level. This indicates that not all of sample distributions are the same.

Since each of the sample areas are representative of the entire population in which they are taken, it would only be reasonable that the difference between the samples would be small. Such is the case in the control area. In the fissure area this does not seem to be the case. The diversity of nearest-neighbor values and a significant F value indicates that there are differences depending on the location of the sample in relation to fissuring. This conclusion can be made because of the fact that care was taken in insuring the similarity of the control and fissure area so that fissuring could be isolated as a cause of change.

During sampling, locational peculiarities such as drainages, gulleys, and fissures within the sampling area were noted. In

addition, unusual vegetation phenomena such as heartiness, lack of ground cover, unusual abundance of a certain species, or the entire lack of vegetation was also noted. Table 4 is a summary of these observations. In addition Table 4 contains the calculated nearest-neighbor values (R) so that associations between the degree of clustering or dispersion and locational peculiarities could be made. From this information it becomes apparent that areas that are without any local peculiarities are very similar in distribution. Natural drainages seemed to have a negligible effect within the control area as the distributions are not significantly different from areas without drainage. Another apparent association is that areas that are downslope from a large fissure have small or no R values indicating that the fissures may be responsible for changes from near random to a clustering distribution. The areas between fissures vary between a near random to a clustering distribution probably indicating different stages in the redistribution process.

## Possible Errors in the Analysis

There is a possibility for error in any statistical analysis. In this study, error could come from several different sources. One possible area of error may come from differences in the control versus the fissure area. It is possible that parameters other than those used in this analysis to insure that the two areas are the same may be pertinent. However, it is felt that the major and most significant parameters were used and although additional parameters may affect the plant population the effect will be small.

Other avenues of error lie in the use of the nearest-neighbor

TABLE  4

Local Peculiarities in Relation to R

| Area | R | Local Peculiarities | Remarks |
|------|-----|---------------------|---------|
| Control  1 | 1.62 | none | none |
| Control  2 | 1.33 | none | Area containes more catclaw than mesquite |
| Control  3 | 1.33 | none | Large presence of catclaw in area |
| Control  4 | 1.46 | Area is near a drainage | none |
| Control  5 | 1.41 | none | Very little ground cover except a little tumble weed |
| Control  6 | 1.43 | none | Some grass as ground cover mesquites look healthy |
| Control  7 | 1.13 | none | none |
| Control  8 | 1.37 | Area has a drainage in it | Mesquites along drainage are much larger |
| Fissure  1 | 0.0 | Area down slope from large fissure | Only two living plants- a mesquite and a catclaw |
| Fissure  2 | 1.34 | Fissure in area | Only two hearty mesquites near a fissure |
| Fissure  3 | 1.47 | Fissure in area along west side | Mesquites are quite hearty |
| Fissure  4 | - | Area down slope from large fissure | Barren- no living plants |
| Fissure  5 | 0.72 | Area between fissures | Mesquites seem hearty but no ground cover |
| Fissure  6 | 1.14 | Area between fissures | none |
| Fissure  7 | 0.38 | Fissure in area | Only two mesquites which are in a fissure |
| Fissure  8 | - | Area down slope from large fissure | Barren- stumps of dead mesquite in area |

analysis. Anytime an area is designated and boundaries drawn there
is a possibility for error. One might ask what the indice may have
looked like if the boundary were drawn differently or would the
results have been different if the area size were larger or smaller?
Both are legitimate questions. In this study the nearest-neighbor
analysis was used as a representative of the entire population. If
only one sample area of the control and fissure areas were used, then
indeed the above questions would be hard to answer. Since several
samples were taken at different locations within the same population,
comparisons could be made between them and the effect of the selected
size and shape of areas would show up by getting a significant F-value
obtained by an analysis of variance. A significant F-value was not
obtained in the control area, showing that each of the eight sample
areas had a distribution that resembled the population distribution
and that size and shape of the selected sample area was somewhat
acceptable. A significant F-value was obtained in the fissure area
however. Therefore, based on the above reasoning the size and shape
of the sample area was not acceptable for that particular population.
For this reason the value of R may not be very satisfactory as an
indicator of the population distribution. In this case they merely
represent the distribution of mesquite within specific areas of the
population. The fact that the size and shape of the sample area was
somewhat acceptable in the control and was not in the fissure area
indicates that there are differences between the two populations,
differences that should not normally exist since soil, elevation,
slope, the plant community, and other parameters are similar.

The inadequacy of the size of the sample area in the fissure

area is further illustrated by the fact that some of the areas had only small numbers of individuals within them or, in two cases, none at all. Calculations made with such small values of n may also be a source of error. This problem may have been alleviated if a larger sample area had been used. The significance of the results would have probably been greater and the strength of the entire procedure enhanced.

## Desertification Analysis

In addition to the nearest-neighbor analysis a small sample t-test was done, based on the number of observations within each sample area, comparing the population densities. It would be a reasonable assumption that the population densities of the two research areas would be similar, based on the criteria used for their selection, if fissuring was not present at either location. The small simple t-test compares the mean number of observations in the control area to the mean number of observations in the fissure area. The formula is:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{S\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}, \text{ where}$$

$$S = \frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{n_1 + n_2 - 2}$$

The critical values are taken from the t-distribution based on $n_1 + n_2 - 2$ degrees of freedom (Ott, Mendenhall, and Larson 1978). A summary of the calculations is given in Table 5. The results indicate that there is a significant difference between the mean number of observations in the control and fissure areas. This

TABLE 5

Summary of Calculations in Obtaining t

| Area | Mean | Var. | Std. dev. | | Pooled s.dev. | Value of | Degrees of freedom | Critical value |
| | $\bar{X}$ | $s^2$ | s | | S | t | | .05 |
| Control | 10.25 | 11.897 | 3.869 | | 3.931 | 3.4429 | 14 | 1.345 |
| | | | | | | | | |
| Fissure | 3.5 | 18.857 | 4.34 | | | | | |

means that there is a significant difference in the mean density
of the sample areas since all the samples had the same area size.
Since the fissure area has a lower mean density (based on the mean
number of observations) it must be going through a desertification
process caused at least in part by fissuring.

Both the control and fissure area have been used for grazing
for about the last hundred years. Mesquite which is now the dominant
plant species in the two areas was an invader which began to encroach
upon the grassland in the late 19th and early 20th centuries being
enhanced by cattle eating the somewhat sweet tasting seed pods and
scattering them through their droppings. At times when overgrazing
threatened the grassland, mesquite seemed to be unaffected and
continued to spread (Harris 1966). This invading process has seemed
to be reversed in the fissure area however, as the density of mesquite
is diminishing at certain locations within the area. These areas
are recognizable as barren spots which contain the remains of once
living plant life and maybe an occasional unhealthy looking mesquite
or catclaw (Figure 14). The barren areas are almost exclusively

Figure 14. Large area undergoing desertification



Figure 15. Large fissure upslope from deserted area

found downslope from large well developed fissures which appear as large gullies that often cross natural drainage ways (Figure 15).

The fissure in Figure 15 is long (over 500 feet), well developed and is located just upslope from the barren area of Figure 14. This barren area is large and can be easily identified on aerial photographs. Using temporal coverage the development of this barren area was traced starting in 1935 when the barren area did not exist. Coverage years include 1935, 1953, 1976, and 1982.

In 1935, prior to any fissuring in the area, the vegetation in the area was quite dense. The greatest mesquite density is in the center of the section on the edge of what appears to be a slope change. In the area where the barren spot is now located the mesquite seemed to be a little less dense than the area just to the west where today most of the fissures are located. The area is still quite wooded however (Figure 16).

The control area as of 1935 was somewhat less dense than the densest part of the fissure area. It does, however, closely resemble the density of the fissure area which is now barren (Figure 17).

In 1953 fissures are present in aerial photographs. The large fissure depicted in Figure 14 is in place along with three others. The barren spot had begun to show up and a measurement of the area shows that some 18 acres were undergoing some sort of thinning. The thickest density of mesquites did not seem to be noticeably affected at that time. A small part of the section containing the fissure area had been converted to farmland (Figure 18).

Figure 16. The fissure area in 1935
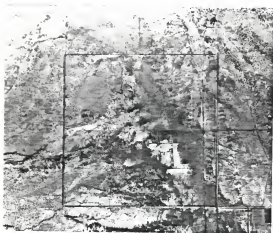


Figure 17. The control area in 1935
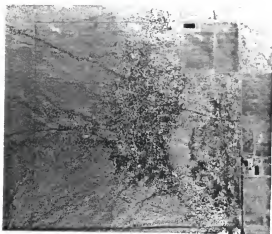
Figure 18. The fissure area in 1953.
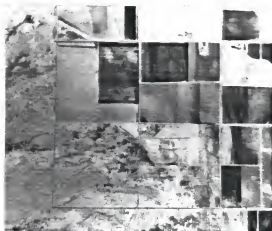


Figure 19. The control area in 1953

In the control area little change had taken place between 1935 and 1953. The density of mesquite may have increased slightly and began concentrating near drainages. About half of the section containing the control area had been converted to farmland by that time (Figure 19).

By 1976 fissuring had intensified and some additional new fissures had appeared in the direction of greatest water withdrawals. The barren area had expanded toward the north and south along the fissure as the fissure lengthened out. The size of ·the barren area had increased to about 37 acres and the amount of vegetation within the area had lessened considerably. By this time it became apparent that the mesquites along the fissure were larger than those at a distance. This effect has been great enough that fissures can be identified using vegetational differences (Figure 20).

In the control area the density of mesquites stayed about the same although it may have become more concentrated near drainages. In comparison with vegetational changes in the fissure area very little has happened (Figure 21).

By 1982 the area undergoing a desertification process had increased to some 65.5 acres. It widened in the northern and central areas and expanded a great deal to the southeast. This extension followed the lengthening of the large fissure shown in Figure 14 in that direction. The mesquites show even greater intensification along fissures with little barren cells showing up in areas downslope from other fissures in the area (Figure 22).

It is interesting to note that in the 23 years between 1953 and 1976 the size of the barren area doubled. In the following 6
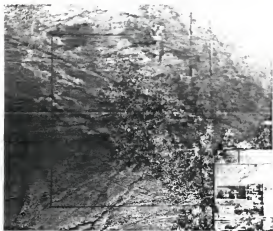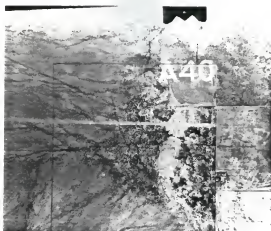
Figure 20. Fissure area in 1976
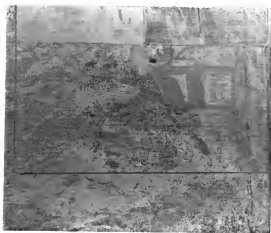


Figure 21. The control area in 1976

Figure 22. The fissure area in 1982

years between 1976 and 1982 the affected area almost doubled again. This indicates that once desertification begins it seems to move more rapidly and more and more area becomes affected.

As of 1982 fissuring extended about 2 miles to the southeast of the study area and there was evidence of thinning in the area downslope from these fissures as well. In the future, it would be possible for these areas to coalesce and become a long narrow band of barren ground occupying several hundred acres.

## Possible Role of Fissuring in Desertification

There is not any environmental factor more important to plant life than the availability of water. On the average land plants require about 400 pounds of water for every pound of plant substance produced. Unfortunately this requirement is not always met. All plant physiological processes occur in the presence of water or

solutions involving water and without it these processes would cease (Wilson, Loomis, and Steeves 1971). Obviously if a plant is deprived of water it cuts back on the production of cells and if deprived enough, it will die.

Mesquite is a phreatophyte, which transpires water from shallow water tables. They often grow along the toe or alluvial fans where soils become a little deeper and there is an adequate supply of water not far from the surface (Todd 1976 and Martin 1963). These areas are often near groundwater boundaries however, since alluvial fans are associated with mountain blocks which may be impermeable or at least considerably less permeable. Therefore if the groundwater supply is discharged near the groundwater boundary the water table would drop considerably between it and the discharge area. Unfortunately this is where the mesquites are located and as the water table drops it becomes more and more difficult for the mesquites to draw water from that source. Consequently the mesquites become more reliant on surface water as the water table drops beyond their reach. The concentration of mesquites around surface drainage ways is evidence of this growing reliance.

In the natural situation, during times of precipitation, water coming off the alluvial fans would slow in the location of the mesquites due to the lesser slopes, and be able to infiltrate, becoming soil moisture available for plant use. If the natural channels are interrupted not allowing the runoff to reach certain areas or the amount of surface runoff is reduced then the amount of moisture available for plant use would be reduced. If these conditions persist the plants which normally would have received sufficient moisture to

survive would perish.

This is the effect of fissures in these areas. Water coming
off the alluvial slopes is intercepted and allowed to infiltrate
rapidly at a single location depriving areas downslope of any surface
flow. If the surface flow increases and the fissures are unable to
allow infiltration as rapidly as the surface flow is coming in, then
the water may begin to flow laterally along the fissures. It is
difficult for any surface runoff to flow across a fissure. If there
is a sequence of fissures then the problem is worsened (Figure 23).
Since fissures are permanent features, downslope areas may not receive
any surface flow for years and plants in the area would have to rely
on precipitation alone which of course is somewhat scarce.

The plants growing near the fissures would not have this
problem. Water trapped by fissures could be utilized by these
plants and they would be able to grow and propogate. The larger
healthier trees growing along fissures is evidence of this occurrence
(Figure 24).

Conclusion

There is a vegetational response to fissuring. A nearest-
neighbor analysis which was conducted in a fissure and non-fissure
area revealed that in normal non-fissure conditions the dispersion
pattern of mesquite was close to being random but leans a little
toward dispersion. When fissuring is present the mesquite distrib-
ution varied from place to place depending upon its location in
relation to fissuring.

An analysis of the variance revealed that there was no

Figure 23.  Sequence of fissuring
trapping surface flow



Figure 24.    Hearty mesquite along
fissure

significant difference between the indices in the non-fissure area
and there was a significant difference between the indices in the
fissure area. This indicated that each of the nearest-neighbor
analyses in the non-fissure area was a fair representative of the
total population and those in the fissure area were not. Based on
the assumption that both the fissure and non-fissure areas were
similar initially it was concluded that there has been a change
in the distribution of mesquite in the fissure area.

A small sample t-test was conducted to test for differences
in numbers of individuals per sample area (density) between the
fissure and non-fissure areas. The results indicated that there
was a significant difference in the two areas with the fissure
area having a lower mean number of individual mesquite plants per
sample area. It can be concluded from this test that in addition
to a redistribution of vegetation a process of desertification
is taking place.

The development of a deserted or barren area within the
fissure area was analyzed using temporal aerial photography. Photograph
coverage of the fissure and non-fissure (control) areas were analyzed
for the years of 1935, 1953, 1976 and 1982. The results of the analysis
indicated that as of 1935, fissuring did not exist nor did a barren
area. By 1953 however, fissuring was present and an area downslope
from one of the largest fissures was beginning to thin out. The
affected area was about 17.75 acres in size. By 1976 fissuring had
intensified and extended. The area undergoing thinning was almost
barren and had increased both northward and southward covering an
affected area of some 37 acres.

As of 1982 the barren area had increased in width and a large area to the southeast appeared to be thinning out given a total affected area of some 65 acres.

It was thought that fissures affected vegetation in the area by depriving some areas of surface runoff through the capture of natural surface water flow and allowing it to move rapidly downward into underlying deposits. Vegetation along the fissures were supplied with adequate water and its growth stimulated, thus a redistribution of the vegetation in the area has occurred. In addition to the redistribution, areas which are totally deprived of surface runoff are undergoing desertification.

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Chapter 5

SUMMARY AND CONCLUSION

There is often a significant environmental consequence when man begins to tamper with fragile natural balances. The withdrawal of water at rates exceeding the rate of replenishment in alluvial aquifers causing land subsidence is one such example. If there are large differences in subsidence rates over short distances, horizontal stresses may be sufficient to pull the sediments apart and form an earth crack or fissure. Fissures in and of themselves also have environmental repercussions which may include plant redistribution and a process of desertification within their locality. Indeed this is the case in the Willcox area of southeastern Arizona. The development of an extensive agricultural system based on the withdrawal of groundwater for irrigation purposes in the middle of this century has upset natural balances within the aquifer resulting in subsidence and fissuring which led to plant redistribution and desertification in fissure areas.

These man-induced environmental changes are by no means the first to occur in the Willcox area. Overgrazing in the late nineteenth and early twentieth century was the cause of a loss of much of the natural grassland in the area and the spread of an invading mesquite population. However, with the development of fissures in the area the hearty mesquite invader is also being threatened along with the grass population.

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A review of the literature revealed that there is an abundance
of studies involved with land subsidence, fissuring, man-induced
plant redistribution, and desertification. However, there was only
one study which tried to make a connection between them. In that
study, which examined sites in the Phoenix, Arizona area, it was
found that fissuring may of had an influence on the plant population
but not to the point that it could be said that desertification was
taking place. It was thought however, that given enough time it
would.

This study was an examination of the fissuring process in
the Willcox area and an assessment of plant redistribution and
desertification associated with it. The examination of fissuring
in the area included an investigation of land subsidence and causes
of differential compaction involved in fissuring. Aquifer cross-
sections were constructed using well logs and topographic data in
areas in or near where fissuring occurred to find possible causes
of differential compaction and a theoretical cross-section was
constructed that would explain fissure progression. The theoretical
cross-section was then compared with an actual sequence located
about 6 miles northwest of the town of Willcox. The actual sequence
was taken from temporal aerial photography which included the years
of 1935, 1953, 1976, and 1982. It was found that much of the
sequence had taken place between 1935 and 1953. Subsequent fissuring
lengthened existing fissures substantially as the newest fissuring
occurred toward the valley as the theoretical model predicted. This
would mean that as groundwater mining and subsidence continues, it
would be expected that existing fissures would lengthen and new

fissuring would occur towards the valley, resulting in larger and
larger areas of the basin being subject to fissuring and its
environmental consequences.

One of the most profound possible environmental consequences
of fissuring and one which is often overlooked, as attested to by
the absence of literature on the subject, is that of vegetation
redistribution and desertification. Fissures affect the natural
vegetation of the area in which they occur by diverting water from
natural drainage ways, allowing it to move rapidly downward into
underlying sediment and thus removing the supply of surface water
normally used by plants downslope.

An analysis of the effect of fissuring on natural vegetation
was done in the fissure area six miles northeast of Willcox which
included the use of a series of nearest-neighbor analyses. The
procedure involved the selection of an area similar to the fissure
area with respect to soil type, plant community, gradient, and elevation
but lacking the occurrence of fissuring. The area was chosen within
close proximity to the fissure area to minimize variation in precip-
itation as well. Eight nearest-neighbor analyses were run in the
fissure and non-fissure area for the purpose of comparing differences
in the population dispersion pattern of mesquite. Mesquite was chosen
because of its resistance to drought and its occurrence in places
where other plant species were unable to exist. A significance test
was also conducted on the nearest-neighbor indices to see which ones
were significantly different from random. In addition an analysis
of variance was done to compare the nearest-neighbor indices within
the fissure and non-fissure area.

The results of these analyses revealed that in normal non-fissure conditions the dispersion pattern of mesquite was near random but leaning in the direction of dispersion. When fissuring was present the mesquite population distribution varied from place to place depending upon its location in relation to fissuring. The analysis of the variance revealed that there was no significant difference between the indices in the non-fissure area and that there was a significant difference between the indices in the fissure area. This information indicated that the individual nearest-neighbor indices in the non-fissure area were a reasonable estimate of the mesquite population dispersion pattern and in the fissure area they were not. These results suggest that fissuring is responsible for a distribution pattern change.

To test the effects of fissuring as an influence causing desertification a small sample t-test was conducted to detect differences in the number of individuals per sample area between the fissure and non-fissure areas. The results of this test indicated that there was a significant difference in the two areas with the fissure area having a lower mean number of individual mesquite plants per sample area.

In addition to the small sample t-test an analysis of desertification was done by observing the development of a barren area located downslope from a large well developed fissure. This was done through the use of temporal aerial photography. Photo coverage included the years of 1935, 1953, 1976, and 1982. The results showed that as of 1935; neither fissures or a barren area existed. By 1953, fissuring was present and an area downslope from the large fissures was beginning to thin out. The affected area was about 17.75 acres in size. By

1976 the thinning area was almost barren and had grown with the intensification and extension of fissuring. The size of the area had grown to about 37 acres. As of 1982, the barren area had increased in width and a large area to the southeast appeared to be thinning out giving a total affect area of some 65 acres.

By the capture of natural runoff and allowing it to move rapidly down fissures in effect changed the natural drainage pattern and deprived areas downslope from receiving runoff vital for the growth of plants. Vegetation in the area responds by clustering along the fissure (where a source of water is available) and dying out in areas that were deprived of moisture.

Since the area affected by fissuring increases as groundwater mining and subsidence continues it would be expected that larger and larger barren areas will develop as well. Since much of the land in the fissure areas are used for grazing purposes the development of barren areas in effect take the land out of production. If these areas become large enough then they may have a significant economic impact to individuals or governmental agencies who own these lands.

In addition to possible economic impacts of desertification in fissure areas, degradation to the aesthetic quality of these Arizona grasslands is also a factor. The presence of old dead stumps and the absence of any grass or shrubs is quite unsightly in comparison to the unaltered natural arrangement of healthy vegetation.

The economic and social implications of fissure-induced desertification are clearly beyond the scope of this study. It should be noted however, if the mining of groundwater in the area is allowed to continue these problems will have to be faced along with the other

problems associated with the loss of stored fresh water, subsidence, and fissuring.

APPENDIX A

## WELL LOCATION SYSTEM IN ARIZONA
## AND SELECTED WELL LOGS

The wells in Arizona are numbered according to their location.
The state is divided into 4 sections with the center at the junction
of the Gila and Salt Rivers. They are labeled A, B, C, and D in a
counterclockwise order starting with A in the upper right quarter.
Townships and ranges are then measured off in all directions forming
a grid. A township may be located by coordinates of the grid. Each
township then is sectioned off into 36 areas usually a square mile
and are called sections. A section is then quartered and assigned
a letter of a, b, c, d in a counterclockwise order with a being
in the upper right quarter. Then the quarter is quartered again
and assigned a letter a, b, c, or d just as before and then the
quarter of that quarter is again assigned a letter in the same
manner. So a well numbered (D-4-5)19caa would be located in the
D quarter of the state (Southeast), township 4, range 5, section 19,
in the northeast quarter of the northeast quarter of the southwest
quarter (see example on following page).

Example of Well Numbering System
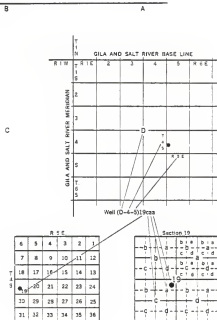


Source: (Brown and Schumann 1969)

Selected Well Logs Used in the Analysis

### (D-13-24)1bcc

| | Thickness (ft) | Depth (ft) |
|---|---|---|
| Sandy loam | 3 | 3 |
| Buck shot clay | 4 | 7 |
| Red clay | 21 | 28 |
| White clay | 28 | 56 |
| Sand and water | 1 | 57 |
| White clay | 53 | 110 |
| Blue clay | 56 | 166 |
| Sand clay | 14 | 180 |
| Yellow clay and gravel | 30 | 210 |
| White clay | 60 | 270 |
| Sand gravel red clay | 30 | 300 |
| Red rock | 10 | 310 |
| TOTAL DEPTH | | 310 |

### (D-13-24)2bca

| | Thickness (ft) | Depth (ft) |
|---|---|---|
| Soil | 5 | 5 |
| Gravel | 5 | 10 |
| Tele | 50 | 60 |
| Shale | 30 | 90 |
| Sand (water) | 45 | 135 |
| Sandy shale | 5 | 140 |
| Brown shale | 7 | 147 |
| Sand | 21 | 168 |
| White shale | 36 | 202 |
| Brown shale | 36 | 238 |
| White shale | 10 | 246 |
| Brown shale | 26 | 274 |
| Sandy shale | 6 | 280 |
| Sand | 8 | 288 |
| Sand (hard) | 2 | 290 |
| Sandy shale | 15 | 305 |
| Herd lime shell or shale | 7 | 312 |
| Blue shale | 13 | 325 |
| Brown shale and gravel | 20 | 345 |
| Blue shale | 19 | 364 |
| Lime shell | 2 | 366 |
| Blue shale | 14 | 380 |
| Herd lime she'e | 10 | 390 |
| Lime shell and shale | 30 | 420 |
| Conglomerate | 105 | 525 |
| Conglomerate (first water vein) | 70 | 595 |
| Shale and gravel | 18 | 613 |
| Shels | 37 | 650 |
| Gravel wash | 3 | 653 |
| Wash with shale breaks | 135 | 790 |
| Sand and gravel | 46 | 836 |
| Solid rock | 7 | 843 |
| TOTAL DEPTH | | 843 |

### (D-13-24)18eee

| | Thickness (ft) | Depth (ft) |
|---|---|---|
| Top soil | 2 | 2 |
| Herd clay and small gravel | 28 | 28 |
| Sand and some clay | 110 | 140 |
| Large gravel, some clay | 210 | 150 |
| Gravel and clay | 55 | 405 |
| Clay, some gravel | 115 | 520 |
| Blue shale, some gravel | 10 | 530 |
| Blue shale | 470 | 1000 |
| TOTAL DEPTH | | 1000 |

### (D-13-24)18dcb

| | Thickness (ft) | Depth (ft) |
|---|---|---|
| Cley | 90 | 90 |
| Send | 25 | 115 |
| Sandy clay | 40 | 155 |
| Cley, send streaks | 55 | 210 |
| Clay | 40 | 250 |
| Send | 15 | 265 |
| Cley | 15 | 280 |
| Cley, sticky | 30 | 310 |
| Cley | 10 | 320 |
| Send | 7 | 327 |
| Cley | 43 | 370 |
| Gravel | 5 | 375 |
| Cley | 32 | 407 |
| Clay and gravel | 33 | 440 |
| Send and gravel | 26 | 466 |
| Conglomerate | 9 | 475 |
| TOTAL DEPTH | | 475 |

### (D-16-25)10dd

| | Thickness (ft) | Depth (ft) |
|---|---|---|
| Top soil | 8 | 8 |
| Yellow conglomerata clay | 24 | 32 |
| Herd conglomerate | 28 | 60 |
| Soft yellow clay | 12 | 72 |
| First water, fine sand | 20 | 92 |
| Soft clay | 28 | 120 |
| Second water | 5 | 125 |
| Yellow clay fill | 68 | 193 |
| Heavy gravel - water | 10 | 203 |
| Herd clay | 35 | 238 |
| Fine sand - water | 2 | 240 |
| Soft yellow conglomerate | 112 | 352 |
| Heavy gravel - water | 18 | 370 |
| Heavy gravel | 142 | 512 |
| Heavy gravel | 8 | 520 |
| Hard gray conglomerate | 20 | 540 |

| (D-16-25)1add - Continued | Thickness (ft) | Depth (ft) |
|---|---|---|
| Soft brown conglomerate. . . . | 33 | 573 |
| TOTAL DEPTH . . . . . . . . | | 573 |

| (D-16-25)25aaa | Thickness (ft) | Depth (ft) |
|---|---|---|
| White lake bed . . . . . . . | 90 | 90 |
| Red sandy clay . . . . . . . | 135 | 225 |
| Good gravel . . . . . . . . | 5 | 230 |
| Red sandy clay . . . . . . . | 270 | 500 |
| Hard conglomerate. . . . . . | 75 | 575 |
| Soft conglomerate, gravel, clay | 45 | 620 |
| Hard conglomerate. . . . . . | 125 | 743 |
| TOTAL DEPTH . . . . . . . | | 745 |

| (D-16-25)6dda | Thickness (ft) | Depth (ft) |
|---|---|---|
| Top soil . . . . . . . . . | 7 | 7 |
| Caliche . . . . . . . . . | 11 | 18 |
| Clay . . . . . . . . . . | 42 | 60 |
| Water sand . . . . . . . . | 2 | 62 |
| Clay . . . . . . . . . . | 73 | 135 |
| Sand and gravel. . . . . . . | 20 | 155 |
| Sandy clay and boulders. . . . | 55 | 210 |
| Fine sand. . . . . . . . . | 12 | 222 |
| Clay and boulders . . . . . | 91 | 313 |
| Rock . . . . . . . . . . | 4 | 317 |
| Sand and gravel (good). . . . | 63 | 380 |
| Clay . . . . . . . . . . | 24 | 404 |
| Lime rock . . . . . . . . | 16 | 420 |
| Hard shale . . . . . . . . | 5 | 425 |
| Sand and gravel. . . . . . . | 62 | 487 |
| Broken clay and sand . . . . | 8 | 495 |
| Conglomerate . . . . . . . | 17 | 512 |
| Hard sand. . . . . . . . . | 4 | 516 |
| Sandy clay . . . . . . . . | 9 | 525 |
| Hard solid rock . . . . . . | 23 | 548 |
| Sand and gravel . . . . . . | 50 | 598 |
| Quartz and chert . . . . . . | 35 | 633 |
| Chert. . . . . . . . . . | 31 | 664 |
| TOTAL DEPTH . . . . . . . | | 664 |

| (D-16-26)8cdd | Thickness (ft) | Depth (ft) |
|---|---|---|
| Surface . . . . . . . . . | 3 | 3 |
| Clay . . . . . . . . . . | 137 | 140 |
| Gravel . . . . . . . . . | 4 | 144 |
| Clay . . . . . . . . . . | 21 | 165 |
| Sand . . . . . . . . . . | 5 | 170 |
| Clay . . . . . . . . . . | 11 | 181 |
| Sand and gravel . . . . . . | 13 | 194 |
| Clay. . . . . . . . . . . | 18 | 212 |
| Sand . . . . . . . . . . | 8 | 220 |
| Cley, gravel . . . . . . . | 40 | 260 |
| Sand. . . . . . . . . . . | 5 | 263 |
| Cley. . . . . . . . . . . | 11 | 276 |
| Send and gravel . . . . . . | 8 | 284 |
| Clay . . . . . . . . . . | 16 | 300 |
| Send end gravel . . . . . . | 8 | 308 |
| Cley . . . . . . . . . . | 9 | 317 |
| Sand . . . . . . . . . . | 7 | 324 |
| Cley . . . . . . . . . . | 34 | 358 |
| Sandy shale . . . . . . . | 12 | 370 |
| Cley . . . . . . . . . . | 20 | 390 |
| Sand and gravel . . . . . . | 15 | 405 |
| Cley . . . . . . . . . . | 43 | 448 |
| Sand . . . . . . . . . . | 10 | 458 |
| Cley . . . . . . . . . . | 22 | 480 |
| Sand . . . . . . . . . . | 4 | 484 |
| Conglomerate . . . . . . . | 76 | 560 |
| Send and gravel . . . . . . | 5 | 565 |
| Cley . . . . . . . . . . | 20 | 585 |
| Conglomerate . . . . . . . | 75 | 660 |
| Sand and Gravel . . . . . . | 10 | 670 |
| Conglomerate. . . . . . . | 135 | 805 |
| TOTAL DEPTH . . . . . . . . | | 805 |

Source: (Brown, Schumann, Kister, and Johnson 1963)

APPENDIX B

DISTANCES BETWEEN INDIVIDUALS
IN SAMPLE AREAS

| Control area | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Distances in feet | 17 | 11 | 16 | 12 | 22 | 10 | 10 | 5 |
| | 5 | 11.5 | 13 | 6 | 8 | 10 | 9 | 5 |
| | 5 | 11.5 | 6 | 6 | 4.5 | 14 | 9 | 11 |
| | 9.5 | 17.5 | 6 | 13 | 4.5 | 7 | 9 | 6 |
| | 7 | 13 | 6 | 6 | 26 | 7 | 10 | 6 |
| | 4 | 25 | 8 | 6 | 36 | 7 | 13 | 8 |
| | 8.5 | | 24 | 24 | 3 | 7 | 13 | 8 |
| | 6 | | 22 | 17 | 3 | 7 | 13 | 13 |
| | 6 | | | 17 | | 8 | 13 | 13 |
| | 18 | | | | | 18 | | 12 |
| | 5 | | | | | 14 | | 9 |
| | 5 | | | | | 21 | | 9 |
| | 6 | | | | | | | 7 |
| | 7 | | | | | | | 21 |
| | 7 | | | | | | | |

| Fissure Area | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Distances in feet | 0 | 35.5 | 15 | 0 | 13 | 5 | 9.5 | 0 |
| | | 35.5 | 15 | | 13 | 5 | 9.5 | |
| | | | 19 | | 8 | 5 | | |
| | | | 20 | | 8 | 8 | | |
| | | | 15 | | | 5 | | |
| | | | 15 | | | 5 | | |
| | | | . | | | 7 | | |
| | | | | | | 8 | | |
| | | | | | | 8 | | |
| | | | | | | 10 | | |
| | | | | | | 10 | | |
| | | | | | | 20 | | |
| | | | | | | 11 | | |

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PLANT REDISTRIBUTION AND DESERTIFICATION DUE TO SUBSIDENCE
FISSURES IN THE WILLCOX AREA, ARIZONA


by


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B.S., Northern Arizona University, 1982


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AN ABSTRACT OF A MASTER'S THESIS


submitted in partial fulfillment of the


requirements for the degree


MASTER OF ARTS


Department of Geography


KANSAS STATE UNIVERSITY
Manhattan, Kansas


1984

ABSTRACT

Since about 1910 groundwater has been used for irrigation
in the Willcox area of southeastern Arizona. At first only small
amounts were withdrawn from the alluvial aquifer of the area but
as agricultural development progressed, larger and larger amounts
began to be withdrawn until discharges began to greatly exceed
recharge. Owing to the nature of the sediments and geology of
the area, when significant amounts of water began to be withdrawn;
the adverse affect of land subsidence and fissuring began to occur.

In addition to subsidence and fissuring a redistribution and
desertification process affecting the natural vegetation began to
appear in areas of fissuring. It was the hypothesis of the researcher
that fissuring is responsible for these vegetational changes and as
the overdraft of groundwater from the area continues, the fissure
area will continue to expand, making it possible for vegetational
changes to occur over larger and larger areas.

The analysis of these processes was divided into two main
parts: 1) the analysis of fissuring in relation to land subsidence
and, 2) the analysis of vegetational changes in relation to fissuring.
The analysis of fissuring included an investigation of subsidence,
the construction of aquifer cross-sections in areas of fissuring to
collect information for constructing a theoretical cross-section to
explain the progression of fissuring, and the comparison of the
theoretical cross-section with the actual fissuring progression
obtained from temporal aerial photographs. The results of the
analysis indicated that as water levels decline and subsidence

continues existing fissures will expand and new fissures will occur in the direction of the valley and area of greatest water level declines and subsidence.

The vegetation analysis included the selection of a fissure area and a non-fissure area which were similar (except with respect to fissuring) and a series of nearest-neighbor analyses were done in each of them for the purpose of investigating the spatial arrangements of mesquite. Mesquite was chosen for analysis because of its dominance in the vegetation community and because of its resistance to drought. Statistical procedures used in conjunction with the nearest-neighbor analyses was a significance test of the nearest-neighbor indices and an analysis of variance of the indices in the fissure and non-fissure areas.

In addition to the nearest-neighbor analyses a small sample t-test was conducted to see if there were significant differences in the number of individuals in the sample areas between the fissure and non-fissure area. This was done to show the occurrence of a desertification process. The desertification process was further examined through the use of temporal aerial photography in which vegetational patterns and the occurrence of a barren area were traced through time.

The results of these analyses indicate that vegetation is undergoing a redistribution process in the fissure area by clustering along the fissures and a desertification process is taking place in areas downslope from fissures that bisect natural drainage.

It was concluded that as groundwater overdraft continues in the Willcox area of southeastern Arizona, the fissuring area will intensify and expand in the direction of the valley and as more

area becomes affected by fissuring, the area will be subject to vegetational changes including desertification.